# Properties of Activated Crumb Rubber Modified Binders

by

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A Thesis Presented in Partial Fulfillment
of the Requirements for the Degree
Master of Science

Approved April 2014 by the
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ARIZONA STATE UNIVERSITY

May 2014

ABSTRACT

Pre-treated crumb rubber technologies are emerging as a new method to produce asphalt rubber mixtures in the field. A new crumb rubber modifier industrially known as "RuBind" is one such technology. RuBind™ is a "Reacted and Activated Rubber" (RAR) that acts like an elastomeric asphalt extender to improve the engineering properties of the binder and mixtures. It is intended to be used in a dry mixing process with the purpose of simplifying mixing at the asphalt plant.

The objectives of this research study were to evaluate the rheological and aging properties of binders modified with RuBind™ and its compatibility with warm mix technology. Two binders were used for this study: Performance Grade (PG) 70-10 and PG 64-22, both modified with 25% by weight of asphalt binder. Laboratory test included: penetration, softening point, viscosity, Dynamic Shear Rheometer (DSR) and Bending Beam Rheometer (BBR). Tests were conducted under original, short and long – term aging conditions.

Observations from the test results indicated that there is a better improvement when RuBind™ is added to a softer binder, in this case a PG 64-22. For short-term aging, the modified binder showed a similar aging index compared to the control. However, long term aging was favorable for the modified binders. The DSR results showed that the PG 64-22 binder high temperature would increase to 82 °C, and PG 70-10 would be increased to 76 °C, both favorable results. The intermediate temperatures also showed an improvement in fatigue resistance (as measured by the Superpave PG grading parameter $|G^*|\sin\delta$). Test results at low temperatures did not show a substantial improvement, but

the results were favorable showing reduced stiffness with the addition of RuBind™. The evaluation of warm mix additive using Evotherm™ confirmed the manufacturer information that the product should have no negative effects on the binder properties; that is the modified binder can be used in a warm mix process.

These results were encouraging and the recommendation was to continue with a follow up study with mixture tests using the RuBind™ modified binders.

# DEDICATION

This thesis is dedicated to my wife, Ana Maria Padilla, who has taken a lot of sacrifices, and has provided emotional support throughout my academic career. Without her support, patience and love I wound not be here.

I also want to dedicate this thesis to my entire family starting with my parents, Manuel Medina and Ana Campillo, and to my brothers and sister, Juan, Jorge, Luis, Santos and Ana, who have been there for me in every single step that I have made in life. Without their support and advice I would not be able to accomplish my goals.

ACKNOWLEDGMENTS

I would like to express my gratitude to my advisor Dr. Kamil Kaloush for trusting in me, and for giving me the opportunity to work with him. The support that I have received from him has given me the confidence to continue with my academic education.

I also want to thank Dr. Shane Underwood for promoting critical thinking and for teaching me to pay extra attention to small details either in testing procedures, data analysis, or technical writing.

I would also like to acknowledge Dr. Waleed Zeiada for teaching me how to operate the equipment, perform binder and mixture testing and to be available every time that I had a question. Thanks are also due to laboratory coordinator Kenneth Witczak for being there whenever I needed him.

I would like to thank the personnel from the Arizona Department of Transportation, Dr. Jeffrey Stempihar for letting me carry out some of my binder testing at the ADOT binder laboratory and for being on my committee. A special thanks to Wei Liu and Breeann Sharma for their willingness to help and for taking their time to perform some testing for my research.

Finally, I would like to thank Dr. Angelo Pinto Monteiro, Director de Obras do Interior, Departamento de Estradas de Rodagem, Rio de Janeiro for his support and keen interest in pre-treated crumb rubber technologies, Dr. Jorge Sousa and Mr. George Way of Consulpav International for providing the RuBind modifier and technical support.

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# Chapter 1 Introduction

## 1.1 Background

For the 2015 fiscal year, President Obama sent a proposal that provides $199 billion over four years to continue investing in highways across the United States (U.S. Department of Transportation 2014). The roadway system plays an important role in society because it allows people to commute to work, school, conduct business, and also increase the community productivity which can lead to an economic growth. The United States roadway system is composed of more than 4 million miles of roads; 2.7 million miles are paved and 1.3 millions are unpaved. More than 90% of the pavements in the United States are flexible pavements (Bureau of Transportation Statistics 1960-2012). Agencies and contractors are always looking for innovative ways of improving the performances of pavements to provide an extended life at a lower cost. Throughout the years, many different technologies or design methodologies had evolved to improve pavement performance. For flexible pavements, some of these improvements have been done with binder modification such as the use of polymers, latex, fibers, mineral fillers and crumb rubber from waste tires. Some of these technologies have some advantages and disadvantages. From past experiences, it is known that rubberized asphalt pavements improve asphalt performance compared to conventional pavements (Way 2012). However, some of the issues of using rubberized asphalt are the high mixing temperature and asphalt plant modification. Pre-activated crumb rubber modifiers have been developed to address some of those issues and to improve the bonding between the aggregates and the asphalt binder.

Some research has been done on the use of "Reacted and Activated Rubber", industrially know as RuBind™, in many different types of Hot Mix Asphalt (HMA) with the purpose of simplifying and making the production of HMA more cost effective. This study summarizes the engineering characterization of the virgin as well as binders modified with RuBind™. Standard binder consistency tests, dynamic shear rheometer and bending beam rheometer tests were conducted to compare two binder grades with and without RuBind™ as a modifier.

RuBind™ is composed of fine crumb rubber, soft bitumen and Activated Mineral Binder Stabilizer (AMBS). As an asphalt modifier it is considered an elastomeric asphalt extender which has been shown to improve the engineering properties of asphalt binder and mixes (Wu, et al. 2012). In a recent study to evaluate the mechanical properties of AMBS modified materials following national specifications, the product has shown 40% greater rutting resistance at high temperatures, 40% higher dynamic stability without the decrease of fatigue and water damage susceptibility with 0.5 to 1.2% lower binder content (Consulpav 2013).

As part of reducing the environmental impact footprint, a warm mix additive was used for the RuBind™ modified asphalt binder. It is known that the use of warm mix technology can reduce the mixing and compaction temperatures as much as 56 °C without sacrificing the binder or mix performance (Kim, Lee and Amirkjanian 2011).

## 1.2 Study Objective

The study objective was to compare the engineering binder properties of conventional (virgin) binder to Reacted and Activated Rubber (RAR) modified binders by conventional Superpave Performance Grade guidelines, and to analyze the aging characteristics of each binder type.

## 1.3 Scope of Work

The scope of this study was limited to evaluating two different asphalt binders: a PG 64-22 and a PG 70-10, both obtained from Holly Frontier Refinery (terminal located in Phoenix). Each binder was modified with the addition of 20% RuBind™ by weight to each, which was selected based on previous research that suggested a range of 17 to 26% of RuBind™. (Consulpav 2013). Even though RuBind™ is designed to be used in the dry process, the intent of this study was to evaluate the binder properties of the asphalt rubber by the wet process. Laboratory tests to characterize these binders followed ASTM Standards. The test results were then analyzed and compared between the conventional virgin binder and the RuBind™ modified binder following Superpave PG criteria. A further analysis was also made to evaluate the effect of RuBind™ on the increase of stiffness of the binder. The binder laboratory tests with their respective ASTM Standards are listed below:

- Penetration Test (ASTM D5)
- Softening Point (Ring and Balls) (ASTM D36)
- Rotational Viscosity (ASTM D4402)
- Dynamic Shear Rheometer (DSR) (ASTM D7175)
- Rolling Thin Film Oven (RTFO) (ASTM D2872)
- Pressure Ageing Vessel (PAV) (ASTM D6521)
- Bending Beam Rheometer (BBR) (ASTM D6648)

### 1.4 Report Organization

This report is divided into five chapters. Chapter 1 provides the background and brief description of the work done in this research including the research objective and scope of work. Chapter 2 summarizes the literature review on rubber modified asphalts, warm mix asphalt, and the RuBind™ product, which was conducted in support of the current research study. Chapter 3 provides information about the materials used, sample preparation, the experimental procedures, and the experimental organization. Chapter 4 presents the results and analysis found from the binder characterization tests. Chapter 5 presents a summary and conclusions of this research as well as a list of future research needs.

# Chapter 2 Literature Review

## 2.1 Crumb Rubber Asphalt Binders

The use of crumb rubber in asphalt pavements is a technology created by Charles McDonald, a City of Phoenix engineer. Asphalt rubber comes from the mixing of crumb rubber from waste tires and asphalt binder. This technology was first introduced in the late 1960's as a surface treatment such as crack sealing and chip seals. By that time, the stockpiles of scrap tires where in the hundreds of millions of tires, so McDonald found that he could use a waste product at a low cost to improve the properties of asphalt binder. In his research he found that a minimum of 15% of crumb rubber was needed to achieve the desired properties. McDonald's work led to patented process, referred to as the wet mix process wherein the asphalt binder is mixed with the crumb rubber at 177 °C for about 45 minutes to let the binder digest the crumb rubber. 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 (Way 2012).

### *2.1.1 Crumb Rubber*

In 1990, over 1 billion of scrap tires were in stockpiles in the United States. The scrap tires in 2010 were estimated to be about 111.5 million of tires. This is about 90% reduction in 20 years, and this was achieved thanks to the extended markets for scrap tires that include: the automotive industry, sports surfacing, molded products or playgrounds and animal bedding, civil engineering applications such as rubberized asphalt pavements (Rubber Manufacturers Association 2011). About 12 million scrap tires are used for crumb rubber modified asphalts (Willis, et al. 2012).

In the asphalt pavement industry, scrap tires are ground into crumbs by different grinding methods, each of which produces particles with different sizes and characteristics. Some of the commonly used methods are: cracker mil process, granulator process, micromill process and the cryogenic process. A description of these methods is shown in Table 2-1.

**Table 2-1 Grinding Methods for Scrap Tires (After: NCAT Report 12-09)**

| 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. |
| Micromill | 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. |

### *2.1.2 Dry and Wet Process*

There are two primary processes of mixing crumb rubber: the dry and wet processes. The method of introducing the crumb rubber to the mix differs from one process to the other but they both modify the properties of the mix and are considered crumb rubber modified asphalt mix.

In the dry process, the crumb rubber is added to the aggregates at a proportion of approximately 1-3% by weight of the aggregate in the mix or 0.9% to 2.7% by weight of the mix before the asphalt binder is added. One of the dry processes is called PlusRide in which 1-3% of crumb rubber with particles size ranging from ¼ inch to No. 10 sieve is added to the mix (Federal Highway Administration 1998). The main factor in the design of the Plus Ride system is the air void content, which is usually around 2-4%. Another two critical factors are the time and temperature for reaction of the binder with the ground rubber, these two factors have to be controlled in order to retain the physical shape and the required stiffness of the ground rubber particles. There have been many projects in different states. Some cases show an improvement in the properties, but some of them have shown a net economic loss compared to conventional pavement mix (Huang, Bird and Heidrich 2007).

The process in which the crumb rubber is added to the asphalt binder to act as a modifier is called the wet process. This process has been used since the 1960's in crack sealing, chip seals and other surface treatment as well as in hot mix asphalt pavements (Way 2012). Overall, results from pavements around the United States have shown that the wet process for rubberized asphalt pavement outperforms both conventional pavement mixes and the dry process. The modified process will depend on the blending temperature, the time for digestion, the mixing mechanism, the size and texture of the crumb rubber and the content of aromatics in the asphalt binder (Federal Highway Administration 1998). The binder modification occurs due to physical and chemical interaction between the asphalt and the crumb rubber. The crumb rubber particles swell because of the absorption of lighter fractions contained in the asphalt binder (Xiao, Amirkhanian and Shen 2009). A subset of the wet process that receives interest from time to time is the terminal blend technique. A terminal blend refers to asphalt cement rubber that has been blended at a supply terminal and reacted long enough to maintain a constant viscosity.

According to Mturi et al. (2012), the digestion or reaction process for crumb rubber asphalt binder can be divided into 4 stages. During the first stage the rubberized asphalt will show an increase in viscosity as the rubber particles increase in dimensions. At this stage the lighter fraction of the binder will diffuse into the rubber networks composed of poly-isoprene and poly-butadiene linked by sulfur-sulfur bridges. As lighter fractions are diffused in the rubber particles the sulfur-sulfur bonds within the rubber particles will thermally dissociate. Stage two, is when the blend has reached a maximum viscosity point after thermal dissociation. Stage three is the period in after the binder has reached it maximum viscosity and starts to decrease due to the loss of the sulphur linkages. The thermal dissociation will continue making the viscosity decrease. Finally, stage 4 is when the rubberized binder has reached constant viscosity (Mturi, O'Connell and Mogonedi 2012).

### *2.1.3 Mechanical Properties of Rubberized Asphalt Binder*

One of the main reasons of using crumb rubber is to improve the properties of asphalt binder. Specific properties addressed by this technique include thermal cracking, fatigue cracking and rutting. Bahia and Davis (1995) evaluated the rheological properties of different asphalt binders modified with varying crumb rubber types and content and found that the addition of crumb rubber on the reduction of stiffness at low temperatures is primarily a function of the rubber content and not sensitive to rubber particle or source of the rubber. However, there was a less significant effect of the crumb rubber on binders with lower stiffness (Bahia and Davies 1995). Gopal et al. (2002) found that crumb rubber content improved the resistance to low temperature cracking but that the amount of improvement depended on the asphalt binder, the crumb rubber content, and the particle size. The addition of crumb rubber did not significantly change the m-value and only few cases showed an increase. It was also shown that the crumb rubber particle size can either increase or maintain the low temperature stiffness of the binder, and no improvement was shown on the m-value.

Gopal et al. also evaluated the impact of crumb rubber on the performance grade of the asphalt cement. The conclusion was that some combinations of crumb rubber size, content, and base asphalt can be used without affecting the low temperature performance grade. However, there are some limited cases that might jeopardize the performance grade at low temperatures (Gopal, Sebaaly and Epps 2002).

The National Center of Asphalt Technology (NCAT) conducted a research study on the effect of ground tire particle size and grinding method on asphalt binder properties. The study was performed on twelve crumb rubber samples blended with a single asphalt binder. Twelve blends were prepared with 10% of crumb rubber by weight of asphalt and two extra blends were made with 15% rubber. The test results on performance grade showed that surface area and particle size of crumb rubber had the most influence in increase the high temperature performance grade. At low temperatures, four out of fourteen samples did not meet the m-value specifications at low temperatures. (Willis, et al. 2012).

A research study made by Bahia and Davies on the effect of crumb rubber modifiers on performance of asphalt binder in which they compared different sources of crumb rubber tire by different grinding process on binder with the following characteristics described in Table 2-2:

**Table 2-2 Asphalt Binder Grade and Composition (After: Bahia and Davis 1994)**

| | **Asphalt Type** | | | |
|---|---|---|---|---|
| | **A** | **B** | **C** | **D** |
| **Grade** | **200/300** | **AR-2000** | **AC-10** | **AC-10** |
| **SHRP PG:** | 46-34 | 58-16 | 58-16 | 58-22 |
| **%Asphaltenes** | 16.2 | 5.0 | 13.0 | 4.8 |
| **% P Aromatics** | 36.0 | 51.0 | 38.7 | 50.0 |
| **%N Aromatics** | 36.1 | 35.3 | 34.6 | 41.3 |
| **%Saturates** | 11.4 | 6.6 | 11.9 | 3.0 |

After running Dynamic Shear Rheometer testing on the modified binders, the results showed an increase in dynamic modulus |G*| making the asphalt binder more resistant to permanent deformation. However, Bending Beam Rheometer test results (stiffness and m-value) showed no significant improvement compared to conventional binder. It was concluded that at high temperatures the effect will come from the type of rubber, at intermediate temperatures it will be dependent on the type of asphalt and at low temperatures, the change in stiffness and m-value are relative small (Bahia and Davies 1994).

#### *2.1.4 Reacted Activated Rubber*

This research studies the characterization of reacted and activated rubber (RAR) in asphalt binders. There are many different technologies used to treat the crumb rubber before adding to the binder. The essential goal of rubber activation is to modify the surface of the rubber so it will enhance the compatibility with a polymer matrix (Kocevski, et al. 2012). Some of these technologies include the use of furfural, hot water activation, grafting of acrylic acid and the use of a reacted and activated elastomers called RuBind™. The pre-treatment or activation of crumb rubber is not new and has been used in other industries.

The same technology of activated rubber can be applied in pavement. One of these activations processes can be done by using furfural. Furfural is an aromatic aldehyde derived from agricultural byproducts. Shatanawi et al. (2012) evaluated the effects of furfural on the rheological properties of binders. Furfural has less aromatic stability compared to benzene, and therefore, it will react more readily during hydrogenation, which will improve compatibility with asphalt. In addition, when furfural is heated it will react with phenol derivatives with the presence of carboxylic acids in asphalt binders to form a thermosetting resin. Thus, adding furfural to crumb rubber creates a more reactive rubber surface that will affect the rheological properties of the crumb rubber binder (K. M. Shatanawi, et al. 2012).

Shatanawi et at. (2009) also evaluated the crumb rubber activation by the hot water activation process. The lack of solubility and compatibility of the crumb rubber particles in the binder can reduce the quality of the binder, and in some cases lead to settlement of the crumb rubber modified binders produced by the wet method. It has been hypothesized that hot water can improve the solubility of crumb rubber in asphalt binders. According to Shatanawi when crumb rubber is mixed with hot water for a certain period of time and temperature, some excess oils and chemicals present in the crumb rubber will be removed and crumb rubber surface activation will be achieved (K. Shatanawi, et al. 2009)

The second method is the surface modification of ground rubber by bulk polymerization of acrylic acid without the use of an initiator. By definition, polymerization is the conversion of a monomer into a polymer without the use of a solvent. Surface modification on the ground rubber particles are obtained by using acrylic acid in a nitrogen atmosphere to keep the oxygen and moisture out of the reaction system. After some reaction time, grafting of the acrylic acid will be done on the rubber particles modifying the rubber particles making them more reactive and compatible to asphalt binder (Kocevski, et al. 2012).

The particular method of interest in this study is reacted and activated elastomeric additive, RuBind™. RuBind™ is a new reacted and activated rubber composed of soft bitumen, fine crumb rubber and activated mineral binder stabilizer (AMBS), Figure 2-1. According to the manufacturer, RuBind™ is produced by a short-time blending and activation process that forms a dried granulated activated rubber. RuBind™ is an elastomeric extender that increases resilience and recovery properties as well as increases PG of a binder and is intended to replace some binder in the mix.

(a) (b) (c)

**Figure 2-1 (a) Soft Asphalt Binder (b) Fine Crumb Rubber (c) AMBS (Source: Consulpav 2013)**

RAR, as mentioned before is composed of bitumen, AMBS, and fine crumb rubber with 100% of the particles passing the No. 30 sieve. The asphalt binder can be any conventional soft bitumen. According to the manufacturer the use of a soft asphalt binder in RAR is used to mitigate some of the increase stiffening caused by the rubber, which consequently enables to produce HMA at common mixing and compaction temperatures. The crumb rubber used comes from truck and automobile scrap tires which are processed and ground by ambient or cryogenic process. According to Consulpav, the optimal particle size for the crumb rubber is finer than 1.0 mm but a max particle size of No. 30 is preferred, Figure 2-2 shows the typical rubber particle gradation for the RAR.

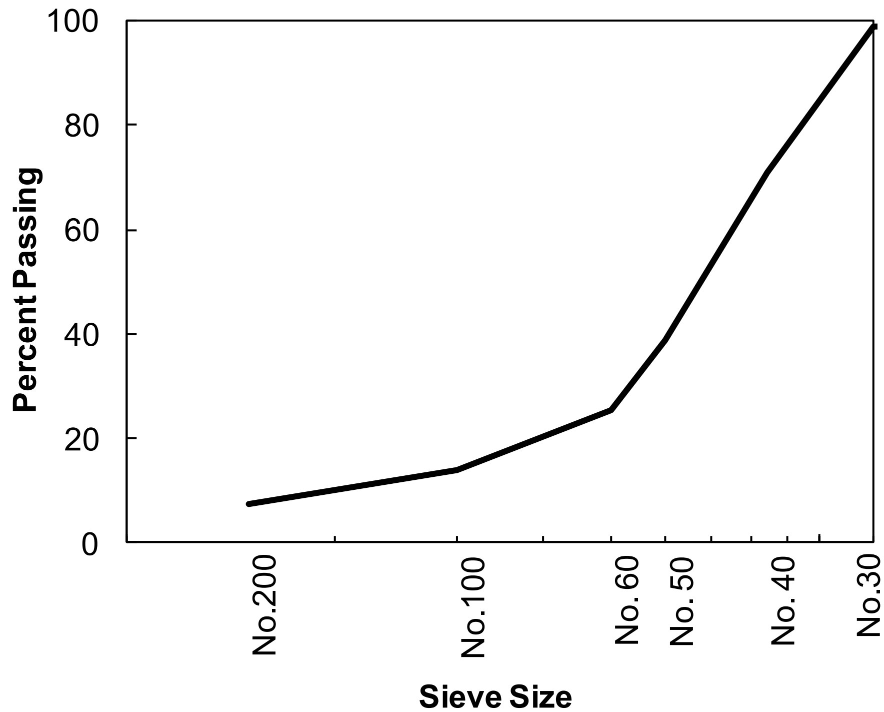
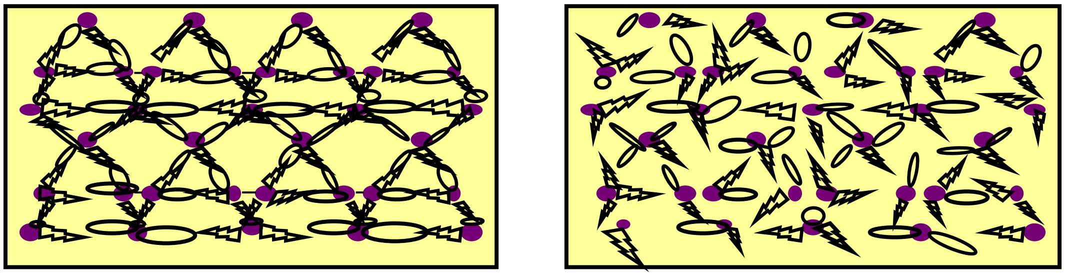



**Figure 2-2 Gradation Chart Distribution on RAR Sample**

The third component of RAR, AMBS is an activated fine raw silica mineral, approximately 40 μm and finer, which is a waste by-product of the phosphate mining industry mining (Consulpav 2013). AMBS is used as a binder stabilizer with the activation provided by the thixotropic properties (shear-thinning) of the asphalt binder. The mechanism of this process is seen in Figure 2-3. Shear-thinning is the characteristic of a non-Newtonian viscous liquid to show higher viscosity at a low shear rate than exists at a high shear rate. This behavior can be contrasted with that of a Newtonian fluid to exhibit the same viscosity regardless of the shear rate. In practice, this behavior means that when the asphalt is stored and during hauling the binder should have a high viscosity to prevent draindown and during mixing and compaction the mixture viscosity will be lower thus making the mix easier to work.



(a) (b)

**Figure 2-3 (a) Steady Structure at Static State (b) Damaged Structure at Active State (Source: Wu, et al. 2012)**

With respect to performance, research has shown that AMBS will increase the water resistance, rutting, and fatigue cracking resistance with 0.5-1.2% lower binder content. A study made by Wu, et al. (2012) showed that after performing an Immersed Marshal Test on mixes with modified binders containing AMBS the residual stability given by Equation increased after adding AMBS. This finding indicates that the mix retained more strength after it was water conditioned (Wu, et al. 2012).

$$MS_0 = \frac{MS_1}{MS} \times 100$$

Where;

$MS_0$ = Residual stability, %

$MS_1$ = Stability after immersed in water for 48 h, kN

MS = Stability after immersed in water for 0.5 h, kN

Souza (2012) also performed the Freeze and Thaw Splitting Test. The parameter used for this test is the tensile strength ratio (TSR) and is calculated by using Equation shown below:

$$TSR = \frac{R_{T2}}{R_{T1}} \times 100$$

Where;

TSR = Tensile strength ratio, %

$R_{T1}$ = Strength without freeze and thaw, MPa

$R_{T2}$ = Strength after freeze and thaw, MPa

The results from this test showed a greater TSR value on mixes with AMBS than conventional mixes, which indicates that the AMBS modified mixtures will perform better with respect to moisture damage (Wu, et al. 2012).

A rutting evaluation on RAR mixes was performed using the standard method T0719-1993. This standard method commonly used by the highway engineering of China, requires the preparation of 30x30x5 cm beams and then test them at a temperature of 60 °C with a rubber wheel load pressure of 0.7 MPa, at a frequency of 42 times per minute moving back and forth a distance of 230 mm (Wu, Yang and Xue 2004). The rutting test results showed that mixes modified with AMBS showed a higher stability value than conventional mixes meaning that has a lower rutting susceptibility (Wu, et al. 2012).

By mass, a typical RAR is made of 56% crumb rubber, 20% bitumen, 20% AMBS and 4% hydrated lime. The composition by volume of RAR, assuming typical specific gravity values from crumb rubber, hydrated lime, bitumen and fine silica (AMBS) are as follow: 65% of crumb rubber, 23% soft bitumen, 10% AMBS and 2% hydrated lime. The basic mechanism of RAR is that as charged crumb rubber particles of inorganic material are contained in a liquid medium, in this case the bitumen, AMBS composed of organic molecules which are hydrophobic partially charged will be attracted to the opposites charge particles from the crumb rubber, and will connect to each other forming a network of particles. This network created with the elastomeric components will enhance the mechanical properties and structure of the modified asphalt binder with better elastic behavior. The manufacturer claims that once the RAR has been dispersed into the asphalt binder it will improve the bonding at the binder-aggregate interface. As a result of this connection it will improve moisture susceptibility. This bonding network will not be possible without AMBS. Figure 2-4 is shows a schematic of this process.

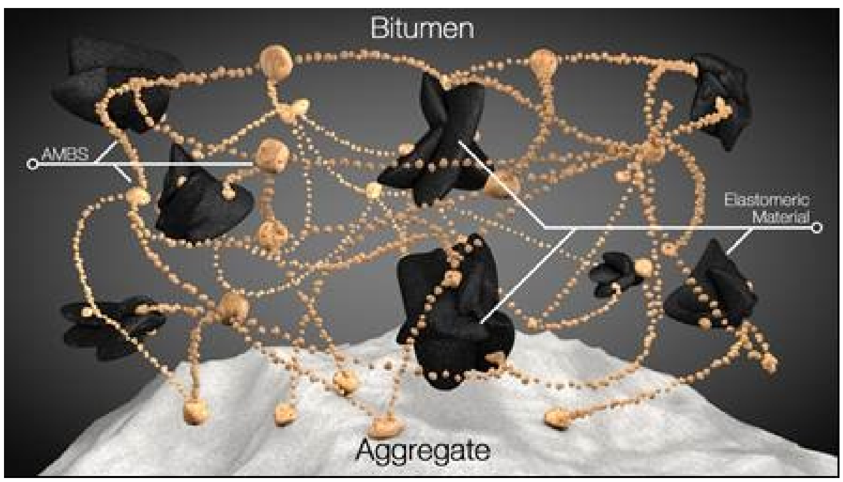



**Figure 2-4 Basic Model and Mechanism (Source: Consulpav, 2013)**

Sousa (2013) reported that a study made with Russian asphalt binders showed an improvement on the rheological properties of the bitumen with the addition of 21% RAR. The original grade of the asphalt binders were: two PG 64-22, PG 64-28, and PG 70-34. The Superpave performance grade criteria showed that all the binders improve their high temperature performance grade to PG 88 to PG 94, this means the RAR modified asphalt binder met specifications at 88 °C and 94 °C. In practice, there are no PG 88 nor PG 94.

Figure 2-5 shows the improvement in PG at high temperatures and not much improvement at low temperatures.

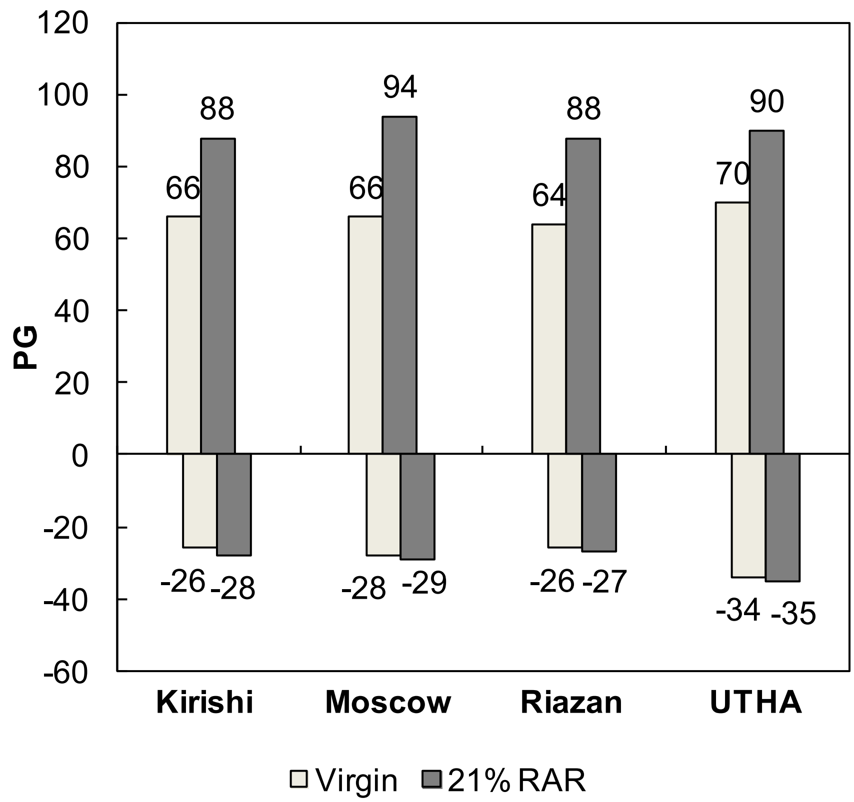



**Figure 2-5 PG Improvement on Different Bitumen after Adding 21% RAR (After: Consulpav, 2013)**

A different study made with Israel neat bitumen graded as PG 70-16, PG 70-16, PG 76-10 and PG 58-22 (S). Only one PG 70-16 and S binders were modified by adding 7, 14, 21 and 28% of RAR. Using Superpave performance grade criteria, Sousa (2013) evaluated the effect of crumb rubber on the performance grade of asphalt binder. It was found that the PG 70-16 binder increased its high temperature performance grade to PG 82 with 21% RuBind™. The high temperature grade of the S binder improved from PG

58 to PG 82. Low temperatures results after doing bending beam rheometer test did not showed any significant improvement for both binders (Consulpav 2013).

## 2.2 Warm Mix Additive

Environmental protection and sustainability has taken on an increased importance all over the world. A few decades ago the use of crumb rubber meant a significant improvement in asphalt mix technologies. More recently, the use of warm mix additives (WMA) in HMA to reduce the mixing and compaction temperatures has become another popular technology to achieve these goals. Agencies across the country have done some studies in warm mix technologies and many of the states has done field experiments approaching 200 projects since 2004, Table 2-3 shows some projects done in the United States (Kim 2010)

**Table 2-3 WMA Projects done by different States (After: Kim, 2010)**

| Organization | Project |
|---|---|
| Caltrans | • Test Track 80m by 8m in 2008<br>• Two WMA pavement sections in I5 Fresno and Merced counties in 2009<br>• Rio Dell//Scotia Rehabilitation Project on U.S. Hwy 101. WMA in rubberized HMA-Gap Graded Mix |
| NCAT | • Test section NCAT test track (2005) |
| Florida | • In 2004 they did a demostration project using Aspha-min<br>• 95 Total WMA projects<br>• 19 current WMA projects |
| Indiana | • 660 tons of WMA with 15% RAP for a county road |
| Texas | • Loop 368 in San Antonio in 2006 |
| Colorado | • WMA section on I-70 |
| Ohio | • Test pavement on Rt 541 using WMA with SBS and 15% RAP |
| Yellowstone National Park | • 30,000 tons of asphalt mixture splitted into different WMA technologies |
| Arizona | • Project SPR-631. Two phase project in the use of WMA in asphalt rubber-asphaltic concrete friction courses. |
| Montana | • I-15, Beaverhead County, Butte District. 17.1 miles (2010) |
| North Dakota | • 5 miles of WMA of from project SS-4-041 2011 |

The use of crumb rubber represented a huge improvement towards a more sustainable pavement practice by recycling or reusing waste tires. The process of producing crumb rubber modified mixes requires higher temperatures to maintain workability during mixing and compaction. Warm mix additive technologies can be combined with rubberized asphalt pavement to reduce mixing temperatures while maintaining the same workability. One of the advantages of warm mix additives in asphalt pavement is the reduction in mixing temperatures, and thus reduction of the carbon footprint. There are several warm mix technologies that are being used in recent years, but can be mainly classified in three groups: wax or organic additives, water foaming, and chemical additives. Waxes or organic additive technology refers to the Fischer-Tropsch paraffin wax which is an asphalt modifier that improves asphalt flow by reducing the viscosity of the binder. The second group is a water foaming technology which consists in adding a small amount of water to hot asphalt, when the water is added it will vaporize and the vapor will be encapsulated in the binder. This will create a foamed binder which improves the aggregate coating and reduces the viscosity of the binder. Zeolites can be used as an alternative to adding water to the hot binder. Zeolites are minerals that contain approximately 20% by weight of water, upon heating the asphalt binder, water is released and the foamed asphalt is produced. The third group consists in chemical additives. Usually manufacturers do not disclose their chemical formulation but they state that their additive improves workability, coating and adhesion at a lower temperature. The additive used for this project was Evotherm provided by Mead Westvaco Asphalt Innovations which, according to the manufacturer is a water free "chemical package" that reduces the internal friction between the aggregate and the thin films of binder when mixing and compaction. It is not disclosed by the manufacturer the mechanism of reducing the internal friction between the aggregates and the binder. The following table (Table 2-4) shows some of the WMA technologies available and their group classification (NCHRP Report 691 2011).

**Table 2-4 WMA Technology (After: Cheng, Lane and Hicks, 2012)**

| Product | Type of Additive |
|---|---|
| Rediset WMX | Chemical |
| CECABASE RT | Chemical |
| Aspha-min | Foaming |
| Double Barrel Green | Foaming |
| WAM Foam | Foaming |
| Green Machine | Foaming |
| Revix | Chemical |
| Hgrant Wamrm Mix System | Foaming |
| Evotherm | Chemical |
| Sasobit | Organic |
| Advera WMA | Foaming |

Previous studies on WMA have shown a reduction of emissions during construction compare to conventional HMA pavements by decreasing the mixing and compaction temperatures. Table 2-5 shows the reduction of emissions during construction by using different WMA technologies. The data presented in this table is a compilation from different projects at different times (Gandhi 2008).

**Table 2-5 Emission Reduction by Different WMA Technology (After: Gandhi, 2008)**

| | Warm Mix Aspahlt Technology | | | |
|---|---|---|---|---|
| **%** | **Aspha-Min[1]** | **Sasobit[2]** | **Evotherm[3]** | **WAM-foam[4]** |
| **$SO_2$** | 17.6 | - | 81 | n/a |
| **$CO_2$** | 3.2 | 18 | 46 | 31 |
| **CO** | n/a | n/a | 63 | 29 |
| **NOx** | 6.1 | 34 | 58 | 62 |
| **THC** | 35.3 | n/a | n/a | n/a |
| **VOC** | n/a | 8 | 25 | n/a |

Some of the disadvantages found by the National Center for Asphalt Technology (NCAT) in WMA are the tendency to rut and the moisture susceptibility of the pavement caused by the temperature reduction and thus not drying the aggregate completely (Akisetty 2008).

## 2.3 Aging of Asphalt Binder

It is known that asphalt binders undergo stiffening over time that the industry commonly refers as aging. Some of the causes of aging are the volatilization of low molecule components of asphalt, oxidation, exudation and steric hardening. It is agreed that the most important factor is the oxidation of the asphalt due to the reaction of asphalt molecules to the atmospheric oxygen.

To better understand the aging process is important to first know the components of asphalt. There are different ways to classify the asphalt components but the most commonly used is done by the selective adsorption-desorption chromatography. The

[1] Data from Charlotte, North Carolina in September 2004
[2] Data from M-95 Iron Mountain, Michigan in September 2006
[3] Data from Road #46 in Ramara, Canada in 2005
[4] Data from FV 82 Frogn in Nesodden, Norway in April 2001

asphaltenes, the most polar component, are first separated and then the maltenes fraction is further separated into saturates, aromatics and resins. Research done by Petersen has shown that polar fractions will promote higher oxidation on less polar fractions. These polar fractions will react with atmospheric oxygen to form ketons and sulfoxides. Asphalt binder that contains high polar aromatics and asphaltenes showed the highest formation of ketones after aging. But this is not the only factor that affects oxidation, it is necessary to understand the chemical functionality, in other words the molecular interaction to form secondary bonds. The higher the bonding forces the higher the viscosity. Also the content of strongly interaction polar functional groups and the solubility power are key factor in the aging characteristics of the asphalt binder (Petersen 1984)

In practice, two aging conditions are evaluated, short term and long term aging. Short term aging is the aging that occurs during production, transportation and construction of the pavement. During this process the pavement is exposed to high temperatures and most of the aging occurs by oxidation and volatilization of low molecule components of the asphalt (Shatnawi 2012). Long term aging occurs when the pavement is exposed to a long period of time to atmospheric oxygen, heating and solar radiation. Long term aging will be mostly caused by oxidation process described earlier.

A study made by Liang and Lee on short and long term aging rheological properties from different crumb rubber content in asphalt binders, showed that after short aging the crumb rubber modified asphalt binder increased the viscosity more significantly than the conventional binder. This research also showed a more significant increase in shear modulus |G*| compared to conventional binder. The increase in |G*| and the parameters $|G^*|/\sin\delta$ and $|G^*|\sin\delta$ shows a better resistance to permanent deformation and fatigue cracking as the crumb rubber content increases (Shatnawi 2012)

## 2.4 Particulate Composite Models

Many models have been proposed to predict the viscosity of composites. Since the viscosity is analogous of stiffness, these models are also interchangeable to predict shear modulus or elastic modulus (Ahmed and Jones 1990). Einstein equation is one of the models commonly used to predict modulus of particulate composites. This model assumes rigid spherical particles, and that the volume fraction of the particulate is the important parameter, and that is not dependent on the particle size and mass (Fu, et al. 2008). Einstein equation to predict viscosity ratio is as follows

$$\frac{\eta_c}{\eta} = 1 + 2.5C_v$$

Where;

$\eta$ = Viscosity of the matrix

$\eta_C$ = Viscosity of the composite

$C_v$ = Volumetric concentration of the filler.

A modification to Einstein equation was done by Roscoe (1952). Roscoe furthers argues that when the volume fraction of particulate filler is over 5%, Einstein model is invalid (Underwood 2011). A better approximation to the viscosity ratio from the composite and the matrix is given by Roscoe's equation as:

$$\frac{\eta_c}{\eta} = \left(1 - C_v\right)^{-2.5}$$

The micromechanical models have had great success in predicting elastic moduli of composites. Micromechanical models, unlike empirical base models, they based their approach on the material properties and particle interaction (Fu, et al. 2008). The micromechanical models used in this study were Hashin and Christensen models given by the following equations respectively.

$$\frac{G_c}{G_m} = 1 + \frac{15\left(1-\nu_m\right)\left(\frac{G_p}{G_m}-1\right)C_v}{7-5\nu_m+2\left(4-5\nu_m\right)\left[\frac{G_p}{G_m}-\left(\frac{G_p}{G_m}-1\right)C_v\right]}$$

$$A\left(\frac{G_c}{G_m}\right)^2 + B\left(\frac{G_c}{G_m}\right) + C = 0$$

Where;

$$A = 8\left(\frac{G_p}{G_m}-1\right)\left(4-5\nu_m\right)k_1C_v^{10/3} - 2\left[63\left(\frac{G_p}{G_m}-1\right)k_2+2k_1k_3\right]C_v^{7/3} +$$
$$252\left(\frac{G_p}{G_m}-1\right)k_2C_v^{5/3} - 50\left(\frac{G_p}{G_m}-1\right)\left(7-12\nu_m+8\nu_m^2\right)k_2C_v + 4\left(7-10\nu_m\right)k_2k_3$$

$$B = -4\left(\frac{G_p}{G_m}-1\right)\left(1-5\nu_m\right)k_1C_v^{10/3} + 4\left[63\left(\frac{G_p}{G_m}-1\right)k_2+2k_1k_3\right]C_v^{7/3} -$$
$$504\left(\frac{G_p}{G_m}-1\right)k_2C_v^{5/3} + 150\left(\frac{G_p}{G_m}-1\right)\left(3-\nu_m\right)\nu_mk_2C_v + 3\left(15\nu_m-7\right)k_2k_3$$

$$C = 4\left(\frac{G_p}{G_m}-1\right)\left(5\nu_m-7\right)k_1C_v^{10/3} - 2\left[63\left(\frac{G_p}{G_m}-1\right)k_2+2k_1k_3\right]C_v^{7/3} +$$
$$252\left(\frac{G_p}{G_m}-1\right)k_2C_v^{5/3} + 25\left(\frac{G_p}{G_m}-1\right)\left(\nu_m^2-7\right)k_2C_v - \left(7+5\nu_m\right)k_2k_3$$

$$k_1 = \left(\frac{G_p}{G_m} - 1\right)\left(49 - 50\nu_p\nu_m\right) + 35\left(\frac{G_p}{G_m}\right)\left(\nu_p - 2\nu_m\right) + 35\left(2\nu_p - \nu_m\right)$$

$$k_2 = 5\nu_p\left(\frac{G_p}{G_m} - 8\right) + 7\left(\frac{G_p}{G_m} + 4\right)$$

$$k_3 = \left(\frac{G_p}{G_m}\right)\left(8 - 10\nu_m\right) + \left(7 - 5\nu_m\right)$$

$G_p$ = Stiffness of the filler

$G_m$ = Stiffness of the matrix

$\nu_p$ = Poisson's ratio of the filler

$\nu_m$ = Poisson's ratio of the matrix

$C_v$ = Volumetric concentration of the filler

There are many models that predict the stiffness of composites. The first two models Einstein's and Roscoe's assumes that the stiffness is a function of the volume fraction of the particles, whereas the Christensen's and Hashin's models consider the properties of both, the matrix and the particles. These models are some of the basic models used to predict stiffness of composites, which can capture a broad range of predicted values.

# Chapter 3 Materials and Experimental Procedures

This chapter provides a description of the materials, samples preparation procedures, and experimental procedures used in this study to accomplish the objective of the research.

## 3.1 Binder

This study included two types of asphalt binders: a PG 64-22 and a PG 70-10 provided by Holly Frontier Refinery from Glendale, Arizona. These two binders were modified with RuBind™ at a rate of 20% by weight of the total blend (RAR+asphalt binder), that is, 25% by weight of the base binder. The volume fraction of RAR in the blend is approximately 18%, and 82% of the binder. The volume was approximated based on typical density of crumb rubber and asphalt binder (Thodesen, Shatanawi and Amirkhanian 2009).

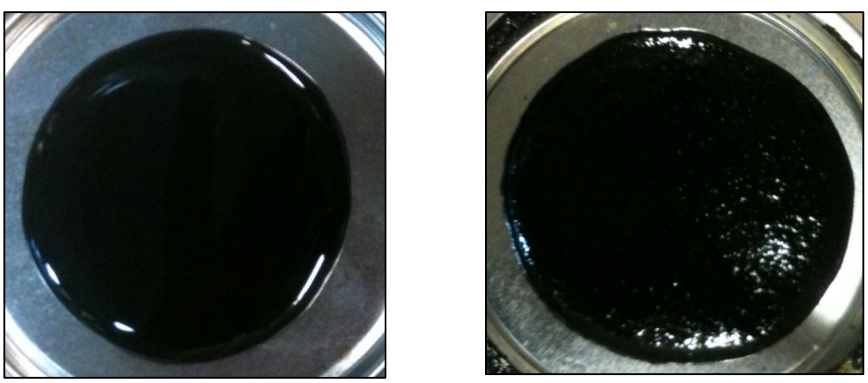
## 3.2 Specimens Preparation

Un-aged virgin binder samples were prepared by heating the binder for two hours until it reached 130 °C, and then placing them to the respective containers in preparation for each test. For penetration test, SC-500 tinned sample containers with 2.2"Dia x 1.6"H were used. For the softening point the binder was poured into the standard rings. Then, 12 g of binder were poured into the Brookfield Viscometer containers to test for higher temperature viscosities.

Modified RuBind™ binder was heated for 3 hours until the binder reached 170 °C. Then 480 g of virgin binder was mixed with 120 g of RAR; this is 20% by total weight of asphalt and RuBind™ combined, or 25% by weight of the asphalt. To maintain the temperature at 170 °C a heating plate was used and mixed at 600 RPM for 30 minutes using an Arrow 1750 electric mixer, Figure 3-1. Once the mixing was done, the binder was poured into the containers for each test.

**Figure 3-1 Arrow 1750 Electric Mixer**

Figure 3-2 shows a picture of the RAR modified binder and the original virgin binder. These pictures show a difference in texture. The original virgin binder has a really smooth and shiny surface as compared to the modified binder which has a rough, gritty surface, a characteristic of crumb rubber modified binders.



(a) (b)

**Figure 3-2 (a) Original Virgin Binder (b) RuBind™ Modified Binder**

Short term aging was performed using the Rolling Thin Film Oven (RTFO) following ASTM D2872 standard procedure. After the aging was carried out, the residue from 8 RTFO bottles were scraped and poured into a clean quarter paint container, and then let sit for testing the following day. Then, the sample container was re-heated for 1 hour and stirred every 30 minutes until the temperature reached 130 °C so that the binder would be fluid enough to be poured into different molds or container for different testing.

Long term aging was performed on a RTFO residue in a Pressure Ageing Vessel (PAV) as per ASTM D6521. After the long term aging, the sample binder was poured into a clean metal container and the samples were tested the next day. The sample container was heated to be fluid enough to pour it into the molds for each test.

The use of warm mix additive evaluation was carried out with the Evotherm™ additive in combination with the PG 64-22 binder. First, virgin binder was heated to 130 °C and then 0.5% of Evotherm™ by weight of asphalt binder was added and mixed for 30 minutes. After the mixing was done, 12 g of binder were poured into viscosity tubes, and 25 mm samples were prepared for DSR testing.

The sample preparation for the RuBind™ modified binder was carried out by the same mixing procedure as before. The only difference is that immediately after RuBind™ was added to the asphalt binder, 0.5% by weight of the binder of Evotherm™ was added and mixed for 30 minutes as prescribed by the manufacturer. Then the blend was poured into the respective molds for DSR and rotational viscosity test.

## 3.3 Warm Mix Additive: Sample Preparation Using Evotherm™

For this part of the project only the PG 64-22 binder was used with Evotherm™. The mixing procedure followed the manufacturer's recommendations. The dosage used for both modified and unmodified asphalt binder was 0.5% by weight of total asphalt binder. The dosage for each blend can be seen in Table 3-1.

**Table 3-1 Asphalt Blend Dosage**

| Material | Modified | Control |
|---|---|---|
| Asphalt PG64-22 (g) | 240 | 300 |
| RuBind™ (g) | 60 | 0 |
| Evotherm™ (g) | 1.2 | 1.5 |

The Control blend consisted of PG 64-22 asphalt binder and Evotherm™ by the dosage described in the previous table. According to manufacturer's recommendations, 300 g batches were made. The previously described procedure for blending was used. Figure 3-3 shows the addition of Evotherm™ to the asphalt binder. After each blend was made, they were poured into their respective containers for Brookfield and DSR testing.

**Figure 3-3 Adding Evotherm™ to Control Asphalt Binder**

## 3.4 Number of Tests

The number of tests for this study is shown in Table 3-2.

**Table 3-2 Number of Tests**

| Test | Age Condition | Description | No. of Tests |
|---|---|---|---|
| Penetration ASTM D5 | Un-aged | 3 temperatures x 4 binders x 1 replicate | 12 |
| | RTFO | 1 temperature x 4 binders x 1 replicate | 4 |
| | PAV | 1 temperature x 4 binders x 1 replicate | 4 |
| Softening Point ASTM D36 | Un-aged | 4 binders x 2 replicates | 8 |
| | RTFO | 4 binders x 2 replicates | 8 |
| | PAV | 4 binders x 2 replicates | 8 |
| Rotational Viscosity ASTM D442 | Un-aged | 4 temperatures x 6 binders x 2 replicates | 12 |
| | RTFO | 4 temperatures x 4 binders x 2 replicates | 8 |
| | PAV | 4 temperatures x 4 binders x 2 replicates | 8 |
| Dynamic Shear Rheometer ASTM D7175 | Un-aged | High temperature x 6 binders x 2 replicates | 12 |
| | RTFO | High temperature x 4 binders x 2 replicates | 8 |
| | PAV | High temperature x 4 binders x 2 replicates | 8 |
| Bending Beam Rheometer ASTM D6648 | PAV | Low Temperature x 4 binders x 2 replicates | 8 |

The total number of test performed was 108. The following Figure 3-4 shows a schematic diagram of the binder testing program.

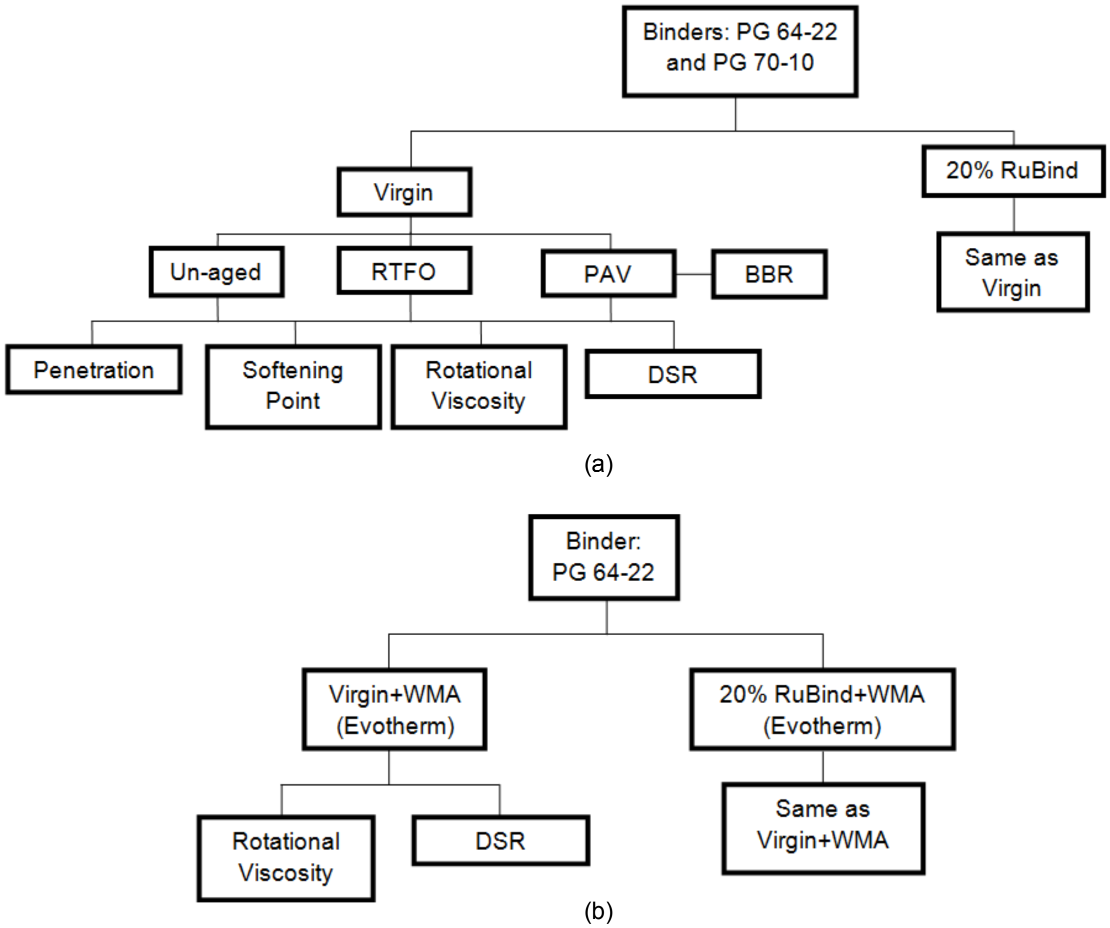



**Figure 3-4 (a) Binder Test Flowchart (b) WMA Test Flowchart**

## 3.5 Binder Characterization

Asphalt binder is a viscoelastic material that has higher modulus and more elastic response at low temperatures; whereas it becomes more like a viscous fluid at high temperatures. Asphalt characterization is very important because it helps in understanding the temperature susceptibility of the consistency and mechanical properties of each binder. Consistency tests were performed to collect information about the behavior of these binders with respect to temperature. The importance of adopting Performance Grade asphalt binder tests is that it allows the measurements of physical properties of the binder that prior research has shown is related to field performance. The binder is tested at the same range of temperatures that the binder will be exposed during its life cycle. Table 3-3 shows some of the advantages of using Superpave performance grade specifications.

**Table 3-3 Prior Limitations vs. Superpave Testing and Specification Features (After: Consulpav, 2013)**

| 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:<br>1. Original asphalt binder prior to mixing with aggregate.<br>2. Aged asphalt binder after HMA production and construction.<br>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. |

## 3.6 Binder Consistency Test-Viscosity Temperature Relationship

### *3.6.1 Penetration*

Penetration test is performed at different temperatures to measure consistency of the binder. Penetration can be correlated to viscosity using empirical formulation. Higher penetration at a given temperature indicates that the binder has a softer consistency. The binder sample was prepared as per ASTM D5 standard specifications. The un-aged binder test was conducted at 4, 24 and 30 °C using a 100 g load for 5 seconds. The RTFO and PAV residues were tested at room temperature of 24 °C. The apparatus used was a Universal Penetrometer using a standard needle shown in Figure 3-5.

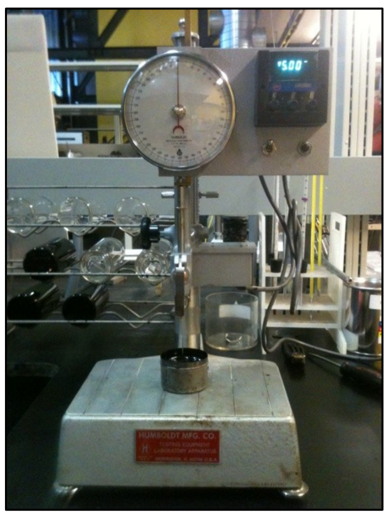


**Figure 3-5 Universal Penetrometer**

Penetration can be converted in viscosity using a model developed at the University of Maryland and it is valid for a wide range of penetration values (Kaloush, et al. 2008). The following equation is used to convert the penetration values into viscosity in poise.

$$\log_{\eta} = 10.5012 - 2.2601 \times \log(pen) + 0.00389 \times \log(pen)^2$$

Where;

η = Viscosity, Poise

pen = Penetration

### *3.6.2 Softening Point*

The softening point of a binder usually corresponds to a viscosity of 13,000 poise. This test method is specified in ASTM D36, and it consists of two brass rings loaded with a 3.5 g steel ball in the center of each ring (Figure 3-6). After the samples are prepared, they are placed in an assembly suspended in a beaker of water at 4 °C and then heated at a specified rate. When the steel ball touches the lower plate, which is at 25 mm below the rings, the temperature is recorded as the softening point. This test as stated in the ASTM standard is useful for establishing uniformity in the sources of supply or shipments. Softening point is also used in binder classification. The relationship of softening point temperature and viscosity was found by Shell Oil Researchers; again a binder at its softening point will have an approximately viscosity of 13,000 poises.

**Figure 3-6 Softening Point Apparatus**

### *3.6.3 Rotational Viscosity*

A rotational viscosity test is used to determine the viscosity of a binder by measuring the torque required to maintain a constant rotational speed of a spindle that is submerge in the binder at the test temperature. This test is commonly used to calculate the viscosity of asphalt binders at high temperatures, so mixing and compaction temperatures of asphalt mixes can be determined. Rotational viscosity test was performed using ASTM D4402 standard. A Brookfield™ viscometer was used with a Thermosel™ temperature control system (Figure 3-7). It is realized that for crumb rubber modified binders the use of ASTM D2196 that allows for using a larger cup size is recommended. However, the RuBind™ particles were small enough that justified the use of ASTM D4402 with no reservations on obtaining reasonable values for comparative purposes. A binder sample of 12 g was placed into the sample holder and then placed into the thermal chamber at temperatures that ranged from 93 to 176 °C. The test was performed using a number 27 spindle at different rotational speeds so that the torque percentage was kept over 10% and under 95%.

**Figure 3-7 Brookfield Rotational Viscometer**

## 3.7 Dynamic Shear Rheometer Test

The importance of this test is to measure the rheological properties of binder. Two of the properties measured are the dynamic shear modulus (|G*|) and the phase angle (δ) at intermediate temperatures (19-45 °C) for pressure aging vessel (PAV) residue and high temperatures (54-82 °C) for original and rolling thin film oven (RTFO) aged binders. The importance of these two parameters is to characterize the viscous and elastic properties of a binder. The phase angle and dynamic modulus will be indicators of the binder elastic and viscous behavior at a given temperature.

The original binder was tested using 25 mm plates with a 1mm gap at 12% strain control mode. The RTFO aged binder residue was tested using a 25 mm plate with a 1 mm gap at 10% strain control mode. The PAV binder residue sample was tested at intermediate temperatures using the 8 mm plate with a 2 mm gap in a 1% strain control mode. The test was done in a Bohlin DSR-II shown in Figure 3-8.

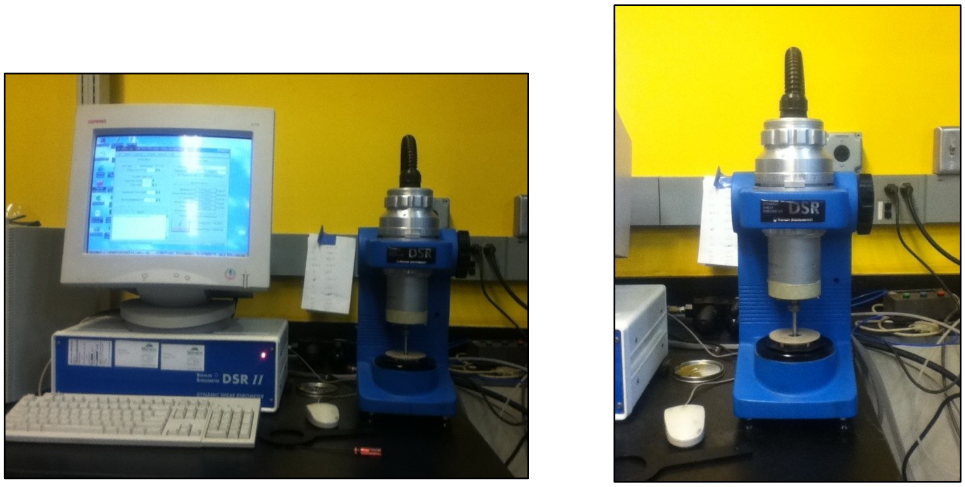



**Figure 3-8 Bohlin DSR-II**

## 3.8 Rolling Thin Film Oven

Short term aging is performed by the Rolling Thin Film Oven test. This aging simulates the aging that the binder undergoes during mixing, hauling and compaction of the HMA. This test procedure is also important in the PG system because the residue is used for DSR testing, and for long term aging in the PAV. This test procedure followed ASTM D 2872 standard. The test was performed by pouring 35 g of binder into a glass bottle. Then, the glass bottles were placed in the RTFO's bottle carriage rotating at 15 rpm, at 163 °C with a jet of air blowing at 4000 milliliters per minute for 85 minutes. Figure 3-9 shows a filled glass bottle and the RTFO used for this test.

(a)

(b)

**Figure 3-9 (a) Glass Bottles, One Empty and Second with 35 g of Binder. (b) Rolling Thin Film Oven.**

### 3.9 Pressure Aging Vessel

Long term aging was carried out using a Pressure Aging Vessel (PAV). Long term aging happens after short term aging that is after mixing, and placement of the asphalt mix. To simulate field conditions, the long term aging in the laboratory is performed using RTFO binder residue. The test was performed as per ASTM D6521. First, 50 g of binder is poured in a circular plate inside the PAV at high temperatures (90-110 °C), and at a pressure of 2.1 MPa for 20 hours, Figure 3-10. As un-aged and RTFO binders are used to characterize rutting potential on the binder, PAV samples are used to evaluate the fatigue cracking, and thermal cracking susceptibility of the binder.

**Figure 3-10 RTFO residue on a PAV plate**

### 3.10 Bending Beam Rheometer

The bending beam rheometer is used to evaluate the stiffness characteristics of the binder at low temperatures. This test is performed at the binder's low service temperature following ASTM D 6648 specifications. It consists in a 125 x 6.35 x 12.7 mm asphalt beam which will undergo a constant load at a constant temperature so that creep or deflection can be measured. At these low temperatures the asphalt binder behaves more of an elastic material; therefore simple beam theory is used to calculate stiffness. By applying a constant load at the midpoint of the beam, creep stiffness and m-value can be calculated. Figure 3-11 shows a picture of an asphalt beam preparation mold.

**Figure 3-11 BBR Sample Molds**

A research performed by SHRP showed that that the equivalent stiffness of two hours under the minimum pavement design temperature is equivalent to the stiffness if temperature is raised 10 °C and after 60 seconds of loading, reducing the testing time significantly. This test then, is run at 10 °C higher than the low temperature specified by the binder grade and is run for four minutes, measuring the deflection and stiffness at load times 8, 15, 30, 60, 120 and 240 seconds (Asphalt Institute 2007).

# Chapter 4 Results and Analysis

## 4.1 Testing Program

Consistency tests and DSR test were carried out using ASTM standard specification on un-aged, RTFO, and PAV aged binders. At high and intermediate temperatures un-aged, RTFO, and PAV binder was used for Superpave performance grade specifications.

For low temperature testing, BBR tests were performed on PAV residue to evaluate the fatigue cracking, and thermal cracking characteristics of each binder. This test was done with the help of the Arizona Department of Transportation technicians at their asphalt binder laboratory.

As mentioned earlier, further rheological properties on a PG 64-22 virgin and RAR modified binder were compared after adding Evotherm™. The objective was to identify any change in rheological properties after running a rotational viscosity test and DSR in the mixing processes. According to the manufacturer there should not be any difference in properties after adding Evotherm™.

## 4.2 Un-aged and RTFO aged Binders

### *4.2.1 Consistency Test Results*

Consistency test results for the virgin PG 64-22 binder and the PG 64-22-RAR modified binder at original and RTFO aging conditions are shown in Table 4-1 through Table 4-4. Figure 4-1 shows the viscosity-temperature relationship by plotting the log of temperature in Rankine and the log log viscosity in centipoise.

**Table 4-1 Consistency Test Results for PG 64-22 Binder**

| Test | Temp (°C) | Temp (°F) | Temp (°R) | Pen (0.1 mm) | Visc (Poise) | Visc (cP) |
|---|---|---|---|---|---|---|
| **Penetration** | 4 | 39.2 | 498.9 | 4.5 | 1.07E+09 | 1.07E+11 |
| **Penetration** | 23.5 | 74.3 | 534 | 44.2 | 6.25E+06 | 6.25E+08 |
| **Penetration** | 27.8 | 82 | 541.7 | 85.3 | 1.42E+06 | 1.42E+08 |
| **Softening Pt.** | 46 | 114.8 | 574.5 | | 13000 | 1300000 |
| **Brookfield** | 92.9 | 199.3 | 659 | | | 6057 |
| **Brookfield** | 120.7 | 249.2 | 708.9 | | | 852 |
| **Brookfield** | 148.4 | 299.2 | 758.9 | | | 219 |
| **Brookfield** | 176.2 | 349.1 | 808.8 | | | 80 |

**Table 4-2 Consistency Test Results for PG 64-22 20% RAR Binder**

| Test | Temp (°C) | Temp (°F) | Temp (°R) | Pen (0.1 mm) | Visc (Poise) | Visc (cP) |
|---|---|---|---|---|---|---|
| **Penetration** | 4 | 39.2 | 498.9 | 4.8 | 9.12E+08 | 9.12E+10 |
| **Penetration** | 25 | 77 | 536.7 | 24.3 | 2.39E+07 | 2.39E+09 |
| **Penetration** | 27.5 | 81.5 | 541.2 | 30.8 | 1.40E+07 | 1.40E+09 |
| **Softening Pt.** | 56.8 | 134.2 | 593.8 | | 13000 | 1300000 |
| **Brookfield** | 120.8 | 249.5 | 709.2 | | | 9115 |
| **Brookfield** | 148.4 | 299.2 | 758.8 | | | 2027 |
| **Brookfield** | 162.2 | 324 | 783.7 | | | 1306 |
| **Brookfield** | 176.1 | 348.9 | 808.6 | | | 965 |

**Table 4-3 Consistency Test Results for RTFO PG 64-22 Binder**

| Test | Temp (°C) | Temp (°F) | Temp (°R) | Pen (0.1 mm) | Visc (Poise) | Visc (cP) |
|---|---|---|---|---|---|---|
| **Penetration** | 23.8 | 74.8 | 534.5 | 20.2 | 3.65E+07 | 3.65E+09 |
| **Softening Pt.** | 55 | 131 | 590.7 | | 13000 | 1300000 |
| **Brookfield** | 93.2 | 199.7 | 659.4 | | | 13950 |
| **Brookfield** | 120.8 | 249.5 | 709.2 | | | 1624 |
| **Brookfield** | 148.4 | 299.2 | 758.9 | | | 362 |
| **Brookfield** | 176.1 | 348.9 | 808.6 | | | 117 |

**Table 4-4 Consistency Test Results for RTFO PG 64-22 20% RAR Binder**

| Test | Temp (°C) | Temp (°F) | Temp (°R) | Pen (0.1 mm) | Visc (Poise) | Visc (cP) |
|---|---|---|---|---|---|---|
| **Penetration** | 24.8 | 76.6 | 536.3 | 16.8 | 5.49E+07 | 5.49E+09 |
| **Softening Pt** | 66.4 | 151.5 | 611.1 | | 13000 | 1300000 |
| **Brookfield** | 134.6 | 274.3 | 734 | | | 11392 |
| **Brookfield** | 148.4 | 299.2 | 758.8 | | | 4286 |
| **Brookfield** | 162.3 | 324.2 | 783.8 | | | 2492 |
| **Brookfield** | 176 | 348.8 | 808.4 | | | 1629 |

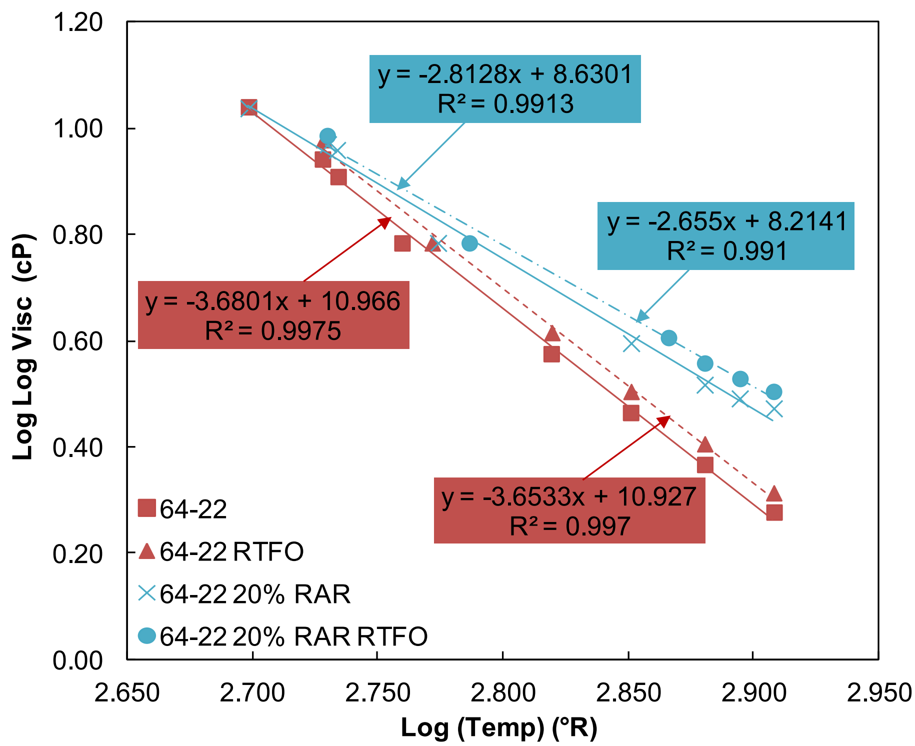



**Figure 4-1 Temperature-Viscosity Relationship Plot for PG 64-22 Binder**

From these results, it was observed that the RAR modified binder exhibited a much higher viscosity than the virgin binder at higher temperatures making it less susceptible to temperature increase. The ratio between the RTFO residue viscosity and the un-aged binder is commonly referred as the Aging Index (Gandhi, Akisetty and Amirkhanian 2009):

$$AI = \frac{\eta_{aged}}{\eta_{un-aged}}$$

Where;

AI = Aging Index

$\eta_{aged}$ = Viscosity of aged binder, RTFO/PAV

$\eta_{un\text{-}aged}$ = Viscosity of un-aged binder

Table 4-5 shows the AI at different temperatures for the PG 64-22 binder. The modified binder showed a lower AI at lower temperatures and a slightly higher AI with increasing temperatures than the conventional binder.

**Table 4-5 Aging Index of PG 64-22 Binder**

| **PG 64-22** | **Temperature (°C)** | | | | |
|---|---|---|---|---|---|
| | **25** | **60** | **135** | **150** | **176** |
| **Original Un-aged-RTFO** | 4.8 | 3.0 | 1.7 | 1.6 | 1.5 |
| **20% RAR Un-aged-RTFO** | 2.0 | 2.2 | 2.1 | 2.1 | 2.0 |

The following Table 4-6 through Table 4-9 summarizes the results from the consistency test on the original binder PG 70-10 and PG 70-10 RAR modified binder at un-aged and RTFO aged conditions. Figure 4-2 shows the viscosity-temperature relationship between original and modified PG 70-10 binder.

**Table 4-6 Consistency Test Results for PG 70-10 Binder**

| Test | Temp (°C) | Temp (°F) | Temp (°R) | Pen (0.1 mm) | Visc (Poise) | Visc (cP) |
|---|---|---|---|---|---|---|
| **Penetration** | 4.0 | 39.2 | 498.9 | 3.8 | 1.5E+09 | 1.54E+11 |
| **Penetration** | 23.5 | 74.3 | 534.0 | 25.5 | 2.2E+07 | 2.15E+09 |
| **Penetration** | 30.0 | 86.0 | 545.7 | 54.2 | 3950000 | 4E+08 |
| **Softening Pt.** | 52.5 | 126.5 | 586.2 | | 13000 | 1300000 |
| **Brookfield** | 93.0 | 199.4 | 659.1 | | | 10914 |
| **Brookfield** | 120.8 | 249.4 | 709.0 | | | 1316 |
| **Brookfield** | 148.4 | 299.0 | 758.7 | | | 305 |
| **Brookfield** | 176.3 | 349.4 | 809.1 | | | 102 |

**Table 4-7 Consistency Test Results for PG 70-10 20% RAR Binder**

| Test | Temp (°C) | Temp (°F) | Temp (°R) | Pen (0.1 mm) | Visc (Poise) | Visc (cP) |
|---|---|---|---|---|---|---|
| **Penetration** | 3 | 37.4 | 497.1 | 3.3 | 2.11E+09 | 2.11E+11 |
| **Penetration** | 23.7 | 74.7 | 534.3 | 19.7 | 3.87E+07 | 3.87E+09 |
| **Penetration** | 31.7 | 89.1 | 548.7 | 42.2 | 6.94E+06 | 6.94E+08 |
| **Softening Pt.** | 58.5 | 137.3 | 597 | | 13000 | 1300000 |
| **Brookfield** | 120.8 | 249.5 | 709.1 | | | 10568 |
| **Brookfield** | 148.6 | 299.4 | 759.1 | | | 2296 |
| **Brookfield** | 162.4 | 324.3 | 784 | | | 1443 |
| **Brookfield** | 176.2 | 349.1 | 808.8 | | | 1103 |

**Table 4-8 Consistency Test Results for RTFO PG 70-10 Binder**

| Test | Temp (°C) | Temp (°F) | Temp (°R) | Pen (0.1 mm) | Visc (Poise) | Visc (cP) |
|---|---|---|---|---|---|---|
| **Penetration** | 26.5 | 79.7 | 539.4 | 15.7 | 6.5E+07 | 6.45E+09 |
| **Softening Pt.** | 61.5 | 142.7 | 602.4 | | 13000 | 1300000 |
| **Brookfield** | 98.6 | 209.6 | 669.2 | | | 16688 |
| **Brookfield** | 120.7 | 249.3 | 709 | | | 2667 |
| **Brookfield** | 148.5 | 299.3 | 759 | | | 502 |
| **Brookfield** | 176.2 | 349.1 | 808.8 | | | 148 |

Table 4-9 Consistency Test Results for RTFO PG 70-10 20% RAR Binder

| Test | Temp (°C) | Temp (°F) | Temp (°R) | Pen (0.1 mm) | Visc (Poise) | Visc (cP) |
|---|---|---|---|---|---|---|
| **Penetration** | 25 | 77 | 536.7 | 14.8 | 7.30E+07 | 7.30E+09 |
| **Softening Pt.** | 67.1 | 152.8 | 612.5 | | 13000 | 1300000 |
| **Brookfield** | 134.6 | 274.3 | 734 | | | 12525 |
| **Brookfield** | 148.6 | 299.5 | 759.2 | | | 5815 |
| **Brookfield** | 162.3 | 324.1 | 783.8 | | | 2835 |
| **Brookfield** | 176.2 | 349.2 | 808.9 | | | 1952 |

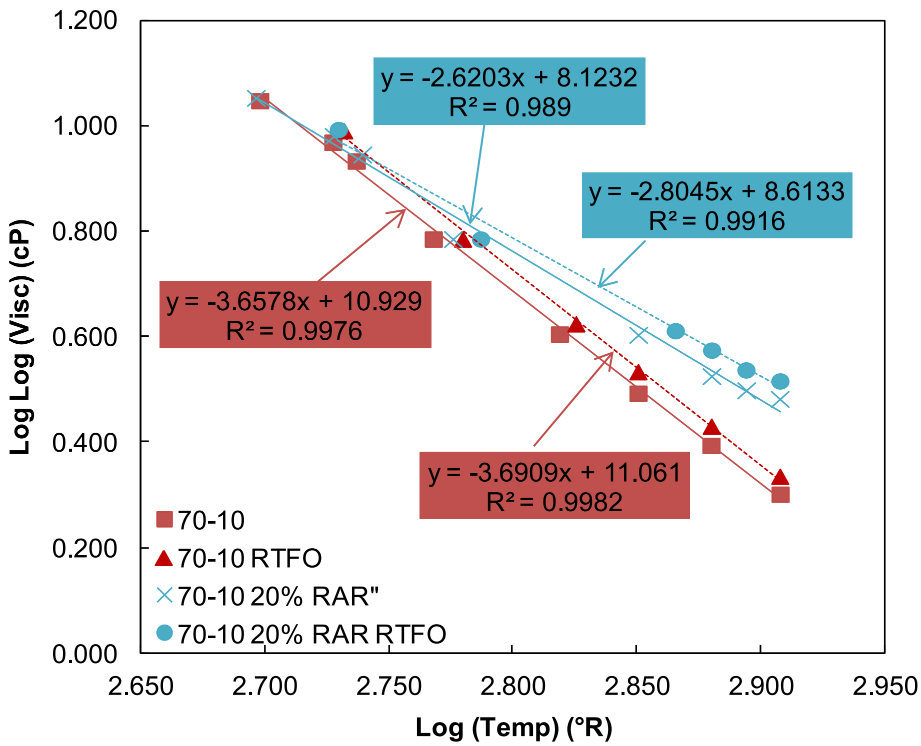



**Figure 4-2 Temperature-Viscosity Relationship Plot for PG 70-10 Binder**

In Figure 4-2, it is observed that RuBind™ also had an improvement on the viscosity-temperature susceptibility at high temperatures. Again, to determine the amount of hardening after aging for each binder, the aging indices are summarized in Table 4-10.

Again, the modified binder showed lower AI at lower temperatures and a slightly higher AI with increasing temperatures than the conventional binder.

**Table 4-10 Aging Index of PG 70-10 Binder**

| PG 70-10 | Temperature (°C) | | | | |
|---|---|---|---|---|---|
| | **25** | **60** | **135** | **150** | **176** |
| **Original Un-aged-RTFO** | 7.7 | 3.7 | 1.8 | 1.6 | 1.5 |
| **20% RAR Un-aged-RTFO** | 1.9 | 2.2 | 2.2 | 2.2 | 2.1 |

It is noted that the RTFO for the rubber modified binders was done for comparative purposes only. Previous Arizona State University and Arizona Department of Transportation studies reported that the RTFO is not typically representative of the aging process you would see for rubber modified binders, and therefore the results are not representative of the aging that happens in the field.

### *4.2.2 Dynamic Shear Rheometer Test Results*

Test strain level and equilibrium time is obtained by performing a linearity test and a time sweep test. A linearity test is a strain sweep test in which a DSR sample is tested at a fixed temperature while changing the strain levels. The objective of this test is to find out the strain levels at which the binder sample behaves as an elastic material. The linearity test was carried out using 25 mm samples at a temperature of 58 °C. Figure 4-3 shows the results from each binder test.

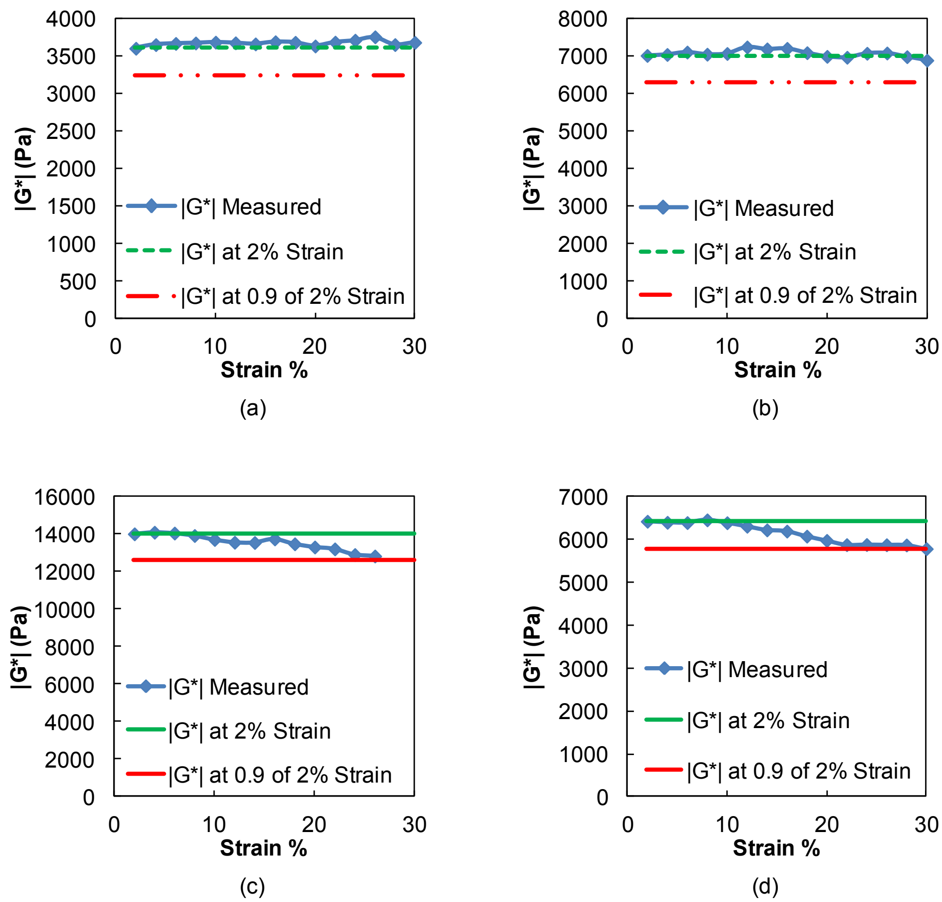



**Figure 4-3 Strain Sweep Test for (a) PG 64-22 Virgin Binder, (b) PG 70-10 Virgin Binder, (c) RAR Modified PG 64-22, and (d) RAR Modified PG 70-10.**

The results from these test showed that in every case all the strains exceeded 12% which is the recommended for testing the un-aged binder under a strain control test. The strain amplitude used for the RTFO samples was 10%. Virgin binders showed linearity at all strain levels as it is seen in Figure 4-3 (a) and (b). The RAR modified binders showed non linear behavior at high strain levels, but showed linear behavior within the testing strain levels, Figure 4-3 (c) and (d).

Temperature equilibrium time is set by performing a time sweep test. The time sweep test was carried out at 58 °C and at strain amplitude of 9% on a 25 mm sample.

The results from these tests are shown in Figure 4-4. Since there was no significant change in the modulus, the equilibrium time was set to 10 minutes.

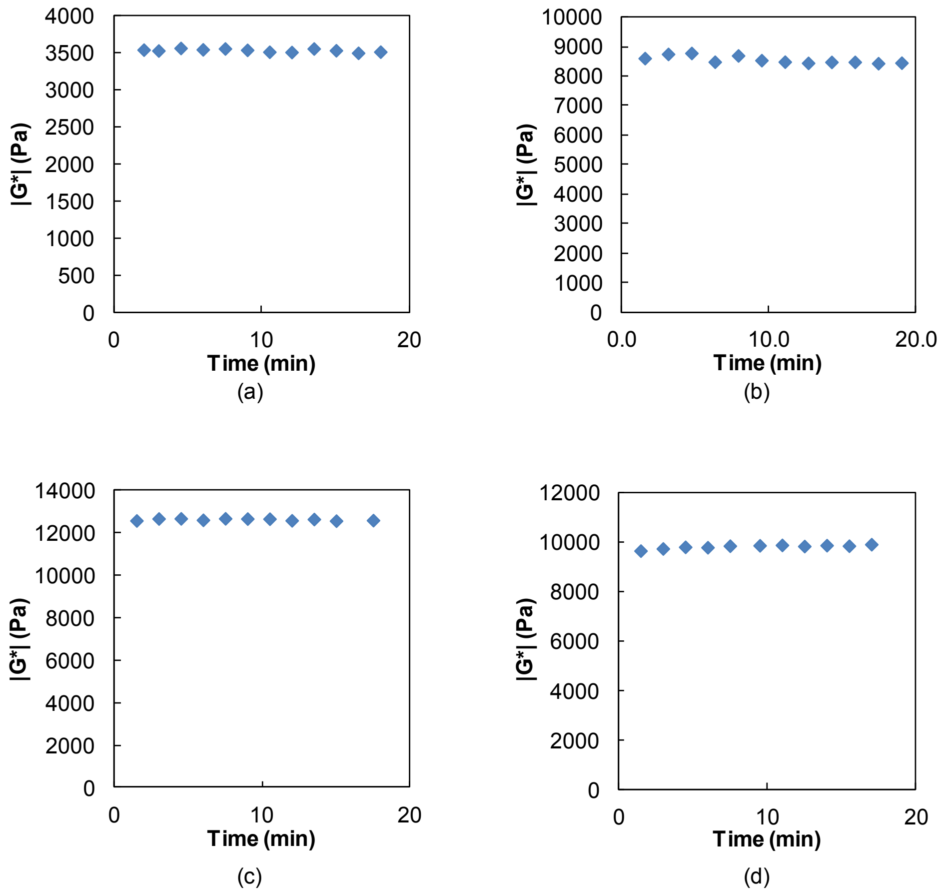



**Figure 4-4 Time Sweep Test for (a) PG 64-22 Virgin Binder, (b) PG 70-10 Virgin Binder, (c) RAR Modified PG 64-22, and (d) RAR Modified PG 70-10.**

After strain sweep and time sweep test was finalized, time and strain levels where set to carry out DSR testing. Two replicates of each binder were tested, and the average modulus and statistical parameters are shown in Table 4-11 for the virgin PG 64-22 binder and RAR modified binder. The Performance Grade Asphalt Binder Specifications states that, for un-aged binders, the magnitude of |G*| divided by the phase angle (δ) should be greater than 1 kPa. Table 4-11 shows that the virgin binder met that criterion at

64 °C but did not meet that criterion at 70 °C. It was seen that by adding RAR it increased the Performance Grade to 82, but it did not meet the specification at 88 °C.

**Table 4-11 DSR Results for PG 64-22 Binder**

| Temp °C | \|G*\| kPa | STDEV | CV | δ Degree | \|G*\|/sinδ kPa | Strain Amp % | Freq rad/sec |
|---|---|---|---|---|---|---|---|
| **58** | 3.4 | 0.11 | 3.39% | 85.00 | 3.4 | 11.815 | 10.08 |
| **64** | 1.5 | 0.09 | 6.22% | 86.80 | 1.5 | 11.99 | 10.08 |
| **70** | 0.7 | 0.01 | 1.20% | 88.10 | 0.7 | 12.05 | 10.08 |

**Table 4-12 DSR Results for PG 64-22 20% RAR Binder**

| Temp °C | \|G*\| kPa | STDEV | CV | δ Degree | \|G*\|/sinδ kPa | Strain Amp % | Freq rad/sec |
|---|---|---|---|---|---|---|---|
| **58** | 13.8 | 0.04 | 0.30% | 65.90 | 15.2 | 12.04 | 10.08 |
| **64** | 7.3 | 0.10 | 1.43% | 70.20 | 7.8 | 11.98 | 10.08 |
| **70** | 3.9 | 0.08 | 2.17% | 74.10 | 4.0 | 12.05 | 10.08 |
| **76** | 2.1 | 0.04 | 1.82% | 77.65 | 2.1 | 12.15 | 10.08 |
| **82** | 1.2 | 0.03 | 2.43% | 80.40 | 1.2 | 12.19 | 10.08 |
| **88** | 0.7 | 0.03 | 4.20% | 82.95 | 0.7 | 12.05 | 10.08 |

The increase of |G*|/sinδ, seen in Figure 4-5, shows that RAR modified binder increased the stiffness by 4 to 6 times the original binder. Results also showed a reduction in the phase angle by approximately 20%.

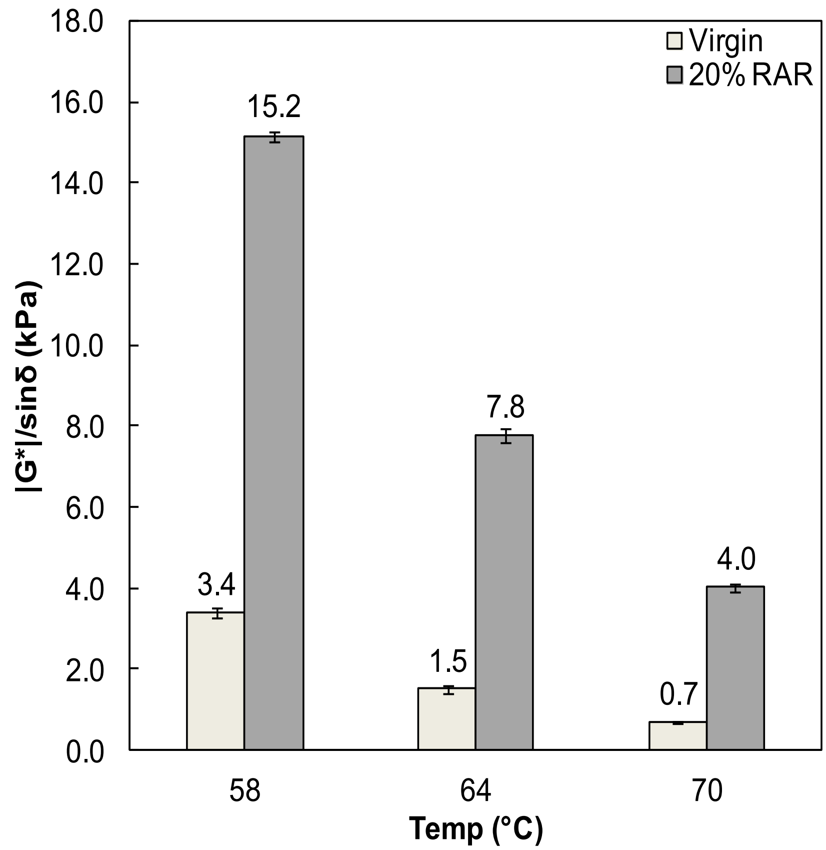



**Figure 4-5 Chart Showing Results from DSR Test for the Un-aged PG 64-22 Binder**

The RTFO aged results for the PG 64-22 binder are shown in Table 4-13 and Table 4-14. These results show a similar trend to the original un-aged binder. The RTFO virgin binder and the RAR modified binder did not meet the criteria of |G*|/sinδ being greater than 2.2 kPa at 70 °C and 88 °C respectively.

**Table 4-13 DSR Results for RTFO PG 64-22 Binder**

| Temp °C | \|G*\| kPa | STDEV | CV | δ Degree | \|G*\|/sinδ kPa | Strain Amp % | Freq rad/sec |
|---|---|---|---|---|---|---|---|
| **58** | 8.1 | 0.04 | 0.51% | 80.35 | 8.2 | 10.10 | 10.08 |
| **64** | 3.5 | 0.07 | 1.87% | 82.95 | 3.5 | 9.93 | 10.08 |
| **70** | 1.6 | 0.05 | 2.96% | 85.45 | 1.6 | 10.00 | 10.08 |

**Table 4-14 DSR Results for RTFO PG 64-22 20% RAR Binder**

| Temp °C | \|G*\| kPa | STDEV | CV | δ Degree | \|G*\|/sinδ kPa | Strain Amp % | Freq rad/sec |
|---|---|---|---|---|---|---|---|
| **58** | 24.7 | 0.49 | 2.00% | 58.95 | 28.8 | 9.97 | 10.08 |
| **64** | 13.5 | 0.15 | 1.09% | 61.55 | 15.4 | 9.97 | 10.08 |
| **70** | 7.4 | 0.00 | 0.02% | 64.60 | 8.2 | 10.05 | 10.08 |
| **76** | 4.2 | 0.02 | 0.45% | 68.00 | 4.5 | 10.03 | 10.08 |
| **82** | 2.4 | 0.01 | 0.42% | 71.30 | 2.5 | 10.16 | 10.08 |
| **88** | 1.4 | 0.02 | 1.34% | 74.70 | 1.4 | 10.13 | 10.08 |

Figure 4-6 summarizes the results from the RTFO samples. After RTFO aging, the |G*|/sinδ parameter increased from 3 to 5 times compared to the virgin binder. The RAR modified binder showed an increase in |G*| by 3 to 4 times, and a decrease in phase angle by approximately 25%.

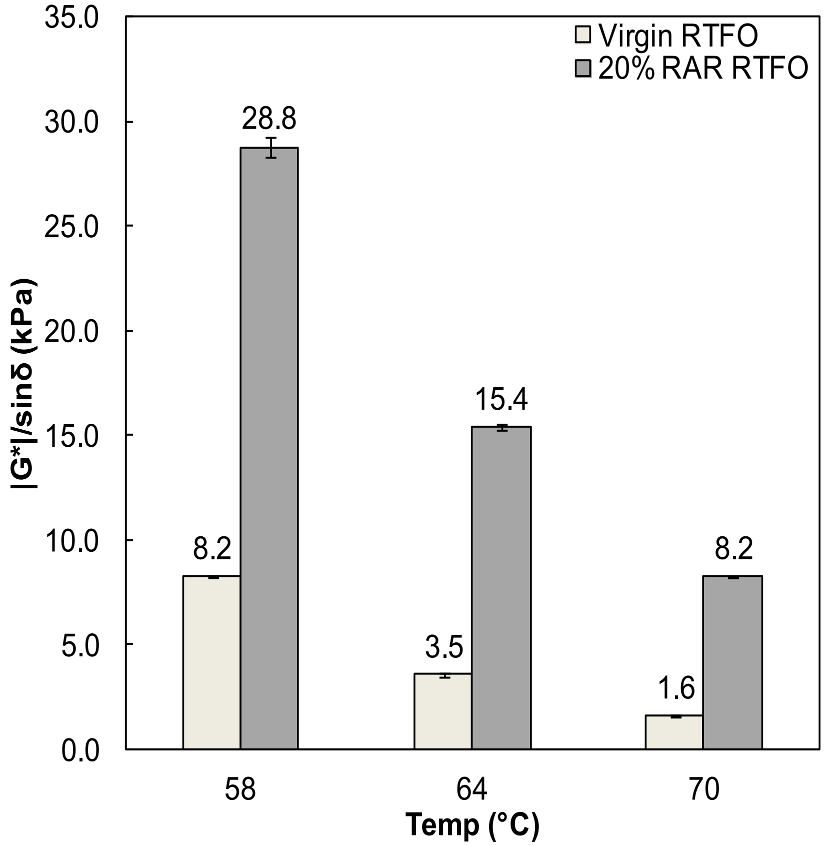



**Figure 4-6 Chart Showing Results from DSR Test for the RTFO PG 64-22 Binder**

In the same manner as the consistency test, an Aging Index was used to compare the relative change in stiffness after the binders were subjected to RTFO aging. The aging index was calculated using the following equation:

$$AI = \frac{|G^*|_{aged}}{|G^*|_{un-aged}}$$

Where;

AI = Aging Index

$|G^*|_{aged}$ = Dynamic shear modulus after aging, RTFO/PAV

$|G^*|_{un\text{-}aged}$ = Dynamic shear modulus un-aged

Table 4-15 summarizes the results from original and RuBind™ modified binder at three different temperatures. It is observed that the AI for the modified binder was slightly lower, which agrees with a lower AI from viscosity at the same temperature range.

**Table 4-15 Ageing Index between RTFO and Un-aged Dynamic Modulus |G*|**

| PG 64-22 | 58 °C | 64 °C | 70 °C |
|---|---|---|---|
| **Original Un-aged-RTFO** | 2.40 | 2.33 | 2.26 |
| **20% RAR Un-aged-RTFO** | 1.78 | 1.85 | 1.92 |

The DSR test results for the PG 70-10 binder are shown in Table 4-16. For the original virgin binder, 2 replicates were tested at 64 to 88 °C in 6 °C increments until the samples did not meet specifications. As expected, the PG 70-10 un-aged binder did not meet the criteria at a temperature of 76 °C. In the case of the RAR modified asphalt binder, 4 replicate tests were performed due to higher than expected variability. Although such high variability was not experienced in the RAR modified PG 64-22 case, the increase here might be associated with the rubber particles size effects. The results shown in Table 4-17 are the averages from the four replicates.

**Table 4-16 DSR Results for PG 70-10 Binder**

| Temp °C | \|G*\| kPa | STDEV | CV | δ Degree | \|G*\|/sinδ kPa | Strain Amp % | Freq rad/sec |
|---|---|---|---|---|---|---|---|
| **64** | 3.5 | 0.02 | 0.50% | 80.65 | 3.6 | 11.90 | 10.08 |
| **70** | 1.7 | 0.02 | 1.32% | 83.20 | 1.7 | 11.98 | 10.08 |
| **76** | 0.8 | 0.00 | 0.33% | 85.05 | 0.8 | 11.57 | 10.08 |

**Table 4-17 DSR Results for PG 70-10 20% RAR Binder**

| Temp °C | \|G*\| kPa | STDEV | CV | δ Degree | \|G*\|/sinδ kPa | Strain Amp % | Freq rad/sec |
|---|---|---|---|---|---|---|---|
| **64** | 6.4 | 0.47 | 7.45% | 72.6 | 6.7 | 12.05 | 10.08 |
| **70** | 3.2 | 0.28 | 8.55% | 76.6 | 4.3 | 12.19 | 10.08 |
| **76** | 1.7 | 0.16 | 9.10% | 79.6 | 1.7 | 12.24 | 10.08 |
| **82** | 0.9 | 0.09 | 9.22% | 82.1 | 0.9 | 12.23 | 10.08 |

From the test results it can be seen that the increase of |G*|/sinδ, and |G*| was two times higher with RAR modified binder than the virgin binder with a reduction in phase angle of approximately 8%. Figure 4-7 shows the difference in stiffness between the virgin binder and the RAR modified binder.

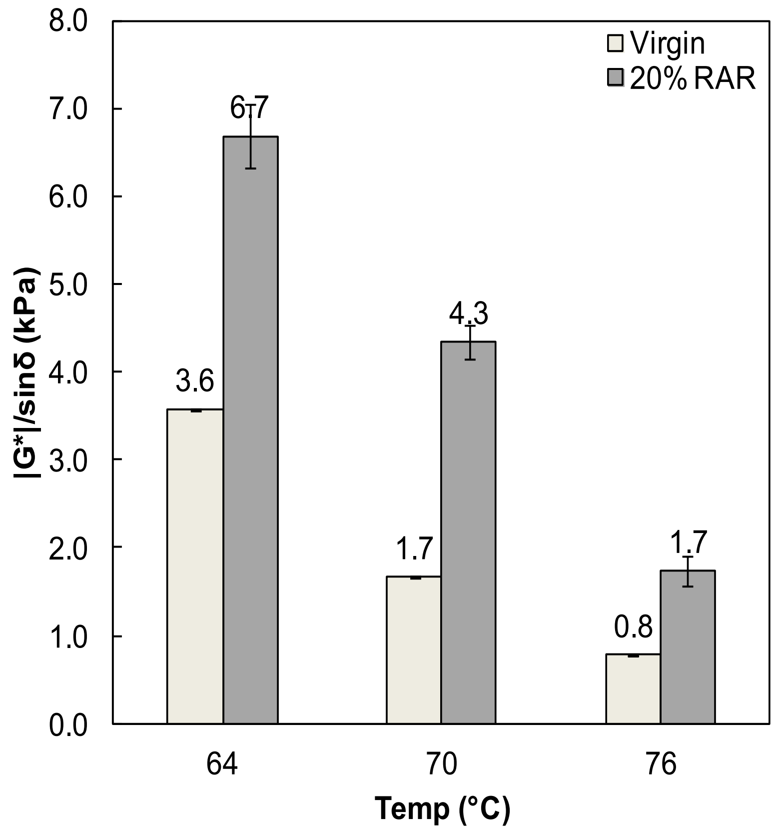



**Figure 4-7 Results from DSR Test for the Un-aged PG 70-10 Binder**

After the PG 70-10 binder was aged in the RTFO, two replicates of each binder were tested. These results are shown in Table 4-18 and Table 4-19. The RTFO aged original binder did not meet the criteria at 76 °C and the RAR modified did not meet the criteria at 88 °C. This time the modified binder showed consistent results with an acceptable coefficient of variance.

**Table 4-18 DSR Results for RTFO PG 70-10 Binder**

| Temp °C | \|G*\| kPa | STDEV | CV | δ Degree | \|G*\|/sinδ kPa | Strain Amp % | Freq rad/sec |
|---|---|---|---|---|---|---|---|
| **64** | 7.3 | 0.11 | 1.50% | 75.10 | 7.5 | 9.9 | 10.08 |
| **70** | 3.4 | 0.07 | 2.14% | 77.75 | 3.5 | 10.0 | 10.08 |
| **76** | 1.6 | 0.04 | 2.69% | 80.40 | 1.6 | 10.1 | 10.08 |

**Table 4-19 DSR Results for RTFO PG 70-10 20 % RAR Binder**

| Temp °C | \|G*\| kPa | STDEV | CV | δ Degree | \|G*\|/sinδ kPa | Strain Amp % | Freq rad/sec |
|---|---|---|---|---|---|---|---|
| **64** | 14 | 0.15 | 1.09% | 61.8 | 15.6 | 10.1 | 10.08 |
| **70** | 7.5 | 0.15 | 1.95% | 65.0 | 8.2 | 10.2 | 10.08 |
| **76** | 4.2 | 0.05 | 1.28% | 68.7 | 4.5 | 10.1 | 10.08 |
| **82** | 2.3 | 0.04 | 1.70% | 71.7 | 2.5 | 10.2 | 10.08 |
| **88** | 1.4 | 0.06 | 4.65% | 75.3 | 1.4 | 10.1 | 10.08 |

The |G*|/sinδ results for temperatures 64, 70 and 76 °C were plotted to see the increase of |G*| after RAR was added. Figure 4-8 shows that the increase in |G*| is about 2-2.4 times greater than the aged original virgin binder, and a decrease in phase angle by approximately 17%

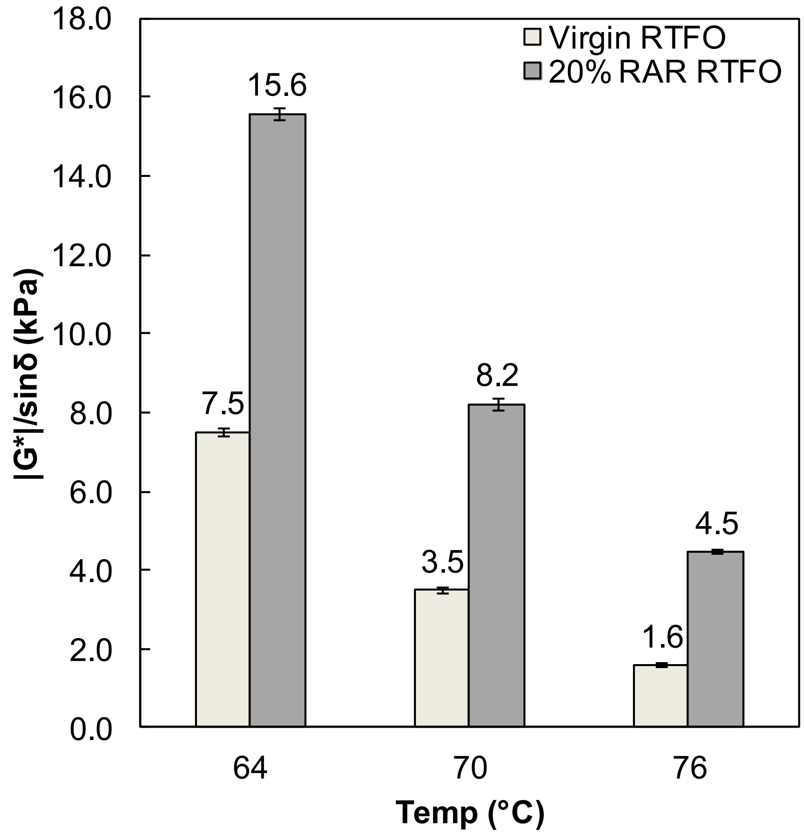



**Figure 4-8 Chart Showing Results from DSR Test for the RTFO PG 70-10 Binder**

The trend in these results shows that with increasing temperature there is an increase in the |G*| ratio for the RAR modified binder, and no change in |G*| ratio for the original virgin binder. Table 4-20 summarizes these results for three temperatures. The AIs for the modified binder were higher than those found for the virgin binder.

**Table 4-20 Ratio between RTFO and Un-aged Dynamic Modulus |G*|**

| PG 70-10 | 64 °C | 70 °C | 76 °C |
|---|---|---|---|
| **Original Unaged-RTFO** | 2.06 | 2.06 | 2.02 |
| **20% RAR Unaged-RTFO** | 2.16 | 2.30 | 2.43 |

In summary, the results from the high temperature DSR tests suggest that the virgin PG 64-22 asphalt binder has increased in performance grade to a PG 82-XX binder and the virgin PG 70-10 asphalt improved its high temperature performance grade to a PG 76-XX asphalt binder. In the case of the virgin PG 64-22 asphalt both the original and RTFO criteria are met at 82 °C. For the virgin PG 70-10 asphalt binder, the un-aged asphalt criterion is the determining quantity.

## 4.3 PAV aged binders

### *4.3.1 Consistency Test Results*

After un-aged binder and short term aged RTFO binder were tested, the next step was to evaluate the long term rheological properties of the binder by performing consistency tests on PAV asphalt binder residue. The results for the PG 64-22 virgin binder and RAR modified binder are shown in Table 4-21 and Table 4-22.

Then, the results from all consistency tests were plotted together in Figure 4-9 to get a visual evaluation of the results. It was found that the RAR modified binder had a marginal increase in stiffness after RTFO aging and that PAV aged virgin binder had a larger increase in stiffness.

**Table 4-21 Consistency Test Results for PAV PG 64-22 Binder**

| Test | Temp (°C) | Temp (°F) | Temp (°R ) | Pen (0.1 mm) | Visc (Poise) | Visc (cP) |
|---|---|---|---|---|---|---|
| **Penetration** | 25.1 | 77.2 | 536.9 | 18.8 | 4.26E+07 | 4.26E+09 |
| **Softening Pt** | 66.0 | 150.8 | 610.5 | | 13000 | 1300000 |
| **Brookfield** | 107.0 | 224.6 | 684.2 | | | 10158 |
| **Brookfield** | 120.8 | 249.4 | 709.0 | | | 3315 |
| **Brookfield** | 148.5 | 299.3 | 759.0 | | | 594 |
| **Brookfield** | 176.1 | 349.1 | 808.7 | | | 171 |

Table 4-22 Consistency Test Results for PAV PG 64-22 20% RAR Binder

| Test | Temp (°C) | Temp (°F) | Temp (°R ) | Pen (0.1 mm) | Visc (Poise) | Visc (cP) |
|---|---|---|---|---|---|---|
| **Penetration** | 25.4 | 77.7 | 537.4 | 51.0 | 4.52E+06 | 4.52E+08 |
| **Softening Pt** | 75.0 | 167.0 | 626.7 | | 13000 | 1300000 |
| **Brookfield** | 134.5 | 274.2 | 733.9 | | | 13107 |
| **Brookfield** | 148.6 | 299.5 | 759.2 | | | 5790 |
| **Brookfield** | 162.4 | 324.2 | 783.9 | | | 2688 |
| **Brookfield** | 176.2 | 349.2 | 808.9 | | | 1633 |

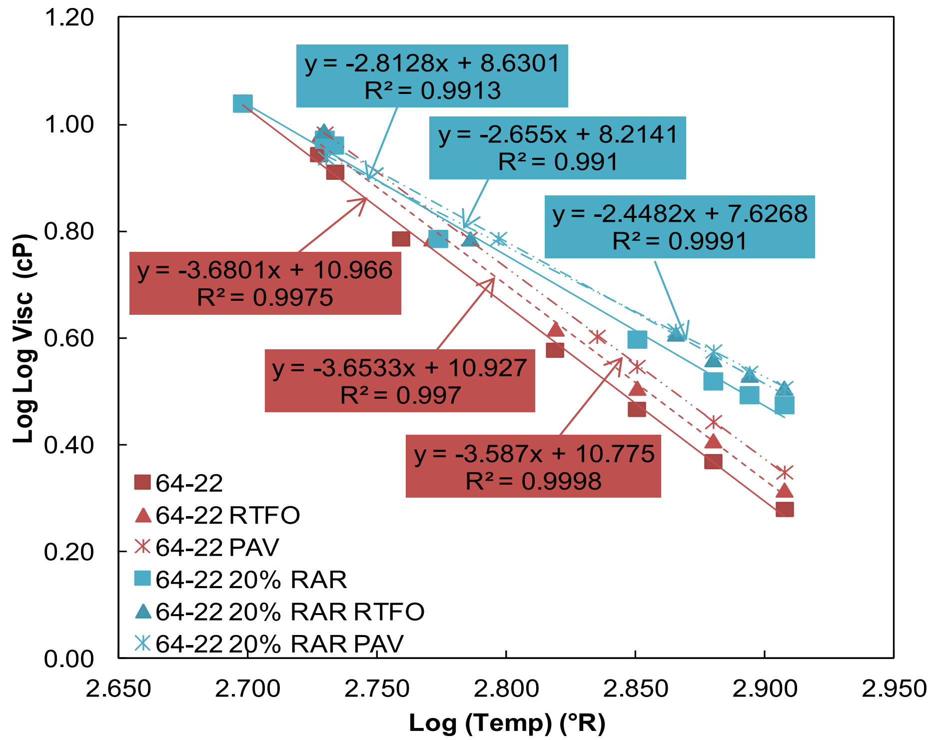



**Figure 4-9 Un-aged, RTFO and PAV Results for PG 64-22 Binder**

The next analysis was to compare the aging indices after PAV and the results showed that the original virgin binder aged more than the RuBind™ modified binder. This was expected since the rubber particles protect the binder from further aging. Table 4-23 show a comparison between RTFO and PAV aging indices. At these 3 temperatures the virgin binder index increased a 40 to 90% as for the RuBind™ modified binder showed an increase in aging index from 0 to 40% with respect to RTFO aging index. The aging indices at 25 and 60 °C for the PAV aged RAR modified binder are lower that the RTFO aged and this is due to an experimental error during the penetration test. The AI for the PAV aged modified binder are also lower than the unmodified binder at all temperatures, except 176 °C where the AI is about the same.

**Table 4-23 PAV and RTFO Aging Index for PG 64-22 Binder**

| PG 64-22 | Temperature (°C) | | | | |
|---|---|---|---|---|---|
| | 25 | 60 | 135 | 150 | 176 |
| **Original Un-aged-RTFO** | 4.8 | 3.0 | 1.7 | 1.6 | 1.5 |
| **Original Un-aged-PAV** | 20.1 | 8.6 | 3.2 | 2.8 | 2.4 |
| **20% RAR Un-aged-RTFO** | 2.0 | 2.2 | 2.1 | 2.1 | 2.0 |
| **20% RAR Un-aged-PAV** | 0.7[5] | 1.4[5] | 2.4 | 2.4 | 2.5 |

The same testing and analysis was done using a PG 70-10 binder after PAV. The results showed the same trends as for PG 64-22. After long term aging the RAR modified binder showed a marginal increase in stiffness compared to the RTFO aged RAR modified binder. The results from this test can be seen in Table 4-24 and Table 4-25.

As it is shown in Figure 4-10, the PAV and RTFO trend lines for the RAR modified asphalt binder are really close to each other, as compared to the original binder, in which the curve shifted up. This shows a greater stiffening taking place in the virgin binder than in the RAR modified binder.

[5] Testing error during PAV penetration test

**Table 4-24 Consistency Test Results for PAV PG 70-10 Binder**

| Test | Temp (°C) | Temp (°F) | Temp (°R ) | Pen (0.1 mm) | Visc (Poise) | Visc (cP) |
|---|---|---|---|---|---|---|
| **Penetration** | 25.1 | 77.2 | 536.9 | 9.5 | 1.99E+08 | 1.99E+10 |
| **Softening Pt** | 85.0 | 185.0 | 644.7 | | 13000 | 1300000 |
| **Brookfield** | 120.8 | 249.5 | 709.2 | | | 18488 |
| **Brookfield** | 148.4 | 299.1 | 758.7 | | | 1761 |
| **Brookfield** | 162.3 | 324.2 | 783.8 | | | 698 |
| **Brookfield** | 176.1 | 349.0 | 808.6 | | | 335 |

**Table 4-25 Consistency Test Results for PAV PG 70-10 20%RAR Binder**

| Test | Temp (°C) | Temp (°F) | Temp (°R ) | Pen (0.1 mm) | Visc (Poise) | Visc (cP) |
|---|---|---|---|---|---|---|
| **Penetration** | 24.6 | 76.3 | 536.0 | 15.3 | 6.77E+07 | 6.77E+09 |
| **Softening Pt** | 82.0 | 179.6 | 639.3 | | 13000 | 1300000 |
| **Brookfield** | 134.7 | 274.4 | 734.1 | | | 14856 |
| **Brookfield** | 148.3 | 299.0 | 758.7 | | | 6161 |
| **Brookfield** | 162.4 | 324.4 | 784.1 | | | 2785 |
| **Brookfield** | 176.1 | 349.0 | 808.7 | | | 1555 |

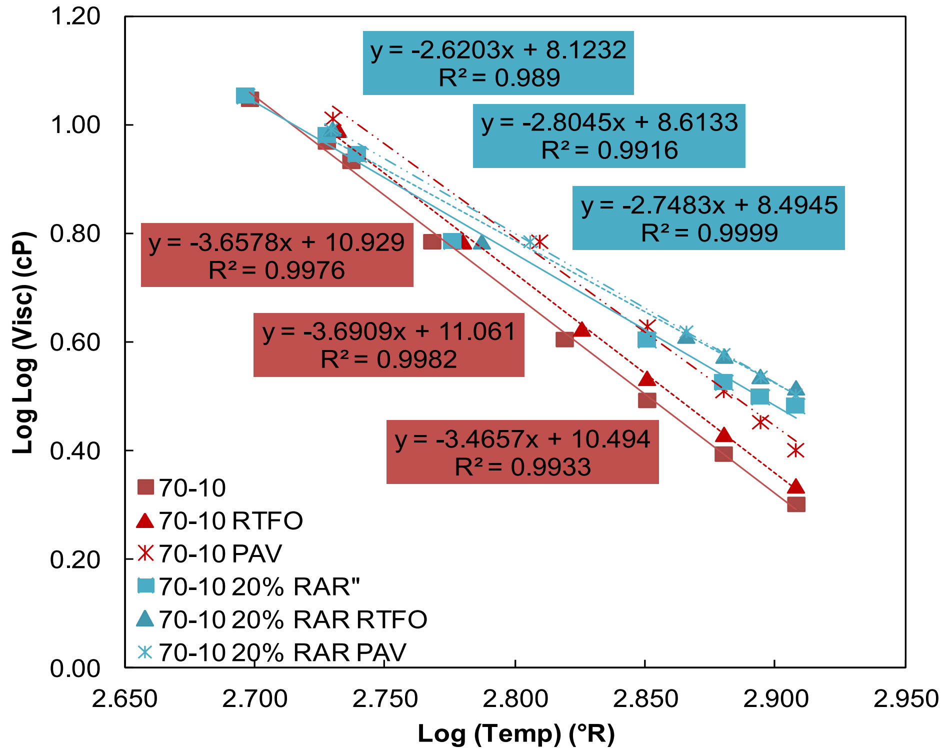



**Figure 4-10 Un-aged, RTFO and PAV Results for PG 70-10 Binder**

In order to better see this aging difference, Table 4-26 shows the aging index for every aging condition. It is clear from this table that the long term aging does not affect the RAR modified asphalt binder as much as the original asphalt binder. This is an encouraging finding as it is more indicative of the good field performance of crumb rubber modified binders.

**Table 4-26 PAV and RTFO Aging Index for PG 70-10 Binder**

| PG 70-10 | Temperature (°C) | | | | |
|---|---|---|---|---|---|
| | 25 | 60 | 135 | 150 | 176 |
| Original Un-aged-RTFO | 7.7 | 3.7 | 1.8 | 1.6 | 1.5 |
| Original Un-aged-PAV | 102.3 | 31.2 | 7.1 | 5.9 | 4.4 |
| 20% RAR Un-aged-RTFO | 1.9 | 2.2 | 2.2 | 2.2 | 2.1 |
| 20% RAR Un-aged-PAV | 5.7 | 3.9 | 2.4 | 2.3 | 2.0 |

### *4.3.2 Dynamic Shear Rheometer*

After performing the DSR test at intermediate temperatures for the PG 64-22 binder it showed an improvement on the fatigue parameter |G*|sinδ. The intermediate temperature criterion for this test specifies that |G*|sinδ should be equal or less than 5000 kPa. The virgin binder did not meet specifications at 22 °C but it met at 25 °C as it is supposed according to the performance grade of this binder, Table 4-27 and Table 4-28. Opposite to what was observed at high temperatures, at intermediate temperatures the stiffness of the RAR modified asphalt decreased. Thus, RAR modified binder improved the fatigue performance and met specifications at 22 °C. Figure 4-11 shows the fatigue parameter |G*|sinδ at different temperatures.

**Table 4-27 Intermediate Temperature DSR Results for PAV PG 64-22 Binder**

| Temp °C | \|G*\| Pa | STDEV | CV | δ Degree | \|G*\|/sinδ Pa | Strain Amp % | Freq rad/sec |
|---|---|---|---|---|---|---|---|
| **28** | 3377 | 55 | 1.62% | 49.6 | 2567 | 1.00 | 10.08 |
| **25** | 5302 | 86 | 1.62% | 46.7 | 3859 | 1.01 | 10.08 |
| **22** | 8220 | 147 | 1.79% | 43.7 | 5680 | 1.01 | 10.08 |

**Table 4-28 Intermediate Temperature DSR Results for PAV PG 64-22 20% RAR Binder**

| Temp °C | \|G*\| Pa | STDEV | CV | δ Degree | \|G*\|/sinδ Pa | Strain Amp % | Freq rad/sec |
|---|---|---|---|---|---|---|---|
| **28** | 2486 | 97 | 3.92% | 45.3 | 1766 | 1.00 | 10.08 |
| **25** | 3736 | 142 | 3.81% | 43.3 | 2559 | 1.03 | 10.08 |
| **22** | 5566 | 162 | 2.91% | 41.1 | 3660 | 1.01 | 10.08 |
| **19** | 8199 | 235 | 2.87% | 39.1 | 5160 | 1.02 | 10.08 |

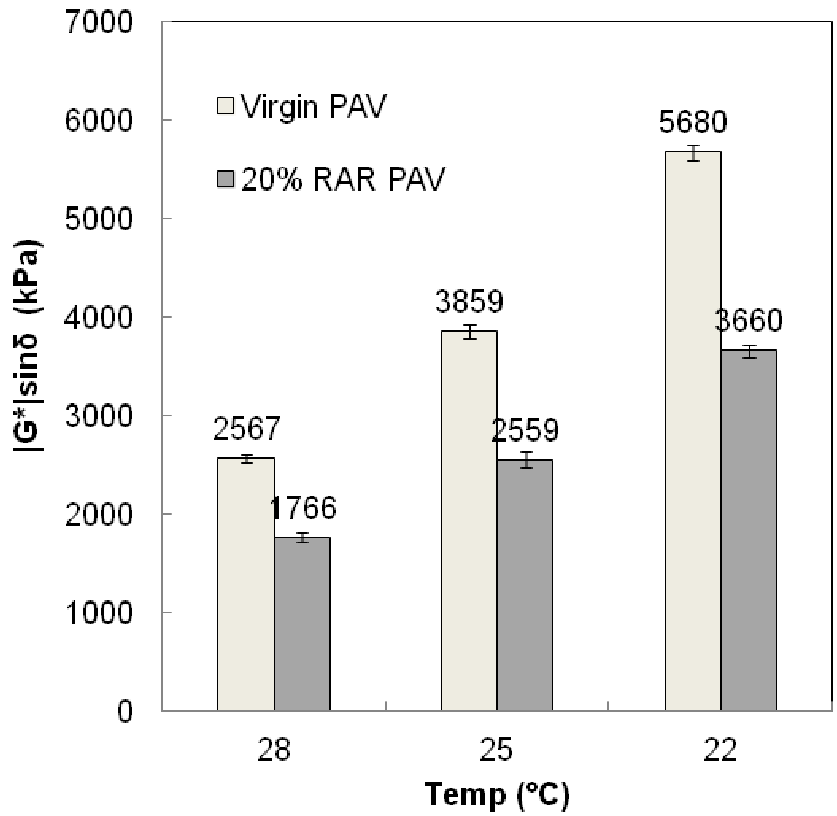



**Figure 4-11 DSR Results at Different Temperatures for PAV PG 64-22 Binder**

The PG 70-10 binder that was used for this project was tested at intermediate temperature to determine the fatigue cracking performance. According to the Performance Grade Asphalt Binder specification table a PG 70-10 binder should meet the criteria for PAV residue at intermediate temperature of 34 °C. This particular virgin binder met specifications at 28 °C and RAR modified binder met specifications at 22 °C. This means that the PG 70-10 virgin binder use will perform at -22 °C and the RAR modified binder will have a good performance at -34 °C. The next Figure shows the DSR test results for PG 70-10 binder.

**Table 4-29 Intermediate Temperature DSR Results for PAV PG 70-10 Binder**

| Temp °C | \|G*\| Pa | STDEV | CV | δ Degree | \|G*\|/sinδ Pa | Strain Amp % | Freq rad/sec |
|---|---|---|---|---|---|---|---|
| **37** | 2352 | 114 | 4.83% | 41.3 | 1553 | 0.99 | 10.08 |
| **34** | 3420 | 199 | 5.82% | 39.3 | 2164 | 1.00 | 10.08 |
| **31** | 4873 | 300 | 6.16% | 37.4 | 2959 | 1.01 | 10.08 |
| **28** | 7009 | 454 | 6.48% | 35.5 | 4064 | 1.02 | 10.08 |
| **25** | 9847 | 640 | 6.50% | 33.6 | 5438 | 1.02 | 10.08 |

**Table 4-30 Intermediate Temperature DSR Results for PAV PG 70-10 20%RAR Binder**

| Temp °C | \|G*\| Pa | STDEV | CV | δ Degree | \|G*\|/sinδ Pa | Strain Amp % | Freq rad/sec |
|---|---|---|---|---|---|---|---|
| **37** | 1216 | 77 | 6.32% | 44.4 | 850 | 1.0 | 10.08 |
| **34** | 1808 | 115 | 6.37% | 42.8 | 1228 | 1.0 | 10.08 |
| **31** | 2668 | 169 | 6.32% | 40.6 | 1735 | 1.0 | 10.08 |
| **28** | 3953 | 267 | 6.76% | 38.7 | 2468 | 1.0 | 10.08 |
| **25** | 5704 | 331 | 5.80% | 36.8 | 3417 | 1.0 | 10.08 |
| **22** | 8149 | 411 | 5.04% | 35.1 | 4679 | 1.0 | 10.08 |
| **19** | 11556 | 671 | 5.81% | 33.2 | 6328 | 0.9 | 10.08 |

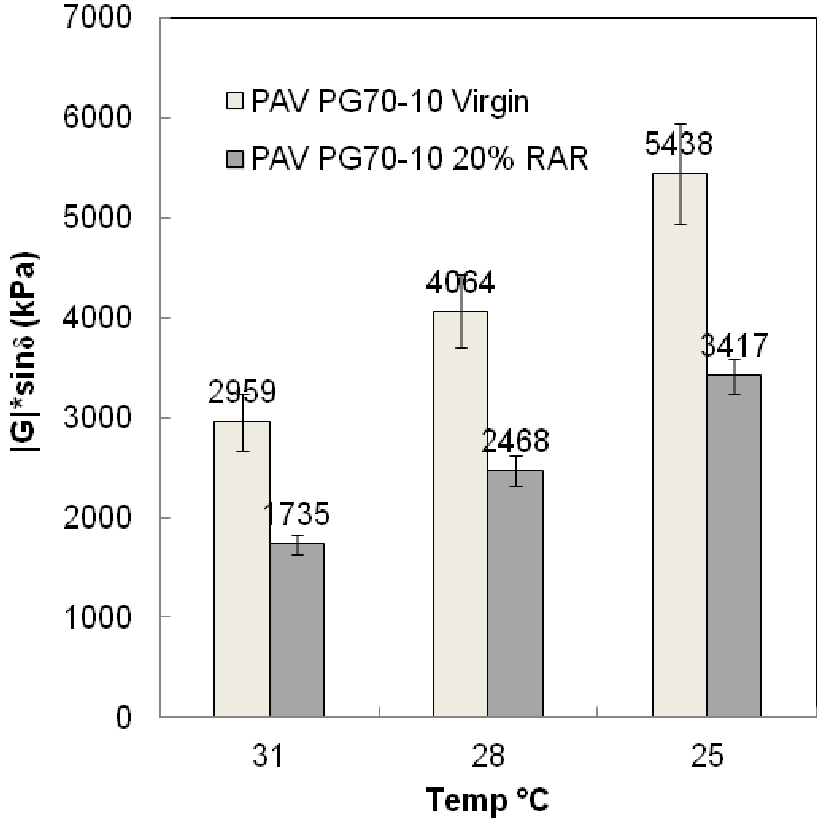



**Figure 4-12 DSR Results at Different Temperatures for PAV PG 70-10 Binder**

### *4.3.3 Bending Beam Rheometer Results*

Bending beam rheometer test is used in the Superpave performance grade system to evaluate the low temperature performance of the binder, by measuring the creep stiffness and the recovery ratio (m-value) using simple beam theory. The criteria for this test states that the stiffness should be less or equal to 300 MPa and that the m-value be greater or equal to 0.3. The test was performed at -12 °C and at -18 °C. Results from each replicate can be seen in APPENDIX C. The average results for virgin and modified PG 64-22 binder are shown in Table 4-31 and Table 4-32. Results shows that RAR modified binder reduced the stiffness and the m-value at both temperatures but did not meet the criteria at -18 °C. In both cases the stiffness was lower than 300 MPa but both did not meet the m-value criterion.

**Table 4-31 BBR Results for PAV PG 64-22 Binder**

| Temp (°C) | Time (s) | Force (mN) | Deflection (mm) | Measured S (MPa) | m-value |
|---|---|---|---|---|---|
| -12 | 60 | 982 | 0.558 | 142 | 0.338 |
| -18 | 60 | 982 | 0.270 | 294 | 0.285 |

**Table 4-32 BBR Results for PAV PG 64-22 20% RAR Binder**

| Temp (°C) | Time (s) | Force (mN) | Deflection (mm) | Measured S (MPa) | m-value |
|---|---|---|---|---|---|
| -12 | 60 | 980 | 0.826 | 96 | 0.331 |
| -18 | 60 | 985 | 0.491 | 162 | 0.288 |

The following plot shows the stiffness over time plotted in a log-log scale (Figure 4-13). From this chart it can be seen that virgin binder is stiffer than RAR modified binder and that the RAR modified binder reduced stiffness by 30 to 45%. However, there was not an improvement at the low temperature performance grade.

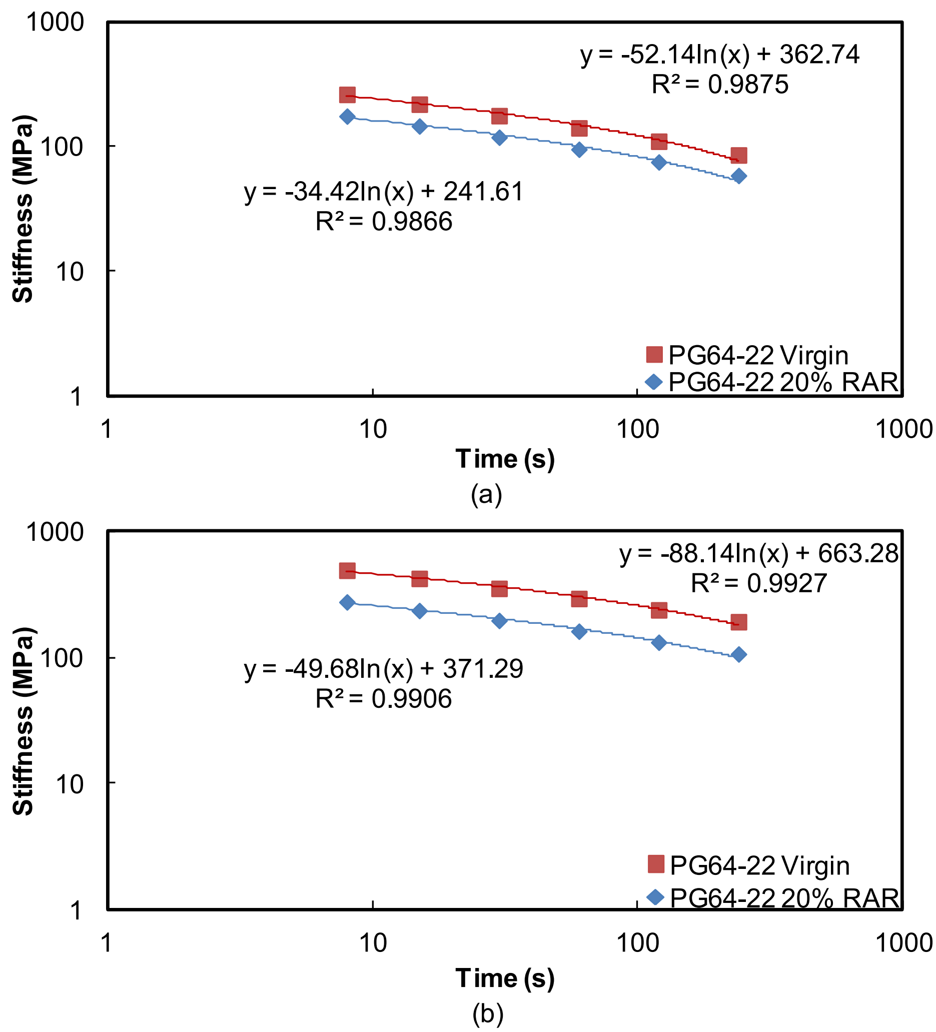



**Figure 4-13 BBR Test Results Stiffness vs Time for PG 64-22. (a) -12 °C. (b) -18 °C.**

PG 70-10 asphalt binder was tested at 0 °C, since this binder performs well at -10 °C. In both cases, the original and RuBind™ modified binder met the stiffness and m-value criteria at this temperature. Table 4-33 and Table 4-34 show the results from BBR test. The BBR test for the PG 70-10 asphalt binder was performed to one temperature, and the low temperature performance grade was not determined. In order to get the low temperature performance grade it is necessary to perform a BBR test at lower temperatures as per Superpave performance grade system until the binder does not meet the criterion.

**Table 4-33 BBR Results for PAV PG 70-10 Binder @ 0 °C**

| Temp (°C) | Time (s) | Force (mN) | Deflection (mm) | Measured S (Mpa) | m-value |
|---|---|---|---|---|---|
| 0 | 60 | 980 | 1.808 | 44 | 0.347 |

**Table 4-34 BBR Results for PAV PG 70-10 20% RAR Binder @ 0 °C**

| Temp (°C) | Time (s) | Force (mN) | Deflection (mm) | Measured S (Mpa) | m-value |
|---|---|---|---|---|---|
| 0 | 60 | 975 | 2.789 | 28 | 0.369 |

Figure 4-14 shows that virgin binder is stiffer than RuBind™ modified binder at 0 °C. The measured stiffness of the RAR modified binder showed a reduction of approximately 36%, and an increase in m-value.

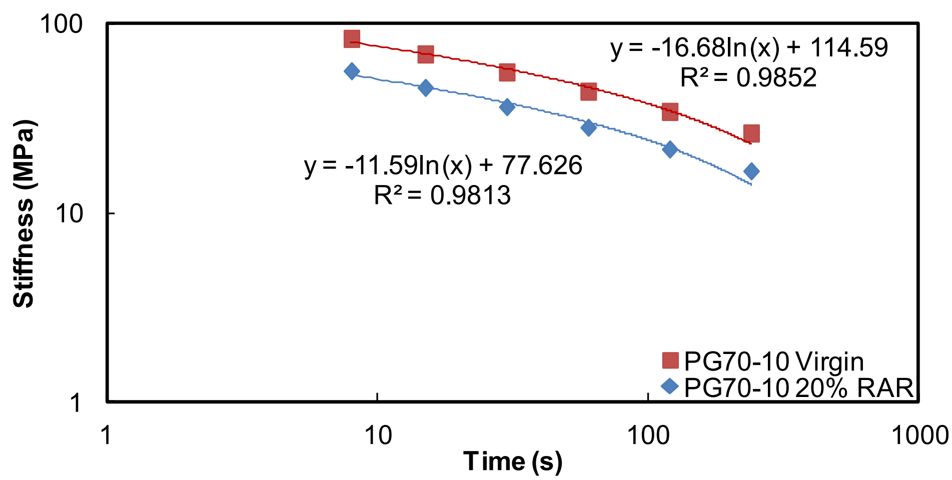



**Figure 4-14 BBR Test Results Stiffness vs Time for PG 70-10 @ 0 °C**

## 4.4 Comparison between RuBind™ AR (RAR) and Conventional Binder

From the test results it was found that RuBind™ improves the rheological properties of softer binders more than stiffer binders. The PG 64-22 and PG 70-10 increased to a PG 82 and PG 76 respectively, the softer binder showing a greater improvement at the high temperature performance grade (Figure 4-15). Even though, the results from both binders showed no improvement at the low temperature performance grade, there was a reduction in stiffness.

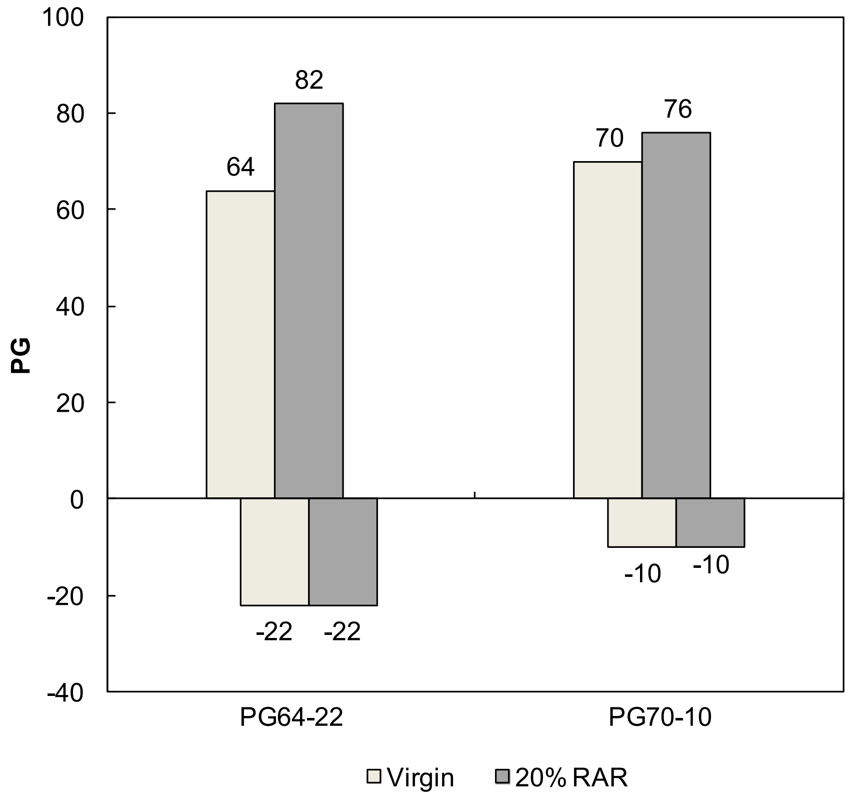



**Figure 4-15 PG Improvement after Adding 20% RAR**

From consistency test results it was found that the modified PG 64-22 binder showed higher stiffening that the modified PG 70-10 binder. Figure 4-16 shows the combined results from un-aged PG 64-22 and PG 70-10; original and RAR modified binder.

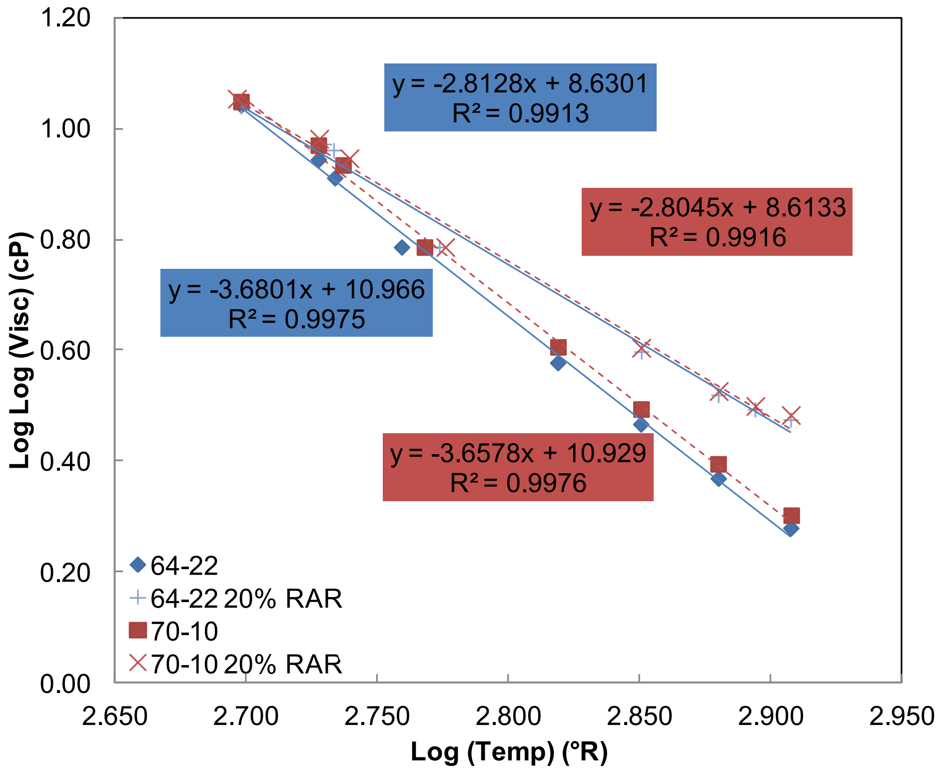



**Figure 4-16 Temperature-Viscosity Relationship for Unaged binders PG 64-22 and PG 70-10**

It was also of interest to compare the A and VTS values obtained in this study's testing program to those typical values reported in the Mechanistical Empirical Pavement Design Guide (MEPDG) software version 1.0. Table 4-35 compares A and VTS values from this study's test results to those reported in the MEPDG. The A and VTS values for the virgin binders are similar and agree with those reported in the MEPDG. The results also suggested that after adding RAR to the binder, the modified binders would likely perform similar to a PG 82-28. This was the case for both binders. The high and intermediate temperature DSR results agree with the values from the MEPDG table.

**Table 4-35 A and VTS Values from Consistency Test and MEPDG**

| TEST | | |
|---|---|---|
| **Binder PG** | **A** | **VTS** |
| **64-22** | 10.966 | -3.680 |
| **64-22 20% RAR** | 8.6301 | -2.813 |
| **70-10** | 10.929 | -3.658 |
| **70-10 20% RAR** | 8.6133 | -2.805 |

| MEPDG | | |
|---|---|---|
| **Binder PG** | **A** | **VTS** |
| 64-22 | 10.98 | −3.680 |
| 70-10 | 10.69 | −3.566 |
| 82-28 | 8.75 | -2.856 |

## 4.5 WMA Test Results

### *4.5.1 Brookfield Rotational Viscosity*

The two blends were tested for viscosity using a Brookfield rotational viscometer, and the measured values were compared to those from the virgin binder and the RuBind™ modified binder without Evotherm™ respectively. When the Evotherm™ control blend viscosity was compared to the previous viscosity from the virgin binder, it showed an increase in viscosity from 8 to 10%. Some studies done at Clemson University has shown an increase in the viscosity of rubberized asphalt binders with Sasobit® at mid range temperatures but reduced viscosity at high temperatures (Akisetty 2008).The RuBind™ modified binder showed a higher increase on viscosity ranging values from 17 to 24% increase. This increase of viscosity might not be caused by Evotherm™, instead it might be caused by the extra heating time and mixing of the binder. Table 4-36 shows the viscosity ratios to blends without Evotherm™. Figure 4-17 shows the measured viscosities at different temperatures.

**Table 4-36 Viscosity Ratios between Blends with and Without Evotherm™**

| Binder | °C | | | |
|---|---|---|---|---|
| | **93** | **121** | **149** | **177** |
| **PG 64-22 + EVOTHERM/PG 64-22** | 1.01 | 1.10 | 1.08 | 1.08 |
| **20% RAR + EVOTHERM/(20% RAR)** | n/a | 1.21 | 1.17 | 1.24 |

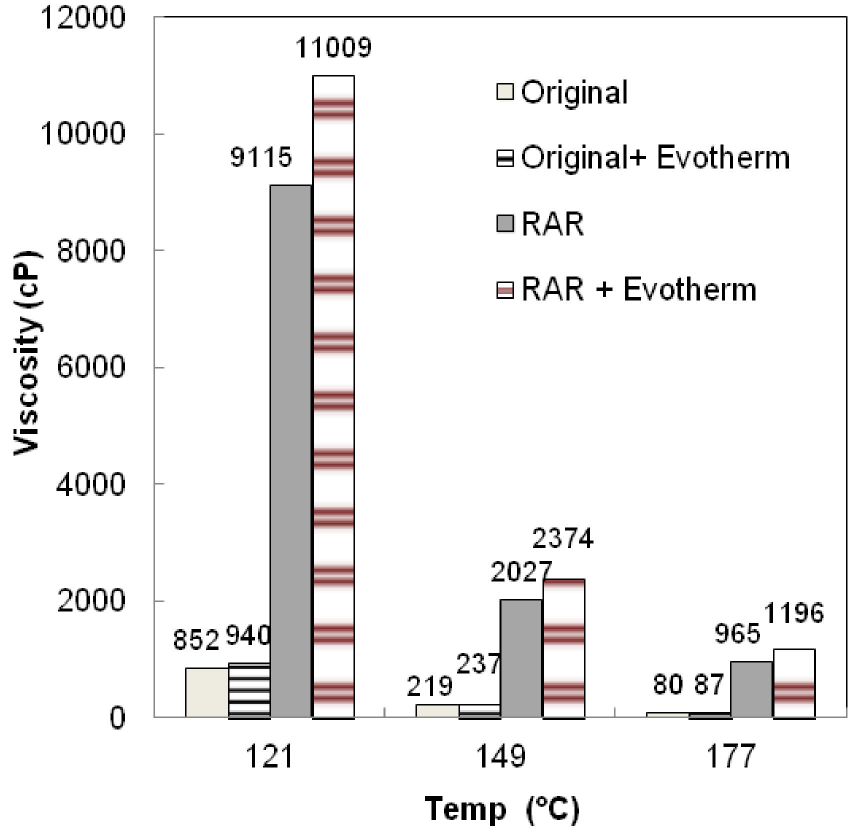



**Figure 4-17 Viscosity Comparison Using Evotherm™**

### *4.5.2 Dynamic Shear Rheometer*

The DSR results showed no significant change in both blends. Two samples of each binder was tested and compared to the same binder without Evotherm™. For the control and RuBind™ modified binder, the change in $|G^*|/\sin\delta$ was 2 and 5% respectively. A study by NCAT showed that sections with Evotherm™ mixtures had similar rutting performance to those from the control section (Akisetty 2008). Table 4-37 shows these ratios and Figure 4-18 shows the measured |G*|/sinδ values for each binder.

**Table 4-37 |G*|/sinδ Ratios between Blends with and Without Evotherm™**

| Binder | °C | | |
|---|---|---|---|
| | 58 | 64 | 70 |
| **PG 64-22 + EVOTHERM/PG 64-22** | 0.96 | 0.98 | 0.98 |
| **64-22 20 % RAR + EVOTHERM/20% RAR** | 1.00 | 0.97 | 0.95 |

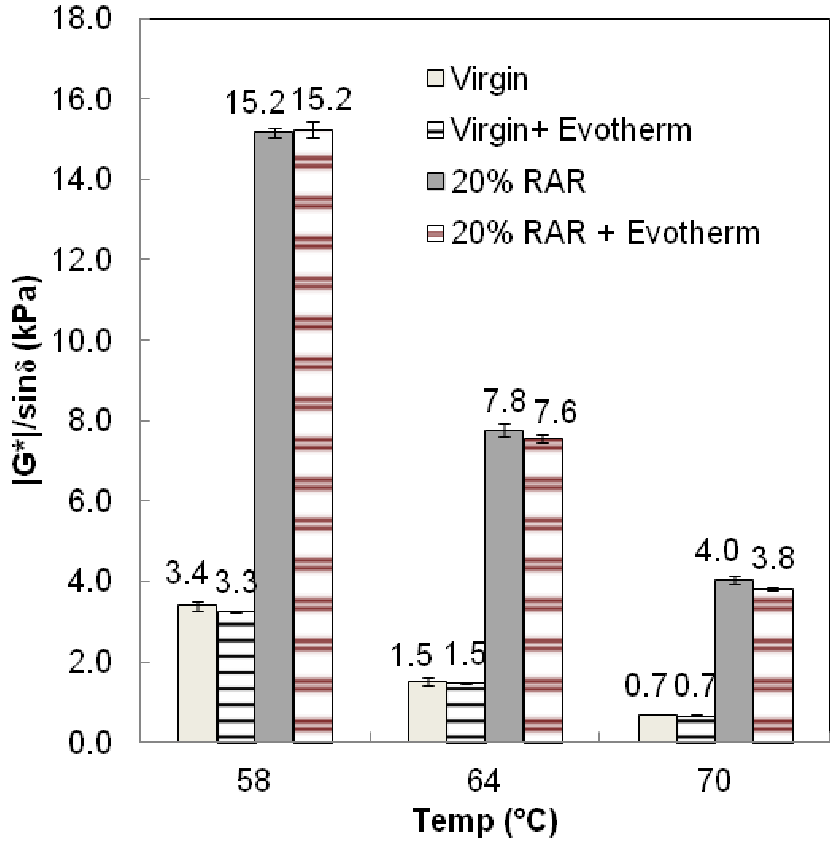



**Figure 4-18 Shear Modulus Comparison Using Evotherm™**

## 4.6 Evaluation of Stiffening Mechanism of the Binder

The previous sections evaluated the improvement at high and low temperature performance grade following Superpave specification. From the test results, it was shown a change in stiffness after RAR modification, but no insight in the stiffening mechanisms occurred by binder modification. Further analysis was made to evaluate, and to get a better insight on the stiffening mechanism of RAR modified binders. The purpose of this analysis was to see if the RAR is acting just as a filler or as a binder modifier. In order to identify the stiffening of the binder, the measured stiffness of both RAR modified binders were compared to values from NCHRP 9-45 Report, in which they evaluated the effect of 17 different mineral fillers on four asphalt binders; these are listed in APPENDIX D (NCHRP 9-45). The use of dilute suspension and micromechanical models were used to predict the effect of rigid inclusions into an asphalt binder matrix.

The stiffness evaluation was first made by comparing the relative densities from the NCHRP 9-45 report and the relative viscosities from RAR at high temperatures, 135 °C. The relative viscosity was computed by dividing the mastic viscosity by the binder viscosity. The NCHRP 9-45 Report had 68 different mastic combinations; only 13 samples were chosen to represent the lower, intermediate and upper range of relative viscosity. Figure 4-19 is a combination of the NCHRP 9-45 report and the RAR test results from this study. The figure shows that the relative viscosity on both RAR samples has higher relative viscosity than the other fillers. Also, binder modified with styrene butadiene styrene (SBS) showed a higher viscosity and higher relative viscosity than any other binder-filler combination. The SBS modified binder with steel furnace slag (FS2 SBS) had the higher relative viscosity in the NCHRP report.

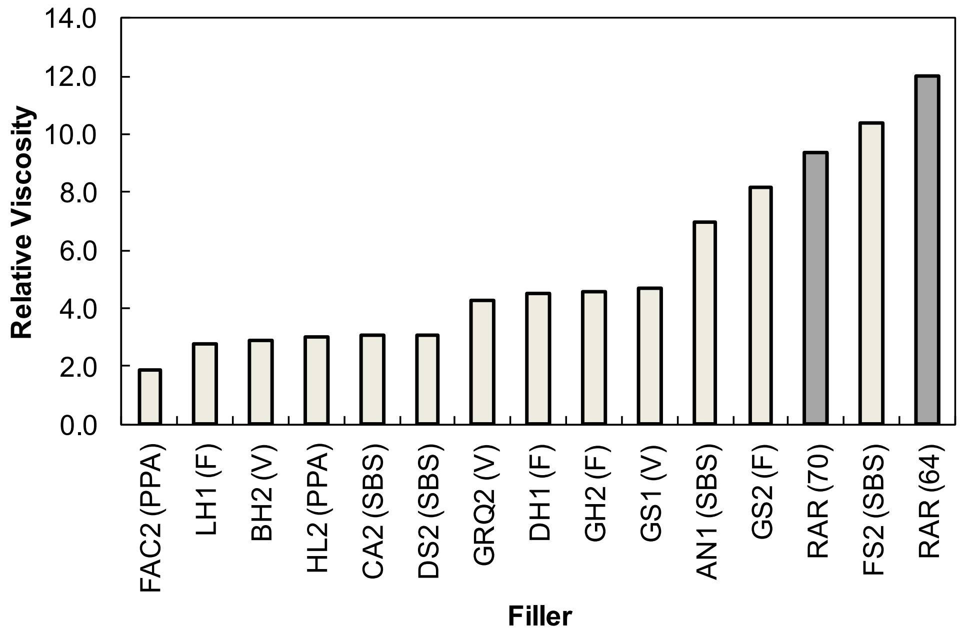



**Figure 4-19 Relative Viscosity at 135 °C from Different Mineral Filler Mastics from NCHRP 9-45 and Results from RAR**

The volumetric concentration of the fillers in the NCHRP 9-45 report ranged from 26 to 30%; the volumetric concentration of RAR in this research was approximately18%. Rigden (1947) showed that the viscosity increased with increasing particle volume fraction independent of the type of filler (Rigden 1947). According to Rigden, if the RAR particles act as a rigid solid, then the relative viscosity should be lower than the other fillers with higher volume fraction used in the report. Figure 4-20 show Rigden approach to the increase of viscosity with increase in volume fraction. If this was the case with RAR fillers with higher volume fraction will have higher relative viscosity. However, the results from RAR contradict Rigden approach and show that the magnitude of the relative viscosity is higher than mastics with higher filler volumetric concentrations.

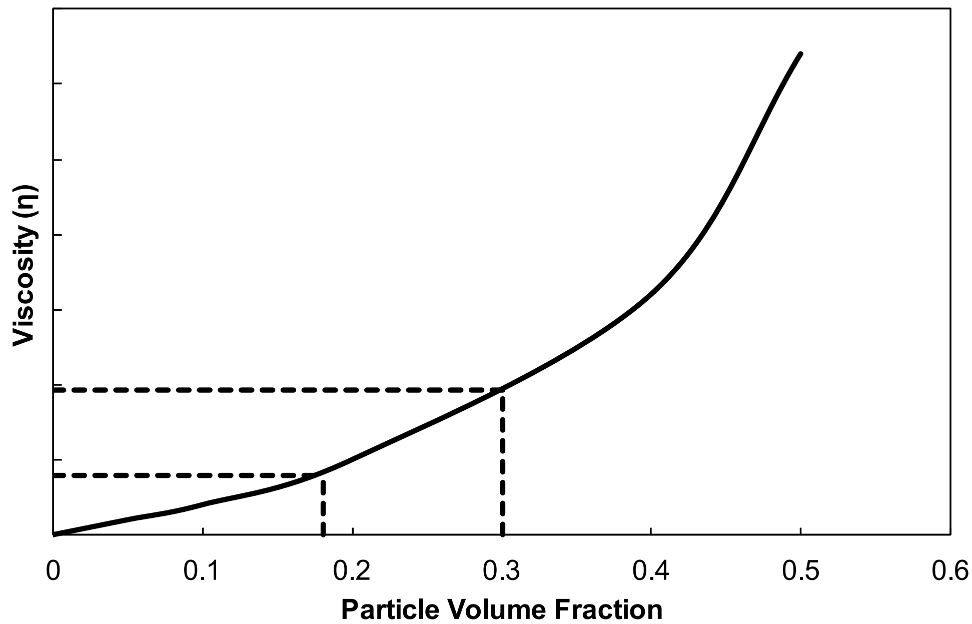



**Figure 4-20 Viscosity-Volume Fraction Relationship. Difference in Viscosity between 18 and 30% Particle Volume Fraction (After Rigden 1947)**

At intermediate temperatures, the relative |G*|sinδ was analyzed from the NCHRP 9-45 Report. From the report, only 14 representative samples were taken out of the 68 mastic combination plus the two RAR samples. Figure 4-21, shows a combination from NCHRP 9-45 results and RAR test results. From the figure, the RAR samples showed a decrease in stiffness at intermediate temperatures; whereas all the mineral filler mastics increased the stiffness.

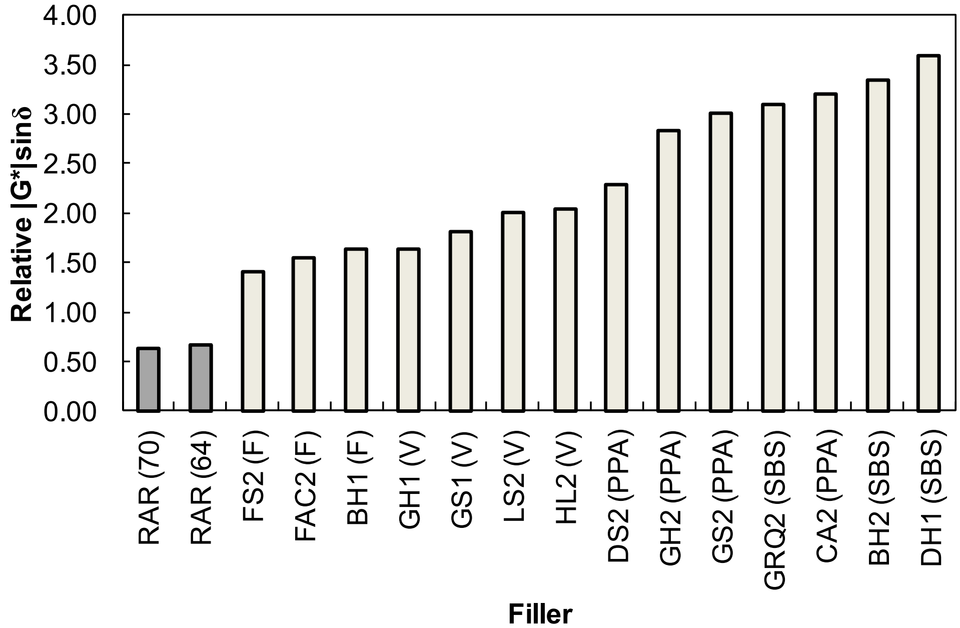
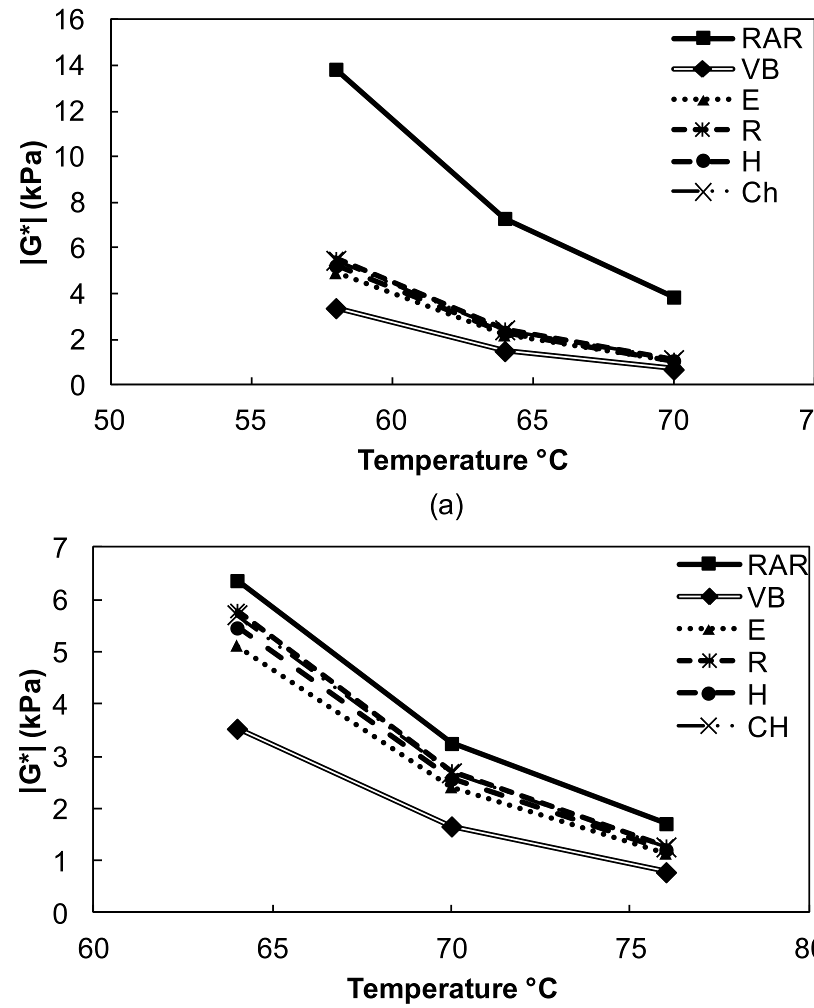



**Figure 4-21 Relative |G*|sinδ at 25 °C from Different Mineral Filler Mastics and RAR (After NCHRP 9-45)**

The second analysis consisted in using particulate filled composite models. The models used were the previously mentioned models; the Einstein, Roscoe, Hashin and Christensen models. All the models underestimate the stiffness of the PG 64-22 RAR binder at high temperatures by 60 to 70% for un-aged binders and by 55 to 60% on RTFO binder samples, Figure 4-22 (a). Ongoing but currently unpublished research using similar models has shown differences ranging from 10 to 50%. Bahia, et al. (1995) used Einstein and Mooney model to predict the viscosity of a crumb rubber modified asphalt and concluded that the underestimated values from the model is an indication that the interaction between the rubber and asphalt is not one involving simple solid inclusions (Bahia and Davies 1995). At high temperatures, the stiffness of the PG 64-22 RAR the change in stiffness might be primarily attributed to the selective absorption of lighter fractions of the asphalt (swelling), and some other physical-chemical mechanism.

However, the PG 70-10 binder stiffening prediction by these models were underestimated by 10 to 30% on the un-aged and RTFO binders, Figure 4-22 (b)




(b)

**Figure 4-22 High Temperatures Stiffness. VB = Virgin Binder, E = Einstein Model, R = Roscoe Model, H = Hashin Model and Ch = Christensen Model; (a) PG 64-22, (b) PG-70-10**

Assuming that the swelling of the rubber increased the size of rubber particles by 50%, in the PG 70-10 RAR binder, this means an increased from 18% to 25% by volume of the composite. Roscoe and Christensen models showed a difference in stiffness that ranged from 0-20% and this is showed in Figure 4-23. An hypothesis drown from this analysis is that the PG 70-10 binder might have a higher asphaltene content and lower lighter fraction content, and therefore less absorption of the lighter oils. So, there could be a low interaction between the PG 70-10 binder and the RAR, and the increase in stiffening might be due to the increase in volume of the rubber. Unfortunately the available data is not enough to prove the hypothesis and thus in order to better understand the behavior of the RAR further testing needs to be done to estimate the change in volume due to swelling and the interaction between different asphalt binders and RAR.

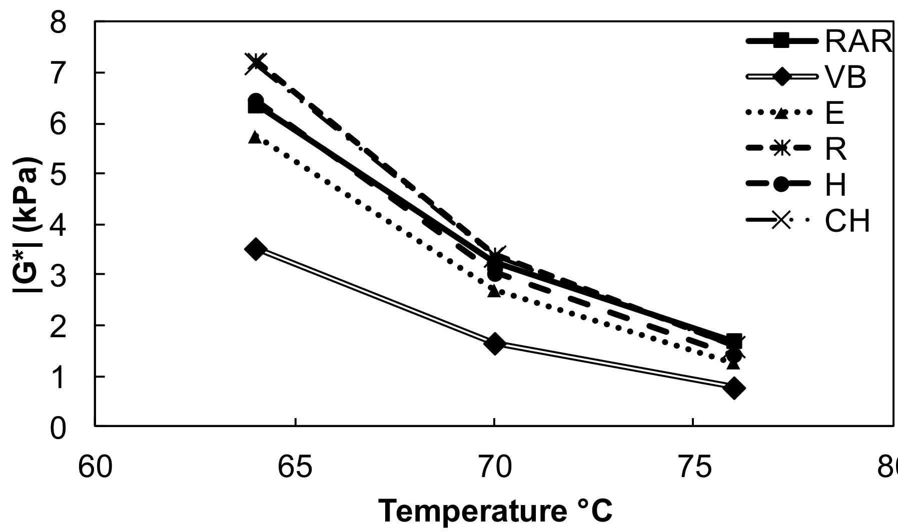



**Figure 4-23 High Temperature Predictions Assuming 21% Volume Fraction of PG 70-10 RAR Modified Binder**

The numerical models at intermediate temperatures overestimate the stiffening of the binder by 50 to 140%, Figure 4-24. At intermediate temperatures the stiffness of the RAR might be similar than the stiffness of the binder, and thus the drop in stiffness of the composite. Based on the measured values and the numerical models at intermediate temperatures, it is believed that the stiffening behavior of the composite is dependent on the swelling of the rubber and the stiffness of the rubber for both binders.

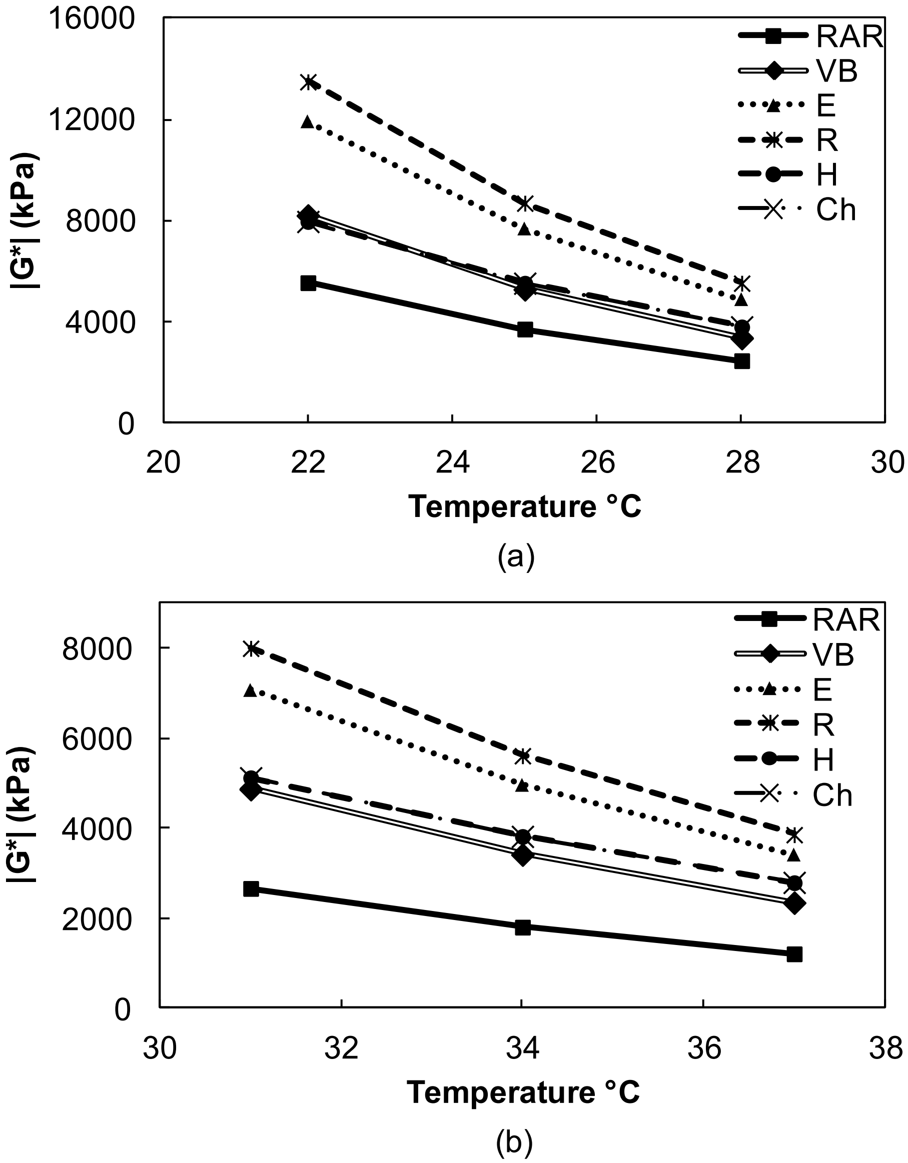



**Figure 4-24 Intermediate Temperatures Stiffness. VB = Virgin Binder, E = Einstein Model, R = Roscoe Model, H = Hashin Model and Ch = Christensen Model; (a) PG 64-22, (b) PG 70-10**

The results from this analysis suggests that the stiffness of the PG 64-22 RAR modified binder is not solely caused by the change in volume but also due to other physical-chemical interaction between the rubber and the binder. The results from the PG

70-10 RAR suggests that the effect of RAR could be asphalt binder dependant. These models are used to get a basic knowledge of the stiffening mechanisms of the particulate composites, and further testing and analysis is needed to better understand the interaction between the RAR and the asphalt binder.

# Chapter 5 Summary, Conclusions and Recommendations

Pre-treated crumb rubber technologies are emerging as a new method to produce asphalt rubber mixtures in the field. A new crumb rubber modifier industrially known as RuBind™ is one such technology. RuBind™ is a "Reacted and Activated Rubber"(RAR) that acts like an elastomeric asphalt extender to improve the engineering properties of the binder and mixtures. It is intended to be used in a dry mixing process with the purpose of simplifying mixing at the asphalt plant.

The objectives of this research study were to evaluate the rheological and aging properties of binders modified with RuBind™ and its compatibility with warm mix technology. Two binders were used for this study: Performance Grade (PG) 70-10 and PG 64-22, both modified with 25% by weight of the asphalt binder. Laboratory test included penetration, softening point, viscosity, Dynamic Shear Rheometer (DSR) and Bending Beam Rheometer (BBR). Tests were conducted under original, short and long term aging conditions.

Overall, the test results from laboratory prepared samples showed an improvement in performance grade, compared to the virgin binder, when RAR was added. Specific conclusions are as follows:

- Consistency tests showed a significant increase in viscosity when adding RAR, and the Temperature-Viscosity plots showed an improvement in temperature susceptibility of the binder.
- In evaluating the aging characteristics of the binder through the aging index approach, the RAR binder had slightly higher RTFO aging indices compared to the virgin binder. However, PAV aging showed very good results for the RAR

modified binders, compared to the virgin binder which had much higher aging indices. This was an interesting observation that may support the concept of the rubber particles protecting and preserving the maltenes in the modified binder.

- The PG 64-22 asphalt binder showed a greater improvement when adding RuBind™ than the PG 70-10 asphalt binder.
- DSR results showed that adding RAR increased the performance grade of each binder. The PG 64-22 binder at high temperatures increased performance from 64 to 82 °C and PG 70-10 increased from 70 to 76°C.
- Intermediate temperature DSR results showed that PG 64-22 and PG 70-10 will improve their low temperature performance to -34 °C.
- BBR results showed that the RAR modified binders had lower stiffness and higher deflections compared to the virgin binders. For the PG 64-22 binder the results showed a reduced stiffness but not a reduction in PG grade for low temperature.
- The addition of Evotherm™ showed an increase in viscosity for the PG 64-22 control binder and the RAR modified binder, but was not statistically significant. The reason for this might be the extra heating time during the mixing.
- High temperature DSR results did not show any change after adding Evotherm™.
- Relative viscosity was compared to different filler mastics from NCHRP 9-45 report, and the results showed that PG 64-22 RAR modified binder at high temperatures had the highest relative viscosity followed by SBS modified binder with steel furnace slag and by PG 70-10 RAR modified binder.

- The same comparison was done at intermediate temperatures, and the results from NCHRP 9-45 report showed that all the mastics increased the $|G^*|\sin\delta$ whereas the RAR modified binders showed a reduction of $|G^*|\sin\delta$. The reason to this might be that the fillers act as rigid particles with high much higher stiffness than the binder, and the stiffness of the rubber at this temperatures are similar to the stiffness of the binder.
- Particulate composite models and micromechanical models used in this study showed that the stiffness of the PG 64-22 RAR modified binder was not solely due to the swelling of the rubber particles, but might be also due to other physical-chemical interaction between the RAR and the asphalt binder.
- The stiffness predictions from the particulate composite models were closer to the measured stiffness of the PG 70-10 RAR modified binder at high temperatures. Then, it was assumed that the rubber particles increase the volume fraction from 18 to 21% due to swelling, and Roscoe and Christensen model predictions showed a difference of 0 to 20%. Conclusions from these observations cannot be drawn, but it gives some insight about the effect of RAR on the PG 70-10 binder. These observations suggest a more detailed specific testing on the swelling of the rubber particles and the interaction with different binder grades.

In practice or field applications, RuBind™ is added to the aggregate directly and the binder is then introduced. This binder study does not represent process as it is best captured from a mixture study. Therefore, it is recommended that a full scale laboratory mixture preparation study be conducted. This follow up study would best simulate the field mixing process and provide the engineering properties of the mixtures prepared with RuBind™ and Evotherm™.

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# APPENDIX A

# CONSISTENCY TEST RESULTS

Penetration Test Results

| PG 64-22 V | | |
|---|---|---|
| | **Temp (°C)** | **Pen (0.1 mm)** |
| 1.1 | 4 | 4 |
| 1.2 | 4 | 5 |
| 1.3 | 4 | 8 |
| 1 | **4** | **4.5** |
| 2.1 | 23.5 | 44 |
| 2.2 | 23.5 | 45 |
| 2.3 | 23.5 | 43.5 |
| 2 | **23.5** | **44.2** |
| 3.1 | 27.8 | 82 |
| 3.2 | 27.8 | 87 |
| 3.3 | 27.8 | 87 |
| 3 | **27.8** | **85.3** |

| PG 64-22 V RTFO | | |
|---|---|---|
| | **Temp (°C)** | **Pen (0.1 mm)** |
| 2.1 | 23.8 | 20.5 |
| 2.2 | 23.8 | 20 |
| 2.3 | 23.8 | 20 |
| 2 | **23.8** | **20.2** |

| PG 64-22 V PAV | | |
|---|---|---|
| | **Temp (°C)** | **Pen (0.1 mm)** |
| 2.1 | 25.1 | 18 |
| 2.2 | 25.1 | 20 |
| 2.3 | 25.1 | 18.5 |
| 2 | **25.1** | **18.8** |

| PG 64-22 20% RAR | | |
|---|---|---|
| | **Temp (°C)** | **Pen (0.1 mm)** |
| 1.1 | 4 | 5.5 |
| 1.2 | 4 | 4 |
| 1.3 | 4 | 5 |
| 1 | **4** | **4.8** |
| 2.1 | 25 | 25 |
| 2.2 | 25 | 24 |
| 2.3 | 25 | 24 |
| 2 | **25** | **24.3** |
| 3.1 | 27.5 | 30 |
| 3.2 | 27.5 | 30.5 |
| 3.3 | 27.5 | 32 |
| 3 | **27.5** | **30.8** |

| PG 64-22 20% RAR RTFO | | |
|---|---|---|
| | **Temp (°C)** | **Pen (0.1 mm)** |
| 2.1 | 24.8 | 17 |
| 2.2 | 24.8 | 17 |
| 2.3 | 24.8 | 16.5 |
| 2 | **24.8** | **16.8** |

| PG 64-22 20% RAR PAV | | |
|---|---|---|
| | **Temp (°C)** | **Pen (0.1 mm)** |
| 2.1 | 25.4 | 49 |
| 2.2 | 25.4 | 52.5 |
| 2.3 | 25.4 | 51.5 |
| 2 | **25.4** | **51.0** |

Softening Point Test Results

| PG 64-22 V | |
|---|---|
| | **Temp (°C)** |
| 1 | 46 |
| 2 | 46 |
| **Avg.** | **46** |

| PG 64-22 V RTFO | |
|---|---|
| | **Temp (°C)** |
| 1 | 55 |
| 2 | 55 |
| **Avg.** | **55** |

| PG 64-22 V PAV | |
|---|---|
| | **Temp (°C)** |
| 1 | 66 |
| 2 | 66 |
| **Avg.** | **66** |

| PG 64-22 20% RAR | |
|---|---|
| | **Temp (°C)** |
| 1 | 57 |
| 2 | 58 |
| **Avg.** | **57** |
| | |
| 3 | 56 |
| 4 | 57 |
| | 56.5 |
| **Avg.** | **56.8** |

| PG 64-22 20% RAR RTFO | |
|---|---|
| | **Temp (°C)** |
| 1 | 66 |
| 2 | 66 |
| **Avg.** | **66** |
| | |
| 3 | 67 |
| 4 | 67 |
| | 67 |
| **Avg.** | **66** |

| PG 64-22 20% RAR PAV | |
|---|---|
| | **Temp (°C)** |
| 1 | 75 |
| 2 | 75 |
| **Avg.** | **75** |

Brookfield Viscosity Test Results

| Replicate 1 PG 64-22 V | | | | Replicate 2 PG 64-22 V | | | |
|---|---|---|---|---|---|---|---|
| **Torque** | **RPM** | **Temp (°F)** | **Viscosity (cP)** | **Torque** | **RPM** | **Temp (°F)** | **Viscosity (cP)** |
| 50% | 2 | 199.5 | 5846 | 53% | 2 | 199.1 | 6491 |
| 50% | 2 | 199.5 | 5811 | 54% | 2 | 199.1 | 6421 |
| 50% | 2 | 199.5 | 5753 | 54% | 2 | 199 | 6022 |
| **Average** | | **200** | **5803** | **Average** | | **199** | **6311** |
| 25% | 7 | 249 | 826.8 | 26% | 7 | 249.3 | 870 |
| 25% | 7 | 249 | 826.8 | 28% | 7 | 249.3 | 903 |
| 25% | 7 | 249 | 826.8 | 28% | 7 | 249.6 | 860 |
| **Average** | | **249** | **827** | **Average** | | **249** | **878** |
| 19% | 20 | 299.4 | 219.1 | 20% | 20 | 299 | 220.3 |
| 19% | 20 | 299.6 | 216.8 | 20% | 20 | 298.8 | 220.6 |
| 18% | 20 | 299 | 215.6 | 20% | 20 | 299.3 | 219.1 |
| **Average** | | **299** | **217** | **Average** | | **299** | **220** |
| 15% | 45 | 349.2 | 75.5 | 16% | 45 | 349 | 84.9 |
| 15% | 45 | 349.5 | 75.5 | 17% | 45 | 348.7 | 85.9 |
| 15% | 45 | 349.5 | 76 | 16% | 45 | 348.8 | 82.8 |
| **Average** | | **349** | **76** | **Average** | | **349** | **85** |

| Replicate 1 RTFO PG 64-22 V | | | | Replicate 2 RTFO PG 64-22 V | | | |
|---|---|---|---|---|---|---|---|
| **Torque** | **RPM** | **Temp (°F)** | **Viscosity (cP)** | **Torque** | **RPM** | **Temp (°F)** | **Viscosity (cP)** |
| 61% | 2 | 199.9 | 13825 | 61% | 2 | 199.6 | 14059 |
| 60% | 2 | 199.8 | 13895 | 59% | 2 | 199.6 | 13942 |
| 61% | 2 | 199.7 | 14200 | 60% | 2 | 199.7 | 13778 |
| **Average** | | **200** | **13973** | **Average** | | **200** | **13926** |
| 49% | 7 | 249.4 | 1650 | 48% | 7 | 249.6 | 1637 |
| 49% | 7 | 249.4 | 1597 | 48% | 7 | 249.7 | 1590 |
| 50% | 7 | 249.2 | 1640 | 49% | 7 | 249.6 | 1630 |
| **Average** | | **249** | **1629** | **Average** | | **250** | **1619** |
| 31% | 20 | 299.5 | 353.8 | 32% | 20 | 299.1 | 371.4 |
| 31% | 20 | 299.5 | 362 | 31% | 20 | 298.9 | 360.9 |
| 32% | 20 | 299.3 | 359.7 | 31% | 20 | 298.8 | 366.7 |
| **Average** | | **299** | **359** | **Average** | | **299** | **366** |
| 23% | 45 | 348.5 | 117.1 | 23% | 45 | 348.8 | 119.8 |
| 22% | 45 | 348.6 | 115.1 | 23% | 45 | 349.1 | 118.2 |
| 22% | 45 | 349 | 116.1 | 23% | 45 | 349.4 | 117.2 |
| **Average** | | **349** | **116** | **Average** | | **349** | **118** |

| Replicate 1 PAV PG 64-22 V | | | | Replicate 2 PAV PG 64-22 V | | | |
|---|---|---|---|---|---|---|---|
| **Torque** | **RPM** | **Temp (°F)** | **Viscosity (cP)** | **Torque** | **RPM** | **Temp (°F)** | **Viscosity (cP)** |
| 44% | 1 | 224.6 | 10123 | 43% | 1 | 224.4 | 10263 |
| 45% | 1 | 224.6 | 10123 | 43% | 1 | 224.5 | 10146 |
| 44% | 1 | 224.5 | 10099 | 43% | 1 | 224.7 | 10193 |
| **Average** | | **225** | **10115** | **Average** | | **225** | **10201** |
| 70% | 5 | 249.2 | 3290 | 72% | 5 | 249.3 | 3299 |
| 72% | 5 | 249.4 | 3327 | 70% | 5 | 249.3 | 3318 |
| 72% | 5 | 249.6 | 3365 | 70% | 5 | 249.4 | 3290 |
| **Average** | | **249** | **3327** | **Average** | | **249** | **3302** |
| 51% | 20 | 299.1 | 603.4 | 50% | 20 | 299.1 | 595 |
| 51% | 20 | 299.3 | 588.2 | 51% | 20 | 299.4 | 587 |
| 50% | 20 | 299.5 | 598.1 | 50% | 20 | 299.6 | 594 |
| **Average** | | **299** | **597** | **Average** | | **299** | **592** |
| 34% | 45 | 348.8 | 170.8 | 33% | 45 | 349.2 | 168.7 |
| 34% | 45 | 349.5 | 174 | 32% | 45 | 348.9 | 170.3 |
| 33% | 45 | 349.4 | 170.8 | 33% | 45 | 348.6 | 169.8 |
| **Average** | | **349** | **172** | **Average** | | **349** | **170** |

| Replicate 1 PG 64-22 20% RAR | | | | Replicate 2 PG 64-22 20% RAR | | | |
|---|---|---|---|---|---|---|---|
| **Torque** | **RPM** | **Temp (°F)** | **Viscosity (cP)** | **Torque** | **RPM** | **Temp (°F)** | **Viscosity (cP)** |
| 35% | 1 | 249.6 | 8553 | 40% | 1 | 249.4 | 9490 |
| 35% | 1 | 249.6 | 8342 | 41% | 1 | 249.5 | 9514 |
| 33% | 1 | 249.3 | 8483 | 40% | 1 | 249.5 | 9326 |
| **Average** | | **250** | **8459** | **Average** | | **249** | **9443** |
| 40% | 5 | 299.1 | 1898 | 45% | 5 | 298.9 | 2104 |
| 39% | 5 | 299 | 1912 | 44% | 5 | 299.1 | 2085 |
| 39% | 5 | 298.8 | 1865 | 44% | 5 | 299.5 | 2071 |
| **Average** | | **299** | **1892** | **Average** | | **299** | **2087** |
| 27% | 5 | 324.5 | 1284 | 28% | 5 | 323.8 | 1350 |
| 25% | 5 | 324.4 | 1233 | 28% | 5 | 323.8 | 1284 |
| 26% | 5 | 324.4 | 1237 | 26% | 5 | 323.9 | 1275 |
| **Average** | | **324** | **1251** | **Average** | | **324** | **1303** |
| 21% | 5 | 348.5 | 946.7 | 21% | 5 | 349.4 | 1022 |
| 20% | 5 | 348.7 | 979 | 21% | 5 | 349.3 | 984 |
| 20% | 5 | 348.9 | 965.4 | 22% | 5 | 348.7 | 1017 |
| **Average** | | **349** | **964** | **Average** | | **349** | **1008** |

| Replicate 1 RTFO PG 64-22 20% RAR | | | | Replicate 2 RTFO PG 64-22 20% RAR | | | |
|---|---|---|---|---|---|---|---|
| **Torque** | **RPM** | **Temp (°F)** | **Viscosity (cP)** | **Torque** | **RPM** | **Temp (°F)** | **Viscosity (cP)** |
| 47% | 1 | 274 | 11294 | 48% | 1 | 274.4 | 11505 |
| 46% | 1 | 274.1 | 11154 | 49% | 1 | 274.5 | 11646 |
| 46% | 1 | 274.5 | 11177 | 49% | 1 | 274.4 | 11576 |
| **Average** | | **274** | **11208** | **Average** | | **274** | **11576** |
| 90% | 5 | 298.8 | 4274 | 93% | 5 | 299.5 | 4340 |
| 88% | 5 | 298.9 | 4241 | 93% | 5 | 299.5 | 4260 |
| 91% | 5 | 299 | 4260 | 93% | 5 | 299.2 | 4340 |
| **Average** | | **299** | **4258** | **Average** | | **299** | **4313** |
| 53% | 5 | 323.8 | 2521 | 54% | 5 | 324 | 2526 |
| 53% | 5 | 323.9 | 2474 | 53% | 5 | 324.4 | 2512 |
| 52% | 5 | 324.4 | 2423 | 53% | 5 | 324.4 | 2498 |
| **Average** | | **324** | **2473** | **Average** | | **324** | **2512** |
| 35% | 5 | 348.7 | 1640 | 35% | 5 | 348.6 | 1645 |
| 34% | 5 | 348.7 | 1631 | 35% | 5 | 348.7 | 1640 |
| 33% | 5 | 348.9 | 1593 | 35% | 5 | 348.9 | 1626 |
| **Average** | | **349** | **1621** | **Average** | | **349** | **1637** |

| Replicate 1 PAV PG 64-22 20% RAR | | | | Replicate 2 PAV PG 64-22 20% RAR | | | |
|---|---|---|---|---|---|---|---|
| **Torque** | **RPM** | **Temp (°F)** | **Viscosity (cP)** | **Torque** | **RPM** | **Temp (°F)** | **Viscosity (cP)** |
| 58% | 1 | 274.3 | 13521 | 55% | 1 | 274.1 | 12818 |
| 56% | 1 | 274.3 | 13427 | 55% | 1 | 274.1 | 12841 |
| 57% | 1 | 274.2 | 13333 | 54% | 1 | 274.1 | 12700 |
| **Average** | | **274** | **13427** | **Average** | | **274** | **12786** |
| 49% | 2 | 299.5 | 5893 | 48% | 2 | 299.5 | 5729 |
| 49% | 2 | 299.6 | 5870 | 48% | 2 | 299.5 | 5718 |
| 49% | 2 | 299.6 | 5882 | 47% | 2 | 299.4 | 5647 |
| **Average** | | 300 | 5882 | **Average** | | **299** | **5698** |
| 57% | 5 | 324.1 | 2709 | 57% | 5 | 324.4 | 2667 |
| 57% | 5 | 324.1 | 2713 | 56% | 5 | 324.1 | 2653 |
| 58% | 5 | 324.7 | 2723 | 56% | 5 | 324 | 2662 |
| **Average** | | 324 | 2715 | **Average** | | **324** | **2661** |
| 36% | 5 | 348.9 | 1668 | 33% | 5 | 348.9 | 1589 |
| 36% | 5 | 349.2 | 1682 | 33% | 5 | 349.3 | 1584 |
| 35% | 5 | 349.5 | 1687 | 33% | 5 | 349.5 | 1589 |
| **Average** | | **349** | **1679** | **Average** | | **349** | **1587** |

PG 64-22 + EVOTHERM Replicate 1 | PG 64-22 + EVOTHERM Replicate 2

| Torque | RPM | Temp (°F) | Viscosity (cP) | Torque | RPM | Temp (°F) | Viscosity (cP) |
|---|---|---|---|---|---|---|---|
| 53% | 2 | 199.7 | 6081 | 22% | 2 | 199.6 | 6151 |
| 53% | 2 | 199.6 | 6092 | 54% | 2 | 199.7 | 6128 |
| 53% | 2 | 199.6 | 6104 | 54% | 2 | 199.8 | 6151 |
| **Average** | | **200** | **6092** | **Average** | | **200** | **6143** |
| 28% | 7 | 249.3 | 913.9 | 28% | 7 | 249.4 | 977.5 |
| 28% | 7 | 249.4 | 927.3 | 28% | 7 | 249.4 | 967.4 |
| 28% | 7 | 249.5 | 923.9 | 29% | 7 | 249.7 | 927.3 |
| **Average** | | **249** | **922** | **Average** | | **250** | **957** |
| 20% | 20 | 299.3 | 234.3 | 21% | 20 | 299.3 | 246 |
| 20% | 20 | 299 | 233.2 | 21% | 20 | 299.6 | 237 |
| 20% | 20 | 299 | 232 | 20% | 20 | 298.9 | 236.7 |
| **Average** | | **299** | **233** | **Average** | | **299** | **240** |
| 17% | 45 | 348.8 | 85.9 | 17% | 45 | 348.9 | 88.5 |
| 16% | 45 | 349.3 | 85.4 | 17% | 45 | 349.3 | 88 |
| 16% | 45 | 349.5 | 84.9 | 17% | 45 | 349.1 | 87 |
| **Average** | | **349** | **85** | **Average** | | **349** | **88** |

| PG 64-22 20% RAR + EVOTHERM Replicate 1 | | | | PG 64-22 20% RAR + EVOTHERM Replicate 2 | | | |
|---|---|---|---|---|---|---|---|
| **Torque** | **RPM** | **Temp (°F)** | **Viscosity (cP)** | **Torque** | **RPM** | **Temp (°F)** | **Viscosity (cP)** |
| 47% | 1 | 249.4 | 11458 | 46% | 1 | 249.5 | 11013 |
| 44% | 1 | 249.2 | 11013 | 43% | 1 | 249.5 | 10802 |
| 45% | 1 | 249.3 | 11060 | 44% | 1 | 249.4 | 10709 |
| **Average** | | **249** | **11177** | **Average** | | **249** | **10841** |
| 52% | 5 | 299.1 | 2442 | 49% | 5 | 299.4 | 2339 |
| 51% | 5 | 298.9 | 2423 | 49% | 5 | 299.2 | 2306 |
| 50% | 5 | 298.9 | 2428 | 48% | 5 | 299 | 2306 |
| **Average** | | **299** | **2431** | **Average** | | **299** | **2317** |
| 32% | 5 | 323.9 | 1565 | 31% | 5 | 324.3 | 1486 |
| 33% | 5 | 323.8 | 1575 | 31% | 5 | 324.3 | 1495 |
| 32% | 5 | 324.2 | 1584 | 30% | 5 | 324.2 | 1476 |
| **Average** | | **324** | **1575** | **Average** | | **324** | **1486** |
| 26% | 5 | 348.8 | 1237 | 22% | 5 | 349.4 | 1129 |
| 26% | 5 | 348.6 | 1233 | 24% | 5 | 349.4 | 1234 |
| 26% | 5 | 348.9 | 1237 | 23% | 5 | 348.7 | 1106 |
| **Average** | | **349** | **1236** | **Average** | | **349** | **1156** |

Consistency Test Results: Binder PG 70-10

Penetration Test Results

| PG 70-10 V | | |
|---|---|---|
| | **Temp (°C)** | **Pen (0.1 mm)** |
| 1.1 | 4 | 4 |
| 1.2 | 4 | 4 |
| 1.3 | 4 | 3.5 |
| 1 | **4** | **3.8** |
| | | |
| 2.1 | 23.5 | 25.5 |
| 2.2 | 23.5 | 26 |
| 2.3 | 23.5 | 25 |
| 2 | **23.5** | **25.5** |
| | | |
| 3.1 | 30 | 55 |
| 3.2 | 30 | 55 |
| 3.3 | 30 | 52.5 |
| 3 | **30** | **54.2** |

| PG 70-10 V RTFO | | |
|---|---|---|
| | **Temp (°C)** | **Pen (0.1 mm)** |
| 2.1 | 26.5 | 15 |
| 2.2 | 26.5 | 16 |
| 2.3 | 26.5 | 16 |
| 2 | **26.5** | **15.7** |

| PG 70-10 V PAV | | |
|---|---|---|
| | **Temp (°C)** | **Pen (0.1 mm)** |
| 2.1 | 25.1 | 8.5 |
| 2.2 | 25.1 | 10 |
| 2.3 | 25.1 | 10 |
| 2 | **25.1** | **9.5** |

| PG 70-10 20% RAR | | |
|---|---|---|
| | **Temp (°C)** | **Pen (0.1 mm)** |
| 1.1 | 3 | 2.5 |
| 1.2 | 3 | 3 |
| 1.3 | 3 | 4.5 |
| 1 | **3** | **3.3** |
| | | |
| 2.1 | 23.7 | 19 |
| 2.2 | 23.7 | 21 |
| 2.3 | 23.7 | 19 |
| 2 | **23.7** | **19.7** |
| | | |
| 3.1 | 31.1 | 41 |
| 3.2 | 31.9 | 43 |
| 3.3 | 32.1 | 42.5 |
| 3 | **31.7** | **42.2** |

| PG 70-10 20% RAR RTFO | | |
|---|---|---|
| | **Temp (°C)** | **Pen (0.1 mm)** |
| 2.1 | 24.9 | 14 |
| 2.2 | 25.1 | 16 |
| 2.3 | 25 | 14.5 |
| 2 | **25** | **14.8** |

| PG 70-10 20% RAR PAV | | |
|---|---|---|
| | **Temp (°C)** | **Pen (0.1 mm)** |
| 2.1 | 24.6 | 15 |
| 2.2 | 24.6 | 15 |
| 2.3 | 24.6 | 16 |
| 2 | **24.6** | **15.3** |

Softening Point Test Results

| PG 70-10 V | |
|---|---|
| | **Temp (°C)** |
| 1 | 52 |
| 2 | 53 |
| **Avg.** | **52.5** |
| | |
| 3 | 52 |
| 4 | 53 |
| | 52.5 |
| **Avg.** | **52.5** |

| PG 70-10 V RTFO | |
|---|---|
| | **Temp (°C)** |
| 1 | 61 |
| 2 | 61 |
| **Avg.** | **61** |
| | |
| 3 | 62 |
| 4 | 62 |
| | 62 |
| **Avg.** | **61.5** |

| PG 70-10 V PAV | |
|---|---|
| | **Temp (°C)** |
| 1 | 85 |
| 2 | 85 |
| **Avg.** | **85** |

| PG 70-10 20% RAR | |
|---|---|
| | **Temp (°C)** |
| 1 | 59 |
| 2 | 58 |
| **Avg.** | **58.5** |
| | |
| 3 | 58 |
| 4 | 59 |
| | 58.5 |
| **Avg.** | **58.5** |

| PG 70-10 20% RAR RTFO | |
|---|---|
| | **Temp (°C)** |
| 1 | 67 |
| 2 | 67.5 |
| **Avg.** | **67.25** |
| | |
| 3 | 67 |
| 4 | 67 |
| | 67 |
| **Avg.** | **67** |

| PG 70-10 20% RAR PAV | |
|---|---|
| | **Temp (°C)** |
| 1 | 82 |
| 2 | 82 |
| **Avg.** | **82** |

Brookfield Viscosity Test Results

| Torque | RPM | Temp (°F) | Viscosity (cP) | Torque | RPM | Temp (°F) | Viscosity (cP) |
|---|---|---|---|---|---|---|---|
| Replicate 1 PG 70-10 V | | | | Replicate 2 PG 70-10 V | | | |
| 50% | 1 | 198.8 | 11388 | 47% | 1 | 199.7 | 10802 |
| 50% | 1 | 198.8 | 11365 | 45% | 1 | 199.7 | 10849 |
| 50% | 1 | 198.8 | 11318 | 46% | 1 | 199.7 | 10427 |
| **Average** | | **199** | **11357** | **Average** | | **200** | **10693** |
| 25% | 5 | 249 | 1284 | 28% | 5 | 249.6 | 1336 |
| 25% | 5 | 249 | 1261 | 29% | 5 | 249.6 | 1368 |
| 25% | 5 | 249 | 1303 | 29% | 5 | 249.5 | 1298 |
| **Average** | | **249** | **1283** | **Average** | | **250** | **1334** |
| 20% | 15 | 299 | 299.9 | 20% | 15 | 299.4 | 306.2 |
| 20% | 15 | 299 | 295.2 | 19% | 15 | 299.1 | 304.6 |
| 20% | 15 | 299 | 292.7 | 20% | 15 | 298.8 | 306.2 |
| **Average** | | **299** | **296** | **Average** | | **299** | **306** |
| 14% | 35 | 350 | 94.4 | 16% | 35 | 349.4 | 104.4 |
| 14% | 35 | 350 | 93.7 | 16% | 35 | 349.2 | 105.8 |
| 14% | 35 | 350 | 93.7 | 16% | 35 | 349 | 103.1 |
| **Average** | | **350** | **94** | **Average** | | **349** | **104** |

| Replicate 1 RTFO PG 70-10 | | | | Replicate 2 RTFO PG 70-10 | | | |
|---|---|---|---|---|---|---|---|
| **Torque** | **RPM** | **Temp (°F)** | **Viscosity (cP)** | **Torque** | **RPM** | **Temp (°F)** | **Viscosity (cP)** |
| 69% | 1 | 209.7 | 17199 | 71% | 1 | 209.5 | 16731 |
| 70% | 1 | 209.4 | 16895 | 69% | 1 | 209.7 | 16754 |
| 71% | 1 | 209.6 | 16473 | 71% | 1 | 209.5 | 16075 |
| **Average** | | **210** | **16856** | **Average** | | **210** | **16520** |
| 59% | 5 | 249.4 | 2671 | 58% | 5 | 249.2 | 2657 |
| 56% | 5 | 249.3 | 2695 | 56% | 5 | 249.3 | 2648 |
| 56% | 5 | 249.3 | 2662 | 58% | 5 | 249.3 | 2671 |
| **Average** | | **249** | **2676** | **Average** | | **249** | **2659** |
| 32% | 15 | 299 | 498 | 33% | 15 | 299.2 | 512.4 |
| 32% | 15 | 299.1 | 492.1 | 32% | 15 | 299.5 | 499.9 |
| 32% | 15 | 299.5 | 506.1 | 33% | 15 | 299.4 | 506.1 |
| **Average** | | **299** | **499** | **Average** | | **299** | **506** |
| 22% | 35 | 349.5 | 148.6 | 23% | 35 | 349.5 | 152 |
| 22% | 35 | 348.7 | 145.3 | 23% | 35 | 349.3 | 150 |
| 22% | 35 | 348.7 | 143.9 | 23% | 35 | 349.1 | 150 |
| **Average** | | **349** | **146** | **Average** | | **349** | **151** |

| Replicate 1 PAV PG 70-10 V | | | | Replicate 2 PAV PG 70-10 V | | | |
|---|---|---|---|---|---|---|---|
| **Torque** | **RPM** | **Temp (°F)** | **Viscosity (cP)** | **Torque** | **RPM** | **Temp (°F)** | **Viscosity (cP)** |
| 80% | 1 | 249.5 | 18746 | 77% | 1 | 249.5 | 18160 |
| 81% | 1 | 249.5 | 18863 | 77% | 1 | 249.5 | 18207 |
| 81% | 1 | 249.5 | 18816 | 76% | 1 | 249.5 | 18137 |
| **Average** | | **250** | **18808** | **Average** | | **250** | **18168** |
| 39% | 5 | 299.3 | 1762 | 38% | 5 | 298.9 | 1790 |
| 38% | 5 | 299 | 1762 | 38% | 5 | 298.8 | 1781 |
| 38% | 5 | 299.3 | 1748 | 38% | 5 | 299.1 | 1720 |
| **Average** | | **299** | **1757** | **Average** | | **299** | **1764** |
| 60% | 20 | 323.9 | 695 | 60% | 20 | 324 | 703 |
| 59% | 20 | 324 | 697 | 60% | 20 | 324.2 | 700.6 |
| 59% | 20 | 324.4 | 693.6 | 60% | 20 | 324.5 | 699.5 |
| **Average** | | **324** | **695** | **Average** | | **324** | **701** |
| 57% | 40 | 348.8 | 336.8 | 58% | 40 | 349.4 | 337.4 |
| 57% | 40 | 348.8 | 333.3 | 57% | 40 | 349.1 | 335.7 |
| 57% | 40 | 348.7 | 331 | 57% | 40 | 348.9 | 335.7 |
| **Average** | | **349** | **334** | **Average** | | **349** | **336** |

| Replicate 1 PG 70-10 20% RAR | | | | Replicate 2 PG 70-10 20% RAR | | | |
|---|---|---|---|---|---|---|---|
| **Torque** | **RPM** | **Temp (°F)** | **Viscosity (cP)** | **Torque** | **RPM** | **Temp (°F)** | **Viscosity (cP)** |
| 45% | 1 | 249.6 | 11177 | 45% | 1 | 249.6 | 10826 |
| 45% | 1 | 249.4 | 11013 | 44% | 1 | 249.6 | 10498 |
| 45% | 1 | 249.2 | 10756 | 42% | 1 | 249.5 | 10193 |
| **Average** | | **249** | **10982** | **Average** | | **250** | **10506** |
| 51% | 5 | 299 | 2385 | 50% | 5 | 299.6 | 2404 |
| 50% | 5 | 299.1 | 2376 | 49% | 5 | 299.6 | 2357 |
| 49% | 5 | 299.5 | 2348 | 48% | 5 | 299.4 | 2348 |
| **Average** | | **299** | **2370** | **Average** | | **300** | **2370** |
| 31% | 5 | 324.4 | 1467 | 32% | 5 | 324.3 | 1481 |
| 31% | 5 | 324.5 | 1504 | 29% | 5 | 324.3 | 1514 |
| 29% | 5 | 324.3 | 1500 | 30% | 5 | 323.9 | 1490 |
| **Average** | | **324** | **1490** | **Average** | | **324** | **1495** |
| 24% | 5 | 349.4 | 1162 | 23% | 5 | 348.7 | 1153 |
| 23% | 5 | 349.3 | 1158 | 23% | 5 | 348.7 | 1158 |
| 23% | 5 | 349.5 | 1162 | 24% | 5 | 349.1 | 1111 |
| **Average** | | **349** | **1161** | **Average** | | **349** | **1141** |

| Replicate 1 RTFO PG 70-10 20% RAR | | | | Replicate 2 RTFO PG 70-10 20% RAR | | | |
|---|---|---|---|---|---|---|---|
| **Torque** | **RPM** | **Temp (°F)** | **Viscosity (cP)** | **Torque** | **RPM** | **Temp (°F)** | **Viscosity (cP)** |
| 52% | 1 | 274.1 | 12536 | 51% | 1 | 274.5 | 12490 |
| 53% | 1 | 274.3 | 12607 | 52% | 1 | 274.5 | 12513 |
| 52% | 1 | 274.5 | 12466 | 49% | 1 | 274.5 | 12536 |
| **Average** | | **274** | **12536** | **Average** | | **275** | **12513** |
| 49% | 2 | 299.5 | 5905 | 48% | 5 | 299.5 | 5753 |
| 48% | 2 | 299.5 | 5706 | 49% | 5 | 299 | 5870 |
| 49% | 2 | 299.5 | 5823 | 50% | 5 | 299.5 | 5835 |
| **Average** | | **300** | **5811** | **Average** | | **299** | **5819** |
| 60% | 5 | 323.8 | 2849 | 60% | 5 | 323.9 | 2831 |
| 60% | 5 | 324.1 | 2840 | 59% | 5 | 324.1 | 2817 |
| 60% | 5 | 324.4 | 2821 | 60% | 5 | 324.5 | 2854 |
| **Average** | | **324** | **2837** | **Average** | | **324** | **2834** |
| 41% | 5 | 349.1 | 1950 | 41% | 5 | 349.4 | 1945 |
| 42% | 5 | 349.2 | 1982 | 40% | 5 | 349.4 | 1926 |
| 42% | 5 | 349.4 | 1978 | 41% | 5 | 349 | 1931 |
| **Average** | | **349** | **1970** | **Average** | | **349** | **1934** |

| Replicate 1 PAV PG 70-10 20% RAR | | | | Replicate 2 PAV PG 70-10 20% RAR | | | |
|---|---|---|---|---|---|---|---|
| **Torque** | **RPM** | **Temp (°F)** | **Viscosity (cP)** | **Torque** | **RPM** | **Temp (°F)** | **Viscosity (cP)** |
| 59% | 1 | 274.6 | 13849 | 68% | 1 | 274.5 | 16145 |
| 58% | 1 | 274.4 | 13755 | 67% | 1 | 274.4 | 16098 |
| 59% | 1 | 274.3 | 13895 | 66% | 1 | 274.5 | 15395 |
| **Average** | | **274** | **13833** | **Average** | | **274** | **15879** |
| 49% | 2 | 299.1 | 5811 | 57% | 2 | 299.6 | 6491 |
| 49% | 2 | 299 | 5800 | 56% | 2 | 299.1 | 6631 |
| 49% | 2 | 298.9 | 5788 | 56% | 2 | 299.4 | 6444 |
| **Average** | | **299** | **5800** | **Average** | | **299** | **6522** |
| 57% | 5 | 324.4 | 2695 | 60% | 5 | 324.6 | 2910 |
| 57% | 5 | 324.3 | 2690 | 61% | 5 | 324.5 | 2901 |
| 56% | 5 | 324.5 | 2695 | 62% | 5 | 324.1 | 2821 |
| **Average** | | **324** | **2693** | **Average** | | **324** | **2877** |
| 33% | 5 | 349.5 | 1523 | 35% | 5 | 348.6 | 1603 |
| 32% | 5 | 349.3 | 1500 | 34% | 5 | 348.8 | 1598 |
| 32% | 5 | 348.9 | 1509 | 35% | 5 | 348.9 | 1598 |
| **Average** | | **349** | **1511** | **Average** | | **349** | **1600** |

APPENDIX B

DYNAMIC SHEAR RHEOMETER TEST RESULTS

Replicate 1 PG 64-22 V

| Temp °C | \|G*\| kPa | δ Degree | \|G*\|/sinδ kPa | Strain Amp % | Frequency rad/sec |
|---|---|---|---|---|---|
| 58 | 3.5 | 84.8 | 3.5 | 11.93 | 10.08 |
| 64 | 1.6 | 86.6 | 1.6 | 12.06 | 10.08 |
| 70 | 0.7 | 88.2 | 0.7 | 12.06 | 10.08 |

Replicate 2 PG 64-22 V

| Temp °C | \|G*\| kPa | δ Degree | \|G*\|/sinδ kPa | Strain Amp % | Frequency rad/sec |
|---|---|---|---|---|---|
| 58 | 3.3 | 85.2 | 3.3 | 11.7 | 10.08 |
| 64 | 1.4 | 87 | 1.4 | 11.92 | 10.08 |
| 70 | 0.7 | 88 | 0.7 | 12.04 | 10.08 |

Replicate 1 RTFO PG 64-22 V

| Temp °C | \|G*\| kPa | δ Degree | \|G*\|/sinδ kPa | Strain Amp % | Frequency rad/sec |
|---|---|---|---|---|---|
| 58 | 8.1 | 80.1 | 8.3 | 10.04 | 10.08 |
| 64 | 3.6 | 82.9 | 3.6 | 9.91 | 10.08 |
| 70 | 1.6 | 85.4 | 1.6 | 10.00 | 10.08 |

Replicate 2 RTFO PG 64-22 V

| Temp °C | \|G*\| kPa | δ Degree | \|G*\|/sinδ kPa | Strain Amp % | Frequency rad/sec |
|---|---|---|---|---|---|
| 58 | 8.1 | 80.6 | 8.2 | 10.16 | 10.08 |
| 64 | 3.5 | 83.0 | 3.5 | 9.95 | 10.08 |
| 70 | 1.5 | 85.5 | 1.5 | 9.99 | 10.08 |

Replicate 1 PAV PG 64-22 20% RAR

| Temp °C | \|G*\| kPa | δ Degree | \|G*\|sinδ kPa | Strain Amp % | Frequency rad/sec |
|---|---|---|---|---|---|
| 28 | 2555 | 44.8 | 1801 | 0.99 | 10.08 |
| 25 | 3836 | 43 | 2615 | 1.04 | 10.08 |
| 22 | 5681 | 40.7 | 3706 | 1.02 | 10.08 |
| 19 | 8365 | 38.9 | 5249 | 1.02 | 10.08 |

Replicate 2 PAV PG 64-22 20% RAR

| Temp °C | \|G*\| kPa | δ Degree | \|G*\|/sinδ kPa | Strain Amp % | Frequency rad/sec |
|---|---|---|---|---|---|
| 28 | 2177 | 44.7 | 1532 | 1.00 | 10.08 |
| 25 | 3264 | 42.7 | 2213 | 1.01 | 10.08 |
| 22 | 4861 | 40.9 | 3180 | 1.00 | 10.08 |
| 19 | 7173 | 38.5 | 4461 | 1.01 | 10.08 |
| 16 | 10395 | 36.4 | 6171 | 1.00 | 10.08 |

Replicate 1 PG 64-22 20% RAR

| Temp °C | \|G*\| kPa | δ Degree | \|G*\|/sinδ kPa | Strain Amp % | Frequency rad/sec |
|---|---|---|---|---|---|
| 58 | 13.8 | 66.40 | 15.1 | 11.94 | 10.08 |
| 64 | 7.2 | 70.80 | 7.7 | 11.90 | 10.08 |
| 70 | 3.8 | 74.60 | 4.0 | 12.06 | 10.08 |
| 76 | 2.1 | 78.30 | 2.1 | 12.10 | 10.08 |
| 82 | 1.1 | 80.90 | 1.2 | 12.16 | 10.08 |
| 88 | 0.7 | 83.20 | 0.7 | 12.01 | 10.08 |

Replicate 2 PG 64-22 20% RAR

| Temp °C | \|G*\| kPa | δ Degree | \|G*\|/sinδ kPa | Strain Amp % | Frequency rad/sec |
|---|---|---|---|---|---|
| 58 | 13.9 | 65.40 | 15.3 | 12.13 | 10.08 |
| 64 | 7.4 | 69.60 | 7.9 | 12.06 | 10.08 |
| 70 | 3.9 | 73.60 | 4.1 | 12.04 | 10.08 |
| 76 | 2.1 | 77.00 | 2.2 | 12.19 | 10.08 |
| 82 | 1.2 | 79.90 | 1.2 | 12.22 | 10.08 |
| 88 | 0.7 | 82.70 | 0.7 | 12.08 | 10.08 |

Replicate 1 RTFO PG 64-22 20% RAR

| Temp °C | \|G*\| kPa | δ Degree | \|G*\|/sinδ kPa | Strain Amp % | Frequency rad/sec |
|---|---|---|---|---|---|
| 58 | 24.3 | 58.9 | 28.4 | 9.98 | 10.08 |
| 64 | 13.4 | 61.3 | 15.3 | 9.93 | 10.08 |
| 70 | 7.4 | 64.2 | 8.3 | 10.00 | 10.08 |
| 76 | 4.2 | 67.6 | 4.5 | 9.99 | 10.08 |
| 82 | 2.4 | 71.0 | 2.5 | 10.12 | 10.08 |
| 88 | 1.4 | 74.1 | 1.4 | 10.17 | 10.08 |

Replicate 2 RTFO PG 64-22 20% RAR

| Temp °C | \|G*\| kPa | δ Degree | \|G*\|/sinδ kPa | Strain Amp % | Frequency rad/sec |
|---|---|---|---|---|---|
| 58 | 25.0 | 59.0 | 29.2 | 9.96 | 10.08 |
| 64 | 13.6 | 61.8 | 15.4 | 10.00 | 10.08 |
| 70 | 7.4 | 65.0 | 8.2 | 10.10 | 10.08 |
| 76 | 4.2 | 68.4 | 4.5 | 10.06 | 10.08 |
| 82 | 2.4 | 71.6 | 2.5 | 10.19 | 10.08 |
| 88 | 1.4 | 75.3 | 1.4 | 10.08 | 10.08 |

Replicate 1 PAV PG 64-22 20% RAR

| Temp °C | \|G*\| kPa | δ Degree | \|G*\|sinδ kPa | Strain Amp % | Frequency rad/sec |
|---|---|---|---|---|---|
| 28 | 2555 | 44.8 | 1801 | 0.99 | 10.08 |
| 25 | 3836 | 43 | 2615 | 1.04 | 10.08 |
| 22 | 5681 | 40.7 | 3706 | 1.02 | 10.08 |
| 19 | 8365 | 38.9 | 5249 | 1.02 | 10.08 |

Replicate 2 PAV PG 64-22 20% RAR

| Temp °C | \|G*\| kPa | δ Degree | \|G*\|sinδ kPa | Strain Amp % | Frequency rad/sec |
|---|---|---|---|---|---|
| 28 | 2177 | 44.7 | 1532 | 1.00 | 10.08 |
| 25 | 3264 | 42.7 | 2213 | 1.01 | 10.08 |
| 22 | 4861 | 40.9 | 3180 | 1.00 | 10.08 |
| 19 | 7173 | 38.5 | 4461 | 1.01 | 10.08 |
| 16 | 10395 | 36.4 | 6171 | 1.00 | 10.08 |

Replicate 3 PAV PG 64-22 20% RAR

| Temp °C | \|G*\| kPa | δ Degree | \|G*\|sinδ kPa | Strain Amp % | Frequency rad/sec |
|---|---|---|---|---|---|
| 28 | 2417 | 45.7 | 1730 | 0.99 | 10.08 |
| 25 | 3635 | 43.6 | 2504 | 1.00 | 10.08 |
| 22 | 5452 | 41.5 | 3614 | 1.01 | 10.08 |
| 19 | 8033 | 39.2 | 5072 | 1.02 | 10.08 |

Replicate 1 PG 64-22+ EVOTHERM

| Temp °C | \|G*\| kPa | δ Degree | \|G*\|/sinδ kPa | Strain Amp % | Frequency rad/sec |
|---|---|---|---|---|---|
| 58 | 3.2 | 85.3 | 3.2 | 11.86 | 10.08 |
| 64 | 1.5 | 86.6 | 1.5 | 11.92 | 10.08 |
| 70 | 0.7 | 88.2 | 0.7 | 11.85 | 10.08 |

Replicate 2 PG 64-22+ EVOTHERM

| Temp °C | \|G*\| kPa | δ Degree | \|G*\|/sinδ kPa | Strain Amp % | Frequency rad/sec |
|---|---|---|---|---|---|
| 58 | 3.3 | 85.3 | 3.3 | 11.94 | 10.08 |
| 64 | 1.5 | 86.8 | 1.5 | 11.91 | 10.08 |
| 70 | 0.7 | 88.2 | 0.7 | 11.99 | 10.08 |

Replicate 1 PG 64-22 20% RAR+EVOTHERM

| Temp °C | \|G*\| kPa | δ Degree | \|G*\|/sinδ kPa | Strain Amp % | Frequency rad/sec |
|---|---|---|---|---|---|
| 58 | 12.5 | 68.4 | 13.5 | 12.06 | 10.08 |
| 64 | 6.2 | 73.2 | 6.5 | 12.10 | 10.08 |
| 70 | 3.2 | 77.1 | 3.3 | 12.10 | 10.08 |
| 76 | 1.7 | 80.1 | 1.7 | 12.20 | 10.08 |
| 82 | 0.9 | 82.1 | 0.9 | 12.06 | 10.08 |

Replicate 2 PG 64-22 20% RAR+EVOTHERM

| Temp °C | \|G*\| kPa | δ Degree | \|G*\|/sinδ kPa | Strain Amp % | Frequency rad/sec |
|---|---|---|---|---|---|
| 58 | 14.3 | 67.9 | 15.4 | 12.15 | 10.08 |
| 64 | 7.3 | 72.7 | 7.6 | 12.13 | 10.08 |
| 70 | 3.8 | 76.6 | 3.9 | 12.14 | 10.08 |
| 76 | 2.0 | 80.0 | 2.0 | 12.17 | 10.08 |
| 82 | 1.1 | 81.9 | 1.1 | 12.1 | 10.08 |
| 88 | 0.6 | 83.6 | 0.6 | 12.12 | 10.08 |

Replicate 3 PG 64-22 20% RAR+EVOTHERM

| Temp °C | \|G*\| kPa | δ Degree | \|G*\|/sinδ kPa | Strain Amp % | Frequency rad/sec |
|---|---|---|---|---|---|
| 58 | 14.1 | 68.7 | 15.1 | 12.21 | 10.08 |
| 64 | 7.2 | 72.6 | 7.5 | 12.15 | 10.08 |
| 70 | 3.7 | 76.8 | 3.8 | 12.20 | 10.08 |
| 76 | 2.0 | 80.0 | 2.0 | 12.09 | 10.08 |
| 82 | 1.0 | 82.1 | 1.1 | 12.16 | 10.08 |
| 88 | 0.6 | 84.0 | 0.6 | 12.18 | 10.08 |

Dynamic Shear Rheometer Test Results: PG 70-10

Replicate 1 PG 70-10 V

| Temp °C | \|G*\| kPa | δ Degree | \|G*\|/sinδ kPa | Strain Amp % | Frequency rad/sec |
|---|---|---|---|---|---|
| 64 | 3.5 | 80.8 | 3.6 | 11.87 | 10.08 |
| 70 | 1.6 | 83.4 | 1.7 | 12.06 | 10.08 |
| 76 | 0.8 | 85.3 | 0.8 | 11.54 | 10.08 |

Replicate 2 PG 70-10 V

| Temp °C | \|G*\| kPa | δ Degree | \|G*\|/sinδ kPa | Strain Amp % | Frequency rad/sec |
|---|---|---|---|---|---|
| 64 | 3.5 | 80.5 | 3.6 | 11.92 | 10.08 |
| 70 | 1.7 | 83.0 | 1.7 | 11.89 | 10.08 |
| 76 | 0.8 | 84.8 | 0.8 | 11.60 | 10.08 |

Replicate 1 RTFO PG 70-10 V

| Temp °C | \|G*\| kPa | δ Degree | \|G*\|/sinδ kPa | Strain Amp % | Frequency rad/sec |
|---|---|---|---|---|---|
| 64 | 7.3 | 75.0 | 7.6 | 9.87 | 10.08 |
| 70 | 3.5 | 77.4 | 3.6 | 10.06 | 10.08 |
| 76 | 1.6 | 80.3 | 1.6 | 10.07 | 10.08 |

Replicate 2 RTFO PG 70-10 V

| Temp °C | \|G*\| kPa | δ Degree | \|G*\|/sinδ kPa | Strain Amp % | Frequency rad/sec |
|---|---|---|---|---|---|
| 64 | 7.2 | 75.2 | 7.4 | 10.02 | 10.08 |
| 70 | 3.4 | 78.1 | 3.4 | 9.94 | 10.08 |
| 76 | 1.5 | 80.5 | 1.6 | 10.05 | 10.08 |

Replicate 1 PAV PG 70-10 V

| Temp °C | \|G*\| kPa | δ Degree | \|G*\|sinδ kPa | Strain Amp % | Frequency rad/sec |
|---|---|---|---|---|---|
| 37 | 2432 | 40.8 | 1591 | 0.99 | 10.08 |
| 34 | 3560 | 38.7 | 2228 | 1.00 | 10.08 |
| 31 | 5085 | 37.0 | 3061 | 1.01 | 10.08 |
| 28 | 7329 | 34.9 | 4196 | 1.01 | 10.08 |
| 25 | 10300 | 33.1 | 5622 | 1.00 | 10.08 |

Replicate 2 PAV PG 70-10 V

| Temp °C | \|G*\| kPa | δ Degree | \|G*\|sinδ kPa | Strain Amp % | Frequency rad/sec |
|---|---|---|---|---|---|
| 37 | 2726 | 40.6 | 1776 | 0.99 | 10.08 |
| 34 | 3972 | 38.8 | 2499 | 1.01 | 10.08 |
| 31 | 5690 | 36.9 | 3418 | 1.01 | 10.08 |
| 28 | 8128 | 34.9 | 4656 | 1.02 | 10.08 |
| 25 | 11438 | 33.0 | 6232 | 0.90 | 10.08 |

Replicate 3 PAV PG 70-10 V

| Temp °C | \|G*\| kPa | δ Degree | \|G*\|sinδ kPa | Strain Amp % | Frequency rad/sec |
|---|---|---|---|---|---|
| 37 | 2271 | 41.8 | 1515 | 0.99 | 10.08 |
| 34 | 3279 | 39.8 | 2101 | 1.00 | 10.08 |
| 31 | 4661 | 37.8 | 2856 | 1.01 | 10.08 |
| 28 | 6688 | 36.0 | 3933 | 1.02 | 10.08 |
| 25 | 9395 | 34.0 | 5254 | 1.04 | 10.08 |

Replicate 1 PG 70-10 20% RAR

| Temp °C | \|G*\| kPa | δ Degree | \|G*\|/sinδ kPa | Strain Amp % | Frequency rad/sec |
|---|---|---|---|---|---|
| 64 | 6.1 | 73.5 | 6.3 | 12.0 | 10.08 |
| 70 | 3.1 | 77.7 | 3.2 | 12.1 | 10.08 |
| 76 | 1.6 | 80.4 | 1.6 | 12.2 | 10.08 |
| 82 | 0.9 | 82.8 | 0.9 | 12.1 | 10.08 |

Replicate 2 PG 70-10 20% RAR

| Temp °C | \|G*\| kPa | δ Degree | \|G*\|/sinδ kPa | Strain Amp % | Frequency rad/sec |
|---|---|---|---|---|---|
| 64 | 6.9 | 70.9 | 7.3 | 12.13 | 10.08 |
| 70 | 3.6 | 74.9 | 7.7 | 12.25 | 10.08 |
| 76 | 1.9 | 78.1 | 2.0 | 12.27 | 10.08 |
| 82 | 1.0 | 80.6 | 1.1 | 12.34 | 10.08 |
| 88 | 0.6 | 83.2 | 0.6 | 12.19 | 10.08 |

Replicate 3 PG 70-10 20% RAR

| Temp °C | \|G*\| kPa | δ Degree | \|G*\|/sinδ kPa | Strain Amp % | Frequency rad/sec |
|---|---|---|---|---|---|
| 64 | 5.9 | 72.9 | 6.2 | 12.11 | 10.08 |
| 70 | 3.0 | 77.0 | 3.0 | 12.14 | 10.08 |
| 76 | 1.6 | 80.0 | 1.6 | 12.09 | 10.08 |
| 82 | 0.9 | 83.0 | 0.9 | 12.13 | 10.08 |

Replicate 4 PG 70-10 20% RAR

| Temp °C | \|G*\| kPa | δ Degree | \|G*\|/sinδ kPa | Strain Amp % | Frequency rad/sec |
|---|---|---|---|---|---|
| 64 | 6.6 | 72.9 | 6.9 | 12.26 | 10.08 |
| 70 | 3.3 | 76.7 | 3.4 | 12.42 | 10.08 |
| 76 | 1.8 | 79.9 | 1.8 | 12.13 | 10.08 |
| 82 | 1.0 | 82.0 | 1.0 | 12.18 | 10.08 |

Replicate 1 RTFO PG 70-10 20% RAR

| **Temp °C** | **\|G*\| kPa** | **δ Degree** | **\|G*\|/sinδ kPa** | **Strain Amp %** | **Frequency rad/sec** |
|---|---|---|---|---|---|
| 64 | 13.6 | 61.8 | 15.5 | 10.20 | 10.08 |
| 70 | 7.4 | 65.2 | 8.1 | 10.15 | 10.08 |
| 76 | 4.1 | 68.9 | 4.4 | 10.08 | 10.08 |
| 82 | 2.3 | 72.0 | 2.4 | 10.14 | 10.08 |
| 88 | 1.3 | 75.3 | 1.4 | 10.13 | 10.08 |

Replicate 2 RTFO PG 70-10 20% RAR

| **Temp °C** | **\|G*\| kPa** | **δ Degree** | **\|G*\|/sinδ kPa** | **Strain Amp %** | **Frequency rad/sec** |
|---|---|---|---|---|---|
| 64 | 13.8 | 61.80 | 15.7 | 10.05 | 10.08 |
| 70 | 7.6 | 64.80 | 8.3 | 10.21 | 10.08 |
| 76 | 4.2 | 68.50 | 4.5 | 10.13 | 10.08 |
| 82 | 2.4 | 71.40 | 2.5 | 10.17 | 10.08 |
| 88 | 1.4 | 75.30 | 1.5 | 10.13 | 10.08 |

Replicate 1 PAV PG 70-10 20% RAR

| **Temp °C** | **\|G*\| kPa** | **δ Degree** | **\|G*\|sinδ kPa** | **Strain Amp %** | **Frequency rad/sec** |
|---|---|---|---|---|---|
| 37 | 1161 | 44.7 | 816 | 0.98 | 10.08 |
| 34 | 1727 | 43.1 | 1181 | 0.96 | 10.08 |
| 31 | 2549 | 40.9 | 1669 | 1.00 | 10.08 |
| 28 | 3764 | 38.9 | 2363 | 1.01 | 10.08 |
| 25 | 5470 | 37.0 | 3293 | 1.02 | 10.08 |
| 22 | 7859 | 35.4 | 4556 | 1.02 | 10.08 |
| 19 | 11081 | 33.4 | 6099 | 0.93 | 10.08 |

Replicate 2 PAV PG 70-10 20% RAR

| **Temp °C** | **\|G*\| kPa** | **δ Degree** | **\|G*\|sinδ kPa** | **Strain Amp %** | **Frequency rad/sec** |
|---|---|---|---|---|---|
| 37 | 1270 | 44.1 | 884 | 0.97 | 10.08 |
| 34 | 1890 | 42.5 | 1276 | 0.98 | 10.08 |
| 31 | 2788 | 40.3 | 1802 | 1.00 | 10.08 |
| 28 | 4141 | 38.4 | 2572 | 0.97 | 10.08 |
| 25 | 5938 | 36.6 | 3541 | 1.01 | 10.08 |
| 22 | 8440 | 34.7 | 4803 | 1.03 | 10.08 |
| 19 | 12030 | 33.0 | 6556 | 0.86 | 10.08 |

# APPENDIX C

## BENDING BEAM RHEOMETER TEST RESULTS

PG 64-22 Replicate 1 (-12 °C)

| **Time (s)** | **Force (mN)** | **Deflection (mm)** | **Measured Stiffness (MPa)** | **Estimated Stiffness (MPa)** | **Difference %** | **m-value** |
|---|---|---|---|---|---|---|
| 0.0 | 0 | 0.000 | 0 | 0 | 0 | 0 |
| 8.0 | 978 | 0.312 | 253 | 253 | 0 | 0.280 |
| 15.0 | 977 | 0.374 | 211 | 211 | 0 | 0.298 |
| 30.0 | 976 | 0.462 | 170 | 170 | 0 | 0.318 |
| **60.0** | **975** | **0.579** | **136** | **136** | **0** | **0.337** |
| 120.0 | 972 | 0.737 | 106 | 107 | 0.943 | 0.357 |
| 240.0 | 973 | 0.948 | 82.8 | 82.7 | -1.21E-01 | 0.377 |

PG 64-22 Replicate 2 (-12 °C)

| **Time (s)** | **Force (mN)** | **Deflection (mm)** | **Measured Stiffness (MPa)** | **Estimated Stiffness (MPa)** | **Difference %** | **m-value** |
|---|---|---|---|---|---|---|
| 0.0 | 0 | 0.000 | 0 | 0 | 0 | 0.000 |
| 8.0 | 985 | 0.290 | 274 | 274 | 0 | 0.269 |
| 15.0 | 987 | 0.347 | 229 | 230 | 0.437 | 0.291 |
| 30.0 | 987 | 0.428 | 186 | 186 | 0 | 0.315 |
| **60.0** | **988** | **0.537** | **148** | **148** | **0** | **0.339** |
| 120.0 | 989 | 0.685 | 116 | 116 | 0 | 0.364 |
| 240.0 | 989 | 0.891 | 89.5 | 89.6 | 1.12E-01 | 0.388 |

PG 64-22 Replicate 1 (-18 °C)

| **Time (s)** | **Force (mN)** | **Deflection (mm)** | **Measured S (MPa)** | **Estimated S (MPa)** | **Difference %** | **m-value** |
|---|---|---|---|---|---|---|
| 0.0 | 0 | 0.000 | 0 | 0 | 0 | 0 |
| 8.0 | 983 | 0.164 | 483 | 484 | 0.207 | 0.232 |
| 15.0 | 984 | 0.190 | 418 | 416 | -0.478 | 0.246 |
| 30.0 | 984 | 0.228 | 348 | 349 | 0.287 | 0.261 |
| **60.0** | **985** | **0.274** | **290** | **290** | **0** | **0.277** |
| 120.0 | 985 | 0.333 | 238 | 238 | 0 | 0.292 |
| 240.0 | 987 | 0.412 | 193 | 193 | 0.00E+00 | 0.307 |

PG 64-22 Replicate 2 (-18 °C)

| Time (s) | Force (mN) | Deflection (mm) | Measured S (MPa) | Estimated S (MPa) | Difference % | m-value |
|---|---|---|---|---|---|---|
| 0.0 | 0 | 0.000 | 0 | 0 | 0 | 0.000 |
| 8.0 | 979 | 0.158 | 500 | 499 | -0.2 | 0.227 |
| 15.0 | 979 | 0.184 | 429 | 430 | 0.233 | 0.248 |
| 30.0 | 978 | 0.220 | 358 | 359 | 0.279 | 0.270 |
| **60.0** | **979** | **0.266** | **297** | **296** | **-0.337** | **0.293** |
| 120.0 | 978 | 0.330 | 239 | 239 | 0 | 0.315 |
| 240.0 | 980 | 0.414 | 191 | 191 | 0.00E+00 | 0.338 |

PG 64-22 20% RAR Replicate 1 (-12 °C)

| Time (s) | Force (mN) | Deflection (mm) | Measured S (MPa) | Estimated S (MPa) | Difference % | m-value |
|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 992 | 0.456 | 175 | 175 | 0 | 0.285 |
| 15 | 991 | 0.55 | 145 | 146 | 0.69 | 0.299 |
| 30 | 990 | 0.678 | 118 | 118 | 0 | 0.315 |
| **60** | **987** | **0.844** | **94.3** | **94.2** | **-0.106** | **0.331** |
| 120 | 985 | 1.064 | 74.6 | 74.5 | -0.134 | 0.346 |
| 240 | 985 | 1.365 | 58.2 | 58.3 | 0.172 | 0.362 |

PG 64-22 20% RAR Replicate 2 (-12 °C)

| Time (s) | Force (mN) | Deflection (mm) | Measured S (MPa) | Estimated S (MPa) | Difference % | m-value |
|---|---|---|---|---|---|---|
| 0.0 | 0 | 0.000 | 0 | 0 | 0 | 0.000 |
| 8.0 | 977 | 0.443 | 178 | 178 | 0 | 0.271 |
| 15.0 | 976 | 0.528 | 149 | 149 | 0 | 0.289 |
| 30.0 | 975 | 0.649 | 121 | 121 | 0 | 0.309 |
| **60.0** | **973** | **0.808** | **97.1** | **97.1** | **-1.57E-06** | **0.330** |
| 120.0 | 971 | 1.020 | 76.8 | 76.7 | -0.13 | 0.350 |
| 240.0 | 971 | 1.310 | 59.8 | 59.8 | -1.28E-06 | 0.370 |

PG 64-22 20% RAR Replicate 1 (-18 °C)

| Time (s) | Force (mN) | Deflection (mm) | Measured S (MPa) | Estimated S (MPa) | Difference % | m-value |
|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 980 | 0.282 | 280 | 280 | 0 | 0.245 |
| 15 | 979 | 0.33 | 239 | 239 | 0 | 0.259 |
| 30 | 978 | 0.396 | 199 | 199 | 0 | 0.275 |
| **60** | **977** | **0.482** | **163** | **163** | **0** | **0.291** |
| 120 | 975 | 0.593 | 133 | 133 | 0 | 0.306 |
| 240 | 974 | 0.734 | 107 | 107 | 0 | 0.322 |

PG 64-22 20% RAR Replicate 2 (-18 °C)

| Time (s) | Force (mN) | Deflection (mm) | Measured S (MPa) | Estimated S (MPa) | Difference % | m-value |
|---|---|---|---|---|---|---|
| 0.0 | 0 | 0.000 | 0 | 0 | 0 | 0.000 |
| 8.0 | 989 | 0.294 | 271 | 271 | 0 | 0.237 |
| 15.0 | 990 | 0.344 | 232 | 232 | 0 | 0.251 |
| 30.0 | 991 | 0.411 | 194 | 194 | 0 | 0.268 |
| **60.0** | **993** | **0.499** | **160** | **160** | **0** | **0.284** |
| 120.0 | 994 | 0.613 | 131 | 131 | 0 | 0.301 |
| 240.0 | 996 | 0.760 | 106 | 106 | 0 | 0.317 |

Bending Beam Rheometer Test Results: PG 70-10

PG 70-10 Replicate 1 (0 °C)

| Time (s) | Force (mN) | Deflection (mm) | Measured S (Mpa) | Estimated S (Mpa) | Difference % | m-value |
|---|---|---|---|---|---|---|
| 0.0 | 0 | 0.000 | 0 | 0 | 0 | 0 |
| 8.0 | 979 | 0.958 | 82.4 | 82.3 | -0.121 | 0.290 |
| 15.0 | 979 | 1.158 | 68.2 | 68.2 | -4.47E-06 | 0.307 |
| 30.0 | 978 | 1.440 | 54.8 | 54.8 | -1.39E-06 | 0.327 |
| **60.0** | **977** | **1.815** | **43.4** | **43.4** | **3.52E-06** | **0.346** |
| 120.0 | 976 | 2.321 | 33.9 | 33.9 | 4.50E-06 | 0.366 |
| 240.0 | 976 | 3.013 | 26.1 | 26.1 | 1.46E-06 | 0.385 |

PG 70-10 Replicate 2 (0 °C)

| **Time (s)** | **Force (mN)** | **Deflection (mm)** | **Measured S (Mpa)** | **Estimated S (Mpa)** | **Difference %** | **m-value** |
|---|---|---|---|---|---|---|
| 0.0 | 0 | 0.000 | 0 | 0 | 0 | 0.000 |
| 8.0 | 986 | 0.948 | 83.9 | 83.8 | -0.119 | 0.291 |
| 15.0 | 986 | 1.146 | 69.4 | 69.4 | 2.20E-06 | 0.309 |
| 30.0 | 985 | 1.427 | 55.7 | 55.7 | 1.37E-06 | 0.328 |
| **60.0** | **983** | **1.800** | **44** | **44** | **0** | **0.348** |
| 120.0 | 983 | 2.306 | 34.4 | 34.4 | 4.44E-06 | 0.368 |
| 240.0 | 983 | 2.999 | 26.4 | 26.4 | -1.44E-06 | 0.387 |

PG 70-10 20% RAR Replicate 1 (0 °C)

| **Time (s)** | **Force (mN)** | **Deflection (mm)** | **Measured S (MPa)** | **Estimated S (MPa)** | **Difference %** | **m-value** |
|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 976 | 1.395 | 56.4 | 56.5 | 0.177 | 0.318 |
| 15 | 975 | 1.708 | 46 | 46 | 0 | 0.335 |
| 30 | 974 | 2.164 | 36.3 | 36.2 | -0.275 | 0.354 |
| **60** | **973** | **2.788** | **28.1** | **28.1** | **1.63E-06** | **0.374** |
| 120 | 974 | 3.653 | 21.5 | 21.6 | 0.465 | 0.393 |
| 240 | 975 | 4.807 | 16.4 | 16.3 | -0.61 | 0.412 |

PG 70-10 20% RAR Replicate 2 (0 °C)

| **Time (s)** | **Force (mN)** | **Deflection (mm)** | **Measured S (MPa)** | **Estimated S (MPa)** | **Difference %** | **m-value** |
|---|---|---|---|---|---|---|
| 0.0 | 0 | 0.000 | 0 | 0 | 0 | 0.000 |
| 8.0 | 980 | 1.418 | 55.7 | 55.7 | 1.35E-06 | 0.314 |
| 15.0 | 978 | 1.733 | 45.5 | 45.5 | 0 | 0.329 |
| 30.0 | 977 | 2.184 | 36.1 | 36 | -0.277 | 0.346 |
| **60.0** | **976** | **2.790** | **28.2** | **28.2** | **2.71E-06** | **0.363** |
| 120.0 | 975 | 3.622 | 21.7 | 21.8 | 0.461 | 0.380 |
| 240.0 | 976 | 4.724 | 16.7 | 16.6 | -5.99E-01 | 0.397 |

# APPENDIX D

## MINERAL FILLERS USED IN NCHRP 9-45

| |
|---|
| PG 64-22 high asphaltenes (F) |
| PG 64-22 low asphaltenes (V) |
| Binder a modified with PPA |
| Binder a modified with SBS |

| **Filler** | **Acronym** |
|---|---|
| Steel Furnace Slag | FS2 (F) |
| Fly Ash Type C | FAC2 (F) |
| Hard Basalt | BH1 (F) |
| Hard Granite | GH1 (V) |
| Soft Granite | GS1 (V) |
| Soft Limestone | LS2 (V) |
| Hydrated Lime | HL2 (V) |
| Hard Dolomite | DS2 (PPA) |
| Hard Granite | GH2 (PPA) |
| Soft Granite | GS2 (PPA) |
| Siliceous Gravel Quartzite | GRQ2 (SBS) |
| Soft Caliches | CA2 (PPA) |
| Hard Basalt | BH2 (SBS) |
| Hard Dolomite | DH1 (SBS) |
| Andesite | AN1 (SBS) |
| Hard Limestone | LH1 (F) |
| Fly Ash Type F | FAF1 |