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EFFECTS OF EXTENDED SHORT-TERM AGING DURATION ON ASPHALT BINDER BEHAVIOUR AT HIGH TEMPERATURES

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Abstract. Many factors affecting pavement performance include variations in binder composition and environmental conditions during asphalt mixture production. Hence, predicting pavement performance is a difficult task. This paper aims to investigate the effects of short term aging on binder viscosity at high temperature. In order to predict the effects of short term aging on the asphalt binder viscosity at high temperatures, a Response Surface Method was performed on the Rotational Viscometer test results. An experimental matrix was planned based on the central composite design for aging duration and test temperature. The test results showed that aging increased the binder viscosity, while increasing test temperature decreased the corresponding value. However, aging effects differ and depend on binder types, test temperatures and aging conditions. It was also found that the Response Surface Method is a fast, effective and reliable method to predict the effects of aging on binder viscosity behaviour at high temperatures.

Keywords: aging, asphalt binder, Response Surface Method, rotational viscometer, viscosity.

1. Introduction

Quality and durability of the pavement depend on the asphalt mixing plants production quality. Aging of asphalt binders indirectly influences pavement durability. According to Bražiūnas and Sivilevičius (2010) if the actual amount of binder in the produced Hot Mix Asphalt (HMA) mixture satisfies job mix formula (JMF) requirements, nevertheless aging may deteriorate pavement performance due to changes in binder chemical composition. Short term aging of asphalt binder occurs during mixing, transportation and construction and varies according to variations in binder and aggregate types, mixing and construction duration and environmental conditions. In this stage, aging occurs at a faster rate due to highest surface area of binder per unit volume and high temperature exposure. To produce a homogeneous asphalt mixture, sufficiently fluid binder is required to coat and bind the aggregate together. Hamzah *et al.* (2015a) found that the extended short term aging increases the complex modulus of asphalt binder. Exposing the mixture to unanticipated conditions such as prolonged exposure to plant burners during mixture production, traffic jam during mixture transportation or construction delays increase the possibility of short-term aging effects severity and also change mixture and compaction temperatures. Hence, this delay affects binder viscosity and consequently asphalt mixture densification under loading (compactability) which directly influences mixture stiffness and volumetric properties. In other words, prolonging the duration of mixing and construction process vary binder viscosity and mixture temperature. Hence, mixture has insufficient viscosity to be properly rolled and compacted without displacing it laterally. If the mixture temperature decrease and binder viscosity increase, achieving proper compaction of the asphalt mixture is not possible. Kassem *et al.* (2012) found that the pavements air voids increase by approximately 10% per 30 °F compaction temperature decrement. Rutting results from the accumulation of small amounts of unrecoverable deformation that occur during each load application. If proper compaction still continues, rutting takes place because of the asphalt mixture's insufficient load-bearing capacity and shear strength to resist repeated heavy loads. McGennis *et al.* (1994) stated that fully incompact pavement or pavement with higher air voids would be excessively subjected to oxidative hardening due to the higher exposure of asphalt mixtures to oxygen. Therefore, characterization of temperature and aging effects on binder viscosity prior to construction allow researchers to enhance pavement performance by resolving some construction distress such as raveling by attaining designed air voids content or required pavement density to develop

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sufficient cohesion among the mixture particles. Mirza and Witczak (1995) employed a simple performance tester and developed the Global Aging System (GAS) to predict asphalt viscosity based on time and pavement depth. Huh and Robertson (1996) proposed a model to predict the effects of aging on binders' kinetics of viscosity change with time and temperature. Chen and Huang (2000) proposed an aging model to predict the changes in paving binders' properties during field age hardening. Hamzah *et al.* (2012a) and Jamshidi *et al.* (2012) evaluated the effects of aging on behaviour of binder viscosity incorporating Sasobit® at high temperatures. Alavi *et al.* (2013) proposed a new model to quantify the effects of binder aging on the visco-elastic behaviour of the asphalt mixture by evaluating carbonyl functional groups of recovered binder and continuous relaxation spectrum of the asphalt mixtures. Mehrez *et al.* (2015) used stochastic model to recognize the linear visco-elastic master curve of asphalt mixtures subjected to different aging durations. Glover *et al.* (2014) developed a model to predict the oxidation rate based on binder kinetics data, temperature profile of the pavement, and mixture characteristics. In this study, a new approach is proposed to predict the aging effects on binders' viscosity using Response Surface Method (RSM).

RSM is a combination of techniques used to build up a series of experiment designs, finding relationships between experimental factors and responses, and to establish the optimum conditions using these relationships (Mason *et al.* 2003). Khodaii *et al.* (2012) employed RSM to evaluate the effects of aggregate gradation and lime content on the tensile strength ratio of dry and saturated hot mix asphalt. Hamzah *et al.* (2013) determined the optimum binder content of WMA incorporating Rediset using RSM. Kavussi *et al.* (2014) utilized RSM to evaluate the effects of aggregate gradation, hydrated lime and Sasobit content on the indirect tensile strength of warm mix asphalt. Ceylan *et al.* (2014) employed RSM to model the Global Sensitivity Analyses (GSA) results for evaluation of Mechanistic-Empirical Pavement Design Guide (MEPDG) input sensitivities across the entire problem domain for continuously reinforced concrete pavement (CRCP). Hamzah *et al.* (2015b) used RSM to determine the effects of aging on the rheological properties of asphalt binders. Haghshenas *et al.* (2015a) studied the optimization of bitumen, grading and lime content, in stripping process of HMA using RSM. In the other work, Haghshenas *et al.* (2015b) successfully used RSM to propose the time dependent models between tensile strength ratio (TSR) as the response parameter and independent factors such as time and hydrated lime and Zycosoil as anti-stripping additives.

In this study, a central composite method was used to design experiment plans for the viscosity and aging index as the test responses. The significance of design factors and their interactions on response values were evaluated using analysis of variance (ANOVA). Mathematical equations were then generated and actual and predicted values of test responses were compared.

2. Materials and methods

2.1. Materials

Four different binders at various aging conditions were used. For ease of reference, binders are designated according to their source and type. 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, respectively. The basic properties of the binders are summarized in Table 1.

2.2. Samples preparation

An accelerated aging test was conducted to determine binders' tendency to oxidation and hardening. 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 in accordance with the procedures outlined in *ASTM D2872 Standard Test Method for Effect of Heat and Air Moving Film of Asphalt (Rolling Thin-Film Oven Test)* except the durations were varied between 0 min to 185 min. Subsequently, the sufficiently fluid un-aged and aged binders were poured into a cylindrical mould. The Rotational Viscometer (RV) test was conducted in accordance to procedures of *ASTM D4402 Standard Test Method for Viscosity Determination of Asphalt at Elevated Temperatures Using a Rotational Viscometer*.

Table 1. Conventional binder properties

Binder type	Specific gravity, g/cm^3	Aging state	Penetration at 25 °C, dmm	Softening point, °C	Ductility at 25 °C, cm	G/Sinδ at 64 °C, Pa	G/Sinδ at 70 °C, Pa	Viscosity at 135 °C, mPa·s
A1	1.020	Un-Aged	80	46	>100	1342	–	300
		85 min Aged	–	–	–	3099	–	475
A2	1.030	Un-Aged	63	49	>100	–	1938	500
		85 min Aged	–	–	–	–	3239	720
B1	1.020	Un-Aged	81	47	>100	2127	–	390
		85 min Aged	–	–	–	3493	–	500
B2	1.030	Un-Aged	62	50	>100	–	1735	510
		85 min Aged	–	–	–	–	3087	690

2.3. Experimental designs

One set of experiment was designed using the central composite method to characterize behaviour of four different asphalt binders at high temperatures as shown in Table 2. Test temperature, binder type and aging duration were selected as the independent variables. Viscosity (v) as an essential parameter to determine mixing and compaction temperature and Aging Index (AI) that was determined based on the relative viscosity shown in Eq (1), are defined as the responses. According to Bražiūnas *et al.* (2013), one of the most common indicators to evaluate aging and consequently provide ranking on the effects of aging process among different asphalt binder, is the aging index based on single-point measurement.

$$AI = \left(\frac{v_A}{v_0} \right), \tag{1}$$

where AI – aging index; v_A – relative viscosity of aged binders, mPa·s; v_0 – relative viscosity of control (un-aged) binders, mPa·s.

2.4. Laboratory tests

The effects of extended aging duration on the rheological properties of binders were investigated in terms of viscosity obtained from the Rotational Viscometer (RV) test. The tests were conducted using spindle No. 27 rotating at the rate of 20 rpm. Consequently, temperature sweeps were applied from 120 °C to 160 °C for the un-aged and short-term aged samples in accordance, with *ASTM D4402* procedures. In order to conduct the test, the mould was placed in the thermo container that was set at the desirable temperature. The results were then recorded once the viscosity became constant what approximately took one hour.

2.5. Analysis methods

RSM is the application of the regression models, experiment design methods and other techniques to determine the responses of the system. To develop a regression model for each response, linear, quadratic and two-factor interaction regression models were evaluated based on sequential F-tests, lack-of-fit tests, and R-square. The significance of each factor (linear, quadratic and interaction terms) for the selected regression model was examined using Analysis of Variance (ANOVA). Insignificant factors were then eliminated and precise models were proposed for predicting the responses. These analyses were conducted using the Design-Expert 6.0.6 software.

3. Results and discussion

Based on the experimental results shown in Table 2, aging duration increment increases the v and AI. On the contrary, increasing test temperature decreases the corresponding values. To formulate aging duration and test temperature effects on v and AI of binders at high temperatures, the ANOVA results obtained from RSM are presented in Table 3. The values of $Prob > F$ less than 0.05 indicate that the model terms are significant. From the results, all the factors for v are significant except B^2, which is insignificant since the F value is more than 5%. Thus, B^2 is excluded from v aging mathematical prediction model. For the AI case, all the factors are significant except AC, which is discarded from the aging prediction model.

To develop models and predict the effects of aging duration on behaviour of asphalt binder at high temperatures, a statistical analysis was conducted using RSM and the results are shown in Table 4. The results indicate that all models are significant since the $Prob > F$ is less than 0.05. From the results, the lack of fit obtained for v and AI are also significant since the $Prob > F$ is less than 0.05. Since, this study attempts to fit the model, the significant value for lack of fit is undesirable. Hence, it implies that the proposed model for v and AI probably affected due to the unexpected variations in samples or test results during the procedure. However, Table 4 shows that the software was able to remove these variations perfectly since the developed models are in reasonable agreement because the R-square are more than 98%. The developed quadratic mathematical equations to predict the v and AI of asphalt binders are shown in Table 5. In the proposed models, aging duration and temperature are regarded as the main parameters that exhibit considerable effects on binder properties during mixing and construction. Aging duration in the Rolling Thin Film Oven Test (RTFOT) is regarded as simulating aging occurrence during mixture production and construction. Meanwhile, test temperature is directly related to variations in temperature during mixture production and construction. From the v and AI equations, test temperatures exhibit negative impact that indicates that temperature increment causes reduction in the v and AI, while aging duration exhibit positive impact on the related responses which shows that additional aging duration increases the corresponding values. However, interaction between test temperature and aging duration exhibits negative impact. It implies that the interaction between temperature and aging leads to reduction in v and AI. Based on the R^2 more than 98%, the most direct use of these models is the prediction of v and AI. The models are quantitative tools which were employed to determine the different circumstances that impacts v and AI, such as extended mixture exposure to plant burners, long haulage distance or delayed paving. In accordance with the Asphalt Institute *Superpave Mix Design SP-2* recommendations, the viscosity of unmodified asphalt binder at mixing and compaction temperatures are 170±20 mPa·s and 280±30 mPa·s, respectively. The models are utilized during compaction to determine whether the binder is sufficiently viscous to satisfy *SP-2* recommendation. In addition, v and AI that are under limits of RV test are possible to be determined by varying aging duration and temperature in the models. Hence, these models enable identification of the changes in binder properties to provide an efficient approach for the construction sector to solve issues related to mix tenderness, mix compactibility, and

Table 2. Matrix of experimental design

Binder type	No.	Test temperature, °C	Aging duration, min	Viscosity v, mPa·s	Aging Index
A1	1	140	92.5	375.0	1.58
	2	120	0	612.5	1.00
	3	140	92.5	387.5	1.63
	4	160	92.5	162.5	1.63
	5	140	0	237.5	1.00
	6	140	92.5	375.0	1.58
	7	160	0	100.0	1.00
	8	140	185.0	475.0	2.00
	9	160	185.0	200.0	2.00
	10	120	185.0	1462.5	2.39
	11	120	92.5	1100.0	1.80
A2	12	140	185.0	687.5	1.83
	13	160	92.5	225.0	1.38
	14	120	92.5	1725.0	1.60
	15	120	0	1075.0	1.00
	16	140	0	375.0	1.00
	17	140	92.5	550.0	1.47
	18	160	0	162.5	1.00
	19	120	185.0	2300.0	2.14
	20	160	185.0	262.5	1.62
	21	140	92.5	537.5	1.43
	22	140	92.5	550.0	1.47
B1	23	160	92.5	162.5	1.18
	24	140	92.5	387.5	1.29
	25	140	92.5	375.0	1.25
	26	140	92.5	387.5	1.29
	27	120	185.0	1375	1.69
	28	140	185.0	462.5	1.54
	29	160	185.0	187.5	1.36
	30	120	92.5	1137.5	1.40
	31	160	0	137.5	1.00
	32	140	0	300.0	1.00
	33	120	0	812.5	1.00
B2	34	160	0	162.5	1.00
	35	120	185.0	2137.5	2.01
	36	120	92.5	1625.0	1.53
	37	140	92.5	525.0	1.35
	38	140	185.0	662.5	1.71
	39	120	0	1062.5	1.00
	40	140	92.5	537.5	1.39
	41	160	92.5	200.0	1.23
	42	140	0	387.5	1.00
	43	140	92.5	525.0	1.35
	44	160	185.0	262.5	1.62

Table 3. Analysis of variance for response surface reduced quadratic model of viscosity and aging index

Title	Factor	Sum of squares	DF	*F* value	*Prob* > *F*	Significant
Viscosity	A	8401666.7	1	1085.2647	< 0.0001	Yes
	B	1062604.2	1	137.25929	< 0.0001	Yes
	C	652982.95	3	28.115824	< 0.0001	Yes
	A^2	1081194.1	1	139.66059	< 0.0001	Yes
	B^2	2964.9123	1	0.3829853	0.5408	No
	AB	706650.39	1	91.27983	< 0.0001	Yes
	AC	406927.08	3	17.521269	< 0.0001	Yes
	BC	69843.75	3	3.0072983	0.0463	Yes
Aging Index	A	0.2688167	1	123.5763	< 0.0001	Yes
	B	4.0920042	1	1881.114	< 0.0001	Yes
	C	0.6231727	3	95.49183	< 0.0001	Yes
	A^2	0.0192212	1	8.836091	0.0059	Yes
	B^2	0.0163737	1	7.527081	0.0103	Yes
	AB	0.1660563	1	76.33686	< 0.0001	Yes
	AC	0.0044833	3	0.687003	0.5673	No
	BC	0.2753125	3	42.18749	< 0.0001	Yes

Note: DF – a degree of freedom; A – test temperature; B – aging duration; C – binder type; AB – interaction between test temperature and aging duration; AC – interaction between test temperature and binder type; and BC – interaction between aging duration and binder type. In order to propose accurate regressions, factors B^2 for viscosity and AC for aging index were eliminated due to *Prob* > *F* more than 5%.

Table 4. Models proposed for viscosity and aging index

Title		Sum of squares	DF	Mean square	*F* value	*Prob* > *F*	Model Type
Viscosity	Model	12432359	13	956335.29	126.12632	< 0.0001	Quadratic (Sig)
	Residual error	227470.82	30	7582.3607			
	Lack of fit	227054.15	22	10320.643	198.15635	< 0.0001	(Sig)
	R-square	> 0.98					
Aging Index	Model	5.4534963	11	0.4957724	234.79875	< 0.0001	Quadratic (Sig)
	Residual error	0.0675673	32	0.0021115			
	Lack of fit	0.0627006	24	0.0026125	4.2945636	0.0193	(Sig)
	R-square	> 0.98					

Table 5. Equations obtained from response surface method

Title	Binder type	Equation
Viscosity	A1	$v = 17600.83807 - 237.55469 \cdot A + 18.04336 \cdot B + 0.80521 \cdot A^2 - 0.11360 \cdot A \cdot B$
	A2	$v = 19822.23958 - 252.03385 \cdot A + 18.85417 \cdot B + 0.80521 \cdot A^2 - 0.11360 \cdot A \cdot B$
	B2	$v = 19528.86837 - 249.95052 \cdot A + 18.51633 \cdot B + 0.80521 \cdot A^2 - 0.11360 \cdot A \cdot B$
Aging Index	A1	$AI = 3.15567 - 0.030685 \cdot A + 0.014687 \cdot B + 1.08882\text{E-}004 \cdot A^2 - 4.69801\text{E-}006 \cdot B^2 - 5.50676\text{E-}005 \cdot A \cdot B$
	A2	$AI = 3.13718 - 0.030685 \cdot A + 0.013245 \cdot B + 1.08882\text{E-}004 \cdot A^2 - 4.69801\text{E-}006 \cdot B^2 - 5.50676\text{E-}005 \cdot A \cdot B$
	B2	$AI = 3.11067 - 0.030685 \cdot A + 0.012795 \cdot B + 1.08882\text{E-}004 \cdot A^2 - 4.69801\text{E-}006 \cdot B^2 - 5.50676\text{E-}005 \cdot A \cdot B$

similar characteristics which are susceptible to short-term aging and influence pavement performance. For instance, pavement target density is achievable when construction sector adjust roller vibration frequency and amplitude. In addition, RSM exhibits high accuracy and capability to propose the regressions with only 44 samples for four types of binder at the wide fluctuation range of temperature and aging duration.

Figure 1 illustrates the contour plot showing the relationship between aging duration and test temperature effects on the viscosity of binders A1, A2, B1 and B2. From the results, increase in test temperature decreases the v, while extended aging duration increases the corresponding values. For instance, the v of binder A1 at 95.5 min aging duration decreases by approximately 73% for temperature increases from 130 °C to 150 °C. Conversely, the v of binder A1 increases by approximately 53% when aging duration is extended from 70 min to 140 min when temperature is maintained at 140 °C. These behaviour of binders are consistent with the results obtained by Hamzah *et al.* (2012b). These differences show that test temperature effects on v are higher compare to the aging duration effects. To certify this conclusion, the main effects of test temperature and aging duration on v is determined using Minitab software and the results are illustrated in Fig. 2. From Fig. 2, aging duration exhibits less significant effects on v compare to test temperature. The maximum discrepancies of effects of test temperature on v are 620%, 715%, 565% and 710% for binders A1, A2, B1 and B2, respectively. The maximum discrepancies of effects of aging duration on v are 120%, 96%, 65% and 84% for binders A1, A2, B1 and B2, respectively. This testifies that test temperature exhibits more significant viscosity of binders compare to the aging duration. The results also show that v reduces drastically at lower temperatures, and then asymptotes at higher temperatures. On the contrary, v increases drastically at lower aging duration and then asymptotes by aging duration increment. The magnitude of the viscosity of binders is also dependent on binder type. From Fig. 1, the effects of source are also determined based on the comparison between the viscosity of binders obtained at 130 °C and 150 °C. For example, the results show that v of binder A2 at 130 °C and 150 °C are respectively 5% and 3% higher compare to the corresponding values of binder B2 for 92.5 min aging duration. It implies that the binders with same penetration grade exhibit different behaviour at

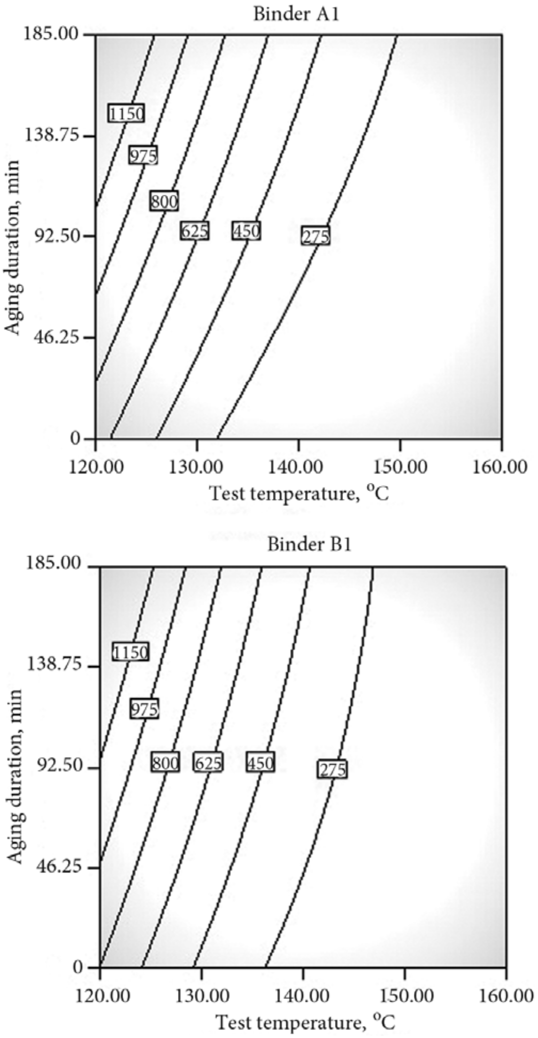

Fig. 1. Binder A1, A2, B1 and B2 viscosity pattern

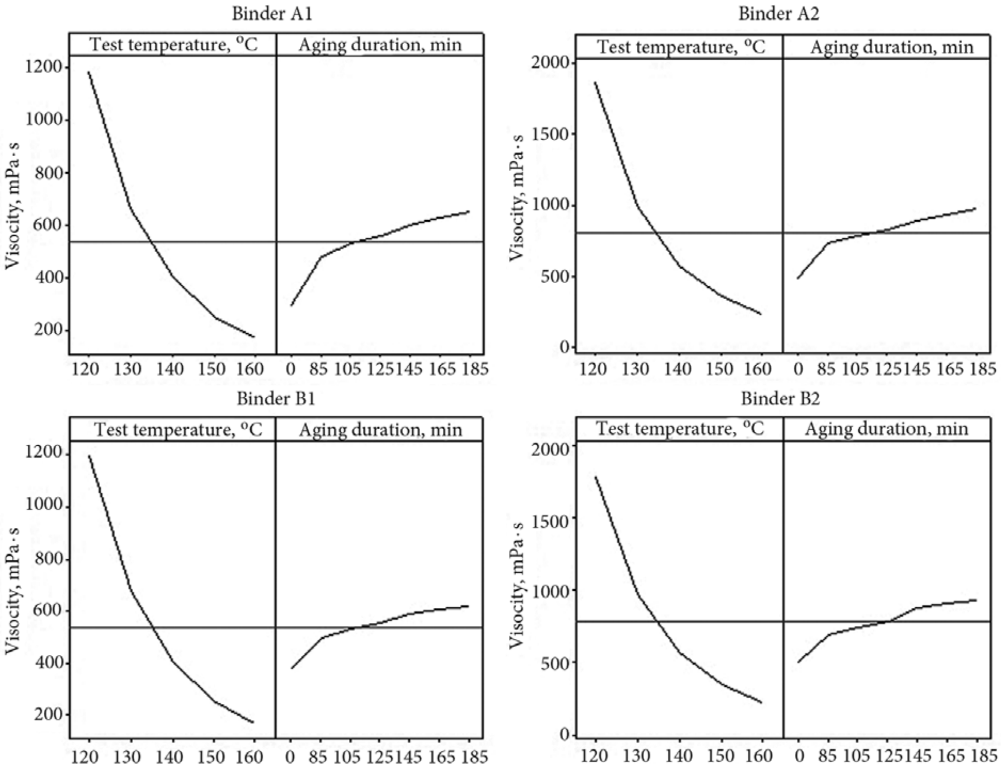

Fig. 2. The main effects of test temperature and aging duration on viscosity of binders A1, A2, B1 and B2

lower temperatures but these discrepancies are reduced by increasing the test temperature.

Figure 3 illustrates the 3D contour plot showing the relationships between aging duration and test temperature effects on the aging index of binders A1, A2, B1 and B2. From the results, increases in the test temperature decreases the AI, while extended aging duration increases the corresponding values. For instance, the AI of binder A1 at 95.5 min aging duration decreases by approximately 6% when temperature is increased from 130 °C to 150 °C. Conversely, viscosity of binder A1 increases by approximately 30% for aging duration increment from 70 min to 140 min when temperature is maintained at 140 °C. The differences showed that test temperature effects on AI are lower compare to the effects of aging duration. These results are consistent with the studies conducted by Jamshidi *et al.* (2012). The comparison between the main effects of test temperature and aging duration on AI are determined using Minitab software and the results are illustrated in Fig. 4. From the graphs, aging duration exhibits more significant effects on AI compare to test temperature. The maximum discrepancies of effects of test temperature on AI are 13%, 17%, 16% and 19% for binders A1, A2, B1 and B2, respectively, while the maximum discrepancies of effects of aging duration on AI are 112%, 85%, 53% and 77% for binders A1, A2, B1 and B2, respectively. This shows that aging duration exhibits more significant effects on AI of binders compare to test temperature. From the results, AI reduces considerably at lower temperatures, and then asymptotes at higher temperatures. On the contrary, aging duration increment causes sharp changes in the AI upward slope. These findings imply that the AI changes more significantly with changes in aging duration but remain approximately unchanged by increment in test temperature. Therefore, AI is proposed as a suitable parameter to study the effects of aging on the rheological behaviour of binders at high temperatures. From Fig. 3, the effects of source are determined by comparing AI of binders obtained at 130 °C and 150 °C. For example, the results show that at 92.5 min aging duration, AI of binder A2 at 130 °C and 150 °C are respectively 5.2% and 4.8% higher compare to the corresponding values of binder B2. It implies that binders with same penetration grade show different behaviour. However, these discrepancies are medium and reduce by increasing the test temperature.

Poulikakos *et al.* (2014) stated that aging level is higher for mixtures containing softer binders in comparison to mixtures containing harder binders. However, from the maximum discrepancies of effects of aging duration on AI, the results show that although this conclusion is valid for binders collected from source A but not source B. Gawel and Baginska (2004) found that the changes in binder properties due to aging effects are dependent on their chemical composition. Hence, the magnitude of the change in binders' AI depends on binder types and their different chemical compositions. In this regard, Fourier Transform Infrared spectroscopy (FTIR) was utilized to determine the differences between chemical compositions of binders and bands. The test was conducted on un-aged samples using Spectrum One apparatus supplied by PerkinElmer Company in the range between 550 cm^{-1} and 4000 cm^{-1}, using eight scans with a resolution of 4.0 cm^{-1}. The results

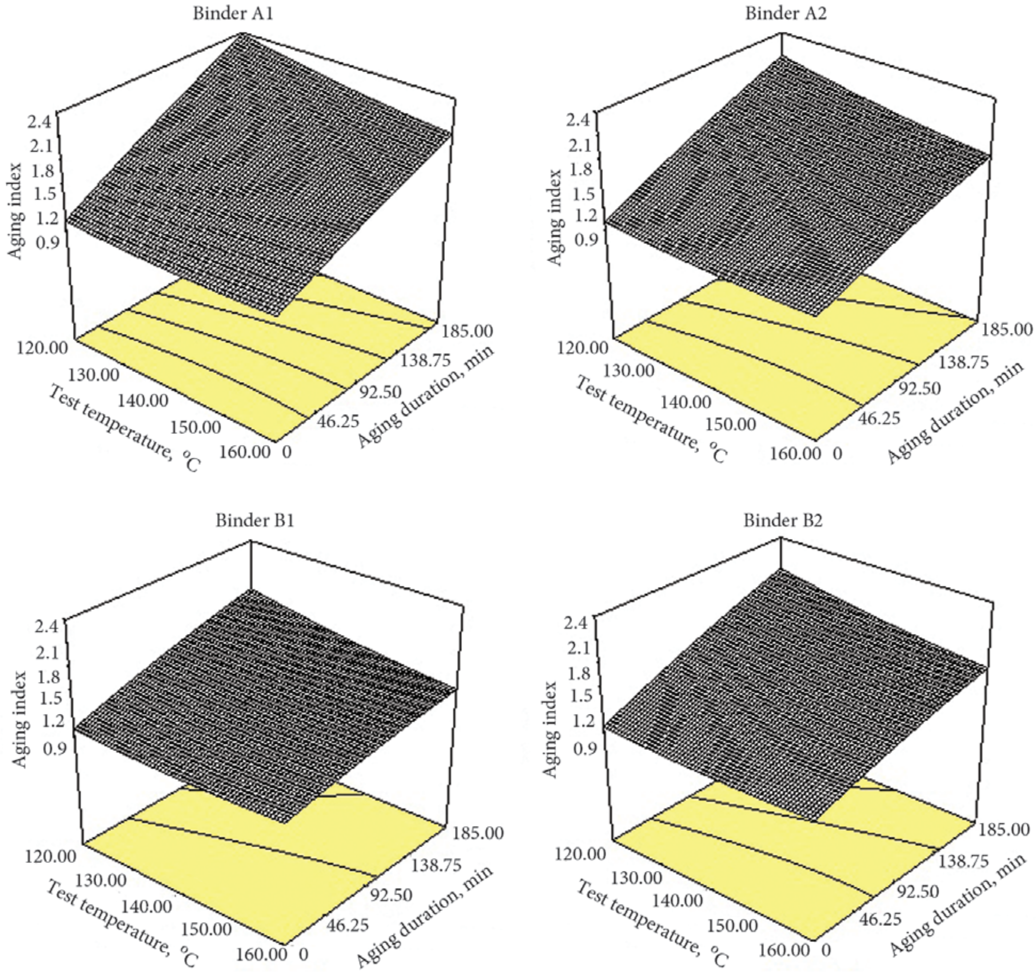

Fig. 3. Binders′ aging index pattern

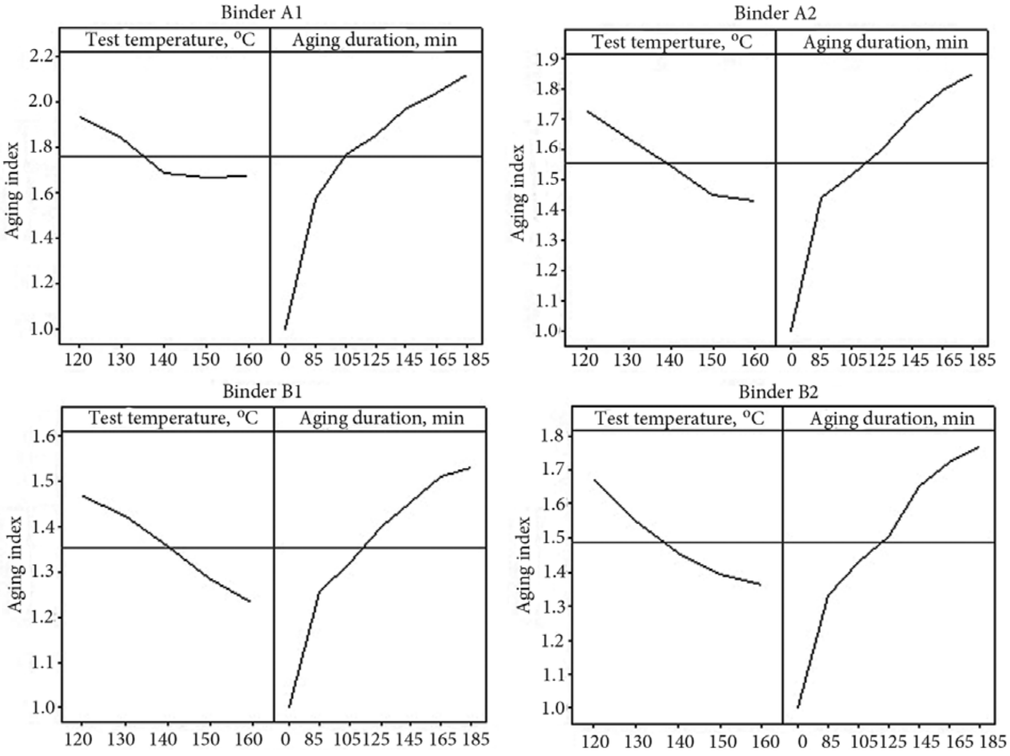

Fig. 4. The main effects of test temperature and aging duration on aging index

of FTIR obtained at the wavelengths around 1600 cm^{-1} (aromatics), 1700 cm^{-1} (carbonyl) and 1030 cm^{-1} (sulfoxids) are typical aging indicators. In this research, to study the difference between sulfoxids and aromatic indexes are exploited due to FTIR strong peak observation at related ranges. The areas under the FTIR spectra lie in the region around 1030 cm^{-1} and 1600 cm^{-1} were measured. To determine sulfoxids and aromatic indexes, each value was then divided by the sum of two areas that are located in the region around 1460 cm^{-1} and 1376 cm^{-1}, which represents the CH_2 (ethylene) and CH_3 (methyl) groups, respectively. The areas below CH_2 and CH_3 groups were chosen, since they remain approximately unchanged for all binders as shown in Fig. 5. The sulfoxids and aromatic indexes are shown in Eqs (2) and (3) (Van der Bergh 2011). The results obtained from these Equations are presented in Table 6.

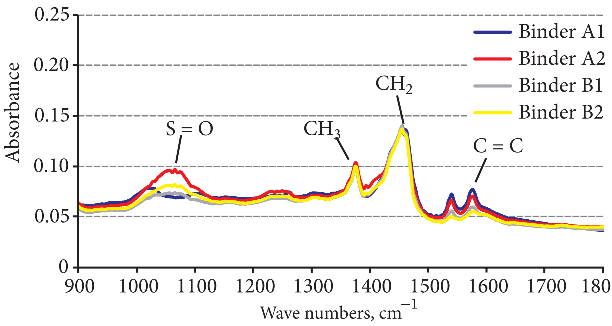

Fig. 5. Infrared spectrum of binders A1, A2, B1 and B2

Table 6. Indexes of un-aged binders

Index type	Binder type			
	A1	A2	B1	B2
Sulfoxids	0.212	0.719	0.326	0.472
Aromatic	0.240	0.224	0.166	0.143

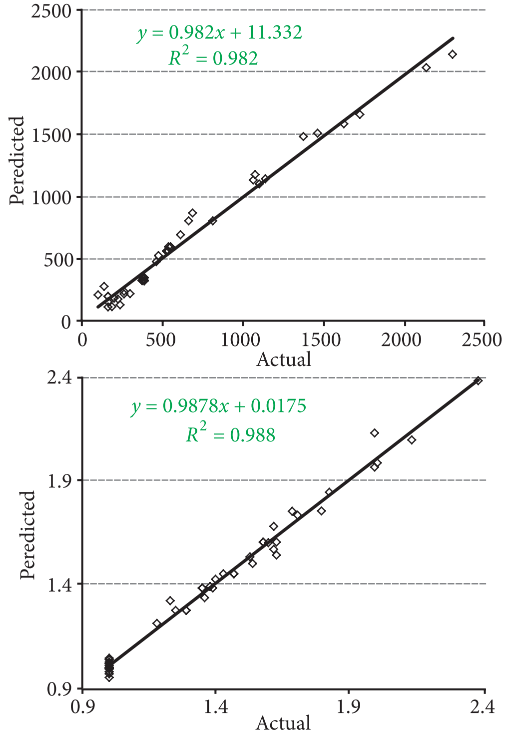

Fig. 6. Predicted viscosity and aging index versus actual results

$$I_s = \frac{A_s}{\left(A_{CH3} + A_{CH2}\right)}, \quad (2)$$

$$I_a = \frac{A_a}{\left(A_{CH3} + A_{CH2}\right)}, \quad (3)$$

where I_s and I_a – sulfoxids and aromatic indexes, respectively; A_s and A_a – areas around sulfoxids and aromatic band; A_{CH3} and A_{CH2} – areas around methyl and ethylene group, respectively.

From Fig. 5, all binders exhibit different trends in the range of sulfoxids and aromatics bands. The results in Table 6 also showed that I_s and I_a are different for all binders. From the results, I_ss vary from source to source and decrease when penetration grade of binders changes from 60/70 to 80/100. From Table 6, binders A2 and A1 exhibit the highest and lowest I_s, respectively. The results also show that when the binder penetration grade changes from 60/70 to 80/100, the I_s decrease by approximately 239% and 45% for binders from source A and B, respectively. It implies that when binder penetration grade changes, the variation of I_s is inconsistent for different sources. The I_s of binders B1 and A2 are approximately 54% and 52% higher compare to the corresponding values of binder A1 and B2. It shows that even binders with the same penetration grade are different in terms of I_s. Table 6 also shows that I_as vary from source to source and increases by binders' penetration grade change from 60/70 to 80/100. However, the I_as for binders from the same source do not show any significant differences. For instance, the I_a of binder A1 is approximately 7% higher compare to the corresponding value of binder A2. The results show that I_a of binders A1 and A2 are approximately 45% and 57% higher compare to the corresponding values of binder B1 and B2. The results show that binders with the same penetration grade but from different sources exhibit different trend in terms of I_a. It implies the importance of source of binders that influences binder properties and behaviour. The differences between I_ss and I_as showed that each binder has its unique chemical composition. This finding affirms the assumption that the changes in AI of binders are dependent on binder type and chemical composition.

Finally, the actual and predicted values of *v* and AI are compared to verify the accuracy of the RSM predicted results. The results shown in Fig. 6 show that both *v* and AI mathematical equations fit into the experimental observation with excellent accuracy. This implies that the RSM is a robust and reliable method to predict the effects of aging on behaviour of binders at high temperatures.

4. Conclusions

Extended aging duration and test temperature effects on binders were quantified in terms of viscosity and aging index and the conclusions are as follows:

1. The Response Surface Method technique exhibits the great ability to quickly and precisely determine the behaviour of binders at various conditions.

2. Extending the aging duration increases viscosity of binders and aging index. However, increasing test temperature leads to reduction in the corresponding values.

3. The effects of test temperature on the viscosity are higher compare to the effects of aging duration, while the effects on aging index are contrariwise.

4. The magnitudes of response changes varied depending on the variation in binder sources and types.

5. The aging index was more susceptible to changes in aging duration. Hence, it is proposed as a suitable parameter to study the effects of aging on the rheological behaviour of bindersat high temperatures.

6. Chemical composition of binders directly influence changes in aging index of binders.

7. The final findings showed that the mathematical equation fits into the experimental observation with high accuracy. Hence, the models are practical to be used and predict the various effects on viscosity and aging index such as long hauling distance, delayed paving, or prolonged exposure to plant burners. The models are also applicable and useful to provide an efficient approach for construction sector to generate enough torque to yield rolling pattern and compaction difficulties to achieve required pavement stiffness and volumetric properties.

8. In this study, temperature and aging duration were selected as the main parameters that exert considerable effects on binder properties during mixing and construction. Therefore, more laboratory studies should be conducted to evaluate other parameters, such as humidity and ultra violet effects on mixture for better simulation of environmental impacts on binder properties and consequently pavement performance during mixing and construction.

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