Rheological Evaluation of Rubberized Bitumen for Sustainable Pavement

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ABSTRACT

The use of modifiers to enhance the rheological properties of asphalt binders and to improve the performance of flexible pavements has been long in practice, especially in the developed countries. The use of performance-based binder tests and specification systems in flexible pavement designs, such as the Superpave Method, has also replaced the traditional methods, such as Marshall Design, in most of the developed world. In most African countries, however, performance-based tests are still not practiced in the binder grading system. In addition, there is no significant effort to minimize pavement distress by using modified binders of improved visco-elastic property. Therefore, the objective of this study was to evaluate the rheological property of an 80/100 penetration grade bitumen partially replaced with different percentages of Reacted and Activated Rubber (RAR). RAR commonly contains 62% Crumb Rubber, 22% soft bitumen, and 16% Activated Mineral Binder Stabilizer (AMBS). Using this modifier laboratory produced samples of 15, 20 and 25 percent RAR by mass of total binder were prepared. Some Dynamic Shear Rheometer (DSR) tests, namely, Amplitude Sweep Test (AST), Frequency Sweep Test (FST) and Performance Grades (PG) determination were carried out. According to the master curves developed from the Frequency Sweep Tests, it is observed that the modifier helps to improve the complex shear modulus (especially the elastic modulus) at high temperature and low frequency, i.e., at the worst loading condition of pavements. The performance grade determination also depicted the increase in PG as content of modifier increases. Generally the study showed that it is possible to improve the rheological characteristics of bitumen by partially replacing with RAR.

KEYWORDS: Asphalt binder, Master curve, performance grade, RAR, Rheology

1 INTRODUCTION

To improve pavement performance, one of the most important methods is producing a new binder with improved physical, chemical and rheological properties. This is done by using different additives to modify and improve visco-elastic properties of asphalt binder. According to the Federal Highway Administration (FHWA), the asphalt binder will affect the various performance aspects of the asphalt mixture such as permanent deformation, fatigue cracking, and low temperature cracking. The Superpave binder specification is intended to select the binder to optimize its effect on the performance of the pavement. The binder is selected based on the climate of the pavement where it will be used by evaluating at the expected highest and lowest pavement temperatures [1].

In view of the above and considering the major pavement distresses in Ethiopia, such as rutting, the concern of this study is to evaluate the rheological characteristics of binder modified with reacted and activated rubber (RAR) industrially known as RuBind™. The evaluation

focuses on high temperature property of binder which is done with the help of fundamental or Dynamic Shear Rheomeer (DSR) tests.

1.1 Rheological Property of Asphalt Binder

The complex shear modulus (G*) as a measure of the total resistance of a material to deformation when repeatedly sheared and phase angle (δ) an indicator of the relative amounts of recoverable and non-recoverable deformation are major rheological parameters of asphalt binders. The value of G* (G star) and δ (delta) for asphalts are highly dependent on the temperature and frequency of loading. At high temperatures (well above pavement temperatures) asphalts behave like viscous fluids as indicated by the vertical arrow and at very low temperatures (well below pavement temperatures) asphalts behave like elastic solids as indicated by the horizontal arrow as shown below in figure 1. At temperatures where most pavements carry traffic, asphalts (like those represented by arrows 1 and 2) simultaneously act like viscous liquids and elastic solids. When loaded, part of the deformation is elastic (recoverable) and part is viscous (non-recoverable). That is the reason why asphalt is called a visco-elastic material. For example, even though both asphalts in figure 1 are visco-elastic, asphalt 2 is more elastic than asphalt 1 because of its smaller δ ($\delta_2 < \delta_1$) while G^*_1 & G^*_2 are equal in value.

If the same load is applied to both asphalts, then Asphalt-1 will display more non-recoverable (permanent) deformation than Asphalt-2 since Asphalt-2 has a relatively large elastic component. This example shows that G*, alone, is not enough to describe asphalt behavior. i.e., the δ value is also needed.

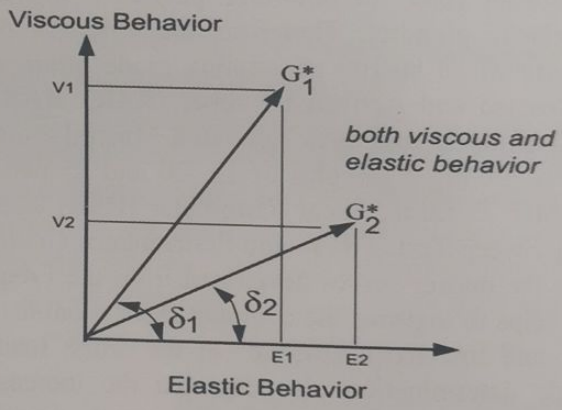


Figure 1: Viscous and Elastic Behavior [3]

1.2 Determination of Rheologic Property Using DSR

The Dynamic Shear Rheometer (DSR) is used to characterize the viscous and elastic behavior of asphalt binders by measuring two important asphalt binder properties: the complex shear modulus (G*) and phase angle (δ). As the force (or shear stress, τ) is applied to the asphalt by the spindle, the DSR measures the response (or shear strain, γ) of the asphalt to the applied force. If the asphalt were a perfectly elastic material, the response would coincide immediately with the applied force, and the time lag between the two would be zero. The time lag between the applied stress and the resulting strain is the phase angle δ. For a perfectly elastic material, the phase angle, δ, is zero, and all of the deformation is temporary. For a viscous material (such as hot asphalt), the phase angle approaches 90 degrees, and all of the deformation is permanent. In the DSR, a visco-elastic material such as asphalt at normal service temperatures displays a stress-strain response between the two extremes [1,3].

2 RESEARCH OBJECTIVE

The main objective of this study is to evaluate the contribution of asphalt binder to the performance of a pavement in rut resistance at high temperature when bitumen is modified with Reacted and Activated Rubber (RAR).

3 MATERIAL AND METHODS

To meet the objective, samples were prepared by partial replacement of 80/100 penetration grade bitumen with 15, 20, and 25% of reacted and activated rubber. Then different laboratory experiments were conducted using DSR equipment. Temperature sweep and frequency sweep test results were manipulated and Microsoft excel solver was employed to fit the data to the sigmoid function equation.

The base or control material is neat bitumen selected for modification considering the commonly used types of penetration grade bitumen in Ethiopia. The bitumen with penetration grade 80/100, which is soft and cheap when compared others, has been selected as a control material for this study. The modifier is Reacted and Activated Rubber (RAR), innovated to solve the tedious wet process of producing Asphalt Rubber Binder, involving very high temperature and long blending and reaction time that makes an asphalt rubber paving mix costly. Reacted and activated rubber is produced by a short-time hot blending and activation in a specially designed process to form a dried granulated material composed of soft asphalt cement (bitumen), fine crumb tire rubber, and an Activated Mineral Binder Stabilizer (AMBS) in optimized proportions [2].

3.1 Sample preparation

The samples were modified binders produced by blending the base asphalt with different contents of Reacted and Activated Rubber. Investigations of different researchers' done using different base bitumen states that around 20 percent by weight of binder have shown a better performance related results. Thus in this study the evaluation is done by preparing modified binder with 15, 20 and 25 percent by weight of total binder. Using a mechanical machine, the blending process has been done by stirring the mix at 600rpm for about 30minutes at an average temperature of 165 °C.

3.2 Dynamic Shear Rheometer (DSR) Tests

Using the dynamic shear rheometer it is possible to carry out different tests. From those different tests Amplitude Sweep, Frequency Sweep and PG determination were conducted for the purpose of this study. In booth tests first the asphalt binder is heated until it is sufficiently fluid to pour and then a small sample of asphalt binder is sandwiched between two plates. But before placing the sample the DSR is set to a particular temperature; this preheats the upper and lower plates, which allows the specimen to adhere to them. Depending up on the ageing condition and the test temperature, specimen size and plate diameter varies. Using a specimen of 1 mm thick and 25 mm diameter, the unaged binder and RTFO residue were tested at high temperatures and for low temperature test specimen sizes of 1mm thick and 8mm in diameter were used.

3.2.1 Performance Grade Determination

According to the superpave, for performance grade determination, set of tests of physical properties at a range of temperatures must be carried out. Moreover, even though tests are to be conducted at different temperatures, requirements of Physical properties will remain the same. For this study only high temperature tests as per AASHTO T 315 were carried out.

3.2.2 Amplitude Sweep Test

Amplitude sweep is an oscillatory DSR test with variable stress or strain amplitude at constant frequency. The sole purpose of this test is to determine the Linear Visco Elastic Range (LVR) of a visco-elastic material. The linear visco elastic part is the region where the applied

oscillation is non destructive. This test was carried out in shear stress control mode with minimum shear stress 100pa and maximum shear stress 90000pa at a constant frequency of 10rad/sec and specific test temperatures (21.1 °c, 37.8 °c & 54.4°c).

3.2.3 Frequency Sweep Test

Frequency sweep is also an oscillatory test with variable frequency and constant amplitude values. Using this test, time dependent shear behaviour can be examined. Short-term behaviour is simulated by rapid movements (at high frequencies) and long term behaviours by slow movements (at low frequencies). Frequency sweep helps to evaluate the rheological property of visco-elastic material by developing a master curve from isothermal plots of the test result. The frequency sweep test was conducted in a strain (1%) controlled mode with varying frequency from 0.1Hz to 25 Hz.

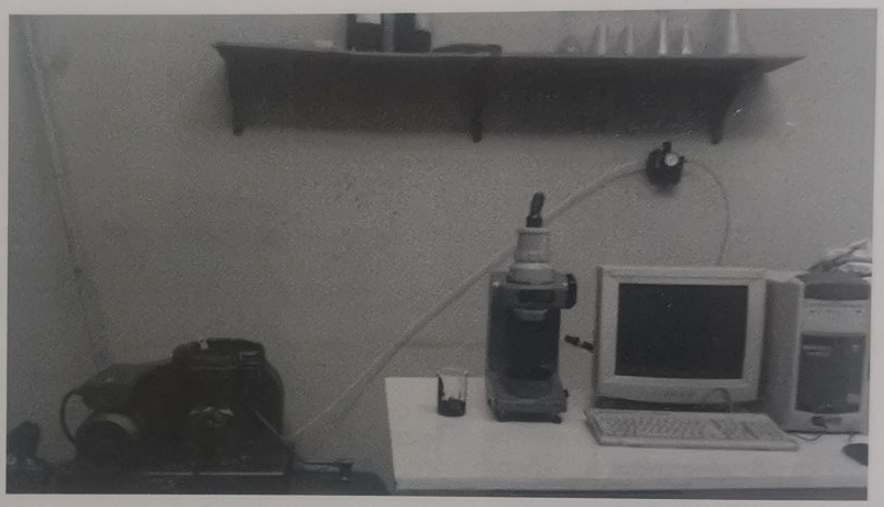
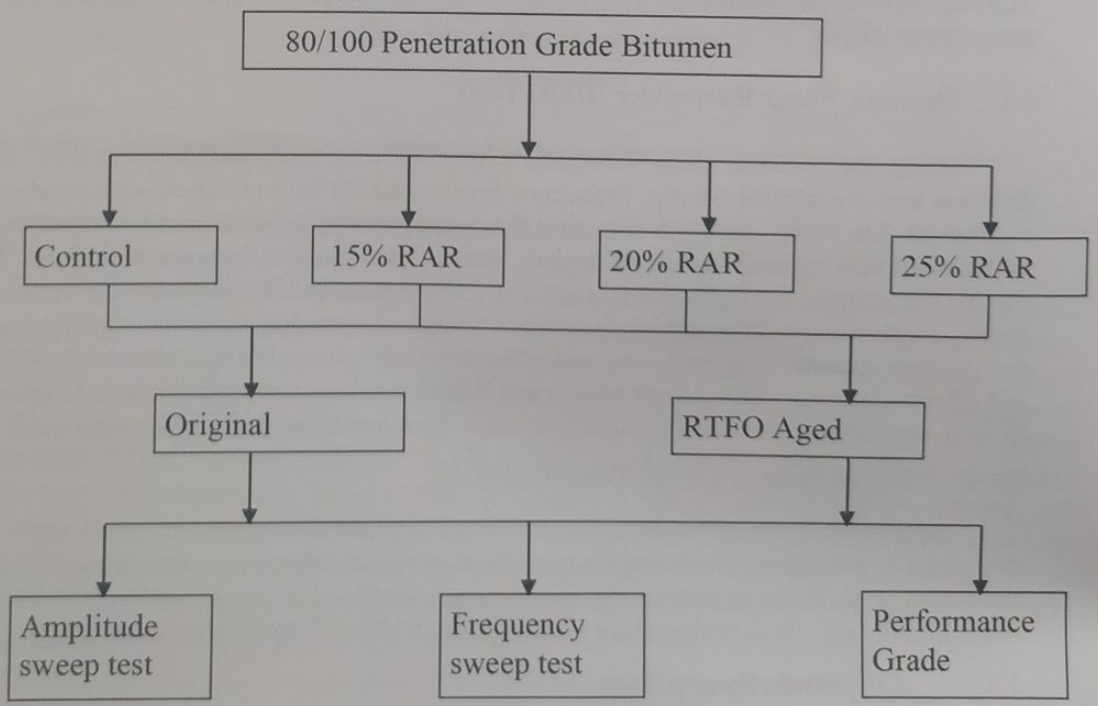


Figure 2: Dynamic Shear Rheometer

3.2.4 Test Flow chart



4 RESULT AND DISCUSSION

4.1 Result From Amplitude Sweep Test

The test results were represented graphically with Log-Log scale of complex shear modulus (G*) in the Y-axis and Strain in percent in the X-axis. As an example figure below shows the amplitude sweep test result for 20% modified binder before RTFO.

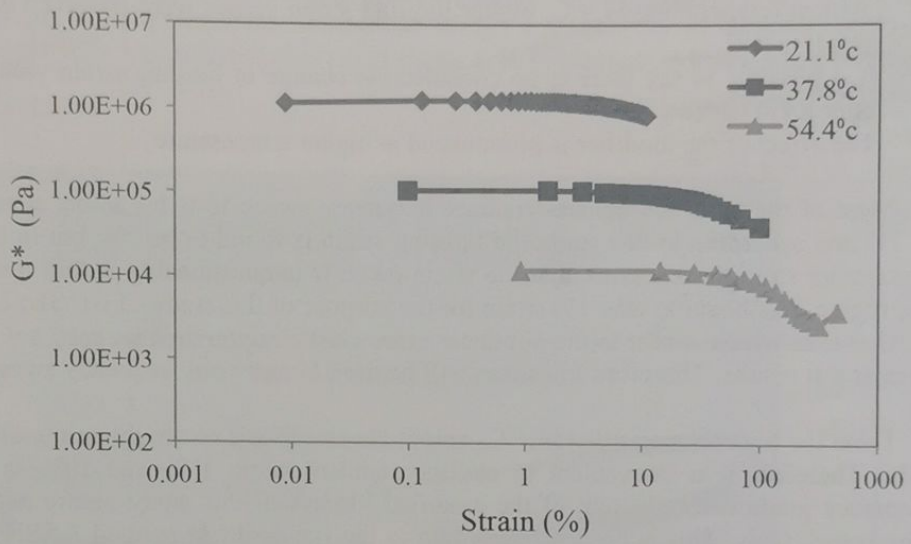


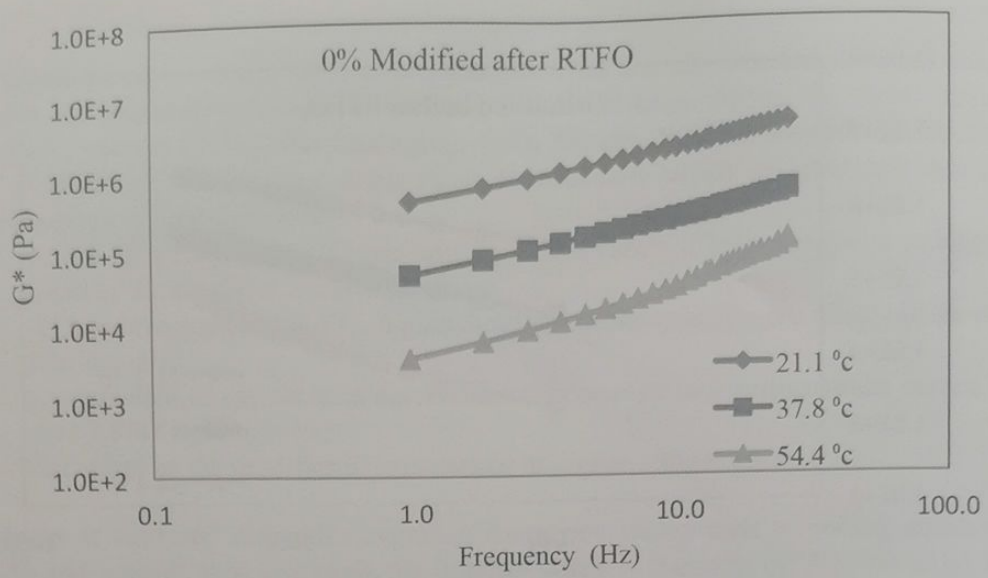
Figure 3: Linear Visco-Elastic Range for 20% Modified Binder before RTFO

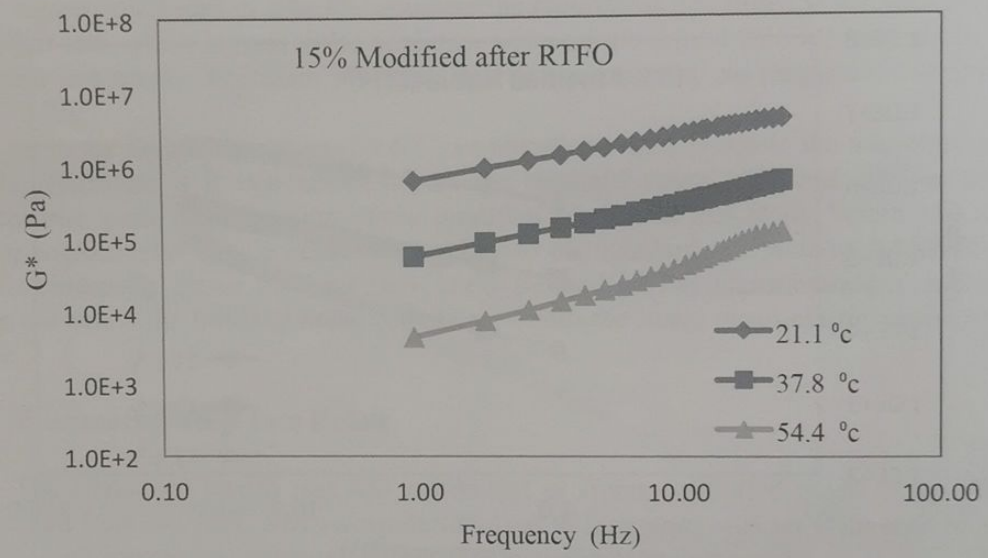
4.1.1 Analysis and Evaluation of AST

Based on the test result represented graphically the limiting strain values were analyzed considering the plateau strain values of each sample. The plateau modulus are the constant results of G* for different values of shear stress and shear strain before the graph declines as shown in figure above. Then, a horizontal line along 0.95G* will be constructed to intersect the curve at a point [5]. Then the strain which corresponds to the intersection point will be taken as the limiting stain value (γ_L).

Table 1: Amplitude Sweep Test Result to Illustrate Linear Visco-Elastic Range

Test Temp.(°c)	Sample (RAR %)	Before RTFO			After RTFO		
		plateau G*	0.95G*	ting Strain	plateau G*	0.95G*	Limiting Strain (%)
21.1	0	5.13E+05	4.87E+05	2	1.02E+06	9.66E+05	2.5
	15	5.15E+05	4.89E+05	2	1.03E+06	9.75E+05	3.3
	20	1.04E+06	9.91E+05	3	1.12E+06	1.06E+06	3
	25	1.10E+06	1.05E+06	2	1.23E+06	1.16E+06	3.3
37.8	0	4.12E+04	3.91E+04	20	6.44E+04	6.12E+04	20
	15	4.21E+04	4.00E+04	16	6.56E+04	6.23E+04	18
	20	9.11E+04	8.66E+04	13	9.31E+04	8.85E+04	13
	25	9.43E+04	8.96E+04	10	1.10E+05	1.04E+05	12
54.4	0	3.20E+03	3.04E+03	74	4.84E+03	4.60E+03	40
	15	3.35E+03	3.18E+03	50	5.15E+03	4.89E+03	50
	20	1.14E+04	1.08E+04	42	1.22E+04	1.16E+04	42
	25	1.24E+04	1.18E+04	25	1.69E+04	1.60E+04	35





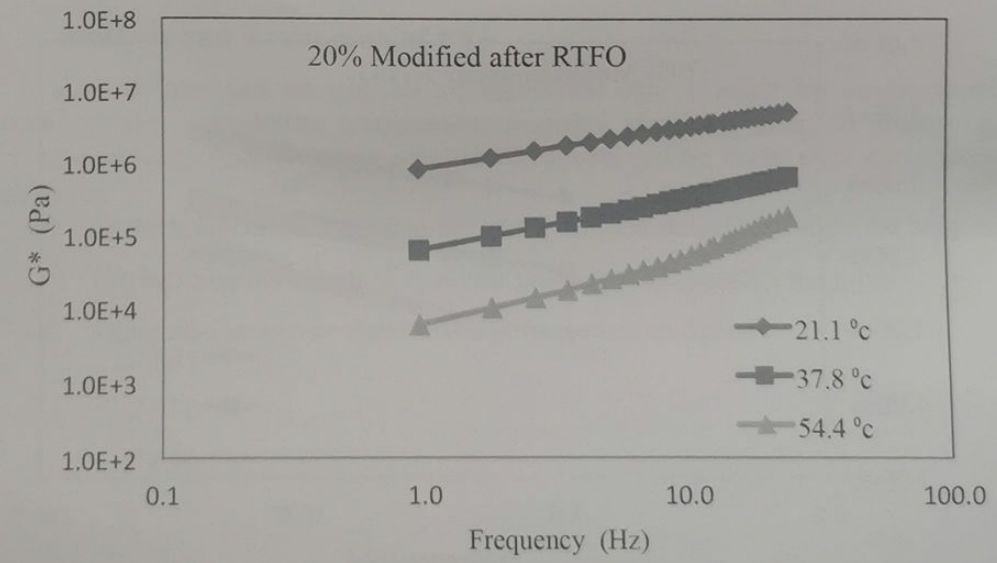


Figure 5: Isothermal plots after RTFO
For simplicity the graph for 25% modified binder is not included here.

Based on the summary table above it is observed that the amplitude sweep test enables to recognize the responses (change) in stiffness and LVE range due to the three factors name'y, temperature, content of modifier and aging. Even though the sole purpose of amplitude swe p test is to determine the limiting strain value of unknown binder as tabulated above, the main effects observed are the following,

- ✓ At test temperature 21.1°C, the limiting strain value of each sample is minimum and the effect of the modifier is not significant
- ✓ At test temperature 54.4°C, higher limiting strain values were observed as the material gets less stiff
- ✓ It is possible to say there is no considerable change in limiting strain values before and after RTFO ageing
- ✓ The effect of the modifier is pronounced at higher temperature

Most of the time, researchers conduct frequency sweep tests by taking strain value from 1% - 2% and according to this study the limiting strain is found to be 2%, but to be well below the maximum strain or to ensure that the strain taken is unquestionably within the linear visco-elastic region, it is better to take 1% strain for the purpose of this study. If we take 2% as an input for further tests which is near to the nonlinear visco elastic region then we may not be able to get consistent test results. Therefore 1% strain will be used to carry out frequency sweep tests of this study.

From the high temperature (54.4°C) amplitude sweep test result, the minimum strain value is 25%. Therefore it is convenient to use the standard strain 12% and 10% as an input for performance grade determination of the modified binders of this study before and after RTFO Ageing respectively. This is because according to the standard test method AASHTO T 315 for specific binder the above 12% and 10% are to be used for PG determination if and only if these values are below the limiting strain value, i.e.; within the linear visco-elastic region of a specific binder.

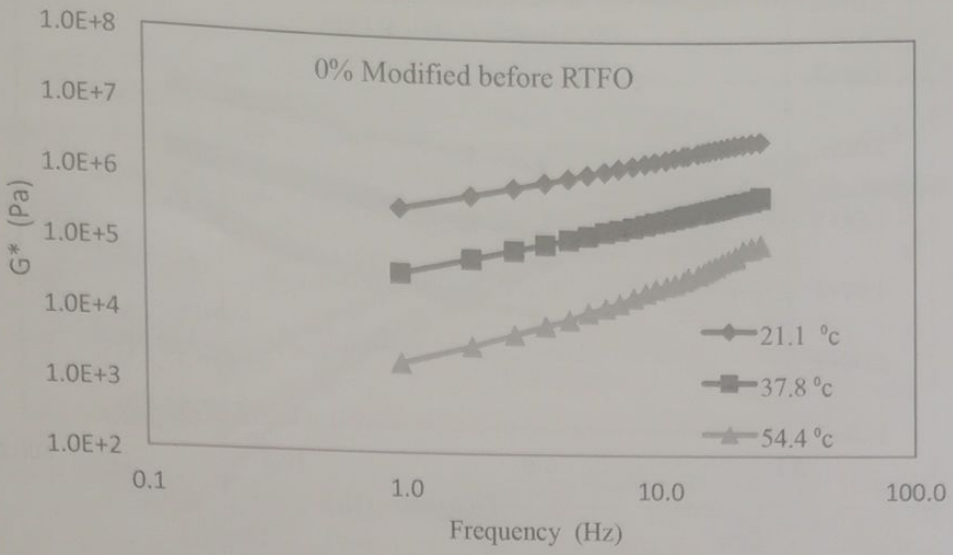
4.2 Frequency Sweep Test Result

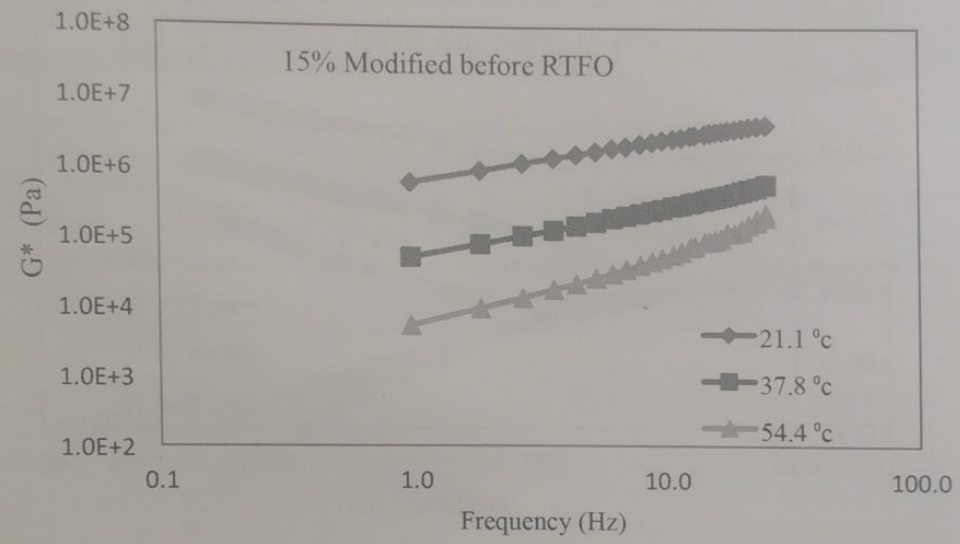
The frequency sweep test was conducted in strain controlled mode using 1% strain as determined from the AST. The sweep or variation in frequency was set from high to low (25Hz-0.1Hz) in an increasing damaging effect. Frequency sweep test results at 21.1°C, 37.8 °C, and 54.4 °C for all samples both aged and un-aged were determined and organized with isothermal graphs as shown below.

4.2.1 Analysis and Evaluation of FST

A kind of brief and straightforward discussion can be made by simply looking at the isothermal graphs; considering temperature, complex shear modulus, frequency, ageing and content of modifiers. And of course a better discussion can be made after developing modulus master curves.

- ✓ As the temperature increases the shear stiffness decreases for all the binders
- ✓ The increase in content of modifier increases the complex modulus
- ✓ Aging also improves shear stiffness (complex modulus)





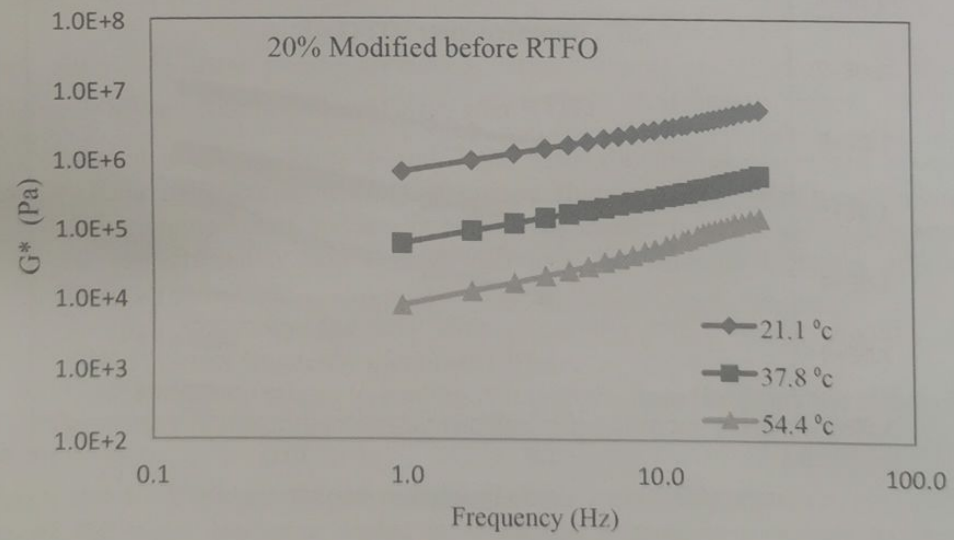
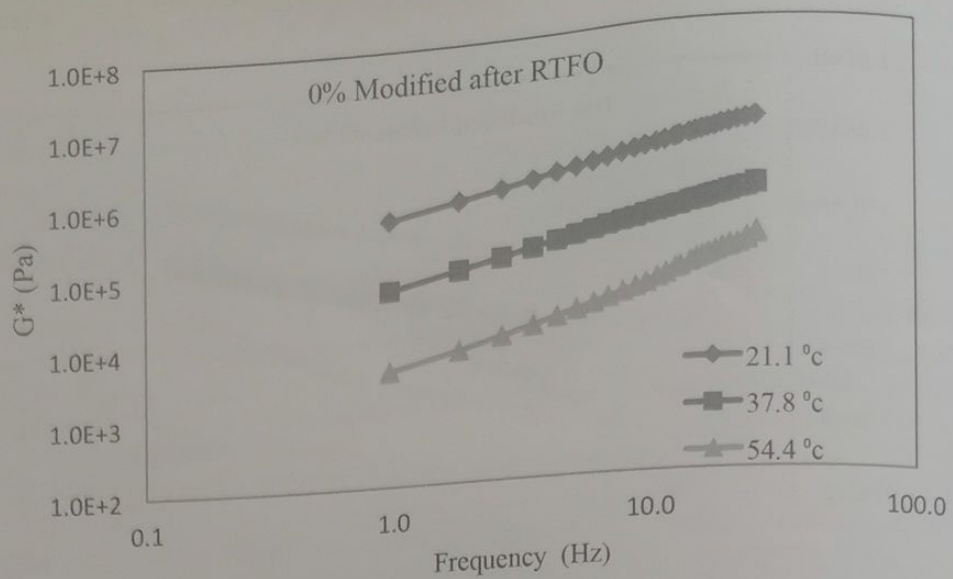
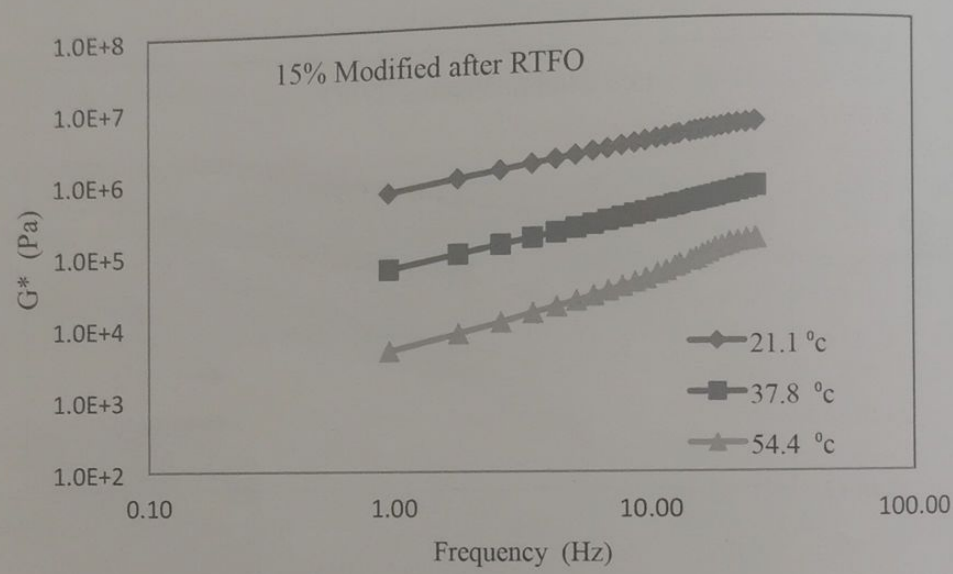


Figure 4: Isothermal plots Before RTFO





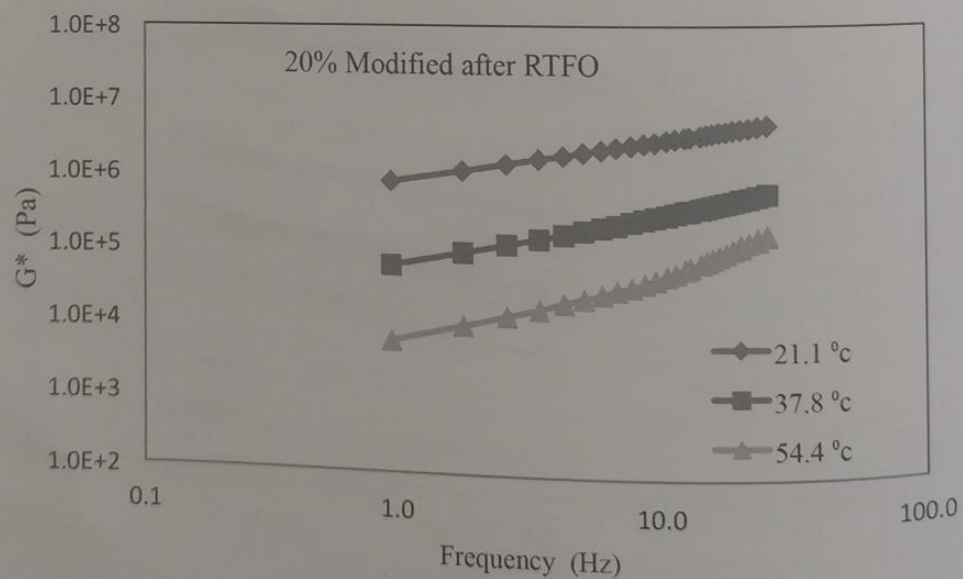


Figure 5: Isothermal plots after RTFO
For simplicity the graph for 25% modified binder is not included here.

Finally modulus master curves were developed following the process above.

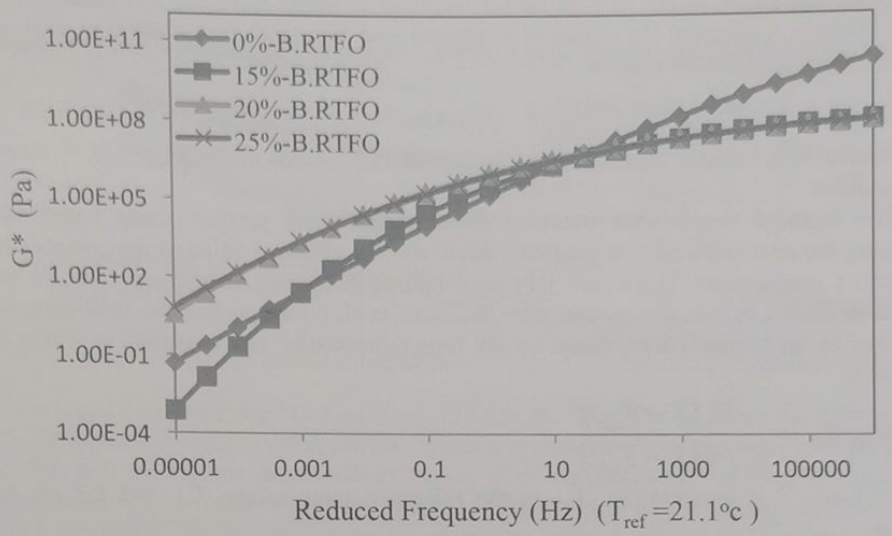


Figure 6: Shear Modulus Master Curve before RTFO

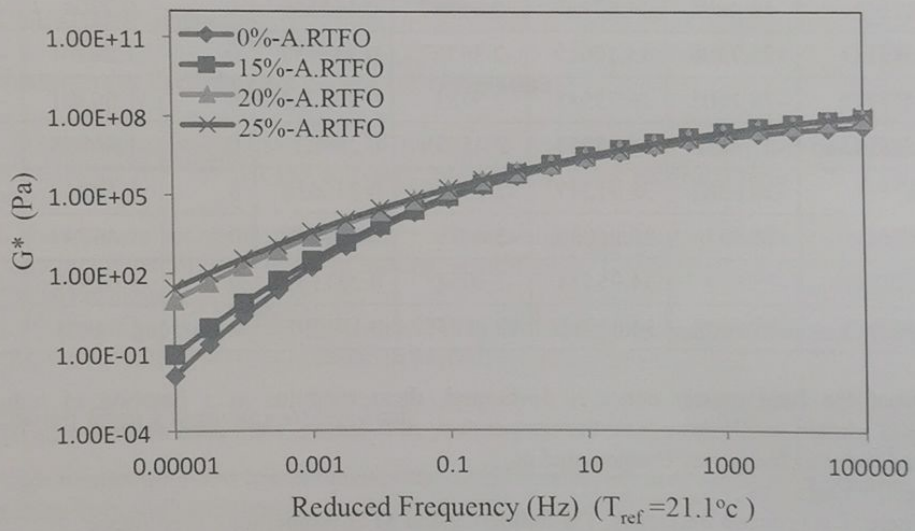


Figure 7: Shear Modulus Master Curve after RTFO

As observed above in figure 6 and 7 the main rheological parameter, complex shear modulus (G*) behaves differently due to temperature, frequency, content of modifier and ageing.

- ✓ At high temperature and low frequency the smaller values of G* were pronounced.
- ✓ At low frequency and high temperature the modulus increases appreciably as modifier increases.
- ✓ At high frequency and low temperature the effect of the modifier makes no difference (for frequency more than10Hz).
- ✓ Since frequency relates to loading rate (speed), from the graph the effect of modifier is evident at typically operating frequency/speed (0.01 to 10Hz).

From above we can summarize that the modifier appreciably improves the complex shear modulus of the virgin binder at higher temperatures. Rutting is a serious problem at high temperature due to slow moving traffic and as observed it is possible to say the modifier improves the pavement performance against this distress by increasing the stiffness of the binder.

4.2.2 Master Curves of Complex Shear Modulus

The rheological properties of asphalt binder are commonly presented in terms of complex modulus and phase angle master curves, which requires determining temperature shift factors and other constants at a reference temperature. Therefore Modulus Master Curves were developed using Microsoft excel solver to best fit the sigmoid function with the test result (G*) for all asphalt binders. Changing the sigmoid constants and the shift factor by trial and error the following sigmoid function is used;

$$\text{Log}\,|G^*| = a + \frac{b}{1 + e^{c\,\log f_r + d}}$$

Where: a, b, c and d: Sigmoid function constants, fr: Reduced frequency, |G*|: Complex shear modulus

The sigmoid coefficients obtained from optimization process using excel solver by minimizing the error between the predicted value and the obtained value of the complex modulus at reference temperature 21.1°c are tabulated below. William-Landel-Ferry (WLF) empirical relationship shown below 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 (aT).

$$\log a_T = \frac{-C_1(T - T_{ref})}{C_2 + (T - T_{ref})}$$

Where, T is temperature, T_{ref} is the reference temperature, C1 and C2 are taken as constants.

Table 2: Shear Modulus Sigmoid Coefficients and Temperature Shift Factors

	a	b	C	d	a21.1	a37.8	a54.4
0%-B.RTFO	-19.4808	34.07687	-0.95887	0.165569	0	-0.9304	-1.60101
15%-B.RTFO	-26.7106	35.17019	-2.38757	0.335357	0	-1.26901	-1.98662
20%-B.RTFO	-28.1605	36.73588	-2.5731	0.258765	0	-1.66301	-2.64152
25%-B.RTFO	-27.1088	35.84958	-2.45338	0.23923	0	-1.66898	-2.56922
0%-A.RTFO	-30.6282	38.71247	-2.73676	0.335618	0	-1.1874	-2.2532
5%-A.RTFO	-26.463	35.06039	-2.4479	0.296778	0	-1.46799	-2.35622
20%-A.RTFO	-25.879	34.95424	-2.3054	0.221133	0	-1.61597	-2.53543
25%-A.RTFO	-24.9805	34.42285	-2.16777	0.194797	0	-1.59821	-2.53673

Before the final master curve is developed, shear modulus as a function of reduced frequency is plotted to illustrate how the temperature shift factors were used as shown in figure below. And reduced frequency is calculated as;

Log f_r = Log f +aT,

Where; f_r is reduced frequency, f is frequency and aT is temperature shift factor

4.3 Results of performance grade (PG) determination test

The high temperature PG test result (output from the software) includes many other parameters and the relevant parameters for determination of the performance grade for both unmodified and modified binders at high temperature were organized in the table below

Table 3: Performance Grade Determination Test Result for Original Binder

Sample (% RAR)	0			15			20			25		
Test Temperature (°C)	52	58	64	52	58	64	64	70	76	70	76	82
Criteria G*/sin delta @10rad/sec. kPa	Min. 1.0kPa			Min. 1.0kPa			Min. 1.0kPa			Min. 1.0kPa		
Specimen -01 G*/sin delta @10rad/sec. kPa	3.80	1.50	0.73	3.91	1.71	0.75	3.09	1.53	0.79	2.06	1.18	0.67
Specimen -02 G*/sin delta @10rad/sec. kPa	3.80	1.60	0.66		1.73	0.80	3.32	1.66	0.87		1.17	0.67
Average G*/sin delta @10rad/sec. kPa	3.80	1.55	0.70	3.91	1.72	0.78	3.21	1.60	0.83	2.06	1.18	0.67
Phase angle (Specimen -01). Deg	85.00	85.50	86.00	81.70	82.80	83.75	76.94	79.91	82.07	76.24	78.73	80.65
Phase angle (Specimen -02). Deg	85.00	86.00	86.00		83.13	83.90	76.18	79.35	81.72		78.12	80.24
Phase angle (Average). Deg	85.00	85.75	86.00	81.70	82.97	83.83	76.56	79.63	81.90	76.24	78.43	80.45
Pass Fail Temp. (Specimen -01). Deg	61.30			62.50			73.80			77.60		
Pass Fail Temp. (Specimen -02). Deg	61.10			62.90			74.60			77.70		
Pass Fail Temp. (Average).Deg	61.20			62.70			74.20			77.65		
Temp Pass. Deg	58.00			58.00			70.00			76.00		

For simplicity PG test result for RTFO residue is not included here.

4.3.1 Analysis and Evaluation of PG Determination

Considering pass fail temperatures from table above, now it is possible to determine the high temperature performance grade of the binders.

Table 4: Determined High Temperature Performance Grade (AASHTO M 320)

RAR (%)	Before RTFO	After RTFO	Performance Grade (AASHTO M320)
0	58	58	PG 58-xx
15	58	58	PG 58-xx
20	70	64	PG 64-xx
25	76	70	PG 70-xx

Now it is observed that there is a PG improvement from PG 58 to PG 64 when the neat bitumen is modified with 20% reacted and activated rubber. When the content of the modifier is increased to 25%, again the PG will be further improved to PG70. The increment in PG clearly shows that modifying bitumen with this rubberized material increases the stiffness of the asphalt binder. Here it is understood that the basic rheological parameter, complex shear modulus (G*) is increasing as percent content of rubber increases. The other important observation here is the PG after RTFO for 20% and 25% modified binder which remains relatively softer after ageing is an indication of less susceptibility of the modified binder for hardening.

5 CONCLUSIONS

5.1 Conclusion from Performance Grade Determination

- PG grade improvement from PG 58 to PG 64 was observed when the neat bitumen is modified with 20% reacted and activated rubber. And when modified with 25% it was raised to PG 70.
- This shows complex shear modulus (G*) is increasing as percent content of rubber increases. Connectively the improvement in rutting performance is expected as stiffness parameter (G*/sin δ) is higher.
- The PG pass temperatures for 20% and 25% modified binders indicate that susceptibility for ageing will decline due to an increase in percentage of modifier.

5.2 Conclusion from Frequency sweep Test

- At high temperature and low frequency the smaller value of shear modulus is pronounced but increases as modifier increases.
- The modulus curves converge to similar value as the frequency increases. It is observed that at frequency around 10Hz and above the binders have the same value of shear modulus where the effect of the modifier became insignificant.
- At very low frequency (such as from 0.01 to 0.0001 Hz or below) and at higher temperatures, the effect of the increase in content of modifier is observed significant with larger values of modulus.
- From this we can summarize that the modifier appreciably improves the complex shear modulus of the neat binder at higher temperature and low frequency (at worse traffic loading condition).

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