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Effects of Aging on the Physical and Rheological Properties of Asphalt Binder Incorporating Rediset®

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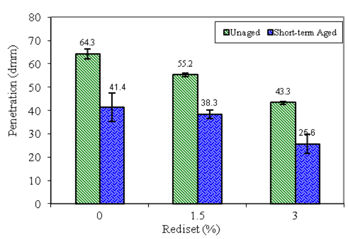
Graphical abstract



Abstract

This paper focuses on physical and rheological properties of virgin asphalt binder blended with different percentage of Rediset® content. The rheological properties of the Rediset® modified binders were characterized before and after being subjected to short-term aging using rotational viscometer (RV) and dynamic shear rheometer (DSR) according to Superpave™ test protocols. The results indicated that the penetration and softening point were consistently decreased and increased, respectively for unaged and short-term aged samples. The penetration index (PI) and viscosity aging index (VAI) were increased as the Rediset® modified binders aged and showed a high significance correlation. The addition of Rediset® in asphalt binder exhibited change in binder rheology after subjected to short-term aged which influenced the rutting parameter. A statistical analysis showed that Rediset® used as warm asphalt additive had significantly increased the G*/Sin δ parameter which indicated greater resistance to rutting.

Keywords: Rheological properties; viscosity; Rediset®; rutting parameter

1.0 INTRODUCTION

Nowadays the use of warm asphalt additive has gained popularity in the production of asphalt mixes and becomes a cost effective method of pavement construction due to its ability to lower the energy required to blend asphalt mixes. Warm mix asphalt is a technology that allows significant reduction of production and paving temperatures of conventional hot mix asphalt without compromising asphalt pavement performance [1].

Environmental awareness has been increasing rapidly over these past few years. The asphalt industry also needs to abide by environmental restrictions. In an asphalt plant, aggregates and bitumen are typically heated between 138°C to 160°C in order to completely remove moisture before being coated with hot bitumen at the desired viscosity [2, 3]. Hence, a significant proportion of the cost of asphalt mix production is associated with supplying the energy needed to raise the aggregate and binder temperatures to the mixing point. The escalating prices of crude oil and asphalt binder have initiated efforts to reduce asphalt production temperature [4].According to Aman and Hamzah [5], energy consumption reduction is brought about by lowering the binder viscosity, hence lowering mixing and compaction temperatures. There are many benefits attained by reducing asphalt production temperatures such as savings in fuel, slowing down the rate of asphalt oxidation and less odour emission. Hamzah *et al.*, [6] reported that Warm mix asphalt (WMA) technologies have been gaining positive response from policy makers, government road agencies and road builders when some laboratories and field studies showed a promising future in perspective of saving and improve performance of asphalt binder and mixtures. There are a variety of WMA additives available in the market, one is chemically produced called Rediset®.

Bitumen may present either elastic or viscous behaviour, or a combination of both. It depends on the temperature and the time over which the bitumen is observed. An adequate viscoelastic response of the bitumen is fundamental to ensure a good performance of the road pavement [7-9]. As reported by Zhang *et al.*, [10], the proportion of bitumen compounds such asasphaltene and resins were increased after the short-term aging. Further aging the bitumen by subjecting to Pressure Aging Vessel (PAV), caused the asphaltenes and resins content to continually increase while the saturates content remained constant. Apparently, severe oxidation on bitumen produces moreasphaltenes which are present in the micelle form in a colloidal structure of bitumen, directly influencing physical and rheological properties of the bitumen [11, 12]. Ghandi *et al.,* [13] conducted study to evaluate the warm asphalt binder aging characteristics after conditioning using rolling thin film oven and pressure aging vessel, and examined the binder rheology via dynamic shear rheometer. They found that the rutting parameter (G*/sin δ) of asphalt binder due to aging condition increased the rutting parameter.

According to Prowell [14], in 2002, the American Association of State Highway and Transportation Officials (ASSHTO) and the Federal Highway Administration (FHWA) had organized and implemented the WMA technologies and evaluated the performance of the WMA. The three most widely used additives to produce WMA are Aspha-Min®, warm mix asphalt-Foam®, and Low-Energy Asphalt®. These additives assisting in reducing the viscosity and expanding the volume of the asphalt binder at lower temperature thus allowed fully coated the aggregates [2, 15]. The study investigated the effects of Rediset® on fundamental properties and rheology of bitumen before and after short-term aging in terms of penetration, softening point, viscosity and rutting parameter.

2.0 EXPERIMENTAL

2.1 Materials

A 60/70 penetration-grade bitumen and Rediset® were used as the base binder and warm asphalt mix additive, respectively. The bitumen used was supplied by Shell Ltd., Malaysia while the Rediset® was supplied by AsaInfratech (M) Sdn. Bhd. Table 1 shows the physical and rheological properties of the 60/70 penetration-grade bitumen.

Table 1 Physical and rheological properties of the 60/70 penetration-grade binders

Binder	Penetration at 25°C (dmm)	Softening point °C	Viscosity at 135°C (Pa.s)	G*/Sin δ at 64°C (kPa)
60/70	64.3	49.6	1.74	4.11

2.2 Samples Preparation

Three levels of Rediset® content were used namely 0%, 1.5% and 3% Rediset® by mass of bitumen. Rediset® was blended with asphalt binder by heating 500 g of virgin asphalt binder at 160°C in an electric blender, to make it fluid enough to mix with Rediset® and to ensure uniformity and homogeneity of the binder mix. Subsequently, the required amount of Rediset® was added to the hot asphalt binder. Both components were blended using an electric propeller mixer for 15 minutes to adequately disperse the Rediset® into the asphalt binder. Then Rediset® modified binder samples were prepared for rolling thin film oven to simulate short-term aging.

2.3 Binder Aging Conditions

Rediset® modified binder samples were subjected to short-term aging by artificially conditioning the samples in the laboratory via the rolling thin-film oven (RTFO) according to ASTM D2872 [16] procedures. In this artificially conditioning, 35 g of binder sample was placed in a glass bottle with a narrow top opening. The glass bottles opening were facing an air jet in the 163°C oven while rotating at 15 rpm for 85 minutes. The air flow was set at a rate of 4000 ml/min. Subsequently, samples were removed and poured into small containers for further tests.

2.4 Penetration Test

The penetration test provides a measure of the consistency or hardness of the bitumen. In this test, a needle of specified dimensions was allowed to penetrate a binder sample, under a 100 g load at 25°C temperature for 5 seconds as outlined in ASTM D5 [17] procedures.

2.5 Softening Point Test

The Softening Point test is defined as the mean temperature at which the bitumen disk softens and sags downwards at a distance of 25 mm under the weight of a standard 3.5 g steel ball. The water bath temperature was raised at 5°C per minute. When the bitumen softened and eventually deformed slowly with the ball moving through the ring. The temperature was recorded when the ball touched the bottom plate. This temperature was designated as the softening point of the bitumen and represents an equi-viscous temperature. The test was carried out in accordance with ASTM D36 [18] procedures.

2.6 Viscosity Test

Viscosity is a fundamental characteristic of bitumen that describes the resistance of fluids to flow. The effects of Rediset® content on the viscosity of unaged and short-term aged asphalt binder samples were evaluated using a Brookfield rotational viscometer. The test was carried out based on ASTM D4402 [19] procedures. The temperature of the thermo-chamber and spindle speed was set at 135°C and 20 rpm, respectively.

2.7 Dynamic Shear Rheometer Test

The Dynamic Shear Rheometer (DSR) test was conducted in accordance with Superpave™ requirements [20] to characterize asphalt binder rheology and elastic behaviour by measuring the complex modulus (G*) and phase angle (δ) of the asphalt binder at different temperatures. According to Specht *et al.,* [21], rheology is the study of the characteristics of fluid and semi-solid materials and the relationships of force and time to deformation in these materials. The complex shear modulus (G*) is one of the most important rheological characteristics ofviscoelastic materials.

In this study, the effects of Rediset® content on the rheological characteristics of unaged and short-term aged warm binder samples at intermediate temperatures were investigated in terms of complex shear modulus(G*) and the phase angle (δ) determined from the Dynamic Shear Rheometer (DSR) test. Temperature sweeps were applied from 46°C to 82°C at 6°C increments for unaged and short-term-aged samples. The samples diameter and thickness were 25 mm and 1 mm, respectively. The loading frequency sweep was 1.59 Hz or 10 radius/s.

2.8 Analysis of Results

The laboratory test results were analyzed by using statistical analysis.The Pearson correlation analysis was performed to determine the correlation between penetration index and viscosity aging index of the asphalt binders containing Rediset®. Analysis of variance (ANOVA) was performed to determine the effects of Rediset® and aging condition on rutting parameter at 95% confidence level.

■3.0 RESULT AND DISCUSSION

3.1 Penetration

Figure 1 shows the penetration values of control and Rediset® modified binder samples before and after subjected to short-term aging. The result indicated that the penetration values for unaged and short-term aged samples were constantly decreased as percentage of Rediset® increased. The penetration of short-term aged of 3% Rediset® modified binder samples had decreased 40.9% compared to 30.6% for short-term aged of 1.5% Rediset® modified binder samples in relation to the respective percentage unaged samples. Rediset®had chemically reduced the binder viscosity and increased the binder stiffness whichresulteddecrease inthe penetration values.

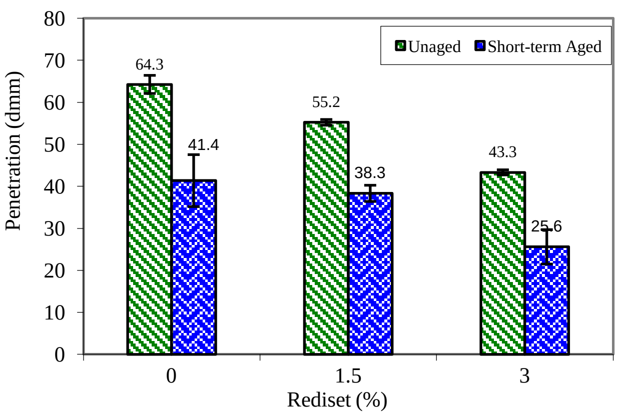


Figure 1 Penetration of binders containing Rediset® for unaged and short-term aged

From Figure 1, it is interesting to note that the penetration value of short-term aged control samples of 3% Rediset® modified binder was reduced to 35.6% when compared to unaged control samples. This percentage of decreasing in penetration value of control sample was higher compared to penetration value of 1.5% Rediset® modified binder sample.According to Cominsky *et al.,* [22], aging caused by oxidation changes the structure and composition of asphalt molecules leads to more brittle and hardened asphalt binder. Clearly, the short-term aged binder penetrations are constantly lowest compared with the unaged binder penetrations.

3.2 Softening Point

Figure 2 shows the effects of Rediset® content on asphalt binder for unaged and short-term aged samples. The result indicated that the softening points for unaged and short-term aged samples were constantly increased as percentage of Rediset® increased. The softening point of unaged 1.5% and 3% Rediset® modified binder samples had increased to 15% and 21.9% respectively. Correspondingly, the short-term aged of 1.5% and 3% Rediset® modified binder samples had increased to 9% and 12.2% compared to short-term aged control samples. The softening point of short-term aged of 3% Rediset® modified binder samples had increased 16.7% compared to 20.5% for short-term aged of 1.5% Rediset® modified binder samples compared to the respective percentage of unaged Rediset® modified binder samples. These weredue to Rediset®reducing the binder viscosity and increasing the elasticity of the asphalt binder to resist deformation, thus resulting in the increased of softening point values. It can be seen that the softening point of short-term aged control samples was increased to 25.9% in relation to unaged control samples. In contrary, the percentage increased of softening point for short-term aged of 1.5% and 3% Rediset® modified binder samples were lower compared to control samples.This finding might due tothe asphalt binder becoming more solid-elastic and a little viscous, as well as increases the stiffness of the asphalt binder by simulating the aging condition. According to Aman [24], Rediset® which a combination of emulsification agents, surfactants and polymers, decreasing binder viscosity to increases binder stiffness. During aging, resins turn into asphaltenes, which change from viscous liquid to an elastic semi-solid state.

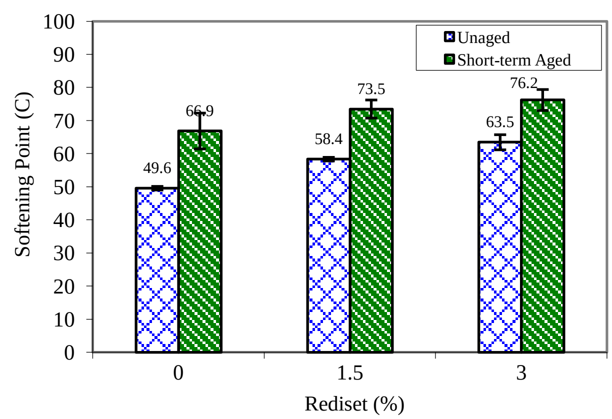


Figure 2 Effects of Rediset® on aging state conditions

3.3 Viscosity of Binder

Figure 3 shows the effects of Rediset® content on the viscosity of unaged and short-term aged for control binder and Rediset® modified binder tested using a Brookfield rotational viscometer at 135°C. It can be noted that the unaged and short-term aged of control binder and Rediset® modified binder viscosities had decreased as Rediset® content increased. Addition of 1.5% and 3% Rediset® in asphalt binder had decreased the viscosities of unaged binder 35% and 47%, respectively. Meanwhile the short-term aged of 1.5% and 3% Rediset® modified binder samples had decreased 24% and 40%, respectively compared to short-term aged control binder. Furthermore the viscosity for short-term aged of 1.5% and 3% Rediset® modified binder samples had increased 42% and 40%, respectively compared to the respective percentage of unagedRediset® modified binder samples. However the viscosities of Rediset® modified binder samples were still lower than control samples due to increase of binder elasticity and binder stiffness.

As reported by Prowell [14], warm asphalt additive significantly reduced the binder viscosity and influence the binder rheology, and affects its homogeneous distribution in the asphalt binder. According to Cominsky *et al.,* [22], the aging condition caused by oxidation changes the structure and composition of asphalt molecules leads to more brittle and hardened asphalt binder.

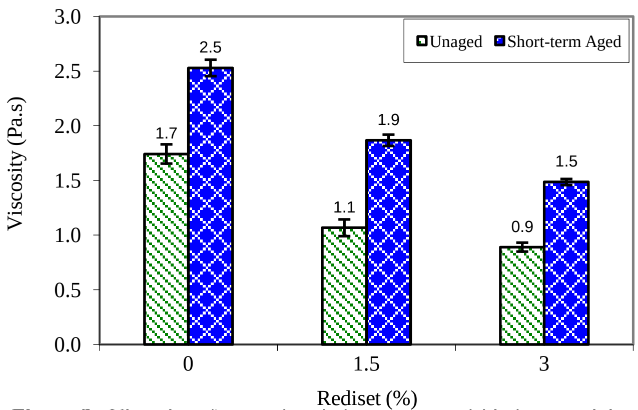


Figure 3 Viscosity of unaged and short-term aged binder containing Rediset® at 135°C

3.4 Penetration Index and Viscosity Aging Index

The penetration index (PI) is a measure bitumen susceptible to temperature and is calculated using Equation 1 [23].

$$\mathrm{PI} = \frac{1952 - 500\log \mathrm{pen} - 20\,\mathrm{SP}}{50\log \mathrm{pen} - \mathrm{SP} - 120} \qquad (1)$$

Where:

pen = penetration at 25°C
SP = softening point

Table 2 shows the effects of Rediset® on Penetration Index (PI) of asphalt binder. The results indicated that penetration index had increased as percentage of Rediset® increased thus physically Rediset® modified binder became more harden.

The Viscosity Aging Index (VAI) is defined by Equation (2). Table 2 also shows the VAI of the asphalt binder containing Rediset®.

$$\mathrm{VAI} = \frac{\text{Viscosity of aged binder containing Rediset}}{\text{Viscosity of unaged binder containing Rediset}} \qquad (2)$$

It can be seen that 1.5% Rediset® modified binder exhibited higher viscosity aging index compared to control binder. This high rate of hardening was contributed to the increasing asphaltene compounds in the asphalt binder due to oxidative process caused by the short-term aging. However viscosity aging index of 3% Rediset® modified binder had slightly decreased due to greater amount of Rediset® added to the asphalt binder.Thiswas due to highest binder viscosities resultedincreaseinbinder stiffness, consequently decreasein aging indices value.

Table 2 Penetration index and viscosity aging index of Rediset® modified binder

Percentage of Rediset	Penetration Index	Viscosity Aging Index
0	-0.86	1.45
1.5	0.67	1.75
3.0	1.42	1.67

The experimental data obtained were analysed using statistical analysis to determine correlation between penetration index and viscosity aging index of the asphalt binder containing Rediset®. Table 3 shows significance Pearson correlation between penetration index and viscosity aging index of the asphalt binders containing Rediset®. This is evident by high penetration index well corresponds to high viscosity aging index of the asphalt binders containing Rediset®.

Table 3 Coefficient of correlation analysis

Correlation between	Pearson correlation	*p*-value (2-tailed)
PI*VAI	0.718	<0.029

Notes : PI –Penetration Index, VAI –Viscosity Aging Index

3.5 Effects of Rediset® Content on Rutting Parameter

Permanent deformation on asphalt pavements defined as unrecoverable the accumulation of small amounts of strain resulting from impact of wheel load considered as a major problem. The effects of Rediset® as warm asphalt additive on rutting parameter was evaluated after conducting RTFO at 163°C. According to Gandhi *et al.,* [13], the binder rheological measured at 64°C would influence the stress and strain relationship due to the action of wheel loads. Figure 4 shows the result of G*/Sin δ for the short-term aged control binder and Rediset® modified binder at different test temperatures. Based on Figure 4, the results indicate a general decreasing trend of the G*/Sin δ as test temperature increases. The short-term aged 3% Rediset® modified binder had higher G*/Sin δ value compared with the control binder and 1.5% Rediset® modified binder. The G*/Sin δ value for short-term aged binder prepared using 3% Rediset® and the control binder tested at 46°C and 82°C were found in ranges of 51.78 kPa to 0.80 kPa and 41.20 kPa to 0.357 kPa, respectively. By incorporating 3% Rediset®, the G*/Sin δ had increased by 20.4% and 29.2% when tested at 46°C and 82°C, correspondingly. The increase of the rutting resistance of Rediset®modified binder could be attributed to the presence emulsification agents, surfactants and polymers in the asphalt binder as discussed in section 3.2, thus increases the G* and reduces the δ.As reported by Aman [24], asphalt binder tested at high temperature reduced the binder viscosity and decreased the binder stiffness make more fluid and less viscous, resulting in a decrease in resistance to plastic deformation of the binder. It can be seen that the G*/sin δ value of the short-team aged binder containing 1.5% and 3% Rediset® tested at 64°C increased by 13.7% and 49.9%, respectively. Clearly, the addition of Rediset® changes in the properties and binder stiffness, and improved the G*/Sin δ value.

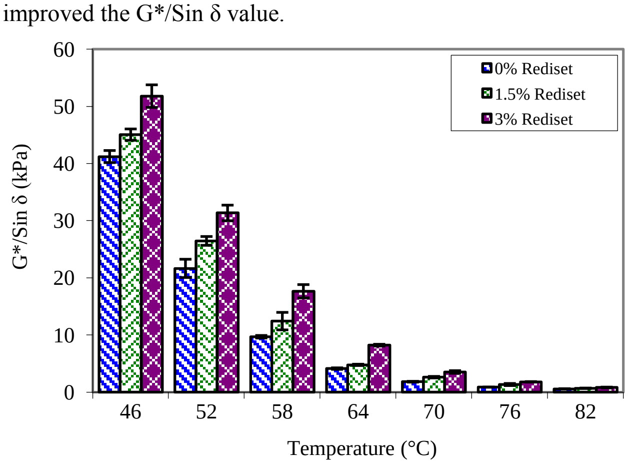


Figure 4 G*/Sin δ of short-term aged at different temperatures

The experimental data obtained were analyzed using two-way Analysis of variance (ANOVA) to identify the effects of testing temperature and percentage Rediset® used on rutting parameter. Table 4 presents the results of two-way Analysis of variance (ANOVA) analysis, which shows the effects of test temperature, percentage Rediset® used and interaction on the rutting parameter. It can be seen that the test temperature and percentage Rediset® used have a significant effect on rutting parameter (p-value less than 0.05), where the interaction between the factors also has a significant effect on rutting parameter.

Table 4 Two-way ANOVA Analysis on rutting parameters

Source	DF	SS	MS	F	*p*-value
Rediset	2	4.90878E+08	245438964	11.01	<0.001
Temp.	6	1.31786E+10	2196430211	98.54	<0.001
Interaction	12	6.26826E+08	52235506	2.34	<0.021
Error	42	9.36145E+08	22289172		
Total	62	1.52324E+10			
R-Sq = 93.85% R-Sq(adj) = 90.93%					

■4.0 CONCLUSION

The penetration and softening point had consistently decreased and increased, respectively before and after short-term aged for binders containing Rediset®. The addition of 3% of Rediset® in the asphalt binder increased the penetration index, but the viscosity aging index value decreased. Furthermore, there was a significant correlation between penetration index and viscosity aging index. The addition of Rediset® in asphalt binders exhibited a distinct change in binder rheology before and after subjected to short-term aging. Rediset® was able to increase the G*/Sin δ thus promote greater resistance to rutting.

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