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Research Paper

Evaluation of the Indirect Tensile Strength of Asphalt Concrete Containing Reclaimed Asphalt Pavement and Waste Oils using Response Surface Method

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Abstract: In spite of many environmental and economic advantages of using reclaimed asphalt pavement (RAP) in the production of new asphalt mixtures, many technical issues remain not very well understood and require further investigation, including the interactions between RAP content, rejuvenator type and rejuvenator content, and their combined effects on engineering properties of the resultant asphalt mixtures. In this study, statistical modeling tools were utilized to gain greater insight into the aforementioned interactions. The indirect tensile strength (ITS), an important engineering property which is related to the resistance against cracking and rutting of asphalt mixtures, has been selected as the primary engineering characterization tool in this investigation. The ITS of asphalt concrete mixes containing RAP (at 25, 50 and 75% by weight of total aggregates) and incorporating waste engine oil (WEO) and waste cooking oil (WCO) as rejuvenating agents (at 5, 10 and 15% by weight of total binder) was investigated using response surface methodology (RSM). As expected, the ITS was found to increase with increasing RAP content and to decreases with increasing oil content. Results also revealed that incorporating WEO resulted in higher ITS of the asphalt mixes compared to WCO. Interaction plots of test results show that the increase of ITS with increasing RAP content depends on the oil content, with higher rate for mixtures with lower oil content, and is independent of oil type. Optimization of ITS in RSM reveals that using 75% of RAP and 5% of WEO results in the highest indirect tensile strength of the mixture.

Keywords: RAP, waste cooking oil, waste engine oil, response surface method, indirect tensile strength

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1. Introduction

Cracking and permanent deformation are the main forms of distress mechanisms of asphaltic layers in pavements. Thermal and fatigue cracking are the main types of cracks in asphaltic mixtures. In addition to the reduction of structural performance, cracking is the beginning of disintegration and results in water infiltration and acceleration of pavement failure. Therefore, cracking has always been a main concern of pavement engineers. The tensile strength of asphaltic mixtures is commonly related to their resistance against cracking [Ziaee et al. 2015]. The higher the tensile strength, the higher is the resistance of the mixture against fatigue and thermal cracking [Huang et al. 2004]. Moreover, the mixtures sustaining higher strains before failure in indirect tensile strength (ITS) test are more resistant to fatigue cracking [Tayfur et al. 2007]. The tensile strength of asphaltic mixtures can be measured by direct or indirect tension. However, due to the presence of undesirable secondary stresses caused by the requirement to clamp the ends of test specimens, direct measurement of tensile strength is not very popular and the method of applying indirect tensile stress is more common. Therefore, measuring the ITS of asphaltic mixtures is an important and popular test configuration. ITS of asphaltic mixtures in dry and wet conditions is also measured to be used as an indicator for resistance against moisture damage. In this study, ITS of asphalt concrete specimens containing a wide range of RAP contents and rejuvenated by different dosages of waste engine or cooking oil has been considered for investigation.

One of the main solid wastes in construction projects is reclaimed asphalt pavement (RAP) produced after milling the damaged asphaltic layers of pavements during reconstruction or rehabilitation of existing pavements. RAP is commonly used as a replacement of virgin aggregates in the production of asphaltic mixtures. The binder in RAP has undergone ageing during the processes of production, laying and service life, which makes it vulnerable to cracking and raveling [Al-Qadi et al. 2012; Mogawer et al. 2013; Zhao and Liu, 2018; Yaghoubi et al. 2013]. Therefore, in many countries, it is not allowed to incorporate a high content of RAP in the production of new asphalt mixtures [Zargar et al. 2012; Presti et al. 2016]. Using rejuvenating agents, which can restore the original chemical composition of aged binder, allows higher RAP concentrations to be used in the production of new asphalt mixtures [Romera et al. 2006; García et al. 2011; You et al. 2011]. Various types of rejuvenators have been used in recycling asphalt mixtures in recent years. Demands on using rejuvenators have increased recently. Therefore, using waste materials, such as waste cooking oil and waste engine oil, as rejuvenators reduces the cost of asphalt production in addition to being an environmentally friendly methodology.

A large volume of engine and cooking oils are discarded every day, which adversely affect the environment. Waste engine oil (WEO) contains heavy metals such as lead, magnesium, zinc and calcium and non-degradable components [Vazquez-Duhalt, 1989; Dominguez-Rosado et al. 2004; Dedene, 2011]. A major fraction of WEO is burned or refined to be used as engine oil. Thanks to the similarity in molecular composition of engine oil and asphaltic binders, as both are derived from crude oil, WEO has been used as rejuvenating agent in recycling asphalt mixtures [Dedene, 2011]. Previous studies have revealed that adding WEO into aged asphalt mixtures can change its chemical, physical and mechanical properties [Jia et al. 2015]. Dokandari et al. [2017] found that by using waste engine oil higher RAP content can be utilized in recycled asphaltic mixtures. Jia et al. [2015] found that the addition of waste engine oil into hot mix asphalt containing RAP can compensate for the increased stiffness due to the presence of aged binder in the RAP. They also found that the optimum asphalt cement content of mixtures and rutting resistance decrease, and fatigue performance is not significantly affected by addition of WEO. Waste cooking oil (WCO) which may be plant or animal derived, is generated by households, restaurants and food industries. Nearly 10^8 tons of frying oil was used worldwide in 2008 [Rosillo-Calle et al. 2009]. Waste cooking oil is also a threat to the environment and its reuse is an environmentally friendly measure. WCO has also been used as a rejuvenating agent for aged asphaltic binder [Asli et al. 2012; Wen et al. 2012; Zargar et al. 2012; Chen et al. 2014; Su et al. 2015; Eriskin et al. 2017; Azahar et al. 2017]. Its low viscosity improves thermal cracking resistance and causes reduction of rutting resistance at high temperatures [Abdullah et al. 2016]. Adding waste cooking oil into asphaltic binder results in softening of modified asphalt and, therefore, increases its vulnerability to rutting resistance. Therefore, WCO may not be a suitable asphalt binder modifier in hot regions. By adding waste cooking oil into aged binder, Zargar et al. [2012] found that using 3–4% of WCO could restore the properties of a 40/50 aged binder to the properties of the original bitumen 80/100. Eriskin et al. [2017] found that the optimum binder content of asphalt concrete decreased, penetration is increased and softening point is decreased by modifying the binder with waste frying oil. Different engineering properties of WCO modified asphaltic mixtures have been investigated. The dynamic modulus of WCO modified asphaltic mixtures has been found to be lower than that of the control mixture [Wen et al. 2012]. Resistance against thermal cracking of WCO modified mixtures has been found to be higher than that of the control mixture [Villanueva et al. 2008; Bailey and Zoorob, 2012]. There are contradicting results about the resistance against permanent deformation. While, Bailey and Zoorob [2012], Wen et al. [2012] and Abdullah et al. [2016] found that the rut depth increases with increasing WCO content, Somé et al. [2016] have revealed that the mixtures modified by sunflower and rapeseed oil have a higher resistance against permanent deformation to the control mixture without rejuvenator. Using 5% of treated and untreated WCO into asphalt concrete, Azahar et al. [2017] found that, the resilient modulus, Marshall stability, indirect tensile strength and creep stiffness are improved by addition of 5% treated WCO. They attributed the improvement to the smoother surface resulted by the treated WCO in modified binder, observed by atomic force microscope (AFM), resulting in improvement of strength of the mixture.

Using statistical analysis methods helps to understand the interaction of independent variables on the dependent variables. Therefore, statistical analysis methods have been used in pavement studies in recent years. One of the methods is the response surface methodology (RSM), which is a set of mathematical and statistical tools for designing experiments, establishing mathematical models between one or more responses and a few variables, evaluating the independent variables and optimization of process [Kushwaha et al. 2010]. The main advantage of response surface method is reduction of the number of experiments required for evaluation of several variables and their interaction. This method consists of three main steps including conducting the designed experiments, developing a model for prediction of the response using experimental results and evaluating the adequacy of the model using statistical analysis. Response surface method can find the optimized values of variables which can produce the highest or lowest value of the desired response. It can also present the main effects and interaction of variables on the responses using 2 and 3 dimensional plots. RSM has been used in experimental studies of various subjects. In recent years it has also been used in asphalt studies [Haghshenas et al. 2015; Hamzah et al. 2015, 2017; Nassar et al. 2016; Golchin and Mansourian, 2017].

A review of the literature shows that the main and interaction effects of RAP and rejuvenator content over a wide range of dosages and type of rejuvenator on the engineering properties of recycled asphalt mixtures and optimization of the properties have not been well understood. Statistical modeling can be used to do this by modeling the relation between the independent and dependent variable. Response surface method, which has been used for many other topics in asphalt research, is an appropriate tool for interpreting asphaltic mixtures containing RAP and rejuvenators for developing models or describing the effects of different factors or finding the optimum mixture. In this study, the indirect tensile strength of asphalt concrete containing different percentages of RAP and rejuvenated by different percentages of waste cooking oil and waste engine oil has been studied using response surface method. RSM has been used to develop a model relating the indirect tensile strength and the independent variables, and to evaluate the main effects and interaction of the independent variables of RAP content, oil content and oil type on the response of ITS.

2. Research Methodology

2.1. Materials

Five types of materials including virgin asphalt, virgin aggregates, waste cooking oil (WCO), waste engine oil (WEO) and reclaimed asphalt pavement (RAP) have been used in this investigation for manufacturing a number of asphalt mixtures. PG58-16 asphalt cement produced by Pasargad Oil Co. in Iran was used as virigin binder in the mixtures. The virigin dolomite aggregates used in this study were collected from an asphalt plant in Zanjan city in Iran. Limestone filler was used for making all the mixtures. The coarse, fine and filler fractions were in compliance with the physical and chemical test requirements of national specification [IHAP, 2012]. The RAP used in this study was obtained from milled asphaltic layers of Zanjan-Myaneh road. RAP was initially graded, after which, its binder content was determined following ASTM-D2172 standard method. After separating the binder, the aggregates were graded and also angularity of coarse fraction was determined to be 91% in two faces, which satisfies the requirements of specification. Gradation of RAP aggregates is shown in Figure 1. As can be seen in Figure 1, the gradation of RAP before and after solvent extraction of asphaltic binder were very close to the edges of the lower and upper limits of gradation No. 4 in Iranian asphalt pavement code [IHAP, 2012]. The gradation of the mixtures manufactured in this study was targeted to be the middle of the limits of gradation No. 4, as shown in Figure 1.

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

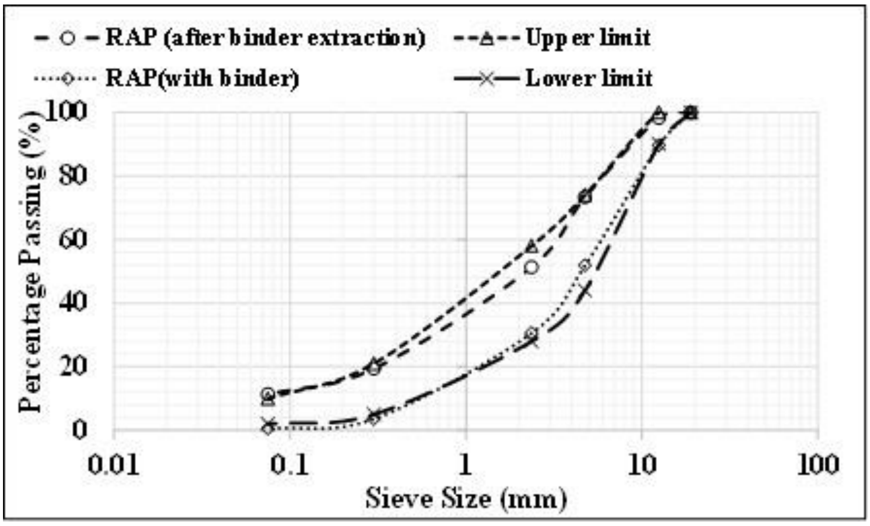


Figure 1. Gradation of RAP before and after binder extraction

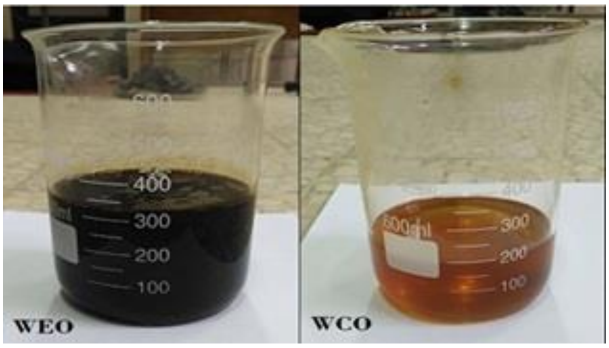


Figure 2. Appearance of waste engine oil (WEO) and waste cooking oil (WCO) used in this research

2.2. Design of Experiments and Fabrication of Samples

Response surface method in Design Expert v.10.0.7.0 was used for designing experiments in this study. The composite central design (CCD) method in RSM was utilised, which is the most popular method for design of experiments. Two numerical and one categorical variables were chosen for this research. The numerical variables include RAP content at 3 levels, namely 25, 50 and 75% (by weight of total aggregates in the mixture), waste oil content at 3 different levels, namely 5, 10 and 15% (by weight of total binder) and the categorical variable was chosen to be type of waste oil at two levels of waste cooking and waste engine oil. Table 1 shows the runs in designed expriments provided by the software. The asphalt mixtures were designed in accordance with Marshall method of mix design and in compliance with ASTM D1559. The optimum binder contents of all mixtures are shown in Table 1. In order to make the samples, the required mass of virgin aggregates were stored in oven set at 170°C for 16 hours to be dried and to attain the target mixing tempearture. The virgin binder was pre-heated in oven set at 150°C. RAP was also pre-heated at 150°C for 1.5 hours. In the first step, the correct amount of waste oil (WEO or WCO) was added to RAP and thoroughly mixed for 60 second until achieving a uniform mixture of them. The heated virgin asphalt cement and aggregates were next added and mixing continued until full coating of all aggregate particles with binder was achieved. The hot asphalt mixtures were then poured into moulds and compacted using Marshall hammer by applying 75 blows per face. The specimens were extuded from the molds after 24 hours and stored at room temperature in preparated for testing. In total 54 asphalt specimens were prepared for this study.

2.3 ITS Tests

Indirect Tensile Strength (ITS) tests were performed as per ASTM-D6931 standard method. The tests were conducted at 25°C on three replicate specimens of each mixture and the average was used for analysis. The specimens used in ITS tests were compacted to have an air voids content within 6.5 to 7.5%, by adjusting the number of blows during compaction. Asphalt specimens were conditioned in a water bath set at the test temperature for 2 hours. For measuring the ITS, the samples were loaded diametrically using Marshall test loading frame at a constant rate of deformation of 50.8 mm/min. The vertical load required for breaking each specimen was measured, and using Equation 1, the ITS (in kPa) was determined.

$$ITS = \frac{2000P}{\pi \quad t \quad D} \qquad (1)$$

Where, P is the load required for breaking the specimen in N, D and t are, respectively, the diameter and thickness of the cylindrical test specimen in mm.

2.4.Method of Analyzing Results

In this study, response surface method (RSM) in Design Expert 10.0.7.0 software was used for modeling and analysis of results and determining the main and interaction effects of variables on the indirect tensile strength. Design Expert uses mathematical and statistical methods for obtaining the best model to characterize the responses. The ITS of asphalt concrete was chosen as the response to obtain the prediction model. The general form of response function is as equation 2.

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

In which, Y is the computed response, β_0 is constant, x_i and x_j are independent variables, β_i and β_{ii} are the coefficients of the linear and quadratic 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, quadratic and interaction terms were determined. The ANOVA analysis in Design Expert was used to evaluate the adequacy of model. Adequate precision (A.P.) for the models was used to evaluate the signals to noise ratios in the analysis. To check the spread of data set away from the mean of the data standard deviation (S.D.) was used from ANOVA analysis. Coefficient of variation (C.V.), which is defined as the ratio of standard deviation to the mean value of a set of data, is used to determine the reproducibility of the developed model. After evaluating the model and its terms, the insignificant terms were deleted and the final model was obtained.

3. Results and Discussion

3.1. Analysis of Variance of Model

As mentioned earlier, the ITS test was conducted on the asphalt concrete containing different dosages of RAP and waste cooking or engine oil. The results of ITS tests are presented in Table 1. Using Design Expert software, response surface method was utilised to study the effects of RAP content, WEO and WCO content and their interaction effect on the ITS and generate an approperiate model to be able to well predict the ITS values using independent variables. The highest degree of polynomial function which has statisticaly significant terms was selected. Linear, 2 factor interaction, quadratic and cubic polynomial equations were evaluated and the quadratic was suggested by software. To check the adequacy of sugested model, the results of ANOVA in Design Expert software were used. The results of ANOVA analysis are provided in Table 2. In this table the p-values for the model and terms are provided. The model 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 model is less than 0.0001 indicating that the model is significant and adequate for prediction of ITS. In addition, the terms A (RAP content), B (oil content) and AB (the interaction of RAP and oil content) have p-values less than 0.05 and are significant factors. According to the F-values, the terms in order of effect on ITS, can be ranked as B, A and AB. However, the terms A^2, B^2, C, AC and BC have p-values more than 0.05 and are not significant. Therefore, to improve the model, the insignificant terms can be deleted. The selected model for prediction of ITS containnig RAP and rejuvenated by WEO and WCO are shown in Equation 3 and 4, respectively.

$$ITS = 415.024 + 7.397A - 12.29883B - 0.27425AB \quad (3)$$

$$ITS = 314.5556 + 7.397A - 12.29883B - 0.27425AB \quad (4)$$

In order to check the adequacy of the developed model and the regression coefficients, the values of determination coefficient (R^2), adjusted R^2, predicted R^2 and adequacy precision from ANOVA analysis in Design Expert are used, which are shown in Table 3. Value of R^2 is an indication of the goodness of fit. A minimum R^2 of 0.8 is needed to consider a model well-fitted [Montgomery, 2008]. The high value of coefficient of determination for a model indicates that there is a satisfying agreement between actual and predicted values. R^2 value of 0.97 for ITS model indicates that only less than 3% of the total variations are not explained by the developed model. The adjusted determination coefficient value of 0.9614 is high, indicating that the model is significant. The high values of R^2 and adjusted R^2 shows that there is a good agreement between the predicted and actual responses [Moghaddam et al. 2015].

Sufficient signal and developed model's adequacy for navigating the design space defined by CCD, to provide parameters for optimum mix design. Adequacy of developed model is checked by adequate precision (AP), which is a measure of signal to noise ratio of the model. AP is measured by comparing the predicted values of the response at the design points with the mean prediction error. An adequate precision value higher than 4, is an implication that the model is good [Montgomery, 2008]. The AP of 35.898 for the model for predicting ITS is an indication of sufficient signal. Moreover, the low difference between the adjusted and predicted R^2 indicates that the model is suitable for prediction of the ITS. The predicted values of ITS by the models shown in equations 3 and 4 are given in Table 1. As can be seen, the model is capable of predicting the ITS values quite accurately.

Table 1. Design of Experiments showing the actual and predicted responses

Runs	RAP content % (A)	Oil content % (B)	Type of waste oil	Measured Response - ITS (kPa)	Predicted Response - ITS (kPa)	Optimum binder content %
1	0	0	N.A.	512	-	4.5
2	25	5	WEO	503	504.227	4.5
3	25	5	WCO	451.15	403.7	4.3
4	25	10	WEO	400.5	408.5	4.5
5	25	10	WCO	293.3	308	4.5
6	25	15	WEO	306.05	273.7	4.5
7	25	15	WCO	216.75	212.3	4.4
8	50	5	WEO	618	654.8	4.5
9	50	5	WCO	524.8	554.4	4.4
10	50	10	WEO	526.6	524.8	4.5
11	50	10	WCO	451.06	424	4.4
12	50	15	WEO	409.6	394.8	4.5
13	50	15	WCO	309.47	294.4	4.4
14	75	5	WEO	795	805.51	4.5
15	75	5	WCO	733	705	4.5
16	75	10	WEO	709	641	4.5
17	75	10	WCO	503.7	540.76	4.5
18	75	15	WEO	453	477	4.5
19	75	15	WCO	371.4	376.48	4.5

Table 2. ANOVA results

	SS[a]	DF[b]	MS[c]	F-value	p-value	significance
Model	4.220E+005	8	52744.34	42.72	<0.0001	Significant
A	1.625E+005	1	1.625E+005	131.59	<0.0001	Significant
B	2.030E+005	1	2.030E+005	164.38	<0.0001	Significant
C	45422.99	1	45422.99	36.79	0.0002	Significant
A^2	473.72	1	473.72	0.38	0.5510	insignificant
B^2	0.30	1	0.30	2.450E-004	0.9879	insignificant
AB	9401.63	1	9401.63	7.61	0.0221	Significant
AC	876.38	1	876.38	0.71	0.4214	insignificant

BC	320.13	1	320.13	0.26	0.6229	insignificant

[a]Sum of Squares
[b]Degrees of Freedom
[c]Mean Squares

Table 3. Indices of model adequacy

Index	S.D.[a]	Mean	C.V.[b]	R^2	Adjusted R^2	Predicted R^2	Adequacy precision
Values	31.36	474.53	6.61	0.9705	0.9614	0.9436	35.898

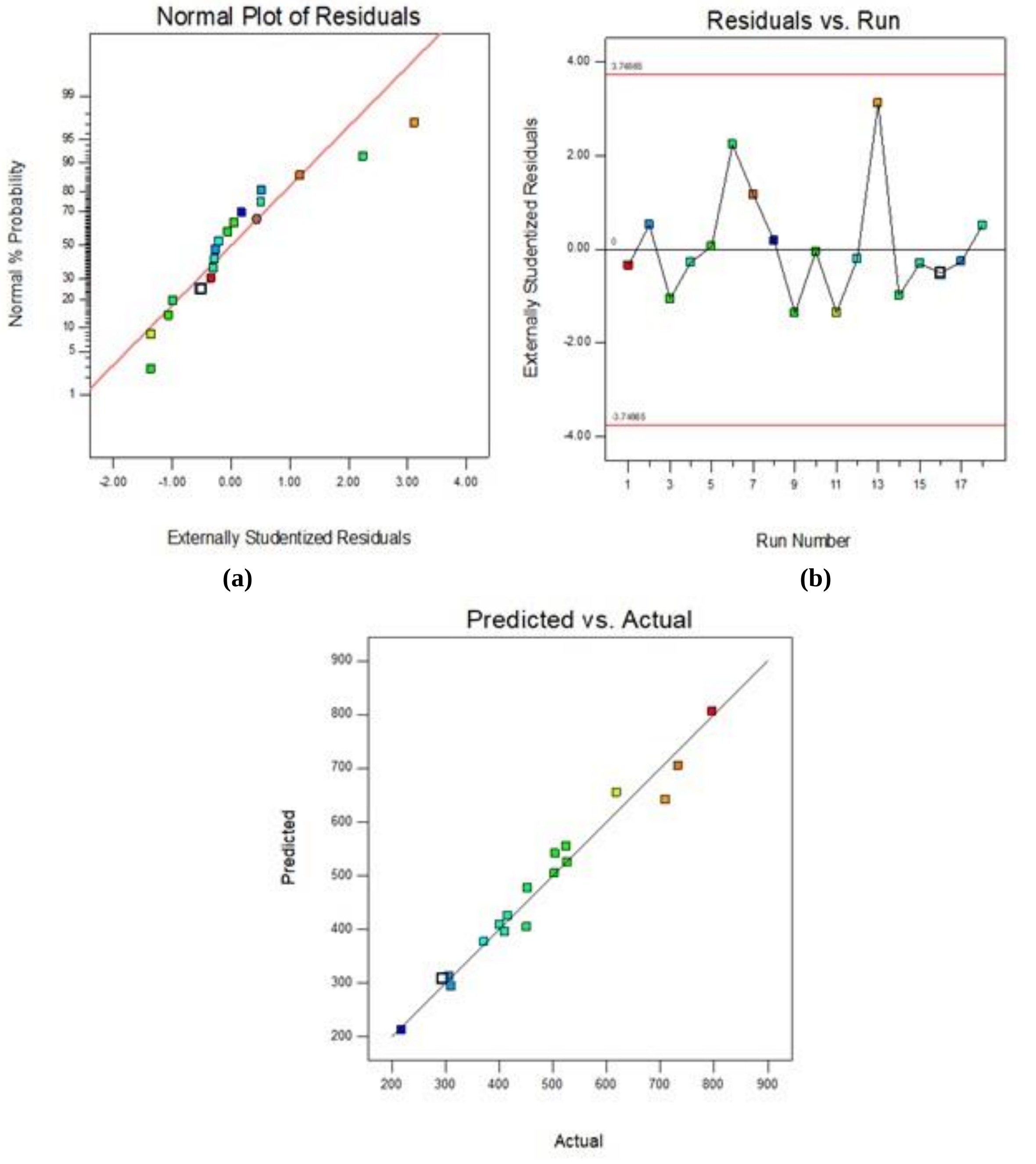
[a] standard deviation
[b] Coefficient of Variation

3.2. Analysis of Residuals and Diagnostic Plots

Figure 3(a) shows the normal probability of residuals, which 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, the residuals fall on the straight line, indicating the normal distribution of the errors and goodness of model for prediction of ITS. Independency of data is tested by the plot of residuals versus run number. Figure 3(b) shows the plot of residuals versus run number for the ITS of the mixtures. As can be seen, the residuals are randomly scattered between the levels and there is no predictable pattern. Figure 3(c) 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 ITS values measured in laboratory.

3.3. One Factor Analysis

In one factor analysis in RSM, variation of response with variation of each factor is presented. These plots are provided for a condition that the other variables are held constant. In this study, the plots of ITS variation with RAP content, waste oil content and type of oil were provided by software. Figure 4(a), (b) and (c) show, respectively, the variation of ITS with RAP content, waste oil content and type of oil. Figure 4(a) is for the conditions that oil content is 10% and oil type is WEO, and Figure 4(b) is for the conditions that RAP content is 50% and oil type is WCO. As can be seen, ITS increases with increasing RAP content, and decreases with increasing oil content. The increase of ITS with the increase of RAP content is attributed to the increase of stiffness of mixture due to the presence of stiff aged binder in RAP. The mixture with higher stiffness can sustain higher load before failure. However, adding oil results in softening of binder and decrease of cohesion which entails reduction of tensile strength. Figure 4(c) reveals that the mixtures rejuvenated with waste engine oil have higher ITS than those rejuvenated with waste cooking oil.



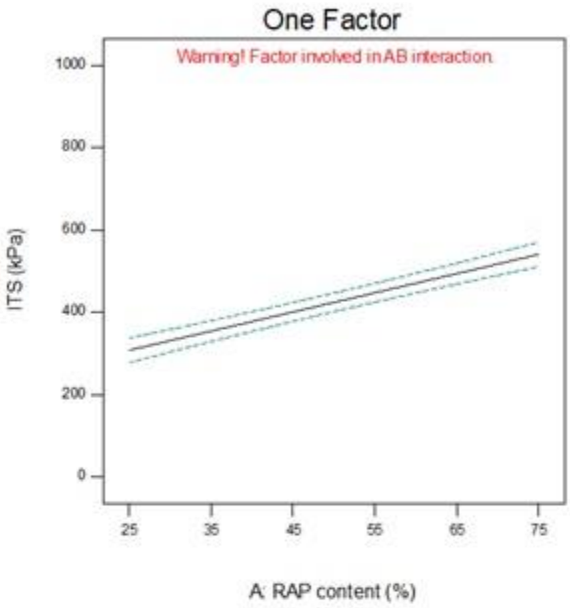
(a) (b)

(c)

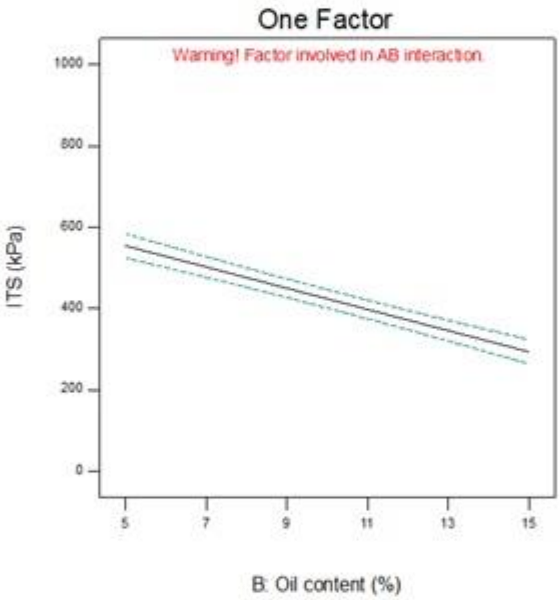
Figure 3. Diagnostic plots (a) Normal probability plot (b) Residual versus runs plot (c) Predicted versus actual plot

3.4.Perturbation Plot

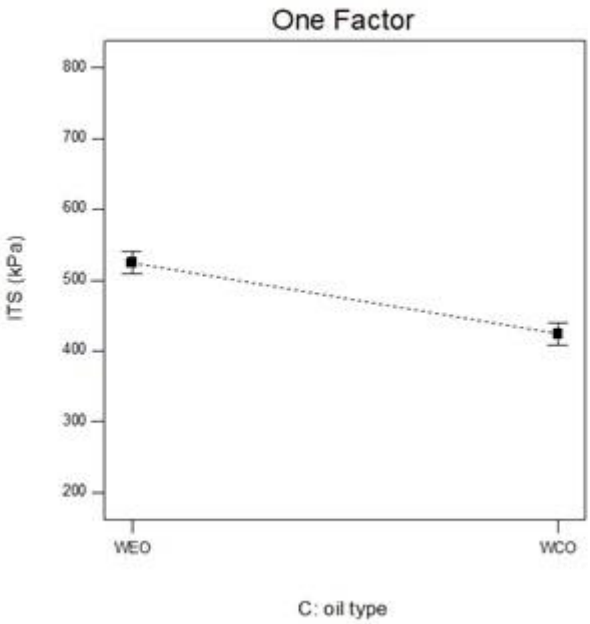
The comparison between all variables at a selected point in the considered design space is done using perturbation plot. The perturbation plots of the ITS are shown in Figure 5(a) and (b) for the mixtures rejuvenated with WCO and WEO, respectively. The ITS response has been drawn by changing only one of the variables over its range, while the other variables were constant. For these plots the oil content was held at 10% and RAP content was held at 50%. As can be seen, for both oils, RAP content has positive and oil content has negative effect on the ITS. Slightly higher slope of ITS variation with oil content than that with RAP content, indicates that the effect of oil content on ITS is more important than RAP content. This can also be seen in Table 1, in which the factor B has a higher F-value than the factor A.



(a)

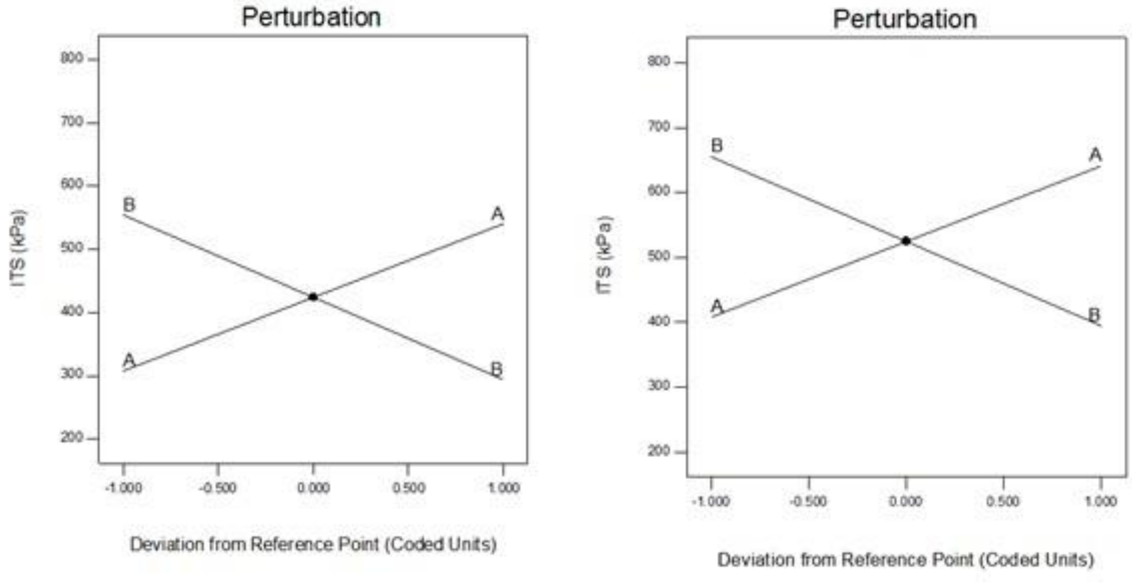


(b)



(c)

Figure 4. One factor plots (a) ITS versus RAP content (b) ITS versus oil content (c) ITS versus oil type



(a) **(b)**

Figure 5. Perturbation plots (a) WCO and (b) WEO

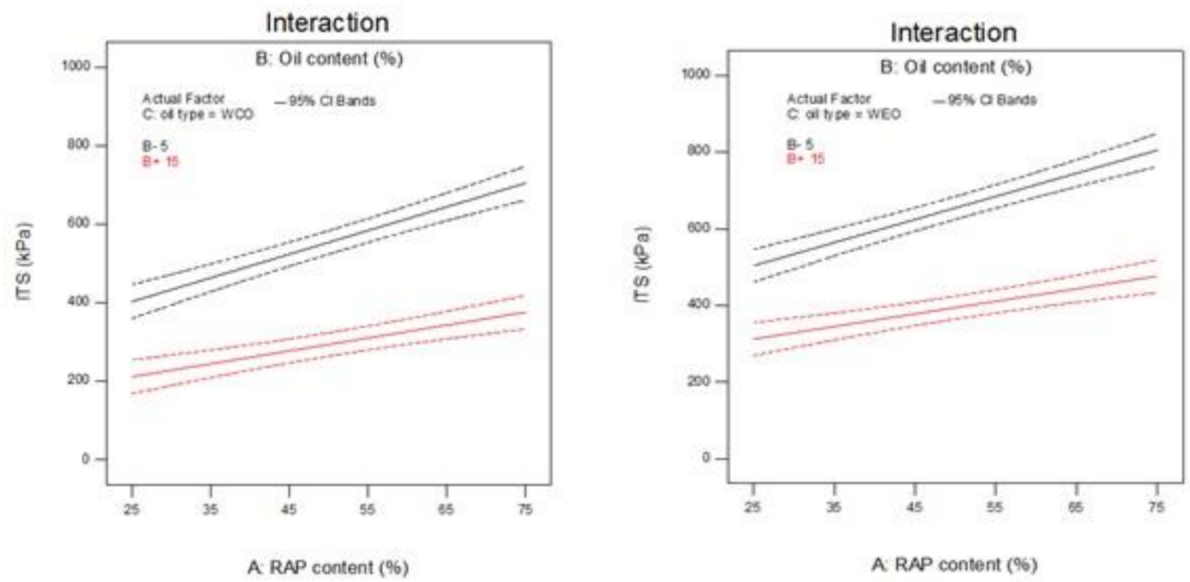
3.5. Interaction Effects of Variables

ANOVA analysis revealed that RAP and waste oil contents have interaction effects on the ITS of the mixtures. However, the interaction effect of RAP and waste oils content and type of oil is not significant, indicating that the variation of ITS with RAP content is different at various oil contents, however, it does not change with type of oil. The interaction plots in RSM can help with interpreting the interaction effects of variables. Figure 6(a) and (b) show, respectively, the interaction effect of RAP and oil content for the mixtures rejuvenated by WEO and WCO. If the curves in interaction plot are parallel it means that the variables do not have interaction effects on the responses, and if they are not parallel it means that the variables have interaction effect and the effect of one of the variables on the response depends on the level of the other variable. As can be seen in Figures 6(a) and (b), the variation curves are not parallel and the increase of ITS with RAP content changes with oil content. In mixture with a low oil content the rate of increase in ITS with RAP content is higher than that in mixture with high oil content. The trend is the same for both waste oils.

Figures 7 and 8 show the 2 and 3D plots of the variation of ITS with RAP and WEO and WCO content, respectively. As can be seen, the ITS increases with increasing RAP content and decreases with increasing oil content. For both rejuvenator types, the highest ITS is achieved when using 5% of oil content. The figures also reveal that higher ITS is achieved by using WEO than using WCO, which can be attributed to the chemical composition of the oils and the compatibility with the binder. The interaction effect of RAP and oil content is also seen in Figures 7 and 8, in which the increase of ITS with RAP content is higher for the mixtures containing lower oil content.

Figure 9 shows the ITS of the mixtures containing different RAP and waste oils content. As can be seen, the optimum mixture is achieved by using 75% of RAP and rejuvenated with 5% of WEO, for which an ITS of 805.462 kPa is achieved. For comparison, 3 samples were made using 100% of natural virgin aggregates and their ITS was measured.

The average ITS was obtained to be 512 kPa, indicating that the optimum mixture has an ITS 57% higher than the control mixture with all natural aggregate and without rejuvenator. High tensile strength as a result of higher stiffness of RAP containing mixtures may not provide desirable performance in terms of resistance against fatigue or low temperature cracking. Therefore, targeting the ITS of the control mixture, by using the optimization in Design Expert, the required WEO and WCO oil content in mixtures containing different percentages of RAP contents can be determined as shown in Table 4. As can be seen in Table 4, lower WCO is required compared to WEO to obtain a recycled mixture with the same ITS, and most likely similar stiffness as that of the control mixture.



(a) **(b)**

Figure 6. Interaction of RAP and oil content plots (a) WCO and (b) WEO

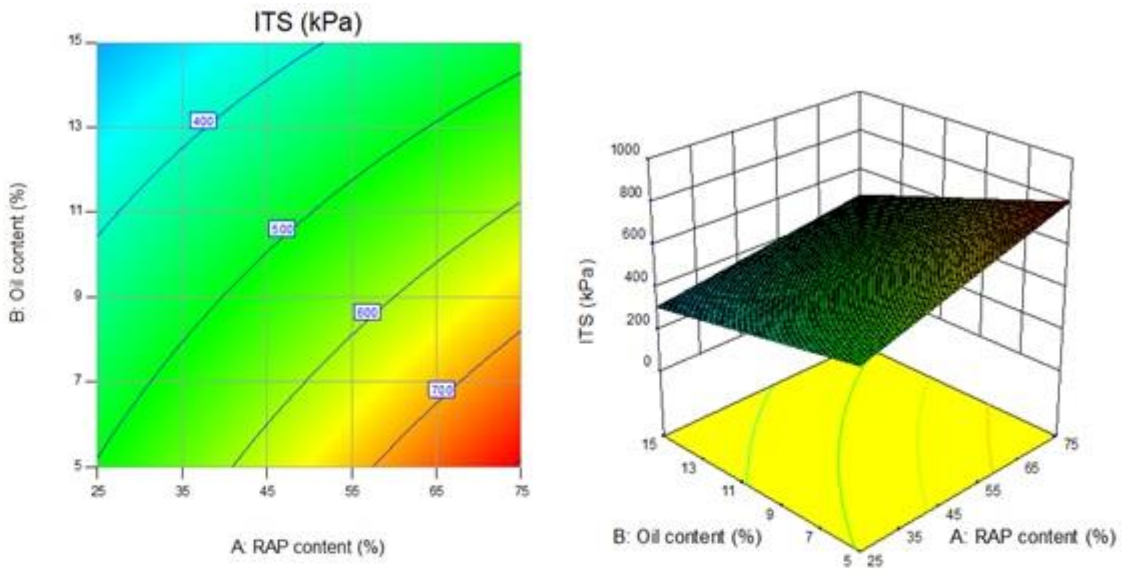


Figure 7. 2 and 3 dimensional plots of ITS variation with RAP and oil content for the mixtures containing WEO

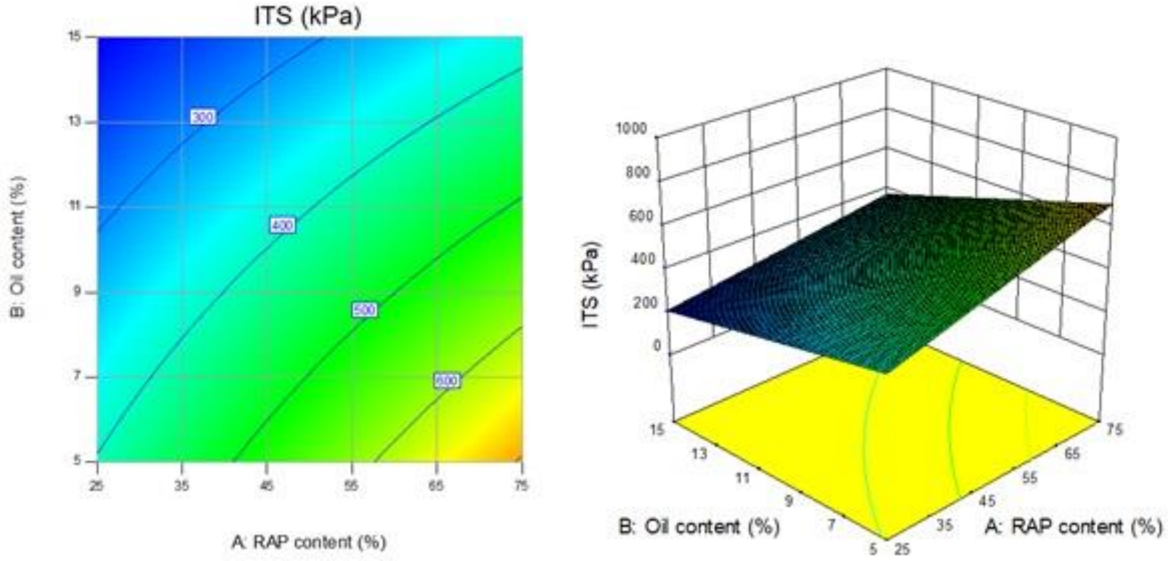


Figure 8. 2 and 3 dimensional plots of ITS variation with RAP and oil content for the mixtures containing WCO

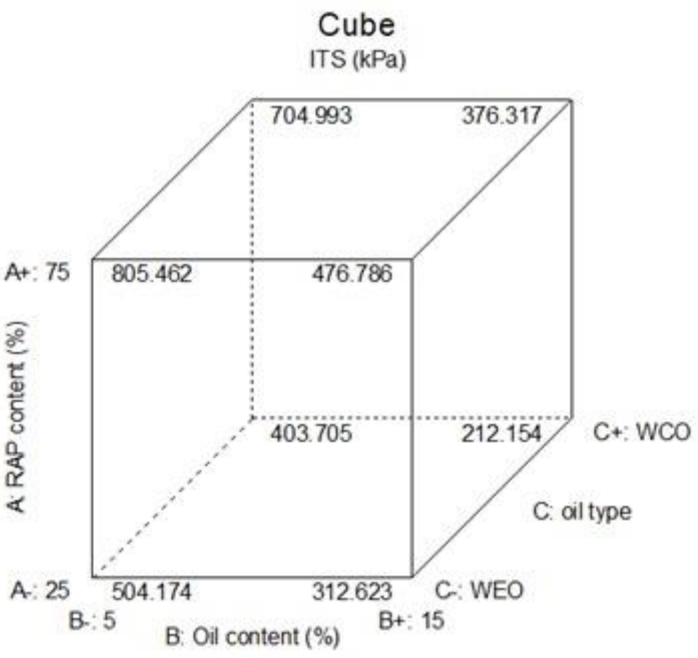


Figure 9. ITS of the mixtures containing different RAP and waste oils content

Table 4. The percentages of rejuvenating oils required to achieve ITS values of control mixture

RAP content %	Type of oil	
	WEO	WCO

25	4.6	2.7
50	10.49	6.62
75	13.92	10.87

4. Conclusions

In this research, the indirect tensile strength of asphalt concrete containing different percentages of reclaimed asphalt pavement and rejuvenated with different dosages of waste engine and waste cooking oil was measured and the results were used for developing a model for the prediction of ITS in Design Expert software. Using 2 and 3 dimensional plots created in design expert, the main effects of independent variables and their interaction on the ITS were evaluated and the optimum RAP and oil content to achieve the highest ITS was determined. The following are the main results from this study.

- The indirect tensile strength increases with increasing RAP content and decreases with increasing waste cooking and engine oil content.
- A linear 2 factor interaction model was found to be well capable for prediction of the ITS of the mixtures.
- The ITS of the mixtures rejuvenated with WEO was higher than those rejuvenated with WCO.
- Interaction effect was found between the RAP and waste oils content on the ITS, with higher rate of increase of ITS with increasing RAP content in mixtures with lower oil content.
- The interaction effect of RAP and waste oils content with type of oil was insignificant.
- The optimum design to achieve the highest ITS was found to be using 75% of RAP and 5% of waste engine oil.
- From the findings in this research, it can be suggested for the asphalt industry to use high contents of RAP without concern on the negative impacts of using high contents of RAP on resistance on cracking. It can be solved by using an appropriate dosage of rejuvenator to have properties similar to the control mixture with the same gradation.
- Further investigations are required to explore the other properties of the mixtures and interaction effects of more variables with the aid of RSM.

5. References

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