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# Effects of Temperature and Shear Rate on Viscosity of Sasobit® -Modified Asphalt Binders

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**Abstract:** In this study, Superpave gyratory compacted samples were prepared at different compaction temperatures, at different asphalt contents and at different no. of gyrations to evaluate the effects of Sasobit® on density of asphalt mix. Dynamic viscosity (η') was measured at temperature ranges from 28°C to 130°C at 6°C interval. From density and viscosity analyses it can be concluded that there exists a critical temperature for a Sasobit® modified asphalt binder such that above the critical temperature Sasobit® reduces the viscosity as well as increases density and below that temperature Sasobit® increases the viscosity as well as reduces the density. Also, the shear rate dependency of steady state viscosity of asphalt binders with and without Sasobit® was analyzed in this study with in the range of 0.0025/s to 250/s. With the addition of Sasobit®, PG 64-22 at 64°C becomes a shear-thinning liquid. The shear rate dependency increases with an increase in percent of Sasobit®. Similar effects of Sasobit® are observed at 100°C in reduced level and shear rate dependency with the addition of Sasobit® is almost negligible at 124°C. Also, the rate of change of viscosity is higher at higher shear rates and lower at lower shear rates. For PG 76-22M, the shear rate dependency increases with an increase in percent of Sasobit® at all the three temperatures. This indicates that if the actual shear rate in the field is higher than what is used for viscosity measurements, the mixing and compaction temperatures currently being used can be reduced. Also in this study, the steady state viscosity data were fit to a simplified CROSS model and the fitting was evaluated by the coefficient of determination values. The zero shear viscosity at 64°C and 76°C were determined for PG 64-22 and PG 76-22M, respectively. Comparative studies between zero shear viscosity and G*/sinδ at various temperatures, dynamic viscosity and steady state viscosity at various temperatures were also conducted.

***Key words****: Density; Dynamic viscosity; Sasobit® ; Shear rate; Warm mix asphalt.*

## Introduction

Due to its environmental friendliness, warm mix asphalt (WMA) is becoming an increasingly popular material for the construction of roadways. Several warm mix technologies are available for reducing asphalt mixing and compaction temperatures, thereby saving energy and reducing emission problems. Among the available technologies, the use of organic additives such as commercial wax shows great promises. Improved compaction was noted at temperatures as low as 88°C [1-4]. Results show that lower plant temperatures can lead to a significant reduction, up to 30 percent, in energy consumption. Also, reduced production temperature leads to a reduction in emission, making WMA an environmentally attractive material. According to previous studies, the reduction in emissions represents a significant cost savings, considering that 30-50 percent of overhead costs at an asphalt plant can be attributed to emission control [1-4].

The influence of natural wax as an additive in asphalt binder and hot mix asphalt (HMA) has been under discussion for decades, implying both negative and positive effects. However, natural wax in asphalt binder is low in content in recent days and of a kind not likely to be harmful to binder or HMA properties [5-6]. Therefore, the use of commercial waxes as additive to asphalt binder in WMA, in order to gain certain positive effects, can be of great interest. Commercial waxes such as Fischer-Tropsch (FT) paraffin wax (Sasobit®) and montan wax (Asphaltan B®) are commonly used in WMA. Sasobit® is a product of Sasol Wax GmbH (Germany) and Asphaltan B® is a product of Romonta, GmbH (Germany). Sasobit® is produced in FT synthesis, where carbon monoxide is converted into higher hydrocarbons in catalytic hydrogenation, followed by a distillation process. The end product consists of mainly fine crystalline long chain aliphatic polymethylene hydrocarbon chains with 40–100 carbon atoms [6]. By comparison, macrocrystalline bituminous paraffin waxes have carbon chain lengths ranging from 25 to 50. The longer carbon chains in the Sasobit® lead to a higher melting point, and the wider wax molecule distribution results in broader melting temperature range and enlarged plasticity span. In the range of 60°C to 90°C, natural asphalt wax is normally completely melted out whereas, the melting temperatures of asphalt with Sasobit® are higher (between approximately 100°C and 130°C) [7].

Effects of Sasobit® in asphalt binders and HMA have been studied previously by several researchers [8-10]. Sasobit® is known to improve flow of asphalt mixes (viscosity depressant) and to reduce the mixing and compaction temperatures by about 18-54°C [11]. In addition, Sasobit® reportedly improved resistance to deformation at higher temperatures for asphalt binder and HMA (rutting) thereby, significantly increasing the high temperature grading of an asphalt binder. However, increase in creep stiffness and reduction in creep rate (m) may be a concern for low temperature grading, specifically in the case of overdosing. Moreover, a lower mixing and compaction temperature can result in incomplete drying of the aggregate. The resulting water trapped in the coated aggregate may cause moisture

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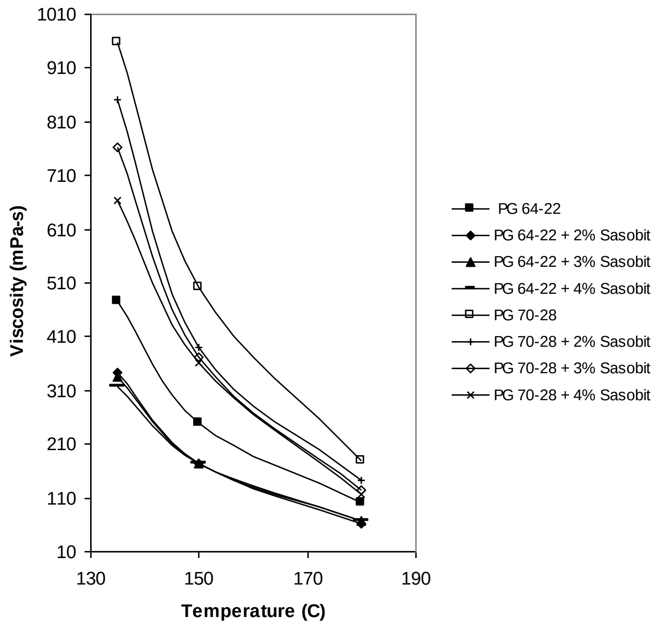


**Fig. 1.** Rotational Viscosity of PG64-22 and PG70-28 (Reproduced from Wasiuddin *et al*. [8]).

damage. Also, reduced-aging property of Sasobit® was reported by some researchers. Despite having significant focus during the past decade on the WMA, the effects of a wider temperature range and shear rates on viscosity of wax-modified asphalt binders and corresponding effect on field mix density are still not clear.

In a previous study, Wasiuddin *et al*. [8] reported that for PG 64-22, all the three percentages of Sasobit® (2%, 3% and 4%) reduced the mixing and compaction temperatures based on the rotational viscosity as can be observed from Fig. 1. The reduction in mixing temperature is 16ºC from 163ºC for all the three percentages of Sasobit®. In the case of PG 70-28, 2%, 3% and 4% Sasobit® reduced the Oklahoma DOT mixing temperature by 10ºC, 12ºC and 13ºC, respectively, from 163ºC. A similar trend was observed for reduction in compaction temperature.

However, in the field, the compaction temperature usually ranges from 85°C to 155°C which includes breakdown and intermediate rolling. Finish rolling normally takes place within a temperature range of 85°C down to 70°C. The researchers in the previous study investigated only the higher compaction temperatures as they used the rotational viscometer. In the current study, the researchers used a dynamic shear rheometer and measured dynamic viscosity (η') at lower compaction temperatures.

In the same previous study, Wasiuddin *et al*. [8] reported that the G*/sin(δ) of the original PG 64-22 with 2% Sasobit® is 1.21 kPa at 64°C. The G*/sin(δ) of the same binder with 3% and 4% Sasobit® are 1.47 kPa and 1.90 kPa, respectively, at the same temperature. Comparatively, the G*/sin(δ) of the original binder is 1.13 kPa. It is evident that the addition of Sasobit® increased the G*/sin(δ) with an increase in percent of Sasobit®. A similar increasing trend of G*/sin(δ) was observed for PG 70-28 with the addition of Sasobit®.

To this end, the authors in the previous study observed that Sasobit® increased the stiffness of asphalt binder at service temperatures and reduced the viscosity at mixing and higher compaction temperatures. In other words, Sasobit® increased the viscosity at service temperatures and reduced the viscosity at production temperatures. This indicates that the viscosity curves of asphalt binder and asphalt binder modified with Sasobit® will have a *critical temperature*. It is imperative that the *critical temperature* should be below the compaction temperature range of asphalt mix. Therefore, the researchers in the present study performed a wider temperature sweep to measure dynamic viscosity of Sasobit® modified asphalt binders and investigate the position of the *critical temperature* and its effect on laboratory and field density. To address this concern adequately, the effect of shear rate on viscosity of asphalt binders with and without Sasobit® have also been studied as the shear rates during mixing and compaction is still unknown.

## Objectives

The overall objective of this study is to investigate the effect of Sasobit® on viscosity of asphalt binders and the density of asphalt mixes. The specific objectives are as follows:

(1) Evaluate dynamic viscosity as defined by G''/ω, from sinusoidal loading using a dynamic shear rheometer at lower compaction temperatures.
(2) Evaluate steady state rotational viscosity using a dynamic shear rheometer at lower compaction temperatures
(3) Understand effect of Sasobit® on field density of asphalt mixes.
(4) Investigate effect of Sasobit® on laboratory density of asphalt mixes.
(5) Evaluate effect of shear rate on steady state viscosity of asphalt binders.
(6) Evaluate G*/sin(δ) at higher pavement service temperatures with and without the addition of Sasobit®.
(7) Develop viscosity models of Sasobit® modified asphalt binders.

## Material Description

Sasobit® is a product of Sasol Wax, South Africa. It is a modifier or an "asphalt flow improver." Both the asphalt binders, PG 64-22 (also known as AC30) and PG 76-22M (also known as PAC40), used in this study were obtained from Ergon Refining Inc., Vicksburg, Mississippi. PG 64-22 is an unmodified binder, whereas PG 76-22M is a polymer-modified binder.

## Laboratory Testing

Three selected percentages of Sasobit®, 1%, 2% and 4% were added to both the binders for rheological testing using a dynamic shear rheometer consisting of parallel metal plates according to AASHTO T315. The tests were run from 28°C to 130°C at 6°C interval. Here only the results from 58°C through 130°C have been reported. Metal plates of 25mm diameter were used. The gap between the upper and lower plates was 0.5mm instead of 1mm. The tests were performed at a frequency of 10 radian/s and the strain was constant at 12%. A superpave mix with ½-in. nominal maximum size was compacted at two different gyrations and at two different asphalt contents to investigate the effect of viscosity reductions on density

**Table 1.** Effect of Sasobit® on Binder Stiffness.

| | Phase Angle, δ, Degree | Complex Shear Modulus, G*, kPa | High Temperature Stiffness, G*/sinδ, kPa | Elastic or Storage Modulus, G', Pa |
|---|---|---|---|---|
| Temperature 64°C | | | | |
| PG 64-22 | 84.4 | 3.1 | 3.1 | 302.8 |
| PG 64-22 + 1% Sasobit® | 82.0 | 4.3 | 4.4 | 602.3 |
| PG 64-22 + 2% Sasobit® | 80.1 | 6.7 | 6.8 | 1148.1 |
| PG 64-22 + 4% Sasobit® | 78.6 | 6.9 | 7.1 | 1375.3 |
| Temperature 76°C | | | | |
| PG 64-22 | 87.4 | 0.7 | 0.75 | 34.4 |
| PG 64-22 + 1% Sasobit® | 84.8 | 1.1 | 1.08 | 96.5 |
| PG 64-22 + 2% Sasobit® | 83.6 | 1.5 | 1.54 | 170.5 |
| PG 64-22 + 4% Sasobit® | 81.5 | 1.5 | 1.47 | 213.3 |
| Temperature 76°C | | | | |
| PG 76-22M | 69.6 | 2.3 | 2.5 | 428.5 |
| PG 76-22M+ 1%Sasobit® | 67.8 | 2.9 | 3.1 | 1082.3 |
| PG 76-22M+ 2%Sasobit® | 67.5 | 3.3 | 3.6 | 1269.0 |
| PG 76-22M+ 4%Sasobit® | 68.5 | 2.9 | 3.1 | 1072.8 |

**Table 2.** Effect of Sasobi® at Lower Compaction Temperature (100°C and 130°C).

| Binder | Dynamic Viscosity, η (Pa.s) at 100°C | Dynamic Viscosity, η (Pa.s) at 130°C |
|---|---|---|
| PG 64-22 | 7.98 | 1.24 |
| PG 64-22 + 1% Sasobit® | 7.76 | 1.08 |
| PG 64-22 + 2% Sasobit® | 10.74 | 1.00 |
| PG 64-22 + 4% Sasobit® | 10.33 | 0.73 |
| PG 76-22M | 30.94 | 4.28 |
| PG 76-22M + 1% Sasobit® | 30.29 | 3.61 |
| PG 76-22M + 2% Sasobit® | 32.47 | 3.47 |
| PG 74-22M + 4% Sasobit® | 30.82 | 2.93 |

of asphalt mixes. For effect of shear rate on steady state viscosity, three temperatures, namely 64°C, 100°C and 124°C for PG 64-22 and three temperatures, 76°C, 100°C and 124°C were used for PG 76-22M. Shear rates were used in the range between 0.0025/s and 250/s.

## Results and Discussions

### Effects of Sasobit® on Binder Stiffness, G*/sinδ

The complex shear modulus, G* is an indicator of the stiffness or resistance of asphalt binder to deformation under load. The complex shear modulus and the phase angle, δ define the resistance to shear deformation of the asphalt binder in the linear viscoelastic region. G*/sinδ is known as high temperature stiffness or rutting factor of asphalt binder. Table 1 shows that an increase in percent of Sasobit® increases the rutting factor of PG 64-22 thereby increasing the rutting resistance. Complex shear modulus, G* and elastic or storage modulus, G' show similar increasing trend. For any viscous material, there exists a phase difference between stress and strain. For a purely viscous materials strain lags stress by 90°. For a viscoelastic material such as asphalt binder, the phase lag is less than 90°. Table 1 shows that phase angle increases with an increase in percent of Sasobit® for PG 64-22.

For PG 76-22M at 76°C, up to 2% Sasobit® increases the rutting factor G*/sinδ and addition of 4% Sasobit® starts reducing it. Similar trends can be observed for complex shear modulus, G* and elastic modulus, G'. In case of phase angle, similar trend but in the other direction is observed. Firstly, this suggests that rate of Sasobit® must be optimized before its use. Secondly, this effect can be justified by the fact that the Sasobit® is an asphalt flow improver and it reduces viscosity at production temperatures. Addition of excess Sasobit® may reduce stiffness properties. In this regard, Sasobit® rate effect can be explained by temperature effect and Table 1 shows the effect on stiffness values if the tests on PG 64-22 are done at 76°C. It can be observed that changes of PG 64-22 is similar to PG 76-22M at 76°C with the addition of Sasobit®.

### Effects of Sasobit® on Dynamic Viscosity at Compaction Temperatures

In the field, the compaction temperature usually ranges from 85°C to 155°C which includes breakdown and intermediate rolling. Finish rolling normally takes place within a temperature range of 85°C down to 70°C. In this study, the results show that the dynamic viscosity, as defined by G"/ω, of asphalt binders reduces with an increase in percent of Sasobit® at higher compaction temperatures, such as 130°C. Table 2 shows that viscosity of PG 64-22 is 1.24 Pa.s at 130°C whereas, viscosity of PG 64-22 with 1%, 2% and 4% Sasobit® are 1.08 Pa.s, 1.00 Pa.s and 0.73 Pa.s, respectively. In case of PG 76-22M at 130°C, a similar reducing trend is observed with an increase in percent of Sasobit®.

**Table 3.** Nuclear Gauge Field Density (Average of 6 Locations and with Permission from Cooper [12]).

| Nuclear Gauge Density (Average of 6 Locations) in Percent | | |
|---|---|---|
| | HMA with Sasobit® in PG 76-22M | HMA with PG 76-22M |
| Directly Behind Screed | 78.7 | 75.2 |
| Roller 1 – Pass 1 | 87.0 | 85.6 |
| Roller 1 – Pass 2 | 89.4 | 88.9 |
| Roller 1 – Pass 3 | 90.0 | 90.1 |
| Roller 1 – Pass 4 | 91.3 | 91.3 |
| Roller 2 – Pass 1 | 91.6 | 91.1 |
| Roller 2 – Pass 2 | 92.4 | 91.9 |
| Roller 2 – Pass 3 | 92.5 | 91.9 |
| Roller 2 – Pass 4 | 93.4 | 92.3 |
| Roller 3 – Pass 1 | 92.9 | 92.3 |
| Roller 3 – Pass 2 | 93.0 | 92.8 |
| Roller 3 – Pass 3 | 93.3 | 92.2 |
| Roller 3 – Pass 4 | 93.2 | 93.0 |

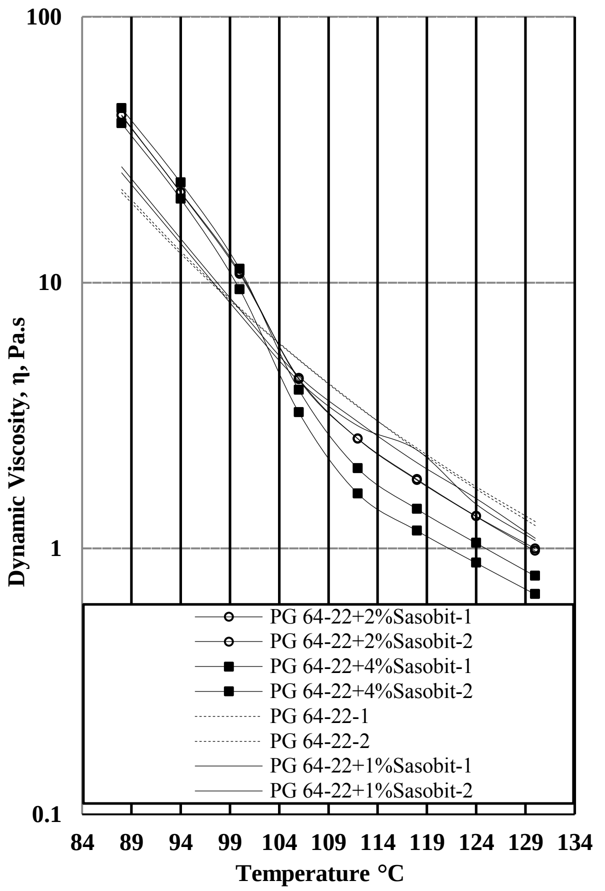


**Fig. 2.** Dynamic Viscosity, η (Pa.s) of PG 64-22 at Compaction Temperatures.

However, this trend is reverse at lower compaction temperatures, such as 100°C. Table 3 shows that at lower compaction temperature such as 100°C, viscosity increases with an increase in percent of Sasobit® thus posing a potential negative effect on field compaction as well as density. Table 2 shows that at 100°C, the viscosity of PG 64-22 is 7.98 Pa.s. This increases up to 10.74 Pa.s for 2% Sasobit®. In case of PG 76-22M, 2% Sasobit® increases the viscosity from 30.04 Pa.s to 32.47 Pa.s. This increase in viscosity with Sasobit® is not sudden as found in temperature sweep tests performed in this study. This will be discussed in the following paragraphs.

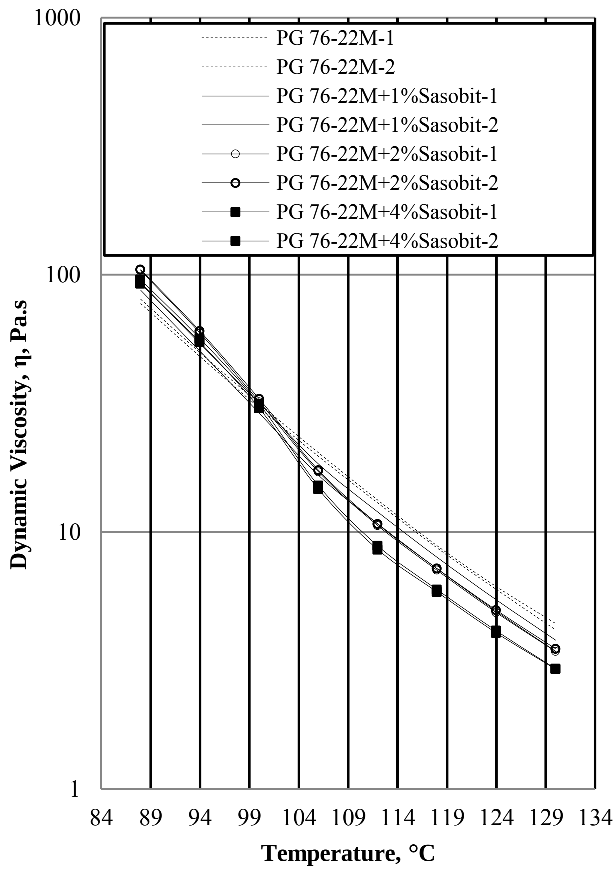


**Fig. 3.** Dynamic Viscosity, η (Pa.s) of PG 76-22M at Compaction Temperatures.

Figs. 2 and 3 show the viscosity of both the binders at a temperature range from 88°C to 130°C at 6°C intervals. It is clearly evident from the figures that Sasobit® reduces viscosity at higher compaction temperatures but it increases viscosity at lower compaction temperatures. There exists a critical temperature for each asphalt binder below which viscosity will increase with addition of Sasobit®. Increase or reduction in percent rate of Sasobit® does not change this critical temperature. Therefore, compaction below the critical temperature can negatively impact density. For PG 64-22, Fig. 2 shows that the critical temperature is 104°C and for PG 76-22, the critical temperature is about 101°C (Fig. 3).

This indicates that for PG 64-22, a mix with Sasobit® will need comparatively more compaction effort below 104°C and for PG 76-22M, this temperature is 101°C.

## Effects of Sasobit® on Density of Gyratory Compacted Samples

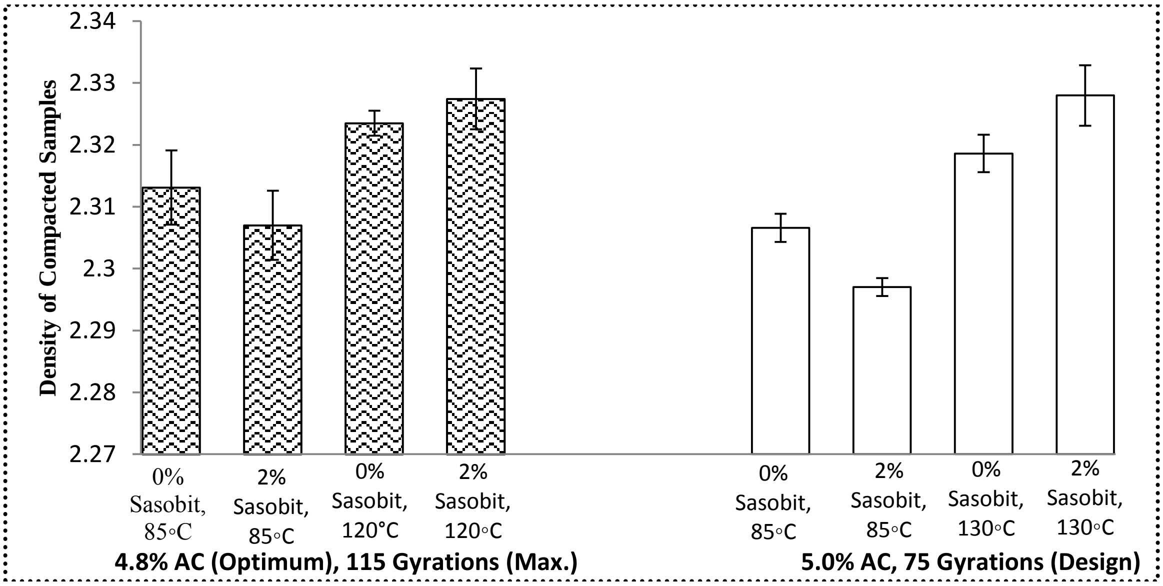


**Fig. 4.** Effect of Sasobit® on Density of Gyratory Compacted Samples.

At first, 12 gyratory compacted samples were prepared at optimum asphalt content of 4.8% PG 64-22 and at maximum gyrations of 115. 3 samples of PG 64-22 and 3 samples of PG 64-22 with 2% Sasobit® were compacted at 120°C which is higher than critical compaction temperature of 104°C. Another 3 samples of PG 64-22 and 3 samples of PG 64-22 with 2% Sasobit® were compacted at 85°C which is lower than critical compaction temperature of PG 64-22. Densities were determined following AASHTO T 166 and the average density of three replicates was presented in Fig. 4. The error bar in Fig. 4 is based on standard deviation of 3 samples. It is evident from Fig. 4 that 2% Sasobit® increases the density of gyratory compacted samples at higher compaction temperature whereas, it reduces the density at lower compaction temperature. Therefore, the effects of Sasobit® on density are similar to the effects on viscosity as found in previous studies [1]. However, for 4.8% asphalt content and 115 gyrations, statistical analyses show that at 85°C compaction temperature, the difference in densities between 0% Sasobit® and 2% Sasobit® samples is not statistically significant at 5% level (p value is 0.38). The difference is not statistically significant at 120°C also (p value is 0.27).

As can be seen in Fig. 4, the standard deviations for the first 12 samples were close to the differences in average densities. At this point, it was hypothesized that use of reduced compactive efforts (design gyrations of 75 instead of maximum gyrations of 115) and increased asphalt content (5.0% AC instead of optimum asphalt content of 4.8%) may help demonstrating the reflection of viscosity changes in density. Therefore, the following 12 samples were prepared at 75 gyrations and 5.0% asphalt content. 3 samples of PG 64-22 and 3 samples of PG 64-22 with 2% Sasobit® were compacted at 130°C. Another 3 samples of PG 64-22 and 3 samples of PG 64-22 with 2% Sasobit® were compacted at 85°C which is lower than critical compaction temperature. Fig. 4 shows the similar trend in this case also. It can be seen that the standard deviation values have reduced in this case. For second set of 12 samples (5% asphalt content and 75 gyrations), statistical analyses show that at 85°C compaction temperature, the difference in densities between 0% Sasobit® and 2% Sasobit® samples is statistically significant at 5% level (p value is 0.0036). The difference is statistically significant at 130°C also (p value is 0.047). Superpave gyratory compactor provides the height of compacted samples. Densities of samples were also calculated based on these heights for cross checking. The densities found in this method were 2.27$\pm$0.006, 2.26$\pm$0.009, 2.28$\pm$0.005 and 2.288$\pm$0.005 gm/cc for 0% Sasobit® at 85°C, 2% Sasobit® at 85°C, 0% Sasobit® at 130°C and 2% Sasobit® at 130°C samples, respectively. The standard deviations of gyratory height densities are slightly higher than those obtained from AASHTO T166.

### Implications of Viscosity Changes on Field Density

Cooper [12] from Louisiana Transportation Research Center (LTRC) conducted a field study using Sasobit®. A mix with PG 76-22M was used with and without 1% Sasobit® in it. The HMA plant temperature was 166°C for both PG 76-22M and Sasobit® mixes. This was done to better compare the Sasobit® mixes with control PG 76-22M mixes. The field asphalt contents were 3.7% and 4.1%, respectively for PG 76-22M and Sasobit® mixes. The breakdown and intermediate rolling were performed with vibration and a steel wheel finished roller was used in static mode only. Nuclear gauge density was measured at 6 locations in both PG 76-22M and Sasobit® sections. Table 3 shows the average nuclear gauge density of 6 locations obtained by Cooper [12].

It can be seen that the average density of 6 locations directly behind the screed are 78.7% and 75.2%, respectively, for PG76-22M with 1% Sasobit® and PG76-22M without Sasobit® while the densities after the finish roller are 93.2% and 93.0%, respectively. This indicates that Sasobit® indeed reduced the viscosity of binder as well as the mix at higher compaction temperature as can be seen from the density directly behind the screed. Sasobit® mix has 3.5% more density than the PG 76-22M mix at the beginning of rolling. As the compaction continues, the mixes cool down and the beneficial effects of Sasobit® cannot be seen anymore. By the time the finisher roller completes, both mixes produce similar densities, 93.3% and 93.0% respectively for Sasobit® and PG 76-22M mixes. This strongly

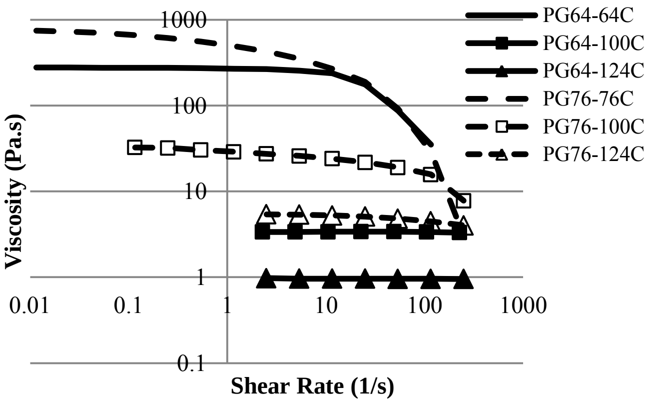


**Fig. 5.** Effect of Temperature on Shear Rate Dependency.

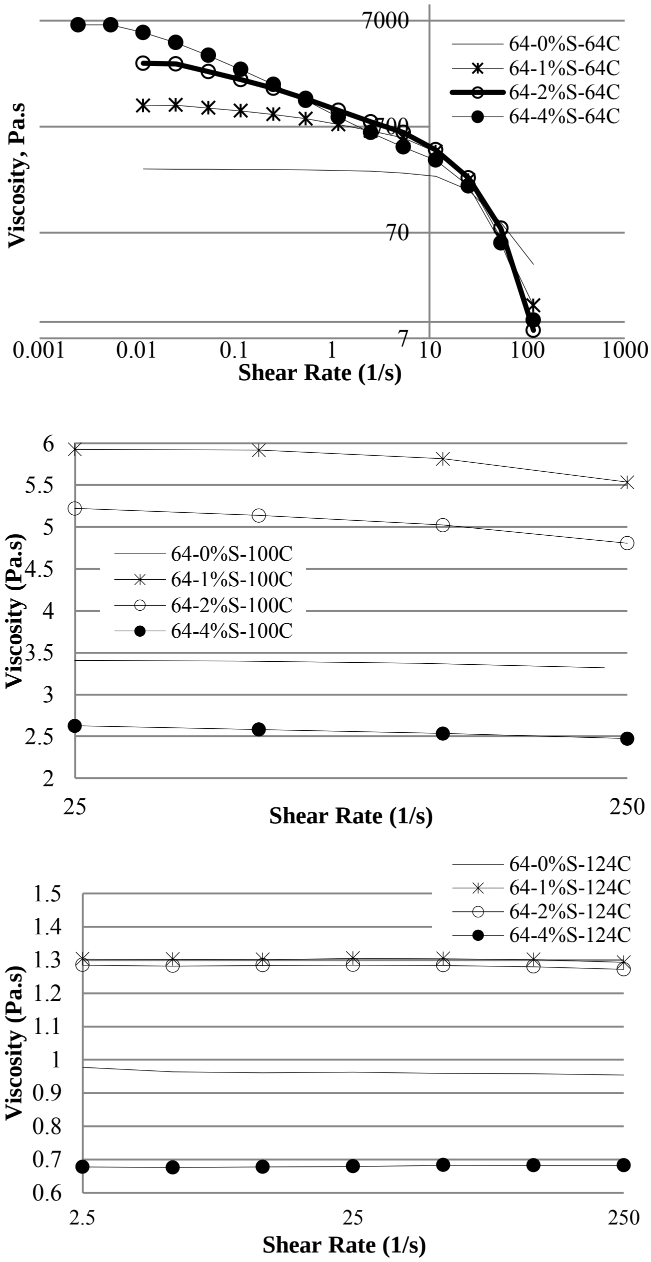


**Fig. 6.** Effects of Shear Rate at 64°C, 100°C and 124°C on PG 64-22 with Sasobit®.

justifies the findings of this study that the beneficial effect of Sasobit® in viscosity reduction can only be obtained at higher compaction temperatures and below the critical compaction temperature the gain in density can be lost. However, the final 0.3% increase in density with Sasobit® may not be related to viscosity reduction by Sasobit® and may be related to the 0.4% higher asphalt content of Sasobit® mixes as used in the Cooper [12] study.

### Effects of Shear Rate on Viscosity

Hot mix asphalt is prepared and compacted at different temperature ranges at different shear rates. Therefore, it is imperative to know the influence of shear rate on viscosity at those temperature ranges. In this study, shear sweep was performed in steady state rotational mode at different temperatures. Fig. 5 shows that the viscosity of PG 64-22 does not vary with shear rate at 124°C indicating that PG 64-22 is a Newtonian liquid. Fig. 5 also shows that PG 64-22 behaves as a Newtonian liquid at 100°C and at 64°C it is Newtonian up to shear rate 10/s.

The behavior of asphalt binders is little complicated in case of polymer modifications. Polymer-modified asphalt binders, such as PG 76-22M used in this study, exhibit shear rate dependency even at production temperatures where unknown shear rates are utilized and shear rate dependency is of practical interests. Fig. 5 shows that at 124°C, the viscosity of PG 76-22M reduces with an increase in shear rate. Similar trends are observed at 100°C and at 76°C except that the shear rate dependency increases with reduced temperatures. Therefore, polymer-modified asphalt binders are non-Newtonian and it is a shear-thinning (pseudoplastic) liquid where liquid will display a decreasing viscosity with an increasing shear rate.

Fig. 6 shows that with the addition of Sasobit®, PG 64-22 at 64°C becomes a shear-thinning liquid from Newtonian liquid. The shear rate dependency increases with an increase in percent of Sasobit®. Similar effects of Sasobit® are observed at 100°C in reduced level and shear rate dependency with the addition of Sasobit® is almost negligible at 124°C as evident from Fig. 6. This figure also shows that the shear rate dependency in general, reduces with an increase in temperatures. Also, the rate of change of viscosity is higher at higher shear rates and lower at lower shear rates. The rate of change of viscosity is very high at shear rates of approximately 250/s (see Fig. 6) and the rate of change is negligible at low shear rates such as 0.01/s indicating that the viscosity reaches a constant value and it does not increase noticeably if the shear rate is further lowered.

As observed, PG 76-22M is a shear-thinning liquid. With the addition of Sasobit®, the shear rate dependency increases with an increase in percent of Sasobit® as can be seen in Fig. 7 for 76°C, 100°C and 124°C. Fig. 7 also shows that shear rate dependency increases with reduction in temperatures. Unlike PG 64-22, PG 76-22M with and without Sasobit® shows shear rate dependency even at 124°C. Like PG 64-22, PG 76-22M with and without Sasobit® also shows that rate of viscosity change is higher at higher shear rates and vice versa.

Superpave requires use of rotational viscometer for viscosity measurements for mixing and compaction temperatures. Recommended 20 rpm in RV type Brookfield viscometer corresponds to 6.8/s. In this study, parallel plate steady state

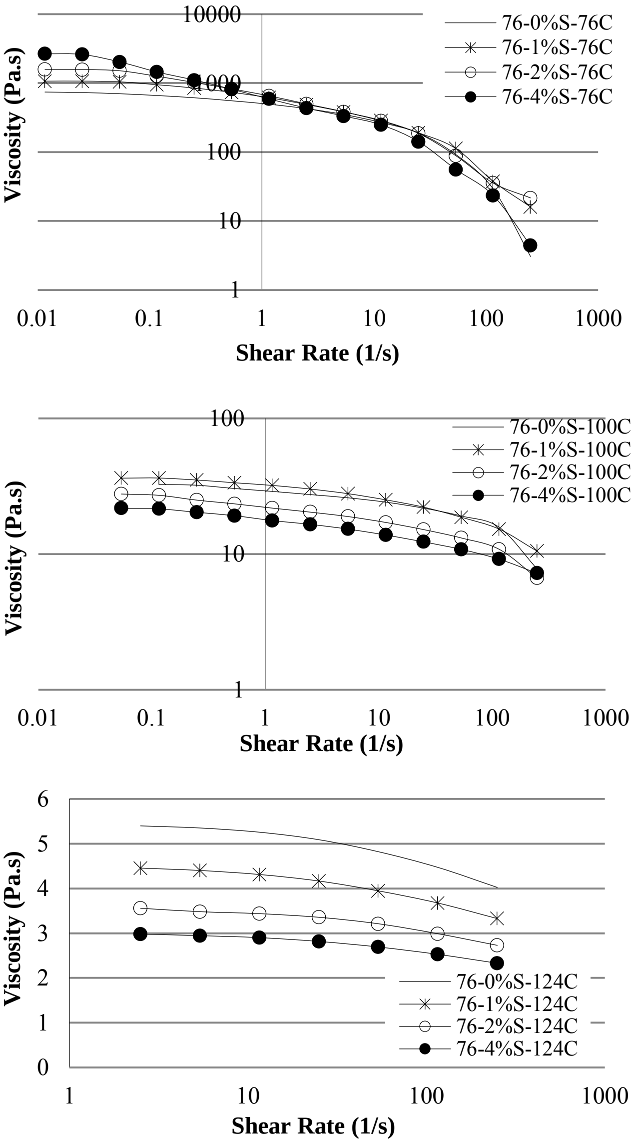


**Fig. 7.** Effects of Shear Rate at 76°C, 100°C and 124°C on PG 76-22M with Sasobit®.

rotational loading was applied. In case of PG 64-22 with and without Sasobit®, rate of change of viscosity is small at shear rate of 6.8/s as can be seen in Fig. 6 for 100°C and 124°C. In case of PG 76-22M, the rate of change of viscosity at 100°C and 124°C is significant with rate of change being higher at 100°C as can be seen in Fig. 7. This indicates a concern over the determination of viscosity of polymer-modified asphalt with and without Sasobit®. If the actual shear rate during the compaction process is higher than 6.8/s then the currently recommend viscosity as well as temperature is overestimated and compaction temperature can be reduced. On the other hand, if the actual shear rate during the compaction process is lower than 6.8/s then the currently recommended viscosity as well as temperature is underestimated and a higher compaction temperature should be used. In the following paragraph the actual shear rate during the compaction process will be discussed based on existing literature.

Khatri *et al*. [13] reported that during the critical part of the compaction process the zero shear viscosity is the most important factor controlling the densification for a given aggregate source and structure. The concept of using low shear viscosity is validated by the rate of change of linear strain rate, which shows that for almost half the compaction period the mixture experiences very low shear rate in the Superpave gyratory compactor. Based on this finding, a procedure to estimate zero shear viscosity using the existing rotational viscometer was developed and zero shear viscosity was proposed for use by Khatri *et al*. [13]. In contrast, Yildirim *et al*. [14] argued that the binder on the aggregate is very thin and might be around 10 microns. Just a very small movement might cause a very high shear rate on the binder. Yildirim *et al*. [14] used equiviscous method and hypothesized that mix with unmodified and modified binders will produce similar $G_{mb}$ at equal viscosity but at different temperatures. With the viscosity and the temperature being known, they found the shear rate in the Superpave gyratory compactor from viscosity-shear rate relationship and observed a very high shear rate and therefore, proposed reduced mixing and compaction temperatures.

In the present study as discussed in previous paragraphs, it was found that Sasobit® changes PG 64-22 from Newtonian to shear-thinning fluid and it also increases the shear rate dependency of PG 76-22M. This indicates that the viscosity as well as temperature reductions due to the addition of Sasobit® is greater than what might be obtained using rotational viscometer at 6.8/s as used currently.

## Viscosity Model

Sybilski [15] proposed a simple equation modeling non-Newtonian behavior of polymer-modified asphalt binders which is a simplified version of the CROSS model. The CROSS model describes a flow curve of shear-thinning liquid in the form of a four-parameter equation:

$$\frac{\eta - \eta_\alpha}{\eta_0 - \eta_\alpha} = \frac{1}{1 + (K\gamma)^m} \tag{1}$$

or, after rewriting:

$$\frac{\eta_0 - \eta}{\eta - \eta_\alpha} = (K\gamma)^m \tag{2}$$

where, $\eta_0$ = zero shear viscosity, $\eta_\alpha$ = viscosity at infinite or very high shear rate, $K$ = constant, material parameter, $\gamma$ = shear rate and $m$ = constant, material parameter.

The value of $\eta_\alpha$ is sometimes hard to measure for high-viscosity liquid and in case of high-viscosity liquid, it can be assumed that $\eta \gg \eta_\alpha$. Therefore, the following simplified equation has been proposed:

$$\frac{\eta_0 - \eta}{\eta} = (K\gamma)^m \tag{3}$$

At high service temperatures, such as 64°C for PG 64-22 and 76°C for PG 76-22M, the asphalt binder is a high-viscous liquid and

**Table 4.** Zero Shear Viscosity and CROSS Model Parameters.

| Binder | Temp. | Zero Shear Viscosity, Pa.s | K | m | CROSS Model Fit, $R^2$ |
|---|---|---|---|---|---|
| PG 64-22 | 64°C | 278.1 | 0.02355 | 0.8264 | 0.9369 |
| PG 64-22 + 1% Sasobit® | | 1116 | 0.44691 | 0.7985 | 0.9287 |
| PG 64-22 + 2% Sasobit® | | 2770 | 1.44891 | 0.8768 | 0.9141 |
| PG 64-22 + 4% Sasobit® | | 6374 | 5.46923 | 0.8883 | 0.8627 |
| PG 76-22M | 76°C | 742.3 | 0.39195 | 0.8275 | 0.9335 |
| PG 76-22M + 1% Sasobit® | | 1070 | 0.44802 | 0.7981 | 0.9712 |
| PG 76-22M + 2% Sasobit® | | 1576 | 0.59452 | 0.9228 | 0.8804 |
| PG 74-22M + 4% Sasobit® | | 2668 | 2.75961 | 0.8402 | 0.9309 |

**Table 5.** Correlation between Zero Shear Viscosity and G*/sinδ.

| Binder | Zero Shear Viscosity at 64°C, Pa.s | G*/sinδ at 64°C | G*/sinδ at 34°C | $R^2$ (Zero Shear Viscosity vs. G*/sinδ at 64°C) | $R^2$ (Zero Shear Viscosity vs. G*/sinδ at 34°C) |
|---|---|---|---|---|---|
| PG 64-22 | 278.1 | 3.12 | 234.55 | 0.628 | 0.529 |
| PG 64-22 + 1% Sasobit® | 1116 | 3.95 | 264.25 | | |
| PG 64-22 + 2% Sasobit® | 2770 | 6.88 | 547.75 | | |
| PG 64-22 + 4% Sasobit® | 6374 | 6.52 | 480.65 | | |
| | Zero Shear Viscosity at 76°C, Pa.s | G*/sinδ at 76°C | G*/sinδ at 34°C | $R^2$ (Zero Shear Viscosity vs. G*/sinδ at 76°C) | $R^2$ (Zero Shear Viscosity vs. G*/sinδ at 34°C) |
| PG 76-22M | 742.3 | 2.453 | 245.9 | 0.2613 | 0.579 |
| PG 76-22M + 1% Sasobit® | 1070 | 3.0655 | 332.45 | | |
| PG 76-22M + 2% Sasobit® | 1576 | 3.539 | 495.95 | | |
| PG 74-22M + 4% Sasobit® | 2668 | 3.132 | 457.15 | | |

therefore, the viscosity of PG 64-22 and PG 76-22M with and without Sasobit® at 64°C and 76°C, respectively were fitted with the simplified CROSS equation as proposed by Sybilski [15]. Table 4 shows the coefficient of determination, $R^2$ values for simplified CROSS model fit. It can be seen that both the binders with and without Sasobit® fit the model very well with coefficient of determination varying between 0.8627 and 0.9369 for PG 64-22 and between 0.8804 and 0.9712 for PG 76-22M.

The material parameter, K which is related to viscosity and called consistency by Sybilski [15], increases with increased viscosity. It can be seen from Table 4 that K values increase with an increase in percent of Sasobit®. The other material parameter, m is a shear compliance factor. The higher the m value the lower is the shear compliance. In general, Table 4 shows that Sasobit® increases the m value for both binders indicating the lower shear compliance of Sasobit® added binders.

## Zero Shear Viscosity

Anderson *et al*. [16] and Sybilski [15] and some others correlated zero shear viscosity with rutting of asphalt pavement. Table 4 shows the zero shear viscosity of asphalt binders with and without Sasobit®. It can be seen that the zero shear viscosity of both the asphalt binders increases with an increase in percent of Sasobit®. The zero shear viscosities were determined at 64°C for PG 64-22 and at 76°C for PG 76-22M. Fig. 6 shows that at 64°C, the rotational viscosities of PG64, PG64+1%Sasobit® and PG64+2%Sasobit® reach approximate constant values at the shear rate of 0.0116/s. Therefore, the viscosity at this shear rate was used as zero shear viscosity. However, for PG64+4% Sasobit®, the shear rate corresponding to zero shear viscosity is 0.0025/s, at which point the viscosity reaches an approximate constant value. As can be seen in Fig. 7, the viscosities of PG76, PG76+1%Sasobit®, PG76+2%Sasobit® and PG76+4%Sasobit® reach approximate constant values at the shear rate of 0.0116/s.

As discussed earlier, G*/sinδ is known to be the rutting factor for asphalt binders. Table 5 shows the G*/sinδ of PG 64-22 with and without Sasobit® at 64°C and 34°C. In case of PG 76-22M with and without Sasobit®, the G*/sinδ were reported at 76°C and 34°C. For asphalt binders PG 64-22 with and without Sasobit®, the $R^2$ values between zero shear viscosity and G*/sinδ at 64°C and between zero shear viscosity and G*/sinδ at 34°C are 0.628 and 0.529. In case of PG 76-22M with and without Sasobit®, the $R^2$ values between zero shear viscosity and G*/sinδ at 76°C and between zero shear viscosity and G*/sinδ at 34°C are 0.261 and 0.579. So, the correlation is better in case of PG 64-22 binders. For both the binders, the correlation is better for G*/sinδ at 34°C.

## Steady State Viscosity and Dynamic Viscosity

Table 6 shows a comparison between steady state viscosity measured in rotational mode and dynamic viscosity measured in sinusoidal mode, both measured in parallel plate dynamic shear rheometer. It can be seen that at all temperatures, dynamic viscosity is higher than steady state viscosity. It can be assumed here that complex viscosity will even be greater than steady state viscosity. Table 6 shows that at higher temperature, such as 124°C, the steady state and dynamic viscosity are comparable. E.g., for PG 64-22 without Sasobit® at 64°C, the steady state and dynamic viscosity are 34.95 Pa.s and 309.3 Pa.s, respectively, whereas, at 124°C, the corresponding viscosity are 0.955 Pa.s and 1.69 Pa.s.

The coefficient of determination between steady state and

**Table 6.** Steady State (Rotational) Viscosity and Dynamic (Sinusoidal) Viscosity.

| Binder | Temperature 64°C | | Temperature 100°C | | Temperature 124°C | |
|---|---|---|---|---|---|---|
| | Steady State Viscosity Pa.s | Dynamic Viscosity Pa.s | Steady State Viscosity Pa.s | Dynamic Viscosity Pa.s | Steady State Viscosity Pa.s | Dynamic Viscosity Pa.s |
| PG 64-22 | 34.95 | 309.3 | 3.319 | 7.98 | 0.9545 | 1.69 |
| PG 64-22 + 1% Sasobit® | 14.3 | 387.95 | 5.535 | 7.765 | 1.293 | 1.5 |
| PG 64-22 + 2% Sasobit® | 8.337 | 657.2 | 4.806 | 10.735 | 1.272 | 1.335 |
| PG 64-22 + 4% Sasobit® | 10.39 | 625.4 | 2.474 | 10.328 | 0.682 | 0.964 |
| $R^2$ Value | 0.7051 | | 0.0828 | | 0.2847 | |
| | Temperature 76°C | | Temperature 100°C | | Temperature 124°C | |
| PG 76-22M | 3.049 | 216.05 | 7.775 | 30.94 | 4.024 | 6.046 |
| PG 76-22M + 1% Sasobit® | 16.02 | 263 | 10.51 | 30.285 | 3.328 | 5.174 |
| PG 76-22M + 2% Sasobit® | 21.63 | 302.4 | 6.658 | 32.465 | 2.73 | 4.907 |
| PG 74-22M + 4% Sasobit® | 4.418 | 270.95 | 7.224 | 30.815 | 2.33 | 4.084 |
| $R^2$ Value | 0.586 | | 0.5708 | | 0.9498 | |

dynamic viscosity has been determined and shown in Table 6. It is evident that for PG 76-22M, the correlation is in general better than PG 64-22. Another observation is that at 100°C, both the binders show lowest coefficient of determination. This is because at 100°C and nearby temperatures, Sasobit® modified asphalt binder has the critical temperature as discussed at the beginning of this paper during the discussion on the effects on compaction temperatures. Overall, on the comparison between steady state and dynamic viscosity it can be concluded that the viscosity from the two methods are better comparable at higher temperature, such as 124°C and because the influence of Sasobit® reaches a turning point at around 100°C, the coefficient of determination values are below 0.95 except in one case.

## Conclusions

In this study, dynamic viscosity (η') of asphalt binders with and without a wax-based warm mix asphalt (WMA) additive, Sasobit® was measured at temperature ranges from 28°C to 130°C at 6°C interval. Laboratory densities of Superpave gyratory samples compacted at different temperatures, at different gyrations and at different asphalt contents were determined to evaluate the effect of viscosity on density. Also, field densities after different compaction steps were analyzed to evaluate the effect of Sasobit® on viscosity. The following specific conclusions can be drawn from this study:

(1) An increase in percent of Sasobit® increases the rutting factor of PG 64-22 thereby increasing the potential for rutting resistance. For PG 76-22M at 76°C, up to 2% Sasobit® increases the rutting factor G*/sinδ and addition of 4% Sasobit® starts reducing it. Firstly, this suggests that rate of Sasobit® must be optimized before its use. Secondly, this effect can be justified by the fact that the Sasobit® is an asphalt flow improver and it reduces viscosity at production temperatures. Addition of excess Sasobit® may reduce stiffness properties. In this regard, rate effect can be explained by temperature effect and it can be observed that changes of PG 64-22 is similar to PG 76-22M at 76°C with the addition of Sasobit®.

(2) Sasobit® reduces viscosity at higher compaction temperatures but it increases viscosity at lower compaction temperatures. There exists a critical temperature for each asphalt binder below which viscosity will increase with addition of Sasobit®. Therefore, compaction below the critical temperature can negatively impact density. For PG 64-22, the critical temperature is 104°C and for PG 76-22, the critical temperature is about 101°C.

(3) The gyratory compacted samples exhibit that Sasobit® added samples have higher densities than without Sasobit® samples at higher compaction temperature whereas, Sasobit® added samples have lower densities than without Sasobit® samples at lower compaction temperature.

(4) Sasobit® indeed reduced the viscosity of binder as well as the mix at higher compaction temperature as can be seen from the density directly behind the screed. Sasobit® mix as monitored in this study has 3.5% more density than the PG 76-22M mix without Sasobit®. As the compaction continues, the mixes cool down and the beneficial effects of Sasobit® cannot be seen anymore. By the time the finisher roller completes, both mixes produce similar densities, 93.3% and 93.0 respectively for Sasobit® and PG 76-22M mixes. This strongly justifies the findings of this study that the beneficial effect of Sasobit® in viscosity reduction can only be obtained at higher compaction temperatures.

For effect of shear rate on steady state viscosity, three temperatures, namely 64°C, 100°C and 124°C for PG 64-22 and three temperatures, 76°C, 100°C and 124°C were used for PG 76-22M. Shear rates were used in the range between 0.0025/s to 250/s. The following specific conclusions can be obtained from steady state viscosity at different temperatures at different shear rates:

(1) PG 64-22 is a Newtonian fluid at 124°C, 100°C and at 64°C it is Newtonian up to shear rate 10/s. Polymer-modified asphalt binders, such as PG 76-22M used in this study, exhibit shear-thinning behavior even at asphalt mix compaction temperatures, such as 124°C where unknown shear rates are utilized and shear rate dependency is of practical interests. Similar trends are observed at 100°C and at 76°C except that the shear rate dependency increases with reduced temperatures.

(2) With the addition of Sasobit®, PG 64-22 at 64°C becomes a shear-thinning liquid. The shear rate dependency increases with an increase in percent of Sasobit®. Similar effects of Sasobit®

are observed at 100°C in reduced level and shear rate dependency with the addition of Sasobit® is almost negligible at 124°C. The shear rate dependency in general reduces with an increase in temperatures. Also, the rate of change of viscosity is higher at higher shear rates and lower at lower shear rates. For PG 76-22M, the shear rate dependency increases with an increase in percent of Sasobit® at all the three temperatures.

(3) The coefficient of determination, $R^2$ values for simplified CROSS model fit show that both the binders with and without Sasobit® fit the model very well with coefficient of determination varying between 0.8627 and 0.9369 for PG 64-22 and between 0.8804 and 0.9712 for PG 76-22M.

(4) The zero shear viscosity were determined at 64°C for PG 64-22 and at 76°C for PG 76-22M. The correlation between zero shear viscosity and G*/sinδ is better in case of PG 64-22 binders. For both the binders, the correlation is better between zero shear viscosity and G*/sinδ at 34°C.

(5) At all the temperatures used in this study, dynamic viscosity is higher than steady state viscosity. Overall, on the comparison between steady state and dynamic viscosity, it can be concluded that the viscosity from the two methods are better comparable at higher temperature, such as 124°C and because the influence of Sasobit® reaches a turning point at around 100°C, the coefficient of determination values are below 0.95 except in one case.

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