Jordan Journal of Civil Engineering, Volume **10**, No. **3**, **2016**

Predicting the Complex Modulus for PAV Aged Asphalt Binder Using a Master Curve Approach for Sasobit Modified Asphalt Binder

Khalid A. Ghuzlan [1)]***and Mohammad O. Al Assi*** [2)]

[1)] Associate Professor, Jordan University of Science and Technology (JUST), Irbid, Jordan.
E-Mail: kaghuzlan@just.edu.jo
[2)] Research Assistant, Jordan University of Science and Technology (JUST), Irbid, Jordan.
E-Mail: moalassi13@eng.just.edu.jo

ABSTRACT

This study is focused on the prediction of the asphalt binder complex modulus at various temperatures and various loading frequencies. The master curve approach was used to predict the asphalt binder behavior for a wide range of temperatures and loading frequencies by applying the time-temperature superposition principle for pressure ageing vessel (PAV) aged asphalt binder mixed with different percentages of sasobit asphalt modifier. The complex modulus was measured using the dynamic shear rheometer (DSR) with a wide range of loading frequencies (0.1 Hz-10 Hz) and a wide range of testing temperatures (16 °C-31 °C). The results showed an increase in the complex modulus with increasing the loading frequency as well as with increasing the sasobit percentage. However, the results showed a decrease in the complex modulus with increasing the testing temperature. The use of the master curve approach showed a high degree of accuracy in predicting the complex modulus for the asphalt binder.

KEYWORDS: Master curve, Aged asphalt binder, Complex modulus, Sasobit.

INTRODUCTION

Warm Mix Asphalt (WMA) is a new technology that allows for the production of asphalt mixtures at lower temperatures than ordinary Hot Mix Asphalts (HMA), (Jamshidi et al., 2015). WMA modifiers reduce the viscosity of asphalt binder at mixing and compaction temperatures, allowing for lower temperatures of mixing and compaction (Iwanski and Mazurek, 2012). Sasobit is one of warm mix asphalt modifiers derived from coal gasification process (Edwards and Redelius, 2003). The performance of sasobit modified asphalt binder was investigated by many researchers (Zhang et al., 2015; Kim et al., 2012; Zhao, 2011). It was found that the performance of sasobit modified asphalt binder depends on the testing temperature in the high temperature range (>100°C), as sasobit melts within the asphalt binder causing a significant reduction in its viscosity. This behavior was found beneficial as it allows for a lower mixing temperature, thereby reducing the energy bill. Liu (2012) found that the addition of sasobit to asphalt binder allows for higher percentages of reclaimed asphalt binder (up to 60% by weight of asphalt) to be added to the mixture without significantly effecting the workability of the mixture and with increasing the complex shear modulus of asphalt binders for temperatures below 95 °C.

The complex shear modulus (G*) for sasobit modified asphalt binder will also be affected. Jamshidi et al. (2013) investigated its performance at high

Received on 21/10/2015.
Accepted for Publication on 14/5/2015.

temperatures (52-82) ^{o}C and intermediate test temperatures (16-34) ^{o}C and found that the increase in sasobit percentage will significantly increase the value of G*, making the samples stiffer. However, the phase angle will decrease and increase the elastic portion of the complex modulus.

Time-Temperature Superposition Principle

Asphalt binder is a viscoelastic material and its properties are dependent on both temperature and loading frequency. The increase in temperature reduces the complex shear modulus of asphalt binder, where the increase in loading frequency reduces the complex shear modulus (Bari and Witczak, 2007).

Based on the time-temperature superposition (TTS) principle, or the temperature-frequency superposition, a master curve is obtained by horizontally shifting different flow curves until they merge into a single smooth curve. Time-temperature superposition can be represented by the following equation:

$$G\,(f,T) = G\,(\,\alpha_T, T_0);\qquad (1)$$

where:

T_0: Reference temperature.

T: Shifted temperature.

α_T: Shift factor.

f: Observed frequency.

The curve of G* *versus* a logarithmic loading frequency is shifted for a single temperature using the shift factor α_T. The shift factor is given by:

$$\alpha_T = \frac{f_0}{f_T}; \qquad (2)$$

where f_T is the frequency applied at testing temperature T, f_0 is the reduced frequency for the given temperature T.

William-Landel-Ferry (WLF) empirical relationship was proposed by Williams et al. (1955) to link the shift factor for each flow curve to the master curve, based on the time-temperature superposition to obtain the shift factor (α_T) in terms of ($T-T_0$):

$$\text{Log}\,\alpha_T = \frac{-C_1\,(T-T_0)}{C_2+T-T_0} \qquad (3)$$

C_1 and C_2 are universal constants equal to 8.86 and 101.6, respectively for temperatures above the glass transition temperature, T_0 is the reference temperature and T is the temperature of the shifted flow curve.

The main objectives of this research are to predict the complex modulus for sasobit modified asphalt binder at different temperatures and different loading frequencies, as well as to investigate the effect of adding different percentages of sasobit on the complex modulus for asphalt binder.

MATERIAL AND METHODS

To satisfy the research objectives, three different percentages of sasobit were added to the PG 70-10 asphalt binder sample (1%, 2% and 3% by weight of asphalt), then mixed until sasobit was completely dissolved into the asphalt binder. Thereafter, the samples were aged using the rolling thin film oven (RTFO), followed by PAV ageing.

Dynamic shear rheometer (DSR) was used to obtain the flow curves for the asphalt binders. A frequency sweep test was performed over a wide range of temperatures representing the intermediate pavement temperature (16 ^{o}C-31^{o}C) for PAV aged asphalt binder samples. Figure 1 shows the testing flow chart used in this research.

An Excel Solver was used to fit the data obtained from the DSR into the sigmoid function equation that best fits the shifted flow curves to obtain the master curve for each sample.

Mixing Sasobit with Asphalt Binder

Sasobit is manufactured by Sasol Wax Company. It has a solid pellet shape with a diameter of 2 mm (Figure 2), according to the manufacturer (Sasol Corp., 2015). Sasobit has a melting point between 85 ^{o}C and 115 ^{o}C. All asphalt binder samples were modified by sasobit by adding the desired percent of sasobit by weight to the asphalt binder. The asphalt must be preheated to 135 °C before adding the modifier, then continuous stirring is required until all pellets are dissolved and the mixture becomes completely homogenous.

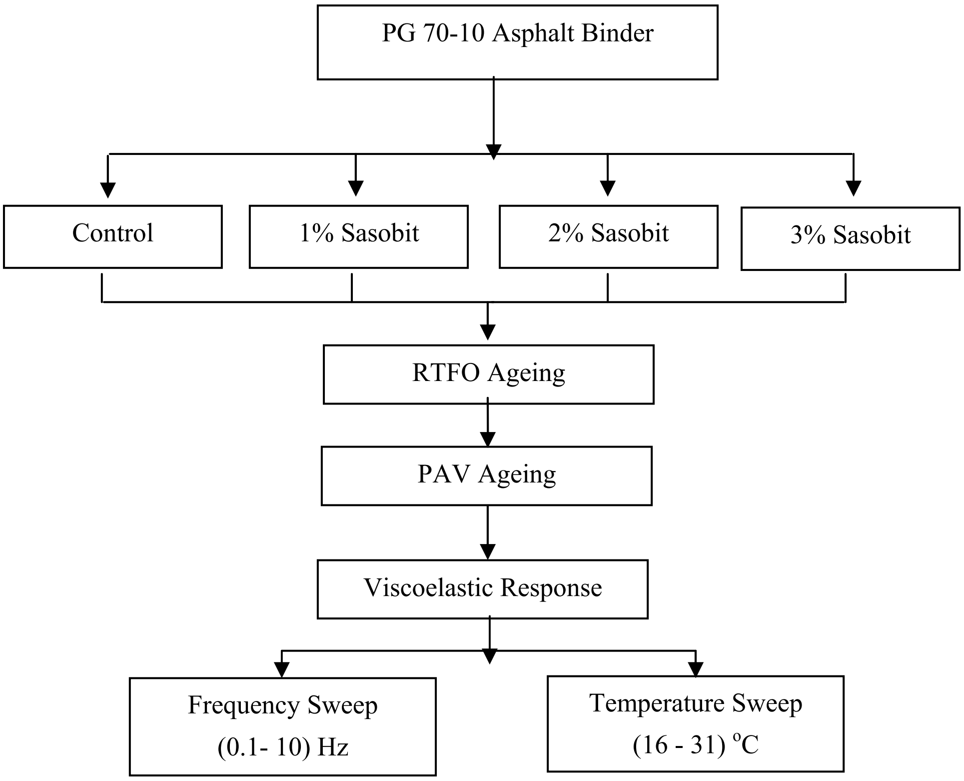

Figure (1): Testing flow chart

Figure (2): Sasobit pellets

Rolling Thin Film Oven (RTFO)

RTFO test was used to age asphalt binder in order to simulate short-term ageing during the mixing and compaction process. Figure 3 shows the RTFO device at Jordan University of Science and Technology (JUST)/Highway Laboratory. Asphalt binder was then poured into the RTFO containers, exactly 35 g each, and placed in the oven for approximately 85 minutes, whereas the oven was held at 163 ^{o}C during the test period. The containers were rotating at 15 revolutions per minute while air was blown into the test cylinders from the nozzle. The rotation allows the asphalt to coat the cylinder container fully from inside.

Figure (3): Rolling thin film oven device

After the test period, each cylinder was placed on a rack to cool for a sufficient period of time and then weighed, where samples with more than 1% asphalt mass loss will be considered to have failed this test and therefore to be rejected.

To conduct the RTFO ageing test, the following steps are required to prepare the samples and check the mass loss specification. The test starts with warming the asphalt sample until it becomes liquid and easy to pour. Simultaneously, the RTFO is heated until it reaches the required 163ºC temperature to start the test. Afterwards, the empty RTFO bottles are weighed and their weights are recorded. Then, 35g of asphalt is poured into each of the RTFO bottles which are left to cool for 15 minutes, before loading the RTFO bottles into the RTFO and starting timing. After 85 minutes, the bottles are removed from the RTFO and left to cool for 15 minutes. Then, the bottles with the aged asphalt are weighed and the percent of mass loss of asphalt is calculated.

Pressure Ageing Vessel Test (PAV)

PAV test was developed to simulate long-term ageing of asphalt binders usually from 7 to 10 years of service life. The ageing process is carried out by exposing the asphalt samples to heat and high pressure. This test is performed on RTFO aged asphalt residues where samples are poured in special pans of 50 g each, then placed on a rack into the vessel. The PAV device shown in Figure 4 is then sealed and ageing takes place for 20 hours at 305 psi at a temperature of 90, 100 or 110^{o}C depending on the climate temperature of the pavement. For Jordan climate, 100^{o}C was selected in the PAV test to account for ageing in moderate climate.

Figure (4): Pressure ageing vessel device

To conduct the PAV ageing test, the following steps are required to prepare the asphalt binder samples. The test starts with turning on the PAV oven and heating it to acquire the desired testing temperature of 100 ºC. Then, RTFO aged asphalt binder is heated until it becomes liquid and 50 g of RTFO aged asphalt binder is poured into the PAV pans and left to cool for 20 minutes. Afterwards, the pans are inserted into the rack and then into the PAV oven and sealed tightly. After the PAV has regained the 100 ^{o}C temperature, the pressure valve is opened to 305 psi. After 20 hours of conditioning, the device is turned off and the pressure is slowly released, then the asphalt pans are removed from the device.

Dynamic Shear Rheometer Test (DSR)

Dynamic Shear Rheometer (Figure 5) is used to determine the viscoelastic behavior of complex materials like asphalt binders. The asphalt sample is sandwiched between two plates. The lower plate is fixed, while the upper plate osculates sinusiodally back and forth resulting in shearing the asphalt binder sample. Complex modulus of asphalt binder (G*) and phase angle (δ) are the results of the DSR test. These two parametes are related to rutting and fatigue performance. The rutting parameter (G*/Sin δ) must be greater than 1 kPa for original unaged asphalt binder and greater than 2.2 kPa for RTFO aged asphalt binder, both tested at high PG temperature. The superpave specification for the fatigue parameter is that for PAV aged asphalt binder, (G*Sin δ) must not exceed 5000 kPa tested at intermediate PG temperature.

The values of complex modulus and phase angle are determined according to Equations 4, 5, 6 and 7, respectively:

$$|G^*| = \frac{\tau_{max}}{\gamma_{\max}}; \qquad (4)$$

$$\delta = \text{time lag}; \qquad (5)$$

$$\tau_{\max} = \frac{2T}{\pi r^3}; \qquad (6)$$

$$\gamma = \frac{\theta r}{h}; \qquad (7)$$

where :

τ_{max}: maximum applied shear stress.

γ_{max}: maximum resulting shear strain.

T: maximum applied torque.

r: radius of the binder specimen.

θ: rotation angle.

h: specimen height.

Figure (5): Dynamic shear rheometer

To conduct the DSR test, the following steps are required, which are the same for the three levels of aged asphalt. The test starts with warming asphalt samples until they become liquid and easy to pour. Then, the DSR environment chamber is run and the desired temperature for testing is selected. From the DSR software, the desired test parameters are set. Then, asphalt samples are poured into the appropriate molds (25 mm or 8 mm in diameter) and left to cool for 5 minutes. When the asphalt binder becomes solid, the samples are removed from the molds and mounted in the testing position. The excess asphalt binder is trimmed to avoid interference with the test results. One should wait until the asphalt binder reaches the testing temperature, then the test is started. Note that the output of the DSR shows directly the final results for each test and no calculations are needed.

Frequency Sweep

Frequency sweep test was performed using 25 test frequencies (0.1 Hz-10 Hz) for the different samples of sasobit modified asphalt binder. Complex viscosity and shear stress corresponding to each frequency were measured. Frequency sweep test indicates how the asphalt binder will behave under different loading rates. Flow and viscosity curves are developed to understand the material flow behavior; i.e., (Newtonian flow behavior, pseudo-plastic flow behavior and dilatant flow behavior). Frequency sweep test was performed for PAV aged asphalt binder samples at the intermediate pavement temperature (31 °C). Figures 6, 7, 8 and 9 summarize the data obtained in the frequency sweep test for the control, 1%, 2% and 3% of sasobit modified samples, respectively.

RESULTS AND DISCUSSION

Master curves shown in Figures 10, 11, 12 and 13 are developed using an excel sheet solver optimization tool to best fit the sigmoid function to the flow curves of the control, 1%, 2% and 3% of sasobit modified samples, respectively.

The sigmoid function to represent the complex shear modulus can be represented by:

$$\log\left|G^{*}\right| = a + \frac{b}{1+e^{c\log f_R + d}} \quad ; \qquad (8)$$

where:

a, b, c and *d*: Sigmoid function constants.

f_R: Reduced frequency.

|*G**|: Complex modulus

The optimization process of the sigmoid function to best fit the obtained G* data from the DSR is carried out by trial and error. By changing the sigmoid constants (coefficients) along with changing the shift factor "α_T" and minimizing the error between the predicted value and the obtained value of the complex modulus. Table 1 shows the values of the four sigmoid coefficients as obtained from the optimization process, along with the percentage of error for each master curve. The shift factors at each temperature are given in Table 2 for each percentage of sasobit asphalt modifier. The master temperature for the asphalt binder samples is 22 °C where the logarithm of the shift factor is equal to zero (shift factor = 1).

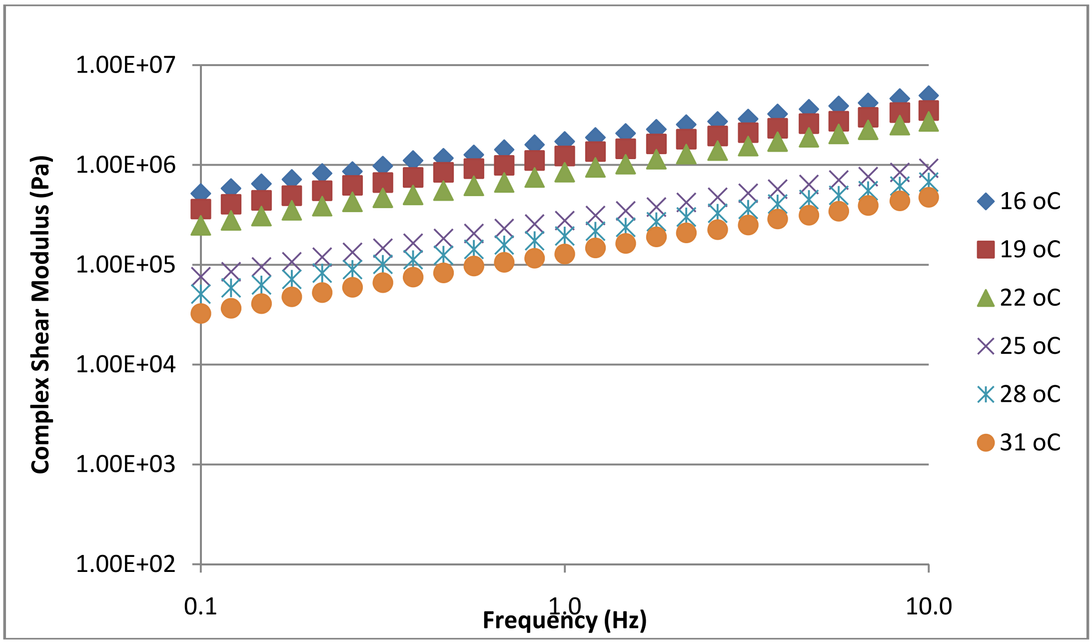

Figure (6): Flow curves for control sample

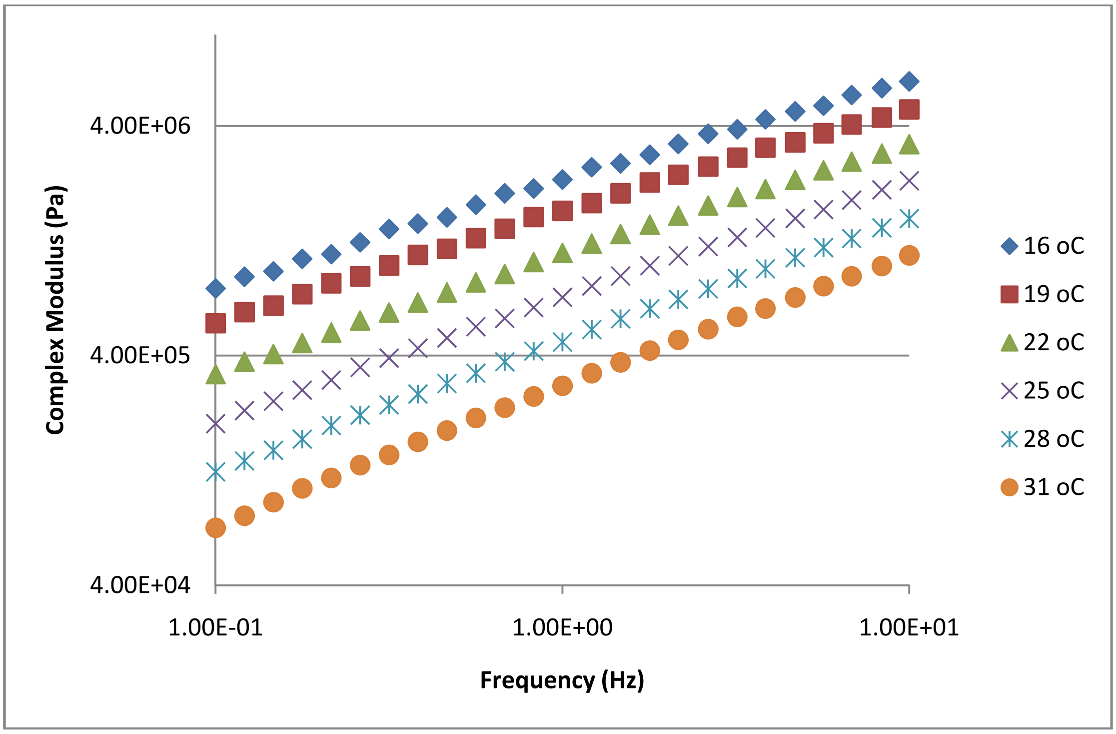

Figure (7): Flow curves for 1% sasobit modified sample

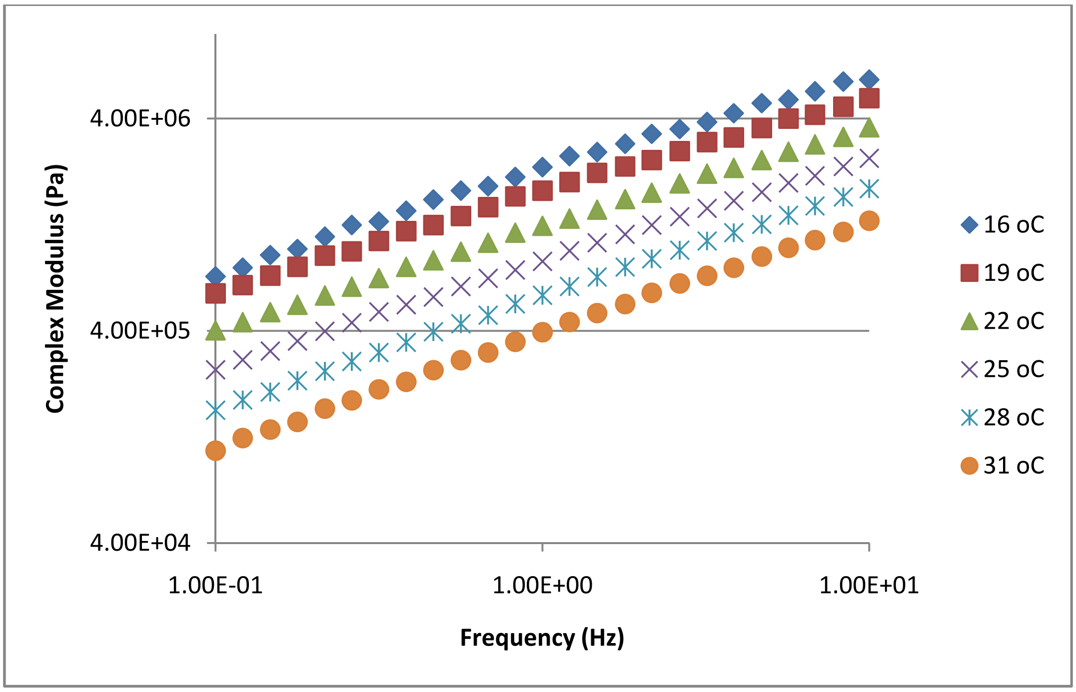

Figure (8): Flow curves for 2% sasobit modified sample

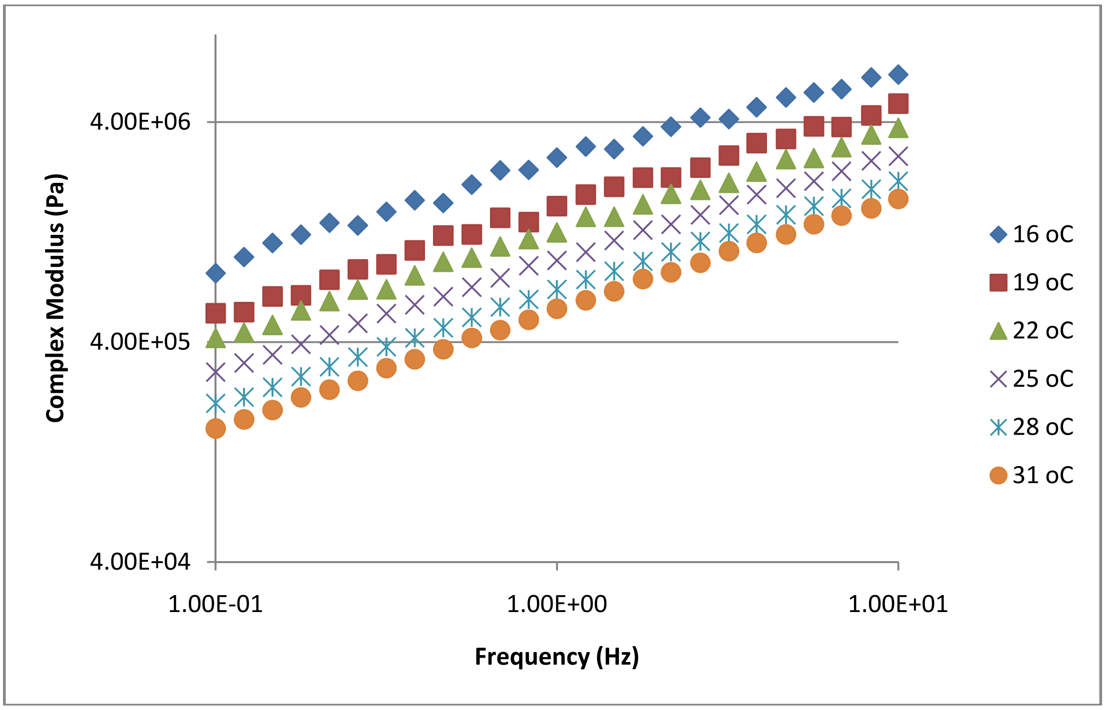

Figure (9): Flow curves for 3% sasobit modified sample

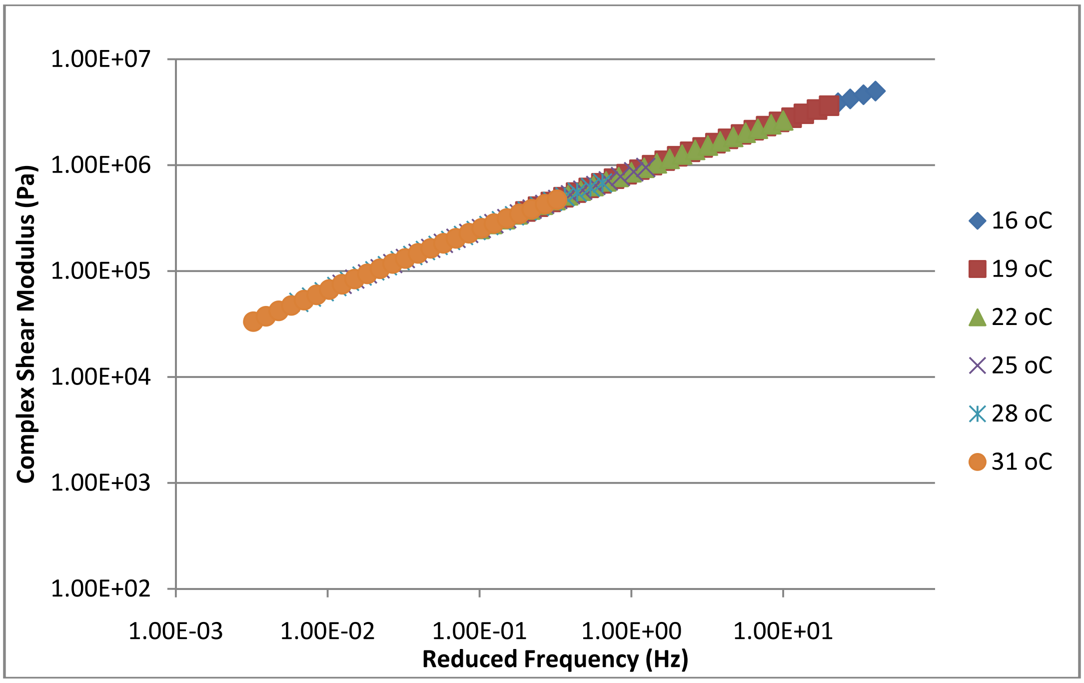

Figure (10): Master curve for control sample

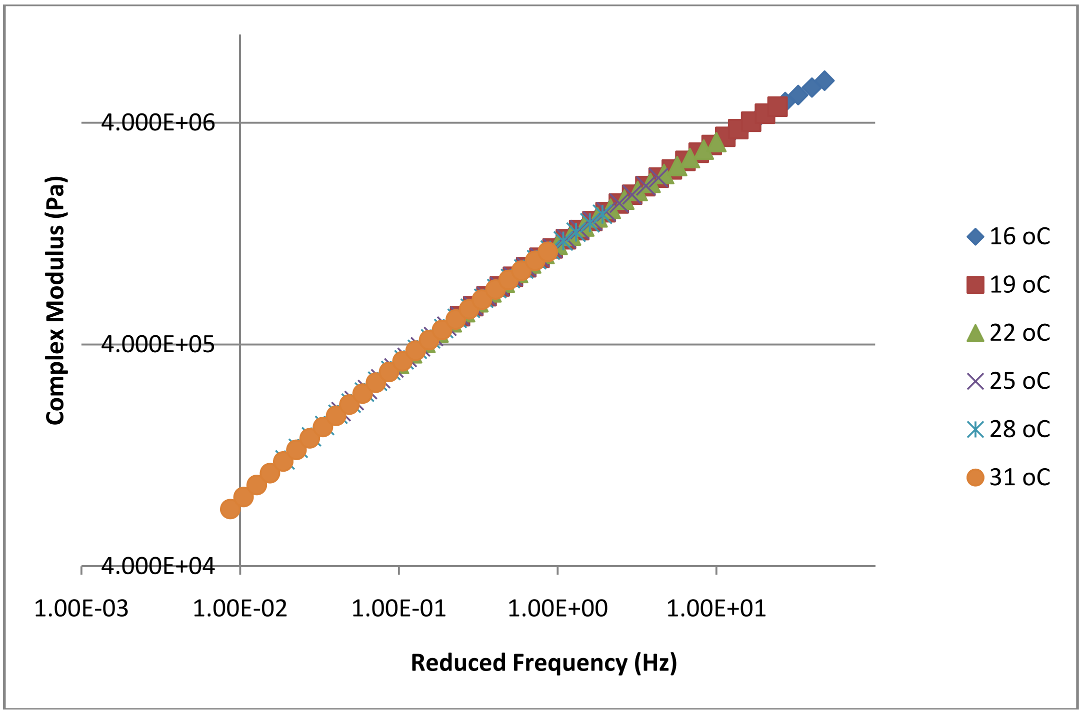

Figure (11): Master curve for 1% sasobit modified sample

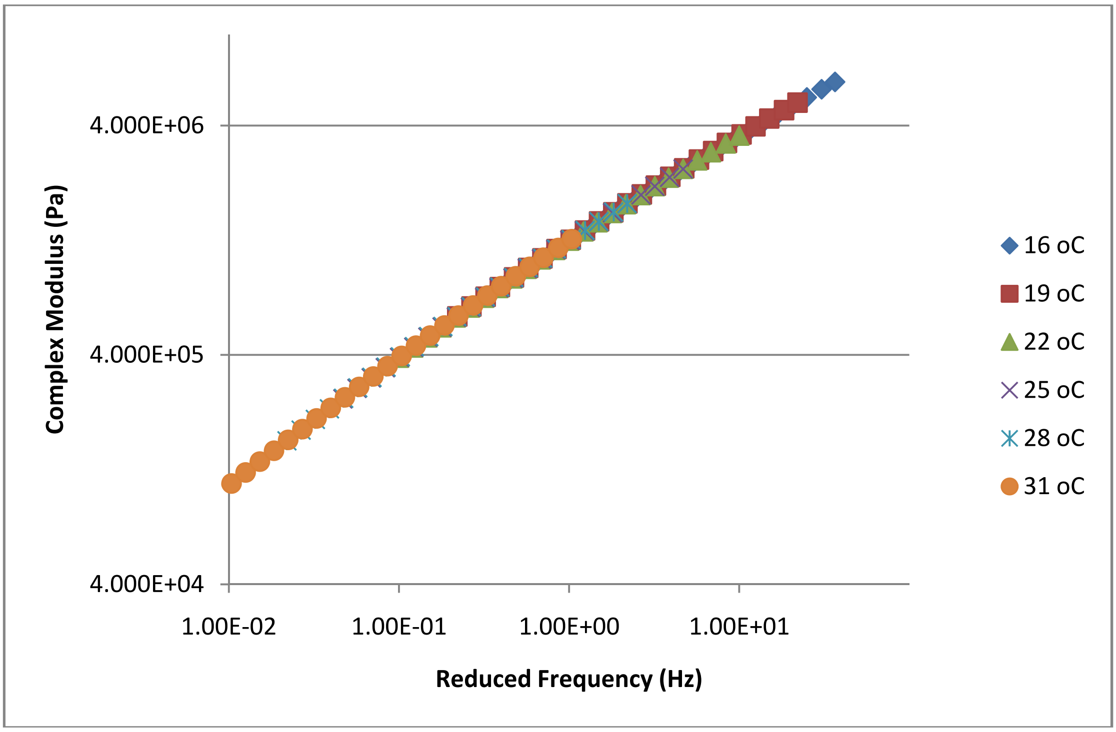

Figure (12): Master curve for 2% sasobit modified sample

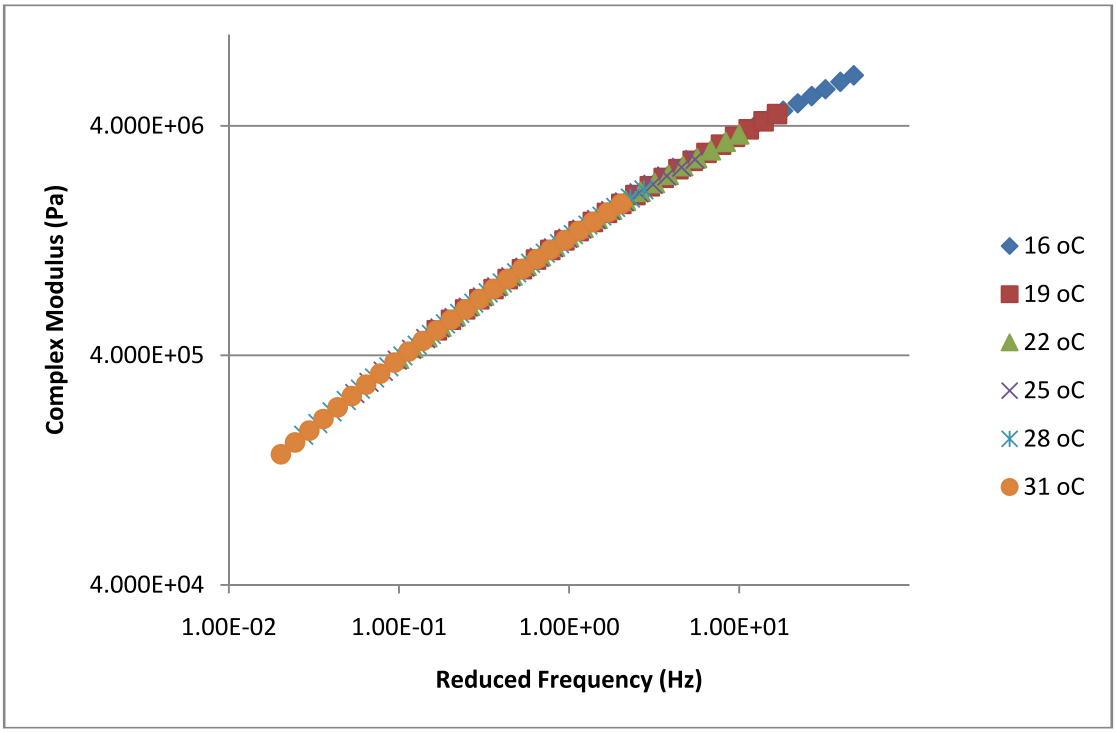

Figure (13): Master curve for 3% sasobit modified sample

Table 1. Summary of master curves and sigmoid function coefficients

	Sigmoid Coefficients				
% sasobit	**a**	**b**	**c**	**d**	**Error (%)**
0%	-8.829	19.04851	-0.1542	-1.2360	8.1E-03
1%	-8.2505	17.0435	-0.2171	-1.6519	6.8E-03
2%	-2.0804	11.0696	-0.2270	-1.0409	8.4E-03
3%	-2.8335	11.1453	-0.2772	-1.4054	2.0E-01

Table 2. Shift factors for different testing temperatures

	Log (α_T)			
T (°C)	**0%**	**1%**	**2%**	**3%**
16	0.60847	0.681365	0.563591	0.673088
19	0.30251	0.384861	0.342463	0.221976
22	0	0	0	0
25	-0.9076	-0.36488	-0.33054	-0.25988
28	-1.1928	-0.71768	-0.65886	-0.56047
31	-1.4915	-1.06243	-0.98502	-0.69454

CONCLUSIONS

The time-temperature superposition approach was performed by solving the sigmoid function four coefficients (a, b, c and d) and obtaining the logarithm of the shift factor at each temperature to obtain the best fit master curve to the complex modulus for each percentage of sasobit modifier.

In light of the study results, the following conclusions are drawn.

- From the master curve plot, the increase in loading frequency is shown to increase the value of complex modulus (G*) for all four percentages of sasobit asphalt modifier.
- Testing temperature and loading frequency are correlated so that an increase in the testing temperature will cause a decrease in the value in (G*), as the top right part of the master curve simulates a high loading frequency (or a low test temperature) and the lower left part of the master curve simulates a low loading frequency (or a high test temperature).
- An increase in the sasobit modifier percentage causes an increase in the complex modulus.Thus, sasobit can be added to the asphalt binder without deteriorating its performance.
- Predicting the value of the complex modulus for any given testing temperature or loading frequency can be carried out by simply substituting the corresponding reduced frequency (f_R) in the sigmoid function, taking the proper shift factor for that temperature into consideration.

RECOMMENDATIONS

- This research focused on the master curve development of sasobit modified asphalt binder at different temperatures and frequencies. However, it is recommended to investigate the rheological properties of sasobit modified asphalt binder.
- It is recommended to investigate the WMA performance (produced with sasobit modified asphalt binder).
- Using WMA will reduce the negative environmental effects of using HMA, since there will be significant reduction in the mixing and compaction temperatures. However, the cost of adding sasobit to the asphalt binder should be considered. The manufacturer recommended using 1.5% of sasobit by the asphalt binder weight. Considering the optimum asphalt content of 5.5% in average, for every one ton of HMA, 55 kilograms of asphalt binder and around 0.83 kilogram of sasobit are needed. Given that the cost of one kilogram of sasobit is less than one dollar, it is very economical to be used in WMA. However, a comprehensive visibility cost study is needed to ensure the application of asphalt binder mixed with different percentages of sasobit asphalt modifier in the Middle East region.

Acknowledgment

The authors would like to thank Sasol Wax (South Africa) for providing the sasobit ® material for testing.

REFERENCES

American Association of State and Highway Transportation Officials. (2009). “Effect of heat and air on a moving film of asphalt (rolling thin-film oven test)”. American Association of State and Highway Transportation Officials (AASHTO), T 240.

American Association of State and Highway Transportation Officials. (2012). “Standard method of test for determining the rheological properties of asphalt binder using a dynamic shear rheometer (DSR)”. American Association of State and Highway Transportation Officials (AASHTO), T 315.

American Association of State Highway and Transportation Officials. (2012). “Accelerated ageing of asphalt binder using a pressurized ageing vessel (PAV). “American Association of State and Highway Transportation Officials (AASHTO), R 28.

Bari, J., and Witczak, M. (2007). “New predictive models for viscosity and complex shear modulus of asphalt binders for use with mechanistic-empirical pavement design guide”. Transportation Research Record: Journal of the Transportation Research Board, 2001, 9-19.

Edwards, Y., and Redelius, P. (2003). “Rheological effects of waxes in bitumen”. Energy Fuels, 17 (3), 511-520.

Iwanski, M., and Mazurek, G. (2012). “Rheological characteristics of synthetic wax-modified asphalt binders”. Polimery, 57 (9), 661-664.

Jamshidi, A., Golchin, B., Hamzah, M., and Turner, P. (2015). “Selection of type of warm mix asphalt additive based on the rheological properties of asphalt binders”. Journal of Cleaner Production, 100, 89-106.

Jamshidi, A., Hamzah, M., and You, Z. (2013). “Performance of warm mix asphalt containing sasobit®: state-of-the-art”. Construction and Building Materials, 38, 530-553.

Kim, H., Lee, S., and Amirkhanian, S. (2011). “Rheology of warm mix asphalt binders with aged binders”. Construction and Building Materials, 25 (1), 183-189.

Liu, W. (2012). “RAP percentage and warm mix additive influence on regenerated asphalt mixture performance”. AMM, 251, 436-441.

Sasobit handling and blending guideline. (2015). [e-book], Sasol Wax North America Corporation. Available at: http://www.sasolwax.us.com [Accessed 10 Sept. 2015].

Williams, M., Landel, R., and Ferry, J. (1955). “The temperature dependence of relaxation mechanisms in amorphous polymers and other glass-forming liquids”. J. Am. Chem. Soc., 77 (14), 3701-3707.

Zhang, J., Yang, F., Pei, J., Xu, S., and An, F. (2015). “Viscosity-temperature characteristics of warm mix asphalt binder with sasobit®”. Construction and Building Materials, 78, 34-39.

Zhao, H. (2011). “Research on performance of sasobit warm mix asphalt and influence of ageing using DSR”. AMM, 128-129, 426-429.