EFFECT OF AGING ON RHEOLOGICAL, CHEMICAL AND THERMODYNAMIC PROPERTIES OF ASPHALT COMPONENTS

Submitted to the 93rd Annual Meeting of the Transportation Research Board
Submitted on August 1, 2013

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Word Count: Abstract (239) + Body (3,757) + Figures and Tables (14x250) = 7,496

ABSTRACT

Many molecular structures are found in asphalts; however, the commonly used classification separates asphalt into asphaltenes and maltenes (resins and oils). Rheology of asphalts depends on the combination of the different constitutive fractions and greatly depends on the degree of association of asphaltenes and the relative quantity of other substances present in the system to stabilize those associations. Asphalts are subjected to an aging process during mixing, laydown and service life that also affects their rheology. The objective of this study was to evaluate the effect of aging on rheological, chemical and thermodynamic properties of the asphalt binder main components: asphaltenes and maltenes. An AC-30 asphalt binder and its individual components were aged using the Rolling Thin Film Oven (RTFO) and the Pressure Aging Vessel (PAV), and were analyzed using a Dynamic Shear Rheometer (DSR). A Iatroscan thin film chromatography and a Polarized Light Microscopy analysis were also used for characterization purposes. A Thermogravimetric analysis (TGA), a Differential Scanning Calorimetry Analysis (DSC) and a Fourier Transform Infrared Spectroscopy (FTIR) analysis of the asphalt binder and its components were performed before and after aging. The results indicated that the thermal stability of the asphalt binder can be attributed mostly to the higher stability and lower susceptibility to oxidation of the asphaltenes at normal handling temperatures for paving operations. Overall, there is clear evidence that aging of the asphalt binder components has an effect on the morphology of the asphalt binder.

INTRODUCTION

Asphalt is a complex organic mixture, composed of hydrocarbons with small percentages of sulfur, nitrogen, and oxygen. Many molecular structures are found in asphalts; however, the commonly used classification separates asphalt into asphaltenes and maltenes (resins and oils). Asphaltenes are generally dark brown, friable solids and are the most complex components with the highest polarity. Resins are generally dark and semi–solid or solid in character. They are fluid when heated and become brittle when cold. On oxidation, resins yield asphaltene type molecules. Oils are usually colorless or white liquids. They have paraffinic and naphthenic structures with no oxygen and nitrogen usually present. On oxidation, they yield asphaltene and resin molecules (*1*).

Asphalt is most commonly modeled as a colloid (micellar model), with asphaltenes as the dispersed phase and maltenes as the continuous phase (*2*). The original micellar model was constructed from interpretations of historical data in which researchers looked for relationships between chemical parameters and pavement performance. According to this model, the rheology of the asphalt is highly affected by the degree to which the resins are effective in keeping the asphaltene fraction dispersed in the oil (*3*). Asphalts which have well-dispersed asphaltenes, exhibit high temperature susceptibilities, high ductility, low rates of age hardening, and Newtonian behavior. Asphalts which have poorly dispersed asphaltenes show low temperature susceptibilities, low ductility, rapid age-hardening, and non-Newtonian behavior (*4*).

Different effects on rheology of the binder can be obtained depending on how the different fractions are combined (*5*). For instance, if the content of asphaltenes is kept constant adding resins will produce a harder binder. The same hardening effect can be obtained by increasing the asphaltenes concentration into a maltenes constant structure. In addition, it is considered that at ambient and intermediate temperatures the rheology of asphalt binders is dominated by the degree of association of asphaltenes and the relative quantity of other substances present in the system to stabilize those associations.

Another factor influencing the rheology, performance and characteristics of asphalt binders is a phenomenon known as aging. Several factors may contribute to this hardening of the asphalt such as oxidation, volatilization, polymerization, and thixotropy (*5-7*). Because asphalt is an organic compound, it is able to react with oxygen in the environment. As the oxidation reaction occurs, it changes the composition of the asphalt, creating a more brittle structure. Volatilization occurs when the lighter constituents of the asphalt evaporate. Polymerization is the means by which resins are thought to combine into asphaltenes, causing an increase in the brittleness of the asphalt along with a tendency toward non-Newtonian behavior. Finally, thixotropy, or an decrease in viscosity over time, also contributes to the aging phenomenon in asphalt.

This report summarizes a comprehensive investigation on the effect of aging on chemical composition and rheological properties of asphalt binder components (asphaltenes and maltenes).

BACKGROUND

To date, there is an increasing interest in understanding the micro-mechanical and chemical behavior of asphalt to better understand rheological properties and their effect on the performance of asphalt mixtures during their service life *(8)*. Even though asphalt binder corresponds to a small percentage of the overall mixture volume, variations in the molecular distribution and micro-mechanical arrangement of the different components in asphalt binder, have a considerable impact in the performance of the mixture. This is due to the fact that small variations in the chemical and structural composition of the asphalt matrix have an effect on the rheological, viscoelastic and thermoplastic behavior of the material *(8)*.

Techniques such as Thermogravimetric Analysis (TGA), Differential Scanning Calorimetry Analysis (DSC), Fourier Transformed Infrared Spectroscopy (FTIR) and Iatroscan thin film chromatography have been used to characterize the chemical composition and thermo dynamical behavior of the asphalt binder: Similarly, techniques such as the following can be used to analyze the micro-mechanical structure and behavior of the asphalt binder: dynamic shear rheometer (DSR), dynamic mechanical analyzer (DMA), atomic force microscopy (AFM), and electron microscopy. The previous techniques can also be used with thermal analysis to better understand the behavior of the material.

OBJECTIVE

The objective of this study was to evaluate the effect of aging on rheological, chemical and thermodynamic properties of the asphalt binder main components: asphaltenes and maltenes.

SCOPE OF WORK

To accomplish the objective of this study, the asphalt binder and its individual components (asphaltenes and maltenes) were aged using the Rolling Thin Film Oven (RTFO) and the Pressure Aging Vessel (PAV), and were also analyzed using a Dynamic Shear Rheometer. The binder was characterized using the Superpave methodology, based on the PG grading of the material and rheological properties were obtained for the same binder and its components at three aging stages or conditions (original, RTFO and PAV) and at two temperatures (25 °C and 64 °C). A Iatroscan thin film chromatography and a Polarized Light Microscopy analysis were also used for characterization purposes. A Thermogravimetric aTGA nalysis of the asphalt binder and its components was performed at the same three aging stages. A DSC Analysis was also performed to observe sample behavior due to the change on temperature in a range from -50°C up to 200°C at the same three aging stages. Finally, the Fourier Transform Infrared Spectrometry was used to determine the functional characteristics of the binder and its individual components before and after aging.

CHARACTERIZATION OF THE BINDER AND ITS COMPONENTS

The tests to characterize the bitumen and modifiers were performed at the National Laboratory for Materials and Structural Models (LanammeUCR, University of Costa Rica). The asphalt binder used in this study was classified as viscosity grade AC-30 provided by RECOPE (Costa Rican Petroleum Refinery). This grade corresponds to the most common binder used in Costa Rican roads.

Iatroscan Chromatography

A chromatography analysis made with the Iatroscan chromatographer showed that the fractions of the original (unaged) bitumen are distributed as follows: Saturated 5,2%, Aromatics 54.9%, Resins 25.8% and Asphaltenes 14.1%. Figure 1 illustrates the binder fractions for the original and the RTFO and PAV aged binder . If compared to the original condition, the asphaltenes presented the lowest change in composition by decreasing 3.0 % at RTFO and 18% at PAV aging stage. On the other hand, resins' composition changed the most with an increase of 33 % at RTFO and 119% at PAV stage. It was also determined that aromatics are more likely to yield resin molecules on aging instead of yielding asphaltene molecules. In addition, there was no indication that resins yield asphaltene-like molecules on aging.

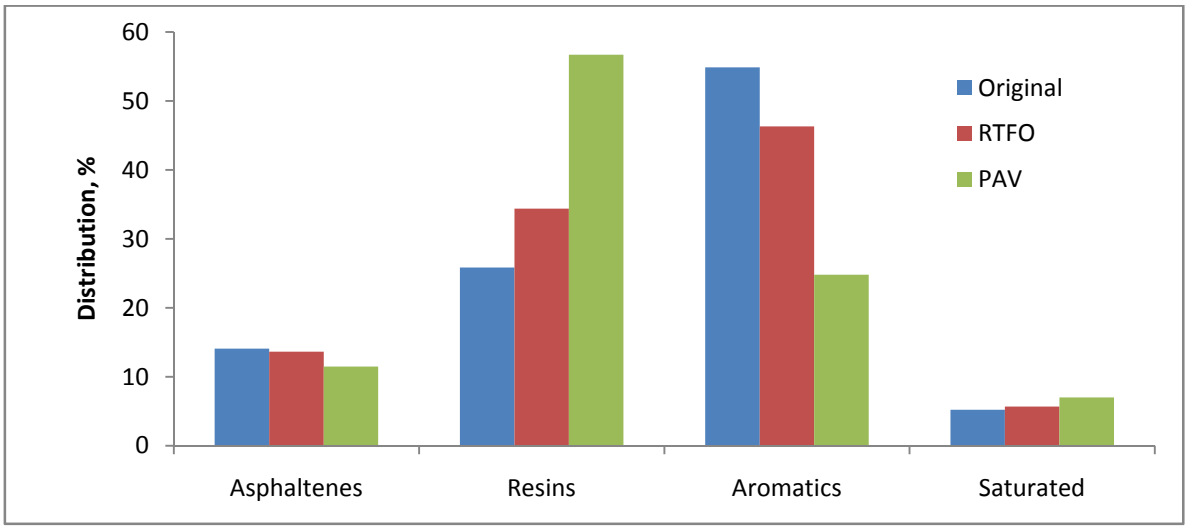
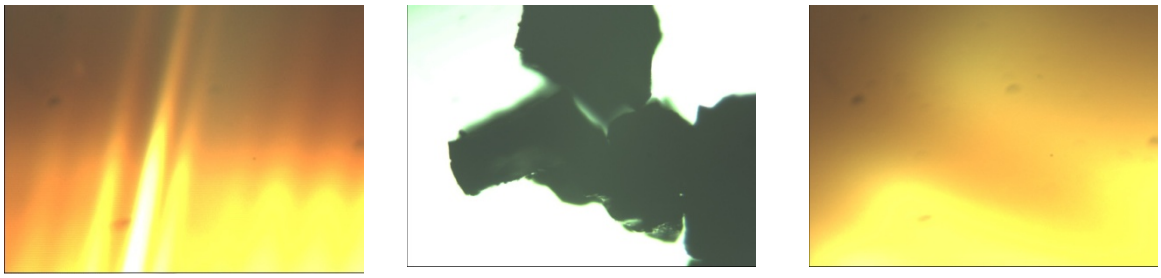


FIGURE 1 Iatroscan Thin Film Chromatography analysis.

Polarized Light Microscopy

Polarized light microscopy (PLM) is a useful method to determine qualitative and quantitative aspects of crystallographic axes and stress concentrations present in various materials (*9*). This technique can also distinguish between isotropic and anisotropic substances. It exploits the optical properties specific to anisotropy and reveals detailed information concerning the structure and composition of materials that are invaluable for identification purposes.

Figure 2 shows a PLM analysis of the binder, asphaltenes and maltenes. The variety of colors observed in the binder sample demonstrate the presence of different components. The green color observed in the asphaltene sample shows the highest stress concentration (harder material) of this component and the lighter colors observed in the maltene sample shows the lowest stress (softer) components. Figure 3 illustrates the effect of aging on the stress concentration of the samples. For instance, the red-brown tone almost disappeared at RTFO and PAV stages and the green (higher stress) tone started to show up, providing evidence that some of the resins and oils were transformed into asphaltene-like substances due to aging.



Original binder | Original Asphaltenes | Original Maltenes

FIGURE 2 Polarized light microscopy analysis of original (unaged) samples

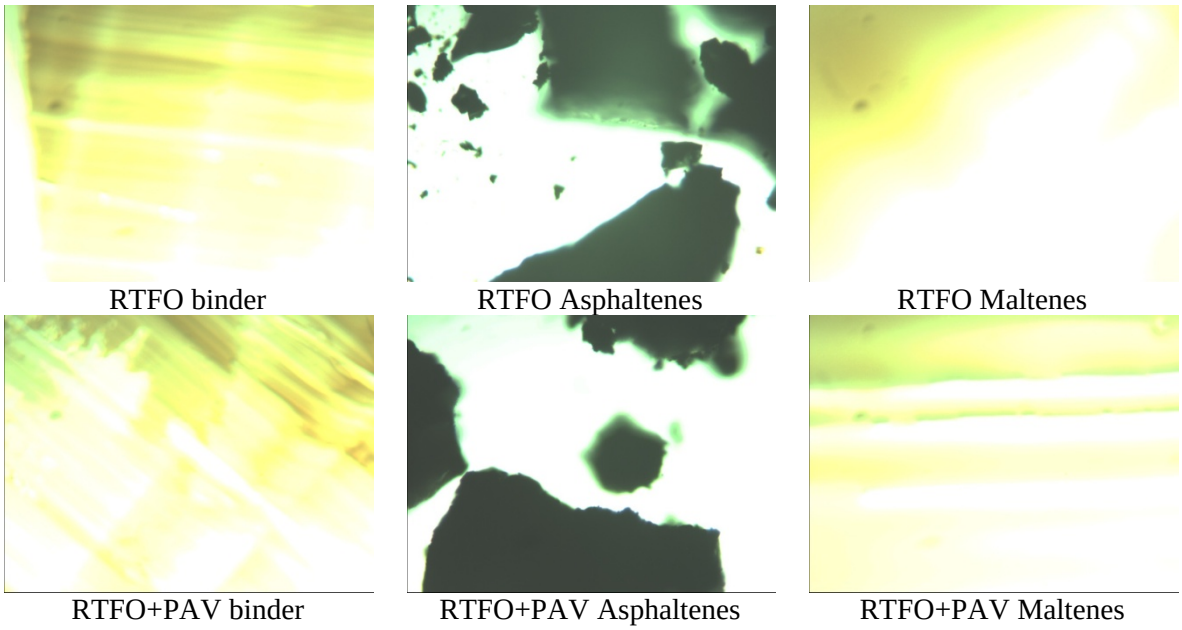


FIGURE 3 Polarized light microscopy analysis of aged samples

RHEOLOGICAL CHARACTERIZATION

The binder characterization was performed following the Superpave methodology for the original bitumen, the short term aged bitumen (RTFO) and the long term aged bitumen (RTFO+PAV). The dynamic shear rheometer was used to measure the complex shear modulus (G*), storage modulus (G'), the loss modulus (G'') and phase angle (δ) of the binder samples in accordance to AASHTO T 315. Table 1 shows the Superpave characterization of the binder which resulted in a PG 64 with an intermediate temperature of 19 °C.

TABLE 1 Performance Grade Results

Condition	|G*| (Pa)	G' (Pa)	G'' (Pa)	G''/G'	δ, degrees	|G*|/sin(δ)
Original 64 °C	1974	164,6	1968	11.96	85.22	1.981
RTFOT 64 °C	5335	884,9	5261	5.95	80.45	5.41
PAV 19 °C	6749000	5157000	4353000	0.84	40.17	4353

The binder used in this study was fractionated into two components - asphaltenes which correspond to 14.1% and maltenes which correspond to the remaining 85.9%. Table 2 shows the results of the DSR tests performed on the binder and the two individual components. In this case a 40 mm plate was used to obtain the complex shear modulus and phase angle. The testing was performed with the same plate for all the stages so the test could be performed on the maltenes and to be able to compare results under the same testing conditions. As expected, the results indicated that with aging the complex modulus, storage modulus and the loss modulus of the binder increase while the phase angle decreases. In other words, aging causes the mechanical properties of the asphalt binder to resemble those of a solid.

Also ss expected, maltenes had lower G* values, higher phase angles, higher G''/G' ratios and lower |G*|/sin(δ) values than the asphalt binder since they account for the majority of the viscous component of the binder at 25 °C. On the other hand, for asphaltenes these four parameters had the opposite behavior compared to maltenes confirming that asphaltenes account for the majority of the elastic component of the binder at 25 °C. When testing at 64 °C a significant decrease in the G''/G' ratio and the phase angle of the maltenes was obtained for all three aging stages. This unexpected behavior was attributed, at this point, to the low viscosity of the maltenes at high temperatures and the limitation of the DSR plate to provide reliable results at such a low viscosity. On the other hand, asphaltenes started to perform more as viscous material with a G''/G' ratio over 1.0. Moreover, they showed a significantly higher phase angle which was closer to the angle obtained for the original binder at the same temperature.

TABLE 2 Rheological analysis of the binder and its individual components

Condition	|G*| (Pa)	G' (Pa)	G'' (Pa)	G''/G'	δ, degrees	|G*|/sin(δ)
Asphalt binder analysis at 25°C						
Original	469500	100600	458600	4.56	77.63	480.7
RTFT	898500	306900	844400	2.75	70.03	956
PAV	1190000	735300	935000	1.27	51.82	1513
Maltenes analysis at 25°C 25°C						
Original	1465	198.6	1451	7.31	82.21	1.478
RTFOT	683.1	174.5	660.5	3.79	75.2	0.7065
PAV	427.9	147.7	401.6	2.72	69.81	0.4559
Asphaltenes analysis at 25°C						
Asphaltenes	1358000	1350000	142500	0.11	6.025	12930
Asphalt binder analysis 64°C						
Original	994.3	203.6	973.2	4.78	78.18	1.016
RTFT	2986	624.1	2920	4.68	77.94	3.054
PAV	9929	3241	9385	2.9	70.95	10.5
Maltenes analysis at 64°C						
Original	161.4	155.9	41.72	0.27	14.98	0.6243
RTFOT	129.5	122.2	43.01	0.35	16.12	0.3901
PAV	109.3	98.93	46.46	0.47	25.15	0.2571
Asphaltenes analysis at 64°C						
Asphaltenes	19190	9906	16440	1.66	58.93	22.41

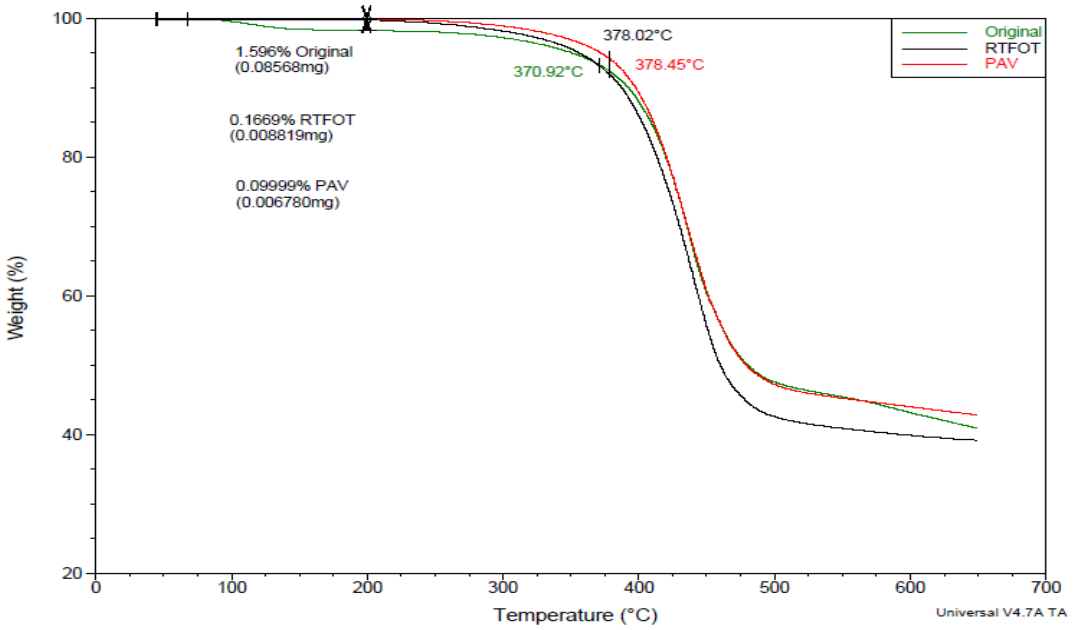
THERMOGRAVIMETRIC ANALYSIS

TGA is a method of thermal analysis in which changes in physical and chemical properties of materials are measured as a function of increasing or decreasing temperature cycles (with constant heating rate), or as a function of time (with constant temperature and/or constant mass loss) (*10*). TGA is commonly used to determine selected characteristics of materials that exhibit either mass loss or gain due to decomposition, oxidation, or loss of volatiles. As shown in Figure 4, the mass loss of asphaltenes decreased when going from the original (unaged) stage to the highest aging

stage. Besides, the lowest temperature of decomposition was observed for the asphaltenes at the original condition (370 ºC) while asphaltenes at RTFO and PAV presented similar decomposition values and significantly higher than the original condition (378 ºC) indicating that the samples had high stability specially below 200 °C.

The test results evidenced that maltenes were also highly stable below 200 °C, however, the mass loss was significantly higher at any aging stage than the asphaltenes. This behavior can be attributed to volatilization or evaporation of the lighter components found in the maltenes. Another significant finding was observed for the decomposition temperature of the maltenes which was about 8% lower than the asphaltenes.

(a)



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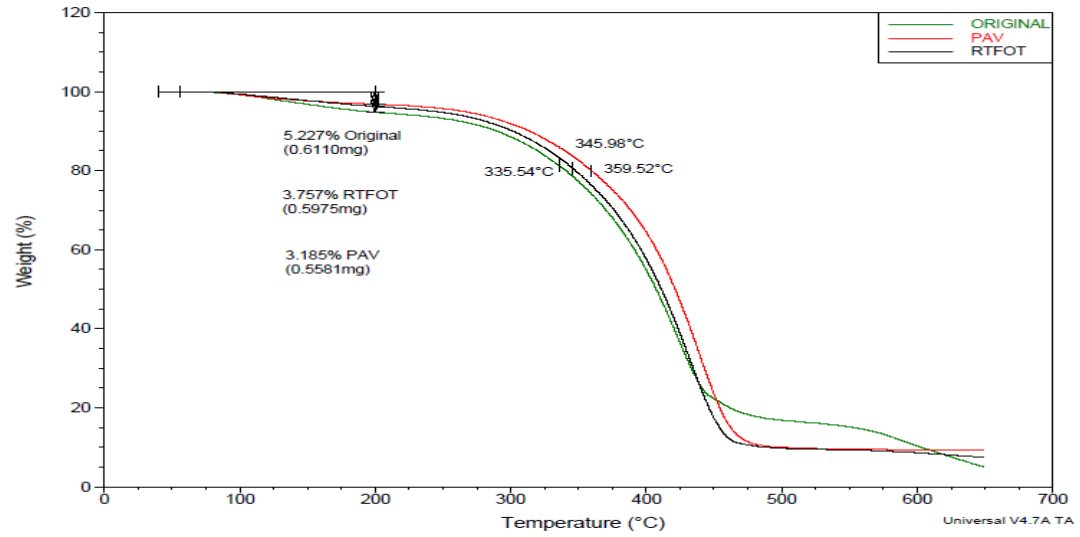


FIGURE 4 Thermo gravimetric analysis (a) asphaltenes, (b) maltenes.

DIFFERENTIAL SCANNING CALORIMETRY ANALYSIS

DSC is widely used for determination of thermal transitions brought about by the first order transitions, such as melting and crystallization of crystallizable species (*11*). Glass transition, Tg, credited as a second order phenomenon taking place in the amorphous region of the sample, can be also defined by DSC, but it depends largely on the nature of the material and its content of crystallizable fractions. Below the glass transition temperature, asphalt behaves like a glass and appears brittle.

DSC analysis was performed to observe sample behavior due to the change on temperature in a range from -50°C up to 200°C. Based on the data collected by the DSC analysis, the glass transition temperature (Tg) was determined when possible. Figure 5 shows how the original asphalt presents a couple of secondary transition (softening) zones between -28 and -23 °C and -0.4 and 8.9 °C due to molecular rearrangement. For the RTFO and PAV stages, secondary transition zones were found at significantly higher temperatures compared to the unaged stage, however, between RTFO and PAV the temperature range for these zones was not significantly different.

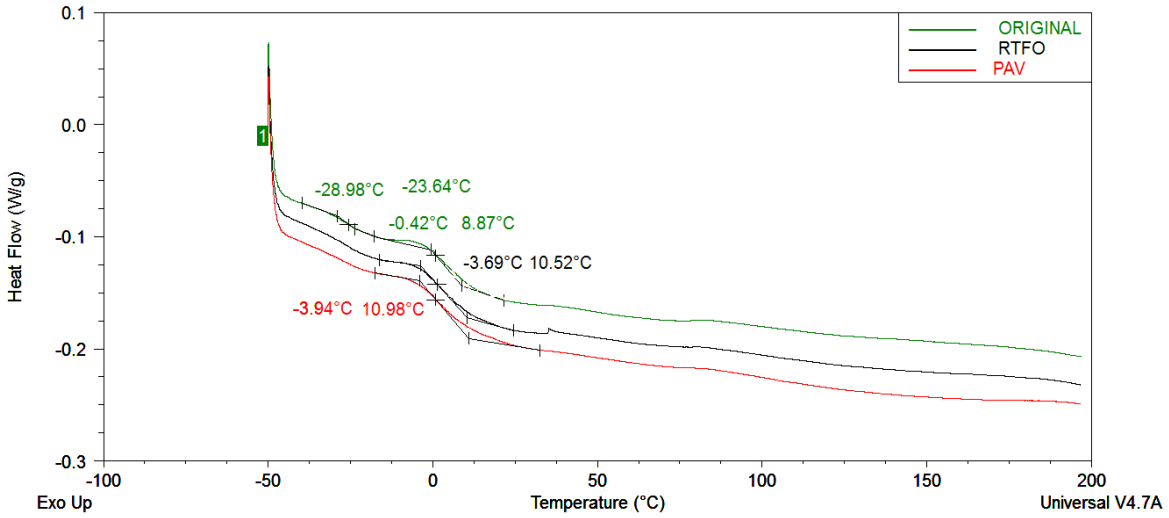


FIGURE 5 DSC Analysis of original asphalt.

When analyzing the asphaltenes at the unaged and RTFO stages an endothermic behavior was observed at 1.6 and 19.4 °C due to molecular rearrangement (Figure 6). On the other hand, an exothermic phenomenon, similar to crystallization, was observed for the RTFO and PAV stages of the asphaltenes at high temperatures also due to molecular rearrangement. This behavior could be correlated to the Superpave intermediate performance temperatures and could help explain fatigue cracking performance.

Maltenes were the only samples that showed glassy transitions as illustrated in Figure 7. In the unaged stage the glassy temperature (Tg) was found to be between -4.5 and 4.9 °C while at the RTFO the Tg ranged from -24.7 to -21.5 °C and it became even lower at the PAV stage with values between -35.8 to -26.12 °C. A decrease in the Tg values as the aging of the maltenes increases explains the unexpected decrease in the complex shear modulus because, as observed with the DSC analysis, aged maltenes tended to flow (became softer) at lower temperatures.

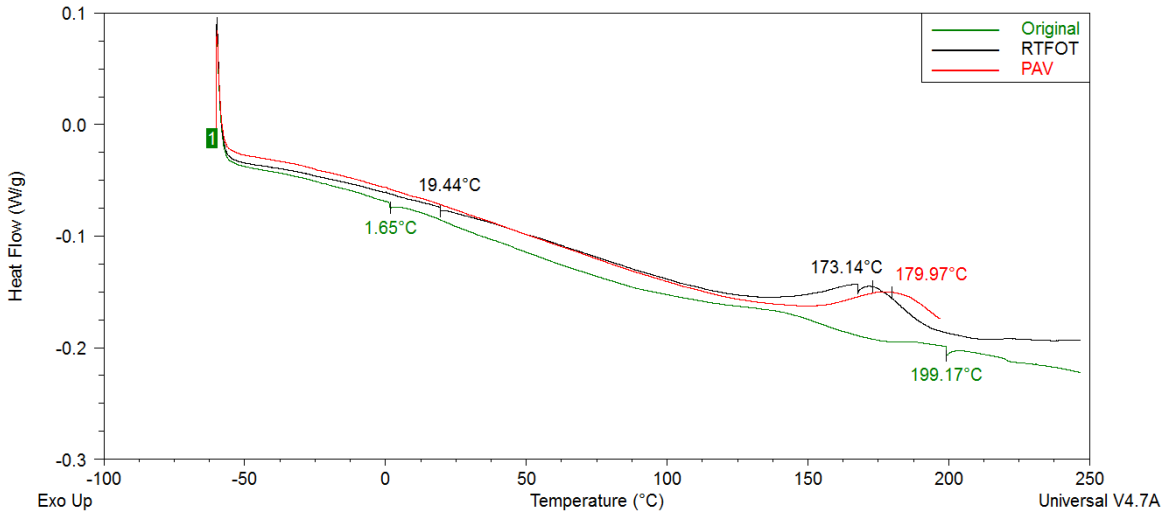


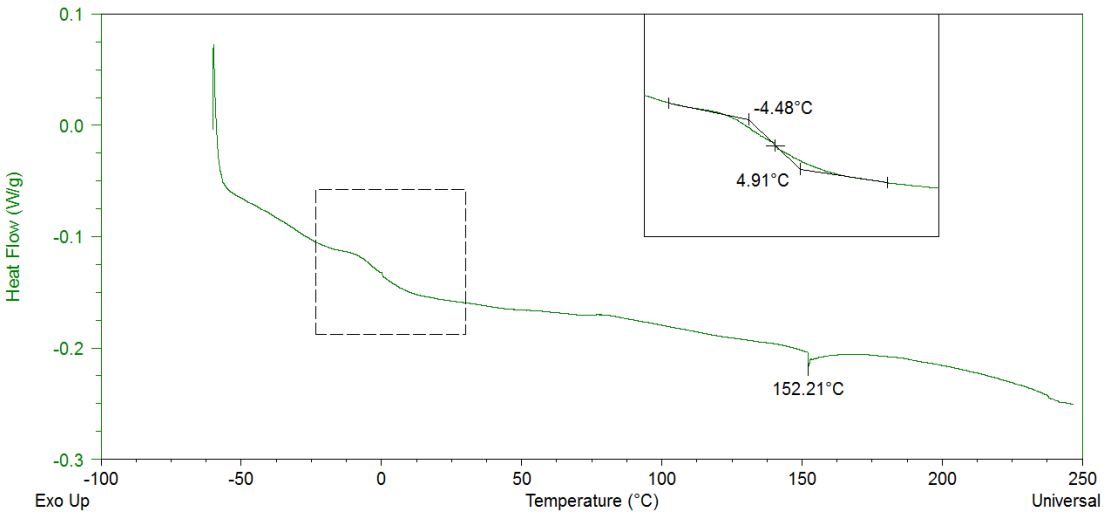
FIGURE 6 DSC Analysis of asphaltenes.

FOURIER TRANSFORM INFRARED SPECTROSCOPY ANALYSIS

FTIR is a technique used to identify and quantify amounts of known and unknown materials (*12*). In this technique, infrared radiation is passed through a sample; some of this radiation is absorbed by the sample and some of it is passed through (transmitted). The resulting spectrum represents the molecular absorption and transmission, creating a molecular fingerprint of the sample (*13-15*).

Figure 8 shows the FTIR spectrums for the binder and its two studied components at the unaged stage. The characteristic bands for the different phases were summarized on Table 3. The differences in the singular components of the asphalt binder are highlighted with respect to the neat asphalt binder. The asphaltenes correspond to a large fraction of complex polar aromatic compounds that are highly insoluble in paraffinic solvents such as *n*-heptane and are solid at room temperature. Because of the type of interactions they present bands typical of the asphalt binder. Additionally, because of the separation process, the sample may be contaminated with other phases due to the string interactions with other components.

(a)



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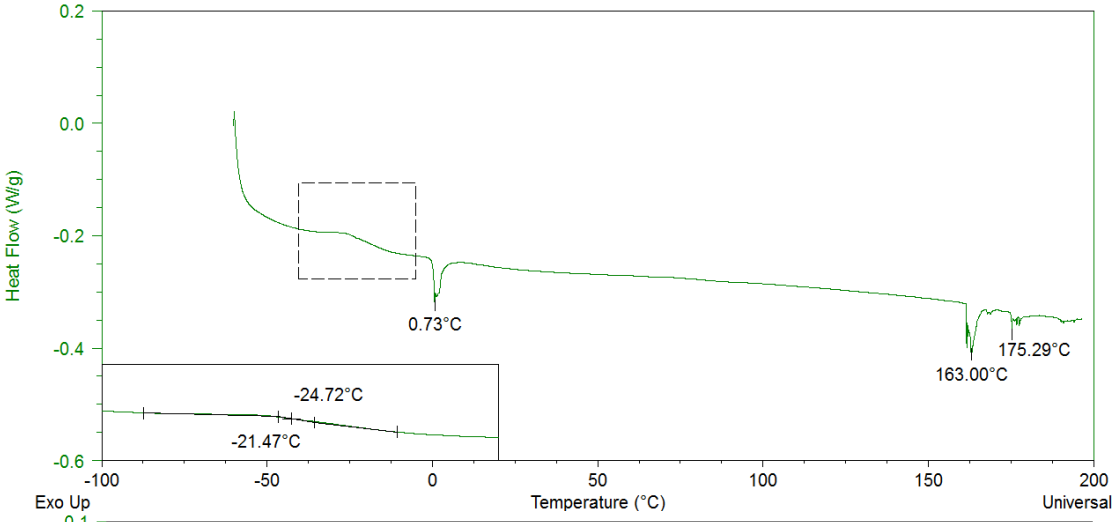

(c)

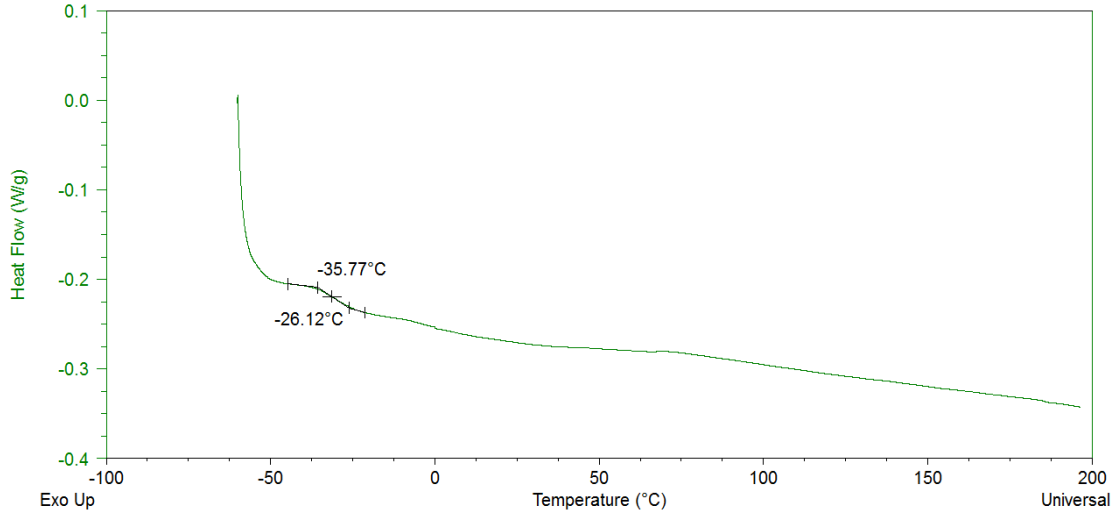

FIGURE 7 DSC Analysis of maltenes (a) original, (b) RTFO, (c) PAV.

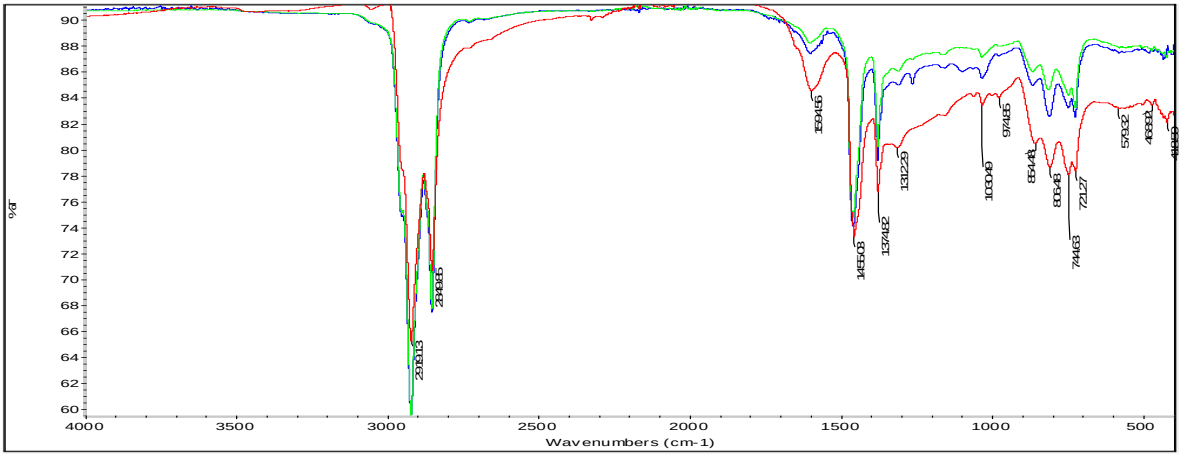

FIGURE 8 FTIR analysis of unaged samples. (Blue = binder, Red = asphaltenes, Green = maltenes).

TABLE 3 FTIR Analysis of unaged samples

Wavelength (cm^{-1})	Asphalt Binder	Asphaltenes	Maltenes
2851- 2920	High intensity band of CH_2 and CH_3 groups (*Saturated hydrocarbons*)	High intensity band of CH_2 and CH_3 groups (*Saturated hydrocarbons*)	High intensity band of CH_2 and CH_3 groups (*Saturated hydrocarbons*)
1600	Low intensity band of C=C (Ar) (*Aromatic hydrocarbons*)	Medium intensity band of C=C (Ar) (*Aromatic hydrocarbons*) **intensified**	Low intensity band of C=C (Ar) (*Aromatic hydrocarbons*)
1500	Medium intensity band of C=C (Ar) (*Aromatic hydrocarbons*)	Medium intensity band of C=C (Ar) (*Aromatic hydrocarbons*)	Medium intensity band of C=C (Ar) (*Aromatic hydrocarbons*) **Lower intensity - possibly combined with 1460 cm^{-1} band**
1450	Medium intensity band of CH_2 and CH_3 groups (*Saturated hydrocarbons*)	Medium intensity band of CH_2 and CH_3 groups (*Saturated hydrocarbons*)	Medium intensity band of CH_2 and CH_3 groups (*Saturated hydrocarbons*)
1340	Medium intensity band of C-N (*Aromatic Amines*)	Medium intensity band of C-N (*Aromatic Amines*)	Medium intensity band of C-N (*Aromatic Amines*)
1170	Low intensity band of R-O-Ar (*Alkyl aryl ethers*)	Low intensity band of R-O-Ar (*Alkyl aryl ethers*)	Low intensity band of R-O-Ar (*Alkyl aryl ethers*)
1030	Low intensity band of R-O-Ar (*Alkyl aryl ethers*)	Low intensity band of R-O-Ar (*Alkyl aryl ethers*)	Low intensity band of R-O-Ar (*Alkyl aryl ethers*)
750	Low intensity band of C-H meta (*Aromatic compounds*)	Low intensity band of C-H meta (*Aromatic compounds*) **lower intensity**	Low intensity band of C-H meta (*Aromatic compounds*) **Higher intensity**
720	Low intensity band of C-H para (*Aromatic compounds*)	Low intensity band of C-H para (*Aromatic compounds*) **lower intensity**	Low intensity band of C-H para (*Aromatic compounds*) **Higher intensity**

(*) The comments in **bold** are with respect to the neat asphalt binder.

The asphalt binder presented physical and chemical changes when subjected to a thermal oxidative process. This can be caused by the loss of volatiles or specimens of low molecular weight, or even by the formation of hydrogen bonds. The groups typically formed asphalt binders upon aging are carboxylic acids (-COOH), ketones (C-CO-C**)** , sulfoxides (R–SO–R) and anhydrides (C-O-C) (*16*). These oxidation products form polar groups with strong interaction increasing viscosity and changing flow properties. An increase in the intensity and appearance of different bands from 805 to 1260 cm^{-1} due to oxidation (anhydrides) can be seen in Figure 9. The characteristic bands for the two aging conditions were summarized on Tables 5 and 6 for the binder and its individual

components. Evidence of asphaltenes and maltenes oxidation was only present for the PAV samples at 1700 cm^{-1} which relates directly to oxygen content (*17*). On the other hand there was a small change in the intensity of different bands from 805 to 1260 cm^{-1} that could be related to oxidation for maltenes at RTFO and PAV conditions.

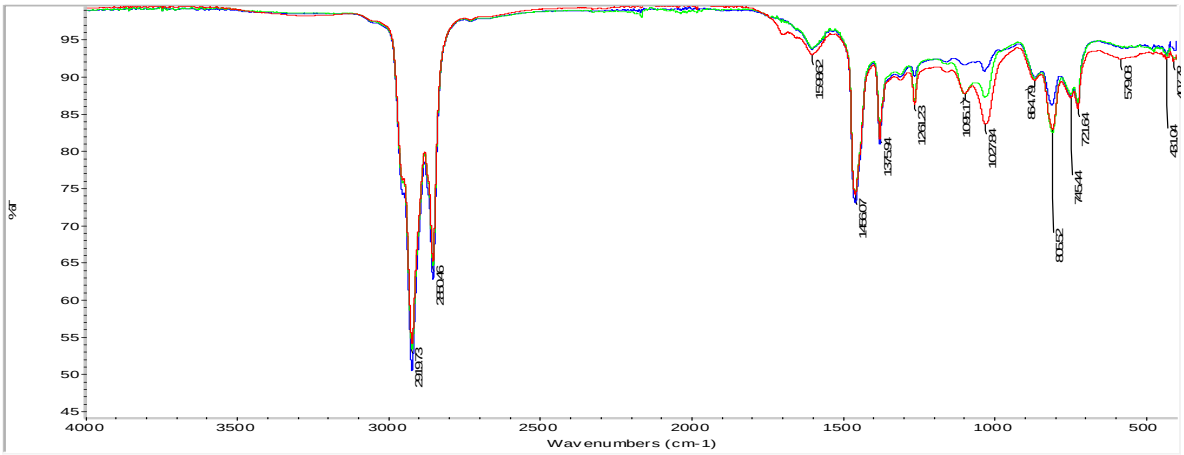

FIGURE 9 FTIR Analysis of the asphalt binder. (Blue = unaged, Green = RTFO, Red = PAV).

TABLE 4 FTIR Analysis of RTFO samples

Wavelength (cm^{-1})	Binder	Asphaltenes	Maltenes
1600	-	Medium intensity band of C=C (Ar) (*Aromatic hydrocarbons*) **intensified**	Low intensity band of C=C (Ar) (*Aromatic hydrocarbons*) **Highly reduced**
1500	-	Medium intensity band of C=C (Ar) (*Aromatic hydrocarbons*) **possibly combined with 1460 cm^{-1} band**	-
1260	Low intensity band of R-N-O Nitrogen oxidation **New band**	Medium intensity band of R-N-O	Medium intensity band of R-N-O. **Not present**
1070	Low intensity band of R-O-R (*ethers*) **New band**	-	-
1030	Low intensity band of R-O-Ar (*Alkyl aryl ethers*) **Significant Increment**	Low intensity band of R-O-Ar (*Alkyl aryl ethers*)	Low intensity band of R-O-Ar (*Alkyl aryl ethers*)
805	Medium intensity band of C-H meta **Significant Increment**	-	-

(*) The comments in **bold** are changes with respect to the unaged samples.

TABLE 5 FTIR analysis of PAV samples

Wavelength (cm^{-1})	Neat Asphalt Binder	Asphaltenes	Maltenes
1700	Low intensity band of RRC=O (carbonyls) **New band**	Low intensity band of RRC=O (carbonyls) **New band**	Low intensity band of RRC=O (carbonyls) **New band**
1600	-	Medium intensity band of C=C (Ar) (*Aromatic hydrocarbons*) **intensified**	Low intensity band of C=C (Ar) (*Aromatic hydrocarbons*) **Significant reduction**
1500	-	Medium intensity band of C=C (Ar) (*Aromatic hydrocarbons*) **Increment**	Medium intensity band of C=C (Ar) (*Aromatic hydrocarbons*) **Not Present**
1450	-	Medium intensity band of CH_2 and CH_3 groups (*Saturated hydrocarbons*) **Increment**	-
1340	-	-	Medium intensity band of C-N (*Aromatic Amines*) **Significant reduction**
1260	Low intensity band of R-N-O Nitrogen oxidation **Higher intensity**	Medium intensity band of R-N-O **Not present**	Medium intensity band of R-N-O. **Not present**
1170	-	-	Low intensity band of R-O-Ar (*Alkyl aryl ethers*) **Not present**
1070	Low intensity band of R-O-R (*ethers*) **New band**	Low intensity band of R-O-R (*ethers*) **New band**	-
1030	Low intensity band of R-O-Ar (*Alkyl aryl ethers*) **Significant increment**	Low intensity band of R-O-Ar (*Alkyl aryl ethers*) **Significant increment**	Low intensity band of R-O-Ar (*Alkyl aryl ethers*) **Significant reduction**
805	Medium intensity band of C-H meta **Significant Increment**	Medium intensity band of C-H meta **Significant Increment**	-
750	-	-	Low intensity band of C-H meta (*Aromatic compounds*) **Decreased**
720	-	-	Low intensity band of C-H para (*Aromatic compounds*) **Decreased**

(*) The comments in **bold** are changes with respect to the unaged samples.

CONCLUSIONS

Based on the results of this study the following conclusions were reached:

- At intermediate temperatures asphaltenes account for the majority of the elastic component of the complex shear modulus of the asphalt binder while maltenes account for the majority of the viscous component. However, at high temperatures it is not clear which component is responsible for either the elastic or viscous behavior of the binder.
- With aging, the amount of asphaltenes in the binder showed the lowest change in composition (highest stability) followed by the saturated fraction while the composition of aromatics and resins seemed to interchange with each other.
- Polarized Light Microscopy is a simple technique that can be implemented to help explain changes in stress states or changes in composition of bituminous materials. This technique provided evidence that some of the resins and oils were transformed into asphaltene-like substances due to aging.
- Thermal stability of the asphalt binder can be attributed mostly to the higher stability of the asphaltenes at normal handling temperatures of the asphalt (below 200 °C).
- For the RTFO and PAV conditions, secondary transition zones were found at significantly higher temperatures (close to ambient temperatures) compared to the unaged stage that could be correlated to the Superpave intermediate performance temperatures and could help explain fatigue cracking performance.

- With aging, the thermodynamic behavior of the maltenes, as demonstrated by their glassy transition behavior, was directly correlated to their rheological performance.
- The higher stability of asphaltenes is responsible for the lower change in composition as observed by the Iatroscan Thin Film Chromatography analysis, and also responsible for the lower susceptibility to oxidation.
- Overall, there is clear evidence that aging of the asphalt binder components has an effect on the morphology of the asphalt binder.

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