ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

EVALUATION OF RUBBERIZED BITUMEN AS PAVEMENT MATERIAL

A Thesis in Road and Transport Engineering

By Atnafu Admas
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A Thesis
Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science

The undersigned have examined the thesis entitled **‘EVALUATION OF RUBBERIZED BITUMEN AS PAVEMENT MATERIAL’** presented by Atnafu Admas, a candidate for the degree of **Master of Science** and hereby certify that it is worthy of acceptance.

Advisor's Name	Signature	Date
Co advisor’s Name	Signature	Date
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UNDERTAKING

I certify that research work titled "**Evaluation of Rubberized Bitumen as Pavement Material**" is my own work. The work has not been presented elsewhere for assessment. Material which has been used from other sources has been properly acknowledged / referred.

Atnafu Admas

Dedicated to my father,

Admas Mengistu

ABSTRACT

Engineers especially in developed countries have been using modified binders to improve the performance of flexible pavements. They use different modifiers to enhance the rheological properties of asphalt binder. And specification is done by applying superpave binder grading system which requires performance based binder tests. In Ethiopia while one of the major pavement distresses is rutting, there is no significant effort to minimize this high temperature distress by using modified binder of improved visco-elastic property, more over the binder grading system does not comprise performance based tests.

Therefore, the objective of this thesis is to evaluate the high temperature performance of asphalt binder modified with Reacted and Activated Rubber (RAR). i.e., to examine the contribution of this modified binder to minimize rutting.

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. The control material was 80/100 penetration grade neat bitumen. To evaluate the visco-elastic properties of these modified samples different Dynamic Shear Rheometer (DSR) tests were carried out. The major DSR tests were Amplitude sweep test (AST), frequency sweep test (FST) and Multiple Stress Creep Recovery (MSCR). Also Performance Grade (PG) determinations at high temperatures were conducted.

From the amplitude sweep test the linear visco elastic range was found to be 2%. Then to be well within visco-elastic region 1% strain was used to conduct frequency sweep test. Master curves developed from frequency sweep test showed that the modifier improves the shear modulus at high temperature and low frequency. The performance grade determination also depicted the improvement in PG as content of modifier increases. Even though the non-recoverable creep compliance improves as modifier increases, it is found that 25% replacement was not convenient in its percent recovery. Therefore the evaluation showed that the 20% modified binder is better in its rutting performance with improved performance grade.

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CHAPTER 1 INTRODUCTION

1.1 Background

This time in Ethiopia one of the active industries is road construction. When we consider the paved roads almost all are flexible pavements with asphalt concrete surfacing. The common problems in flexible pavements are pavement distresses which usually need continuous effort to tackle them. There are several ways to improve performance of asphalt concrete pavements. Some of the methods are improving the pavements material mix design, improving the construction methods, enhancing maintenance techniques and producing a new binder with improved physical, chemical and rheological properties [1]. 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, the expected traffic, and the location in the pavement structure. The binders are evaluated at the expected highest pavement temperature and lowest pavement temperatures [1].

One of the most important solutions for pavement distress is to develop a new binder with the help of an additive. And if the binder selection and specification has to be considering the climate where the road way exists, it is necessary to produce a modified binder for every locality by knowing its pavement temperature.

Considering major pavement distresses in Ethiopia, the concern of this study is to evaluate the rheological characteristics of unmodified binder and binder modified with reacted and activated rubber (RAR) industrially known as RuBind^{TM}. The evaluation focuses on high temperature property of binder which will be done with the help of fundamental or Dynamic Shear Rheomeer (DSR) tests.

1.2 Statement of the Problem

Producing a new binder with improved physical, chemical and rheological properties is one of the major methods to improve the performance of pavements by providing an extended life at a lower cost. In Ethiopia most of the paved road-ways are flexible pavements, therefore it is crucial to work on improvement of performance of pavements by using modified binders and related methods. In developed countries performance based asphalt binder specifications, Superpave binder grading system is in use. Recently the more advanced asphalt binder specification method using the Multiple Stress Creep Recovery (MSCR) test has been developed. This MSCR method is becoming popular since it best predicts rutting and convenient to consider different levels of traffic. But in Ethiopia still conventional binder testing and specification system is in use. Therefore it is necessary to bring a change towards methods of binder characterization, which will help to prepare specification of asphalt binders in accordance with performance grade and second to be able to produce modified binder with improved rheological properties to enhance pavement performances by minimizing rutting and other distresses.

1.3 Objectives

1. General objective

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

2. Specific objectives

The specific objectives are;

1. To determine visco-elastic ranges of modified binders using Amplitude Sweep Test.
2. To evaluate rheological properties of the binders by developing master curves from Frequency Sweep Test.
3. To evaluate permanent deformation using Multiple Stress Creep Recovery Test.
4. To determine Performance Grades of the binders for comparison.

Conducting the above fundamental binder tests, to create motivation towards advanced binder characterization can also be considerable supplementary objective of this thesis.

1.4 Limitations

For DSR tests there is no complete facility to carry out the laboratory works at full scale. Because of this, during the experimental works there were some limitations especially related to sample preparation.

- To blend the modifier with the virgin bitumen, there was no convenient heater to maintain the mixing temperature. Simple common hot plate was used by trying to maintain the temperature from 160^{o}c to 170^{o}c.
- A mechanical drilling machine at the mechanical laboratory of the school was used to carry out the wet mix at 600rpm.
- The stirrer used was homemade.
- There was no technology to check the composition of the modifier and thus it was used by simply accepting the production description.
- In view of latest equipments available recently, the DSR used is old equipment and it may have associated limitations like stress resolution and other precisions.
- Because of the absence of Pressure Aging Vessel (PAV), Bending Beam Rheometer (BBR) and Direct Tension Test (DTT), low temperature binder characterization was not conducted for PG determination.

CHAPTER 2 LITERATURE REVIEW

In accordance with the objective of the study this literature review is compiled focusing on permanent deformation, asphalt-cement behavior, binder modification and related topics.

2.1 Pavement Rutting

Permanent deformation or rutting in asphalt pavements is one of the most significant types of deterioration which usually consists of longitudinal depressions in the wheel paths. The Distress Identification Manual for the Long-Term Pavement Performance Project defines rut as "a longitudinal surface depression in the wheel path that may have associated transverse displacement" [5]. Rutting can also be defined as the accumulation of small amounts of non-recoverable strain resulting from applied loads to the pavement. Wheel path deformation is a combination of densification (volume change) and shear deformation (no volume change) from the repetitive application of traffic loads.

This rut deformation, characterized by a surface cross section that is no longer in its proper or design position not only decreases the useful service life of the pavement but also creates a safety hazard for the road users depending on its level [4].

2.1.1 Classification and Types of Rutting

From several classifications, the one provided in 1979 by the Federal Highway Administration, classified rutting into three levels of severity:

1. Low, from 6 to 12.5 mm (0.25 to 0.5 inches),
2. Medium, from 12.5 to 25 mm (0.5 to 1.0 inches), and
3. High, over 25 mm (1 inch).

For normal cross slope, a rut depth of 12.5 mm (0.5 inch) is typically accepted as the maximum allowable rut depth [3].

Among the many causes of wheel path rutting (e.g., underlying HMA weakened by moisture damage, abrasion, traffic densification and others), there are two types of rutting based on the principal causes.

1. Too much repeated stress being applied to the native soil

This type of rutting is caused by too much repeated stress being applied to the native soil (i.e., sub-grade), sub-base, or base below the asphalt layer. Although stiffer paving materials will partially reduce this type of rutting, it is normally considered more of a structural problem rather than a materials problem. It is often the result of too thin pavement section because there is simply not enough depth of cover on the sub-grade to reduce the stress from applied loads to a tolerable level. It may also be the result of a sub-grade that has been unexpectedly weakened by the intrusion of moisture. This accumulated deformation occurs in the sub-grade rather than in the overlying asphalt layers.

2. Accumulated deformation in the asphalt layers.

Shear deformation of properly compacted pavements due to large shear stresses in the upper portions of asphalt layer is dominant [3, 2]. This is rutting caused by an asphalt mixture that is too low in shear strength to resist the repeated heavy loads. Sometimes surface course may not itself be prone to rutting, but may simply conform to an underlying asphalt course that is too weak.

2.1.2 Prediction of Rutting

Rutting can be predicted by conducing binder tests and/or mixture tests. In case of mixture a standardized accelerated laboratory test to predict HMA rutting potential that is relatively inexpensive and useful for quality control/quality assurance (QC/QA) testing would be of great benefit. Currently the most common type of standardized laboratory test of this nature is a loaded wheel tester (LWT). Numerous types of LWT equipments are available, such as the Georgia Loaded Wheel Tester, the Asphalt Pavement Analyzer (APA), the Superfos Construction Rut Tester, the Hamburg Wheel Tracking Device (HWTD), and the French Laboratoire Central des Ponts et Chaussées (LCPC) Wheel Tracker [4].

To predict permanent deformation from binder, there are no adequate alternatives of test methods. The former rut indicator ‘$G^*/\sin\delta$’ became ambiguous according to different laboratory and field studies. Several studies have shown an inadequacy of the M 320 specification to sufficiently characterize asphalt for high temperature performance grading of modified binders. Recently, a new Multiple Stress Creep and Recovery (MSCR) test method (AASHTO T 350) along with the specification (AASHTO M 332) have been proposed to address the shortcomings of the M 320 specification. The MSCR test method allows better characterization of the high temperature performance-related properties of unmodified and modified binders. This is because the MSCR parameter, non-recovered compliance (J_{nr}) better relates to permanent deformation of the binder contributions [45, 47].

2.1.3 Effects of Pavement Materials on Rutting

In addition to climate, compaction and loading conditions rutting is influenced by properties of the mixture and the constituent materials (aggregate, mineral fillers and asphalt cement).

1. Mixture

If an asphalt mixture ruts, it is because the mixture has insufficient shear strength to support the stresses applied. Overall pavement performance is dependent on the properties of the aggregate, bitumen, contact of aggregate and bitumen, etc. as well as their relative influence change through time to the end of their service life (till the failure due to excessive permanent deformation or cracking).

The performance of the asphalt mixtures depends on the load frequency and temperature, and also, there is a strong dependency in terms of the voids content. By ageing, their flow ability decreases, that may play an important role in permanent deformation development. Various factors affecting the permanent deformation as well as effects of their changes are given in Table 2-1.

Table 2-1: Factors Affecting Rutting of Asphalt Mixtures [2, 4 & 8]

Factor		**Change in Factor**	**Rutting Resistance**
Aggregate	Surface texture	Smooth to rough	Increase
	Gradation	Gap to continuous	Increase
	Shape	Rounded to angular	Increase
	Size	Increase in maximum size [1]	Increase
Binder	Stiffness [2]	Increase	Increase
Mixture	Binder content	Increase	Decrease
	Air void content [3]	Increase	Decrease
	voids in mineral aggregate [4]	Increase	Decrease
	Method of compaction	...[5]	...[5]
Test of Field Conditions	Temperature	Increase	Decrease
	State of stress/strain	Increase in tire contact pressure	Decrease
	Load repetitions	Increase	Decrease
	Water	Dry to wet	Decrease (if mixture is water sensitive)

1 Assuming constant layer thickness.

2 Refers to stiffness at temperature at which rutting propensity is being determined. Modifiers may be utilized to increase stiffness at critical temperatures, thereby reducing rutting potential.

3 When air void contents are less than about 3 %, the rutting potential of mixtures increases.

4 It is argued that very low (i.e., less than 10 %) voids in mineral aggregate should be avoided.

5 The method of compaction, whether laboratory or field, may influence the structure of the system and therefore the propensity or tendency for rutting.

2. Binder

Rutting from weak asphalt mixtures is a high temperature phenomenon. While this might suggest that rutting is solely an asphalt binder problem, it is more correct to address rutting by considering the mineral aggregate and asphalt cement [1].

In fact, Mohr-Coulomb equation ($\tau = C + \sigma \times \tan \phi$) can again be used to illustrate how both materials can affect rutting. In this case, τ is considered the shear strength of the asphalt mixture. The cohesion term (C) can be considered the portion of the overall mixture shear strength provided by the asphalt cement. Because rutting is an accumulation of very small permanent deformations, one way to ensure that asphalt cement provides its "fair share" of shear strength is to use an asphalt cement that is not only stiffer but also behaves more like an elastic solid at high pavement temperatures. i.e., when a load is applied to the asphalt cement in the mixture, it tends to act more like a rubber band and spring back to its original position rather than stay deformed.

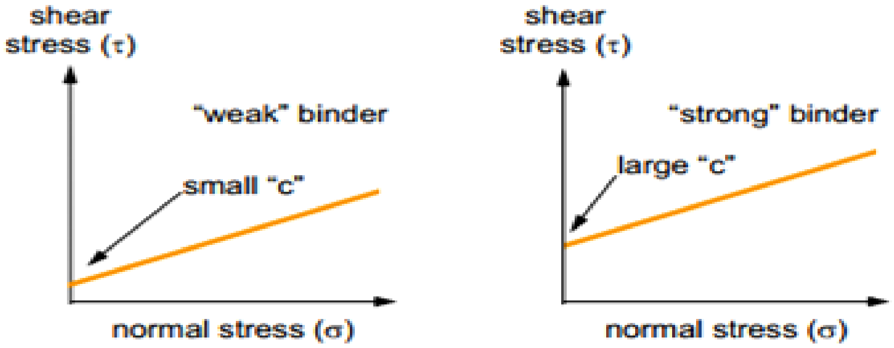


Figure 2-1: Asphalt Binder Contribution to Mixture shear strength [1, 2]

2.2 Bitumen Fundamentals

2.2.1 Introduction

Asphalt binder is defined by the American Society for Testing and Materials (ASTM) as a dark brown to black cementitious material in which the predominating constituents are bitumen that occur in nature or are obtained in petroleum processing. In the crude oil refineries, the cementatious material is in the bottom of the vacuum distillation columns. The residue of this vacuum distillation is then known as steam refined asphalt cement. As cement, asphalt is especially valuable to the pavement applications because it is strong, readily adhesive, highly waterproof, and durable. It provides limited flexibility to mixtures of mineral aggregates. It is also highly resistant to the reaction with most acids, alkalis, and salts.

2.2.2 Composition of the Bituminous Materials

The chemical composition of bitumen consists of different fractions, known as SARA fractions, (saturates, aromatics, resins and asphaltenes) [42]. These fractions are grouped in to Asphaltenes and Malthens. Malthenes is further classified as saturates, aromatics and resins. Asphaltenes are known to be the insoluble part of asphalt in n-heptane, and the other group (saturates, aromatics and resins) together represent the soluble part of asphalt in n-heptane. And the elementary analysis of asphalt contains carbon (80 - 88%), hydrogen (8 - 11%), sulphur (0 - 6%), oxygen (0 - 1.5%), and (0 - 1%) nitrogen [50].

2.2.3 Behavior of Bitumen

The most mysterious property of an asphalt binder is its temperature susceptibility which makes it desirable and tricky at the same time. i.e., its measured properties are very dependent on its temperature. Asphalt cement is sometimes referred to as a visco-elastic material because it simultaneously displays both viscous and elastic characteristics. At high temperatures, asphalt cement acts almost as a viscous fluid. In other words, when heated to a high enough temperature (e.g., > 100 ^{o}C), it displays the consistency of a lubricating fluid such as motor oil. At very low temperatures (e.g., < 0 ^{o}C), asphalt cement behaves mostly like an elastic solid. i.e., it acts like a rubber band. When loaded it stretches or compresses to a different shape. When unloaded, it easily returns to its original shape. At intermediate temperatures, which also happen to be those in which pavements are expected to function, asphalt cement has characteristics of both a viscous fluid and an elastic solid [1].

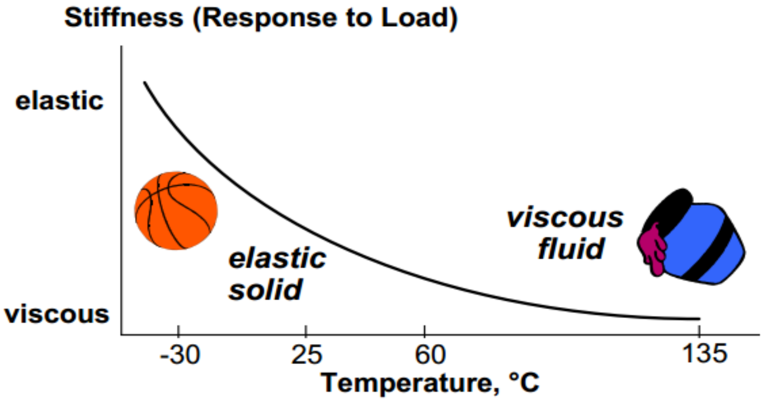


Figure 2-2: Visco-Elastic Behavior of Asphalt [1, 30]

1. High Temperature Behavior

At high temperatures (e.g., desert climate) or under sustained loads (e.g., slow moving trucks), asphalts cements act like viscous liquids and flow. This viscous behavior is characterized by its Viscosity, which is the material characteristic, used to describe the resistance of liquids to flow [30].

2. Low Temperature Behavior

In cold climates (e.g., winter days) or under rapid loading (e.g., fast moving trucks), asphalt cement behaves like an elastic solid. Elastic solids are like rubber bands; when loaded they deform, and when unloaded, they return to their original shape. If too much load is applied, elastic solids may break. Even though asphalt is an elastic solid at low temperatures, it may become too brittle and crack when excessively loaded. This is the reason low temperature cracking sometimes occurs in asphalt pavements during cold weather. In these cases, loads are applied by internal stresses that accumulate in the pavement when it tries to shrink and is restrained [30].

3. Intermediate Temperature Behavior

Most environmental conditions lie between the extreme hot and cold situations. In these climates, asphalt binders exhibit the characteristics of both viscous liquids and elastic solids. Because of this range of behavior, asphalt is an excellent adhesive material to use in paving, but an extremely complicated material to understand and explain. When heated, asphalt acts as a lubricant, allowing the aggregate to be mixed, coated, and tightly-compacted to form a smooth, dense surface. After cooling, the asphalt acts as the glue to hold the aggregate together in a solid matrix. In this finished state, the behavior of the asphalt is termed viscoelastic; it has both elastic and viscous characteristics, depending on the temperature and rate of loading.

Conceptually, this kind of response to load can be related to an automobile shock absorbing system. These systems contain a spring and a liquid filled cylinder. The spring is elastic and returns the car to the original position after hitting a bump. The viscous liquid within the cylinder dampens the force of the spring and its reaction to the bump. Any force exerted on the car causes a parallel reaction in both the spring and the cylinder. In hot mix asphalt, the spring represents the immediate elastic response of both the asphalt and the aggregate. The cylinder symbolizes the slower, viscous reaction of the asphalt, particularly in warmer temperatures. Most of the response is elastic or visco-elastic, (recoverable with time), while some of the response is plastic and non-recoverable.

2.2.4 Visco-Elastic Characterization of Bitumen

The visco-elastic nature of asphalt binder varies with the variation in temperature which requires to be characterized with the best technology available. Visco-elastic means that it simultaneously shows the behavior of an elastic material (e.g. rubber band) and a viscous material (e.g. molasses). The relationship between these two properties is used to measure the ability of the binder to resist permanent deformation and fatigue cracking. To resist rutting, a binder needs to be stiff and elastic; to resist fatigue cracking, the binder needs to be flexible and elastic. The balance between these two needs is a critical one.

The Dynamic Shear Rheometer (DSR) is used to characterize the viscous and elastic behavior of asphalt binders. It does this by measuring the complex shear modulus (G*) and phase angle (δ) of asphalt binders. G* is a measure of the total resistance of a material to deforming when repeatedly sheared. Delta (δ) is an indicator of the relative amounts of recoverable and non-recoverable deformation. 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 below in figure 2-3.

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 2-3 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.

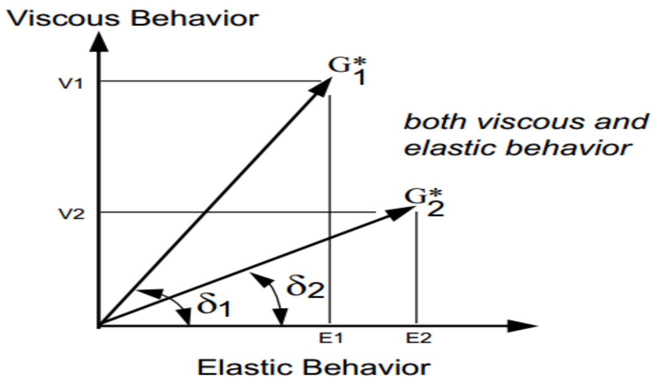


Figure 2-3: Viscous and Elastic Behavior [30]

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.

1. The working principle of DSR [28, 30]

The operation principle of the DSR is straightforward. An asphalt sample is sandwiched between an oscillating spindle and the fixed base. As shown in figure 2-4 below the oscillating plate (often called a "spindle") starts at point A and moves to point B. From point B the oscillating plate moves back, passing point A on the way to point C. From point C the plate moves back to point A. This movement, from A to B to C and back to A comprises one cycle.

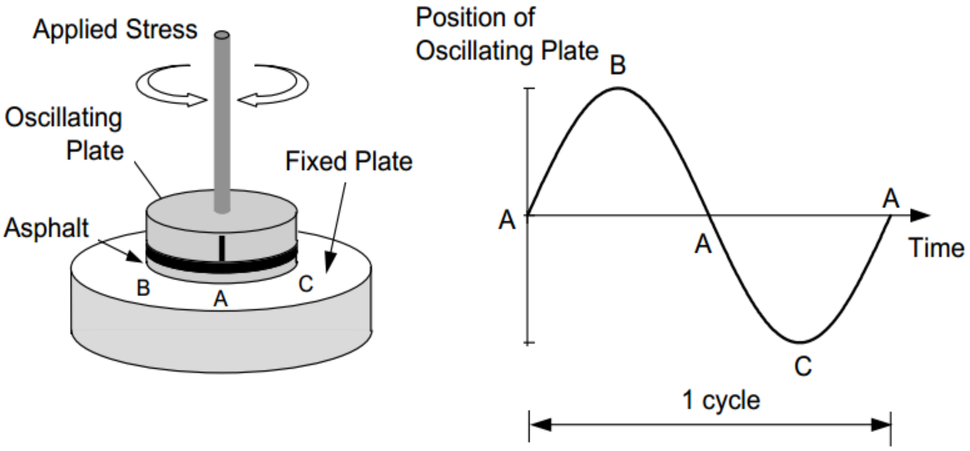


Figure 2-4: Dynamic Shear Rheometer Geometry [30]

Based on the geometry and the applied torque, the formulas used by the rheometer software to calculate τ_{max} and Υ_{max} are:

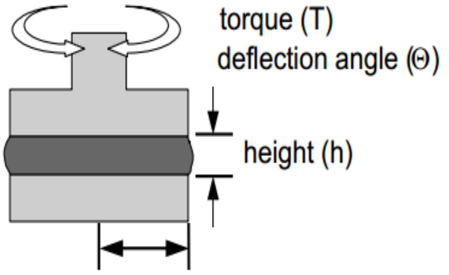


Figure 2-5: DSR Geometric Parameters

$\tau_{max} = 2T/\pi r^3$

$\Upsilon_{max} = \Theta r/h$

Where, T = maximum applied torque

Θ = deflection (rotation) angle

r = radius of specimen or plate (12.5 or 4mm)

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.

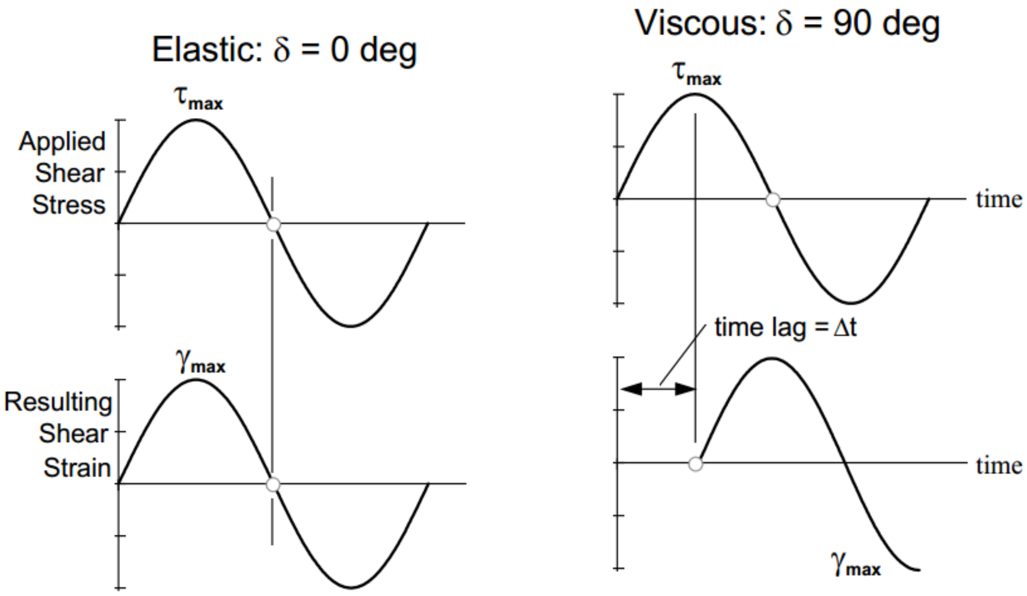


Figure 2-6: Stress-Strain Output for a Constant Stress Rheometer [30]

The relationship between the applied stress and the resulting strain in the DSR quantifies both types of behavior, and provides information necessary to calculate two important asphalt binder properties: the complex shear modulus (G*) and phase angle (δ).

G* is the ratio of maximum shear stress (τ max) to maximum shear strain (γ max). 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, as shown below.

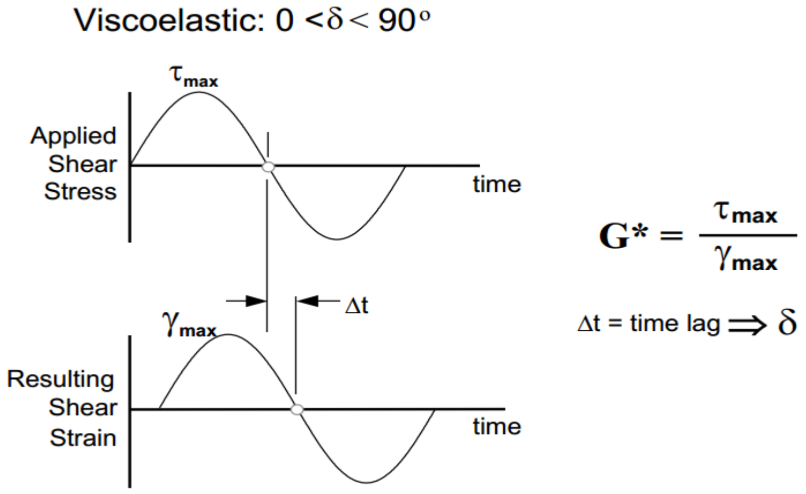
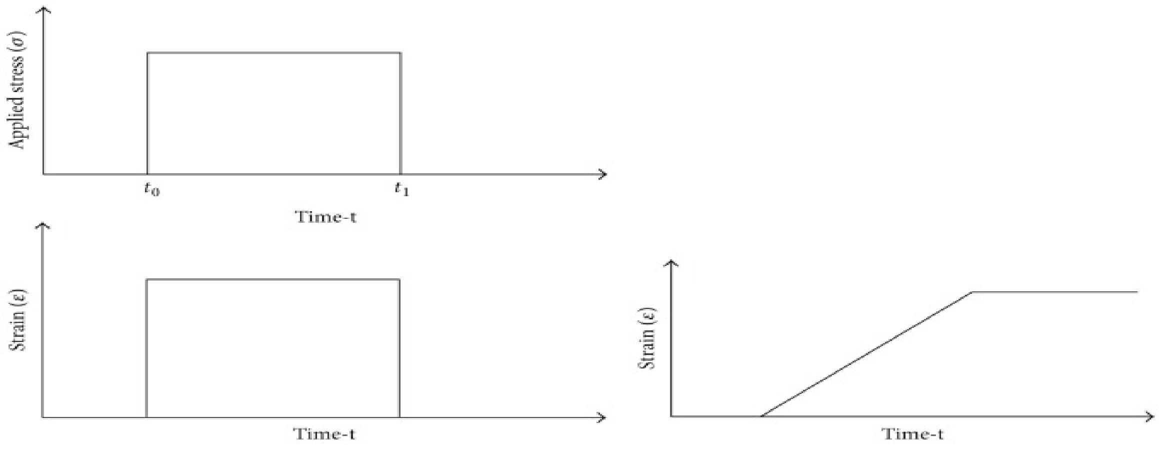


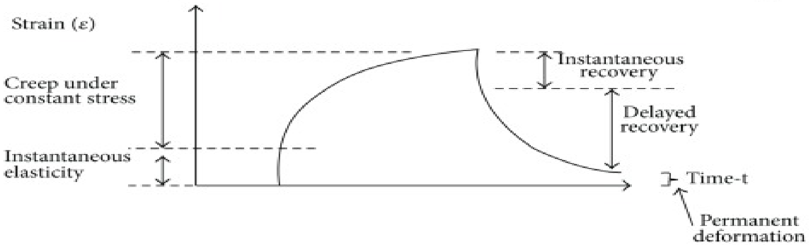
Figure 2-7: Stress-Strain Response of a Viscoelastic Material [30]

Now the question is how this property would be connected with rutting or permanent deformation. When we consider a single loading phenomenon with specific stress, loading time and temperature then the resulting deformation will remain partially unrecovered as shown in figure 2-8 below.



(a) Elastic response

(b) Viscous response



(c) Viscoelastic response

Figure 2-8: Visco-Elastic Material under Specific Loading Condition [17]

It is therefore the accumulation of all the unrecovered deformation due to number of loads that will be finally expressed as rutting.

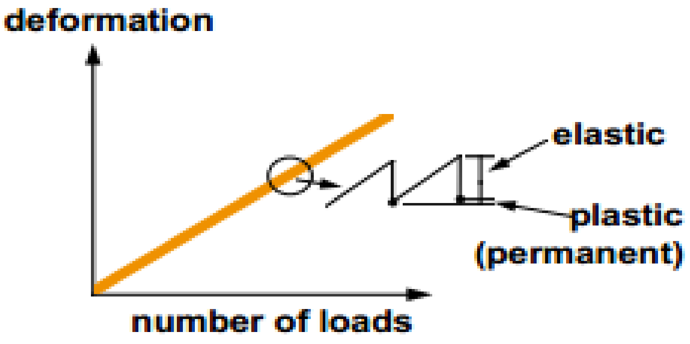


Figure 2-9: Deformation Due to Number of Loads

2.3 Bitumen Ageing

Aging is the change in structures and composition of asphalt molecules that results hardening and embrittlement of binders during construction and service life of pavements.

There are two mechanisms of aging, irreversible and reversible. The main one, irreversible aging is characterized by chemical changes due to loss of volatiles and oxidation [40]. The reaction of asphalt molecules with oxygen from the environment known as oxidation causes a more brittle structure and that is the origin of the terms "oxidative hardening" or "age hardening". The other irreversible form of hardening which occurs during hot mixing and construction is called "volatilization." At high temperatures, volatile components evaporate from the asphalt. These light, oil-like components, if allowed to remain, would otherwise soften the asphalt.

The reversible phenomenon called "physical hardening" occurs when asphalt cement is exposed to low temperatures for long periods. As the temperature falls, asphalt shrinks in volume and there is an accompanying increase in asphalt hardness. Physical hardening is more pronounced at temperatures less than 0^{o}C and must be considered when testing asphalt cements at very low temperatures [30].

There are two distinct phases of aging, short-term aging during the construction phase of an asphalt pavement and long-term aging during the service life. Short-term aging begins at the mixing plant and ends when the compacted pavement has cooled; long-term aging proceeds thereafter [36].

To simulate or test aging, several methods are employed. For the age hardening occurring during plant mixing and lay-down the most utilized test is Rolling Thin Film Oven Test (RTFOT, AASHTO T 240 & ASTM D-2872). And to simulate long-term ageing during service the Pressure Ageing Test (PAV, AASHTO PP1) was adopted in SHRP binder specifications [36, 38].

One of the roles of aging tests is to evaluate susceptibility of a mixture for aging at its initial condition and the likely performance in aged condition. The second significant role is to enable specimens to be prepared for the accelerated performance tests (fatigue, rutting, and thermal cracking), Moreover it is very important for specification preparation of binders [36].

The risk of rutting due to aging can be evaluated in different ways. According to SHRP specifications [19, 30] the ratio G*/sinδ at 1.6 Hz presents the impact of the module with the phase shift value. SHRP specifications set indirectly and by means of the temperature, a minimum value is 1 KPa report before RTFOT and a value of 2.2 KPa after RTFOT. The higher Temperature aging indices (TAI) was proposed to indicate the effect of RTFO aging in rheological properties with respect to un-aged condition at high temperatures [41]. The indices use the measured rutting parameters at high in-service temperatures as ratio of G*/sinδ (RTFO) to G*/sinδ (Org).

The index values show that when the temperature of aging increases, the rutting resistance is better [37].

2.4 Bitumen Modification

Conventional bitumen has a limited range of rheological properties and durability that are not sufficient to resist pavement distresses. Therefore, to minimize the damage of pavement surface and improve durability of flexible pavement, the conventional bitumen needs to be improved in regards with performance related properties, such as resistance to permanent deformation (rutting) and fatigue cracking.

In general some of the reasons of modification can be listed as follows;

- ✓ Extend the range of temperatures
- ✓ Longer lasting pavements
- ✓ Cheaper pavement (in the long run)
- ✓ Reduce moisture damage in mixes
- ✓ Stick chips better and faster
- ✓ Address construction issues and many others

Benefits that may be derived from binder modification include [47]:

- ✓ Improved consistency
- ✓ Reduced temperature susceptibility
- ✓ Improved stiffness and cohesion
- ✓ Improved flexibility, resilience and toughness
- ✓ Improved binder-aggregate adhesion
- ✓ Improved resistance to in-service ageing

From many different the most commonly used modifiers are [47]:

- ✓ Styrene Butadiene Styrene (SBS) pellets or powder;
- ✓ Ethylene Vinyl Acetate (EVA) pellets
- ✓ Rubber crumb modifier
- ✓ Styrene Butadiene Rubber latex
- ✓ Natural hydrocarbon modifier
- ✓ F-T synthetic waxes.

Some of the limitations or disadvantages of modifiers are;

- ✓ Lack of composition standards
- ✓ Lack of established performance criteria
- ✓ Necessity for quality control
- ✓ Usage restrictions
- ✓ Application precautions
- ✓ Limited service experience

Currently, the most commonly used polymer for bitumen modification is the styrene–butadiene–styrene (SBS) followed by other polymers such as styrene butadiene rubber (SBR), ethylene vinyl acetate (EVA) and polyethylene.

SBS block copolymers are classified as elastomers that increase the elasticity of bitumen and they are probably the most appropriate polymers for bitumen modification. SBS copolymers derive their strength and elasticity from physical and cross linking of the molecules into a three dimensional network. The polystyrene end blocks impart the strength to the polymer while the polybutadiene rubbery matrix blocks give the material its exceptional viscosity. When SBS is blended with bitumen, the elastomeric phase of the SBS copolymer absorbs the oil fractions from the bitumen and swells up to nine times as much as its initial volume. At suitable SBS concentration, a continuous polymer phase is formed throughout the polymer modified bitumen (PMB) and significantly modifies the base bitumen properties.

EVA based polymers are classified as plastomer that modify bitumen by forming a tough, rigid, three-dimensional network to resist deformation. Their characteristics lie between those of low density polyethylene, semi-rigid, translucent product and those of a transparent and rubbery material similar to plasticized polyvinyl chloride (PVC) and certain types of rubbers. This type of polymers have revealed as good modifiers which improve permanent deformation and thermal cracking.

Polymers are usually provided in the form of pellets or powder which can be subsequently diluted to the required polymer content by blending with base bitumen by using low to high shear mixer. Blending pellets with base bitumen results in a special polymer concentration suitable for different applications. In spite of the significant research which has been carried out related to the SBS and EVA modified PMBs in road applications, more studies have to be undertaken on the compatibility and in the interaction between the SBS, EVA polymer and the base bitumen [52].

2.5 Crumb Rubber Modifier (CRM)

Crumb Rubber Modifier (CRM) technology is a general term to identify a group of concepts which incorporate scrap tire rubber into asphalt paving materials [12]. This technology was first introduced in the late 1960’s as a surface treatment such as crack sealing and chip seals. Then after McDonald found that he could use it to improve the properties of asphalt binder. Crumb rubber modified asphalt was first introduced in asphalt pavements in the 1980’s and is especially used in gap and open graded mixes. The use of crumb rubber in asphalt pavement improved the mechanical properties of pavements, resistance to cracking and rutting as well as the reduction of environmental issues such as noise, energy consumption and CO_2 emissions.

Some of the commonly used grinding methods to produce crumb rubber are listed and described in Table 2-2 below.

Table 2-2: Grinding Methods for Scrap Tires [20].

Name	**Method**	**Size (mm)**	**Other Characteristics**
Cracker mill	Most commonly used method. Grinding is controlled by the spacing and speeds of the drums. The rubber particles are reduced by tearing as it moves through a rotating corrugated steel drum.	5-0.5	High surface area. Irregular shapes. Usually done at ambient temperatures.
Granulator	Uses revolving steel plates to shred the tire particles	9.5-0.5	Cubical particles. Low surface area.
Micro mill	Water is mixed with crumb rubber to form a slurry which is then forced through an abrasive disk	0.5-0.075	Reduces particle size beyond that of a granulator or cracker mill.
Cryogenic	Liquid nitrogen is used to increase the brittleness of the crumb rubber. Once frozen it can be ground to desired size	0.6-0.05	Hammer mills and turbo mills are used to make different particle size.

The basic processes used to add the crumb rubber into an asphalt paving material can be divided into two categories, the wet process and dry process.

The wet process defines any method that adds the CRM to the asphalt cement to produce a modified binder product. The blend has to be uniform with a heating system capable of maintaining uniform and constant reaction temperature (typically 175 to 200 ^{O}C) without generating hot spots which can burn the modified binder. The reaction time can be achieved from 45 minutes to 1 hour and then after the modified binder is ready for use.

The dry process defines any method of adding CRM directly into the hot mix asphalt mix process, typically pre-blending the CRM with the heated aggregate prior to charging the mix with asphalt. This process is normally used when a rubber aggregate product is desired. The aggregate and CRM are "dry" blended for approximately 15 seconds before the asphalt cement is added to the batch. The entire batch is then mixed to obtain a uniformly coated mixture prior to discharge.

Advantages of Crumb Rubber Modified Bitumen (CRMB) [43];

- ✓ Lower susceptibility to daily & seasonal temperature variations,
- ✓ Higher resistance to deformation at elevated pavement temperature
- ✓ Better age resistance properties,
- ✓ Higher fatigue life of mixes,
- ✓ Better adhesion between aggregate & binder, Prevention of cracking & reflective cracking, and
- ✓ Overall improved performance in extreme climatic conditions & under heavy traffic condition.

Despite the proven advantages, there is no significant implementation of rubber modified hot mix asphalts because of the following reasons (disadvantages):

- ✓ The tedious wet process involving very high temperature (over 190°C) and long blending and reaction time (45 min. up to 1hr).
- ✓ The complexity and cost of the blending unit that must be installed in every asphalt mixing plant.
- ✓ The necessity to re-heat the hot asphalt rubber binder after longer rest periods.
- ✓ The high cost of the Asphalt Rubber paving mixes as compared to conventional HMAs (ranges between 20-100% higher prices).

To overcome the main disadvantages of AR technology one solution newly found is the "Reacted and Activated Rubber" (RAR) [29].

2.6 Reacted and Activated Rubber (RAR)

Reacted and Activated Rubber (RAR) is an elastomeric asphalt extender that modifies the plain bitumen by increasing its PG grading, resilience, and recovery properties. Different types of HMA produced with RAR showed much better Stability, Rutting and Fatigue resistance under attractive cost/benefit conditions [29]. RAR, industrially known as RuBind is composed of plain soft bitumen, fine crumb rubber, and an Activated Mineral Binder Stabilizer (AMBS) at optimized proportions. RAR is produced by a short-time hot blending and activation in a specially designed process to form a dried granulated activated rubber.

Asphalt cements or bitumen graded as Pen 100-200 to Pen 35/50, or AC 20, or PG 52 to PG 70, are used. The use of the softer bitumen enable to produce HMAs at common mixing and laying temperatures without losing the proper workability, despite the addition of the crumb rubber.

Crumb Rubber is usually scrap tires that are processed and finely ground by any proven industrial method. The scrap tires consist of combination of automobile tires and truck tires, and should be free of steel, fabric or fibers before grinding. For production of RAR, the crumb rubber particles should be finer than 1.0 mm. A #30 mesh maximum particle size is preferred.

The Activated Mineral Binder Stabilizer (AMBS) is a new micro-scale binder stabilizer that was developed to prevent excessive drainage of the bitumen in SMA mixes during mix haulage, storage and laying. This stabilizer (industrially known as "iBind") is an activated micro-ground raw silica mineral (40 µm and finer), which is a waste by-product of Phosphate Industries mining. The activation was aimed at obtaining Shear-Thinning and improve other properties for the bitumen, since the mastic in the mix should possess high viscosity at rest (haulage, storage and after laying) - for reducing drain-down, and low viscosity in motion (mixing and laying) - for maintaining the proper workability.

Tests on Superpave mixes have shown that by replacing part of the bitumen binder with the AMBS stabilizer (up to 15%), improvement of mix properties (fatigue, rutting and water damage resistance) was obtained. In this application it was found that the AMBS bitumen stabilizer also promotes the structural capacity of the binder and the HMA. In addition to the engineering advantages, an analysis of the environmental benefits was performed. Generally, the comparison of the environmental indicators analyzed, clearly demonstrate a quantitative decline in the negative environmental indicators, as well as, the economic cost per ton SMA mix, when using AMBS as compared to cellulose fibers in SMA or regular dense and Superpave mixes [29].

Figure 2-10: a) Soft Asphalt b) Fine Crumb Rubber c) AMBS [29]

2.7 Rheological Data Presentation

Data obtained from DSR (rheological data) can be represented in different forms to analyze the rheological properties of a binder in different ways.

1. Isochronal Plot

Isochronal Plot is a curve representing the behavior of visco-elastic function at a constant frequency. Curves of complex modulus or phase angle versus temperature at constant frequency are isochrones [33, 34]. Isochronal plot helps to compare complex modulus or phase angle at different temperatures and also to evaluate other properties like temperature susceptibility [9].

2. Isothermal Plot

Isothermal plot can be defined as a curve or an equation representing the behavior of visco-elastic function at a constant temperature. Curves of complex modulus or phase angle versus frequency at a constant temperature are isotherms [34]. The plot helps to compare different visco-elastic properties mainly G* & δ at unvarying temperature but at a range of frequency. i.e., it uses to study time dependency of a material [9].

3. Black space Diagram

This can be described as a graph of log complex modulus [33] plotted as a function of phase angles. The diagram is useful to plot the two important rheological parameters (G* & δ) in a single curve without referring frequencies and temperatures [35]. The decrease in complex shear modulus (G*) with the increase in phase angle δ depends on the binder types. This implies that black diagram depicts whether the binder is modified or conventional [17]. Also it is important to evaluate the quality of test data [15, 32].

4. Master Curves

Master curves are constructed using the principle of time temperature superposition because of the relationship between temperatures and frequencies (times of loading) [15].

From the data collected over a range of temperatures and frequencies we can have several rheological graphs. To represent those graphs with one master curve a standard reference temperature must be selected. Then, the data at all other temperatures are shifted relative to this reference temperature and at a reduced frequency until a smooth curve is generated. The master curves of the complex modulus, storage modulus, loss modulus and phase angle with the change in frequency can be constructed in this manner [32]. And this master curve is useful to obtain interpolated values of property of any combination of temperature (T) or frequency inside the range covered by the measurement. Master curves allow the rheological data to be presented over a wide range of frequencies and temperatures in one plot. Therefore, to avoid presenting a large number of graphs, the results are mainly presented and analyzed as master curves [9].

2.8 Summary

Rutting is one of the major pavement distresses in our country. Shear failure rutting occurs due to poor quality of aggregate, filler, binder and/or weak mix. From those factors the effect of binder is significant at high temperature. To minimize rutting it is important to improve rheological properties of binder. Binder modification with rubber is used as one of the methods to improve visco-elastic properties. The new modifier Reacted and Activated Rubber (RAR) is chosen for this study. Rheological data presentation methods such as isothermal plots, black space diagram and master curves are very vital to evaluate viscoelastic properties of both modified and unmodified binders.

CHAPTER 3 METHODOLOGY AND EXPERIMENTAL WORKS

3.1 Introduction

This chapter provides information on the research method and procedure of this thesis. The research methodology applied for this study is experimental. According to statement of the problem and thesis objectives stated, it is necessary to conduct different experiments which allow arriving at a reasonable conclusion as a result of virgin binder treatment using partial replacement with Reacted and Activated Rubber modifier. Therefore the research design or simply the experimental method describes the types of materials to be tested, sample preparation, types of tests, test procedures and related things under this chapter. As per the objective the evaluation is related to visco-elastic property and thus the appropriate tests selected for this purpose are AST, FST, MSCR and PG determination.

Amplitude sweep is chosen since it is an oscillatory shear test helpful to delineate the region between linear visco-elastic range and non-linear visco-elastic range of a binder. The linear visco elastic range is the region with linear shear stress-strain relation that means the complex shear modulus is constant within this range that makes it easier to interpret. But the non linear portion is the difficult part to talk about. The laboratory produced samples are newly modified binders and therefore to carry out further fundamental tests with in the linear visco-elastic region of the modified binder it is first mandatory to know the visco-elastic range of the unknown binder by conducting amplitude sweep test.

The selection of Frequency sweep test is based on its advantage to evaluate the rheological properly of a binder in terms of basic rheological parameters such as shear modulus (G*) and phase angle (δ). Where, rheology refers to the property of deformation and flow of a binder under different loading conditions. The outputs from frequency sweep test helps to develop modulus master curves and phase angle master curves so as to interpret rheological properties as frequency, temperature and percent of modifier varies. In common terms, using this test we can evaluate loading time dependency of a binder, i.e. effect due to slow moving (sustained load) and fast moving traffic at different climatic condition.

Performance Grade (PG) determination, current superpave binder specification system in developed countries is preferred based on the advantages over limitations of other methods as described in table 3-1 below.

Table 3-1: Prior Limitations vs. Superpave Testing and Specification Features [20].

Limitations of Penetration, AC and AR Grading System	**Superpave Binder Testing and Specification Features That Address Prior Limitations**
Penetration and ductility tests are empirical and not directly related to HMA pavement performance	The physical properties measured are directly related to field performance by engineering principles.
Tests are conducted at one standard temperature without regard to the climate in which the asphalt binder will be used.	Test criteria remain constant, however, the temperature at which the criteria must be met changes in consideration of the binder grade selected for the prevalent climatic conditions.
The range of pavement temperatures at any one site is not adequately covered. For example, there is no test method for asphalt binder stiffness at low temperatures to control thermal cracking.	The entire range of pavement temperatures experienced at a particular site is covered.
Test methods only consider short-term asphalt binder aging (thin film oven test) although long-term aging is a significant factor in fatigue cracking and low temperature cracking.	Three critical binder ages are simulated and tested: 1. Original asphalt binder prior to mixing with aggregate. 2. Aged asphalt binder after HMA production and construction. 3. Long-term aged binder.
Asphalt binders can have significantly different characteristics within the same grading category.	Grading is more precise and there is less overlap between grades.
Modified asphalt binders are not suited for these grading systems.	Tests and specifications are intended for asphalt "binders" to include both modified and unmodified asphalt cements.

Multiple stress and creep recovery test is a latest method and extraordinary for some reasons, one it is the test which best predicts rutting at binder level and gives good information about binder elastic recovery. Second helps to make a better PG classification than the current superpave PG specification system.

3.2 Materials

The materials prepared for different experimental works are four in type. These are unmodified 80/100 penetration grade bitumen which is the base material, bitumen modified with 15% RuBind, bitumen modified with 20% RuBind, and bitumen modified with 25% RuBind.

3.2.1 Control Material

The base or control material is unmodified bitumen selected for modification considering the commonly used types of penetration grade bitumen in Ethiopia. According to table 8.3 of the ERA manual pavement design volume-I [51], three penetration grades of bitumen and their respective requirements is described. From those the bitumen with penetration grade 80/100, which is the softer or less stiff when compared to the others listed in the table, has been selected as a control material for this study.

In view of the objective of the study, the softer bitumen is selected to evaluate its stiffness and resistance against rutting when blended with the described modifier.

For the control material described above, both conventional and fundamental tests have been conducted. Conventional tests like penetration, ductility and softening point were carried out to check the conformity of the penetration grade of the unmodified bitumen. Also RTFOT was carried out both for conformity check and to condition the sample for further fundamental DSR tests. Finally the unmodified bitumen undergoes different DSR tests to evaluate the rheological properties.

Table 3-2: Requirements for Penetration Grade Bitumen [51]

Test		**Test Method (ASTM)**	**Penetration Grade**		
			40/50	**60/70**	**80/100**
Based on Original Bitumen					
Penetration at 25^{o}c		D 5	40-50	60-70	80-100
Softening point (^{o}c)		D 36	49-59	46-56	42-51
Flash point (^{o}c)	Min	D 952	232	232	219
Solubility in trichloroethylene (%)	Min	D 2042	99	99	99
TFOT heating for 5h at 163 ^{o}c		D 1754			
a) Loss by mass (%)	Max		0.5	0.5	0.8
b) penetration (% of original)	Min	D 5	58	54	50
c) Ductility at 25 ^{o}c	Min	D 113		50	75

3.2.2 Modifier

As it is described well in the literature review part of this paper, the modifier is a new material which is Reacted and Activated Rubber (RAR) industrially and commercially known as RuBind. RAR is a new material innovated to solve the tedious wet process of producing Asphalt Rubber Binder, involving very high temperature and long blending and reaction time as a result this makes an asphalt rubber paving mix costly.

Reacted and activated rubber is a dried granulated material composed of soft asphalt cement (bitumen), fine crumb tire rubber, and an Activated Mineral Binder Stabilizer (iBind) in optimized proportions.

3.2.3 Laboratory Produced Materials

The laboratory produced materials or samples are modified binders produced by blending the base asphalt with different contents of Reacted and Activated Rubber. Investigations of different researchers' states that around 20 percent by weight of binder has 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 as shown in table below.

Table 3-3: Laboratory Produced Modified Samples

percent by weight	Mass of RAR/modifier (g)	Mass of neat Bitumen (g)	Total mass of binder (g)
15%	106.5	603.5	710.0
20%	111.5	446	557.5
25%	117.77	443.3	561.07

Neat bitumen was heated until it is sufficiently fluid. Then sufficient quantity of the heated bitumen and RAR has been mixed. Using a mechanical machine the blending process has been done by stirring at 600rpm for about 30minutes at an average temperature of 165 oc. In this process the difficulty was to keep the mix temperature constant. This has been done using a hot plate by trying to control the temperature fluctuation between 160 and 170 OC during the 30 minutes of mixing time. Homemade stirrer and container were used as shown in figure below.

Figure 3-1: Locally Reproduced Container and Stirrer

Figure 3-2: Mixing Lab Produced Specimen Using Mechanical Machine

3.3 Sample Preparation

3.3.1 Sample Preparation for Conventional Tests

The sample preparation for conventional tests has been done in accordance with the respective standards of test methods.

For penetration test the samples were heated until sufficiently fluid to pour. The heating process has been done for about 20-30 minutes by string manually to prevent local overheating and at the time the temperature was ranging from 110 to 140^{o}c. Then the fluid hot bitumen was poured to the sample containers. And the same hot bitumen at the same time was poured for ductility tests to ductility molds. The sample for softening point was heated for 25 to 40 minutes at a temperature from 120 - 135^{o}c.

This is done by carefully stirring to prevent local overheating and avoid of air bubbles. The sample finally poured to the specimen rings.

And to prepare for Short Term Aging, the asphalt binder sample was heated using a hot plate at a temperature ranging 110 to 105°C until it is completely fluid to pour. The hot sample then poured to RTFO bottles each 35 gm for short term ageing.

3.3.2 Sample Preparation for Fundamental Tests

Commonly there are two ways to prepare the sample:

1. Asphalt can be poured directly onto the spindle in the proper quantity to provide the appropriate thickness of material
2. A mold can be used to form the asphalt disk, then the asphalt is placed between the spindle and fixed plate of the DSR.

In the first method, experience is necessary to apply the proper amount of asphalt. There must not be too much or too little material. If there is too little, the test will be inaccurate. If there is too much, excess sample trimming will be required.

In the second method, asphalt is heated until fluid enough to pour. The heated asphalt is poured into a silicone mold and allowed to cool until solid enough to remove the asphalt from the mold. After removal from the mold, the asphalt disk is placed between the fixed plate and the oscillating spindle of the DSR. As before, excess asphalt beyond the edge of the spindle should be trimmed.

Regardless of the method used to prepare the sample, the final step in preparing the specimen is to slightly readjust the gap (move them closer together by 50 microns) between the spindle and lower plate so that a slight bulge is evident near the edge of the spindle. This step normally occurs immediately prior to testing [30].

For the purpose of this study the binder is heated until sufficiently fluid and poured to softening ring since there was no silicon mold. To make suitable for both 25mm of high temperature tests and for intermediate temperature 8mm plate the specimens were prepared as shown in figure below.

Figure 3-3: Specimen Prepared for DSR Test

In the case of 25mm test procedure one full softening ring mold specimen was used and to carry out using 8mm plate the same sample has been cut into three pieces and sometime four pieces as shown above in fig. 3.3 above.

3.4 Conventional Tests

1. Penetration Test

Penetration measures the consistency (hardness or softness) of asphalt binder. The standard test method for penetration of bituminous materials is described under ASTM D5 or AASHTO T 49. The penetration is determined by measuring the distance in tenths of millimeter that a standard needle vertically penetrates a sample of the material under a specified load at a specified temperature within a specific period of time. In normal condition 100g of loading at a temperature of 25°C and 5sec. of testing time is common. Higher values of penetration indicate softer consistency and the lower the value the harder the bitumen is. Penetration can also be used as indirect measure of viscosity by correlating using empirical formulation.

Figure 3-4: Penetrometer

2. Softening Point

Standard method of test for softening point (Ring and Ball Apparatus) is stated in ASTM D 36 or AASHTO T 53. To carry out the test two disks of specimens are prepared using shouldered brass rings. Then the rings (samples) loaded with a 3.5g steel ball at the center of each ring (sample) will be placed in an assembly and immersed in a beaker of water. The water initially at 5^{o}c will be heated at a controlled rate usually 5^{o}c per minute. Finally the softening point will be the mean of temperatures recorded when the two balls enveloped with soft bitumen touches the lower plate 25mm below the rings.

Softening point helps to classify bitumen, check uniformity and signify its tendency to flow at elevated temperature. Higher softening point indicates the lower temperature susceptibility and preferred in warm climates.

Figure 3-5: Softening Point Ring and Ball Apparatus

3. Ductility

According to ASTM D113 or AASHTO T 51, which describes the standard test method, the ductility of bituminous materials is measured by a distance in centimeters to which the standard briquette of bituminous sample can be stretched before the thread breaks when pulled apart at a specified speed and a specified temperature. If no special reason, the standard test temperature which will be maintained using water bath is 25°C (77°F) and the rate of pull to elongate the sample is 5cm per minute.

The ductility test measures the adhesive property of bitumen and its ability to stretch.

Figure 3-6: Ductilometer

4. Short Term Ageing (Conditioning)

The aging test conducted here is the short term one, which is a conditioning step that simulates construction aging of asphalt binders as rutting is more critical phenomenon at earlier service life. In most cases either Thin-Film Oven Test (TFOT) or Rolling Thin film Oven test (RTFOT) is used for binder aging. In this study RTFO has been preferably used since the test was developed as an improvement to the TFOT. In case of TFOT asphalt samples are placed in shallow pans and heated in an oven for 5hrs to accomplish simulated aging. The aging process was improved from TFOT to RTFO for the following reasons:

- ✓ Due to the rolling action, asphalt binder is continuously exposed to heat and air flow.
- ✓ Modifiers, if used, usually remain dispersed in the asphalt binder due to the rolling action.
- ✓ The duration of the test is of 85 minutes only rather than the 5 hours for the TFOT.

The rolling thin film oven consists of an oven chamber with a vertical circular carriage. Sample bottles rest in the carriage and the assembly rotates about the carriage center. A fan circulates air in the chamber. At the bottom of the rotation, an air jet blows hot air into the sample bottle.

Basic procedure of RTFO Ageing Test

The Rolling Thin-Film Oven test is conducted as per AASHTO T 240, which is the standard method of test for “Effect of Heat and Air on a Moving Film of Asphalt”.

Preheat the oven for a minimum of 2 hrs prior to testing in such a way that the oven will equilibrate at 163+/- 0.5^{o}c when fully loaded and the air is on. After preparation of the oven a 35 ±0.5 g of asphalt binder is poured in each bottle and placed in the carriage. Then setting the airflow at a rate of 4000 ml/min, the carriage will rotate at a rate of 15 rev/min. The samples are subjected to these conditions for 85 min. The conditions in the test are not exactly as found in the field but experience has shown that the amount of hardening in the RTFO test correlates reasonably well with that observed in a conventional batch mixer (Whiteoak, 1990).

The RTFO test helps to determine the change in mass as a mass percent of the original material. Most importantly physical and rheological changes will be evaluated by performing appropriate tests on the asphalt before and after moving film oven.

Figure 3-7: Rolling Thin Film Oven

3.5 Dynamic Shear Rhometer (DSR) Tests

Several fundamental and research based binder tests can be carried out using dynamic shear rheometer. From those different tests for the purpose of this study performance grade determinations, Amplitude sweep test, Frequency sweep test and the multiple stress creep recovery have been performed.

Basic Test Procedure

The Standard test method for determining the rheological properties of asphalt binder using dynamic shear rheometer is described in AASHTO T315-10.

First the asphalt binder is heated until it is sufficiently fluid to pour and to prepare the test specimens. 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 upon the type of asphalt binder being tested the test temperature, specimen size and plate diameter varies.

Using a specimen 0.04 inches (1 mm) thick and 1 inch (25 mm) in diameter, the unaged asphalt binder and RTFO residue are tested at the high temperature specification for a given performance grade (PG) binder. The measurement of a small phase angle (δ) is a result of these lower temperatures that make the specimen quite stiff. Hence, to have a measurable phase angle (δ) to be determined, a thicker sample (0.08 inches (2 mm)) with a smaller diameter (0.315 inches (8 mm)) is used. The DSR apparatus used is as shown in figure 3-8.

Figure 3-8: Dynamic Shear Rheometer Setup

For a sample 0.04 inches (1 mm) thick and 1 inch (25 mm) in diameter, test temperatures greater than 115°F (46°C) are used whereas for a sample 0.08 inches (2 mm) thick and 0.315 inches (8 mm) in diameter, test temperatures between 39°F and 104°F (4°C and 40°C) are used.

To suit the desired size of specimen the upper spindle is lowered until the gap between the plates equals the test gap plus 0.002 inches (0.05 mm). Due to the compression, excess material will come out which is then trimmed around the edge of the test plates using a heated trimming tool. The test plates further moved together to the selected testing gap by eliminating the additional 0.05 gap. This creates a slight bulge in the asphalt binder specimen's perimeter.

The test specimen is kept at near constant temperature by heating and cooling a surrounding environmental chamber. The test is started up only after the specimen has been at the desired temperature for at least 10 minutes. The instrument measures the maximum applied stress, the resulting maximum strain, and the time lag between them while the top plate oscillates in a sinusoidal waveform. The calculation of the complex modulus (G*) and phase angle (δ) is done automatically with the help of the software. Based on the material being tested (e.g., unaged binder, RTFO residue or PAV residue) the determination of a target torque at which to rotate the upper plate is carried out using the DSR software. To ensure that the measurements are within the specimen's region of linear behavior this torque is chosen. The range of the phase angle (δ), from about 50 to 90°, and while that of the complex modulus (G*), from about 0.07 to 0.87 psi (500 to 6000 Pa), are the typical values obtained from the DSR for asphalt binders. The complete viscous behavior is essentially the δ of 90°. The polymer-modified asphalt binders usually exhibit a higher G* and a lower δ value. Hence, it is meant that compared to the unmodified asphalt cements they turned out to be more elastic and a bit stiffer.

3.5.1 Performance Grade Determination

The Superpave is a binder specification and mix design procedure developed by Strategic Highway Research Program (SHRP). This binder specification system works based on climate at which the pavement is expected to serve by evaluating the contribution of the binder in resistance to permanent deformation, low temperature cracking and fatigue cracking in asphalt pavements.

According to the superpave, to carry out performance grade determination new set of tests of physical properties at a range of temperatures must be carried out. The performance grade (PG) of the binder is designated as PGxx-yy, where xx represents the average seven days maximum temperature and yy represents the minimum temperature. In this grading system, even though tests are to be conducted at different temperatures, requirements of Physical properties will remain the same.

Table 3-4: Set of Binder Tests According to Superpave

Description	**Test Type**	**Aging Condition**	**Test Temperature**
Construction	Rotational Viscometer	No aging	Very high
Rutting	DSR (25mm plate)	No aging	High
		RTFO aged	
Fatigue cracking	DSR (8mm plate)	PAV aged (after RTFO)	Intermediate
Thermal cracking	DTT & BBR	PAV aged (after RTFO)	Low

In view of the above and based on the objective of the study, the PG test is carried out at high temperature considering rutting only. Thus the types of samples were original binder and RTFO aged binder. And the test plates used were 25mm in diameter for a 1mm thickness of specimen. There were two basic reasons for why only high temperature tests. The first is because the objective of the study focuses on rutting. The second reason was the unavailability of pressure aging vessel (PAV) to carry out long term ageing for intermediate and low temperature tests.

3.5.2 Amplitude Sweep Test

Amplitude sweep is an oscillatory DSR test with variable stress or strain amplitude at constant frequency. The main or 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. In most cases log-log graph on the same scale is plotted as strain in the x-axis and shear modulus in the y-axis. The complex shear modulus G* versus strain plot was used to determine the linear visco-elastic (LVE) region.

Several options are there to determine the limit of the LVE range [7].

1. Automatic analysis using a software analysis program: After the user has defined the bandwidth of tolerance, a special analysis program determines the limiting value.
2. Visual or manual analysis:

   a) By simply observing the curve the limiting strain value (γ_L) can be taken at the point where the curve noticeably falls. To make this easier a straight line (analysis tangent) can be drawn along the level of the plateau value.

   b) From the data table considering the G* which does not deviate significantly from the plateau value in the LVE range, the corresponding strain can be taken as limiting value. During this process the bandwidth of the tolerated deviation has to be defined by the user as 1%, 5%, or 10% in most cases by considering the type of binder.

   This study has followed this manual analysis method and 5% was chosen as deviation tolerance. In this way all those values which are below 95% of the plateau value are considered to be outside the LVE range.

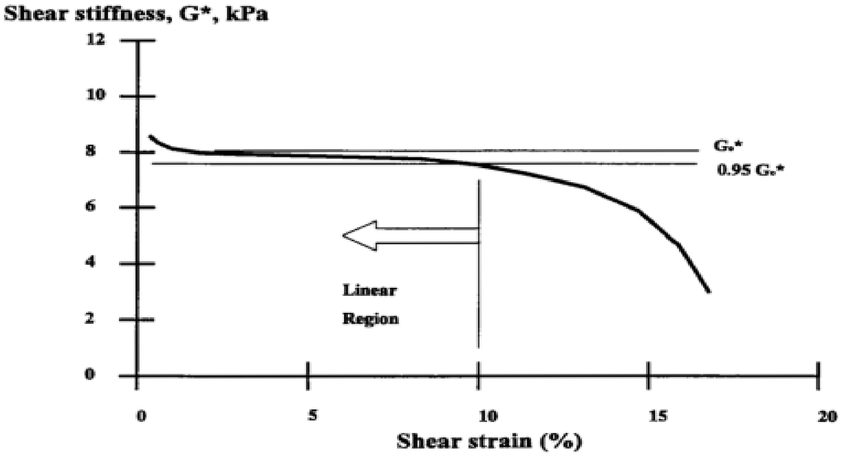


Figure 3-9: Amplitude Sweep to Determine Visco-Elastic Region (Airey) [50]

The amplitude sweep test was carried out following the test standard AASHTO T 315 at a constant frequency of 10rad/sec at specific test temperatures (21.1 ^{o}c, 37.8 ^{o}c & 54.4^{o}c). The test was in shear stress control mode with minimum shear stress 100pa and maximum shear stress 90000pa.

3.5.3 Frequency Sweep Test

Frequency sweep is also an oscillatory test with variable frequency and constant amplitude values. Using this test time dependent shear behavior can be examined. Short-term behavior is simulated by rapid movements (at high frequencies) and long term behaviors 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 controlled mode varying from 0.1Hz to 25 Hz. From the amplitude sweep test the limiting strain value was found to be 2%. Based on this result the strain input value taken for frequency sweep test was 1%, which was chosen to examine the binder well within linear visco-elastic range.

3.5.4 Multiple Stress Creep Recovery (MSCR) Test

The Multiple Stress Creep Recovery (MSCR) test is the latest improvement to the Superpave Performance Graded (PG) Asphalt Binder specification. This new test and specification listed as AASHTO T350 and AASHTO M332 provide the user with a new high temperature binder specification that more accurately indicates the rutting performance of the asphalt binder and is blind to binder modification. A major benefit of the new MSCR test is that it eliminates the need to run tests such as elastic recovery and phase angle procedures designed specifically to indicate polymer modification of asphalt binders. Several studies have shown that the $G^*/\sin(\delta)$ based specification does not correlate well with field performance [16].

The test protocol (AASHTO T350) requires that a 25-mm diameter and 1-mm thick asphalt specimen is subjected to 10 cycles of one second creep loading followed by 9 seconds rest period at stress levels of 100 Pa and 3200Pa at the high PG temperature using a DSR. In this way 20 cycles at the 0.1-kPa stress level followed by 10 cycles at the 3.2-kPa stress level for a total of 30 cycles will be done. The first 10 cycles at 0.1 kPa will be used for conditioning the specimen. There are no rest periods between creep and recovery cycles or changes in stress level. The total time required for completing the two-step creep and recovery test is 300s. the sample has to be residue from T 240 (Rolling Thin-Film Oven Test). From the test we can determine the following main parameters,

i. Non-recoverable creep compliance
ii. Percent difference between non-recoverable creep compliance
iii. Average percent recovery
iv. Percent difference in recovery
v. MSCR based new PG grade and test temperature

3.6 Test Temperature and Work Plan

To plan the work it is necessary to know the number of test repetitions considering the applicable standard test temperatures for this study.

1. Test temperature

Unlike conventional tests which are single temperature, according to superpave fundamental binder tests must be carried out at different temperatures. There are different standard test temperatures, which require determining and selecting the relevant and specific test temperatures considering the climate and the test type. Here we can consider two standards of test temperatures. One is as per the superpave binder specification, high test temperatures are 46 ^{o}c, 52 ^{o}c, 58 ^{o}c, 64 ^{o}c, 70 ^{o}c, 76 ^{o}c and 82 ^{o}c. There are also intermediate and low test temperatures. The second is the MEPDG standard test temperatures which mostly are used to conduct Amplitude Sweep and Frequency Sweep tests. The common temperatures in this case are 54.4^{o}c (130^{o}F), 37.8^{o}c (100^{o}F), 21.1^{o}c (70^{o}F), 4.4 ^{o}c (40^{o}F) and 10 ^{o}c (-10 ^{o}F).

For the purpose of this study from the above indicated high temperatures 52 ^{o}c, 58 ^{o}c, 64 ^{o}c, 70 ^{o}c, 76 ^{o}c and 82 ^{o}c are used for performance grade determination and for MSCR tests. Amplitude sweep and frequency sweep tests were carried out with 54.4^{o}c, 37.8^{o}c, and 21.1^{o}c test temperatures.

During selection of test temperatures we have to consider the climatic condition of the area in question and relate with test standards. This is because the high temperature performance grade of bitumen is given considering the maximum temperature of the area at which the bitumen is going to be used as a pavement material. And obviously it is possible to use this grade bitumen for pavements with lower design temperature as far as it is economical. But for higher temperature than the convenient grade and for high traffic volume the binder has to be modified and improved in its grade.

In case of our country, Ethiopia the high temperature area is Dallol with maximum air temperature 50 ^{o}c, and thus it is necessary to determine the pavement design temperature of this hottest area. This will help us to decide the maximum range of test temperature and to predict the type of high temperature binder that we are looking for.

The maximum pavement design temperature of Dallol was calculated as follows in accordance with SHRP-A-410.

$T_s = T_a + 0.00618\,\phi^2 + 0.2289\,\phi + 24.4$

Where,

Ts is pavement surface temperature (design Temperature)

Ta is average maximum air temperature

Φ is latitude

(Dallol has 50 °c maximum air temperatures and latitude is 14 °)

$T_s = T_a + 0.00618\,\phi^2 + 0.2289\,\phi + 24.4$

$= 50 + 0.00618(14)^2 + 0.2289(14) + 24.4 = 78.81$

Ts = 82 °c

Based on the above calculation, the maximum range of test temperature for this study would be 82°c, and this will help to evaluate the modified binder whether it qualifies to be used for pavements in hottest areas in Ethiopia like Dallol or not.

2. Work Plan

The work plan is organized taking minimum test replicates and minimum spectrum of test temperatures to minimize the lab work as much as possible.

Table 3-5: Work Plan

SN	**Description**			**Number of Tests**		
	sample Type	**Sample condition**	**Activity/Test**	**Test Replicate**	**Temperature Replicates**	**Number of Tests**
1	0% RAR	Un-aged	Conventional Tests			9
			PG determination	2	3	6
			AST @ 21.1, 37.8 & 54.4^{o}c	2	3	6
			FST @ 21.1, 37.8 & 54.4 ^{o}c	2	3	6
			RTFOT	2	1	2
		RTFO Aged	AST @ 21.1, 37.8 & 54.4 ^{o}c	2	3	6
			FST @ 21.1, 37.8 & 54.4 ^{o}c	2	3	6
			PG determination	3	3	9
			MSCR @ 21.1, 37.8 & 54.4 ^{o}c	2	3	6
			MSCR @ 52, 58 & 64 ^{o}c	2	3	6
2	15% RAR	Un-aged	AST @ 21.1, 37.8 & 54.4 ^{o}c	2	3	6
			FST @ 21.1, 37.8 & 54.4 ^{o}c	2	3	6
			PG determination	2	3	6
			RTFOT	1	1	1
		RTFO Aged	AST @ 21.1, 37.8 & 54.4 ^{o}c	2	3	6
			FST @ 21.1, 37.8 & 54.4 ^{o}c	2	3	6
			PG determination	2	3	6
			MSCR @ 21.1, 37.8 & 54.4 ^{o}c	2	3	6
			MSCR (high temp.)	2	3	6
3	20% RAR	Un-aged	AST @ 21.1, 37.8 & 54.4 ^{o}c	2	3	6
			FST @ 21.1, 37.8 & 54.4 ^{o}c	2	3	6
			PG determination	2	3	6
			RTFOT	2	3	6
		RTFO Aged	AST @ 21.1, 37.8 & 54.4 ^{o}c	2	3	6
			FST @ 21.1, 37.8 & 54.4 ^{o}c	2	3	6
			PG determination	2	3	6
			MSCR @ 21.1, 37.8 & 54.4^{o}c	2	3	6
			MSCR (high temp.)	2	3	6
4	25% RAR	Un-aged	AST @ 21.1, 37.8 & 54.4 ^{o}c	2	3	6
			FST @ 21.1, 37.8 & 54.4 ^{o}c	2	3	6
			PG determination	2	3	6
			RTFOT	1	1	1
		RTFO Aged	AST @ 21.1, 37.8 & 54.4 ^{o}c	2	3	6
			FST @ 21.1, 37.8 & 54.4 ^{o}c	2	3	6
			PG determination	2	3	6
			MSCR @ 21.1, 37.8 & 54.4 ^{o}c	2	3	6
			MSCR (high temp.)	2	3	6
					Total Number of Tests	**231**

The test repetition indicted in table 3-5 above represents the required number of tests for analysis. But what is actually carried out is by far more than that. There were a number of tests carried out to practice the test procedures and the equipment. Also repetitions of tests for inconvenient result and other reasons due to power interruption and personal mistakes were not included below in the table.

3.7 Summary

A unmodified 80/100 penetration grade bitumen was used as a control material and modified with 15%, 20% and 25% reacted and activated rubber by total mass of binder. The modified samples were prepared by mixing in lab at an average temperature of 165^{o}c for about 30 minutes with 600 rpm. The modified sample preparation was a bit difficult because of absence of standard stirrer and suitable heater.

The fundamental tests carried out were Amplitude Sweep, Frequency Sweep, Multiple Stress Creep Recovery and Performance Grade Determination. These tests were carried out for the first time in the lab of the school and the country as a whole.

CHAPTER 4 TEST RESULT AND ANALYSIS

4.1 Introduction

This chapter covers or presets matters related to experimental works. It starts with test parameter setup and trial tests. This part helped to acquire adequate experience on how to conduct the tests in a better way. Then for the types of tests and their basic procedures described in chapter three, the test results have been organized under this chapter. Furthermore the analysis is carried out and represented in tables and graphs so as to evaluate the binders eventually.

4.2 Test Parameter Setup

Some of the challenges in using the Dynamic Shear Rheometer (DSR) were related to test parameter setups. For this reason it was necessary to carry out several trail tests to check the suitability of different input parameters for different types of tests.

The focus of the setup was mainly on input parameters like to make it either stress controlled or strain controlled and second to limit the ranges of the values. There are ranges of values (such as stress, strain, frequency, temperature) to be chosen by the performer considering type of binder, type of test, test temperature, equipment and related things.

For instance in this study during trial experiments of amplitude sweep tests the variable stress inputs were from 10 to 60,000MPa. At low temperature (stiffer binder) the graph from this trial test was simply strait line with no significant decline, which makes it difficult to determine the limiting strain value. As a result it was necessary to increase the maximum stress value to 90,000MPa.

4.3 Conventional Test Results

The control material, 80/100 penetration neat bitumen selected for modification since it is softer was checked for its conformity by conducting conventional tests. And the test results are represented as follows.

Table 4-1: Summary of Convention Test Results

Type of Test	Test trial	Before RTFO			After RTFO		
		Sample 1	Sample 2	Final Result	Sample 1	Sample 2	Final Result
Penetration	Trial-1	99.00	98.00		80.00	77.00	
	Trial-2	102.00	98.00		77.00	82.00	
	Trial-3	97.00	94.00		75.00	79.00	
	Average	99.33	96.67	98	77.33	79.33	78
Ductility	Brucket-1	100+	100+		100+		
	Brucket-2	100+	100+		100+		
	Brucket-3	100+	100+		100+		
	Average	100+	100+	100+	100+		100+
Softening point	Ring-1	44.00	46.00				
	Ring-2	46.00	48.00				
	Average	45.00	47.00	46.00			
RTFO Loss by Mass (%)	Bottle-1				0.09%		
	Bottle-2				0.06%		
	Average				0.07%		0.07%

The conventional test result of the neat bitumen was checked for its conformity with its specification. As shown in table 4.2 below the binder qualifies to be modified and to be evaluated with further fundamental tests as a control material.

Table 4-2: Test Result Vs Specification Requirements of 80/100 Grade Bitumen

Test Type	Specification Requirements	Test Result
Penetration at 25 ^{o}c	80-100	98
Ductility at 25 ^{o}c	100 (Min)	100+
Softening point	42-51	46
After RTFO		
a) Loss by mass (%)	0.8 (Max)	0.07
b) penetration (% of original)	50 (Min)	80
c) Ductility at 25 ^{o}c	75 (Min)	100+

4.4 Amplitude Sweep Test (AST)

The amplitude sweep tests were carried out for each specimen with similar loading condition ranging from 100 Pa to 90000 Pa in a stress controlled mode at a constant frequency of 10rad/sec.

4.4.1 Amplitude Sweep Test Result

The test results are represented graphically in Appendix B 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 4-1 below shows the amplitude sweep test result for 20% modified binder.

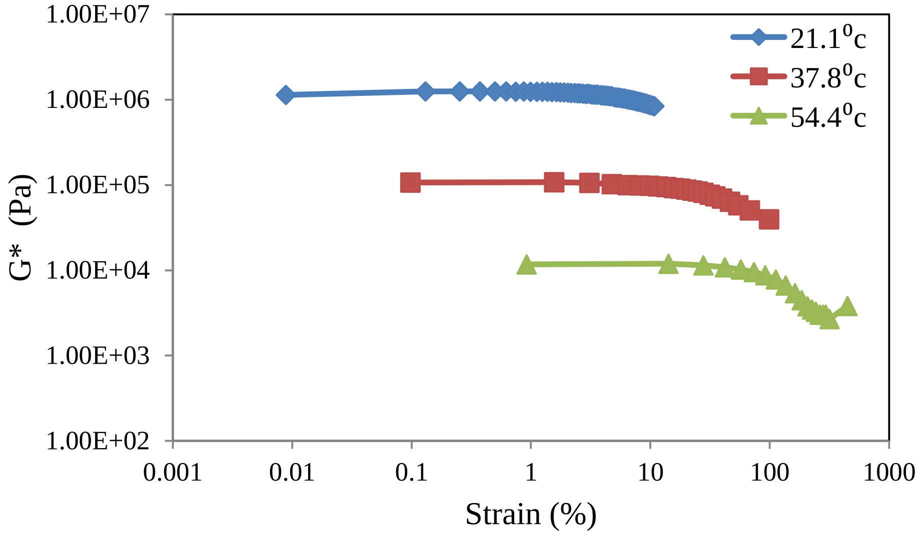


Figure 4-1: Linear Visco Elastic Range for 20% Modified Binder before RTFO

4.4.2 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 values are almost constant values of G* for different values of shear stress and shear strain before the graph declines as shown in figure 4-1 above. Finally for each and every curves of amplitude sweep results, a horizontal line along 0.95G* will be constructed to intersect the curve at a point. Then the corresponding strain value of that intersection point will be considered to be the limiting stain value (γ_L).

Table 4-3: Summary of Limiting Strain Values

Test Temp.(^{o}c)	Sample (RAR %)	Before RTFO			After RTFO		
		plateau G*	0.95G*	Limiting 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

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 temperature, content of modifier and aging.

Even though the sole purpose of amplitude sweep test is to determine the limiting strain value of unknown binder as tabulated above, the main effects observed are the following,

- ✓ At 21.1^{o}C temperature the limiting strain value for each sample is minimum and the effect of the modifier is not significant
- ✓ At 54.4^{o}C temperature higher limiting strain values are 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 several researchers conduct tests by taking strain value from 1% - 2% and according to this study the maximum 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 (54.4ºC) 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.

4.5 Performance Grade (PG) Determination

To determine the performance grades of the given samples, high temperature oscillatory DSR test was employed. According to the standard test procedure, AASHTO T 315, 12% strain for original and 10% strain for RTFO aged samples were used.

4.5.1 Results of Performance Grade (PG) Determination Test

Only high temperature results were organized since the PG grade determination has been conducted for high temperatures only. It is because the objective of the study was set by assessing available lab equipments to evaluate rubberized bitumen performance at high temperature. There is no pressure aging vessel, bending beam rheometer and direct tension testing equipments for low temperature binder characterization. Even though absence of the low temperature characterization has no effect on this study it was helpful to give the complete PG specification of the binders being evaluated.

The high temperature 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 tables below in table 4-4 and table 4-5 before and after RTFO respectively.

Table 4-4: Performance Grade Determination Test Result for Original Binder

Sample (% RAR)	**0**			**15**			**20**			**25**		
Test Temperature (^{o}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		

Table 4-5: Performance Grade Determination Test Result for RTFO Residue Binder

Sample (% RAR)	**0**			**15**			**20**			**25**		
Test Temperature (^{o}C)	52	58	64	52	58	64	64	70	76	70	76	82
Criteria G*/sin delta @10rad/sec. kPa	Min. 2.2kPa			Min. 2.2kPa			Min. 2.2kPa			Min. 2.2kPa		
Specimen -01 G*/sin delta @10rad/sec. kPa	7.67	2.97	1.24		3.13	1.52		3.55	1.96	3.71	2.16	
Specimen -02 G*/sin delta @10rad/sec. kPa	6.94	2.78	1.14		3.01	1.46		4.03	2.12	3.53	2.03	
Average G*/sin delta @10rad/sec. kPa	7.31	2.88	1.19		3.07	1.49		3.79	2.04	3.62	2.10	
Phase angle (Specimen -01). Deg	81.87	84.26	85.64		80.50	81.10		70.75	73.37	64.96	67.08	
Phase angle (Specimen -02). Deg	82.27	84.48	85.93		80.63	81.20		69.32	72.05	66.59	68.82	
Phase angle (Average). Deg	82.07	84.37	85.79		80.57	81.15		70.04	72.71	65.78	67.95	
Pass Fail Temp. (specimen -01). Deg	60.00			60.30			68.90			75.70		
Pass Fail Temp. (specimen -02). Deg	59.60			60.70			69.60			75.10		
Pass Fail Temp. (Average).Deg	59.80			60.50			69.25			75.40		
Temp Pass. Deg	58.00			58.00			64.00			70.00		

4.5.2 Analysis and Evaluation of PG Determination

Considering pass fail temperatures from table 4.4 and 4.5 above it is possible to determine the true grade (continuous performance grade) of the binders. The pass fail temperature is represented graphically for comparison purpose in figure 4-2 below. The high temperature continuous PG grade classification will be PG 59.8-xx, PG 60.5-xx, PG 69.25-xx & PG 75.4-xx for 0%, 15%, 20% and 25% modified binders respectively.

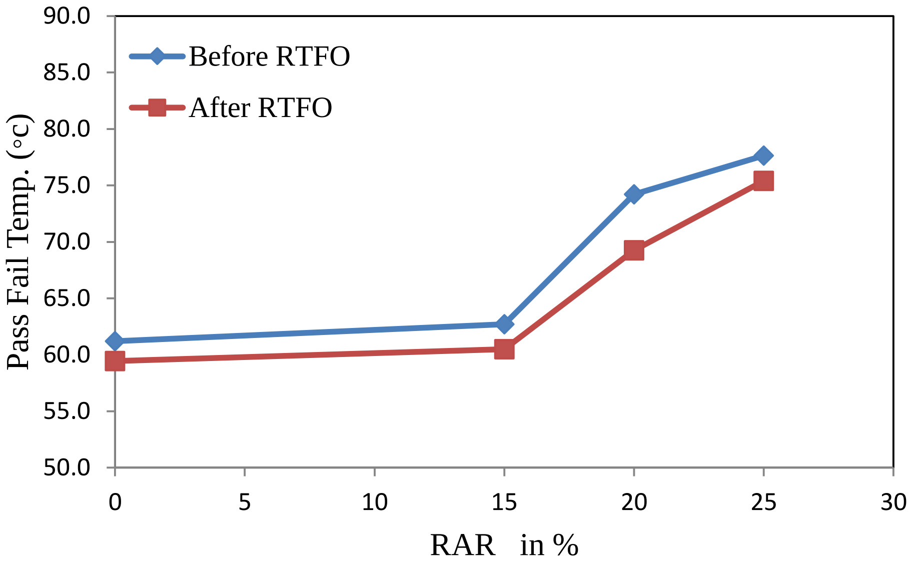


Figure 4-2: PG Pass Fail Temperature for Comparison

Table 4-6: 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

From the table above it is observed that there is a PG grade 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% then 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. Based on this it is possible to guess that the improvement in rutting performance was pronounced due to the modifier. But these days it is proven that the current performance grade stiffness parameter ($G^*/\sin\delta$) is weak in predicting rutting potential. Therefore it is better to further evaluate the modified binder by running Multiple Stress Creep Recovery (MSCR) tests since the parameter from this test termed as non-recoverable creep compliance best relates with rutting than any other parameter from binder test. The other important observation from the table is the PG (temperature pass) before and after RTFO for 20% and 25% modified binder which remains softer after ageing is an indication of not susceptible for hardening.

4.6 Frequency Sweep Test (FST)

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^{o}c, 37.8 ^{o}C, and 54.4 ^{o}C for all samples both aged and un-aged were determined and organized as stated below.

4.6.1 Frequency Sweep Test Result

The major rheological parameters determined from the FST tests are the complex shear modulus and the phase angle. These parameters were organized in two ways as:

1. Isothermal plots with log-log scale for complex shear modulus, and
2. Black space diagram in semi log graphs for phase angle

Based on these graphs or plots it is possible to make some rheological discussions, but it is essential to make the observation and discussion after developing master curves.

1. Isothermal plots

Using isothermal plots the complex shear modulus as a function of frequency for all binders were represented in Appendix C. See figure 4-3 below as a sample.

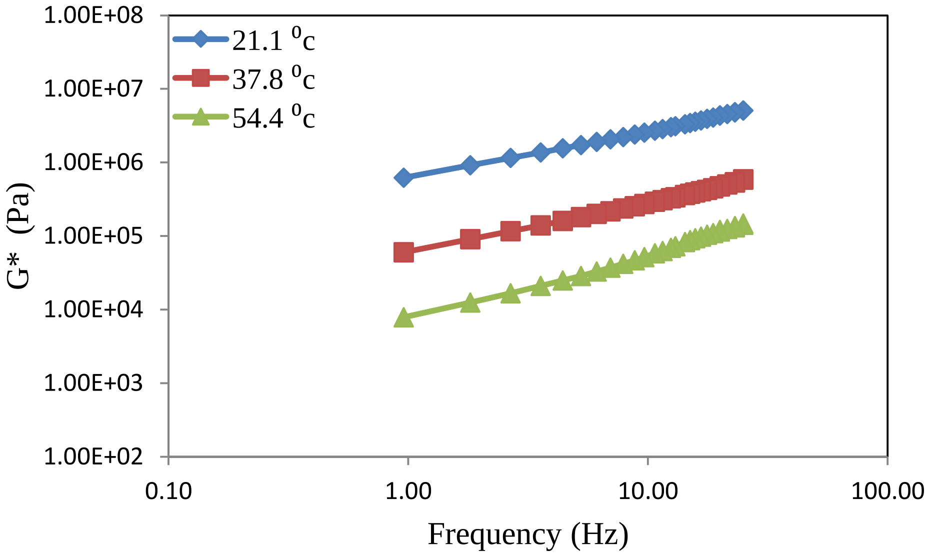


Figure 4-3: Isothermal Plots of 20% Modified Binder before RTFO

2. Black space diagram

The phase angle (δ) is represented with a black space diagram in a semi log scale as shown in Appendix D. Below is a sample diagram for 20% modified binder.

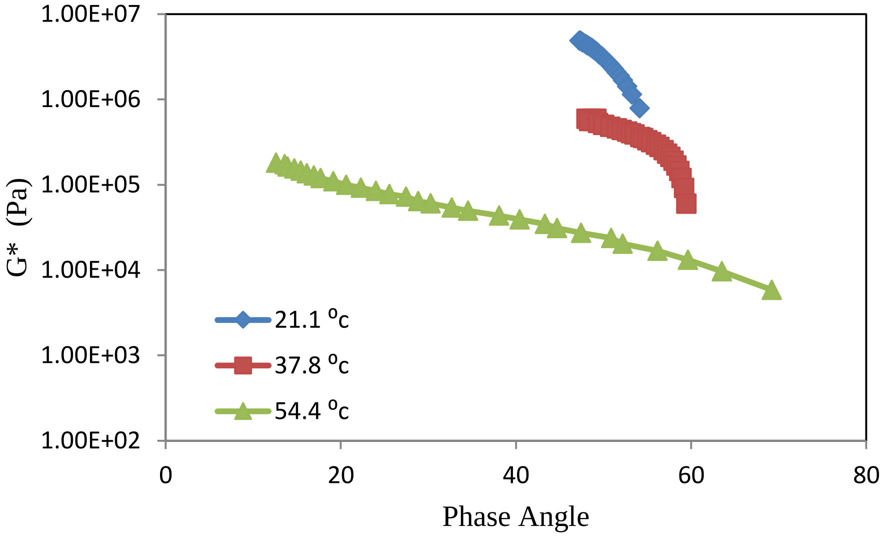


Figure 4-4: Black Space Diagram for 20% Modified Binder after RTFO

As explained more in section 4.6.6, it is difficult to obtain consistent output of phase angles (like for 54.4^{o}C above) when compared to shear modulus results.

4.6.2 Analysis and Evaluation of FST

1. Isothermal Plots

A brief discussion can be made by simply looking at the isothermal graphs considering temperature, complex shear modulus, frequency, ageing and content of modifiers.

- ✓ 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)

2. Black Space Diagram

The black space diagrams are helpful to evaluate the quality of the test data. In view of this the graphical data representation for all binders of this study has a good quality since the data of each graph was not dispersed.

4.6.3 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 to determine temperature shift factors and other constants at a specific reference temperature. Therefore further analysis is made to produce master curves for a better integrated and generalized evaluation of the binders as described below.

Modulus Master Curves were developed using Microsoft excel solver to best fit the sigmoid function for all asphalt binders. The sigmoid function to best fit the obtained G* data from the DSR is carried out with trial and error by changing the sigmoid constants and the shift factor. The sigmoid function to calculate the complex shear modulus is represented as;

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

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 in table 4-7.

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.

The shift factors included in table below were also obtained through the optimization process along with the sigmoid constants.

Table 4-7: 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
15%-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 4-5 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

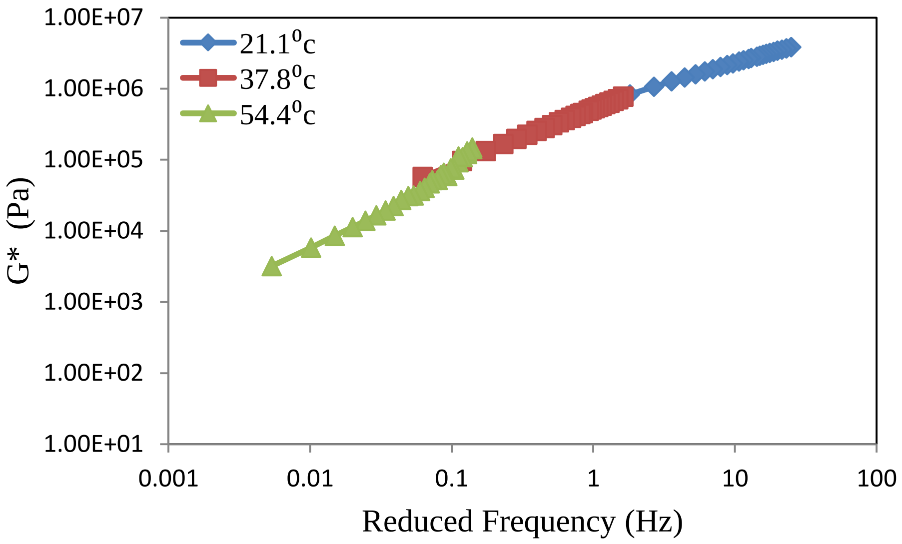


Figure 4-5: Temperature Shift @21.1ºc Ref. Tem. For 0% Modified After RTFO

Following the process above, finally modulus master curves were developed for both modified and unmodified binders before and after RTFO.

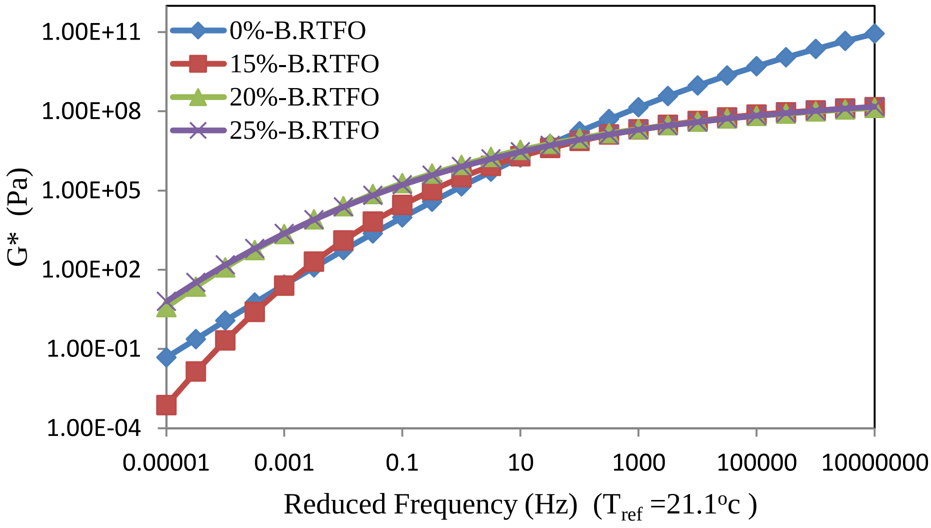


Figure 4-6: Shear Modulus Master Curve before RTFO

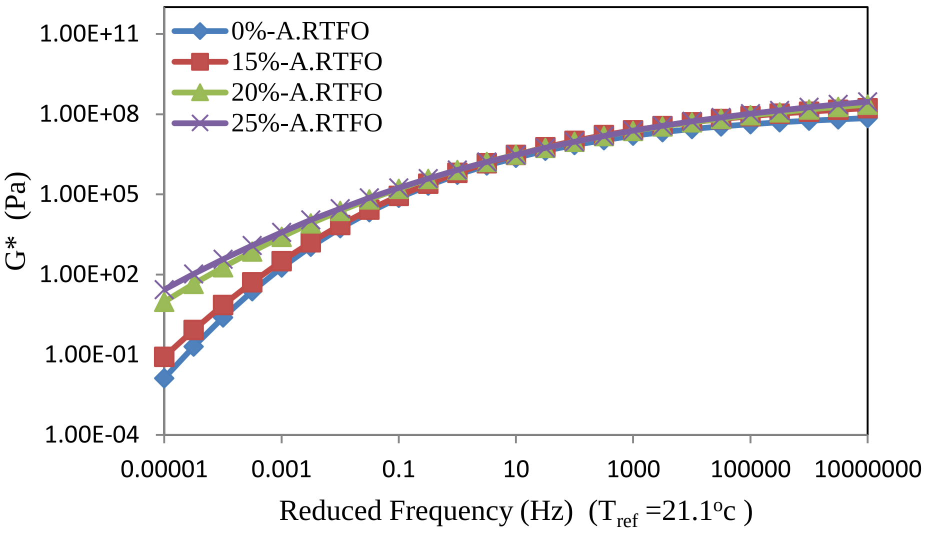


Figure 4-7: Shear Modulus Master Curve after RTFO

As observed above in figure 4-6 and 4-7 the main rheological parameter, complex shear modulus (G*) behaves in different ways as a result of temperature, frequency, content of modifier and ageing.

- ✓ For all binders in almost similar pattern shear stiffness decreases as temperature increases.
- ✓ At high temperature and low frequency the smaller value of shear modulus is 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 the modifier improves the pavement performance against this distress by increasing the stiffness of the binder.

4.6.4 Analysis of Variance (ANOVA)

ANOVA was performed taking values of the complex shear modulus (G*) obtained at selected values 0.01Hz, 1.0Hz, and 100Hz frequencies for the reference temperature of 21.1°C.

Table 4-8: Summary of ANOVA Result

Description	95% of Confidence Interval					
	0.01 Hz		1 Hz		100 Hz	
	F value	P value	F value	P value	F value	P value
0%, 15%,20% and 25% Before RTFO	10.57	0.023	17.38	0.009	0.21	0.885
0%, 15%,20% and 25% After RTFO	3.23	0.143	0.23	0.869	0.24	0.868

As tabulated above with significant level 0.05 the one way ANOVA of null hypothesis 'mean shear modulus is the same for all independent variable categories' shows different results of P values. The P value has increased as frequency increases. From this we can consider that the result is statistically significant at lower frequencies to reject the null hypothesis and insignificant at higher frequencies to accept the null hypothesis. Therefore the statistical analysis supports the previous conclusion which says the modifier improves the binder at low frequency and high temperature but not at high frequency and low temperature. This implies the modifier is better at maximum damaging effect of heavy traffic during high temperature with low speed of loading rate.

4.6.5 Phase Angle Master Curve

Following relatively similar procedure like what is done for modulus master curves and with a slightly different form of the generalized logistic function the binder phase angle master curves were developed as follows.

The sigmoid /logistic function was;

$$\delta = 90 * bd \ \frac{e^{(c+d(logf_r))}}{(1+e^{(c+d*logf_r)})^2}$$

Where:

b, c and d: Sigmoid function constants.

f_r: Reduced frequency.

δ: Phase angle

Table 4-9: Phase Angle Sigmoid Parameters and Temperature Shift Factors

	b	c	d	a21.1	a37.8	a54.4
0%-B.RTFO	3.287	0.501	1.021	0.000	-0.763	0.000
15%-B.RTFO	2.505	0.149	1.191	0.000	-0.714	0.000
20%-B.RTFO	2.227	-0.113	1.205	0.000	-0.548	0.000
25%-B.RTFO	2.333	-0.020	1.094	0.000	-0.539	0.000
0%-A.RTFO	2.624	0.012	1.234	0.000	-0.505	0.000
15%-A.RTFO	2.802	0.193	1.122	0.000	-0.624	0.000
20%-A.RTFO	2.671	0.024	0.991	0.000	-0.480	0.000
25%-A.RTFO	1.990	-0.299	1.215	0.000	-0.285	0.000

Using the excel solver the sigmoid function parameters were obtained and tabulated above in table 4-9 including the temperature shift factors. Then the phase angle master curves for all the binders before and after RTFO aging were produced as presented below in figure 4-9 and figure 4-10.

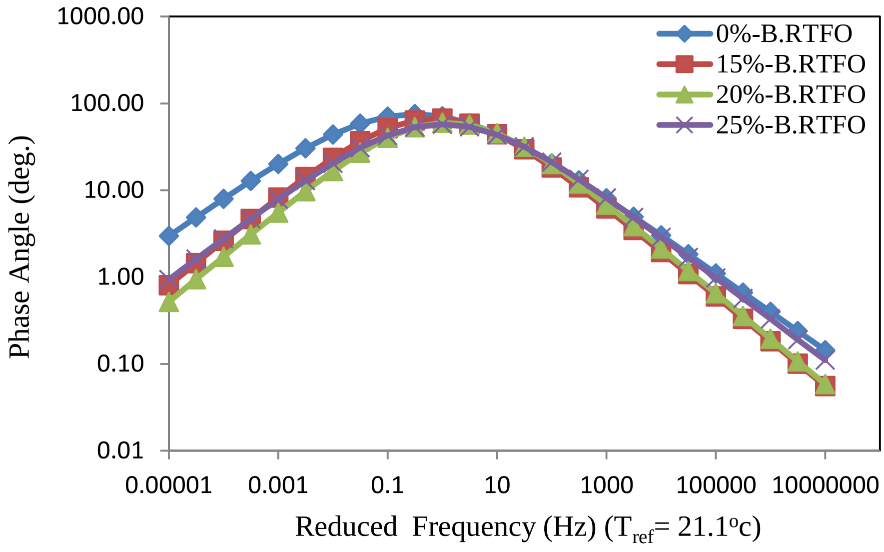


Figure 4-8: Phase Angle Master Curve before RTFO

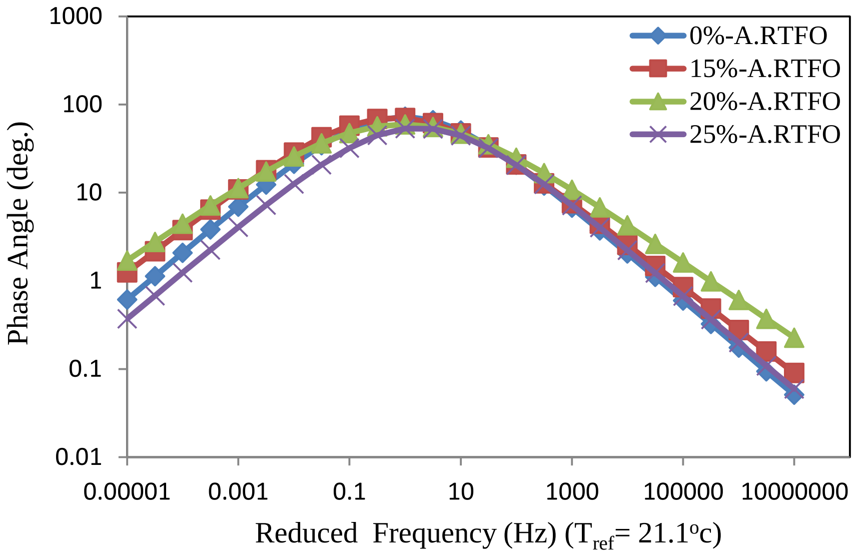


Figure 4-9: Phase Angle Master Curve after RTFO

- The phase angle master curves in figure 4-8 and 4-9 demonstrate the decrease in phase angle at high temperature and low frequency as content of modifier increases
- Thus the decrease in phase angle indicates the increase in elastic modulus

- Comparing phase angle master curves before and after RTFO ageing, it is possible to say that the neat bitumen is more sensitive for aging than modified binders.

In general to consider the realistic loading conditions of pavements, frequency from 0.01Hz to 10Hz requires special observation. At this range of frequency improvement in elastic property is observed due to replacement of binder. In other words with in this operation range of frequency as a result of the increase in percent modifier shear stiffness increases while phase angle decreases.

4.6.6 Illustrative Comparison of Rheological Results

The frequency sweep test has been carried out at test temperatures 21.1 ^{o}c, 37.8 ^{o}c, and 54.4^{o}c using 8mm parallel test plates. Even though 54.4^{o}c is a high temperature test for which we always use a 25mm plate, sometimes it is possible to conduct this temperature test using 8mm plate in a very careful manner.

The reason why 8mm plate is used at 54.4 ^{o}c temperature for this study was the stress resolution of the DSR. The stress resolution of the DSR for both 8mm and 25mm was not similar. Therefore to carry out the test at the same range of stress level 8mm plate was used for all test temperatures because of its option to use wide range of stress inputs.

Finally for the purpose of comparison additional test for 20% modified binder after RTFO was carried out at 54.4 ^{o}c using 25mm plate. Then it was observed that the phase angle result in this second case was consistent and convincing by looking at fit and measured phase angle values in addition to phase angle master curves. But this was not true for shear modulus values. Sample graphs for comparison purpose have been presented from figure 4-10 to figure 4-l3 below.

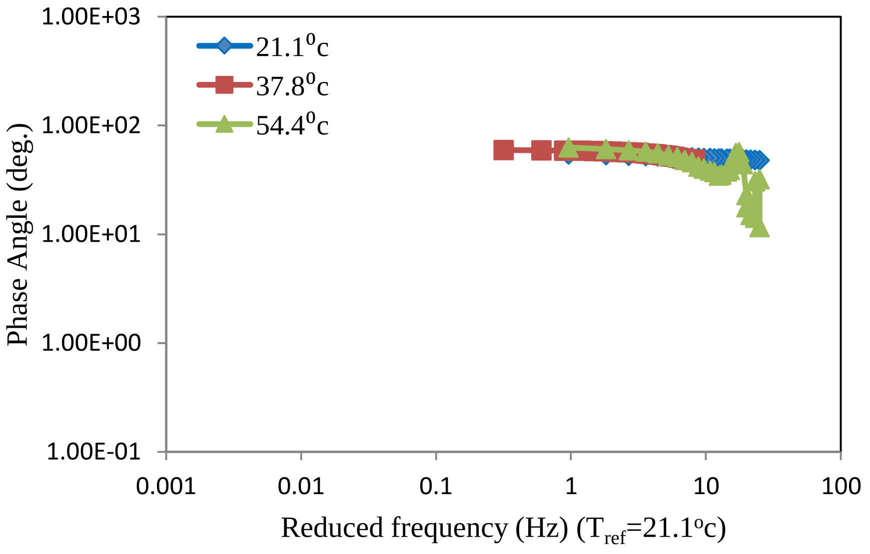


Figure 4-10: Phase Angle for 20% Modified After RTFO (with 8mm plate)

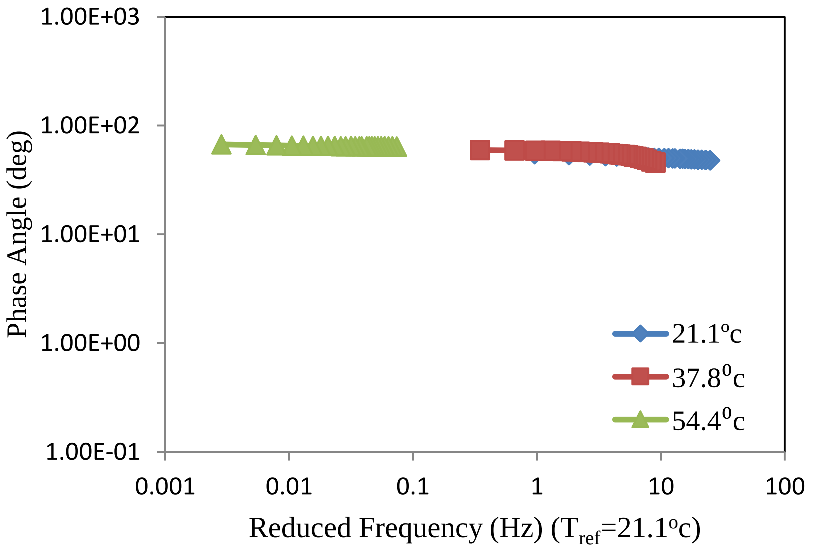


Figure 4-11: Phase Angle for 20% Modified After RTFO (25mm plate for 54.4°c only)

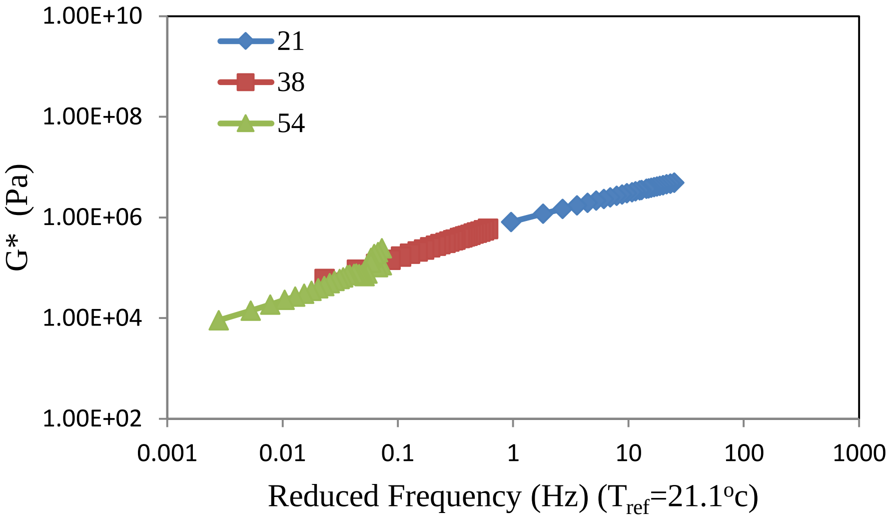


Figure 4-12: Modulus for 20% Modified after RTFO (using 8mm Plate)

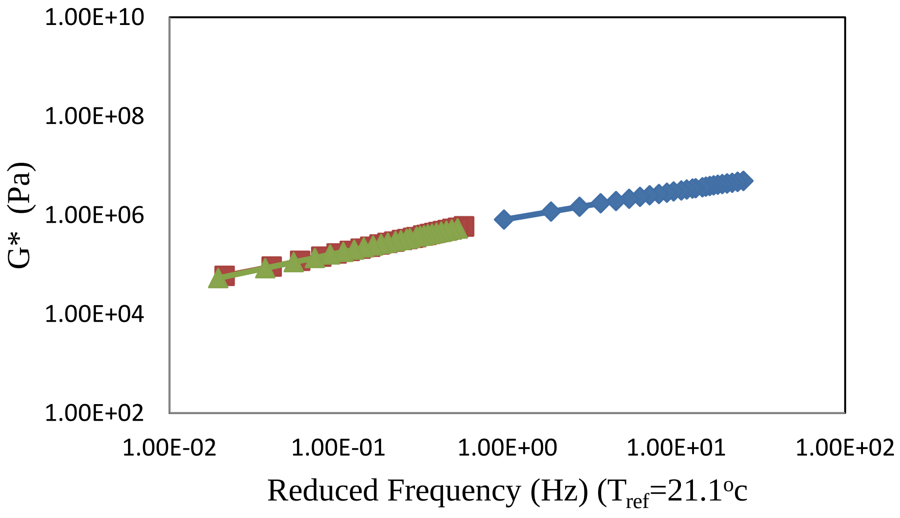


Figure 4-13: Modulus for 20% Modified after RTFO (25mm Plate @54.4°c only)

When we observe the graphs it was appropriate to conduct at 54.4oc using 25mm plate for phase angle while using 8mm plate at the same temperature gives a better result of shear modulus. The phase angle is very sensitive and not easy in its nature, but the shear modulus is very indicative and reliable. Therefore to conduct the experiment with 8mm plate was the only better choice for this study.

4.7 Multiple Stress Creep Recovery (MCSR) Test

MSCR test was conducted after the determination of the performance grade of each sample. The PG is then used to establish the MSCR test temperatures as organized in table below.

Table 4-10: MSCR Test Temperatures Based on PG

RAR (%)	PG	Test Temperature (^{o}C)		
0	58	52	58	64
15	58	52	58	64
20	64	58	64	70
25	70	64	70	76

4.7.1 MSCR Test Results

The MSCR test result (software output) contains huge data to represent in tables here. Therefore as an illustration for only 0% modified binder the test result is organized graphically as shown in figure 4-14 below. See Appendix F for all other Modified Binders.

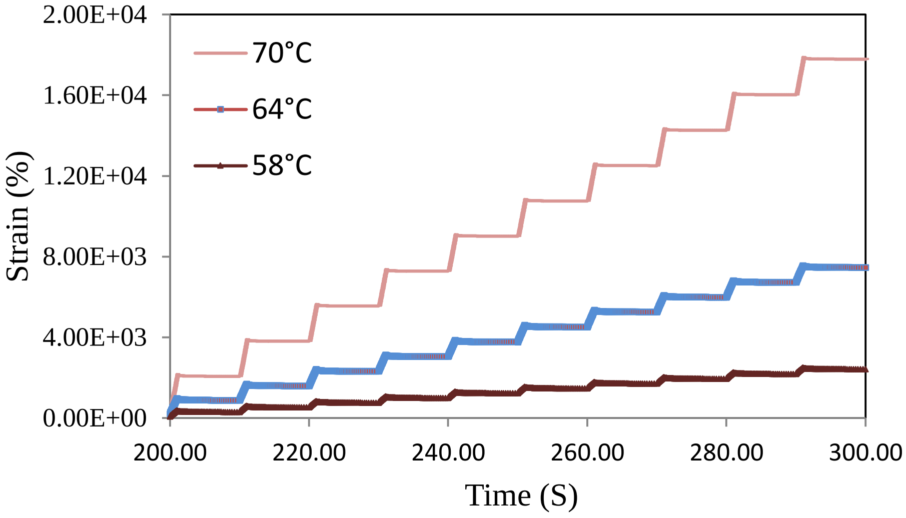


Figure 4-14: MSCR Graph for 0% Modified Binder

4.7.2 Analysis and Evaluation of the MSCR Test

The analysis is carried out considering the main purposes of MSCR test. Rutting prediction, indication of elastic response and specification preparation of a binder are the main purposes. To evaluate those properties the main parameters are non-recoverable creep compliance, percent creep compliance difference and the percent elastic recovery. Non-recoverable creep compliance (Jnr) is calculated as non recoverable strain divided by applied stress (0.1kpa or 3.2kPa). Percent difference in creep compliance is computed as (Jnr@3.2kPa - Jnr@0.1kPa) / Jnr@0.1kPa multiplied by 100. And the percent elastic recovery is computed as (strain@1sec – strain@10sec) *100 / strain@1 sec, which must be greater than 25% or 35% depending on traffic volume. The calculated values are organized using separate table for each type of binder as follows.

Table 4-11: Summary of Analyzed Jnr and % Recovery for 0% Modified Binder

Description	**Test Temperature (°c)**		
	52	**58**	**64**
percent Recovery at 0.1kPa	11.47	7.39	6.58
percent Recovery at 3.2kPa	4.89	1.28	0.11
Percent Recovery difference (%)	57	83	98
Jnr at 0.1kPa	1.01	2.93	6.94
Jnr at 3.2kPa	1.15	3.57	8.72
Jnr Difference (%)	13	22	26

Table 4-12: Summaries of Analyzed Jnr and % Recovery for 15% Modified Binder

Description	**Test Temperature (°c)**		
	52	**58**	**64**
percent Recovery at 0.1kPa	32.17	26.33	20.47
percent Recovery at 3.2kPa	12.31	4.38	1.73
Percent Recovery difference (%)	62	83	92
Jnr at 0.1kPa	0.92	2.35	5.86
Jnr at 3.2kPa	1.30	3.76	8.81
Jnr Difference (%)	42	60	50

Table 4-13: Summaries of Analyzed Jnr and % Recovery for 20% Modified Binder

Description	**Test Temperature (ºc)**		
	58	**64**	**70**
percent Recovery at 0.1kPa	63.23	56.11	48.54
percent Recovery at 3.2kPa	24.82	11.44	4.64
Percent Recovery difference (%)	61	80	90
Jnr at 0.1kPa	0.30	0.84	1.90
Jnr at 3.2kPa	0.70	2.20	5.31
Jnr Difference (%)	133	160	179

Table 4-14: Summaries of Analyzed Jnr and % Recovery for 25% Modified Binder

Description	**Test Temperature (ºc)**		
	64	**70**	**76**
percent Recovery at 0.1kPa	86.80	75.56	66.23
percent Recovery at 3.2kPa	27.49	12.69	5.62
Percent Recovery difference (%)	68	83	92
Jnr at 0.1kPa	0.10	0.38	0.95
Jnr at 3.2kPa	0.70	1.98	4.76
Jnr Difference (%)	599	423	401

Now it is possible to evaluate all the binders by contrasting the calculated basic MSCR parameters with respect to the limits of those parameters described under standard specification for performance graded asphalt binder using MSCR test, AASHTO M 322.

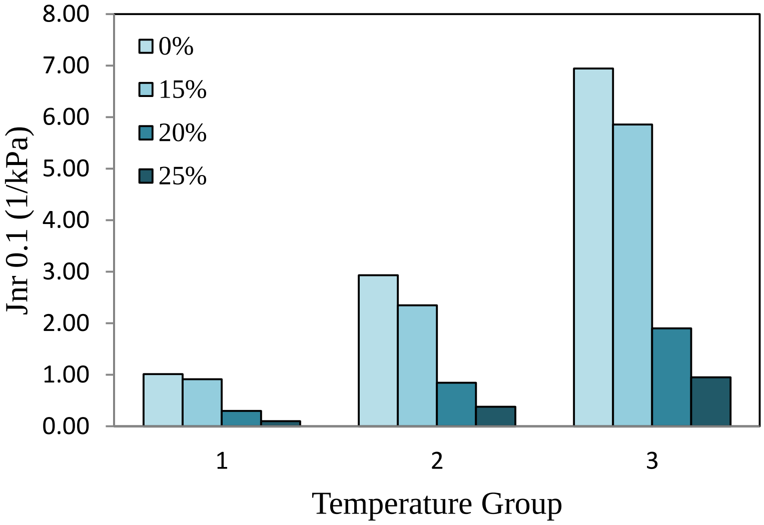
Table 4-15: Binder Specification Requirement Based on MSCR test

Traffic Designation	**Traffic level (ESALs)**	**Load Rate**	**Jnr $_{3.2}$, Max kPa^{-1}**
Standard Traffic "S"	<10 million	>70 km/h	4.5
Heavy Traffic "H"	10 to 30 million	20 to 70 km/h	2
Very Heavy Traffic "V"	>30 million	<20 km/h	1
[a] Extremely Heavy Traffic "E"	>30 million	<20 km/h	0.5

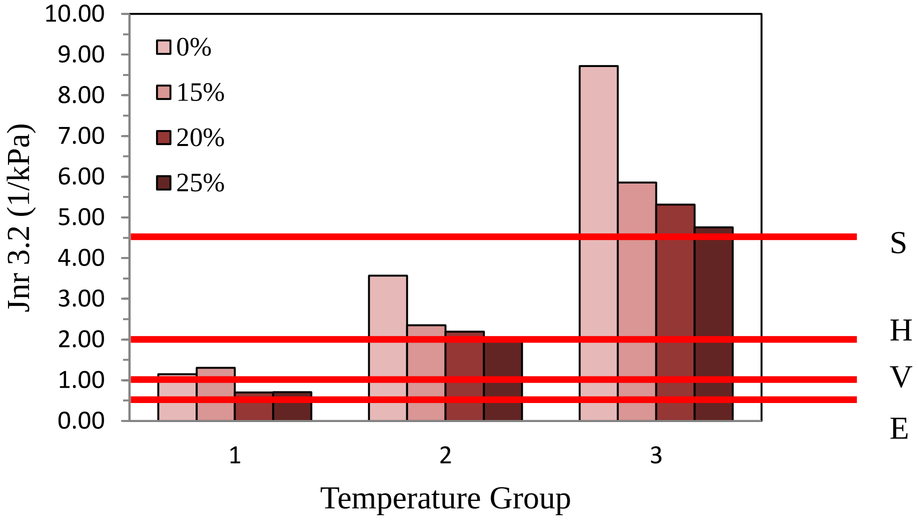
[a] such as toll plazas or port facility

Percent difference in non-recoverable creep compliance between 0.1kPa and 3.2kPa is also a requirement with maximum value 75%.

The non recoverable creep compliance (Jnr) at 3.2kPa is the fundamental parameter to evaluate rutting potential. To examine this, the Jnr determined for both neat and modified binders were graphically represented below.



a)



b)

Figure 4-15: Jnr kPa^{-1} a) 0.1kpa and b) 3.2kPa at Respective Test Temperatures

The graph represents the Jnr in three groups which refers their respective high test temperature in increasing order from left to right.

That means the test temperature in the graph is organized as, PG temperature group -1 at 52°C ,52°C, 58°C and 64°C; group -2 at 58°C, 58°c , 64°C and 70°C and finally, group -3 at 64°C, 64°C, 70°C and 76°C for 0%, 15%, 20% and 25% modified binders respectively.

Based on the observation above considering non recoverable creep compliance alone the following brief discussion can be made.

- Based on AASHTO M 332 as described above in table 4-15 the horizontal lines denoted by S, H, V and E in figure 4-15(b) represents the standard Jnr values related to traffic.
- The neat bitumen (0% modified) and the 15% reacted and activated rubber modified binder have similar Jnr results. These two binders with test temperature 52, 58 & 64°c will not be used for heavy and extremely heavy traffic in all cases of their test temperatures. Both the binders can be used for standard traffic at pavement design temperature 58°c and for simply heavy traffic at 52 °C.
- The 20% modified binder with test temperatures 58, 64 & 70°C can be used for very heavy traffic at 58 and for standard traffic at 64 °C. This binder shows a significant improvement than the previous two binders in rutting resistance by enhancing up the neat bitumen by one PG grade as per MSCR test also.
- A very good Jnr result is observed for 25% modified binder but it does not mean this binder is better than all those above because of other requirements such as stress sensitivity and workability.
- To prove the improvement in rut performance, it is possible to make a clear comparison of Jnr values at the same test temperature (64°C). At this temperature the Jnr values are 8.72 and 2.2 for 0% and 20% modified binders respectively, which is a huge difference in rut resistance as per AASHTO M 332.

According to this study the modification of the binder with 15% shows slight improvement in fundamental engineering properties but not significant change in PG and Jnr values. That means it has similar rutting performance with the control material which will make it less effective to modify with this content. The 25% modified binder was a bit harsh during blending and this can indicate that the mix with this binder will be less workable than others. And most importantly the very large percent difference in creep compliance will not make suitable to use this content of modification.

Therefore with well controlled mechanism of binder blending (time, temperature & rpm) the modification of 80/100 penetration grade bitumen with 20% by mass of binder with Reacted and Activated Rubber significantly improves the rutting performance.

The other important parameter is elastic recovery, and hence comparison of percent recovery is done considering two test temperatures. The first is at respective PG temperatures of binders and second at similar test temperature which is 64°c. In both cases the percent recovery clearly increases as percentage of binder replacement with modifier increases as illustrated in figure 4-16 below.

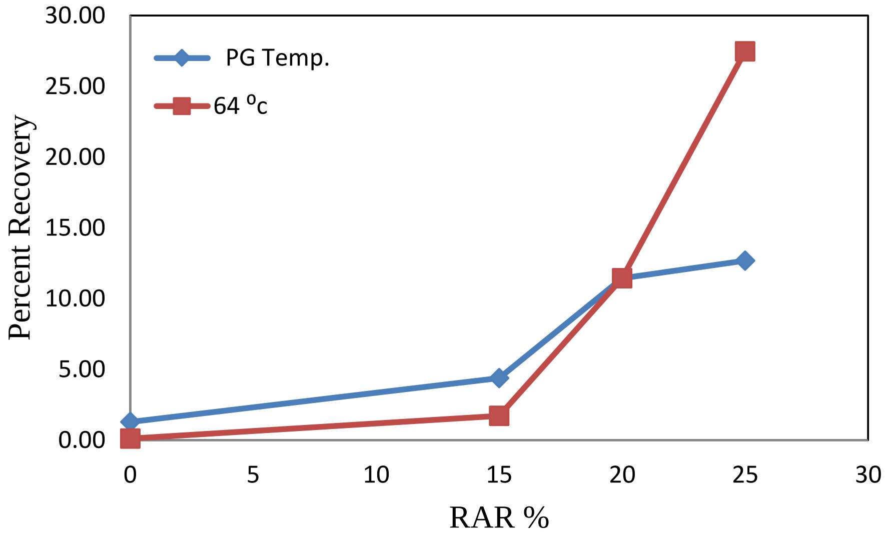


Figure 4-16: Percent Recovery as Content of Modifier Increases

4.8 Summary

Test results obtained from Amplitude Sweep, frequency Sweep, Performance Grade Determination, and Multiple Stress Creep Recovery were organized and analyzed under this chapter. What is observed is summarized as follows.

- The test temperatures for Amplitude Sweep and Frequency Sweep were 21.1 °c, 37.8 °c, and 54.4°c using 8mm parallel test plates.
- At 54.4 °c temperature, it was convenient to carry out with 25mm plate, but the stress resolution of the DSR for both 8mm and 25mm was not similar. Therefore

to carry out the test at the same range of stress level for all binders 8mm plate is used for all test temperatures.

- For comparison one sample test was carried out at 54.4 with 25mm. It is observed that the phase angle result in this case was consistent and convincing by looking at fit and measured phase angle values in addition to phase angle master curves. But not the shear modulus values.
- As observed form amplitude sweep test linear visco elastic range increases as temperature increases despite the decrease in shear modulus.
- The least strain level out of all the maximum limiting strain values was found to be 2% at 21.1^{o}c. Considering this limiting value 1% strain was chosen to carry out frequency sweep test. This is because to conduct the test well within the linear visco-elastic range.
- The modulus master curves show that at low frequency and high temperature the shear stiffens increases as percent modifier increases.
- And the phase angle master curve depicts the decrease in phase angle at low frequency and high temperature due to the increase in modifier.
- In general from the master curves the binder modification in this study improves the shear stiffness by increasing the elastic modulus, especially at high temperature within the ideal operating range of frequency (0.01Hz to 10Hz).
- PG determination indicates that 15% modification does not bring any change, but modifying with 20% has improved the PG 58 neat bitumen to PG 64 modified binder.
- The MSCR also showed that there is an improvement in non-recoverable creep compliance as content of modifier increases. At this point even though the creep compliance of 25% modification is the greater value the binder is not suitable in its percent difference of non-recoverable creep compliance. Therefore here also 20% modification is appropriate considering MSCR parameters.

In general from the analysis it is observed that to modify the 80/100 penetration grade neat bitumen with 20% reacted and activated rubber will improve the performance of the binder at high temperature and low frequency. Thus rubberized binder is recommendable to minimize rutting.

CHAPTER 5 CONCLUSIONS AND RECCOMENDATIONS

5.1 Conclusions

This study is done to evaluate if rubberized bitumen improves fundamental engineering properties related to rutting performance or not. In addition to other experiments the latest MSCR test known in its best rut performance indicator parameter has been conducted to examine rut resistance. The rubberized modifier is a new material composed of crumb rubber, plain bitumen and activated mineral binder stabilizer. This new Reacted and Activated Rubber (RAR) industrially known as RUBind^{TM} with a content of 15%, 20%, and 25% percent by mass of binder was blended with 80/100 penetration grade bitumen to prepare a total of four types of samples including the neat bitumen as a control material. There was no adequate facility to produce those samples in a well controlled way; due to this locally reproduced mixing tools were used.

- The wet process was done by mixing the modifier with neat bitumen for 30minutes at an average temperature of 165^{o}c, which saves energy and time when compared to conventional rubber. The former conventional rubber modification is tedious which requires 45minutes to one hour blending time with a temperature over 190^{o}C.

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.

Conclusion from Frequency sweep Test:

- For all binders in almost similar pattern shear stiffness decreases as temperature increases.
- 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 is insignificant.
- At very low frequency (such as from 0.01 to 0.0001 Hz or below) and high temperature the effect of content of modifier is observed with difference in 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.

Conclusion from Multiple Stress Creep Recovery Test:

- The neat bitumen (0% modified) and the 15% reacted and activated rubber modified binders have similar Jnr results. Thus to modify the neat binder with 15% will not improve the binder considerably.
- The 20% modified binder shows a significant improvement and can be used for very heavy traffic at 58 ^{o}C and for standard traffic at 64^{o}C as observed.
- A very good Jnr result is observed from 25% modified binder but it does not mean this binder is better than all others, very large percent difference in creep compliance is pronounced that makes the modified binder unsuitable.
- By looking at the current best rut indicator parameter (Jnr @3.2) and comparing the value for neat and 20% modified binder at the same temperature (64^{o}C), i.e, 8.7 and 2.2 respectively, it is evident that the modifier improves the rut performance of the neat bitumen significantly.
- In general with well controlled mechanism of binder blending (time, temperature & speed) the modification of 80/100 penetration grade bitumen with 20% Reacted and Activated Rubber by mass of binder significantly improves the rutting performance.

5.2 Recommendations

- The study showed that it is possible to improve the performance grade of a binder with addition of 20 % RAR, thus it is recommendable to use this modified binder in Ethiopia around wide areas with pavement design temperature 64°C and below.
- Rutting resistance alone is not the only important evaluation therefore it is necessary to evaluate the rubber modified bitumen for fatigue performance.
- The hottest area in Ethiopia, Dallol has estimated pavement design temperature between 76 and 82. Therefore it would be advisable to try to produce and evaluate rubber modified binder using 60/70 or 40/50 penetration grade neat bitumen as the base material.
- It would be better if Ethiopian Roads Authority support and encourage rubber modified related pavement technology considering its advantage to minimize pavement distress due to rutting in Ethiopia.
- It is also advisable if Ethiopian Roads Authority and other stake holders in the area of road construction show interest to use the latest binder specification system using Multiple Stress Creep Recovery test (AASHTO M 332) which is the new method that best relates with rutting performance. Moreover it is because binder characterization has to be considering specific local condition of loading, temperature and others.
- Finally, to produce Reacted and Activated Rubber (RAR) is expensive which requires a detailed feasibility study first. Therefore, it is recommendable to import this material and construct trial section of a pavement using the 20% modified binder as per this study. This will help to practice the technology and to prove its economical benefit.

5.3 Future Study

1. Fatigue performance of 20% Reacted Activated Rubber (RAR) modified bitumen
2. Fatigue and rut performance of RAR modified 60/70 bitumen
3. Performance grade (PG) map of Ethiopia
4. Major pavement distresses and their significance in Ethiopia

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APPENDIX A: ANOVA Analysis Using **MINITAB 14**

Analysis of Variance (ANOVA)

One-way ANOVA:
For 0.01 Hz

0% B.RTFO, 15% B.RTFO, 20% B.RTFO, 25% B.RTFO

```
Source  DF          SS         MS      F      P
Factor   3  1034173602  344724534  10.57  0.023
Error    4   130393898   32598475
Total    7  1164567500

S = 5710   R-Sq = 88.80%   R-Sq(adj) = 80.41%


                             Individual 95% CIs For Mean Based on
                             Pooled StDev
Level       N   Mean  StDev  -------+---------+---------+---------+--
0% B.RTFO   2    529     10  (------*-------)
15% B.RTFO  2   1890    877   (------*-------)
20% B.RTFO  2  26900  11172                 (-------*------)
25 B.RTFO   2  19850   2192             (------*-------)
                             -------+---------+---------+---------+--
                                    0     15000     30000     45000

Pooled StDev = 5710
```

0% A.RTFO, 15% A.RTFO, 20% A.RTFO, 25% A.RTFO

```
Source  DF          SS         MS     F      P
Factor   3   908292600  302764200  3.23  0.143
Error    4   374670780   93667695
Total    7  1282963379

S = 9678   R-Sq = 70.80%   R-Sq(adj) = 48.89%


                               Individual 95% CIs For Mean Based on
                               Pooled StDev
Level         N   Mean  StDev  -------+---------+---------+---------+--
0% A.RTFO     2   7998  11175  (-----------*-----------)
15% A.RTFO_1  2   7625   3642  (-----------*-----------)
20% A.RTFO_2  2  24700   6364             (----------*-----------)
25% A.RTFO_3  2  32200  14001                 (-----------*-----------)
                               -------+---------+---------+---------+--
                                      0     16000     32000     48000

Pooled StDev = 9678
```

One-way ANOVA:
For 1 HZ

0% B.RTFO, 15% B.RTFO, 20% B.RTFO, 25 B.RTFO

```
Source  DF           SS           MS      F      P
Factor   3  8.42177E+11  2.80726E+11  17.38  0.009
Error    4  64609000000  16152250000
Total    7  9.06786E+11

S = 127092   R-Sq = 92.87%   R-Sq(adj) = 87.53%


                                 Individual 95% CIs For Mean Based on
                                 Pooled StDev
Level          N    Mean   StDev  ---+---------+---------+---------+------
0% B.RTFO_1    2  143500    2121  (------*------)
15% B.RTFO_1   2  345000  111723        (------*------)
20% B.RTFO_1   2  937000  216375                         (------*------)
25 B.RTFO_1    2  803500   72832                     (------*------)
                                  ---+---------+---------+---------+------
                                     0    350000    700000   1050000

Pooled StDev = 127092
```

0% A.RTFO, 15% A.RTFO, 20% A.RTFO, 25% A.RTFO

```
Source  DF           SS           MS     F      P
Factor   3  1.03963E+11  34654201250  0.23  0.869
Error    4  5.91993E+11  1.47998E+11
Total    7  6.95955E+11

S = 384705   R-Sq = 14.94%   R-Sq(adj) = 0.00%


                                 Individual 95% CIs For Mean Based on
                                 Pooled StDev
Level          N    Mean   StDev  ----+---------+---------+---------+-----
0% A.RTFO1     2  555950  712834  (--------------*--------------)
15% A.RTFO1    2  643000  176777    (---------------*---------------)
20% A.RTFO1    2  808000   45255       (---------------*---------------)
25% A.RTFO 1   2  829000  224860       (----------------*---------------)
                                  ----+---------+---------+---------+-----
                                      0    500000   1000000   1500000

Pooled StDev = 384705
```

One-way ANOVA:
For 100 Hz

0% B.RTFO, 15% B.RTFO, 20% B.RTFO, 25 B.RTFO

```
Source  DF           SS           MS     F      P
Factor   3  2.73817E+13  9.12723E+12  0.21  0.885
Error    4  1.74274E+14  4.35686E+13
Total    7  2.01656E+14

S = 6600650   R-Sq = 13.58%   R-Sq(adj) = 0.00%



Level           N      Mean     StDev
0% B.RTFO_1_1   2  10035000  11971318
15% B.RTFO_1_1  2   7310000    466690
20% B.RTFO_1_1  2   4950000   5543717
25 B.RTFO_1_1   2   8425000    106066

                Individual 95% CIs For Mean Based on Pooled StDev
Level                  +---------+---------+---------+---------
0% B.RTFO_1_1                (---------------*---------------)
15% B.RTFO_1_1            (---------------*---------------)
20% B.RTFO_1_1         (---------------*---------------)
25 B.RTFO_1_1              (---------------*---------------)
                       +---------+---------+---------+---------
                -8000000         0   8000000  16000000

Pooled StDev = 6600650
```

0% A.RTFO , 15% A.RTFO, 20% A.RTFO , 25% A.RTFO

```
Source  DF           SS           MS     F      P
Factor   3  1.02331E+13  3.41103E+12  0.24  0.868
Error    4  5.79119E+13  1.44780E+13
Total    7  6.81450E+13

S = 3804993   R-Sq = 15.02%   R-Sq(adj) = 0.00%


                                      Individual 95% CIs For Mean Based on
                                      Pooled StDev
Level           N      Mean    StDev  -+---------+---------+---------+--------
0% A.RTFO 100   2   7080000  7523616  (--------------*--------------)
15% A.RTFO100   2  10135000   374767        (--------------*--------------)
20% A.RTFO 100  2   9335000   685894       (--------------*--------------)
25% A.RTFO 100  2   9210000   834386      (--------------*--------------)
                                      -+---------+---------+---------+--------
                                       0   5000000  10000000  15000000

Pooled StDev = 3804993
```

APPENDIX B: Linear Vico-Elastic Range

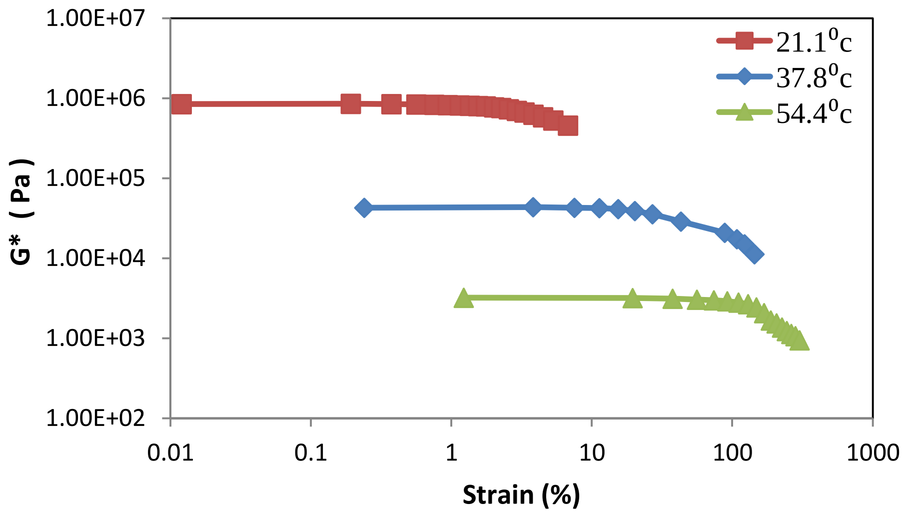


Figure B-1: Linear Visco Elastic Range (0% Modified Before RTFO)

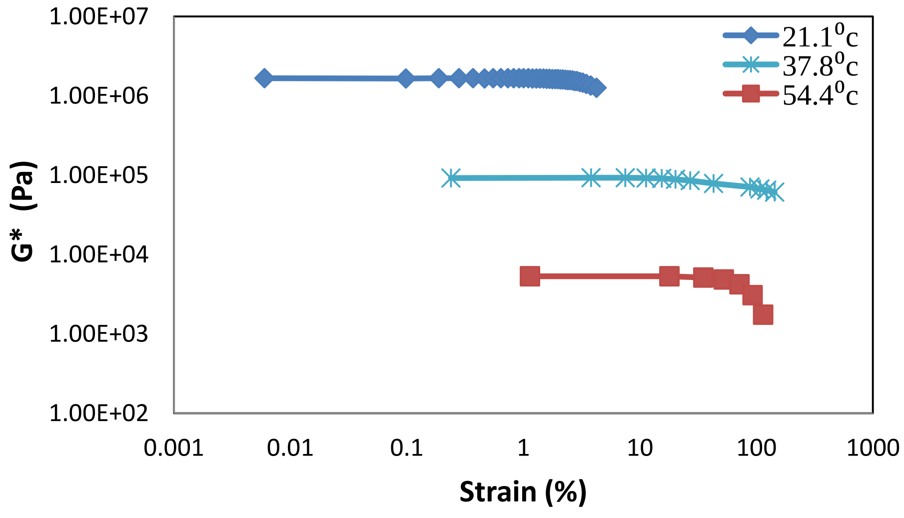


Figure B-2: Linear Visco Elastic Range (0% Modified After RTFO)

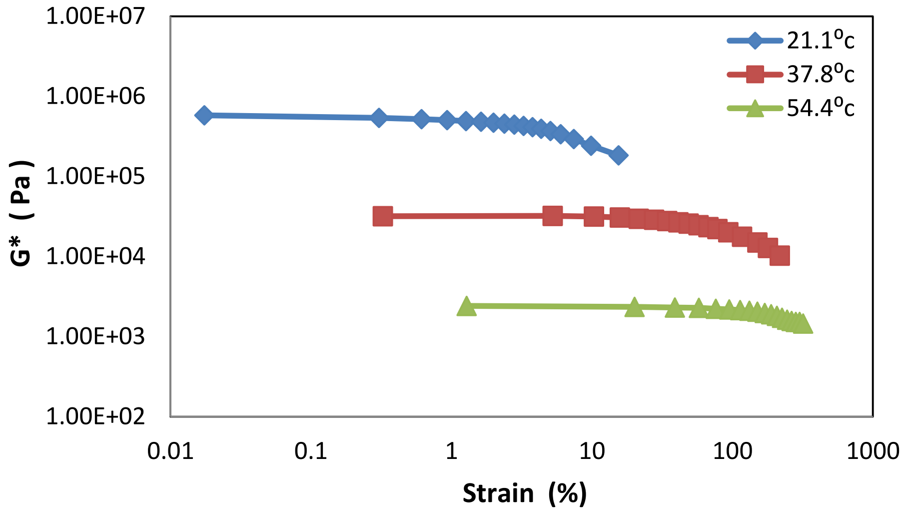


Figure B-3: Linear Visco Elastic Range (15% Modified before RTFO)

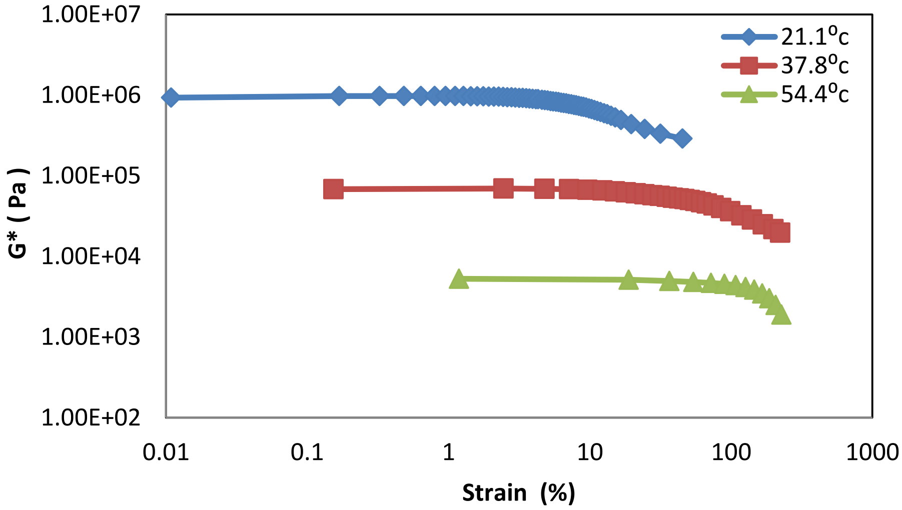


Figure B-4: Linear Visco Elastic Range (15% Modified after RTFO)

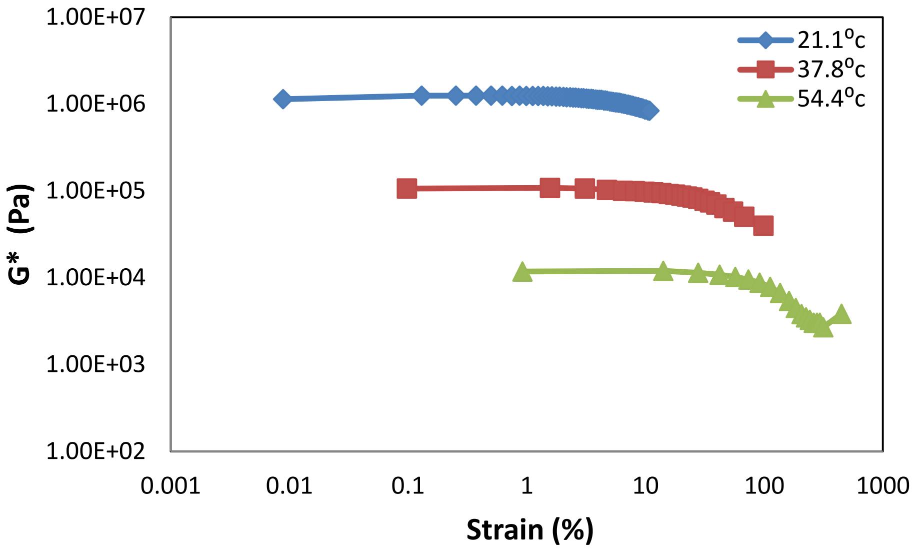


Figure B-5: Linear Visco Elastic Range (20% Modified before RTFO)

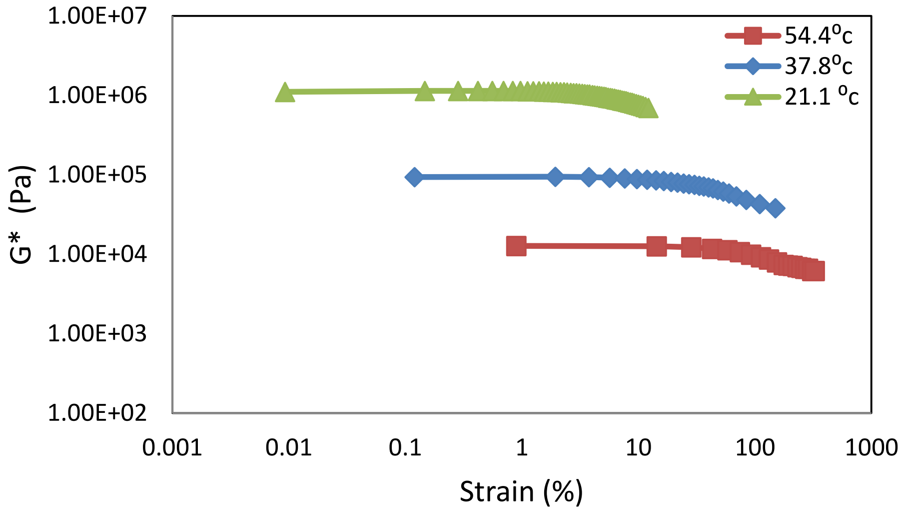


Figure B-6: Linear Visco Elastic Range (20% Modified after RTFO)

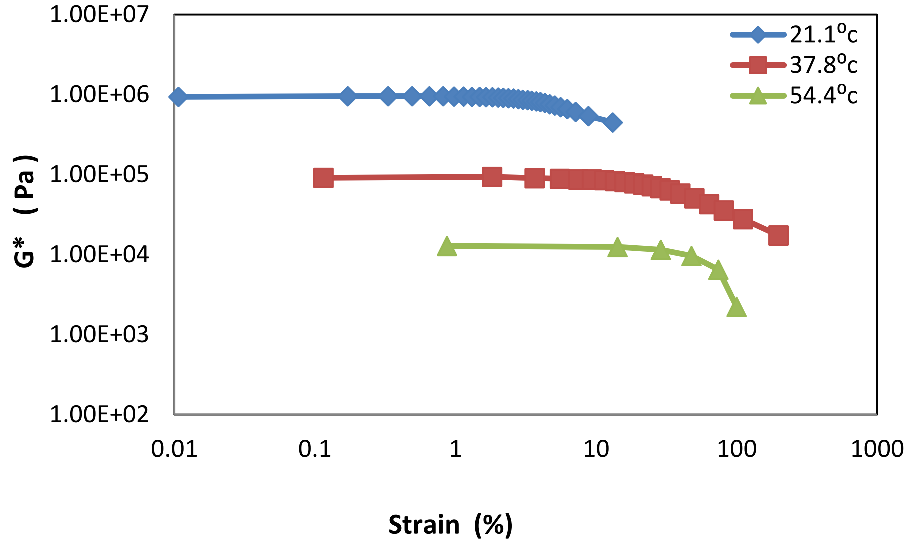


Figure B-7: Linear Visco Elastic Range (25% Modified before RTFO)

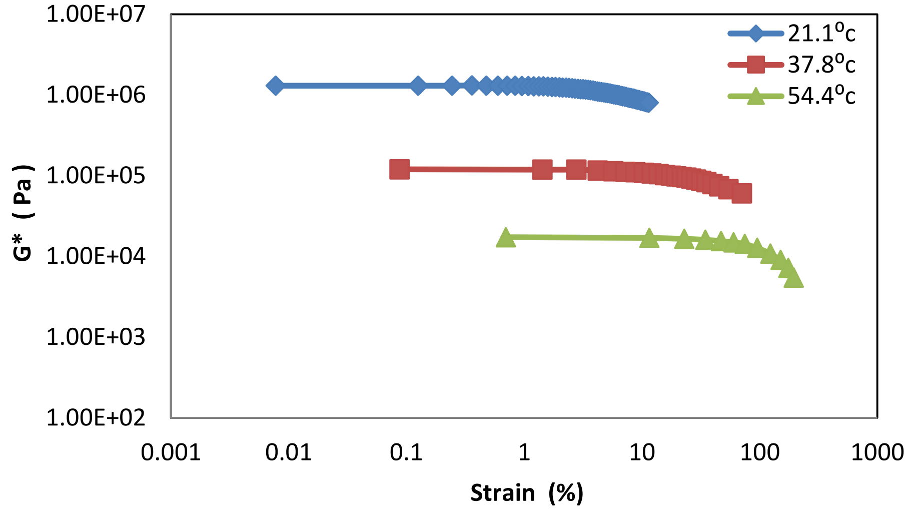


Figure B-8: Linear Visco Elastic Range (25% Modified after RTFO)

APPENDIX C: Isothermal Graphs

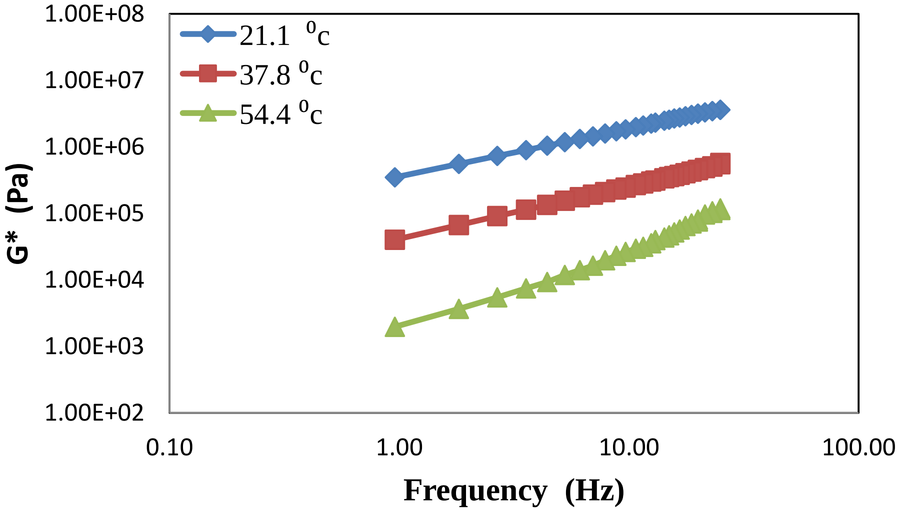


Figure C-1: Isothermal plots (0% Modified before RTFO)

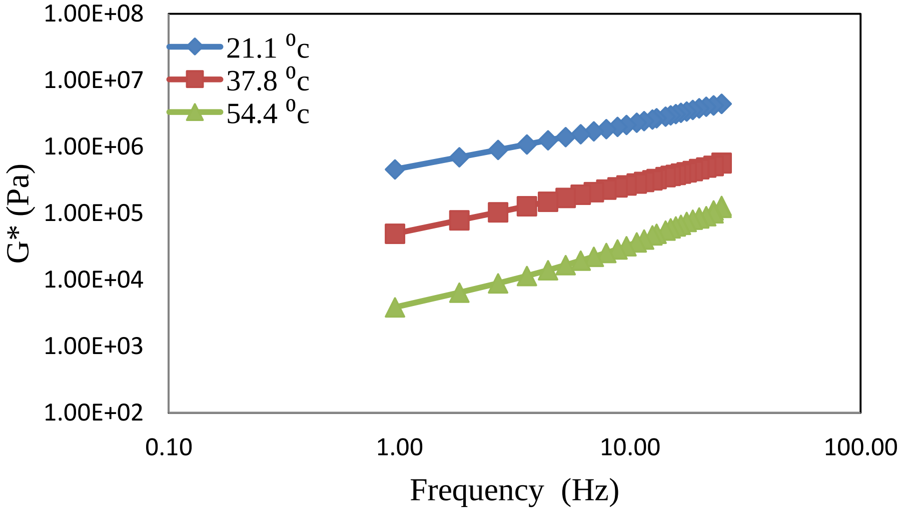


Figure C-2**:** Isothermal plots (0% Modified before RTFO)

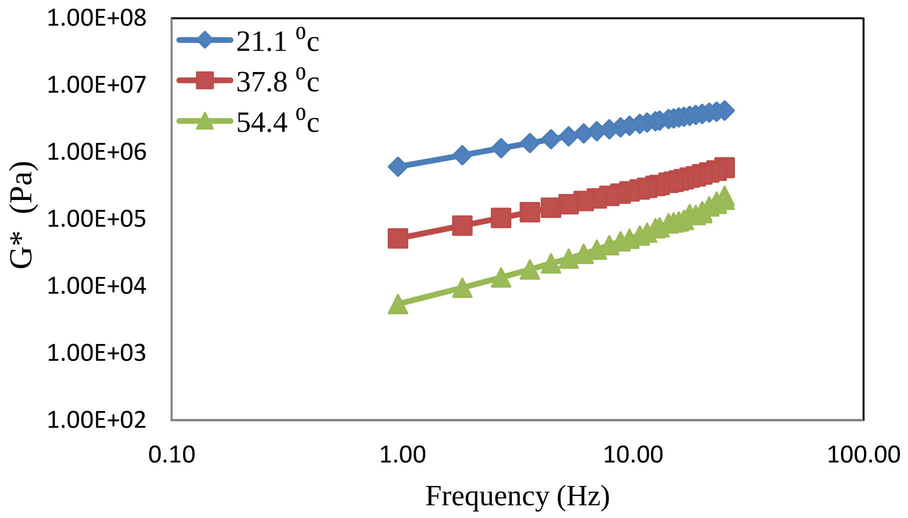


Figure C-3: Isothermal plots (15% Modified before RTFO)

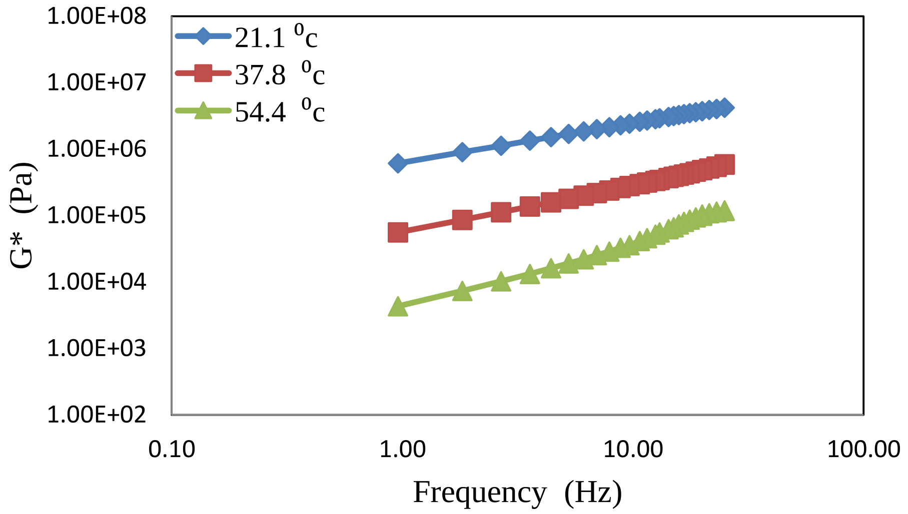


Figure C-4: Isothermal plots (15% Modified after RTFO)

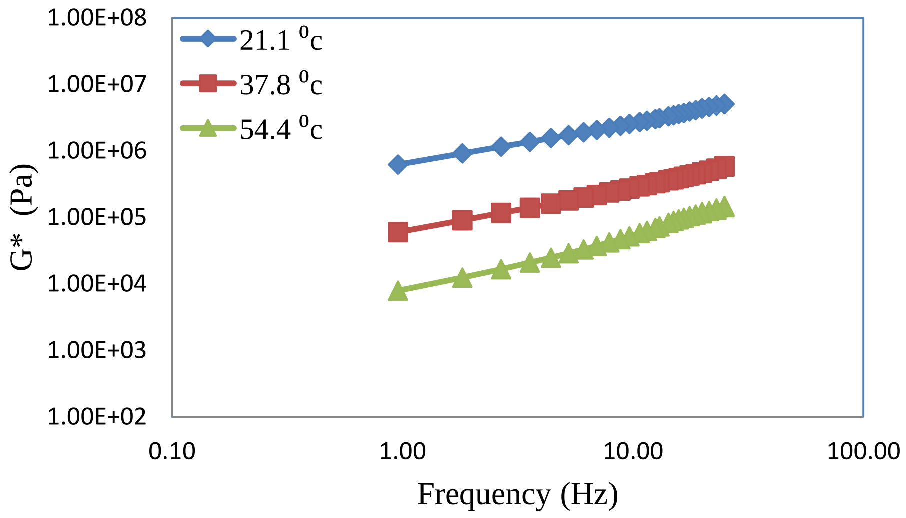


Figure C-5: Isothermal plots (20% Modified before RTFO)

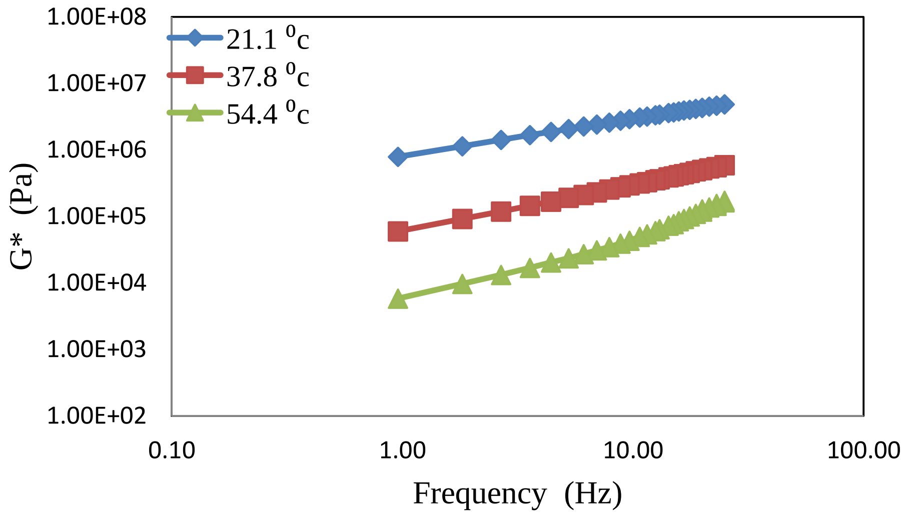


Figure C-6: Isothermal plots (20% Modified after RTFO)

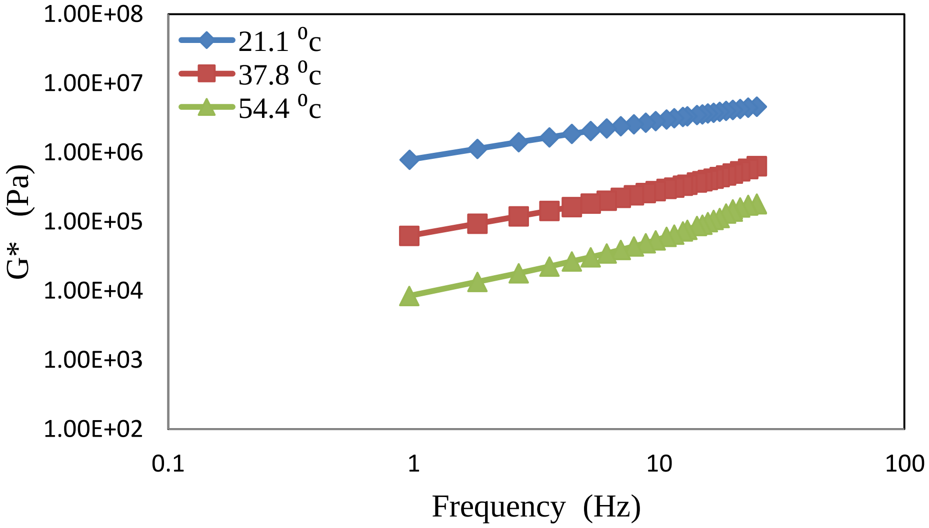


Figure C-7: Isothermal plots (25% Modified before RTFO)

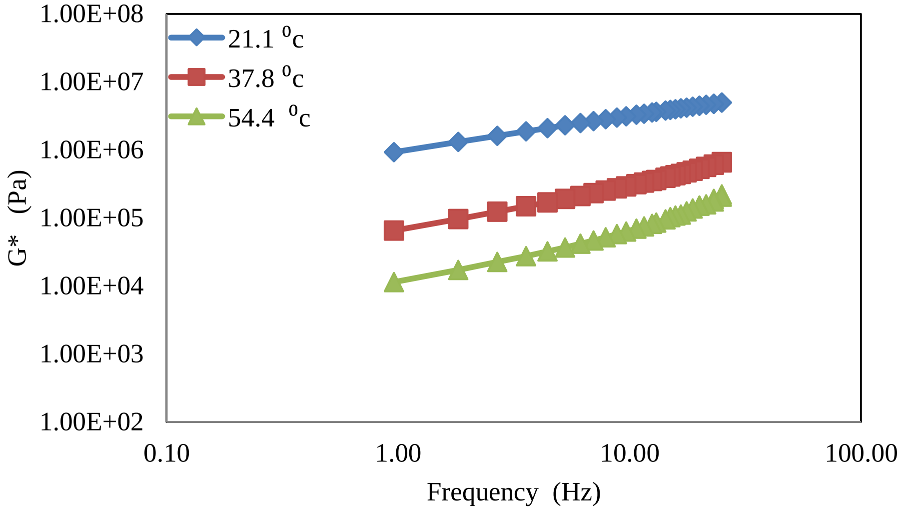


Figure C-8: Isothermal plots (25% Modified before RTFO)

APPENDIX D: Phase Angle Graphs

The phase angle (δ) is represented with a black space diagram with a semi log scale as plotted below for all types of binders. Here also Log G* is in the Y-axis and Phase angle takes the X-axis.

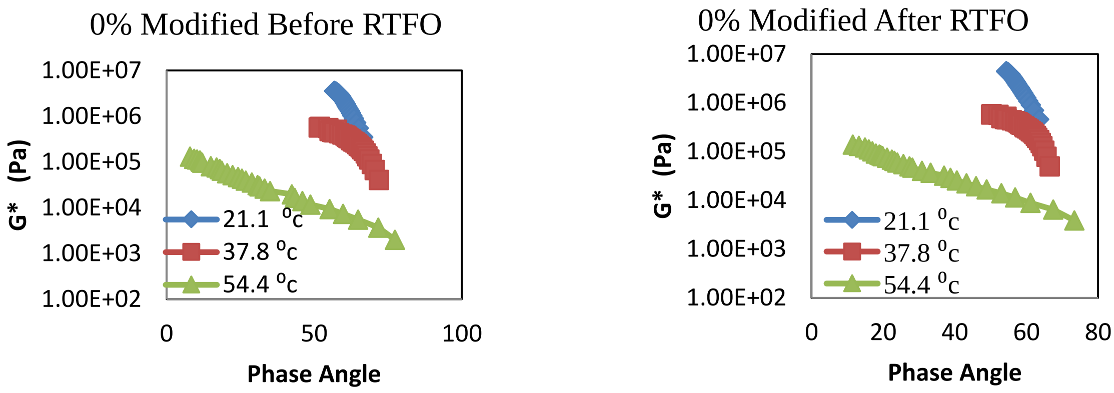


Figure D-1: Black space Diagram for 0% Modified Before and After Aging

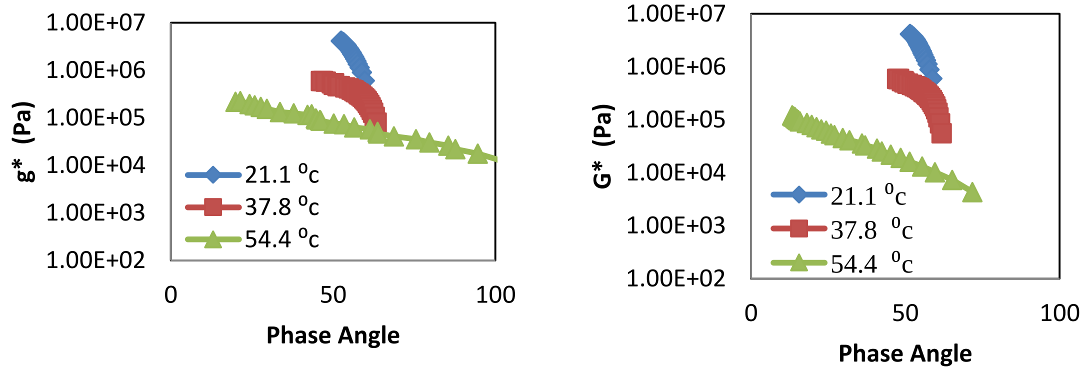


Figure D-2: Black space Diagram for 15% Modified Before and After Aging

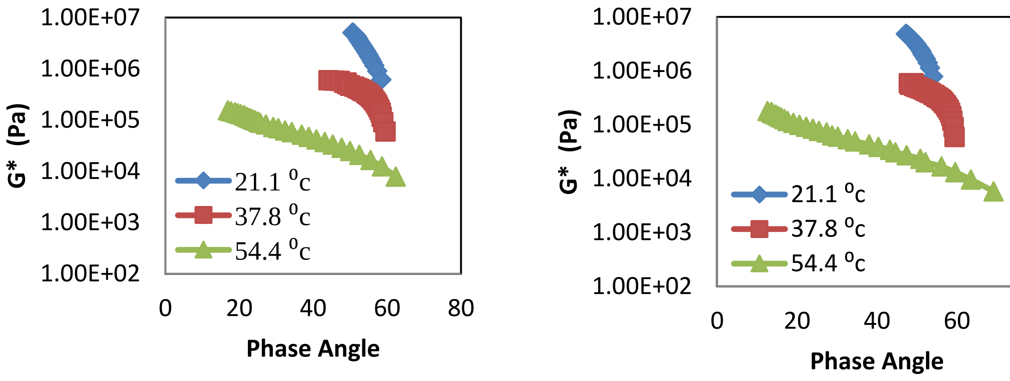


Figure D-3: Black space Diagram for 20% Modified Before and After Aging

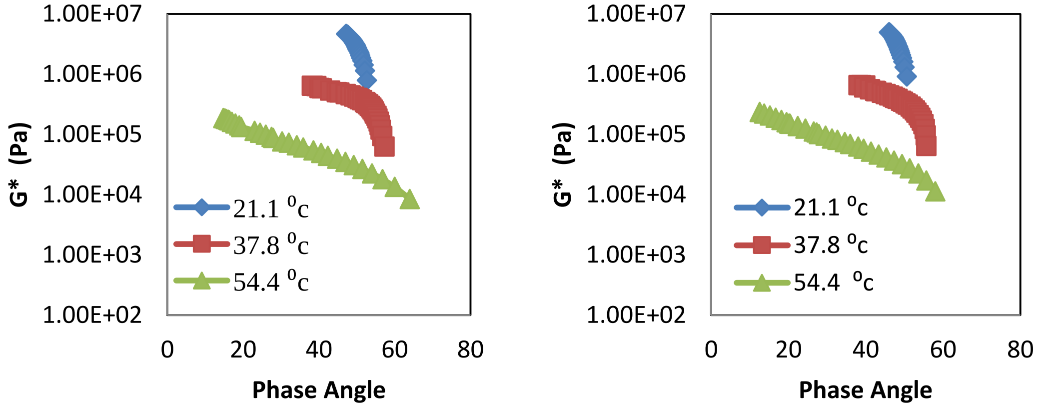


Figure D-4: Black space Diagram for 25% Modified Before and After Aging

APPENDIX E: Modulus Master Curves

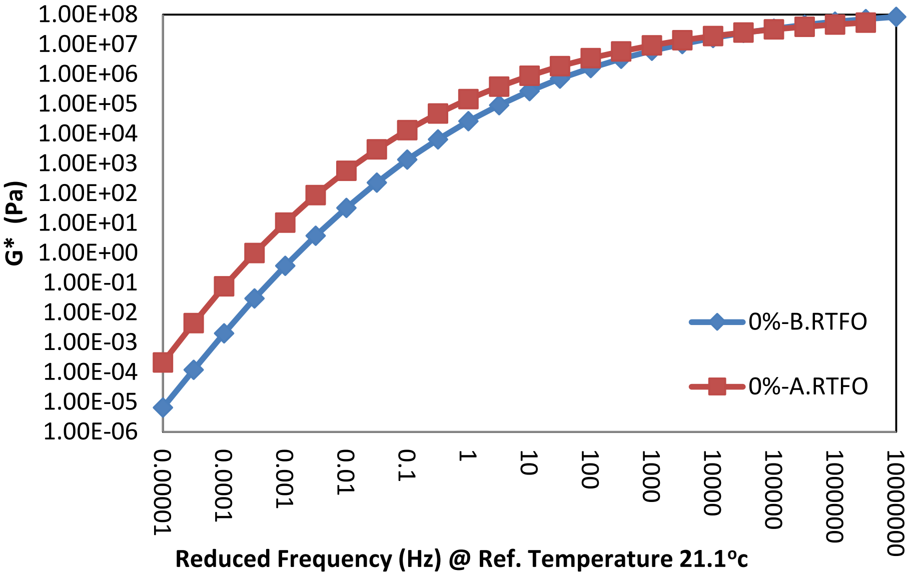


Figure E-1: Modulus Master Curve for 0% Modified Binder before and after Aging

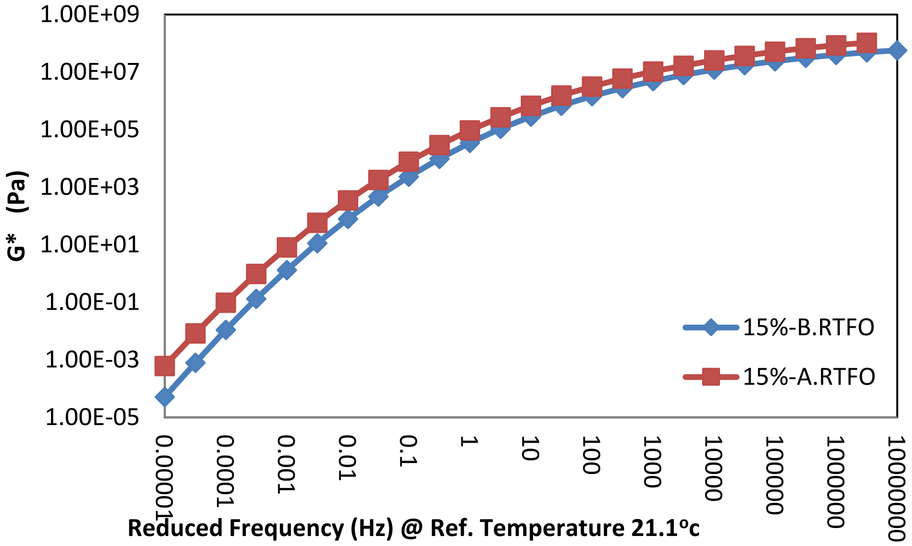


Figure E-2: Modulus Master Curve for 15% Modified Binder before and after RTFO

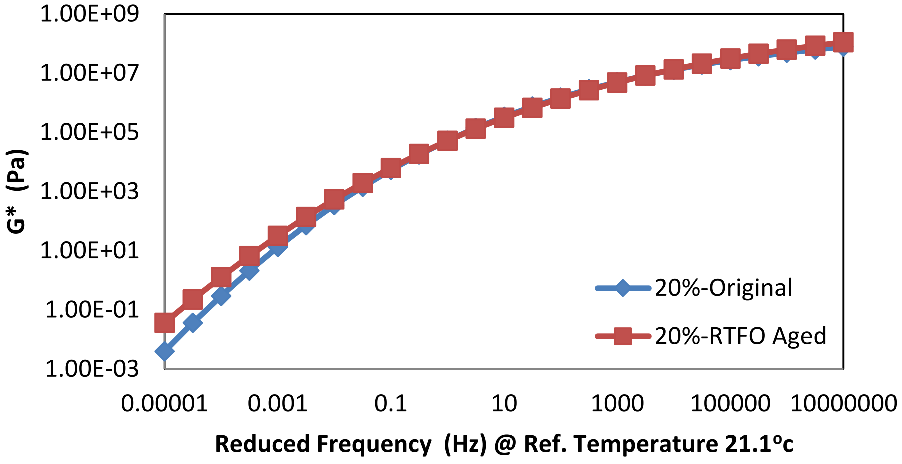


Figure E-3: Modulus Master Curve for 20% Modified Binder before and after RTFO

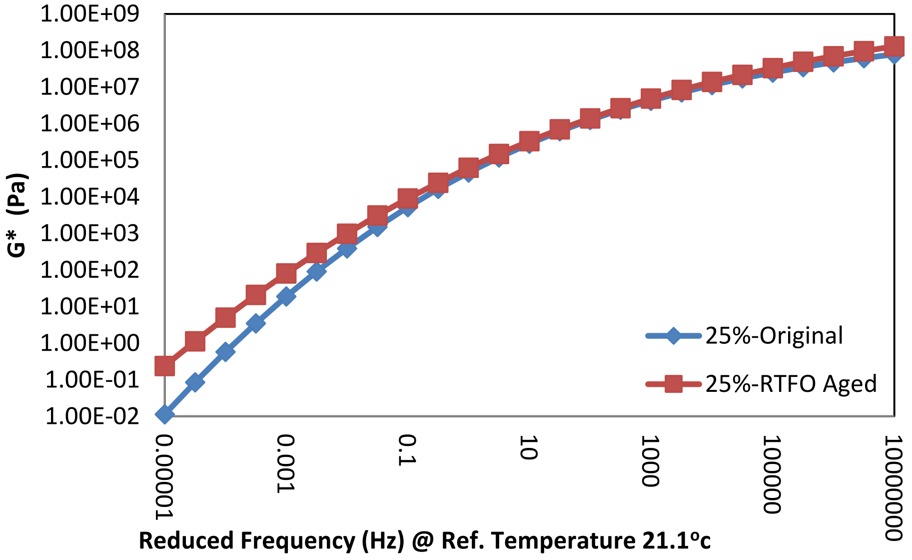


Figure E-4: Modulus Master Curve for 25% Modified Binder before and after RTFO

APPENDIX F: Graphs of MSCR Test Results

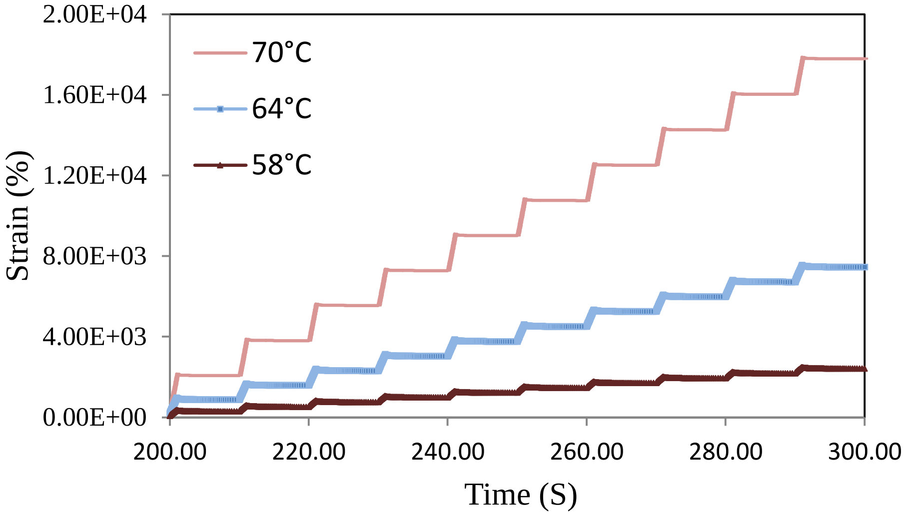


Figure F-1: MSCR graph @ 52^{o}c for 0% Modified Binder

The MSCR test result (software output) contains huge data to represent in tables here. Therefore the test result is organized graphically here in Appendix F.

The figure F-1 above shows similar graph with the sample graph included in the analysis part (chapter 4). The rest below are represented in different form of a graph but the same kind of output.

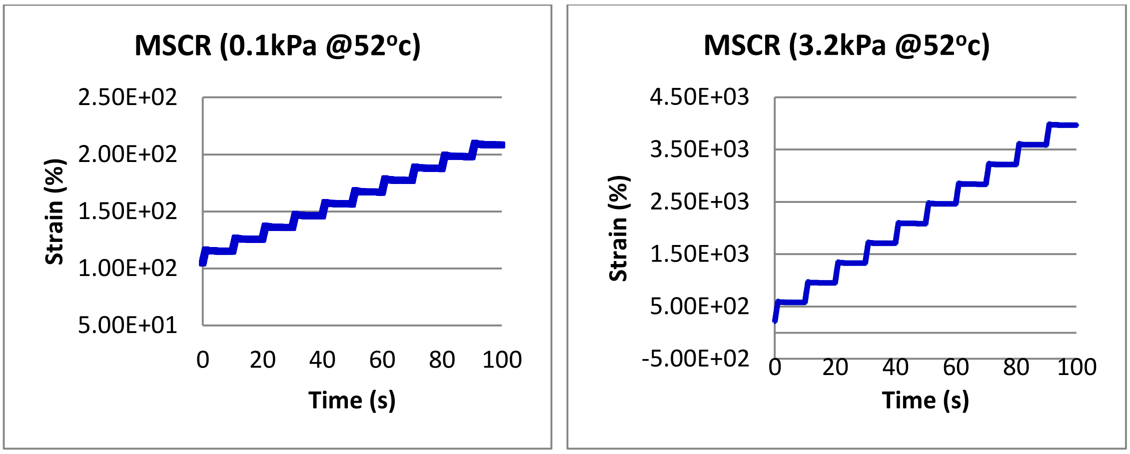


Figure F-2: MSCR graph @ 52ºc for 0% Modified Binder

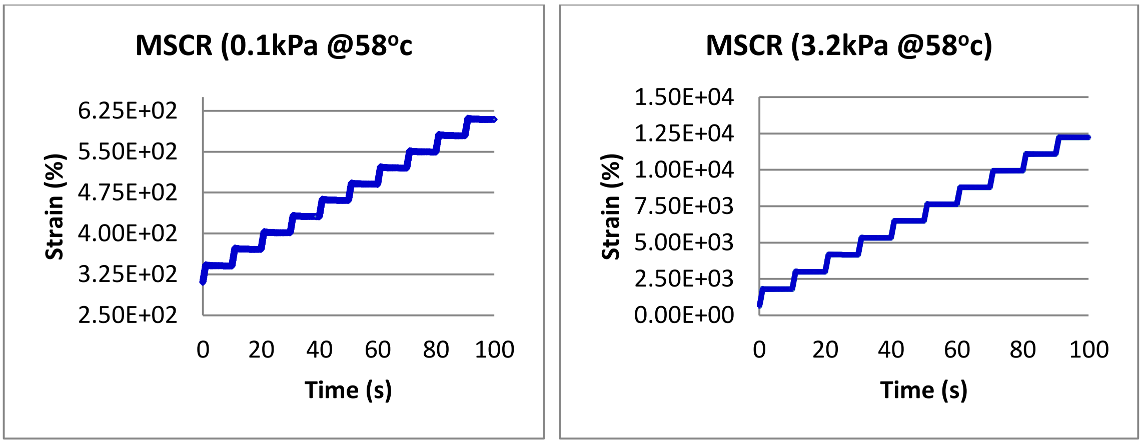


Figure F-3: MSCR graph @ 58ºc for 0% Modified Binder

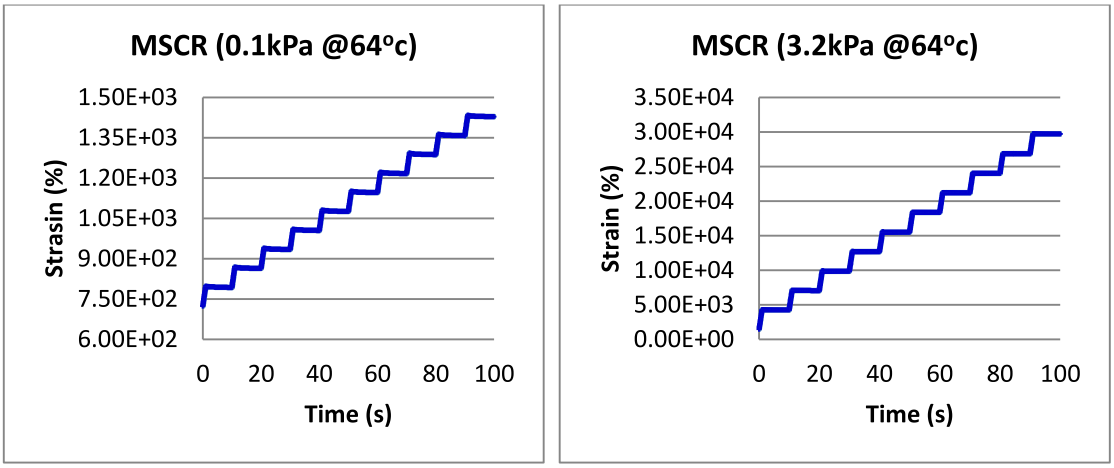


Figure F-45-1: MSCR graph @ 64ºc for 0% Modified Binder

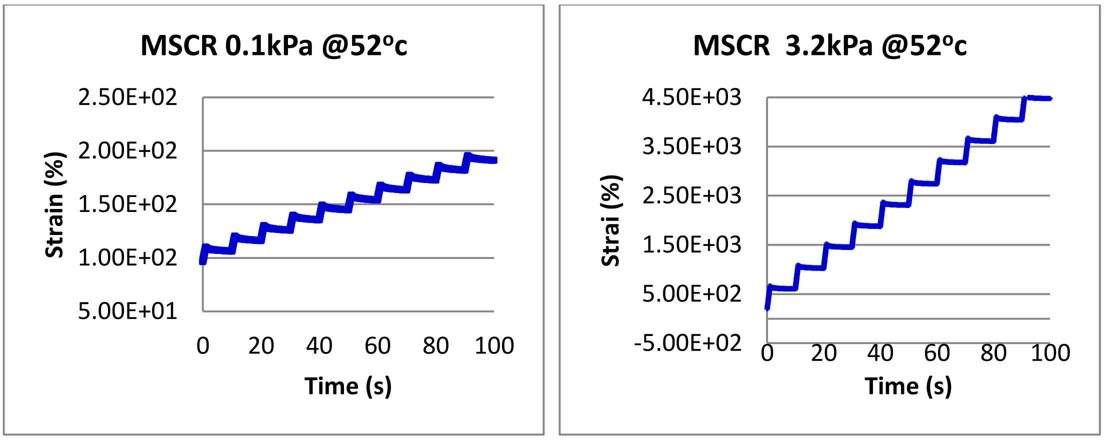


Figure F-5: MSCR graph @ 52°c for 15% Modified Binder

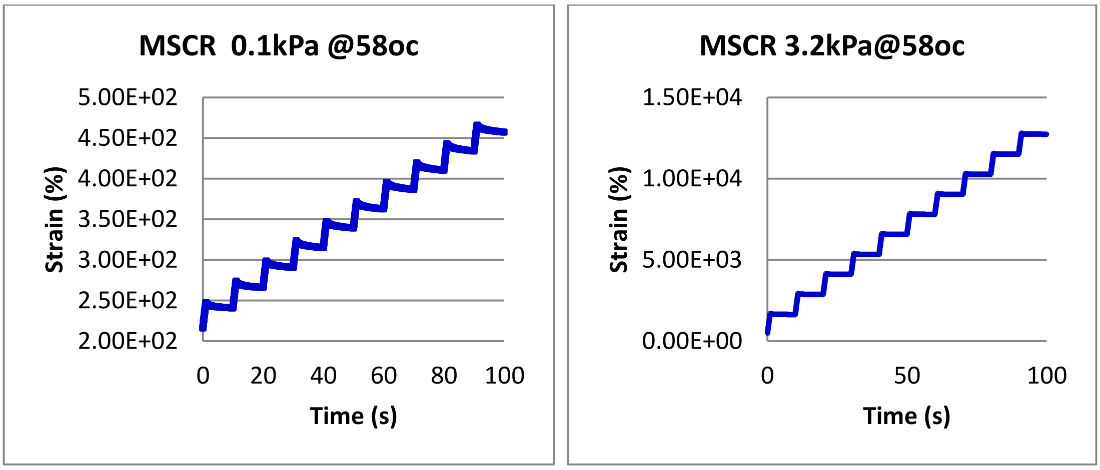


Figure F-6: MSCR graph @ 58°c for 15% Modified Binder

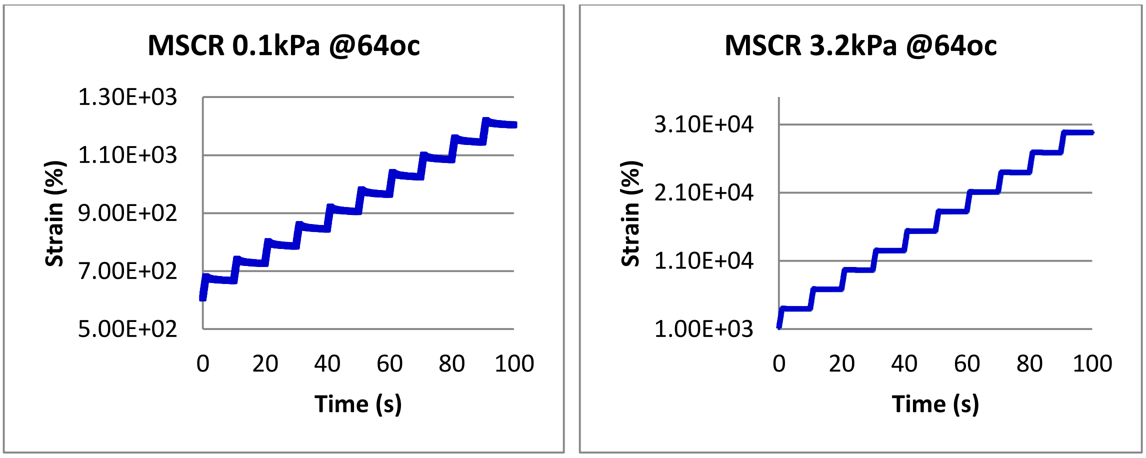
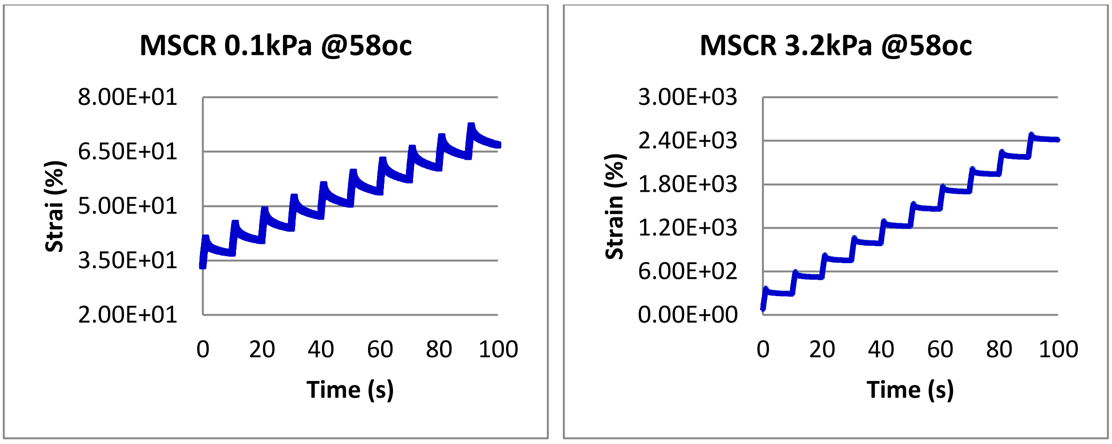


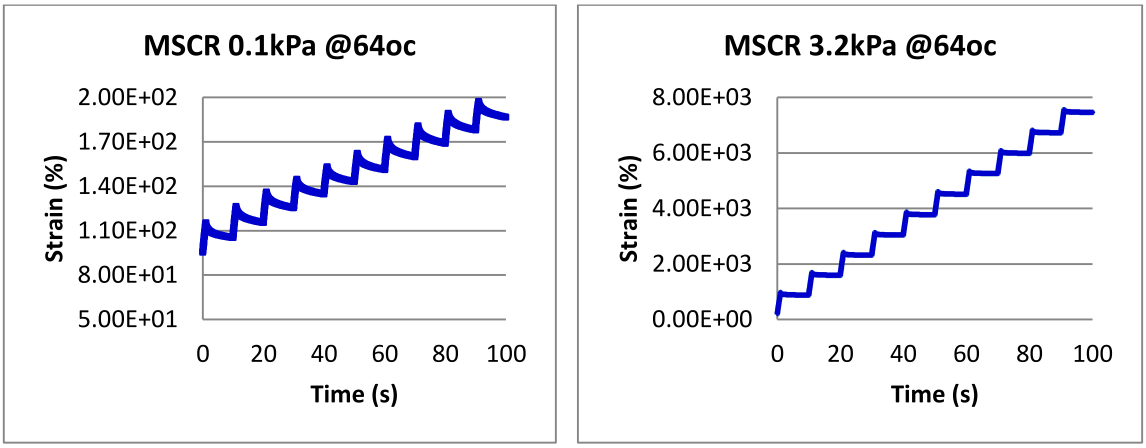
Figure F-7: MSCR graph @ 64°c for 15% Modified Binder



MSCR 0.1kPa @58oc

MSCR 3.2kPa @58oc

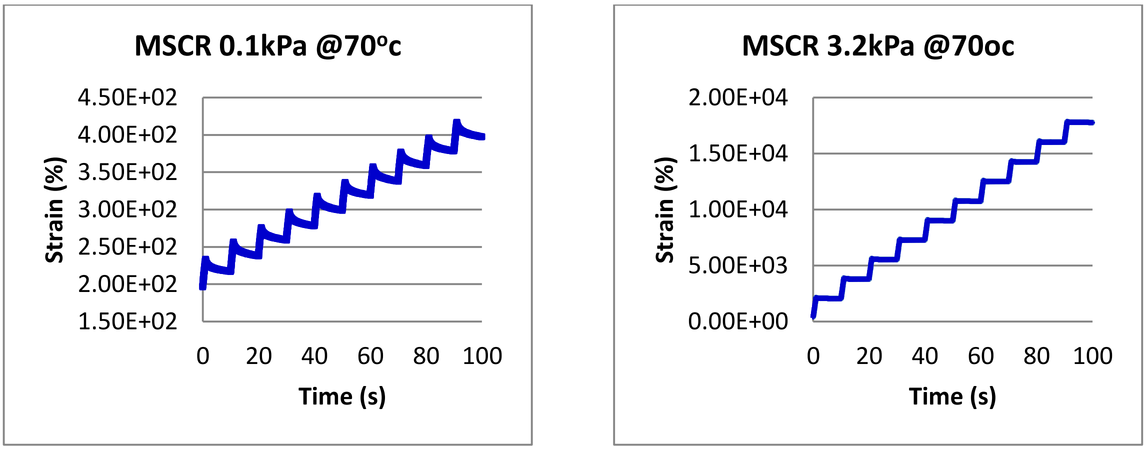
Figure F-8: MSCR graph @ 58°c for 20% Modified Binder



MSCR 0.1kPa @64oc

MSCR 3.2kPa @64oc

Figure F-9: MSCR graph @ 64°c for 20% Modified Binder



MSCR 0.1kPa @70°c

MSCR 3.2kPa @70oc

Figure F-10: MSCR graph @ 70°c for 20% Modified Binder

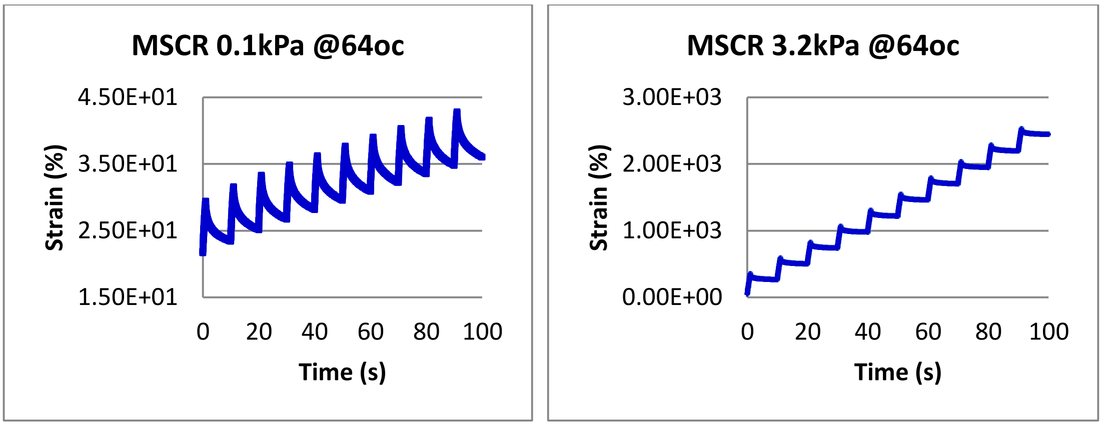


Figure F-11: MSCR graph @ 64°c for 25% Modified Binder

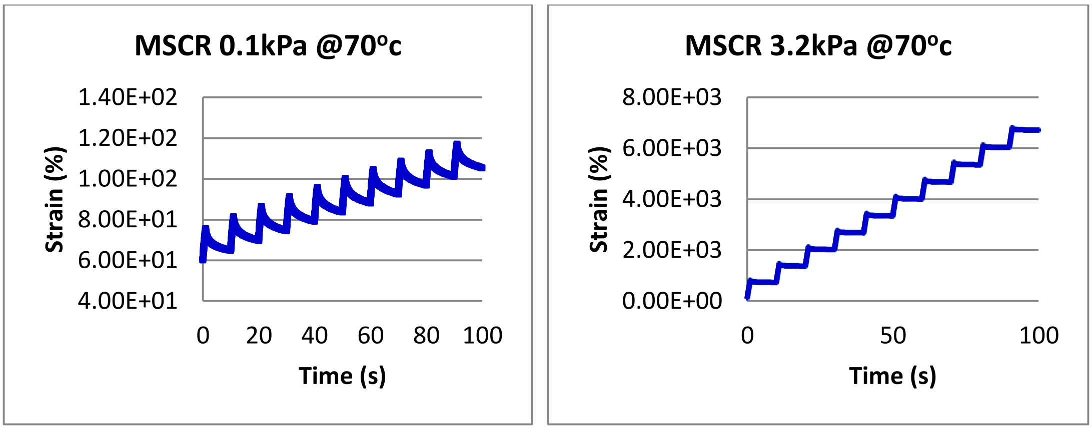


Figure F-15-2: MSCR graph @ 70°c for 25% Modified Binder

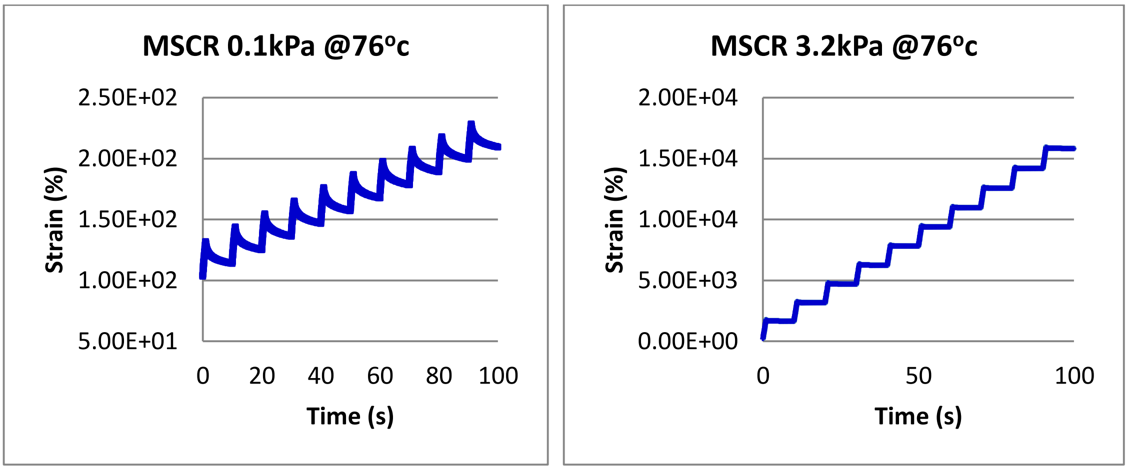


Figure F-13: MSCR graph @ 76°c for 25% Modified Binder