

A Laboratory Investigation on the Rheological Properties of Asphalt Binder Containing Rediset

Meor Othman HAMZAH ^a, Babak GOLCHIN ^b

^{a,b} *School of Civil Engineering, Engineering Campus, Universiti Sains Malaysia, 14300 Nibong Tebal, Seberang Perai Selatan, Penang, Malaysia*

^a *E-mail: cemeor@yahoo.com*

^b *E-mail: golchin_babak@yahoo.com*

Abstract: Rediset is a chemical warm mix asphalt additive that can reduce the viscosity of asphalt binder at a given temperature, hence reducing the mixing and compaction temperatures of asphalt mixes. This paper evaluates the viscosity, rutting and fatigue parameters of conventional asphalt binder blended with 0%, 1%, 2%, 3%, and 4% Rediset using the Rotational Viscometer and the Dynamic Shear Rheometer. In addition, aging factors were calculated to evaluate binder properties under unaged and short-term aged conditions. Statistical analyses of the data showed that using Rediset to decrease the viscosity of the asphalt binder at high temperatures does not adversely effects the fatigue and rutting behavior of the asphalt binder subjected to different aging conditions.

Keywords: Warm mix asphalt, rutting, fatigue, viscosity, analysis of variance

1. INTRODUCTION

Warm mix asphalt (WMA) additives are materials which can be used to reduce the mixing and compaction temperatures of asphalt mixtures. Usage of such materials can decrease both fuel consumption and emissions of asphalt plants and hence can be considered as an environmentally sustainable technology. Therefore, warm mix asphalt technology can be important to policymakers, decision makers, suppliers and researchers.

Rediset is a chemical water-free WMA additive developed by Akzo Nobel, Netherlands (Arega et al. 2011). This material, as a fatty polyamine and a non-foaming WMA additive, has a non-ionic component (Xiao et al. 2012; Xiao et al. 2011) and contains a long chain of aliphatic hydrocarbon and a $-NH_3^+$ group structure that promotes both active and passive adhesion (Syroezhko et al. 2011). It is a combination of cationic surfactants and organic additives into which the surfactants can improve the aggregate surfaces wetting potential with binder by active adhesion and the other components that reduces binder viscosity (Prowell et al. 2007). This product can be blended wet with the asphalt binder or can be added to the asphalt mixture right after the addition of binder (Chowdhury and Button, 2008). If it is directly blended with binder at the refinery, it does not require any modification of the plant. Otherwise, a minimal plant modification is required to add this product in the mixing drum close to where the asphalt binder is added to the aggregate (Chowdhury and Button, 2008).

Not much research has been conducted on the effects of Rediset on the asphalt binder properties. Bennert *et al.* 2010) evaluated the effects of Rediset and other WMA additives on the workability and compactability of a PG 76-22 asphalt binder. They observed that the rotational viscosity of asphalt binder containing 2% Rediset is lower than asphalt binder blended with 1.5% Sasobit, 0.6% Evotherm 3G and control base binder. Arega *et al.* 2011)

used Rediset, Sasobit, Cecabase, and two types of Evotherm for characterizing the reduced short-term aging temperature effect on the rheological properties of asphalt binders. They reported that reduced temperature in short-term aging process and presence of additives are two factors that reduce the viscosity of warm mix asphalt binders. Xiao *et al.* (2012) investigated the influence of 1.5% Rediset content in comparison with other dosage of WMA additives on the rheological properties of the three PG 64-22 asphalt binders in short-term aged condition. They noticed that the viscosity of binders with Rediset and Sasobit is lower than binders containing Evotherm and Cecabase. Syroezhkoa *et al.* (2011) reported that 3% Rediset cannot practically change the ductility of the asphalt binder. Xiao *et al.* (2011) used 1.5% Rediset to determine the rheological properties of eight asphalt binders at high performance temperatures. They found that Rediset and Evotherm increase the high failure temperature of the six binder types tested. Estakhri *et al.* (2010) conducted a laboratory and field study on the WMA in Texas. Their results indicated that at 104.4°C, 121.1°C and 159.4°C; the viscosity of binder with blended Rediset and Sasobit are lower than that of the base binder, while this value for Advera and Evotherm are higher than the base binder viscosity.

In the above investigations, researchers compared the effects of the manufacturer's recommended dosage of additives with each other. The effects of Rediset content have therefore not comprehensively evaluated. Additionally, the behavior of different binder sources varies under different aging conditions. It is postulated that the recommended dosage of Rediset by the manufacturer might be inappropriate for modification of various asphalt binder under different aging conditions. Therefore, the main objective of this research is to evaluate the effects of Rediset content on the rheological properties of asphalt binder subjected to unaged, short-term and long-term aging.

In Malaysia, rutting and fatigue are the most common surface distress. In this paper, the SHRP protocol was used for the evaluation of the rutting and fatigue properties of asphalt binder containing Rediset subjected to the appropriate aging conditions. The viscosity of the asphalt binder, as important criteria in evaluation of warm mix asphalt additives, was measured using a Rotational Viscometer. The analysis of variance (ANOVA) was used to analyze the laboratory test data statistically. A flow chart illustrating the methodology is shown in Figure 1.

2. MATERIALS AND EXPERIMENTAL PROCEDURES

2.1 Materials

A PG64 asphalt binder sourced from the Middle East was chosen as the conventional asphalt binder with properties presented in Table 1. The Rediset warm additive used was produced by Akzonobel.

2.2 Production of Rediset Modified and Aged Asphalt Binder

Different laboratory procedures were conducted to prepare the Rediset modified samples. In each step, the asphalt binder was heated to 130°C for blending 0%, 1%, 2%, 3%, and 4% of Rediset by mass of binder using a low shear stirrer for 30 minutes. These binder were then artificially short-term aged according to ASTM D2872 (ASTM, 2006a) procedures via the Rolling Thin Film Oven (RTFO) at 163°C for 85 minutes. Subsequently, the Pressure Aging vessel (PAV) was used to subject the binder to long-term aging according to ASTM D6521

(ASTM, 2006b) procedures at 100°C for 20 hours.

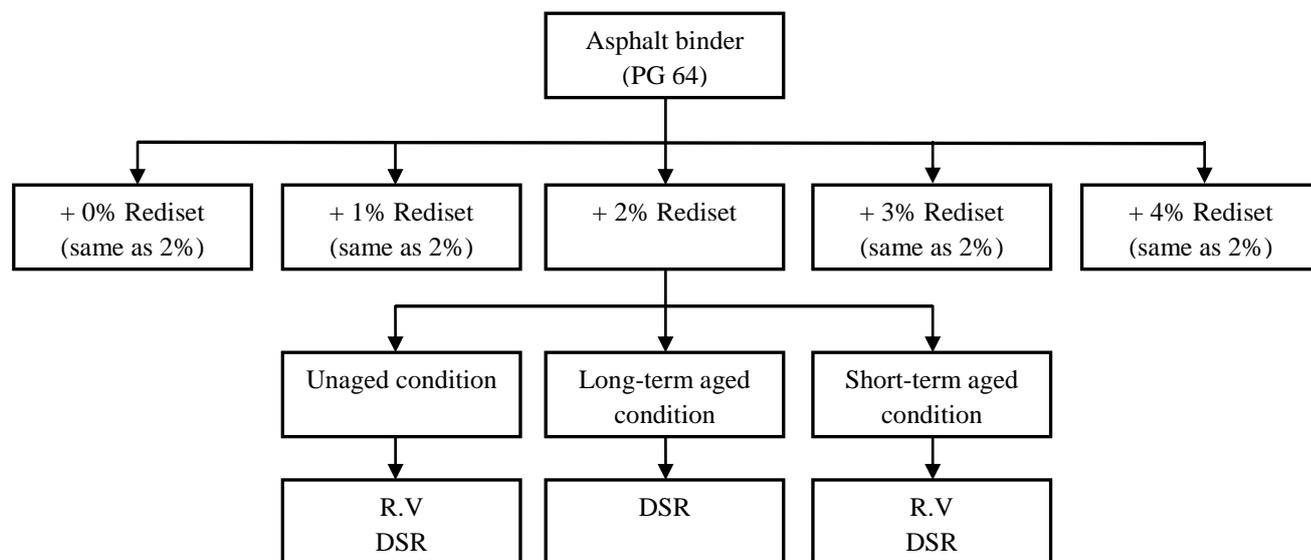


Figure 1. Test variables used in this investigation

Table 1. Properties of asphalt binder.

Aging condition	Properties	Value
Original binder	Viscosity at 135°C (Pa.s)	0.38
	$G^*/\sin \delta$ at 64°C (Pa)	1653
	Failure temperature (°C)	68
	Softening point (°C)	45
	Penetration (0.1 mm)	80
	Ductility (cm)	>100
	Flash point (°C)	331
Short-term aged binder (RTFO)	$G^*/\sin \delta$ at 64°C (Pa)	2442
	Failure temperature	65
Long-term aged binder (RTFO+PAV)	$G^*\sin \delta$ at 25°C (MPa)	2.58

2.3 Testing Procedures

A Brookfield Rotational Viscometer and Dynamic Shear Rheometer were used to determine the rotational viscosity and both rutting and fatigue resistance of the binder containing Rediset.

2.3.1 Rotational viscometer

The rotational viscosities of 11 g asphalt binders were measured at 20 rpm at 120°C, 130°C, 140°C, 150°C, and 160°C for evaluating the effects of Rediset on unaged and short-term aged binder. In addition, the viscosity of binders at 135°C right after being blended, one week after blending as well as two weeks after blending but conditioned at ambient temperature, were tested to monitor the changes in viscosity over time.

In previous research on warm mix asphalt, the viscosity has been extensively used as

an important parameter to evaluate the asphalt binder's behavior at very high temperatures (Arega *et al.* 2011; Xiao *et al.* 2012; Xiao *et al.* 2011; Kim *et al.* 2011; Akisetty *et al.* 2009; Shang *et al.* 2011; Lee *et al.* 2009; Silva *et al.* 2010). For short-term aged binder, this value is a factor that can be related to the viscosity of the binder in the asphalt mixture after being stored in a heated silo or transported over longer distances (Arega *et al.* 2011).

2.3.2 Dynamic shear rheometer

In rutting characterization of the binders, unaged and short-term aged samples with 1 mm thickness were tested using the Dynamic Shear Rheometer (DSR) on 25 mm diameter parallel plates. These tests were carried out at 46°C to 82°C at 6°C increments to determine the complex modulus (G^*), phase angle (δ), and $G^*/\sin\delta$. Fatigue characterization was performed on 4 samples with 2 mm thickness using the same DSR machine but using 8 mm diameter parallel plates. The tests were conducted at 16°C to 31°C at increment 3°C for determining the G^* , δ , and $G^*\sin\delta$. All tests were performed in oscillatory loading condition on strain control mode at 1.59 Hz.

In previous warm asphalt binder studies, G^* and δ have been directly and indirectly used in evaluation of the rutting resistance of asphalt binders (Arega *et al.* 2011; Xiao *et al.* 2012; Xiao *et al.* 2011; Kim *et al.* 2011a; Akisetty *et al.* 2009; Shang *et al.* 2011; Lee *et al.* 2009; Silva *et al.* 2010; Kim *et al.* 2011b). These parameters were measured by DSR according to SHRP protocols in oscillatory loading condition at high service temperature for very small deformation. The critical values for rutting resistance are 1000 and 2200 Pa for unaged and short-term aged condition, respectively. High $G^*/\sin\delta$ indicates high rutting resistance for asphalt binders. In addition, $G^*\sin\delta$ has been used as an effective parameter in fatigue resistance analysis of binders containing warm additives in long-term aged state (Arega *et al.* 2011; Kim *et al.* 2011a; Lee *et al.* 2009; Hamzah *et al.* 2010) measured by the DSR at midrange temperature. Higher $G^*\sin\delta$ implies lower resistance to fatigue cracking.

3. RESULTS AND DISCUSSION

3.1 Rotational Viscosity

3.1.1 Rotational viscosity of unaged binder

The rotational viscosity of unaged asphalt binder can be used to specify the pumpability characteristics of a binder and to determine the appropriate asphalt mixing and compaction temperatures (Anderson *et al.* 1994). Aggregate can be easily coated by asphalt binder at lower viscosities. The viscosity of the base binder and binder with different Rediset contents were plotted against temperature as shown in Fig. 2. From the results, addition of 4%, 3%, 2% and 1% of Rediset into the base binder at 120°C decreases the binder viscosity by 33.3%, 29.9%, 24.1%, and 18.4%, respectively. Also, the change in viscosity at temperatures ranging from 120% to 140°C is higher than the equivalent range from 140% to 160°C. For example, addition of 2% Rediset into the base binder at 120°C decreases the base binder viscosity by 24.1%. At 160°C, the corresponding value is 15.4%. From Fig. 2, lower viscosity of Rediset modified binder is related to the higher Rediset content.

Table 2 shows the statistical analysis of the viscosity results for unaged binder based on the statistical software. From Table 2, blending 1%, 2%, 3% and 4% Rediset into the base binder at 120°C, 140°C and 160°C has significant effect on viscosity. Increasing the Rediset

content from 1% to 2% and from 2% to 3 % does not have significant effects on viscosity at 140°C. Similarly, at test temperature 160°C, increasing Rediset content from 1% to 2%, 2% to 3% and 3 to 4% does not exhibit any significant effect on the viscosity.

Fig. 3 depicts the fitness of exponential function with R^2 of 0.997 for viscosity of binder with 1% Rediset. Similar functions with high R^2 can be developed for other Rediset contents.

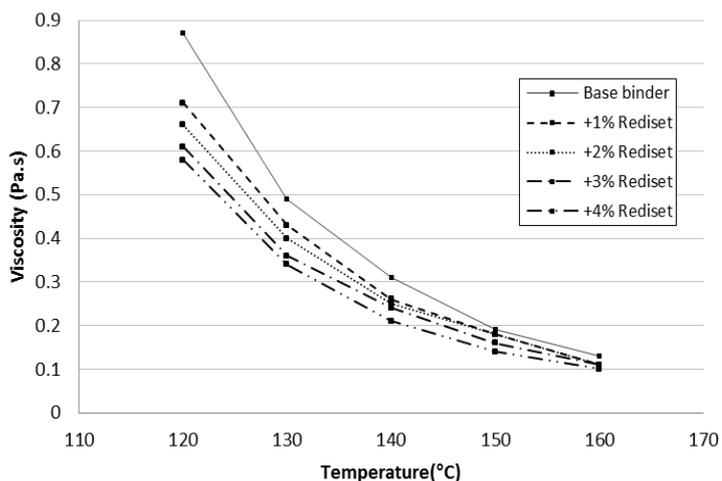


Figure 2. Relationship between viscosity and temperature for PG64 binder

Table 2. Statistical analysis of viscosity at unaged condition.

Temperature Rediset content (%)	120°C					140°C					160°C				
	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4
0	-	Y	Y	Y	Y	-	Y	Y	Y	Y	-	Y	Y	Y	Y
1		-	Y	Y	Y		-	N	Y	Y		-	N	N	Y
2			-	Y	Y			-	N	Y			-	N	Y
3				-	Y				-	Y				-	N
4					-					-					-

Y Significant effect at 95% confidence interval
 N Not significant effect at 95% confidence interval

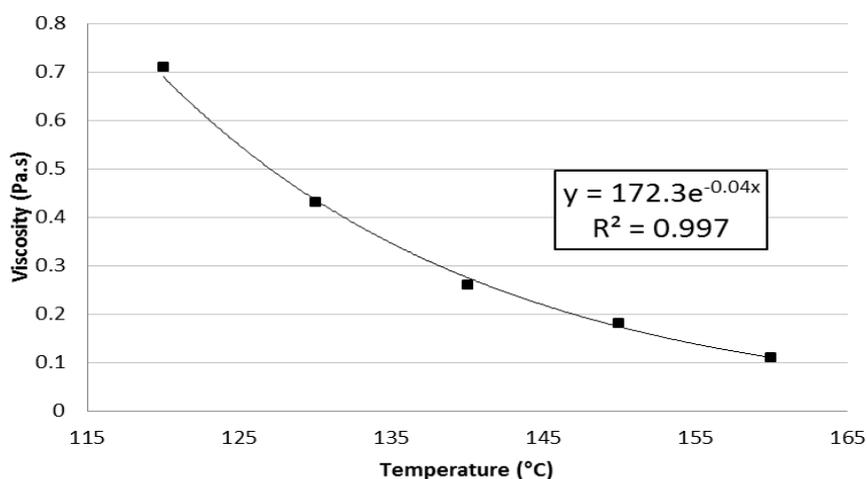


Figure 3. Relationship between viscosity and temperature of binder modified with 1% Rediset

3.1.2 Rotational viscosity of short-term aged binder

The relationship between viscosity of short-term aged binder versus temperature for binders modified with different Rediset contents is presented in Fig. 4. The results show an increase in viscosity due to aging but a decrease in viscosity due to addition of Rediset in the binder. The viscosity of the aged and Rediset modified binder with 3% and 4% Rediset content is lower than the viscosity of the corresponding base binder which implies that the viscosity of the Rediset modified binders in compacted mixtures in the field that has been subjected to short term aging is less than the viscosity of the base binder in the storage tanks in an asphalt plants. In addition, the viscosity of the short-term aged binder blended with 2% Rediset is approximately equivalent to that of the unaged binder.

The statistical analysis results of the viscosity of the short-term aged binder are shown in Table 3. From Table 3, at 120°C and 140°C, increasing the Rediset content has significant effect on viscosity. At 160°C, the corresponding increase from 1% to 2%, 2% to 3%, 3% to 4% and 2% to 4% dose not exhibit significant effect on viscosity.

The outcomes of calculating relative change in viscosity due to aging (aging factor) as a function of temperature and Rediset content is shown in Fig. 5. From Figure 5, the minimum aging factor takes place at 2% and 3% Rediset content (except 120°C).

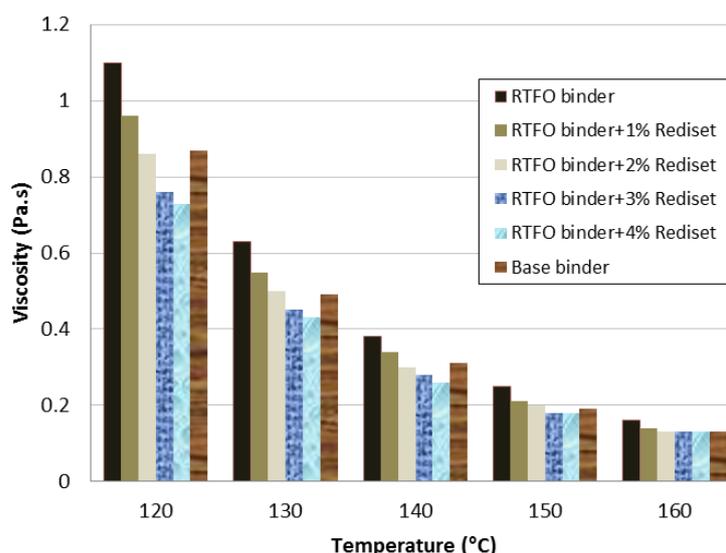


Figure 4. Rotational viscosity values of base binder and RTFO-aged binders containing Rediset

Table 3. Statistical analysis of viscosity at short-term aged condition.

Temperature	120°C					140°C					160°C				
Rediset content (%)	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4
0	-	Y*	Y	Y	Y	-	Y	Y	Y	Y	-	Y	Y	Y	Y
1		-	Y	Y	Y		-	Y	Y	Y		-	N**	Y	Y
2			-	Y	Y			-	Y	Y			-	N	N
3				-	Y				-	Y				-	N
4					-					-					-

* Significant effect at 95% confidence interval

** Not significant effect at 95% confidence interval

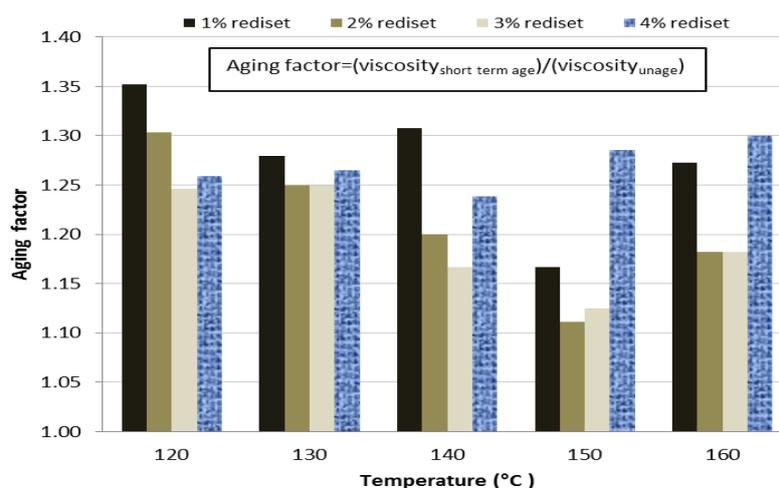


Figure 5. Relative change in viscosity of binder containing Rediset due to aging

3.1.3 Storage of binder containing Rediset

The possibility of storing binders containing Rediset over a long time can be an important subject in the production of warm mix asphalts in asphalt plants. For this reason, the viscosity of the asphalt binder at 135°C right after blending with Rediset and also one and two weeks after blending were monitored and presented in Fig. 6. For preparing the homogenized samples, all stored binders were manually stirred for one minute and then poured in the storage cylinders. Fig. 6 shows that the viscosity of the Rediset-modified binders is relatively constant over time. This indicates that two weeks storage of different binders blended with different Rediset content do not affect their viscosities.

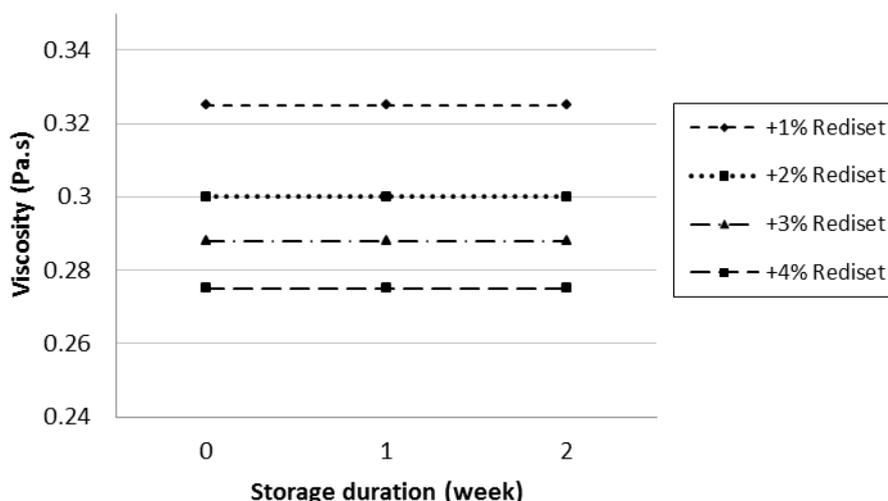


Figure 6. Variation in viscosity of binder containing Rediset tested at 135°C over time

3.2 Evaluation of Rutting Resistance

3.2.1 Rutting resistance in unaged state

Fig. 7 shows the $G^*/\sin\delta$ for asphalt binder with 0%, 1%, 2%, 3% and 4% Rediset at 46°C to 82°C. At temperatures higher than 52°C, higher Rediset content leads to higher rutting resistance. The minimum $G^*/\sin\delta$ takes place at 1% Rediset. Although the $G^*/\sin\delta$ at some temperatures and Rediset contents is less than the $G^*/\sin\delta$ of the base binder, the performance grading of the warm mix asphalt binder remains unchanged. It shows that under the same loading and temperature conditions, binder with Rediset exhibits sufficient rutting resistance like the base binder. Table 4 shows the statistical analysis results of rutting parameters at 52°C, 64°C and 76°C. From the results, increasing Rediset content does not significantly affect the rutting factor for unaged condition at 52°C and 64°C.

The variation of G^* and δ with temperature for binders blended with various Rediset content is presented in Fig. 8. The results show that there is no effect on the phase angle for binders blended with 1%, 2% and 3% Rediset. Fig. 8 also shows that the lowest G^* occurs with binder prepared at 1% Rediset content.

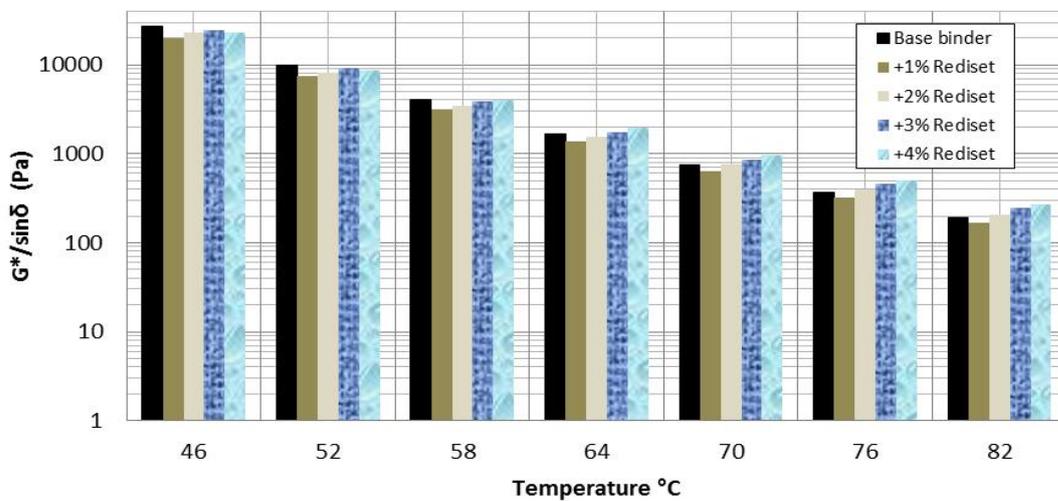


Figure 7. $G^*/\sin\delta$ of base and binders containing various Rediset content and in unaged condition

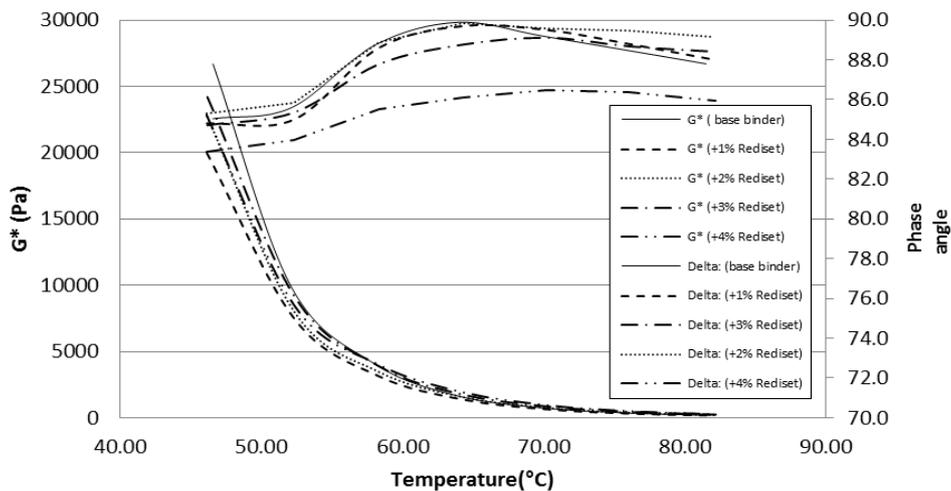


Figure 8. Relationship between G^* and δ and temperature of base and binders containing various Rediset content in unaged condition

Table 4. Statistical analysis of rutting parameter at unaged condition.

Temperature Rediset content (%)	52°C					64°C					76°C				
	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4
0	-	Y*	Y	N**	Y	-	N	N	N	N	-	N	N	N	N
1		-	N	Y	Y		-	N	N	N		-	N	N	N
2			-	Y	N			-	N	N			-	N	N
3				-	N				-	N				-	N
4					-					-					-

* Significant effect at 95% confidence interval

** Not significant effect at 95% confidence interval

3.2.2 Rutting resistance of short-term aged binder

Fig. 9 illustrates the relationship between $G^*/\sin\delta$ versus temperature for binders blended with different Rediset content at various test temperatures. Similar to the trends observed in unaged binders, the performance grade of the short-term aged binders remain unchanged. The corresponding relationship between G^* and δ with temperature for different Rediset content is shown in Fig. 10, while Table 5 shows the statistical analysis results of the rutting parameter. From Table 5, the increase in Rediset content does not exhibit any significant effect on the rutting parameter at 64°C and 76°C for binders subject to short-term aging.

Fig. 11 shows the variations in aging factor due to temperature and Rediset content. The aging factor is defined as the ratio of $G^*/\sin\delta$ after and before aging. A high value implies a high rate of aging. It can be seen that the aging factors of binders blended with 1% and 2% Rediset content are higher than the base binder when tested at 46°C, 52°C, 58°C, 64°C, 70°C and 82°C. Furthermore, the aging factor of base binder is higher than binder containing 3% and 4% Rediset at all temperatures except 52°C. In addition, this factor decreases when the Rediset content increases from 1 to 4% at temperatures ranging from 58°C to 82°C.

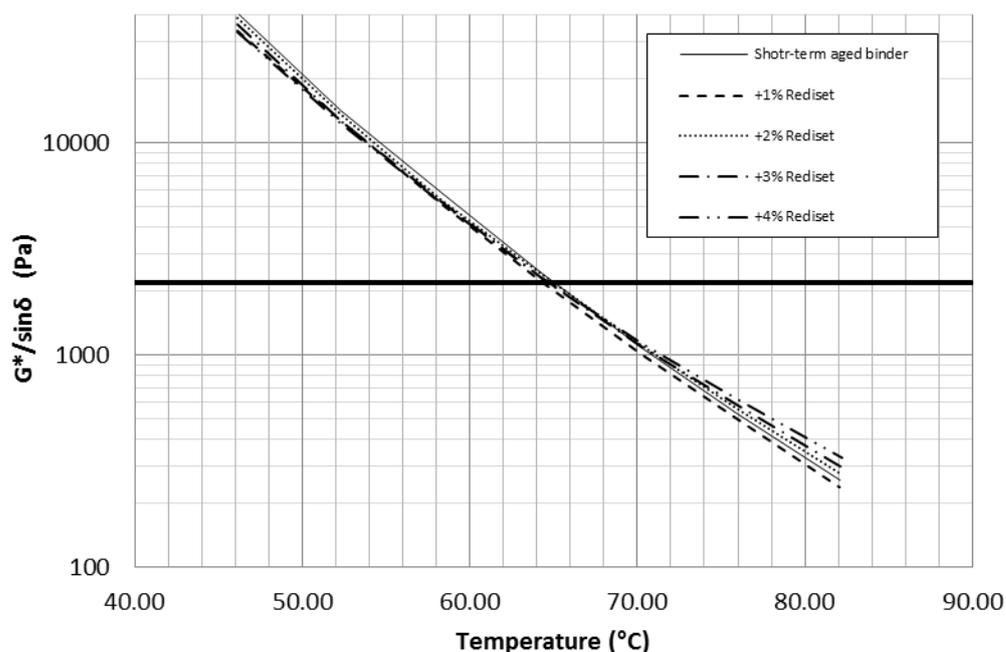


Figure 9. Relationship between $G^*/\sin\delta$ and temperature of binders containing different Rediset content subjected to short-term aging

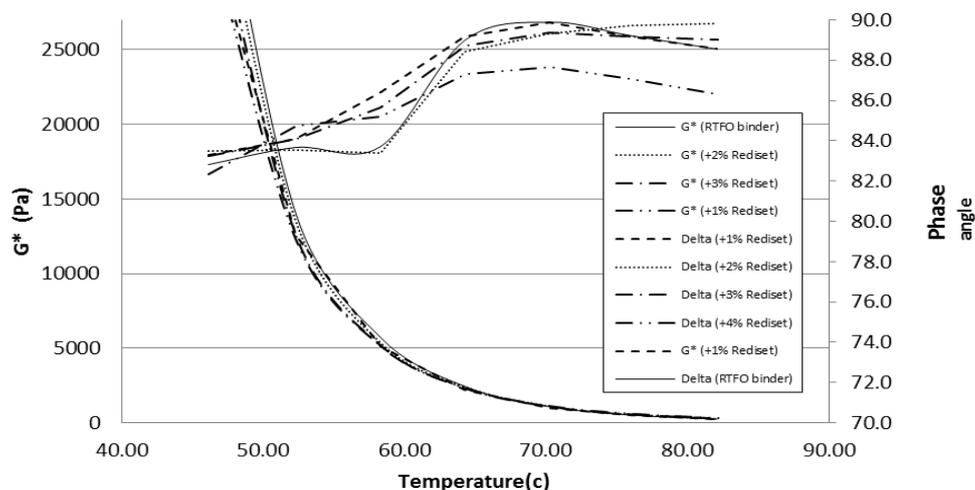


Figure 10. Relationship between G^* and δ and temperature of base and binders containing different Rediset content subjected to short-term aging

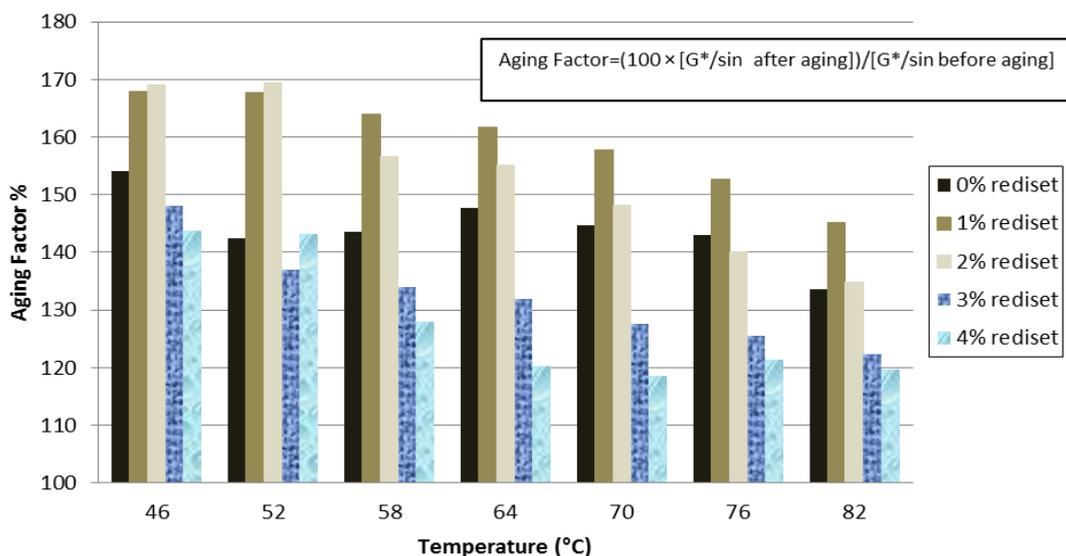


Figure 11. Aging factor versus temperature of base and binders containing different Rediset content

Table 5. Statistical analysis of rutting parameter at short-term aged condition.

Temperature	52°C					64°C					76°C				
	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4
Rediset content %	-	Y*	N**	Y	Y	-	N	N	N	N	-	N	N	N	N
0	-	Y*	N**	Y	Y	-	N	N	N	N	-	N	N	N	N
1	-	-	N	N	N	-	-	N	N	N	-	-	N	N	N
2	-	-	-	N	N	-	-	-	N	N	-	-	-	N	N
3	-	-	-	-	N	-	-	-	-	N	-	-	-	-	N
4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

* Significant effect at 95% confidence interval

** Not significant effect at 95% confidence interval

3.3 Evaluation of Fatigue Resistance

Fig. 12 presents the $G^* \sin \delta$ value for binders blended with 0%, 1%, 2%, 3% and 4% Rediset

content at temperatures between 16°C to 31°C. From Fig. 12, the fatigue resistance of binder containing Rediset appears to slightly improve by increasing the Rediset content. However, statistical analysis of data at temperatures 19°C, 25°C and 31°C (Table 6) showed that Rediset content does not have significant effect on the $G^* \sin \delta$. As expected, the fatigue resistance increases as the temperature increases. Also, the asphalt binders containing 1% and 2% Rediset do not conform to the Superpave failure criteria when tested at 16°C.

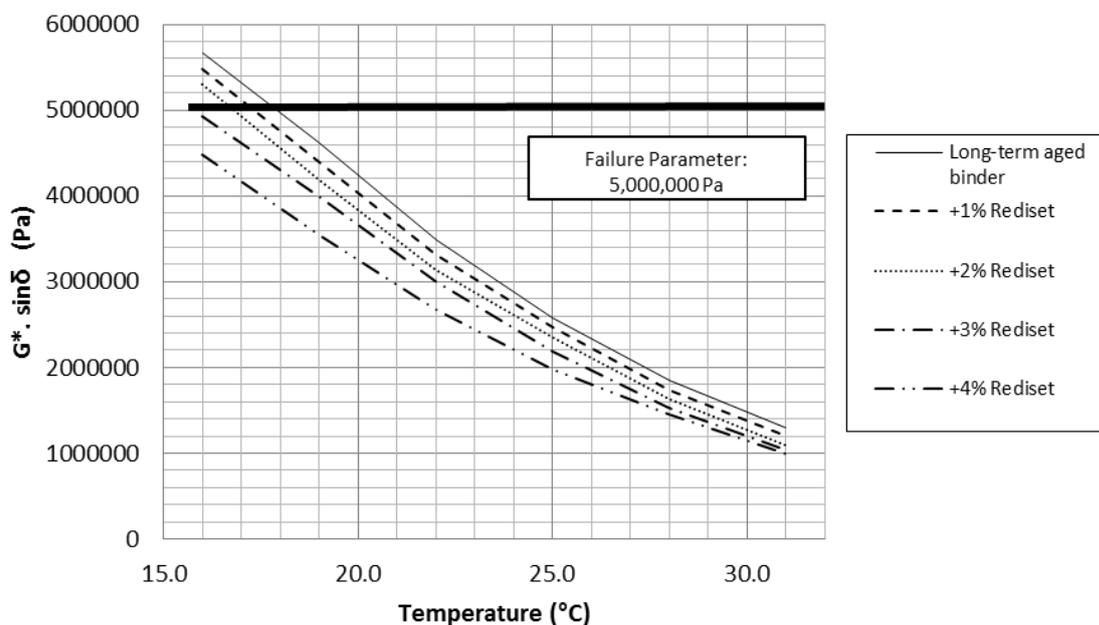


Figure 12. Relationship between $G^* \sin \delta$ and temperature of base and binders containing different Rediset content subjected to long-term aging

Table 6. Statistical analysis of fatigue parameter at long-term aged condition.

Temperature Rediset content (%)	19°C					25°C					31°C				
	0	1	2	3	4	0	1	2	3	4	0	1	2	3	4
0	-	N*	N	N	N	-	N	N	N	N	-	N	N	N	N
1	-	-	N	N	N	-	-	N	N	N	-	-	N	N	N
2	-	-	-	N	N	-	-	-	N	N	-	-	-	N	N
3	-	-	-	-	N	-	-	-	-	N	-	-	-	-	N
4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

* Not significant effect at 95% confidence interval

3.4 Ranking of Binders

The general ranking of asphalt binders based on viscosity at very high temperature, rutting resistance at high temperature, and fatigue resistance at intermediate temperature is presented in Table 7. From Table 7, binders containing 3% and 4% Rediset exhibit the highest fatigue resistance when subjected to long-term aging as well as having the highest rutting resistance in unaged condition and the lowest viscosity at very high temperatures. Additionally, the binder containing 1% Rediset exhibits lower rutting and fatigue resistance compared with binder containing 2%, 3% and 4% Rediset.

Table 7. Ranking based on the rheological properties of base binder and asphalt binder incorporating different Rediset content.

Rediset content	Rotational Viscosity unaged state	Rotational Viscosity Short-term aged state	G*/sinδ unaged state at 64°C	G*/sinδ Short-term aged state at 64°C	G*sinδ long-term aged state at 25°C
0%	5	5	3	1	5
1%	4	4	5	5	4
2%	3	3	4	2	3
3%	2	2	2	4	2
4%	1	1	1	3	1

Note: 1=best, 5=worst

3.5 Environmental and Economical Evaluation

A simple environmental and economical implications due to using Rediset was carried out using a method proposed by Hamzah et al (2010) based on the required heat energy and corresponding green house gas emissions (GHG).

Using the approach adopted by Hamzah et al (2010), the environmental and economical effects measured in terms of GHG emissions and required energy of Rediset on warm mix production process was compared with the corresponding HMA mix. The results are shown in Table 8. From this table, the use of Rediset evidently decreases the environmental pollution from an asphalt plant in terms of CO₂, N₂O, and CH₄ as well as energy consumption. This comparison was made based on production of 1000 ton of asphalt mixture incorporating granite aggregates. Other assumptions are stated in Table 8.

Table 8. Environmental and economical effects of Rediset in the production process of warm mix asphalt in comparison with HMA

Asphalt mixture*	Mixing temperature (°C)	Required Energy** (MJ)	Environmental pollutions (Green House Gas emissions***)		
			CO ₂ (kg CO ₂ /Unit)	N ₂ O (kg CO _{2e} /Unit)	CH ₄ (kg CO _{2e} /Unit)
HMA	160	121730	8401	93	5
WMA	120	83140	5738	63	3

* Assumed specific heat capacity of aggregate and asphalt binder = 790 and 920 J/kg/°C.

** Energy consumption to heat up aggregate and binder from 20°C to mixing temperature in mega joule.

*** Assumed fuel type used by asphalt plant is diesel.

4. CONCLUSIONS

Blending Rediset in asphalt binder decreases its viscosity at very high temperatures and improves the fatigue resistance at intermediate temperatures. The presence of Rediset does not significantly affect the rutting resistance of asphalt binder. It is therefore beneficial to utilize Rediset for modification of asphalt binder as a warm mix additive based on SHRP criteria for high and intermediate temperature conditions. From this study, incorporating 3% and 4% Rediset can improve binder viscosity and fatigue parameters better than 1 and 2%. Meanwhile, these Rediset contents do not adversely affects the high performance grade of the asphalt binder. Thus, it can be concluded that there are more advantages in terms of binder rheological properties, when higher Rediset contents are incorporated in conventional asphalt binders.

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