Chapter

Application of Response Surface Method for Analyzing Pavement Performance

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Abstract

Hot mix asphalt (HMA) is a common material that has been largely used in the road construction industries. The main constituents of HMA are asphalt binder, mineral aggregate, and filler. The asphalt binder bounds aggregate and filler particles together and also waterproofs the mixture. The aggregate acts as a stone skeleton to impart strength and toughness to the structure, while the filler fills pores in the mixture which can improve adhesion and cohesion as well as moisture resistance. The HMA behavior depends on individual component properties and their combined reaction in the mixture. Asphalt binder properties change due to different factors. Over the years, asphalt pavement materials age, causing binder embrittlement which adversely affects pavement service life. Response Surface Method (RSM) is a set of techniques that are used to develop a series of experiment designs, determining relationships between experimental factors and responses, and using these relationships to determine the optimum conditions. Incorporating RSM in pavement technologies can beneficially help researchers to develop a better experimental matrix and give them the opportunity to analyze the changes in pavement performance in a faster, more effective, and reliable way.

Keywords: hot mix asphalt, road construction, short-term aging, pavement performance, optimization

1. Introduction

Infrastructure plays a pivotal role in all countries' social and economic development. The road construction industry consumes a huge amount of energy and non-renewable materials. According to the literature, the United States followed by China, Canada and Australia annually produced approximately 500, 150, 45, and 8 million tons of asphalt mixtures, respectively, which lead to the dedication of a significant amount of funds not only to pavement construction but also on pavement maintenance and rehabilitation (M & R) [1–3]. Incorporation of high-quality construction materials, proper construction strategy and equipment, and consequently evaluation of pavement performance along with proper M&R activities, can prevent premature failures in road networks and supply safety and convenience for road users.

Hot Mix Asphalt (HMA) has been widely used for road construction. HMA mainly consists of asphalt binder, mineral aggregate, and filler. The HMA behavior depends on individual component properties and their combined reaction in the mixture. However, the binder is the dominant constituent that controls asphalt mixtures' overall performance. Asphalt binder is a complex organic material. The primary factor affecting the durability of the asphalt mixtures is binder age hardening. Aging in itself is a complex physico-chemical phenomenon. Aging by changing asphalt binder chemical and rheological properties cause binder embrittlement which adversely affects pavement service life [4, 5]. Aging can be divided into short-term and long-term stages. Short-term aging is a result of binder volatilization and oxidation which increase binder viscosity and results in stiffer mixture. Although aging enhances the load-bearing capacity and permanent deformation resistance of pavements by producing stiffer mixtures, it can also cause or accelerate several distresses such as fatigue, low-temperature cracking, and moisture damage by reducing pavement flexibility.

A study to clearly understand the effects of short-term aging on asphalt binder and mixture properties may help to predict asphalt mixtures performance and design a better mixture which can lead to longer-lasting pavements that require less maintenance cost and time while being in service. In this regard, different conditioning scenarios and failure aspects were studied to understand the binder and mixtures' performance before and after aging. Response Surface Method (RSM) as one of the promising methods was therefore employed to assist the experimental matrix design and evaluation procedures.

RSM can establish the relationships between experimental factors and responses by combining and analyzing a series of experiment designs. RSM has been widely used in several disciplines such as environment, material and chemical sciences as well as pavement engineering. Khodaii et al. (2012) used RSM to evaluate the effects of aggregate gradation and lime content on the tensile strength ratio of dry and saturated hot mix asphalt [6]. Jamshidi et al. (2013) determined the changes in the rheological properties of asphalt binder which was modified by different amount of Sasobit at high temperatures using RSM [7]. Kavussi et al. (2014) used the same technique to evaluate the effects of aggregate gradation, hydrated lime and Sasobit content on the indirect tensile strength of warm mix asphalt (WMA) [8]. Hamzah et al. (2015) utilized the RSM to study the effects of elongated short-term aging on the rheological properties of binder at intermediate temperatures [9]. Hamzah and Omranian (2016) studied the effects of aging on the asphalt binder behavior at high temperatures by applying RSM [10]. Saha and Biligiri (2017) used RSM to optimize the asphalt mixtures fracture toughness characteristics that affect cracking performance [11]. RSM was also employed by Omranian et al. (2018, 2020) to study the impact of short-term aging on mixtures fracture and volumetric properties, respectively [12, 13]. Li et al. (2018) evaluated the incorporation of recycled pavement concrete on mixtures mechanical properties. It was found that the three RSM relation models were fit well and effectively represent the mixtures characteristics after a series of fatigue and freeze–thaw cycles [14]. Long et al. (2019) studied the impacts of corrosion, fatigue, and fiber content on the pavement concrete mechanical properties and revealed that RSM model fits well with pavement performance [15]. In other material study, Hou et al. (2020) clearly demonstrated the great potential of RSM in developing magnesium phosphate cement in patch repair and maintenance works [16]. Bala et al. (2020) successfully used RSM to optimize nano-silica and binder content for nanocomposite-modified asphalt mixtures for replacing and reducing the application of polymer-modified binders [17]. Lapian et al. (2021) also determined the optimum conditions of incorporating plastic waste in asphalt mixing, using RSM, to improve the performance in terms of mixtures failure resistance under repetitive loading [18]. The successful application of RSM technique in the previous studies indicates its capability to characterize the complex behavior of asphalt binders and mixtures.

In this article, the effects of aging on the asphalt binder and mixtures performance will be discussed. The aging conditions and experimental plans were designed using the RSM. RSM was also used to develop regression models and predict the binder and mixture's behavior subjected to short-term aging.

2. Materials and methods

In this study, four different binders were used for both binder and three of them were selected for mixture testing. Following the previous publications and for ease of reference, binders and mixtures are designated according to their source, type and constituents [9, 12]. Binders A1 and A2 refer to the conventional penetration grade 80/100 and 60/70 binders from Source A, respectively. Binders B1 and B2 refer to the conventional penetration grade 80/100 and 60/70 binders from source B, respectively. The basic properties of the binders are summarized in **Table 1**. Mixtures were also designated in accordance with source and binder grade. To simplify the nomenclature, mixtures produced with binders 60/70 and 80/100 from source A are referred to as A60 and A80, respectively, while mixtures produced with binder 80/100 from source B is designated as B80.

Granite aggregates, and filler are other mixture constituents that were used in this study. The median aggregate gradation in accordance with Malaysian Public Works Department (PWD) specifications (as shown in **Table 2**) for mixture type AC14 was used [19].

The effects of aging on binders were evaluated from the differences between their un-aged and aged rheological properties. The Rolling Thin Film Oven (RTFO) was used to produce a homogenous artificial short-term age asphalt binder following the procedures outlined by Hamzah and Omranian (2016) [10]. To prepare mixtures, binders and batched aggregates with fillers were mixed at a temperature between 160 °C and 170 °C (based on the viscosities obtained from the Rotational Viscometer test). Loose mixtures were placed in a conventional oven which was set to the compaction temperature to simulate short term aging. The short-term aged loose mixtures were then compacted using the Servopac gyratory compactor to 4% air voids. Exposure of the pavement to the environmental condition while in service

Binder type	Specific gravity (g/cm3)	Aging state	Penetration at 25 °C (dmm)	Softening point (°C)	Ductility at 25 °C (cm)
A1	1.020	Un-Aged	80	46	>100
		85 min Aged	—	—	—
A2	1.030	Un-Aged	63	49	>100
		85 min Aged	—	—	—
B1	1.020	Un-Aged	81	47	>100
		85 min Aged	—	—	—
B2	1.030	Un-Aged	62	50	>100
		85 min Aged	—	—	—

Table 1.
Conventional binder properties.

Sieve size (mm)	Min-Max passing limitation (%)	Selected median gradation (%)
20	100	100
14	90–100	95
10	76–86	81
5	50–62	56
3.35	40–54	47
1.18	18–34	26
0.425	12–24	18
0.150	6–14	10
0.075	4–8	6

Table 2.
Aggregate gradation [12].

was finally simulated by placing the compacted samples in a humidity (H) and ultraviolet (UV) chamber. This procedures are in line with the study conducted by Omranian et al. (2020) [13].

Two sets of experiment was designed using the central composite method to separately characterize behavior of asphalt binders and mixtures as shown in **Table 3**. In the case of binder evaluation, test temperature, binder type and aging duration were selected as the independent variables (IVs), while the complex modulus and viscosity are defined as the responses. In the case of mixture evaluation, the IVs used include

No.	Aging parameters or IVs for mixtures			No.	Aging parameters or IVs for binders	
	Aging temperature (°C)	Aging duration (h)	H & UV chamber (h)		DSR testing temperature (°C)	Aging duration (h)
1	160	4	4	1	82	92.5
2	160	0	0	2	46	0.0
3	140	2	2	3	82	185.0
4	140	2	2	4	46	185.0
5	140	4	2	5	64	92.5
6	140	2	0	6	64	92.5
7	140	0	2	7	46	92.5
8	120	0	4	8	64	0.0
9	140	2	2	9	64	185.0
10	160	2	2	10	82	0.0
11	140	2	2	11	64	92.5
12	120	4	4	12	64	92.5
13	120	4	0	13	64	185.0
14	120	2	2	14	64	0.0
15	160	4	0	15	64	92.5
16	120	0	0	16	82	0.0
17	140	2	2	17	82	92.5

No.	**Aging parameters or IVs for mixtures**			**No.**	**Aging parameters or IVs for binders**	
	Aging temperature (°C)	**Aging duration (h)**	**H & UV chamber (h)**		**DSR testing temperature (°C)**	**Aging duration (h)**
18	140	2	4	18	46	92.5
19	160	0	4	19	46	0.0
				20	46	185.0
				21	82	185.0
				22	64	92.5

Table 3.
Matrix of experimental plan.

aging temperature, aging duration in a conventional oven and duration that samples were conditioned in the humidity and ultraviolet chamber, while the compaction energy index (CEI) and fracture toughness or stress intensity factor (K) were selected as responses or dependent variables (DVs).

3. Results and discussion

ANOVA analysis was performed to develop models. The significant values that influence the responses were first selected for the model development. Different models were studied to fit the experimental results and the most accurate was nominated based on the higher R-square. Eventually, the mathematical model to predict the responses was developed by RSM. Since these procedures were repeated for both binders and mixtures samples, **Table 4** only presents the ANOVA, selected model type and mathematical regression models developed for complex modulus of binders.

Steps	**Factor**	**Sum of squares**	**DF**[a]	**F value**	**Prob > F**		
ANOVA procedures	A[b]	30573.37	1	229.74	< 0.0001		
	B[c]	5021.94	1	37.74	< 0.0001		
	C[d]	2845.49	3	7.13	0.0010		
	A^2	9289.86	1	69.81	< 0.0001		
	B^2	73.62	1	0.55	0.4630		
	AB	6302.33	1	47.36	< 0.0001		
	AC	3883.88	3	9.73	0.0001		
	BC	541.44	3	1.36	0.2757		
Proposed models	Factor	Sum of Squares	DF[a]	Mean Square	F Value	Prob > F	Model Type
	Model	59108.52	10	5910.85	43.59	< 0.0001	Quadratic (Sig)
	Residual error	4474.36	33	135.59			
	Lack of fit	4473.51	25	178.94	1677.49	< 0.0001	(Sig)
	R-squared	0.93					

Steps	Factor	Sum of squares	DF[a]	F value	Prob > F
Developed regression models	Binder type	Equations			
	A1	$y^e = +393.59482 - 12.52088 * A + 0.91926 * B + 0.095669 * A^2 - 0.011920 * A * B$			
	A2	$y = +481.57055 - 13.68645 * A + 0.91926 * B + 0.095669 * A^2 - 0.011.920 * A * B$			
	B1	$y = +379.40260 - 12.33686 * A + 0.91926 * B + 0.095669 * A^2 - 0.011.920 * A * B$			
	B2	$y = +501.65104 - 13.95958 * A + 0.91926 * B + 0.095669 * A^2 - 0.011.920 * A * B$			

[a]Degree of Freedom.
[b]Test Temperature.
[c]Aging Duration.
[d]Binder Type.
[e]Complex modulus.
In order to propose accurate regressions, factors B^2 and BC were eliminated due to "Prob > F" greater than 5%.

Table 4.
Procedures to develop models for complex modulus [9].

After testing and preliminary analysis of model development, **Figure 1** illustrates the contour plot of relationship between aging duration and test temperature effects on the complex modulus of binders A1, A2, B1 and B2. It can be seen that growth in test temperature declines the complex modulus. In addition, prolonged aging duration escalates the complex modulus. As an example, the complex modulus of binder A2 declines by approximately 400%, when temperature increases from 52 °C

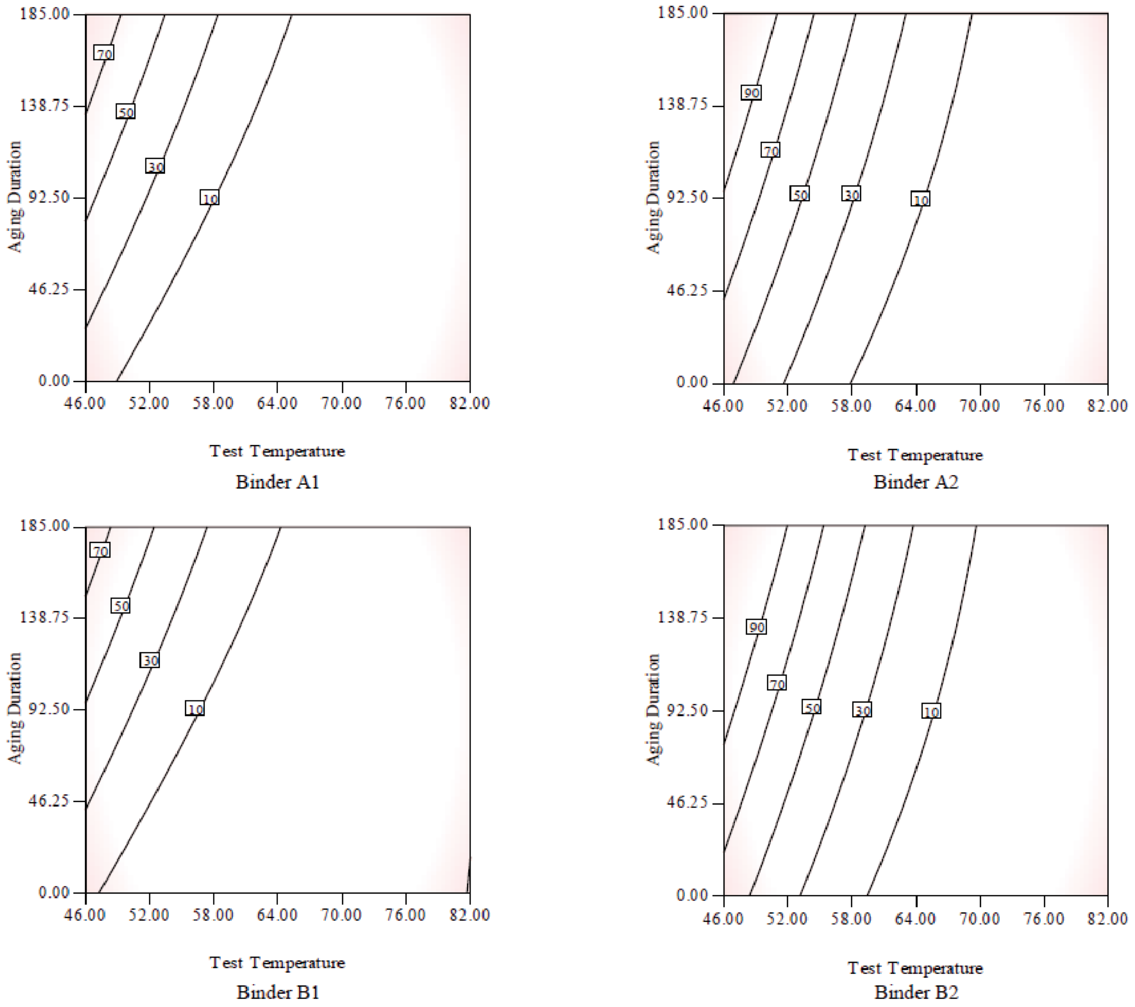


Figure 1.
Binders' complex modulus pattern (kPa).

to 64 °C. However, the corresponding vale of binder A2 at 52 °C approximately 28% increases when aging duration is extended approximately 70 minutes. The results can be correlated to the impacts of extended aging on volatilization and oxidation of the binders which increases complex modulus. On the other hand, temperature increment relates to the binder tendency to behave as a viscous material, hence, the complex modulus decreases. Changes in complex modulus at different conditions show higher test temperature effects on complex modulus compared to the aging duration. The complex modulus is also reliant on the different chemical composition of binder type. The impacts of origin at 52 °C and 70 °C are also determined. For instance, the results show that complex modulus of binder B2 is approximately 10% higher compared to the complex modulus for binder A2 at 52 °C when they are aged 92.5 minutes. While the corresponding values of both A2 and B2 binders exhibit no significant differences at 70 °C. Binders exhibit different rheological behavior when the temperature varies. From the results, it can therefore be concluded that the RSM exhibited a great potential to estimate the changes in binder behavior by fitting the developed models into the experimental outcomes [9]. According to Wang et al. (2019) changes in aging temperature can significantly influence rheological response at both short and long term aging levels [20]. However in this study, the impact of aging temperature is only explored on behavior of asphalt mixtures. It is, therefore, recommended that RSM, due to its capability, can be employed to perform such effects on complex modulus of binders in the future.

The relationship between aging duration and test temperature effects on the viscosity of binders are shown in the form of contour plots in **Figure 2**. The results

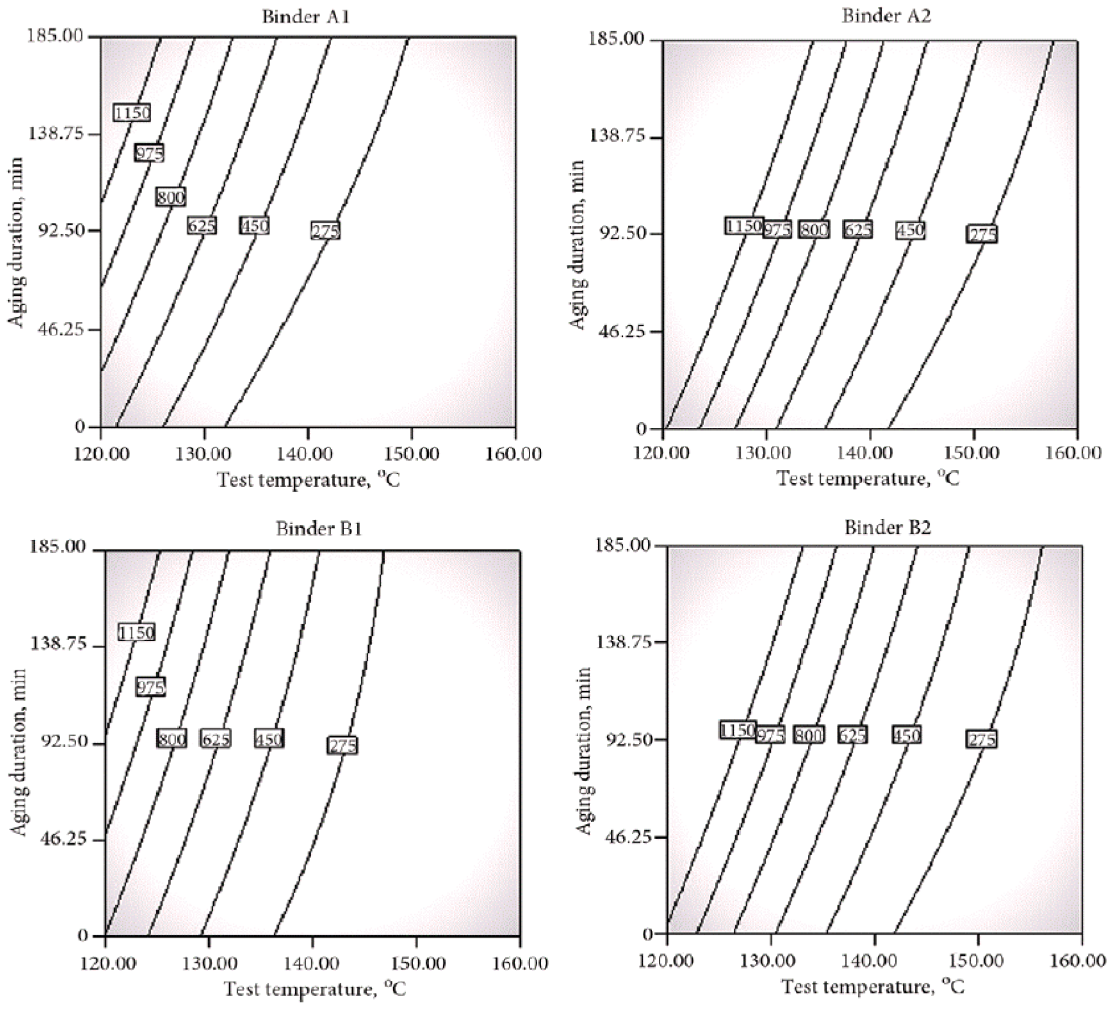
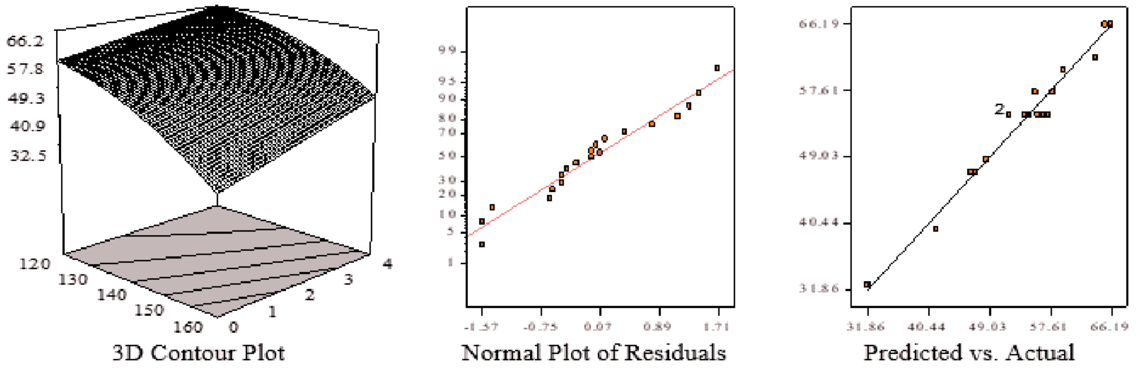


Figure 2.
Binders' viscosity pattern.

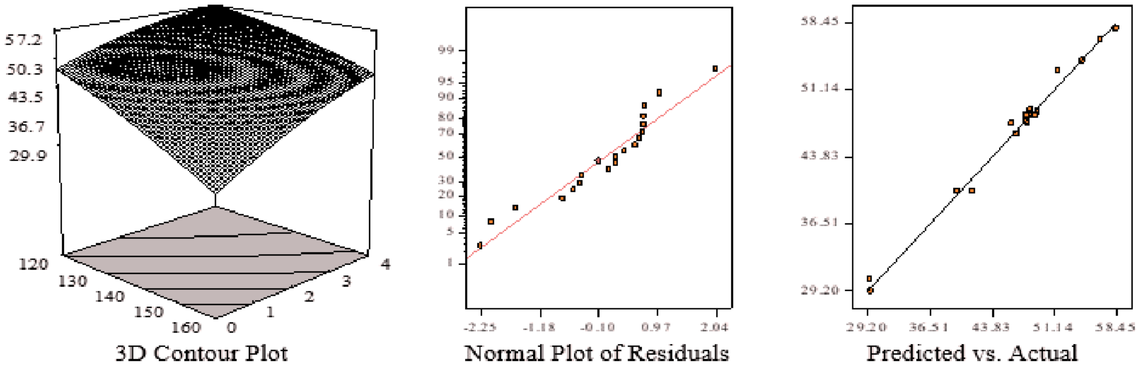
show that the viscosity decreases by temperature increment. On the other hand, the viscosity increases when aging duration is extended. For example, the viscosity of binder A1 decreases more than 70% when temperature increases from 130 °C to 150 °C. On the contrary, the corresponding value at 140 °C increases by approximately 53% when aging is extended from 70 to 140 minutes. From these result it can be understood that the aging duration impacts are lower compared to the test temperature. The figures obtained from RSM show that the maximum changes by temperature fluctuation are on 620%, 715%, 565% and 710% for binders A1, A2, B1 and B2, respectively, while the maximum changes by aging extension are 120%, 96%, 65% and 84% for binders A1, A2, B1 and B2, respectively. This testifies that RSM has a great potential to identify the different IVs impacts on the DVs. It can also be found that test temperature exhibits more significant viscosity of binders compare to the aging duration. The RSM outcomes also show that the viscosity reduces radically at lower temperatures, whereas asymptotes at higher temperatures. Conversely, viscosity increases radically at lower aging duration and then asymptotes by extending aging duration. The viscosity of binders are directly dependent on their types and sources. The comparison between the viscosity of binders from different sources was performed and the results indicated that viscosity of binder A2 at 130 °C is almost 5% higher compared to the corresponding values of binder B2. This difference lowered to 3% at higher temperature (150 °C). According to Yan et al. (2017) increasing temperature reduces the viscosity and makes binder fluid. It also causes higher binder molecular activities that results in more chemical reaction with oxygen [21]. Both procedures have significant effects on aging which was confirmed by RSM outcomes. Base on the RSM results it can be clearly concluded that the binders with same penetration grade exhibit different behavior at lower temperatures but these discrepancies are reduced by increasing the test temperature [10].

The impacts of aging temperature, aging duration in a conventional oven and duration that samples were conditioned in the humidity and ultraviolet chamber as IVs on Compaction Energy Index (CEI) are presented in the form of 3D counter plots in **Figure 3**. This figure also presents the relation between DVs and CEI based on normal plots of residuals and the actual versus predicted plots. The 3D counter plots indicate that CEI increased by aging duration increment. Conversely, the corresponding value decreased by increasing aging temperature. The CEI fluctuations differ by aging condition variation. For example in the case of mixtures produced using binder A60, the maximum discrepancies of aging temperature effects on CEI is 35.5%, while the maximum discrepancies of aging duration effects on the corresponding value is 27%. These results indicate the RSM great capability to differentiate between IVs impacts and great potential to find the relations between the outcomes. The 3D counter plots also show that extension of aging duration at higher temperature causes higher impacts on CEI compared to lower temperatures such as 120 °C which can found according to the steeper slope of aging duration effects at 160 °C compared to the corresponding value at 120 °C. The effectiveness of higher aging temperature can be correlated to the existence of lighter oily fraction volume in the binders, which accelerates the volatilization as clearly was detected by RSM. These results are in line with the results outlined by Omranian et al. (2018) [22]. The RSM great capability to estimate the CEI with respect to the IVs can be also understood from the even or normal distribution of residuals along the fitting lines as shown in **Figure 3**. Furthermore **Figure 3** shows all predicted DVs from mathematical equations fit into the experimental observation with excellent accuracy based on the actual versus predicted results plots. These findings clarify the RSM robustness and reliability to predict effects of IVs on the CEI [13].

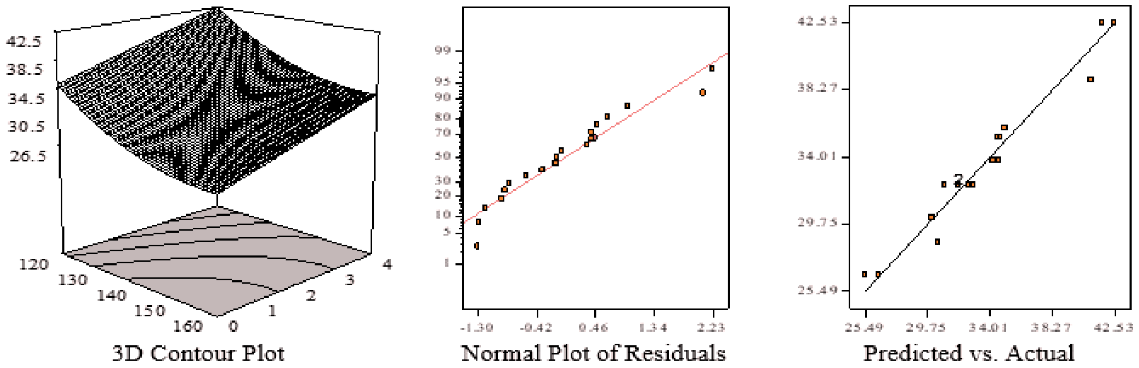
The 3D counter plots showing the effects of aging temperature, aging duration in a conventional oven and duration that samples were conditioned in the humidity



Binder A60



Binder A80



Binder B80

Figure 3.
Mixtures' compaction energy index pattern.

and ultraviolet chamber as IVs on fracture toughness (K) are displayed in **Figure 4**. The results show that test temperature increment reduces the K. It can also be seen that the corresponding value escalates when aging temperature and aging duration increases. However, the changes in the fracture toughness can be related to the binder type or binder content. According to Chen and Solaimanian (2019) although binder content did not significantly influence the aging index, aging significantly changed flexibility index and stiffness of samples [23]. The aging temperature exhibits fairly low impacts on the slight elevation of K for lower aged mixtures. On the other hand, the corresponding value significantly increases by aging temperature increment particularly when the mixtures were aged for 4 h in the oven. The effects of extended aging duration at 120 °C is inferior compared to the corresponding value at 160 °C, which can be clearly observed from the steeper slope of aging duration raise obtained from RSM. The results can be correlated to the higher volatilization and oxidation rates at higher temperature which was clearly detected by RSM. The fracture toughness fluctuates more significantly at 10 °C which result in more obvious changes in the K pattern in the case of mixtures produced using binder A60. According to the literature, softer binders are more vulnerable to aging, while the stiffer binder consists less light oily fraction, hence, their aging

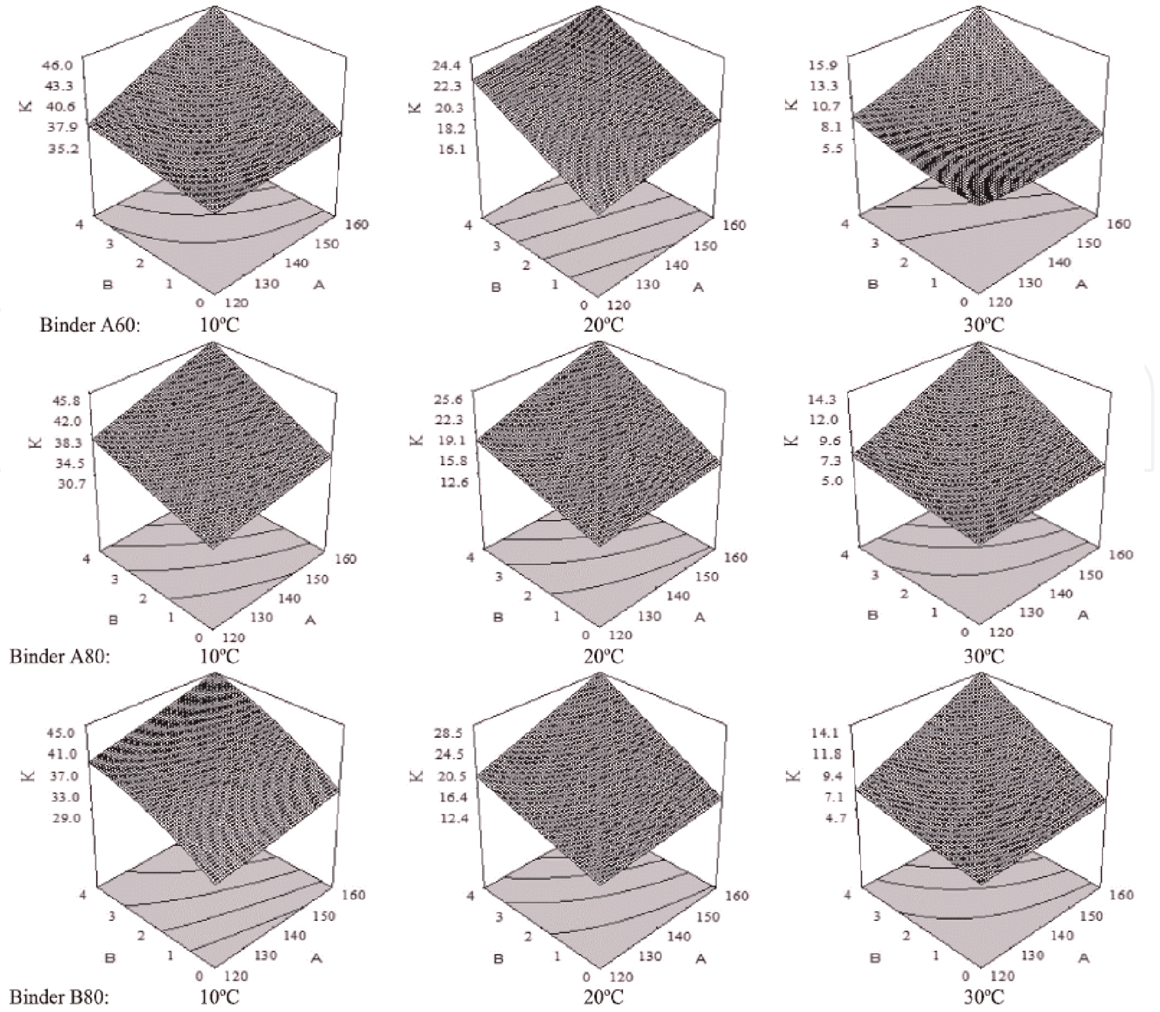


Figure 4.
Mixtures' fracture toughness pattern.

susceptibility is lower. Softer binders may lose higher proportion of lighter oily fraction both at low and high temperatures, hence, faster volatilization. Furthermore, It can be seen that mixtures contain binder A60 and extremely aged exhibit approximately similar fracture toughness at 10 °C compared to the corresponding values of the mixtures with the same conditions and produced by binder A80. These results are aligned with the mixtures' brittleness performance. The harder binders are more brittle particularly at lower temperatures, while the are stiffer at higher temperatures. Hence, the mixtures produced using binder A60 exhibit higher fracture toughness at higher testing temperatures (20°C and 30°C) compared to the corresponding values of the mixture produced using softer binders. These variations and different IVs impact on the fracture toughness of mixtures are detected by RSM, which indicates the software robustness and applicability [12].

4. Conclusion

Extended aging duration and test temperature effects on binders were quantified in terms of their complex modulus and viscosity using response surface method. The RSM exhibited the ability to develop precise regression models with R-square higher than 90%. The experimental results indicate that extending the aging duration increases the binder complex modulus and viscosity, while increasing test temperature leads to the corresponding values reduction. The effects of test temperature on the viscosity are higher compare to the effects of aging duration. It was found based on the extreme changes in the results. For instance, the maximum viscosity changes by temperature fluctuation was approximately 6 to 7 times higher than the corresponding value maximum changes by aging extension.

This work also evaluated the effects of different aging scenarios on the mixtures' compaction energy index and fracture properties using RSM. Similar to binders, RSM exhibited great capability to predict the mixtures performance in terms of CEI and fracture toughness by precise regression models development. The overall results indicate that IVs (individually and together) significantly affect CEI and fracture properties. Extended aging resulted in a higher K and CEI. Mixtures produced using stiffer binders exhibited higher energy requirements for compaction, which resulted in a higher CEI. Test temperature increment declined K, which can be contributed to the reduction in the binder viscosity due to the test temperature elevation. Although the magnitudes of changes in the responses, for both binder and mixture samples, varied depending on the variation in binder sources and types, RSM accurately detected the changes in the responses. RSM also determined the changes in the changes in the aging rate at higher and lower aging temperatures.

Employing the experimental design obtained from RSM reduced the sample size. The sample size reduction resulted in time, energy, and money saving for the entire project. Although the required number of samples significantly reduced, yet RSM detected the IVs and DVs relation and the IVs influence on the responses with an excellent accuracy. Hence, The RSM technique exhibits the ability to quickly and precisely determine the behavior of binders at various conditions. These advantageous impacts of RSM were also concluded in other studies [9, 12, 17, 24].

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Conflict of interest

There is no conflict of interest.

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