Evaluation of Fatigue Properties of Asphalt Mixtures Containing Reclaimed Asphalt Using Response Surface Method

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Abstract

This paper presents the effects of different amounts of reclaimed asphalt on fatigue life of asphalt mixtures. Central composite method was used to design the experiments based on response surface method (RSM). Binder type (Pen 60/70 and Pen 85/100), reclaimed asphalt pavement (RAP) content (25, 50 and 75%) and loading strain (150, 250 and 350 micro strain) were selected as independent variables, while 50% of initial stiffness, fatigue life and final stiffness of asphalt mixtures were chosen as dependent variables. In this research study, fatigue properties of asphalt mixtures were measured by using the four-point bending beam. The RSM analyses showed that all independent variables were significant factors for predicting the 50% of initial stiffness and fatigue life. In addition, analysis of the tests results showed that the mixtures containing higher amount of RAP at lower strains, had higher final stiffness. Furthermore, the fatigue life of specimens increased, when the level of test strains decreased. Also at the lower level of loading strain, by increasing the RAP content, the fatigue life was not decreased.

Keywords: Asphalt mixture, fatigue, stiffness, RAP, RSM

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1. Introduction

Asphalt concrete recycling is one of the asphalt pavement rehabilitation methods. Milling and post-processing of old asphalt concrete pavement is referred as reclaimed asphalt pavement (RAP). Each year millions of tons of asphalt concrete are produced from damaged asphalt pavements in the world. The disposal of this waste material in landfills has been a traditional solution, but the shortage of landfill areas, environmental regulations and related costs have prevented the safe disposal of these waste products. Due to the high price of asphalt binder, the application of RAP is widely considered [Yaghoubi et al, 2013]. Investigations show that using RAP will result in technical, economical, and environmental benefits [West et al, 2013].

Since, RAP contains aged asphalt binder, the use of higher amount of RAP is a main concern in the production of asphalt mixtures. Incorporating higher RAP contents into hot mix asphalt (HMA) may produce mixtures with lower stiffness values as compared to the mixtures without RAP [Sabouri et al, 2015]. Despite these problems, most of transportation departments are encouraging the use of RAP in flexible pavements because of its economic and environmental benefits. In the United of States, the percentage of RAP permitted for use in asphalt concrete mixes is generally limited to 25% [Boriack et al, 2014]. Although, most of transportation departments are expressing their concerns about the performance of RAP [Copeland, 2011; West et al, 2013], Boriack et al indicated that the addition of different amounts of binder to the 40% RAP mixtures decreased the rutting and fatigue resistance of asphalt mixtures [Boriack et al, 2014].

Vukosavljevic showed that fatigue life of field mixture samples decreased with inclusion of RAP, so that the adding of 30% RAP significantly decreased the fatigue life of mixtures and 20% screened RAP material would not compromise the mixture properties [Vukosavljevic, 2006]. Norouzi et al, evaluated the fatigue performance of asphalt mixtures containing RAP using viscoelastic continuum damage (VECD) method and concluded that in general, the use of RAP, especially high RAP content, decreased the fatigue resistance of hot-mix asphalts [Norouzi et al, 2014].

Mannan et al, showed that fatigue life of asphalt mixtures containing 35% RAP was lower than that of asphalt mixtures without RAP [Mannan et al, 2015]. In another research, Mangiafico et al measured the fatigue life of asphalt mixtures with 0, 20, 40 and 60 % RAP [Mangiafico et al, 2014]. They analyzed the test results using analysis of variance (ANOVA) and concluded that there was probably an optimum RAP content (from 20 to 40%) that increased the fatigue resistance of asphalt mixtures. Tabakovic et al showed that asphalt mixtures containing up to 30% RAP improved the fatigue life of asphalt mixtures as compared to the mixtures containing virgin materials [Tabakovic et al, 2010]. Ajideh et al evaluated the fatigue life of asphalt mixtures with high percentage (50%) of RAP utilizing scanning laser detection (SLD) technology and indicated that specimens with 50% RAP exhibited equal or better fatigue performance compared to those with the control mix under the controlled-stress testing [Ajideh et al, 2013]. Basueny et al measured the fatigue life of asphalt mixtures containing 0, 15, 25 and 40 % RAP and concluded that no general trend was between the amount of RAP and the number of cycles to reach fatigue failure [Basueny et al, 2016]. In addition, they indicated that high fatigue resistance was observed in asphalt mixtures containing 40 % RAP.

Literature review shows that there is less consistency among researchers about the effects of RAP on fatigue performance of asphalt mixtures. Therefore, one of the main objectives of current study is to clarify the influence of various percentage of RAP on fatigue performance of asphalt mixtures. In this study, fatigue properties of asphalt mixtures containing 25, 50 and 75% of RAP were measured by beam fatigue test apparatus and the results were analyzed using response surface method (RSM).

2. Material and Methods

2.1 Aggregate

The aggregate used in this research was obtained from an asphalt plant located in the west part of Tehran province. The nominal maximum aggregate size was 19 mm. Tables 1 and 2 show the aggregate properties and aggregate gradation, respectively.

Table 1. Aggregate properties

Test	Test method	Results	Acceptable range(according to Iran asphalt pavement code)
Specific gravity	ASTM C-127	2.485	-
Los Angeles abrasion (%)	AASHTO T-96	16	≤25
Water absorption (Coarse aggregate) (%)	AASHTO T-85	2.6	≤2.8
Water absorption (Fine aggregate) (%)	AASHTO T-84	2.5	≤2.8
Percent fracture (one face) (%)	ASTM D5821	93	≥80
Percent fracture (two faces) (%)	ASTM D5821	81	≥75
Elongation index	BS 812	15	≤15
Flakiness index	BS 812	25	≤30

Table 2. Aggregate gradation

Sieve size (mm)	Percent passing	Lower limit	Upper limit
25	100	100	100
19	92	90	100
9.5	70	56	80
4.75	50	35	65
2.36	36	23	49
0.3	11	5	19
0.075	5	2	8

2.2 Base Binders

Two asphalt binders, 60/70 and 85/100 (Pen 60/70 and Pen 85/100), based on penetration grade were used in this study. The properties of these binders are presented in Table 3.

2.3 Reclaimed Asphalt

Reclaimed asphalt in this research was prepared from an asphalt pavement in Tehran province. Tables 4, 5 and 6 show the properties of aggregate, aggregate gradation and binder extracted from reclaimed asphalt, respectively.

Table 3. Properties of two types of asphalt binders used

Test	Test method	Results		Acceptable range	
		60/70	85/100	60/70	85/100
Specific gravity (25° C)	ASTM D70	1.016	1.000	-	-
Flash point (Cleveland)(°C)	ASTM D92	310	298	≥232	≥232
Penetration (25° C)(0.1 mm)	ASTM D5	69	85	60-70	85-100
Ductility (25° C) (cm)	ASTM D113	>100	>100	>100	>100
Softening point (°C)	ASTM D36	49	48	49-56	45-52
Kinematic viscosity @ 120 ° C (Centistokes)*	ASTM D2170	832	797	-	-
Kinematic viscosity @ 135 ° C (Centistokes)*	ASTM D2170	440	372	-	-
Kinematic viscosity @ 150 ° C **(Centistokes)***	ASTM D2170	137	133	-	-

This test was performed to obtain the appropriate mixing and compaction temperatures of asphalt mixtures

Table 4. Properties of reclaimed asphalt aggregate

Test	Test Method	Results
Bitumen content	ASTM D2172	5.4
Water absorption (Coarse aggregate) (%)	ASTM C127	2.1
Water absorption (Fine aggregate) (%)	ASTM C128	2.51
Specific gravity (Coarse aggregate)	ASTM C127	2.495
Specific gravity (Fine aggregate)	ASTM C128	2.502

Table 5. Aggregate gradation of reclaimed asphalt

Sieve size (mm)	Percent passing
19	100
9.5	98
4.75	78
2.36	52
0.3	17
0.075	9

Table 6. Properties of extracted binder

Test	Test method	Results
Penetration (25° C)(0.1 mm)	ASTM D5	20
Softening point (°C)	ASTM D36	72
Kinematic viscosity @ 135 °C (Centistokes)	ASTM D2170	1977

2.4 Mix Design and Fabrication of Specimens

The optimum binder contents of the control mixtures were determined using Marshall design method (ASTM D1559) with 75 blows on each side. The optimum binder contents were 5.5% and 4.9% for mixtures containing Pen 60/70 and Pen 85/100, respectively. The mixtures containing different amounts of RAP were made by the same optimum binder content, so that the amount of asphalt binder would not confound the analysis of the test results.

2.5 Beam Fatigue Test

In this research, the fatigue resistance of asphalt mixtures was obtained using four-point bending beam method (ASTM D7460) using the IPC global universal testing machine (UTM-14). For preparing the specimens of fatigue test, the asphalt mixtures were compacted by means of a wheel compactor and then sawn to prepare the specimen with dimension of 380 × 50 × 63 mm. The fatigue tests were conducted by placing the beams of asphalt mixtures (380 × 50 × 63 mm) in repetitive four-point loading at strain levels of 150, 250 and 350 microstrains. During the test, the beams were held in place by four clamps and a repeated haversine load was applied to the two inner clamps (Figure 1). The loading frequency rate was set at 10 Hz. The deflection due to the loading was measured at the center of the specimen. Tests were performed at 20°C, because fatigue cracking is usually considered as an asphalt mixture distress at intermediate temperatures [Stuart and Mogawer, 2002; Al-Khateeb, 2008]. Maximum tensile stress, maximum tensile strain and flexural beam stiffness were calculated by equations 1-3, respectively for each load cycle.

$$\sigma_t = \frac{3aP}{bh^2} \qquad (1)$$

$$\varepsilon_t = \frac{12\delta h}{3L^2 - 4a^2} \quad (2)$$

$$S = \frac{\sigma_t}{\varepsilon_t} \quad (3)$$

Where σ_t is the maximum tensile stress, a is the center to center spacing between clamps (m), P is the load applied by the actuator (N), b is the average specimen width (m), h is the average specimen height (m), ε_t is the maximum tensile strain, δ is the maximum deflection at center of beam (m), L is the length of beam between outside clamps and S is the flexural beam stiffness.

The stiffness at the 50th load cycle was considered as initial beam stiffness. The fatigue criteria of the beam specimen were defined as the stiffness reduced to 50 percent of the initial beam stiffness or failure the beam (whichever occured first).

2.6 Central Composite Design Method (CCD)

In this study, fatigue properties of asphalt mixtures containing 25, 50 and 75% RAP were measured by the beam fatigue test apparatus and the results were analyzed using response surface method. For this purpose, central composite design (CCD) method was used for designing the experiments. CCD is a fractional factorial experimental design that is able to present a relationship between responses and test factors over a range of factor levels [Nassar, Thom and Parry, 2016]. RAP content and loading strain were considered as numerical test variables, while the binder type was considered as a categorical test variable. Table 7 presents the experiment matrix for the test factors and responses. In this table, asphalt binder types of A and B are related to asphalt binders of 60/70 and 85/100, respectively. Figure 2 shows the framework of the research.

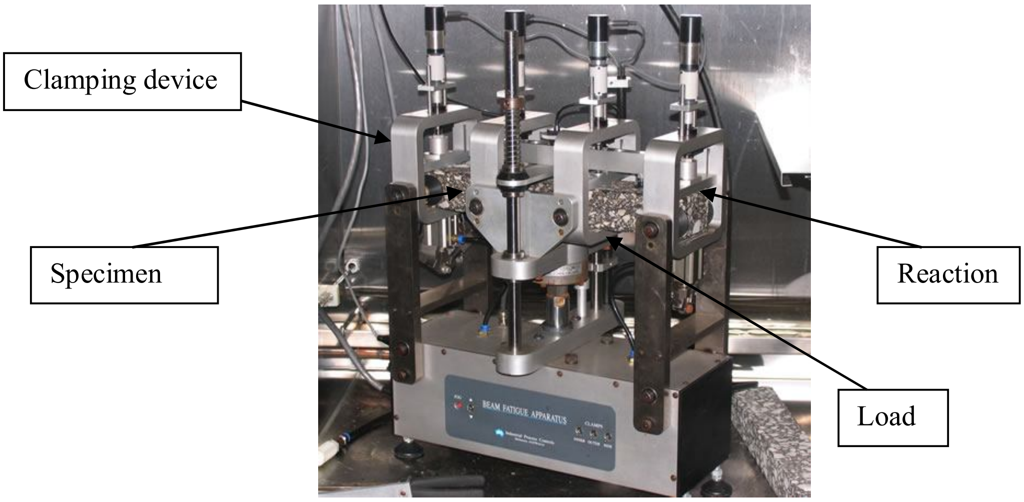

Figure 1. Beam fatigue test device

Table 7. Experiment matrix and obtained fatigue results

Test factors (Independent variables)			Test responses (Dependent variables)		
RAP content	**Asphalt Binder type**	**Loading strain**	**50% of initial stiffness**	**Fatigue life (Number of cycles)**	**Final stiffness**
25	A[*]	150	2091	2500000	2920
25	A	250	2035	907000	2035
25	A	350	2637	216560	2637
25	B[**]	150	2403	2500000	3113
25	B	250	2653	2315040	2653
25	B	350	2228	711420	2228
50	A	150	2399	3000000	5214
50	A	250	2424	501940	2424
50	A	350	2099	40950	2099
50	B	150	2946	2507690	4146
50	B	250	3131	803690	3131
50	B	350	2126	340430	2126
75	A	150	3491	2500000	4829
75	A	250	3509	396210	3509
75	A	350	1629	33160	1629
75	B	150	4404	2500000	4822
75	B	250	3722	281040	3722
75	B	350	3759	36210	3759

[*] 60/70 Asphalt binder; [**] 85/100 Asphalt binder

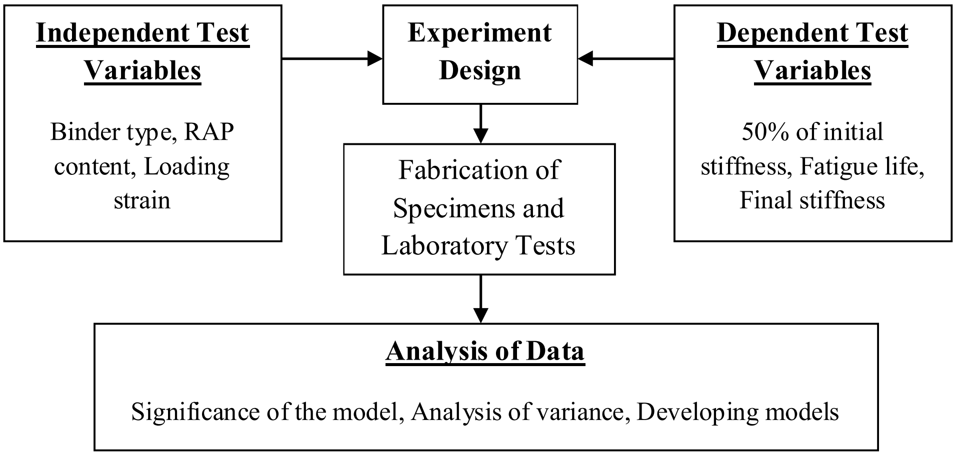

Figure 2. Research framework

2.7 Response Surface Method (RSM)

RSM is a collection of statistical tools for designing experiments, generating mathematical models and evaluating the influences of the experiment factors and optimizing the process [Kushwaha, Sirvastava and Mall, 2010]. Resulted data from the experimental tests were used to develop mathematical models via statistical techniques. The significant of the model was evaluated by F-test and lack of fit test while goodness of fit was evaluated by R-squared. The influences of the experiment factors were evaluated by analysis of variance (ANOVA). Equations 4, 5 and 6 show simple forms of linear, two-factor interaction (2FI) and quadratic models for two independent factors, respectively:

$$Y=C_0+C_1X_1+C_2X_2 \quad (4)$$

$$Y=C_0+C_1X_1+C_2X_2+C_{12}X_1X_2 \quad (5)$$

$$Y=C_0+C_1X_1+C_2X_2+C_{12}X_1X_2+C_{11}X_1^2+C_{22}X_2^2 \quad (6)$$

Where Y is the response, X_1 and X_2 are the independent factors, and C_0, C_i, C_{ii}, and C_{ij} are the intercept, linear, quadratic, interaction coefficients, respectively. Recently, RSM has been used in asphalt mixture studies [Hamzah et al, 2015; Haghshenas et al, 2015; Nassar, Thom and parry, 2016; Hamzah, Gungat and Golchin, 2016]. Design-expert 6.0.6 software is a popular statistic tool for designing of experiments and analysis based on RSM [Myers, Montgomery and Anderson-Cook, 2009]. In this study, this software was used for designing the experiment, selecting appropriate mathematical models to fit data, analysis of variance (ANOVA) and plotting the graphs.

3. Results and Discussion

The effects of binder type, RAP content and loading strain on 50% of initial stiffness, fatigue life and final fatigue stiffness are presented in Table 7. This table shows that at a fixed loading strain, 50% of initial stiffness and final stiffness of beam specimen generally increases when RAP content increases. For each RAP content, higher final stiffness of beam specimen is normally related to the lower level of loading strain. Similarly, higher number of cycles at the end of fatigue test is observed for specimen subjected to lower level of loading strain. In higher level of strain (250 and 350), when RAP content increases, the fatigue life decreases.

In next sections, the effects of test parameters on the 50% of initial stiffness, final stiffness and fatigue life of asphalt specimens are separately discussed.

3.1 50% of Initial Stiffness

Three regression models including quadratic, linear and two-factor interaction models were examined to fit data for prediction of 50% of initial stiffness. Analysis of data showed that two factor interaction model was a suitable regression model as shown in Table 8. This model showed lower p-value in sequential F-test and acceptable R-squared value. Although the R^2 value of this model is relatively low, however Prob>F value is low. Lower Prob>F value is more preferable. ANOVA results are presented in Table 9. This table shows that RAP content, loading strain, binder type, interaction between RAP content and loading strain have significant effects on the 50% of initial stiffness of the beam specimens. A “Prob>F” value less than 0.05 demonstrates significant factors and significant interactions between two factors. The degree of significance of RAP content is higher than that of the loading strain and binder type. Higher F value shows higher degree of significance for the test factors (see F-values in Table 9).

Table 8. Models proposed for prediction of fatigue properties

Title	Sum of Squares	DF*	Mean Square	F Value	Prob> F	Model type
50% of Initial stiffness						
Regression	1.66E+06	3	5.53E+05	2.74	0.0936	2FI**
Residual error	9.20E+05	4	2.30E+05			
R-squared	0.7706					
Ln (Fatigue life)						
Regression	4.48	3	1.49	13.07	0.0006	2FI
Residual error	0.62	4	0.15			
R-squared	0.9689					
Final stiffness						
Regression	1.34E+07	3	4.45E+06	10.39	0.0007	Linear
Residual error	9.13E+05	4	2.28E+05			
R-squared	0.6901					

[*] Degree of freedom

[**] Two-factor interaction model

Table 9.Analysis of variance (ANOVA)

50% of Initial stiffness				
Factor*	Sum of Squares	DF**	F value	Prob> F
A	3.49E+06	1	17.3	0.0016
B	8.84E+05	1	4.38	0.0602
C	1.42E+06	1	7.05	0.0224
AB	1.04E+06	1	5.14	0.0446
AC	6.23E+05	1	3.09	0.1064
BC	48	1	2.38E-04	0.988
Ln (Fatigue Life)				
Factor	Sum of Squares	DF	F value	Prob> F
A	5.06	1	44.24	< 0.0001
B	28.68	1	250.82	< 0.0001
C	1.02	1	8.9	0.0124
AB	2.95	1	25.76	0.0004
AC	0.47	1	4.13	0.0669
BC	1.06	1	9.31	0.011
Final stiffness				
Factor	Sum of Squares	DF	F value	Prob> F
A	3.72E+06	1	8.7	0.0106
B	9.30E+06	1	21.73	0.0004
C	3.21E+05	1	0.75	0.4011

[*] A, RAP content; B, Loading strain; C, Binder type;

[**] Degree of freedom.

Proposed equations for prediction of 50% of initial stiffness of beam specimens from fatigue test are expressed by equations 7 and 8. Regression coefficients of these equations indicate that by increasing the RAP content, the 50% of initial stiffness of specimens increases while interaction between RAP content and loading strain decreases the value of 50% of initial stiffness. Figure 3 shows counter plot of the 50% of initial stiffness versus the RAP content and loading strain. From the figure, 50% of initial stiffness decreases when RAP content reduces. For example, minimum value of this response is related to mixtures containing 25% RAP. This can be attributed to the combination of recycled and virgin materials. In addition, higher level of stiffness is observed at lower strains. For example, maximum value of this stiffness occurs at 150 microstrain. In Figure 4, the predictive and actual values of 50% of initial stiffness are illustrated.

Binder type A (7)

$$\begin{aligned} \text{50\% of initial stiffness} = {} & 281.0833 \\ & +57.53167 \quad * \text{RAP content} \\ & +4.48167 \quad * \text{Loading strain} \\ & -0.1439 \quad * \text{RAP content} * \text{Loading strain} \end{aligned}$$

Binder type B (8)

$$\begin{aligned} \text{50\% of initial stiffness} = {} & 843.0833 \\ & +57.53167 \quad * \text{RAP content} \\ & +4.48167 \quad * \text{Loading strain} \\ & -0.1439 \quad * \text{RAP content} * \text{Loading strain} \end{aligned}$$

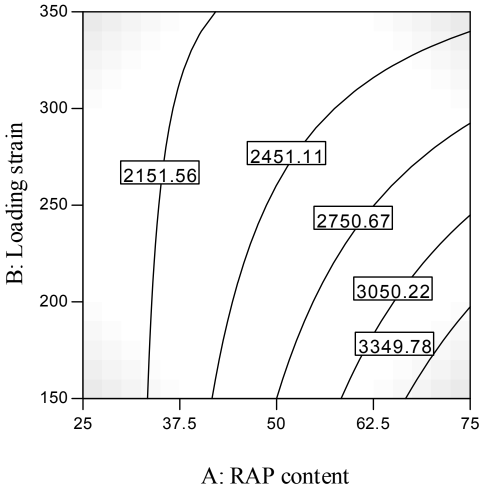

Figure 3. Counter plot of 50% of initial stiffness versus RAP content and loading strain

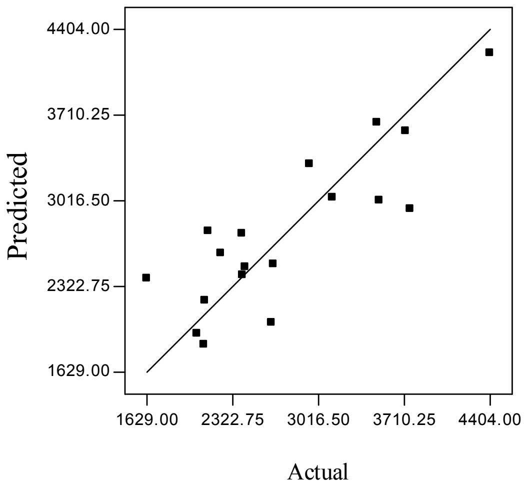

Figure 4. Predictive and actual values of 50% of initial stiffness

3.2 Fatigue Life (FL)

Regression analysis using RSM showed that transformed values of fatigue life (Ln(FL)) show acceptable regression parameters for developing mathematical equations (see Table 8). According to Table 8, a two-factor interaction regression model was used to quantify the influence of RAP content, loading strain, binder type on FL value. This model shows a high R^2 value and low Prob>F value. ANOVA results are presented in Table 9. From the table, RAP content, loading strain, binder type, interaction between RAP content and loading strain and interaction between binder type and loading strain had significant effects on the prediction value of Ln(FL). Equations 9 and 10 show the relationship between test factors and Ln(FL). These regression equations show that RAP content has positive effect on Ln(FL) while loading strain and interaction between loading strain and RAP content has negative effect on Ln(FL). Counter plot of Ln(FL) versus loading strain and RAP content is presented in Figure 5. From the figure, Ln(FL) increases when loading strain decreases. At lower level of loading strain, increasing the RAP content from 25% to 75% does not show significant effect on Ln(FL). On the other hand at higher level of loading strain, Ln(FL) increases when RAP content decreases. As a result, minimum value of this response occurs at 75% RAP content and at higher level of loading strain.

In addition, Figure 6 shows the predictive and actual values of Ln(FL). The closeness of the actual and predicted values to the 1:1 line expresses the capability of the developed regression models for predicting the value of Ln(FL).

Binder type A

Ln(FL) = 15.52446 (9)
+0.042649 * RAP content
-0.0063 * Loading strain
-0.00024 * RAP content * Loading strain

Binder type B

Ln(FL) = 15.30464 (10)
+0.02677 * RAP content
-0.00034 * Loading strain
-0.00024 * RAP content * Loading strain

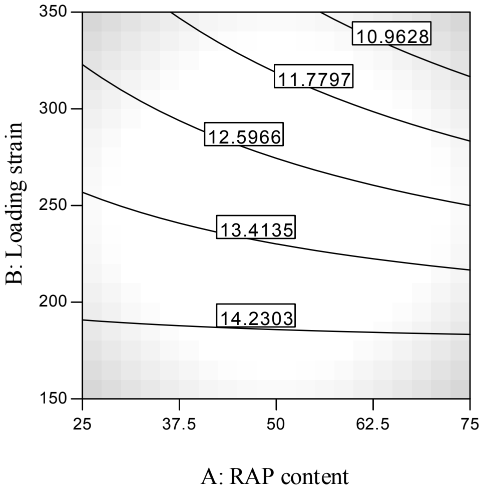

Figure 5. Counter plot of Ln(FL) versus RAP content and loading strain

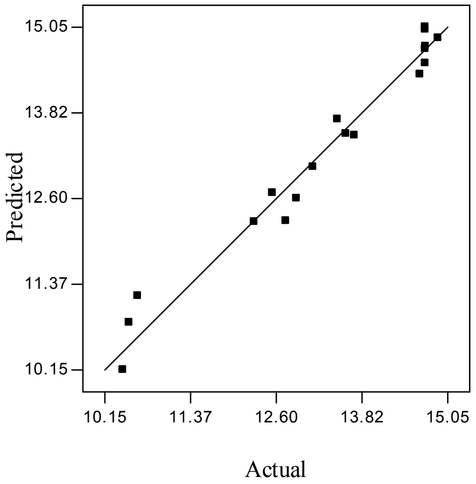

Figure 6. Predictive and actual values of Ln(FL)

3.3 Final Stiffness

Based on the parameters mentioned in Table 8, a liner regression model can be selected for the prediction of the value of final stiffness. Although the R^2 value of this model is relatively low, however Prob>F value is low. Lower Prob>F value is more preferable. ANOVA results indicate that RAP content and loading strain exhibit significant effects on the value of final stiffness. Equations11 and 12 express the relationship between final stiffness and test factors. According to these equations, Figure 7 shows the effect of RAP content and loading strain on the predicted value of final stiffness. From the figure, by increasing RAP content or by decreasing loading strain, the final fatigue stiffness of beam specimens increases. It means that, asphalt mixtures containing high amount of RAP at all level of loading strain (from 150 to 350 microstrains) will not show a lower level of final fatigue stiffness. Figure 8 presents the predicted versus actual values for final stiffness.

Binder type A

$$\begin{aligned} \text{Final stiffness} = {} & 4120.139 \\ & +22.28 \quad * \text{ RAP content} \\ & -8.805 \quad * \text{ Loading strain} \end{aligned} \qquad (11)$$

Binder type B

$$\begin{aligned} \text{Final stiffness} = {} & 4387.25 \\ & +22.28 \quad * \text{ RAP content} \\ & -8.805 \quad * \text{ Loading strain} \end{aligned} \qquad (12)$$

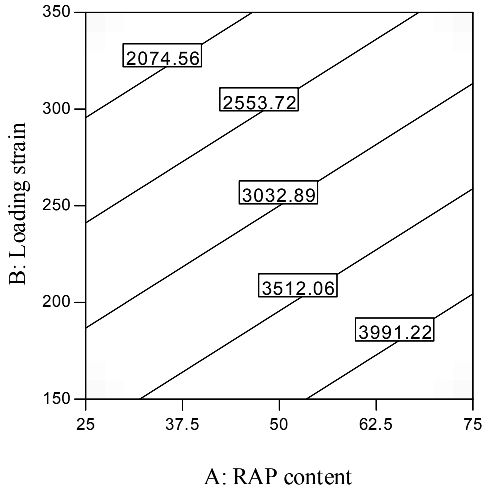

Figure 7. Counter plot of final stiffness versus RAP content and loading strain

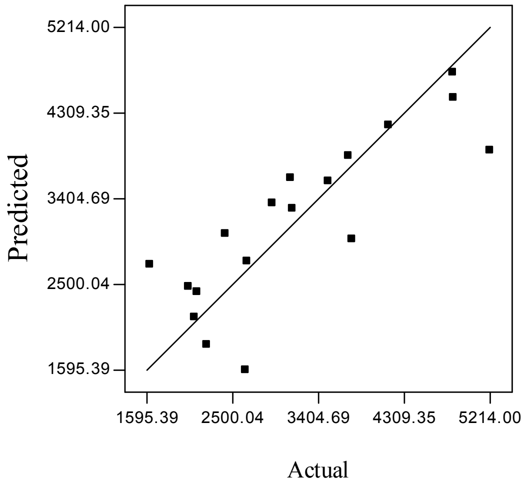

Figure 8. Predictive and actual values of final stiffness

4. Conclusions

In this study, fatigue properties of asphalt mixtures containing different amounts of RAP were tested at various loading strain and quantified through RSM for two conventional asphalt binders in Iran. RSM was statistically used for designing experiment and analyzing data. Also, interaction effects between test factors were simultaneously evaluated. RSM analyses showed that RAP content and loading strain had significant effect on 50% of stiffness, final stiffness and fatigue life. Also interaction between RAP content and loading strain exhibited significant effect on 50% of stiffness and fatigue life. A liner regression relationship was observed between final fatigue stiffness and test factors. In this research, the number of tests and level of strains have been limited. Based on this limitation, obtained results showed that by increasing the level of strain, the values of final stiffness, fatigue life and 50% of fatigue stiffness decreased. Mixtures containing higher amount of RAP showed higher final and 50% of stiffness in fatigue tests. At lower level of loading strain, increasing the RAP content from 25% to 75% did not change the transformed value of fatigue life (Ln(FL)). Generally, specimens with higher amount of RAP tested at lower level of strains exhibited a better fatigue stiffness.

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