RHEOLOGICAL PROPERTIES OF MODIFIED AND UNMODIFIED ASPHALT CEMENTS

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ABSTRACT

This paper discusses the performance of three different types of asphalt from a rheological perspective using the Strategic Highway Research Program (SHRP) Superpave asphalt cement testing equipment. Three different types of binders were evaluated : Styrene-Butadiene-Styrene modified asphalt cement, catalytically air oxidized asphalt cement and plain unmodified asphalt cement. Comparison of asphalt cement rheological properties like complex modulus (G*), phase angle (δ), stiffness (S), low temperature deformation characteristics (d) and rate of change of stiffness (m-value) were performed at a wide range of temperatures. Also included are the elastic recovery (E_R) results for the three different types of asphalt cements. The purpose of comparing the performance in various different stages of asphalt cement aging is to determine the relative hardening that happens during the life of a performance graded asphalt cement. This oxidative hardening can result in premature failure in pavements. Asphalt cements that are catalytically air blown harden more than the polymer modified and plain unmodified asphalt cements (indicating considerable stiffening). The low temperature rheological properties as determined from the Bending Beam Rheometer reveal that the air blown asphalt tends to show the highest stiffness. The elastic recovery apparatus also showed considerable brittleness in catalytically air-oxidized asphalt (minimal elastic recovery).

RÉSUMÉ

Cet exposé discute de la performance de trois types différents de bitume à partir d'une perspective rhéologique utilisant l'équipement d'essai des bitumes Superpave du programme stratégique de recherche routière (SHRP). Trois types de liant ont été évalués: le bitume modifié au styrène-butadiène-styrène, le bitume oxydé à l'air par catalyse et le bitume ordinaire non modifié. La comparaison des propriétés rhéologiques du bitume comme le module complexe (G*), l'angle de phase (δ), la rigidité (S), les caractéristiques de déformation à basse température (d) et le taux de changement de la rigidité (valeur-m) a été faite à un grand intervalle de températures. Sont aussi inclus les résultats du recouvrement élastique (E_R) des trois bitumes différents. L'objectif de comparer la performance à divers stages du vieillissement du bitume est de déterminer le durcissement relatif qui survient durant le vie d'un bitume classé selon la performance. Ce durcissement par oxydation peut entraîner une rupture prématurée des revêtements bitumineux. Les bitumes oxydés par catalyse à l'air durcissent plus que les bitumes polymères et les bitumes ordinaires non modifiés (montrant une rigidité considérable). Les propriétés rhéologiques à basse température telles que déterminées par le rhéomètre à poutre en flexion révèlent que les bitumes oxydés à l'air tendent à montrer la plus forte rigidité. L'appareil de recouvrement élastique montre aussi une fragilité considérable dans le bitume oxydé par catalyse à l'air (recouvrement élastique minimum).

1   INTRODUCTION

This paper provides an insight into the rheology of various different types of asphalts that are in use all around the world in pavement construction. The rheological properties of asphalts that are compared in this presentation are those derived from SHRP standards. Genetic asphalt properties like complex modulus (G*), Phase angle (δ), stiffness (S), rate of change of stiffness (m-value), deflection behavior (d) at low temperature and rotational viscosity are measured using SHRP equipment for three primary asphalts namely plain unmodified asphalt (PUA), air-oxidized asphalt (AOA) and polymer modified asphalt (PMA). The rheological properties are evaluated as a function of temperature, which provides a direct comparison of performance as a function of thermal effects. The mechanical properties thus evaluated also provide considerable insight into the effect of mechanical loading on a pavement system made using these types of asphalts.

Age hardening of asphalt binders during plant mixing and in the field is simulated in the laboratory using the Rolling thin film oven (RTFO, Stage 1) and Rolling thin film oven plus Pressure Aging Vessel (RTFO+PAV, Stage 2) respectively. This is an important step in evaluating binder rheological properties because predicting future performance while using the SHRP properties using the original binder can be misleading since the effect of age hardening and the rheological implications of the same are not considered. This methodology serves well, when successive plots for Stage 1 and Stage 2 processed asphalt cement are overlaid on the original binder results.

Elastic recovery (E_R) is also critical in evaluating performance of asphalt binders. As discussed earlier, the original binder is not the best source of deriving performance information. It is believed that if a larger elastic recovery exists in the original binder then the chances of superior performance of the Stage 2 processed asphalt is likely to be high. However, during this research it was determined that although all the asphalts under consideration achieved some level of elastic recovery in the case of the original binders, not all retained this critical property when processed through Stage 2.

2   BACKGROUND

There has been a considerable change in the asphalt production industry in the past two decades. Most of these changes are related to improvement in asphalt rheology and engineering properties. The crude refining process by which asphalts are produced however remain mostly unchanged over the past several decades. Initially there were three primary engineering properties or characteristics that were considered critical for any successful asphalt, namely: consistency (also called viscosity), purity and safety (AI-MS-4 [1], Roberts *et al.,* [2], Barth [3], Kandhal and Koehler [4]). After the Strategic Highway Research Program (SHRP) was initiated in 1987, the rheological properties of asphalt have undergone a fundamental change and engineering concepts have been introduced while characterizing the asphalt [Corbett and Scheweyer [5], AASHTO [6], D'Angelo and Fee [7]). The new classification of asphalt binders, which is based upon temperature and statistical reliability, has provided design engineers with new tools to characterize performance over a wide temperature range.

The current SHRP specification and subsequent future revisions deal with original, RTFO and RTFO+PAV processing of the asphalt binder and further determining performance parameters like complex modulus and phase angle. It is an established fact that for long lasting pavements a selected asphalt binder and subsequent mix should be resistant to rutting, fatigue cracking and low temperature cracking (Bhutta and Al-Qadi [8], Bhutta [9]). Although the first two failure mechanisms have been

extensively studied, the thermal cracking potential has not received the same amount of attention, other than switching to a performance-graded (PG) specification system.

The change in engineering properties of asphalts that occurs in the various types of asphalts as they progress through time in the asphalt mixing plant and in the field has been addressed thoroughly by SHRP. The equipment used in the laboratory to simulate the oxidative hardening of asphalts in a plant mixing operation is the RTFO (by air blowing hot air). The field related oxidative hardening is represented by processing the asphalt through a PAV (by aging asphalts at high temperature and pressure) (AASHTO [6]).

There are three primary types of asphalt binders that are used in the pavement construction industry, namely: plain unmodified asphalt, air oxidized asphalt and polymer modified asphalt. There have been several studies linking performance of the different types of asphalt binders under low temperature conditions (Bouldin *et al.,* [10], Hesp *et al.,* [11], Burlie *et al.,* [12], Fréchette and Shalaby [13]). There is significant evidence that polymer modified binders retain a significant portion of the viscoelasticity that is present in the asphalt binder system before the construction process [(Bhutta and Al-Qadi [8], Bhutta [9], Burlie *et al.,* [12], Fréchette and Shalaby [13], Linde and Johansson [16]). This is particularly relevant to fatigue and low temperature thermal cracking performance.

This paper describes the rheological properties of different types of asphalt binders as a function of temperature both at the high and low temperature zones of the PG system, with special consideration to low temperature and fatigue performance.

3   ASPHALT TYPES

Three types of asphalt were included in this study:
1. Plain Unmodified Asphalt (PUA)
2. Air Oxidized Asphalt (AOA)
3. Polymer Modified Asphalt (PMA)
A brief description of the structural makeup of the three different types of asphalts follows.

3.1   Plain Unmodified Asphalt (PUA)

Plain unmodified asphalts (or base asphalts) are those types of asphalts that are produced directly from the petroleum distillation process and generally do not require any modification. The asphalts that are available in this category have a very limited supply source with only specific grades being available for pavement construction. Most of the times minor corrections to improve the low temperature properties are required in the base asphalt and are achieved by adding a thinning agent (low viscosity oils or extender oils) which will improve the relevant properties without significantly affecting the high end temperature. The amount of extender oil added to the system is highly dependent upon the high temperature PG and the amount of improvement that is required at the bottom end to achieve a specific low temperature property. The quantities of extender oils can be significant depending upon the PG of the original asphalt. The production of these asphalts in PG 64-28 and higher grades is quite difficult because the final product's quality is highly dependent on the crude type and economical incentives.

3.2   Air Oxidized Asphalt (AOA)

Air oxidized asphalts are produced by injecting air into a base asphalt in the presence of a catalyst. Air oxidation is sometimes also referred to as the polymerization of the base asphalt molecules by using the

oxygen molecules available in air. Without the catalyst the air oxidation process is not cost effective and can consume significant amount of energy for specific grade advances. Air oxidized asphalts, though originally produced for roofing asphalts, have found their way into the paving industry and are widely used in pavement construction. The economics of producing AOA can create significant economical benefits to the end users and producers in the paving industry (Kamel and Laverne [14]).

From a rheological perspective, the oxygen present in the air reacts with asphalt and, depending upon the properties of the original asphalt, can result is a product that can have significantly improved high-end temperature range. As indicated earlier, the air-blowing procedure is an oxidation process and is carried out at a higher temperature so that oxygen brings about a dehydrogenation of asphalt with a resultant formation of asphaltenes. At normal temperatures the reaction of oxygen with asphalt molecules is very much dependent upon the environmental and mechanical loading conditions that a pavement experiences. Generally, a film of hard material initiated by the process of oxidative polymerization of the asphalt molecules is formed at the surface of the asphalt film, which, if undisturbed, will prevent further reaction of oxygen with the material. If the film is cracked, new surfaces of the asphalt molecules are exposed, which in turn will permit additional oxidation to occur. In the field the mechanical and environmental factors acting on the pavement cause significant breakdown of the oxidatively polymerized surface of the asphalt, thereby providing a brand new surface of the molecule to be available for oxygen reaction at all times.

Oxidation of asphalts at temperatures associated with the mixing of asphalt cements and aggregates is rapid. The amount of hardening that occurs during the hot mix process is a function not only of temperature but also the thickness of the asphalt film, time of exposure, and type of atmosphere present (oxygen rich or oxygen depleted). Typically, the various factors said to contribute to age hardening of asphalt binders are oxidation, volatilization, polymerization, thixotropy, separation and syneresis.

3.3   Polymer Modified Asphalt (PMA)

Polymer modified asphalts are a form of engineered asphalt where, in the presence of a reactant, base asphalts are chemically combined with polymers like Styrene-Butadiene-Styrene (SBS) at elevated temperatures to form a superior product with enhanced engineering properties. The asphalt, when reacted with SBS polymer, can develop enhanced rut, low temperature and fatigue resistance. Sometimes Styrene-Ethylene-Butadiene-Styrene (SEBS) polymers are also used to impart resistance to environmental and age-related field hardening to the asphalt. Generally, the polymer modification process is used to improve both the high and low temperature grade of the asphalt (Grubba [15]).

The polymer modified asphalt used in this research study was an SBS modified system. The process of polymerization is defined as combining like molecules to form larger molecules that have more stable and, in most cases, superior engineering properties. In the case of SBS modified asphalts the formation of larger superior molecules is accomplished by adding polymers that are compatible with the asphalt and have the requisite molecular weight (Linde and Johansson [16]). The percentages of styrene and butadiene in the polymer are responsible for introducing enhanced rigidity and elasticity in the modified system respectively, whereas the overall molecular weight of the polymer works towards improving the low and high temperature properties. Usually a reactant is required to form a better bond between the asphalt molecules and the polymer itself and the reaction is achieved at elevated temperatures. Generally, the bond formed between the asphalt and the polymer molecules is irreversible except with certain types of polymers like Ethylene-Vinyl Acetate (EVA). Recently a new class of polymers referred to as Styrene-Ethylene-Butadiene-Styrene (SEBS) has also been used in asphalt modification. The SEBS polymers resist the age related hardening of the modified asphalt that happens in the field.

4 ASPHALT CLASSIFICATION

A full set of SHRP testing was run on the three types of asphalts to determine the actual PG grade. The objective was to determine if there is a significant difference in the properties of the asphalt even though they have the same PG grade. Initially two types of asphalts were selected to be characterized in this study, namely:

- PG 58-34
- PG 64-28

The equations used in the determining the high-end temperature of the original and RTFO aged asphalt are described below:

$$T_{Pass/Fail} = \frac{\left[k - \left\{DSR_2 - T_2\left(\frac{DSR_2 - DSR_1}{T_2 - T_1}\right)\right\}\right]}{\left[\frac{DSR_2 - DSR_1}{T_2 - T_1}\right]} \tag{1}$$

where: $T_{Pass/Fail}$ = Pass/Fail temperature for original and RTFO aged binder at high temperature
k = Intercept Constant, $k = 1.0$ for original binder and $k = 2.2$ for RTFO aged binder
$DSR_2 = G^*/Sin\delta$ at the high end of the high temperature (e.g. 64°C for PG 58-34) (where $G^*/Sin\delta$ represents Dynamic complex modulus divided by Sine of Phase angle at 64°C)
$DSR_1 = G^*/Sin\delta$ at the low end of the high temperature (e.g. 58°C for PG 58-34)
T_2 = High end of the high testing temperature and
T_1 = Low end of the high testing temperature.

The controlling temperature is the minimum of the two values calculated from Eq 1. Eqs 2 and 3 are used in the determination of low-end temperature of the RTFO+PAV processed asphalt and are shown below:

$$m_{Pass/Fail} = 10^{\left[T_1 + \left(\frac{1.8 - 6m_1}{m_2 - m_1}\right)\left\{\frac{LogS_1 - LogS_2}{T_1 - T_2}\right\} + LogS_1 - T_1\left\{\frac{LogS_1 - LogS_2}{T_1 - T_2}\right\}\right]} \tag{2}$$

$$S_{Pass/Fail} = Log(300) - LogS_1 + \frac{T_1\left\{\frac{LogS_1 - LogS_2}{T_1 - T_2}\right\}}{\left\{\frac{LogS_1 - LogS_2}{T_1 - T_2}\right\}} \tag{3}$$

where:

$m_{Pass/Fail}$ = Low temperature pass/fail using the m-value (slope of the log stiffness-log time curve at $t = 60$ seconds)
$T_{Pass/Fail}$ = Low Temperature pass/fail using the Stiffness value
m_1 = m-value at high end of the low temperature (e.g. -24 °C for PG 58-34)
m_2 = m-value at low end of the low temperature (e.g. -18 °C for PG 58-34)
T_1 = High end of the low temperature test
T_2 = Low end of the low temperature test
S_1 = Stiffness at the high end of low temperature and
S_2 = Stiffness at the low end of the low temperature.

The controlling temperature is the maximum of the two values calculated from Eq. 2 and Eq. 3. Table 1 indicates the properties of the three asphalts and their classification.

Based upon the mathematical calculations using Eqs 1 through 3 the actual Performance Grade of the three different types of asphalt were determined. The SHRP properties of the three different types of asphalts used in research study are described in Table 1.

Table 1: Performance Graded Asphalt Cement Strategic Highway Research Program (SHRP) Test Results

PG 58-34				PG 64-28			
Function	Plain Unmodified Asphalt (PUA)	Air Oxidized Asphalt (AOA)	Polymer Modified Asphalt (PMA)	Function	Plain Unmodified Asphalt (PUA)	Air Oxidized Asphalt (AOA)	Polymer Modified Asphalt (PMA)
G*/Sinδ @ 58 °C (kPa) – Original	4.301	1.067	1.403	G*/Sinδ @ 64 °C (kPa) – Original	1.227	1.089	1.868
G*/Sinδ @ 64 °C (kPa) – Original	1.993	0.561	0.768	G*/Sinδ @ 70 °C (kPa) – Original	0.625	0.560	0.955
G*/Sinδ @ 58 °C (kPa) – RTFO Aged	11.826	4.925	2.606	G*/Sinδ @ 64 °C (kPa) – RTFO Aged	3.307	3.230	3.682
G*/Sinδ @ 64 °C (kPa) – RTFO Aged	5.394	2.665	1.318	G*/Sinδ @ 70 °C (kPa) – RTFO Aged	1.593	1.538	1.907
Stiffness @ -24 °C (MPa)	235	209	182	Stiffness @ -24 °C (MPa)	508	428.5	387.0
Stiffness @ -18 °C (MPa)	104	98.1	84.7	Stiffness @ -18 °C (MPa)	268	202.5	190.0
m-value @ -24 °C	0.306	0.312	0.312	m-value @ -24 °C	0.235	0.266	0.256
m-value @ -18 °C	0.351	0.327	0.376	m-value @ -18 °C	0.301	0.310	0.321
PG	**61-34.8**	**58.8-36.9**	**59.9-35.1**	**PG**	**66.3-28.1**	**65-29.4**	**69-29.9**

Note: G*/Sinδ represents the dynamic complex modulus divided by Sine of the phase angle;
   m-value is the slope of the log stiffness-log time curve at $t = 60$ seconds;
   RTFO = rolling thin film oven; PG = Performance Grade

Based upon the test results shown in Table 1 it is clear that the performance grades for the three types of PG 58-34 asphalt cement are within 2°C of each other. This low level of deviation from the actual PGAC high and low temperature levels allows a one to one comparison between the three different types of asphalt in PG 58-34 category without losing testing integrity.

On the other hand, the results from PG 64-28 for the three different types of asphalt show a considerable difference, particularly at the high temperature end. The variation is as wide as 4°C between polymer modified asphalt and air-oxidized asphalt. Although all three asphalts are characterized as PG 64-28, it would be unadvisable to compare the PMA and AOA asphalts on one to one basis as done in PG 58-34

category. Because of such large differences in the SHRP performance properties PG 64-28 was subsequently dropped from the rheological study.

A simple rheological plan was instituted to determine the performance of different types of asphalts. The asphalt grade under study, as discussed above, was PG 58-34. The rheological study included evaluation of the mechanical properties of the three different types of asphalt as a function of temperature. In addition, three different stages in the life of asphalt binder were characterized. These stages include:

a) The original binder (as it is stored in tanks at plants and/or terminals)
b) RTFO Aged (Stage 1), simulating the binder properties as it is processed through the asphalt mix plant (It is known that considerable oxidation and relative hardening of the asphalt material takes place in the plant under temperatures as high as 165°C.) and
c) RTFO+PAV Aged (Stage 2), simulating the binder properties as it is oxidizes in the field under environmental conditions.

The following sections describe the individual mechanical properties and the effect of environment on mechanical properties related to short and long-term performance.

5   RHEOLOGICAL PROPERTIES

The key engineering and rheological parameters that affect performance are determined using the SHRP equipment, which includes Dynamic Shear Rheometer (DSR) and Bending Beam Rheometer (BBR). The engineering parameters evaluated are defined in Eqs. 4 and 5 in terms of complex dynamic modulus at frequency 'ω' [$G^*(\omega)$] which is a primary engineering function, phase angle (δ) for high temperature performance and Stiffness [$S(t)$], rate of change of stiffness (m-value) and deflection [$d(t)$] for low temperature performance.

$$G^*(\omega) = \frac{|\tau(\omega)|}{|\gamma(\omega)|} = \sqrt{G^{/2}(\omega) + G^{//2}(\omega)} = \frac{1}{J(t)} \qquad (4)$$

where:

$G^{/}(\omega)$ = Storage modulus in Pa at frequency ω = $G^*(\omega) \bullet Cos\delta$
$G^{//}(\omega)$ = Loss modulus in Pa at frequency ω = $G^*(\omega) \bullet Sin\delta$
$\tau(\omega)$ = Magnitude of dynamic shear stress response (Pa)
$\gamma(\omega)$ = Magnitude of applied dynamic shear strain (m/m)
δ = $Tan^{-1}[G^{//}(\omega) / G^{/}(\omega)]$ and
$J(t)$ = Shear creep compliance at time t (Pa)

As seen from Eq. 4, a dynamic complex modulus is normally measured and reported in terms of shear response. The phase angle δ indicates the lag in the stress response compared to the applied strain. For purely elastic materials, the phase angle will be zero, whereas for purely viscous materials the phase angle will be 90°. Both the complex dynamic modulus [$G^*(\omega)$] and the phase angle (δ), when combined in engineering terms, (see Eq. 4) can provide an estimate of the storage and loss modulus for a specific asphalt. The complex dynamic modulus (measure of the engineering strength of the medium) and the phase angle (measure of viscoelasticity in the medium) at high temperatures can be measured directly using the DSR, under the SHRP protocol. The complex dynamic modulus is inversely proportional to creep compliance of the material which in turn is a critical viscoelastic function providing an engineering measure of material response to loading.

The low temperature properties of the asphalt can be measured using the BBR device. The device applies a load 'P" to an asphalt beam at low temperature and derives the Stiffness at time 't', S(t) using the parameters in Eq. 5.

$$S(t) = \frac{PL^3}{4bh^3 d(t)}$$

(5)

where: P = Load applied, N
        L = Span length (mm)
        b, h, and d = Width, height and thickness of the asphalt beam and
        d(t) = Beam deflection at mid span

Eq. 5 is derived from the elementary bending beam theory where deflection $= d(t) = \dfrac{PL^3}{48EI}$

where: E = 1/D(t) = S(t) = Modulus of elasticity (Pa) and
        I = Moment of inertia = $bh^3/12$, mm^4

When a stiffness verses time curve at low temperature is plotted, an important parameter called the rate of change of stiffness (m-value) can be estimated. The m-value of asphalt provides an indication of the adaptability of the material to changing environmental conditions.

5.1   Rheology of Plain Unmodified Asphalt

The rheological study of PUA evaluated in this project involved estimation of the SHRP properties including the complex dynamic modulus and phase angle at high temperature and stiffness, rate of change of stiffness and the deflection characteristics at low temperature (see Figures 1 through 6).

5.2   Rheology of Air-Oxidized Asphalt

Figures 6 though 10 show the variation of the SHRP engineering properties of air-oxidized asphalt as measured using the DSR and BBR at various temperatures.

5.3   Rheology of Polymer Modified Asphalt

Figures 11 though 15 show the variation of the engineering properties of polymer modified asphalt as measured using the DSR and BBR at various temperatures.

6   DISCUSSION OF SHRP RESULTS

Significant differences can be seen in performance between the PUA, AOA and PMA products from an engineering perspective. Figures 1 through 15 show the detailed rheological performances of the various asphalts under review. For easier access to performance characteristics during the various stages of age-related hardening, the properties are plotted for the original, RTFO (Stage 1) and RTFO+PAV (Stage 2) of the rheological development. The following sections provide a discussion of the relative performance of these products, while comparing the engineering properties.

6.1   Complex Modulus (G*)

Figures 1, 6 and 11 show the variation of the complex dynamic modulus between PUA, AOA and PMA. There is considerable increase in the complex modulus at temperatures below the 58°C temperature level. Based upon SHRP PG system the chance of PG 58-34 (for a 98% reliability level) to be used for operational temperatures above 58°C is only 2%. Based on the reliability level, all the PG 58-34 show considerable increases in G* during the temperature sweep.

Although it is desirable to have a high G* value, it comes with its detrimental effects, especially when the rheological properties after Stage 1 and Stage 2 oxidation are concerned. High complex modulus after Stage 2 oxidation will undoubtedly result in a high stiffness/complex modulus at low temperatures resulting in undue thermal and fatigue distress (trend of G* towards the low temperature side). Figure 1 shows the increase in G* from a 1.959 kPa level to 5.198 kPa after Stage 1 (RTFO) and 21.995 kPa after Stage 2 (RTFO+PAV). It is also noted that as the operational temperature decreases below 58°C, the asphalt rheology after Stages 1 and 2 shows a nonlinear increase in complex modulus.

In the case of air oxidized asphalt (see Figure 6) the increase in G* is even higher than that reported in PUA. At 58°C, G* for the original asphalt is 1.059 kPa, whereas after Stage 1 (RTFO) and Stage 2 (RTFO+PAV) the binder G* is 4.645 kPa and 37.643 kPa respectively. This is a considerable increase in G*, indicating a greater susceptibility to low temperature cracking.

Figure 11 shows the increase in G* for PMA. At 58°C, G* of the original asphalt is 1.356 kPa level. After Stage 1 (RTFO) the binder G* is 2.504 kPa and rises to a level of 7.199 kPa after Stage 2 (RTFO+PAV). This increase in G* is considerably less than in the PUA and AOA materials and points towards a significantly improved resistance to thermal cracking while keeping the level of G* at appreciably reasonable levels of rut resistance.

6.2   Phase Angle (δ)

Phase angle (δ) indicates the level of viscoelasticity that exists in the system. It is always prudent to have a certain level of viscous behavior of the system at low temperatures. Since Stage 2 oxidation is of primary concern while comparing the phase angles between PUA, AOA and PMA materials, it is reasonable to maintain that the lower the phase angle, the more susceptible the material becomes towards thermal cracking and fatigue at low temperatures (δ = 0° implies pure elastic and δ = 90° implies pure viscous behavior).

While comparing Figures 2, 7 and 12 for the three different types of asphalts, it is clear that the polymer modified asphalt has a higher phase angle at all times as compared to plain unmodified and air oxidized asphalts. At 58°C the asphalt PMA indicates a phase angle of 68° as compared with 54.8° for AOA and 62° for PUA (during Stage 2). The extension of the Phase angle (δ) curve towards the low temperature side shows that the PMA still has a higher level of viscous behavior in the system at lower temperatures as compared with AOA and PUA.

In general the engineering properties of PMA are superior to those of PUA and AOA based upon the G* and δ levels.

6.3   Stiffness [S(t)]

Bending Beam Rheometer (BBR) provides information about the low temperature performance of the asphalt cement by primarily measuring the stiffness and rate of change of stiffness (m-value). SHRP limits the value of stiffness to 300 MPa at the low end of the operational temperature of the asphalt cement for performance purposes. Stiffness tests are performed on the various asphalts using the BBR at –24 °C, and the levels are measured after 60 sec of loading.

The measured stiffness at –34°C is 235 MPa for the PUA, 209 MPa for the AOA and 182 MPa for PMA. In addition to the stiffness levels, the spacing of the three curves i.e. original, after Stage 1 and after Stage 2 oxidation is also very critical. The closer the three respective curves are after their various oxidative stages, the more resistant the asphalt binder is to oxidative hardening (implying nearly similar trend at various levels of oxidation). The PMA stiffness curves are the most closely packed out of the three

asphalt types (see Figures 3, 8 an 13). The largest spacing between the curves is noted in the PUA followed by AOA material.

One potential benefit of the three different stiffness curves is that a global master curve can be generated by combining the three curves using viscoelastic concepts, thus providing information on stiffness levels over a considerably large span of life of the asphalt.

6.4   Rate of Change of Stiffness (m-value)

The rate of change of stiffness is critical for all types of asphalts since it is an indicator of the response time for an asphalt to changes in temperature. As a rule the longer the material takes to adjust its stiffness to a thermal change, the more susceptible the material is to thermally induced stresses. SHRP sets a minimum limit of 0.300 for the m-value for any measured asphalt after Stage 2 processing.

Figures 4, 9 and 14 provide the m-value variation of the asphalt as a function of low temperature for the three types of asphalts in their various stages of oxidative hardening. The PUA (m-value = 0.306) shows the poorest m-value as compared to AOA (m-value = 0.312) and PMA (m-value = 0.312). The nearly equivalent performance of the PMA and AOA is attributed to the fact that the m-value is not noticeably affected by the addition of polymers, but rather it is the stiffness that is improved. There is normally no change in the m-value of asphalts when polymers are added to the system.

6.5   Deflection Characteristics [d(t)]

Deflection characteristics of asphalt beams at low temperature provide insight into deformation behavior relative to mechanical as well as thermal loading. The information presented in Figures 5, 10 and 15 indicates that at –24 °C the PMA shows a deflection level of 0.546 mm under a load level of ±980 mN, while AOA and PUA beams indicate a deflection level of 0.724 mm and 0.717 mm respectively. At low temperatures large deflections under mechanical and environmental loading can cause fatigue cracking to appear more quickly in a flexible pavement which is constructed with PUA and AOA materials. This excessive deflection behaviour in general leads to the conclusion that the asphalt cements that portray larger deflections at low temperatures are more susceptible to fatigue cracking.

Table 2 provides the information presented above as a function of SHRP property change form the original state binder to Stage 2 oxidized binder for the various PGACs at 58°C.

Table 2: Relative change in SHRP Binder Properties from Original to after Stage 2 Oxidation

Property	Plain Unmodified Asphalt	Air Oxidized Asphalt	Polymer Modified Asphalt
δ - $\Delta_{\text{Original to Stage 2}}$	16	20	7
G^* - $\Delta_{\text{Original to Stage 2}}$	20	39	5.5
$d(t)$ - $\Delta_{\text{Original to Stage 2}}$	0.35	0.30	0.11
$S(t)$ - $\Delta_{\text{Original to Stage 2}}$	120	60	40
m-value - $\Delta_{\text{Original to Stage 2}}$	0.11	0.11	0.09

Note: δ - $\Delta_{\text{Original to Stage 2}}$ = change in phase angle from original to Stage 2 at high temperature;

G^* - $\Delta_{\text{Original to Stage 2}}$ = change in dynamic complex modulus form original to Stage 2 at high temperature;

$d(t)$ - $\Delta_{\text{Original to Stage 2}}$ = change in deflection from original to Stage 2 at low temperature,

$S(t)$ - $\Delta_{\text{Original to Stage 2}}$ = change in stiffness from original to Stage 2 at low temperature and

m-value - $\Delta_{\text{Original to Stage 2}}$ = change in rate of change of stiffness from original to Stage 2 at low temperature for the PG 58-34
asphalt.

6.6 Brookfield Viscosity

Air oxidized asphalts generally use a catalyst to accelerate the oxidative polymerization process (Kamel and Laverne [14]). These catalysts are always present in the asphalt system even after the pavement construction process and under ordinary thermal conditions, they don't effect the rheological properties by a large extent. However, whenever the air temperature is increased, the potential of oxidative hardening in the system increases because the catalyst starts the reaction with the asphalt again. For this reason the viscosity of the AOA increases at higher temperatures more than that of more stable systems like PMA and PUA (see Figure 16). Although the increase in viscosity may improve the high temperature properties, the process of oxidative hardening causes excessive brittleness in the system when temperatures drop. The system therefore becomes more susceptible to low temperature issues relative to asphalt rheology.

7 ELASTIC RECOVERY RESULTS

Elastic recovery (E_R) tests were performed on the three different types of PGACs in both original and after Stage 2 oxidation . Elastic Recovery is normally performed on original asphalts, but to estimate long-term performance and estimate the retained viscoelastic nature of the asphalt system several years after production, Stage 2 processed material was also added to the test matrix to assess the amount of recovery that exists in the asphalt in the later part of the pavement's life.

Elastic recovery tests were performed on both the original and Stage 2 processed asphalt for all the three types of asphalts. E_R is expressed as a percentage and the tests were performed as per LS-208 or ASTM D113-86 test standard. The test method involves pulling an asphalt dog-bone sample for a specific distance at a specific rate. Once the deformation in the briquette is achieved, the deformed specimen is cut in the middle and the elastic recovery in the system determined as a function of initial deformation. Mathematically E_R is defined as follows:

$$E_R \ (\%) = \text{Elastic Recovery} \ (\%) = \frac{E - X}{E} \tag{4}$$

where: E = Original elongation of specimen (cm) – generally 20 cm; and
    X = Elongation of specimen with severed ends just touching (cm).

Table 3 indicates the E_R results as determined in the laboratory for the original and Stage 2 processed asphalts.

Table 3: Elastic Recovery (E_R) Results for Plain Unmodified Asphalt, Air Oxidized Asphalt and Polymer Modified Asphalt in Original Condition and after Stage 2 Oxidation

Plain Unmodified Asphalt		Air Oxidized Asphalt		Polymer Modified Asphalt	
Original[1]	RTFO+PAV[2]	Original[1]	RTFO+PAV[2]	Original[1]	RTFO+PAV[2]
12.5%	Broke at 4.25 cm Recovery = 2.75 cm	7.5%	Broke at 4.3 cm Recovery = 2.75 cm	66.5%	Broke at 10.2 cm Recovery = 4.75 cm

1.   The original material extended to the required 20 cm elongation. The stretched sample was severed in the middle and the recovery in the asphalt noted. The resulting E_R value is reported in percentage.

2.   The sample was stretched as per the test specifications, but that sample broke at a deformation level lower than 20 cm. The recovery in the sample as a function of original length was then measured to ascertain the elastic recovery of the PAV+RTFO material.

The results presented in Table 3 indicate that the PMA material is still very elastic after Stage 2 oxidation. The material stretches for nearly 10.2 cm before fracture. The elastic rebound from that point onward on the fractured system was measured as 4.75 cm. At low temperatures, if an asphalt system does not have some viscous properties it becomes prone to low temperature and/or fatigue cracking. A large recovery in the Stage 2 oxidized system indicates that the asphalt retains a reasonable level of viscoelasticity several years after construction, which is beneficial to its long-term performance.

The PUA and AOA achieve 4.25 cm and 4.3 cm deformations in the sample before fracture. The elastic rebound in the fractured samples was 2.75 cm for both samples. In general, the performance of PUA and AOA is nearly the same after Stage 2 oxidation.

PMA out-performs the PUA and AOA material from an E_R perspective. The deformation levels and the elastic rebound in the PMA system that is present after Stage 2 oxidation indicates that the material will still retain a significant portion of viscoelasticity several years down the road, leading to improved performance.

8   FUTURE RESEARCH

This research project indicates that the curves (G*, δ, S, m-value and deflection) for the original asphalt binders including Stage 1 and Stage 2 oxidation show a rheological trend, which can lead to development of property master curves using the theory of viscoelasticity. The master curves can then be used to estimate limits where material property under investigation becomes detrimental to material performance. Master curves in this scenario will relate asphalt material properties to time and are used widely in linear viscoelastic theory (Bhutta and Al-Qadi [8]). The process of determining the master curve would require estimation of the viscoelastic shift factors (a_T) and then using viscoelastic principles to generate the final property behaviour curve over a long span of time.

As an extension of this research, University of Carleton is currently working on a study to investigate low temperature fatigue performance of mixes created using asphalt cement after Stage 2 oxidation. Results from that project will be available by December 2000.

9   CONCLUSION

This is a purely rheological study detailing the mechanical performance parameters of PUA, AOA and PMA for PG 58-34 grade asphalt. Mechanical properties of the various asphalt binders were evaluated using SHRP equipment at three different stages in the life of the pavement. In all the engineering results, PMA outperforms the AOA and PUA at both high temperatures and low temperatures. The performance parameters measured in this project included Dynamic Complex Modulus (G*), Phase Angle (δ) at high temperatures and Stiffness [S(t)], rate of change of stiffness at low temperature (m-value) and deflection characteristics [d(t)] at low temperatures. AOA, by its very nature of manufacture, is a brittle material to start with and displays a sharp rise in dynamic complex modulus, indicating extreme thermal susceptibility, leading to cracking and fatigue as test temperatures are reduced. The level of relative viscoelasticity in the three different types of asphalts also indicates that the PMA retains a large portion of its viscous nature as opposed to PUA and AOA at low temperatures. The S, m-value and deflection characteristics of PMA as opposed to AOA and PUA illustrate the definite superior performance of PMA, which exhibits an appropriate response to thermal changes while retaining a respectable level of

viscoelasticity. The elastic recovery results also indicate that the performance of PMA is superior to PUA and AOA for as the original, and after Stage 1 and after Stage 2 binder oxidation.

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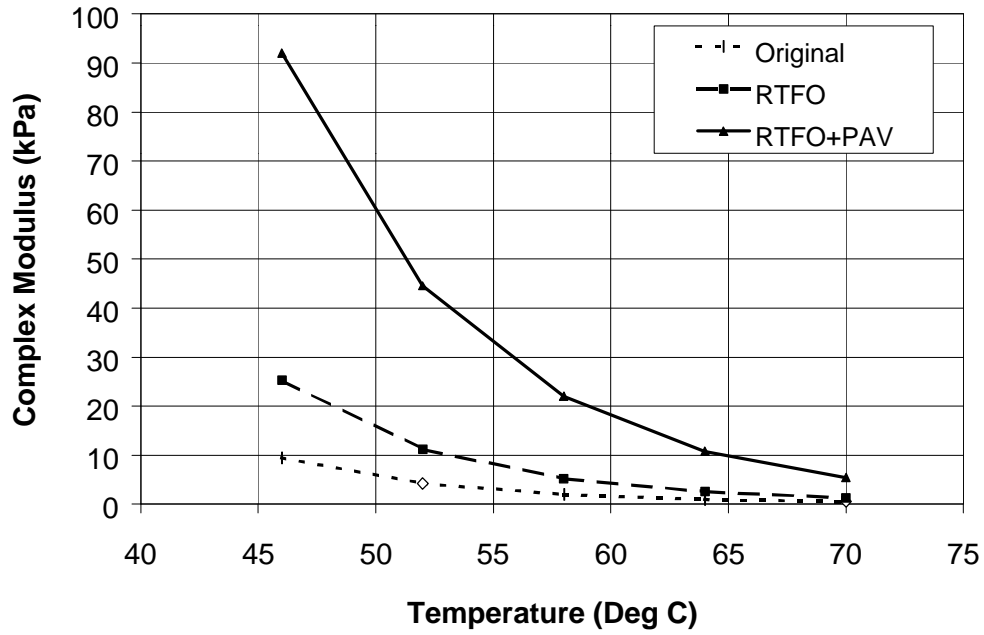
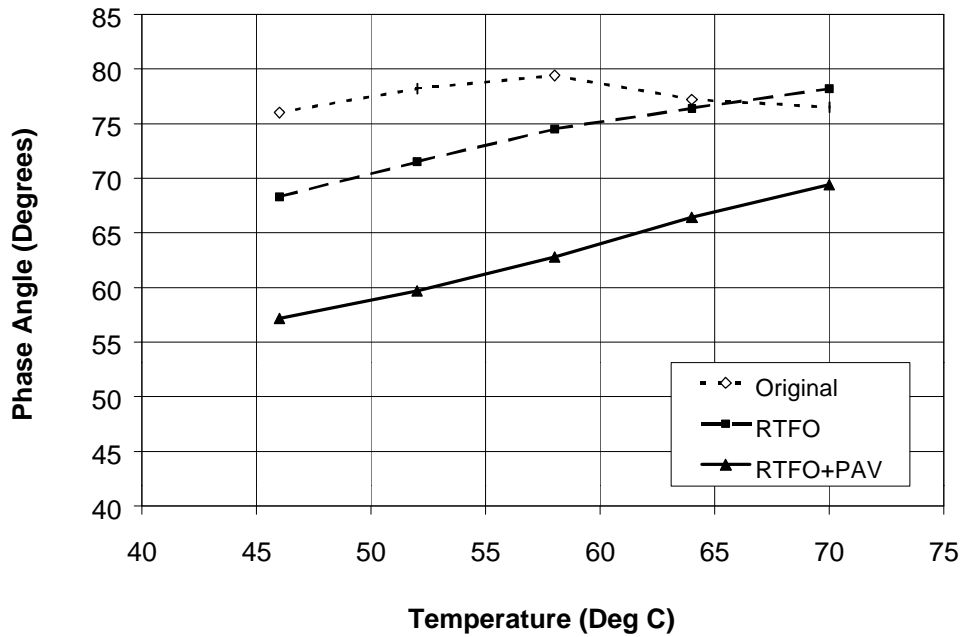**Figure 1: Complex Dynamic Modulus (G*) as a Function of Temperature for Plain Unmodified Asphalt**

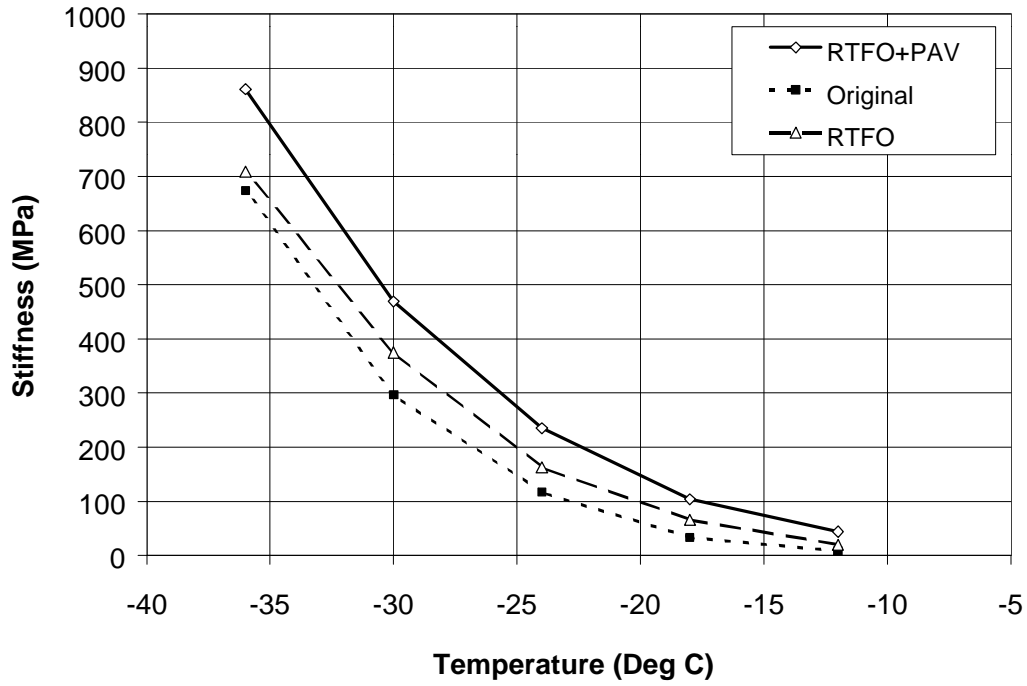**Figure 2: Phase Angle (δ) as a Function of Temperature for Plain Unmodified Asphalt**

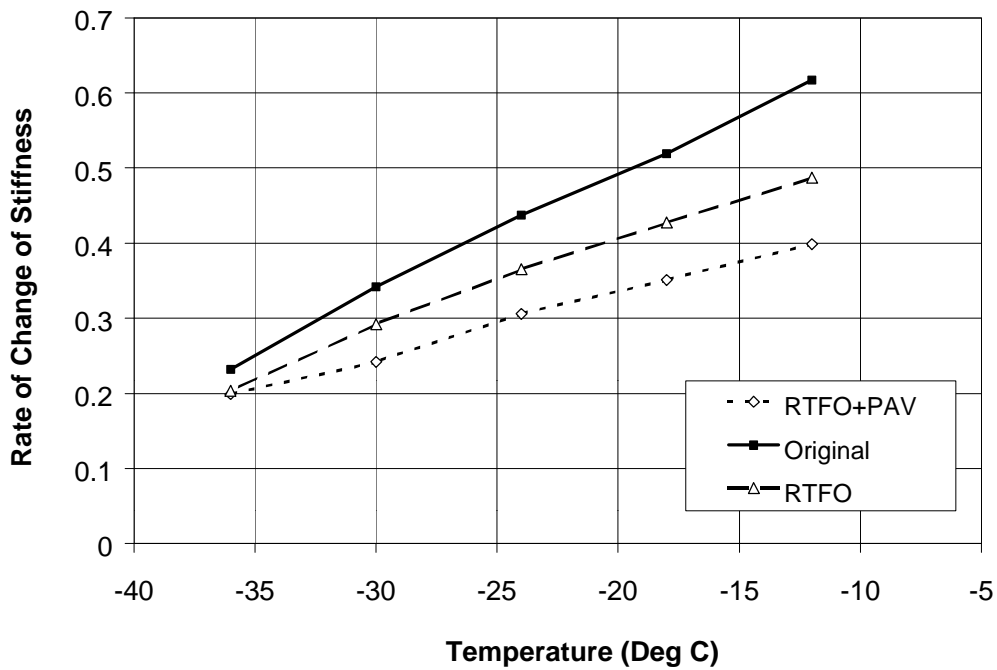**Figure 3: Stiffness [S(t)] as a Function of Temperature for Plain Unmodified Asphalt**

Figure 4: Rate of Change of Stiffness (m-value) as a Function of Temperature for Plain Unmodified Asphalt
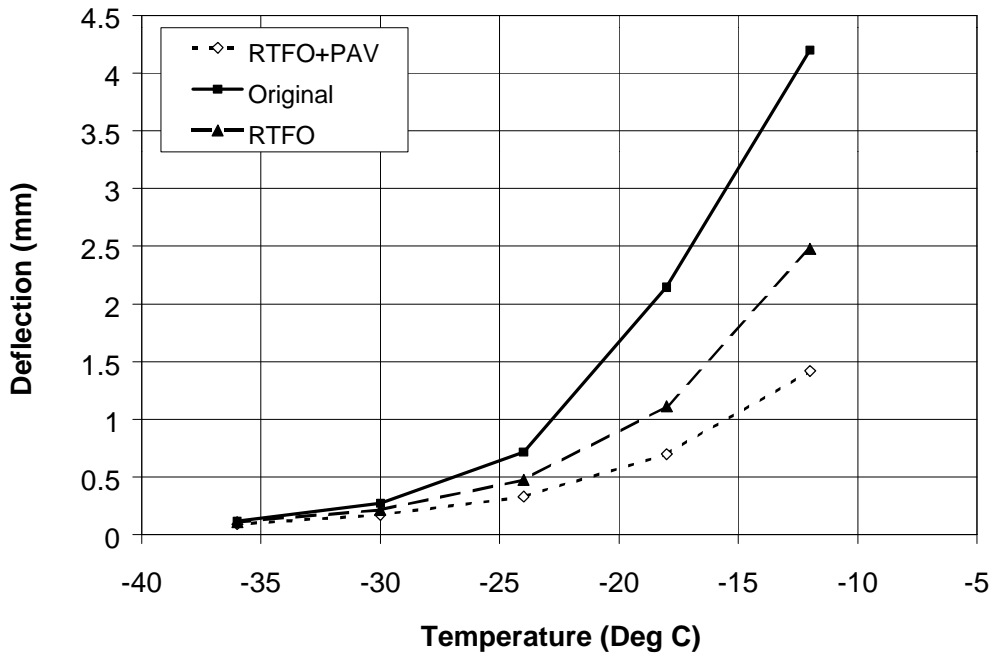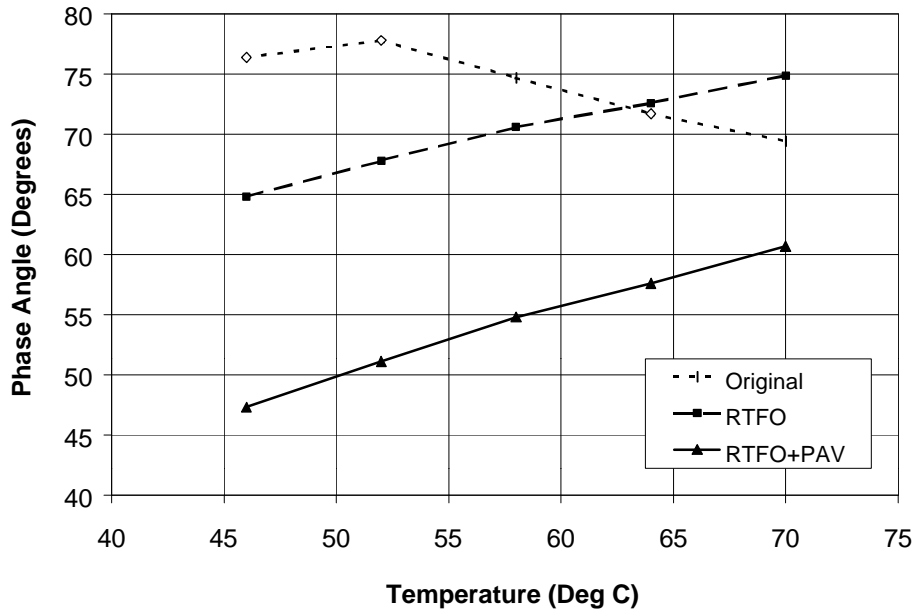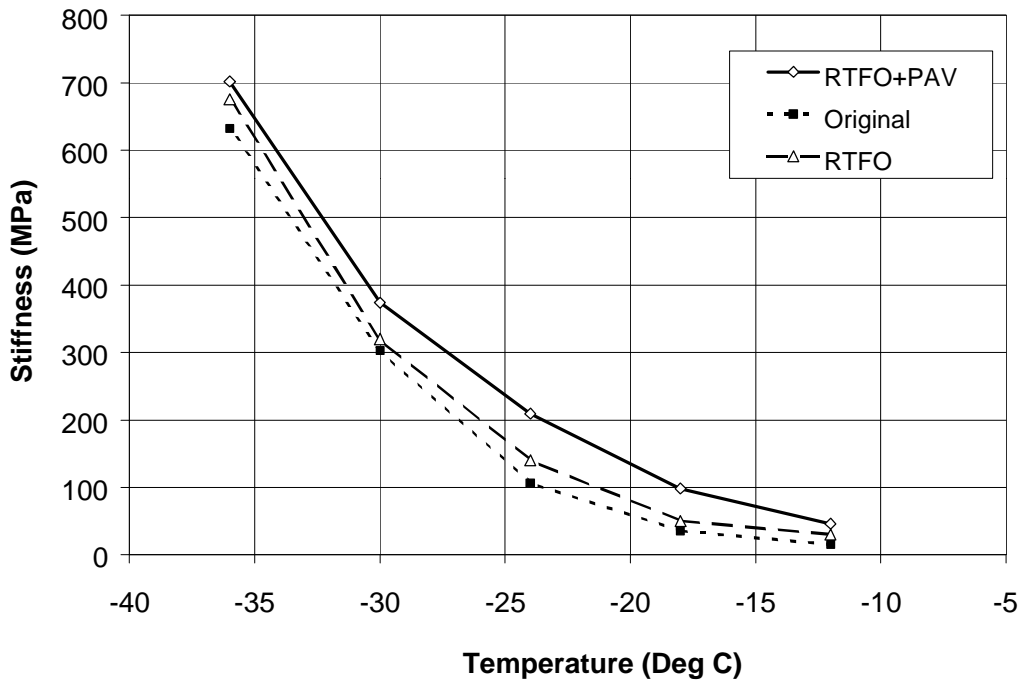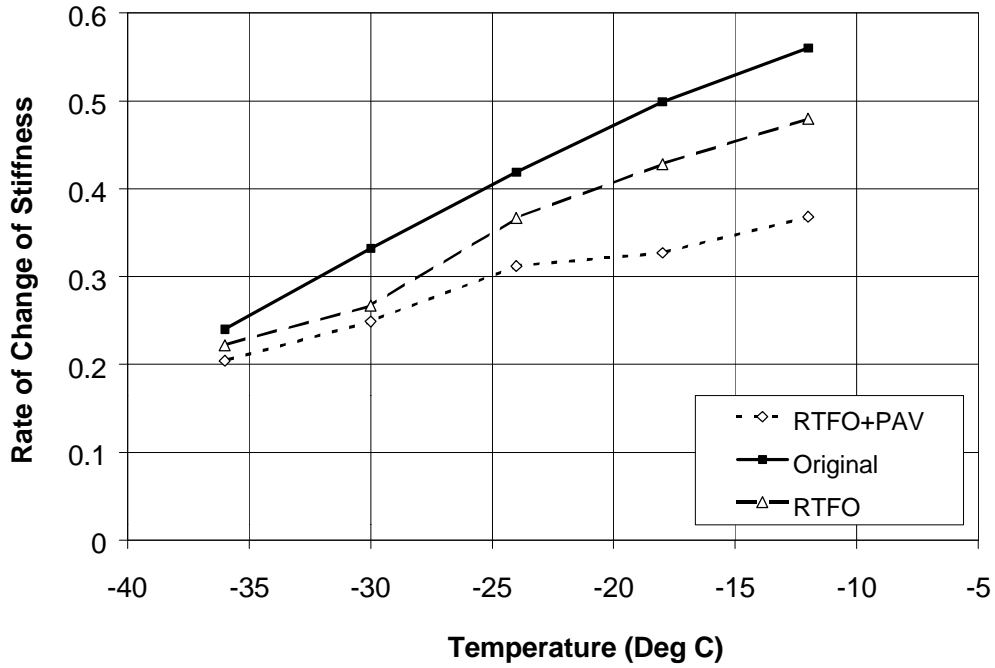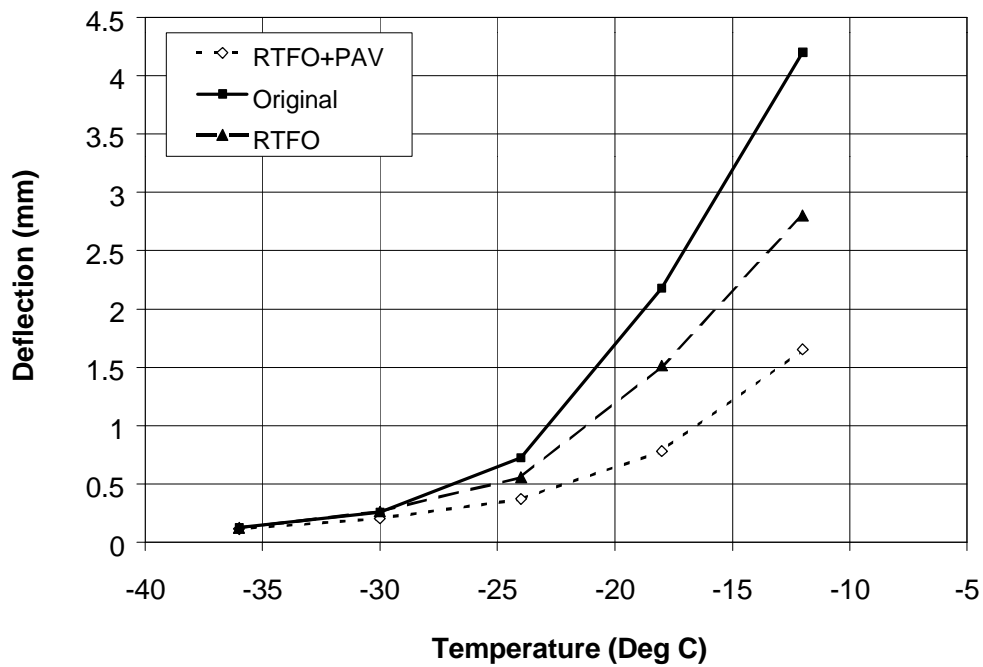
Figure 5: Bending Beam Rheometer Deflection Characteristics [d(t)] as a Function of Temperature for Plain Unmodified Asphalt
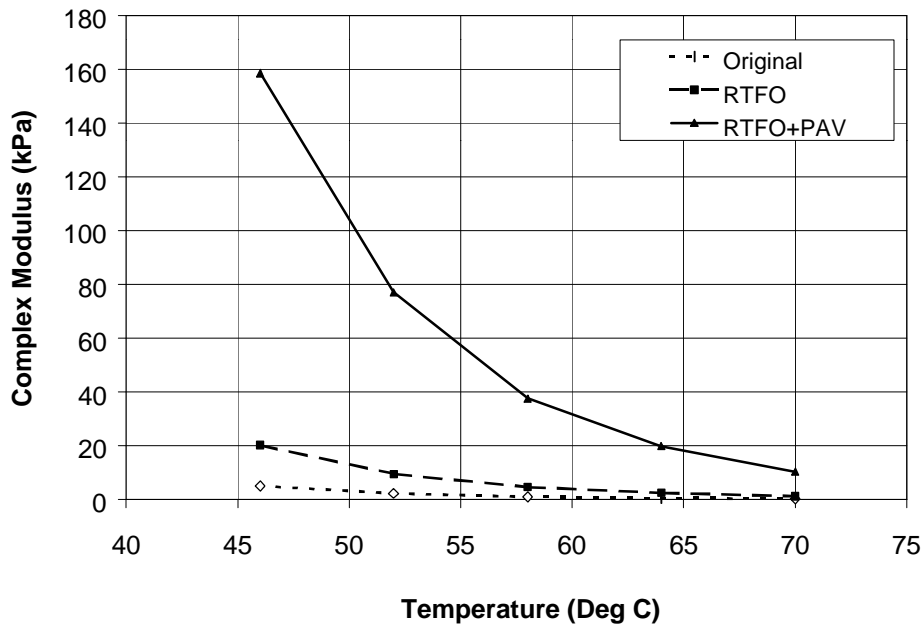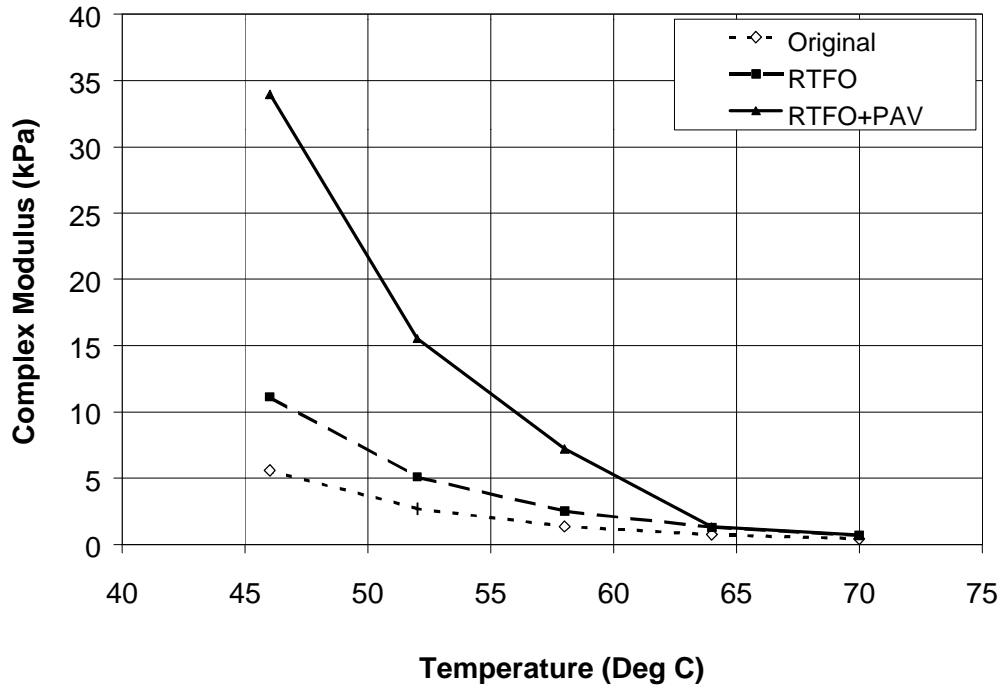

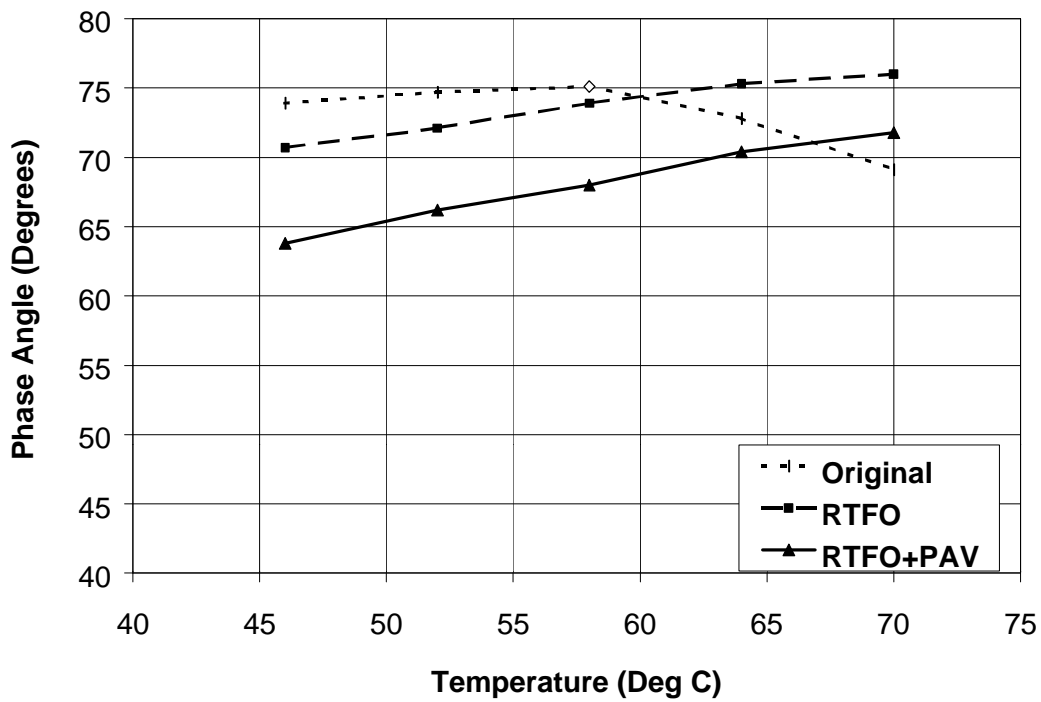**Figure 6: Complex Modulus (G*) as a Function of Temperature for Air Oxidized Asphalt**

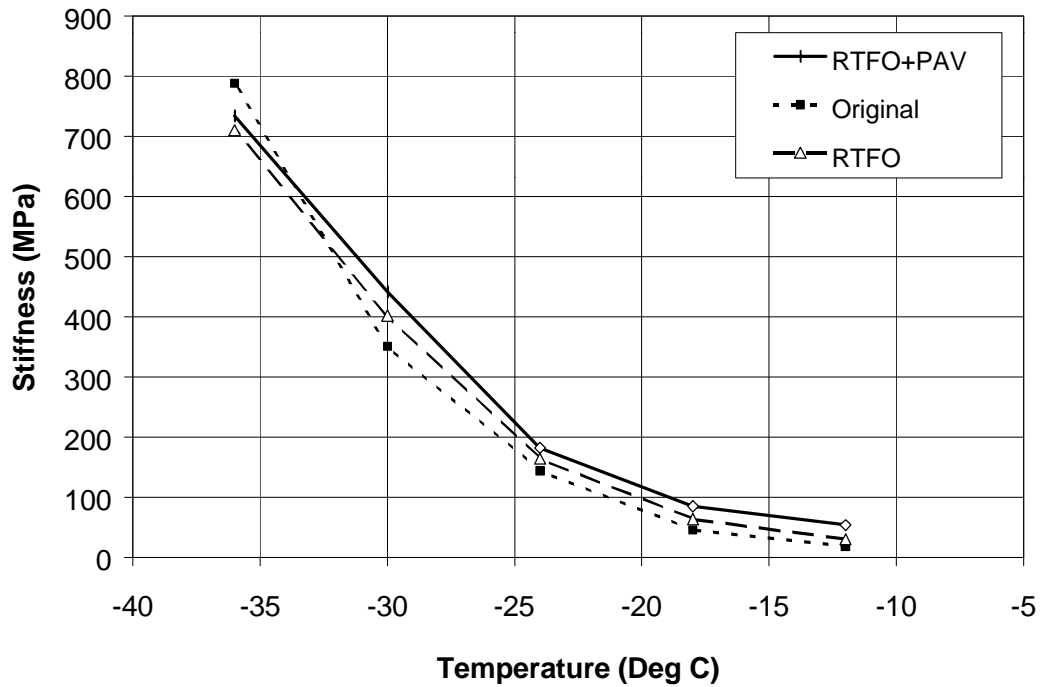**Figure 7: Phase Angle (δ) as a Function of Temperature for Air Oxidized Asphalt**

Figure 8: Stiffness [S(t)] as a Function of Temperature for Air Oxidized Asphalt

Figure 9: Rate of Change of Stiffness (m-value) as a Function of Temperature for Air Oxidized Asphalt

Figure 10: Bending Beam Rheometer Deflection Characteristics [d(t)] as a Function of Temperature for Air Oxidized Asphalt

Figure 11: Complex Modulus (G*) as a Function of Temperature for Polymer Modified Asphalt

Figure 12: Phase Angle (δ) as a Function of Temperature for Polymer Modified Asphalt

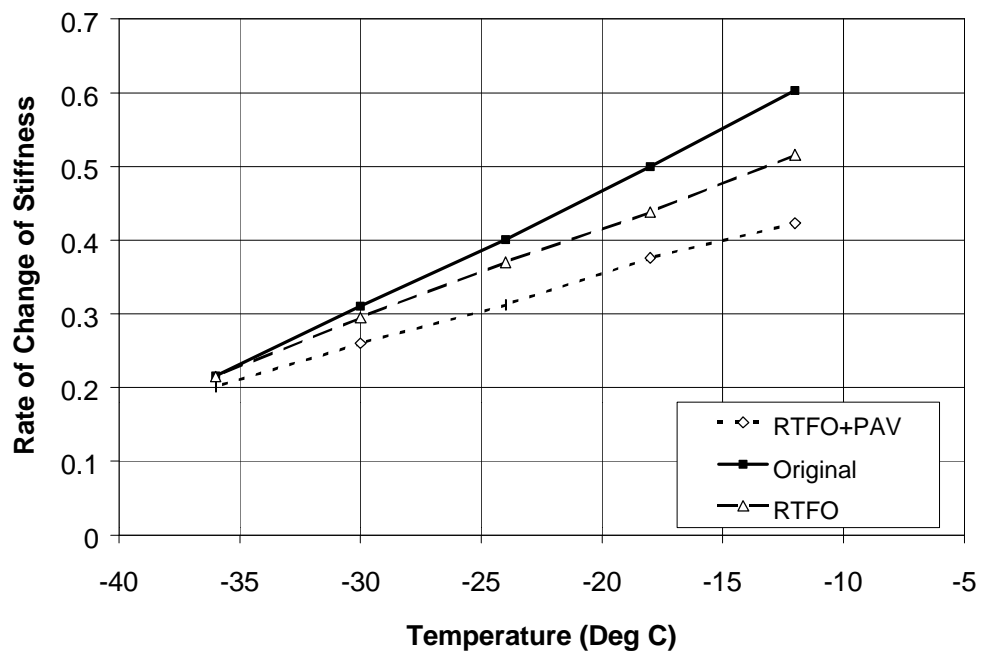**Figure 13: Stiffness [S(t)] as a Function of Temperature for Polymer Modified Asphalt**

Figure 14: Rate of Change of Stiffness (m-value) as a Function of Temperature for Polymer Modified Asphalt
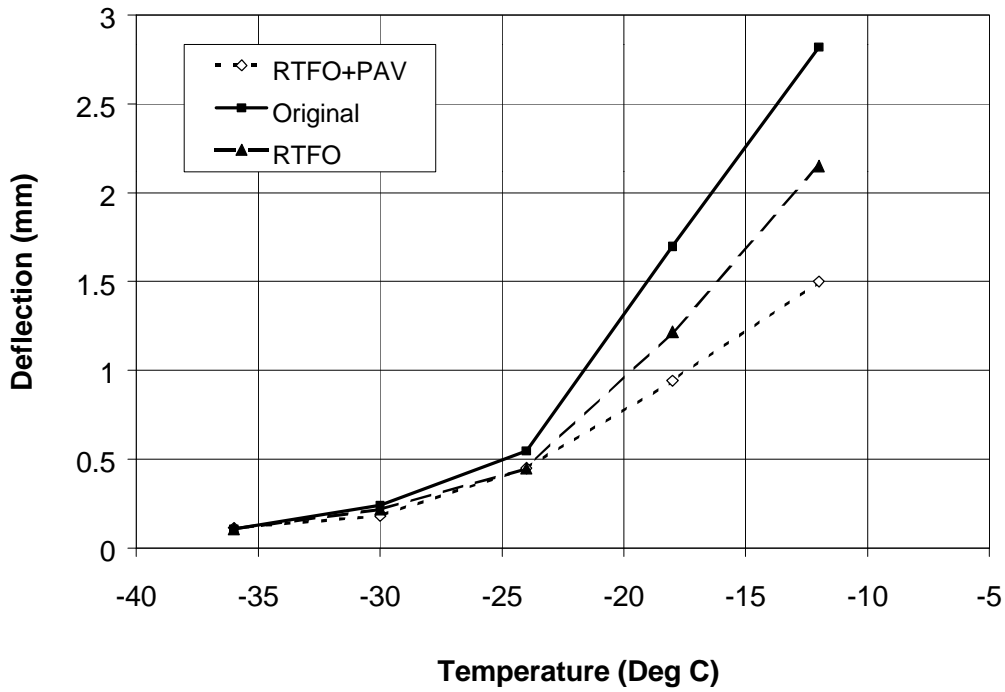
Figure 15: Bending Beam Rheometer Deflection Characteristics [d(t)] as a Function of Temperature for Polymer Modified Asphalt
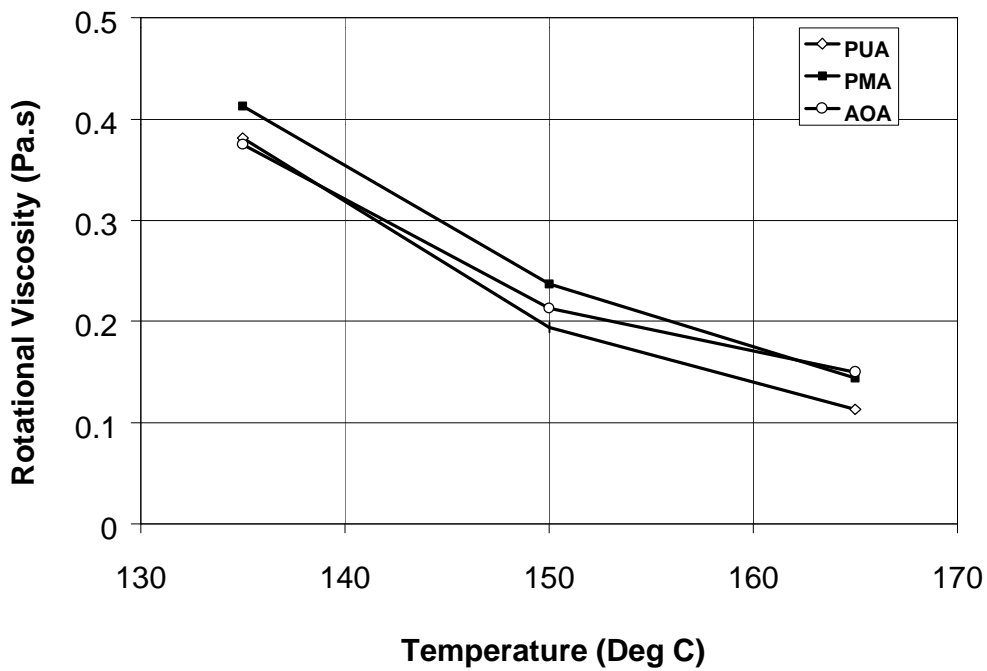

Figure 16: Rotational Viscosity as a Function of Temperature for Plain Unmodified Asphalt (PUA), Air Oxidized Asphalt (AOA) and Polymer Modified Asphalt (PMA)