Characterization of Unmodified and SBR Latex-Modified Evotherm® Warm Mix Binder

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Acknowledgements

We acknowledge Jonathan MacIver and Everett Crews of MeadWestvaco for continuous discussion, and Cathy Willis, Margaret Clark and William Kirk of BASF Corporation for conducting experiments.

ABSTRACT

The Evotherm® warm mix process developed by MeadWestvaco is the direct substitution of asphalt binder with a cationic asphalt emulsion. Field trials by McAsphalt in Canada have demonstrated a 30°C and 60°C reduction in the mixing and compaction temperatures, respectively, when compared to conventional hot mix using the same aggregate and asphalt.

A procedure to recover the representative emulsion residue for the Evotherm® warm mix system was developed. Here, approximately 80g of Evotherm emulsion is poured into a Thin-Film Oven Test (TFOT) pan and dried in a forced air oven at 80°C for 20 hours. Results of conventional and Superpave binder characterization testing demonstrate that the recovery procedure developed here closely simulates the heat history that the Evotherm® emulsion is exposed to during mixing and paving in the field and further indicate that pavement constructed using unmodified Evotherm® warm mix binder after 10-15 years of in-service life would be as flexible as freshly-placed conventional hot mix pavement. The polymer network formed in the SBR latex-modified Evotherm® residue does not prevent oxidation of the asphalt binder, but rather reduces the net effect of undesired changes in rheological properties of the asphalt binder upon age or oxidative hardening. Thus, modification with SBR latex polymer is expected to further prolong the service life of the Evotherm® warm mix asphalt pavement.

RÉSUMÉ

Le procédé d'enrobés chauds Evotherm® développé par MeadWestvaco est la substitution directe du bitume par une émulsion cationique de bitume. Des essais en chantier par McAsphalt au Canada ont démontré une réduction respective de 30°C et 60°C des températures de malaxage et de compactage comparé à l'enrobé à chaud conventionnel utilisant le même granulat et bitume.

Un procédé pour récupérer le résidu représentatif de l'émulsion de l'enrobé chaud Evotherm® a été développé. Ici, environ 80g d'émulsion Evotherm est versé dans le récipient de l'essai d'étuvage en feuil mince (TFOT) et séché pendant 20 heures. Les résultats des essais de caractérisation du liant conventionnel et Superpave montrent que le procédé de récupération développé ici simule de près l'histoire de chaleur que l'émulsion Evotherm® subit durant le malaxage et la pose en chantier et indique aussi que le revêtement construit avec le liant d'enrobés chauds Evotherm® non modifié serait après 10-15 ans de service aussi flexible qu'un revêtement bitumineux conventionnel fraîchement posé. Le réseau de polymère formé dans le résidu Evotherm® modifié au latex SBR n'empêche pas l'oxydation du bitume, mais réduit plutôt l'effet net des changements non désirés des propriétés rhéologiques du bitume avec l'âge ou le durcissement par oxydation. Ainsi, on s'attend qu'une modification avec polymère au latex SBR prolonge la durée de service du revêtement d'enrobé bitumineux chaud Evotherm®.

1.0 INTRODUCTION

Conventional asphalt mixes are generally heated to 150°C or greater at the hot mix plant and subsequently compacted at around 140°C. There have been several new technologies developed to reduce the mixing and compaction temperatures of conventional hot mix asphalt. These new processes are collectively known as warm mix asphalt and reduce the mixing temperature by at least 25°C [1-3]. Lower hot mix plant and compaction temperatures result in a reduction in fuel consumption, lower emissions, and reduced heat and age hardening of the asphalt binder.

Currently there are four processes being evaluated in North America:

Sasobit® by Sasol International
Aspha-min® zeolite by Eurovia (Hubbard Group)
WAM Foam® by Shell and Kolo Veidekke
Evotherm® by MeadWestvaco

Sasobit® is a synthetic wax of higher melting point with carbon chain length ranging from C_{45} to C_{100} plus [4]. It is described as an "asphalt flow improver, both during the asphalt mixing process and during laydown operation, but still maintains the original viscosity at the in-service pavement temperatures. Typically the mixing and compaction temperatures can be lowered 15-20°C". Sasobit® reportedly forms a crystalline network structure in the binder that leads to added stability.

Aspha-min® and WAM Foam® are based on foamed asphalt technology [5]. Aspha-min® is composed of a hydrated zeolite that contains approximately 20 percent water by weight. This water is released under high temperature when it is added into the aggregate-asphalt mix and causes the asphalt cement to foam while mixing with the aggregate.

WAM Foam® is similar to Aspha-min®. However, it is based on a two-component binder system in which a soft binder is used in conjunction with a foamed hard binder during the mixing stage [6]. The soft binder is mixed with the aggregate at a lower temperature and then a hard asphalt based emulsion is added to induce foaming. The foaming action imparts workability to the mix at lower temperatures.

The steam in the foamed asphalt would condense to form fine water droplets in the asphalt below 100°C, which would cause a sharp reduction in the workability of the Aspha-min® and WAM Foam® systems. These fine water droplets would remain trapped within the bulk asphalt and could migrate to the asphalt-aggregate interface. An anti-stripping agent would then be needed to prevent premature asphalt stripping with these foam-based processes.

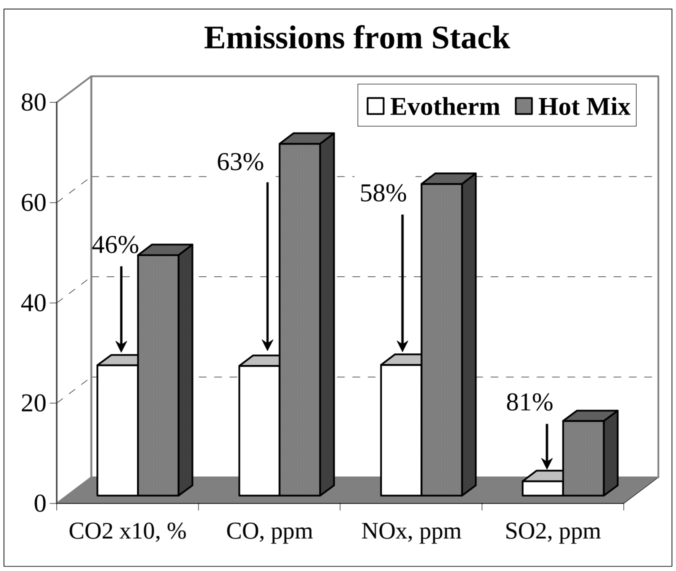
The Evotherm® process developed by MeadWestvaco is the direct substitution of asphalt binder with a cationic asphalt emulsion [7]. The base asphalt, mix production, and laydown operation remain the same. The process can be best understood as the traditional asphalt emulsion based cold mix system using warm aggregate. The thin water film between the aggregate and asphalt droplets improves workability of the mix down to temperatures below 90°C during the paving operation (much like a curling stone slides on the ice). This is supported by observations during field trials conducted by McAsphalt: (i) The truck box was very clean after the Evotherm® mix was dropped into the paver hopper, (ii) The mix flowed out of the truck the same as conventional hot mix and there was no evidence of the mix agglomerating due to the lower temperature, and (iii) The Evotherm® warm mix laid and compacted just like hot mix asphalt.

The thin water film also exerts as much as 10 MPa of capillary pressure that promotes quick coalescence of the asphalt droplets during curing after compaction. The positively charged head groups of the cationic emulsifiers in the Evotherm® emulsion adsorb onto the aggregate surface and expose their hydrocarbon tails towards the water phase. This makes the aggregate surface oil-wet to promote strong asphalt adhesion for improved moisture resistance. The lower viscosity of the Evotherm® asphalt binder at elevated temperature (approximately 1000x reduction at 80°C when compared with the viscosity at 25°C) also ensures quick coalescence of the asphalt droplets. This allows the mix to develop to its final strength in only a few hours instead of a few weeks to a month when compared with the conventional asphalt emulsion cold mix system.

2.0 EVOTHERM® FIELD TRIALS BY MCASPHALT

2.1 Plant Production

Comprehensive reports have been issued on Evotherm® trials at Aurora, Ontario on August 8, 2005 [8], City of Calgary on September 28, 2005 [9] and Ramara Township Road 46 on October 4 and 5, 2005 [10]. Both conventional hot mix and Evotherm® warm mix systems were compared side-by-side using the same asphalt and aggregate for all three trials. The trial at Ramara Township also included plant stack gas testing to determine whether or not the Evotherm® warm mix system produced less emissions than a conventional hot mix system. Ramara Township trial details are summarized in Figure 1.



McAsphalt Trial in Oct. 4-5, 2005

	Plant Production		
	Aggregate	Asphalt	Compaction
Hot Mix	155°C	155°C	140°C
Evotherm	125°C	*95°C	90°C

* Emulsion temperature

	Av. Stack Gas Temperature
Hot Mix	162°C
Evotherm	121°C

	Fuel Oil Consumption Litres/Tonne
Hot Mix	11.4
Evotherm	5.2

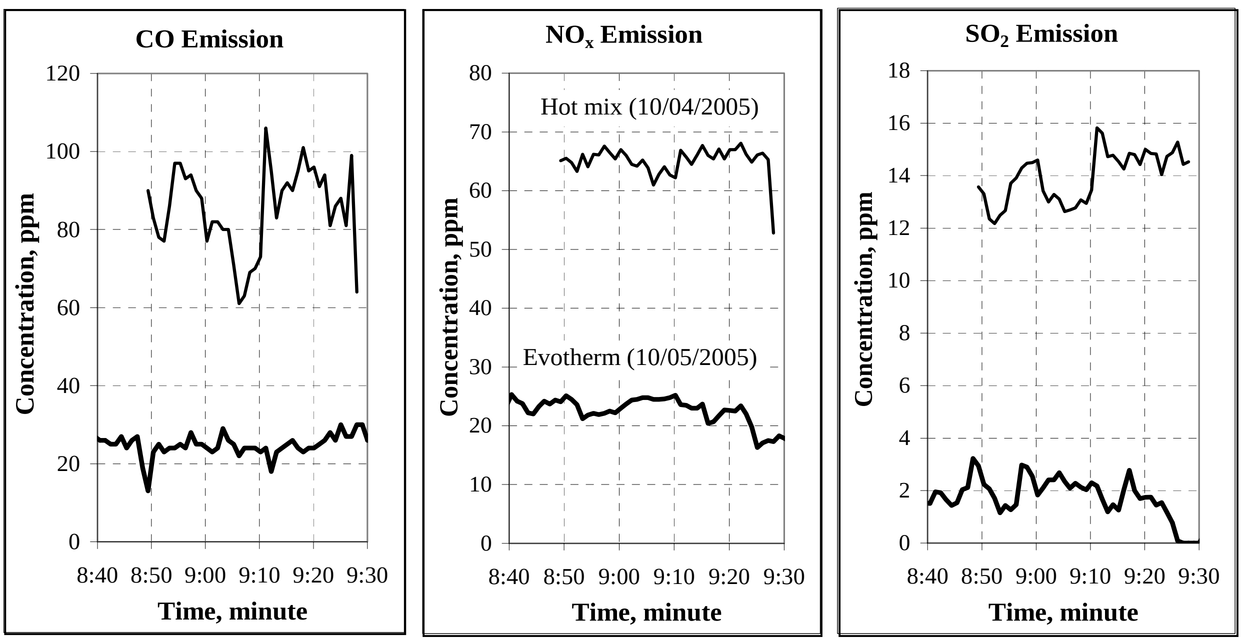
Note: CO2 is Carbon Dioxide, CO is Carbon Monoxide, NOx is Nitrogen Oxide and SO2 is Sulphur Dioxide.

Figure 1. Summary of Evotherm® and Hot Mix Plant Production at Ramara Township [10]

For the control hot mix system, PG 58-28 base asphalt maintained at 150 to 155°C in the storage tank was mixed with aggregate heated at 150 to 155°C. The jobsite was approximately 15 km from the plant (20 minute truck haul). This resulted in a temperature at the paver of 145°C for the hot mix system. Alternatively, the Evotherm® warm mix emulsion was maintained at a temperature of 93 to 95°C and mixed with aggregate at 125 to 130°C. This resulted in a mix discharge temperature of only 93°C and a field compaction temperature of only 85°C.

Because of the reduction in asphalt-aggregate mixing temperature realized with the Evotherm® warm mix system, the average stack gas temperature was only 121°C, 41°C cooler than the conventional hot mix system. The reference average stack gas volumetric flow rate was 8.92 Rm^3/s vs. 9.44 Rm^3/s, respectively, for the Evotherm® warm mix and conventional hot mix systems (ref. conditions of 25°C, 101 kPa). The reduction in mixing temperature also translated to a significant savings in fuel oil consumption from 11.4 litres/tonne for hot mix to 5.2 litres/tonne for Evotherm® warm mix.

Stack gas analysis showed more than a 50 percent reduction in average combustion gas, CO, NO_x and SO_2, emission levels. This is to be expected for the Evotherm® warm mix system based on the significantly lower mixing temperature and reduced fuel oil consumption level. This reduction in combustion gas emissions is clearly seen when viewing the real-time, continuous emissions monitoring data from the Ramara Township trial shown in Figure 2.

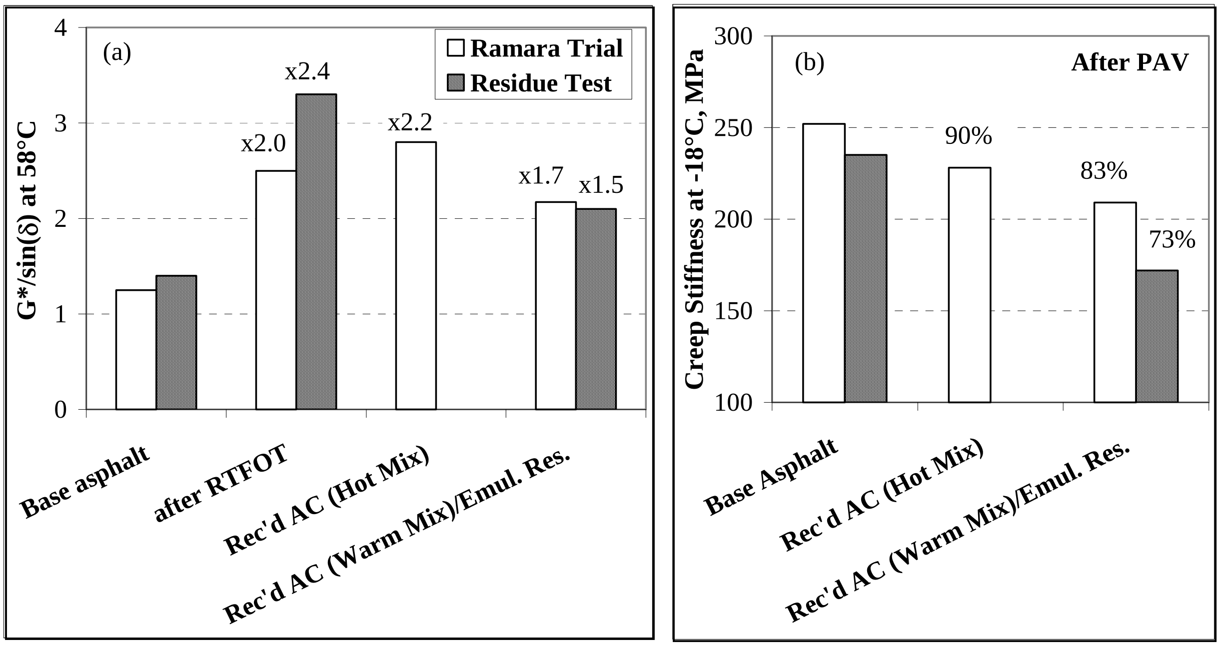


Note: CO is Carbon Monoxide, NOx is Nitrogen Oxide and SO2 is Sulphur Dioxide.

Figure 2. Stack Gas Emission Data for Hot Mix and Evotherm Trial at Ramara Township

2.2 Core Analysis

Asphalt cement was also recovered from field core samples to examine the extent of aging that the hot mix and Evotherm® warm mix binders were exposed to during production and laydown. The PG 58-28 base asphalt had a penetration value of 124 dmm (25°C, 100g, 5s). The penetration value of the recovered asphalt cement from the hot mix core was 81 dmm; 63 percent of the original value. This reduction is caused by increased heat aging encountered during hot mix production and field application.



Note: RTFOT is Rolling Thin Film Oven Test, AC is Asphalt Cement, and PAV is Pressure Aging Vessel.

Figure 3. Superpave binder characterization of the base and recovered asphalt cement from core samples taken during the Ramara Township Trial are compared against the recovered Evotherm® warm mix emulsion residue using the procedure developed in this study.

Results of Superpave binder characterization of the base and recovered asphalt cement from the hot mix and Evotherm® warm mix core samples are summarized in Figure 3. The measured G*/sin(δ) value of the base asphalt was 1.3 kPa at 58°C and increased to 3.0 kPa after RTFO-aging, which simulates heat aging of the asphalt binder during the mixing process. The measured G*/sin(δ) values of the recovered asphalt binder from the field core samples were 2.8 and 2.2 kPa for the hot mix and Evotherm® warm mix systems, respectively. Results again confirm that the Evotherm® binder experiences a lesser degree of heat aging during the mixing process. Superpave fatigue and cold fracture resistance {G*×sin(δ)<5 MPa and creep stiffness,S<300 MPa} data determined by Dynamic Shear Rheometry (DSR) and Bending Beam Rheometry (BBR) also indicate that the Evotherm® binder does not age harden as much as conventional hot mix binder even after accelerated aging in the Pressure Aging Vessel (PAV).

3.0 RECOVERY PROCEDURE FOR EVOTHERM WARM MIX BINDER

3.1 Overview and Heat History

It has been successfully demonstrated in the past that a latex-modified asphalt emulsion is not an emulsion of polymer-modified asphalt, but rather an emulsion containing dispersed latex particles in the aqueous phase [11] as shown in Figure 4. Menisci of water containing latex polymer particles form between asphalt droplets when water starts to evaporate from the asphalt emulsion. The latex particles continue to migrate together with the water, accumulate at the menisci, and eventually transform to a continuous polymer honeycomb structure surrounding the asphalt particles.

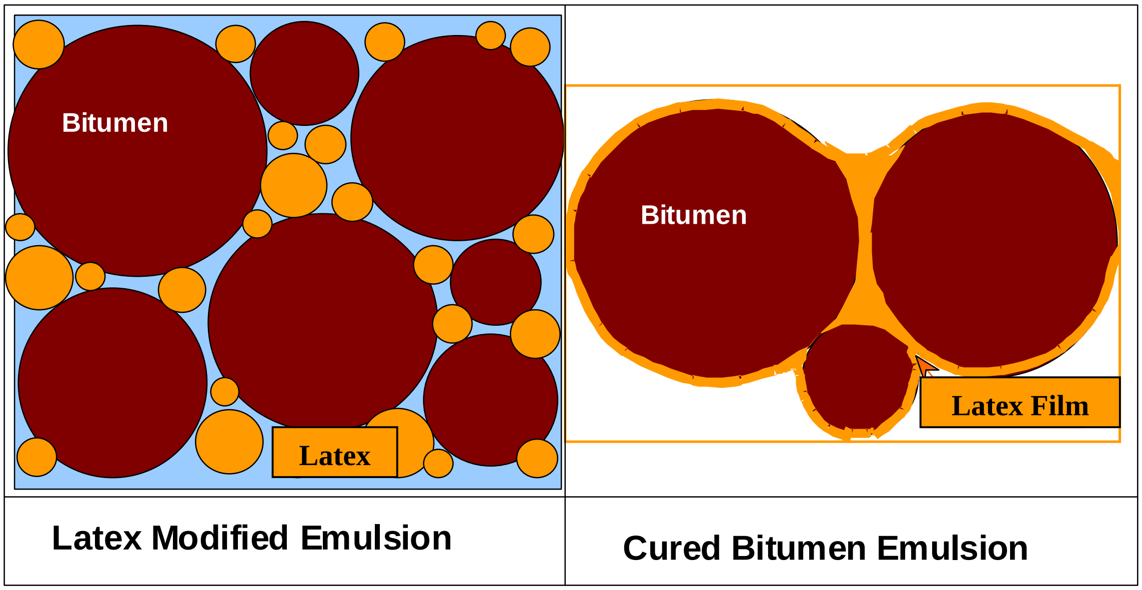


Figure 4. Illustration of Polymer Network Formation in Latex-Polymer Modified Asphalt Emulsion

The residue recovery procedure should closely simulate the curing behaviour of the Evotherm® emulsion during mixing and paving operations. It has been demonstrated that the excess heat applied to the emulsion during conventional residue recovery procedures (i.e., evaporation and distillation methods) significantly alters the polymer morphology in the recovered residue and hardens the asphalt binder. Forced airflow and RTFO drying procedures [12] were previously developed to simulate curing of the asphalt emulsion when used at ambient temperatures, such as during chip seal, slurry, microsurfacing, and cold mix system applications. This procedure was modified for the Evotherm® warm mix emulsion to better simulate the heat profile generated during plant mixing and field application.

Table 1 summarizes the measured temperature profile of the Evotherm® warm mix during the Aurora, Ontario trial conducted by McAsphalt on August 8, 2005 [8]. The table indicates that the Evotherm® warm mix emulsion would be exposed to between 120 and 130°C for a short period at the mix plant followed by 70 to 100°C for the next 1 to 2 hours during transport and laydown at the jobsite.

Table 1. Measured Temperature Profile during Plant Mixing and Field Paving Operation

Location	Temp., °C
Mixing temperature	130
Discharge temperature	100
In hopper of paver	97
Just behind the screed of paver	92
at edge of mat	87
at center of mat	92
After pneumatic roller	73
Pavement 4 hrs after lay down*	52

*25mm below the surface

Based on this standard temperature profile, a recovery procedure was specifically developed for the Evotherm® warm mix emulsion which simulates the heat history of the asphalt during the first few hours of mix production and laydown to one day after the paving operation. From a Superpave binder testing perspective, following recovery, the residue is treated like conventional hot mix binder that has been subjected to RTFO-aging. It is next aged in the PAV followed by complete Superpave binder fatigue and low temperature property characterization.

3.2 Production of Evotherm® Warm Mix Emulsion

Unmodified emulsion and emulsions modified with 1.5 and 3.0 percent Butonal® NX1118 SBR latex (BASF Corp.) were produced using PG 58-28 asphalt (McAsphalt Industries, Ltd.) with 0.5 percent Indulin® PC1606A emulsifier (MeadWestvaco Corp.). The soap solution was adjusted to pH=2.0 with HCl prior to emulsion production, and the finished emulsion exhibited 1.9<pH<2.3. The emulsion was then stored in a sealed container in a forced airflow oven maintained at 80°C. The Brookfield viscosity (80°C, #27 spindle at 20 rpm) of unmodified emulsion was 190 mPa·s at 69.5 percent residue. Brookfield viscosity of the 1.5 and 3.0 percent Butonal® NX1118 latex-modified emulsions were 650 mPa·s at 71.6 percent residue and 340 mPa·s at 72.0 percent residue, respectively.

3.3 Recovery of Evotherm® Binder

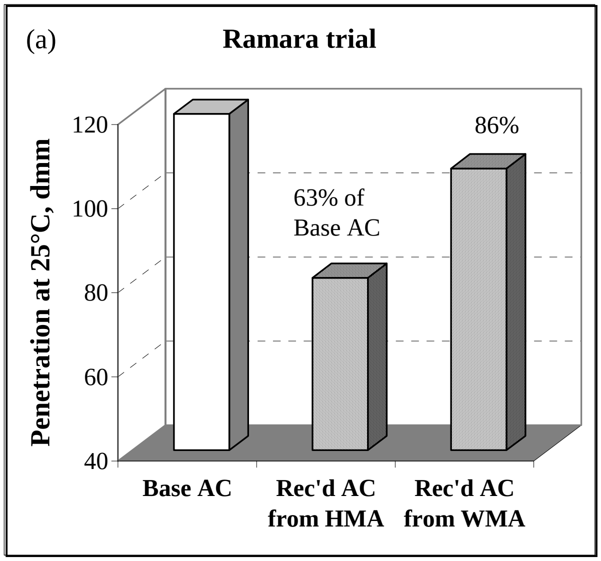
80g of Evotherm® warm mix emulsion is added into a PAV test pan to produce a liquid depth of less than 5 mm. The pan is next placed in a forced airflow oven preheated to 80°C. After 20 hours at 80°C, the pan and residue are removed from the oven and allowed to cool to room temperature. The pan can be placed into a 130°C oven for 10 to 15 minutes following cooling to room temperature to soften the residue and allow for pouring into a metal can for thorough stirring/mixing with a metal rod. This procedure produces approximately 50g of emulsion residue. The recovered Evotherm® binder (emulsion residue) described above is characterized as conventional hot mix binder that has been subjected to RTFO-aging, as defined by the Superpave binder characterization protocol [13].

For preparation of the aged residue sample, the PAV pan is placed in the Superpave PAV apparatus and heat aged at 100°C for 20 hours under 2.1 MPa air pressure. The sample is removed from the PAV and cooled to room temperature, then de-aerated in a vacuum oven for 30 minutes at 130°C. Hot stage photomicrographs of the 1.5 percent and 3.0 percent Butonal® NX1118 latex-modified Evotherm® warm mix emulsion residues confirm that the SBR latex polymer network structure remains in this PG 58-28 base asphalt even after PAV aging.

4.0 BINDER CHARACTERIZATION OF UNMODIFIED EVOTHERM® BINDER

4.1 Base Asphalt and Unmodified Evotherm® Binder

As discussed in Section 2.2, the recovered asphalt binder from the hot mix field core typically retains only 60 percent of the original penetration of the base asphalt due to heat hardening during conventional hot mix processing. In contrast, the Evotherm® warm mix binder maintains 80 percent of the original penetration due to reduced processing and application temperatures (see Figure 5). The penetration of the base PG 58-28 asphalt used for this study was 96 dmm (25°C, 5s, 100g) and after RTFO-aging became 54 dmm (56 percent of original base asphalt penetration). The recovered residue from the unmodified Evotherm® emulsion retained 89 percent (85 dmm) of the original penetration.



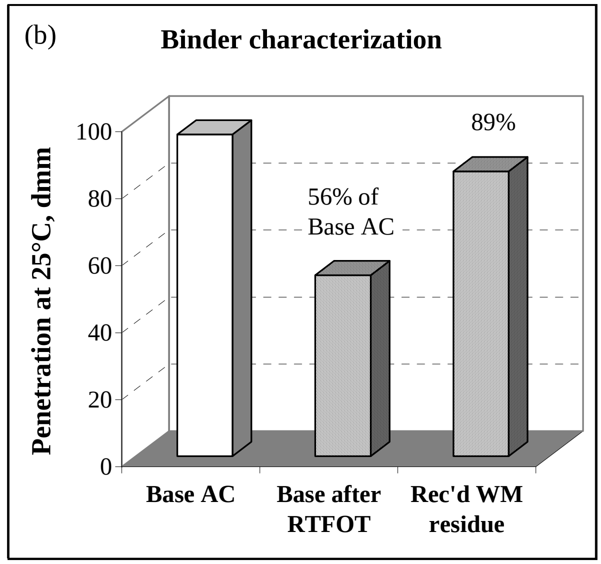
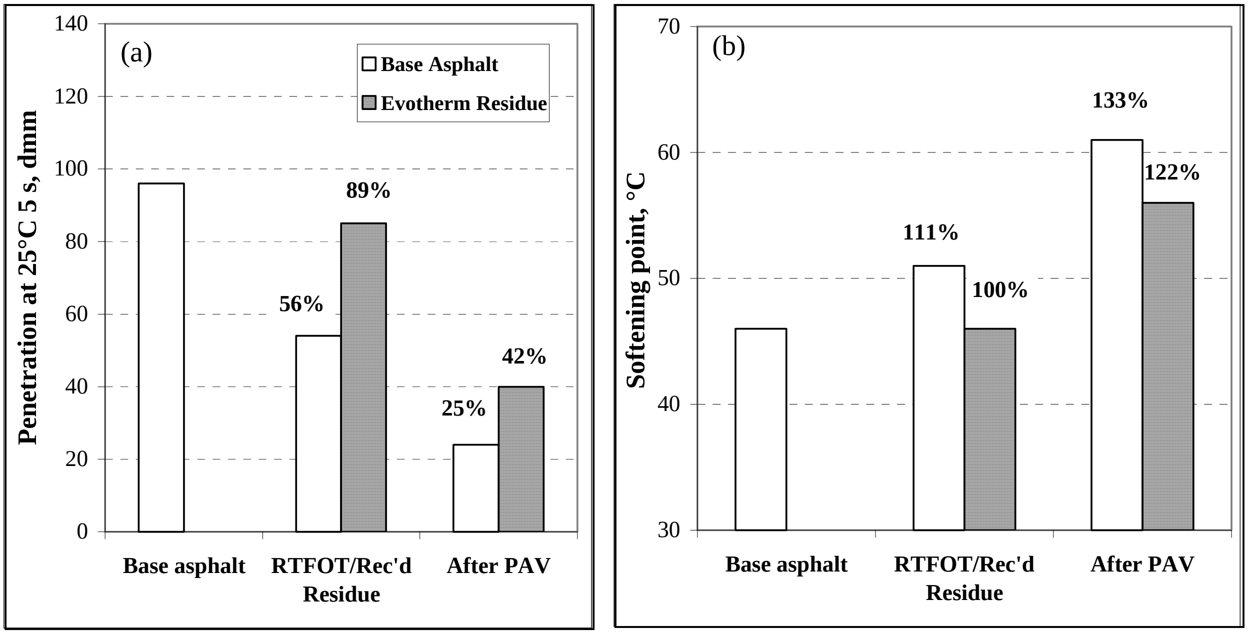


Figure 5. (a) Comparison of penetration of the base asphalt and recovered asphalt cement from Hot Mix Asphalt (HMA) and Evotherm® Warm Mix Asphalt (WMA) core samples taken during the Ramara Township trial (b) Data demonstrates that the residue recovery procedure developed here closely simulates the heat history of the mixing and paving process when using the Evotherm® warm mix emulsion system.

The penetration of the base PG 58-28 asphalt used for this laboratory study was reduced to 24 dmm from 96 dmm after both RTFO and PAV-aging. In comparison, the recovered Evotherm® emulsion binder produced from the same base AC was 40 dmm after PAV-aging (Figure 6a). The measured softening points of the base asphalt and the recovered Evotherm® binder are shown in Figure 6b. The softening point of the base asphalt was 46°C, increasing to 51°C and 61°C (111 and 133 percent of the base AC, respectively) after RTFO- and PAV-aging. The recovered Evotherm® residue had the same softening point as the base asphalt (45°C), and increased to only 56°C (122 percent of the base AC) after PAV-aging.

As previously discussed, McAsphalt also conducted Superpave binder characterization on the base and recovered asphalt cement from the core samples, as summarized in Figure 3. The measured G*/sin(δ) of the base asphalt used for the Ramara trial was 1.3 kPa at 58°C and increased to 2.5 kPa (2.0x increase) after RTFO-aging. The G*/sin(δ) values of the recovered asphalt binder from the field core samples were 2.8 (2.2x increase) and 2.2 kPa (1.7x increase) for the hot mix and Evotherm® warm mix systems, respectively. The G*/sin(δ) of the base asphalt used for this study (semi-solid bars in Figure 3) increased from 1.4 kPa to 3.3 kPa (2.4x increase) after RTFO-aging and that of the recovered Evotherm® emulsion residue prepared with the same base asphalt increased only 1.5x (2.1 kPa) at 58°C.

This data shown in Figures 3 and 6 demonstrates that the residue recovery procedure developed here closely simulates the heat history of the mixing and paving process when using the Evotherm® warm mix emulsion system.



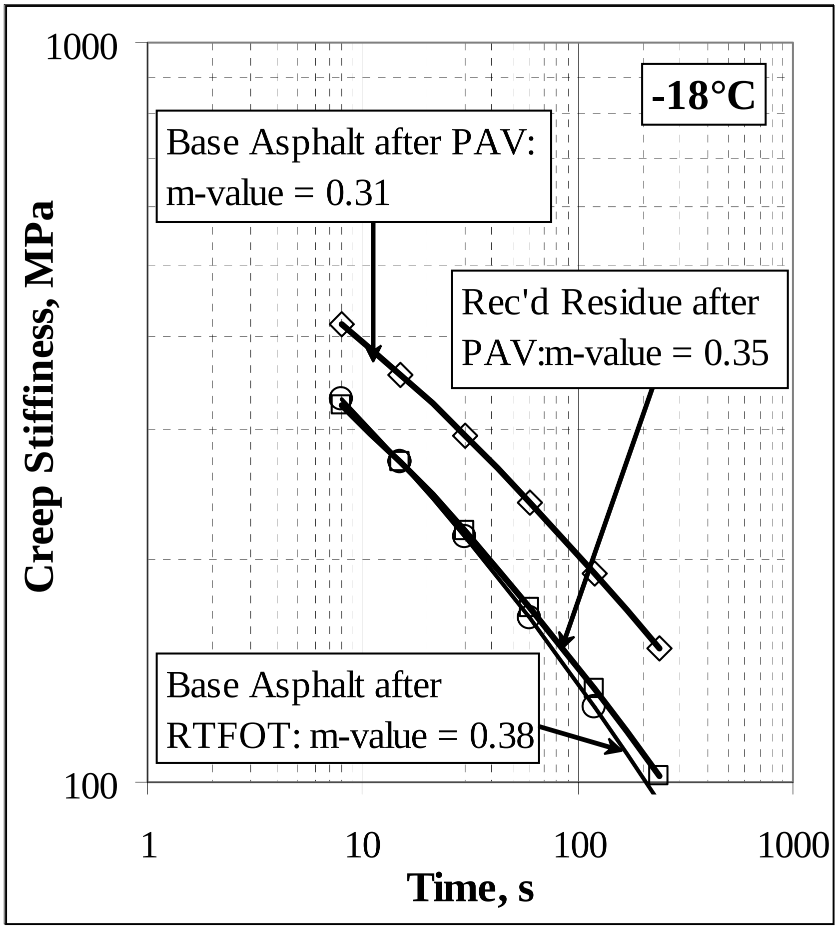
Note: RTFOT is Rolling Thin Film Oven Test, PAV is Pressure Aging Vessel.

Figure 6. (a) Measured penetration and (b) softening point of the base asphalt and recovered Evotherm® emulsion residue prepared from the same PG 58-28 base asphalt. The recovered Evotherm® binder maintains higher penetration and lower softening point when compared to the RTFO- and PAV-aged base AC.

Results shown in Figure 3 also include the creep stiffness at 60 seconds, S(60), at -18°C of the base and recovered asphalt cement from the hot mix and warm mix core samples. The extracted and recovered asphalt samples were each PAV-aged prior to testing in the BBR. The S(60) value of the base asphalt was 252 MPa with m-value = 0.30. The S(60) values for the recovered asphalt cement from the hot mix and Evotherm® warm mix cores were 228 (90 percent of the base AC) and 209 (83 percent) MPa with the same m-values of 0.31, respectively. The results appear to suggest that the recovered AC from the Evotherm® warm mix core maintains greater cold temperature flexibility than the recovered asphalt from the control hot mix core.

However, artefacts from the process used for extraction of the binder from the core could explain the observed low temperature flexibility of the extracted AC's in both cases. The measurement was repeated on the PG 58-28 base asphalt used in this study and on the recovered Evotherm® binder prepared using this same base AC. Results are included in Figure 3 (semi-solid bars). Measured S(60) of the base AC after PAV-aging was 235 MPa with m-value = 0.31. The S(60) of the Evotherm® residue was only 73 percent of the base AC (172 MPa with m-value = 0.35). For comparison, the BBR testing on the base asphalt after RTFO-aging was also conducted, and measured stiffness as a function of time is plotted in Figure 7. The figure also includes the measured stiffness vs. time plots for the base AC and Evotherm® residue after PAV-aging.

It is surprising to observe that the base asphalt after RTFO-aging and Evotherm® binder (emulsion residue) after PAV-aging exhibit very similar creep stiffness vs. time curves at this test temperature.



Note: RTFOT is Rolling Thin Film Oven Test, PAV is Pressure Aging Vessel.

Figure 7. Measured creep stiffness of the base asphalt and unmodified Evotherm® binder after PAV-aging at –18°C. The data for the base asphalt after RTFO-aging is also included for comparison.

The Superpave RTFO-aging procedure was developed to simulate heat hardening of the asphalt cement during the hot mix process and the accelerated aging procedure, whereas PAV-aging simulates the oxidative hardening of the asphalt cement after 10 to 15 years of service life in the field. Therefore, the results shown in Figure 7 suggest that the Evotherm® warm mix pavement after 10 to 15 years of service life could still maintain similar cold fracture resistance when compared to freshly-placed conventional hot mix pavement.

4.2 Dynamic Shear Rheometry at Wide Temperature Range

The creep stiffness, penetration, and softening point data consistently indicate that the Evotherm® binder experiences a lesser degree of heat and oxidative hardening during the RTFO- and PAV-aging processes. It was decided to conduct detailed visco-elastic measurements on the base AC and Evotherm® residue at a wide temperature range in order to further validate these observations.

Road Pavements – Bituminous Bound Materials, Clause 928 in the European Union (EU) specifies that G* should be determined at 0.4 Hz (instead of 10 rad/s or 1.64 Hz for Superpave test protocol) over the temperature range from –10°C to 90°C. The specification then defines the temperature at G*=2 kPa as the high equi-stiffness temperature, T_{2kPa} and G*=2 MPa as the low equi-stiffness temperature, T_{2MPa}. The specification also requires determining the complex modulus at 5, 25, and 60°C and defines them as $G^*_{(5°C)}$, $G^*_{(pen)}$ and $G^*_{(60°C)}$, respectively. The phase angle at 5 and 25°C are also defined as $\delta_{(low)}$ and $\delta_{(high)}$, respectively.

Figure 8 illustrates the complex modulus of the base AC (neat, after RTFO- and PAV-aging) and unmodified Evotherm® residues (recovered, after PAV-aging) from –30 to 75°C. T_{2kPa}, T_{2MPa}, and other quantities defined in EU Clause 928 are summarized in Table 2. Rheological measurements were obtained using the strain-controlled Rheometrics RDA-700 (TA Instruments). Parallel plates of 8 mm diameter were used below 40°C, and 24 mm discs used above 35°C. Both plate diameters were used in the overlapping 5°C region. Strain level was adjusted to provide the maximum sensitivity over a wide range of stress levels.

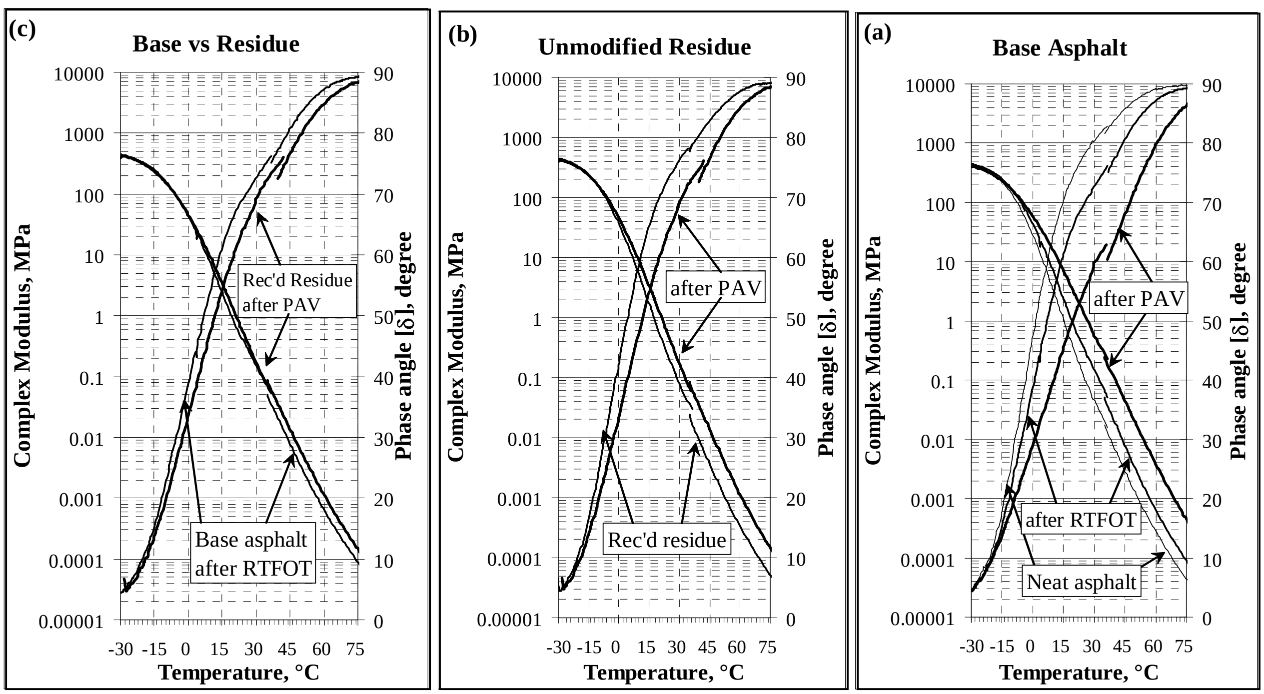


Figure 8. (a) Complex modulus, G* and phase angle, δ of the base asphalt and (b) Evotherm®. Binder G* of the base asphalt sharply increases after RTFO- and PAV-aging, whereas the Evotherm® binder shows only limited increase in G* after PAV-aging. (c) Evotherm® binder after PAV-aging maintains almost the same G* vs. temperature relationship as the base asphalt after only RTFO-aging.

Figure 8a demonstrates that G* of the base neat asphalt changes nearly 10 million times and $5° < \delta < 90°$ in the temperature range studied. This asphalt cement behaves as a brittle solid at low temperature and becomes a viscous liquid of limited elasticity ($\delta \approx 90°$) at elevated temperatures.

Table 2. Physical properties of base PG 58-28 asphalt and unmodified Evotherm® residue as defined by EU Clause 928. The glass transition temperature, T_g, as estimated from the maximum in G" is also included.

	Base asphalt			Unmodified residue	
	Neat	RTFOT	PAV	Residue	PAV
T_{2kPa}, °C	47	54	65	48	56
T_{2MPa}, °C	12	16	22	14	18
$G^*_{(5°C)}$, MPa	10	20	30	12	20
$G^*_{(pen)}$, kPa	110	350	1100	200	420
$G^*_{(60°C)}$, kPa	0.3	0.55	3.8	0.32	1.2
$\delta_{(low)}$, degree	58	46	33	51	42
$\delta_{(high)}$, degree	78	70	55	73	65
T_g, °C	-14	-14	-14	-14	-14

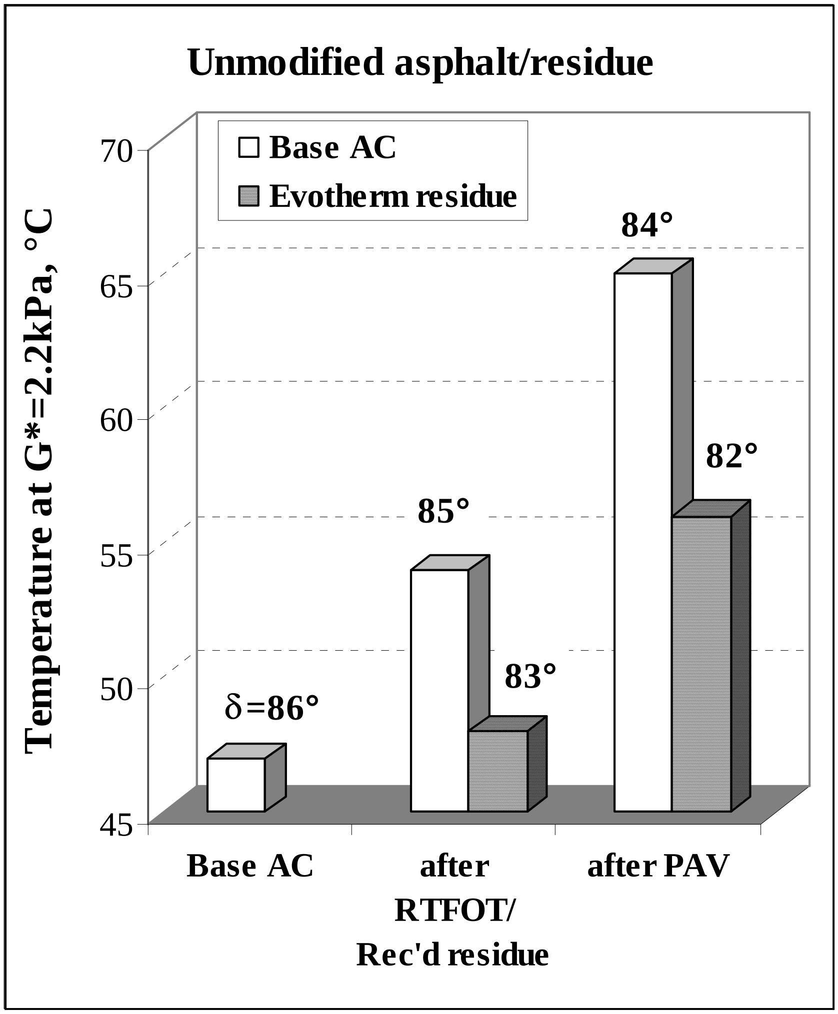
Figure 8a compares changes in binder properties of the base asphalt after heat (RTFO) and oxidative (PAV) aging processes, and Figure 8b contains the same rheological data for the Evotherm® warm mix emulsion residue as- recovered and after PAV-aging. These figures demonstrate that the complex modulus, G* of the base asphalt increases sharply after PAV-aging at above ambient temperature. The increase in G* of the recovered Evotherm® binder after PAV-aging is less pronounced. In Figure 7, it was demonstrated that the creep stiffness values of the base asphalt after RTFO-aging and the Evotherm® binder after PAV-aging are very similar to each other at –18°C. Results shown in Figure 8c demonstrate that this similarity in rheological behaviour is not only limited to low temperature, but also applies to the rheology of the binders over the entire temperature range that the asphalt cement would be exposed to in the field.

The temperature at G*=2.2 kPa for the base AC and recovered Evotherm® binders are compared in Figure 9. The figure also includes the phase angle, δ, at this particular temperature. In addition to reduced heat and oxidative hardening effects, the Evotherm® warm mix emulsion residue appears to have slightly higher elasticity than the base asphalt, as evidenced by lower δ values.

4.3 Glass Transition Temperature

The maximum value in loss modulus, G" when measuring against temperature corresponds to the glass transition temperature, T_g of the asphalt binder [14]. Below T_g, the asphalt binder becomes brittle. A previous study investigating Valero PG 64-22 asphalt [15] showed a 5°C increase in T_g from -16 to -11°C after PAV-aging. A similar increase in T_g after PAV-aging was also observed with Cenex AC-20 asphalt [16].

Measured G" vs. temperature relationships for the base asphalt and unmodified Evotherm® emulsion residue are summarized in Figure 10. These include neat, after RTFO- and PAV-aged samples of the base asphalt (Figure 10a) and Evotherm® residue as-recovered and after PAV-aging (Figure 10b). The estimated T_g of all samples studied here shows the same T_g of -14°C, independent of recovery process or heat (RTFO) and oxidative aging (PAV) processes. This observation is in clear contrast to the previous study with Valero PG 64-22 asphalt, providing further evidence of the inherent complexity of asphalt binder rheology.

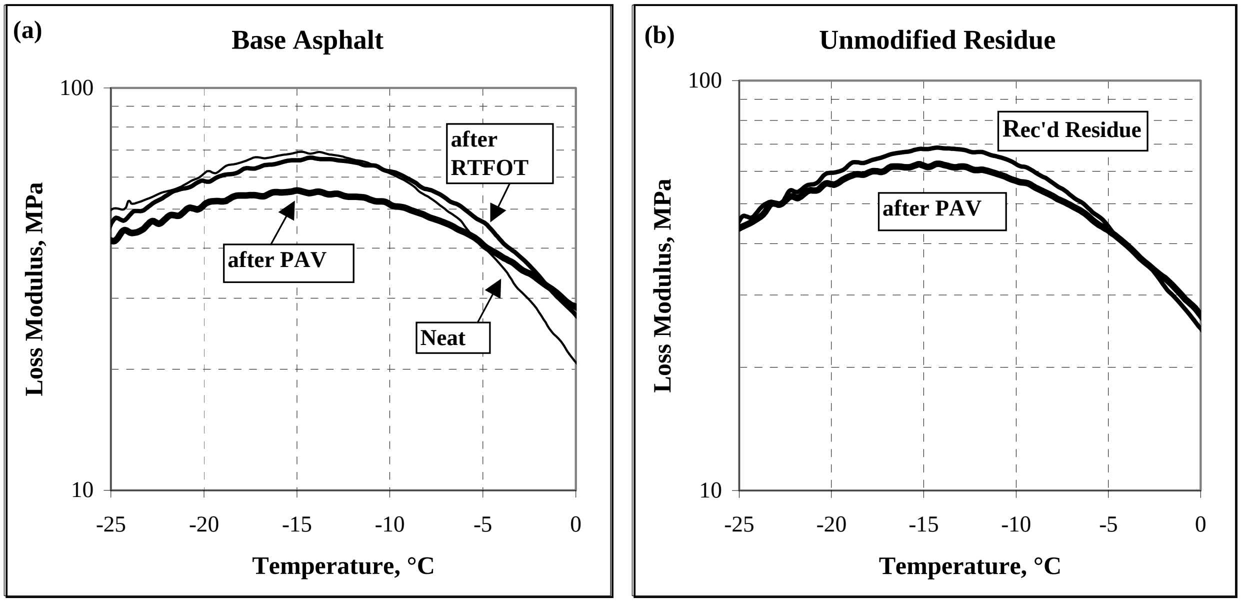


Note: RTFOT is Rolling Thin Film Oven Test.
PAV is Pressure Aging Vessel.

Figure 9. Estimated temperatures at G*=2.2 kPa for base Asphalt Cement (AC) and Evotherm® residue. The Evotherm® residue shows lesser degree of heat and oxidative aging than the base AC.

4.4 Fatigue Resistance under Cumulative High Strain Stresses

Figure 11 illustrates results of the fatigue resistance test at 7°C of the base AC and recovered, unmodified Evotherm® residue under repeated high strain stresses. In this test, the binder is subjected to 1, 5, and 10 percent strain at 10 rad/s for 30 minutes while monitoring the reduction in the complex modulus. Between these increases in strain level, the sample is allowed to relax for 15 minutes. A very low strain of 0.1 percent was applied to monitor the healing process during this relaxation period. Detailed description of this procedure can be found in [17].

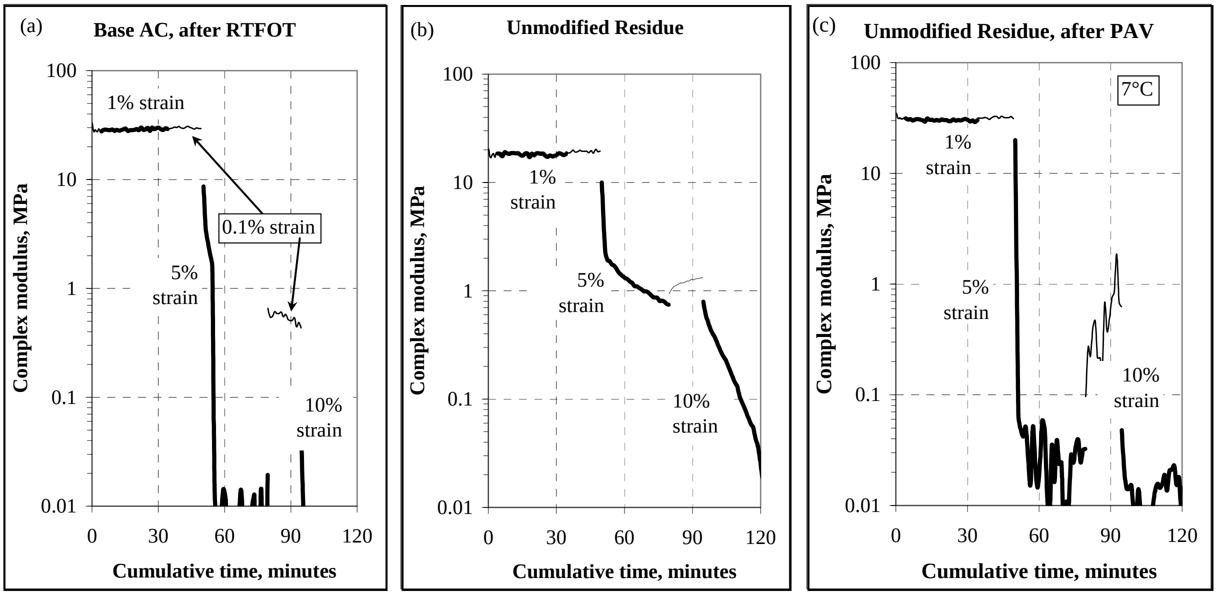


Note: RTFOT is Rolling Thin Film Oven Test, PAV is Pressure Aging Vessel.

Figure 10. (a) Measured loss modulus, G" vs. temperature of the base PG 58-28 asphalt cement and (b) Evotherm® residue. The maximum in G" corresponds to the glass transition temperature, T_g of the asphalt sample. The heat (RTFO) and oxidative (PAV) aging processes appear to have no effect on the measured T_g, which was –14°C for all samples.

The asphalt pavement becomes susceptible to fatigue cracking when the asphalt cement becomes brittle due to oxidative hardening. The Superpave binder specification defines the fatigue resistance of the PAV-aged sample as G*xsin(δ)<5 MPa at the specified test temperature. The measurement is conducted at 1 percent strain and 10 rad/s. Data shown in Figure 11 was collected at a lower temperature than would be specified by the standard SHRP fatigue test since G* ≈ 20 – 30 MPa at 1 percent strain for the base asphalt after RTFO-aging, as well as for the Evotherm® binder as-recovered and after PAV-aging. The complex modulus, G* values of all samples show no reduction in the binder strength at 1 percent strain level for 30 minutes (2880 stress cycles). When the strain level is increased to 5 percent after 15 minutes of relaxation (at 0.1 percent strain), G* of the base asphalt after RTFO-aging dropped sharply to between 1 and 10 kPa (0.001 – 0.01 MPa); below 0.1 percent of its original strength. The asphalt cement fractured under these repeated high strain-stresses.

In contrast, the unmodified Evotherm® binder as-recovered maintained G* of above 1 MPa during the majority of the 5 percent strain cycles and above 10 kPa even at the end of the 10 percent strain cycles (see Figure 11b). As seen in Figure 11c, the fatigue resistance of the recovered Evotherm® residue is significantly reduced after PAV-aging. However, the fatigue resistance of the Evotherm® binder after PAV-aging is as good or better than the base asphalt after RTFO-aging. These data again suggest that the Evotherm® warm mix pavement after 10 to 15 years of service life would behave similarly to freshly-placed, conventional hot mix pavement.



Note: RTFOT is Rolling Thin Film Oven Test, PAV is Pressure Aging Vessel.

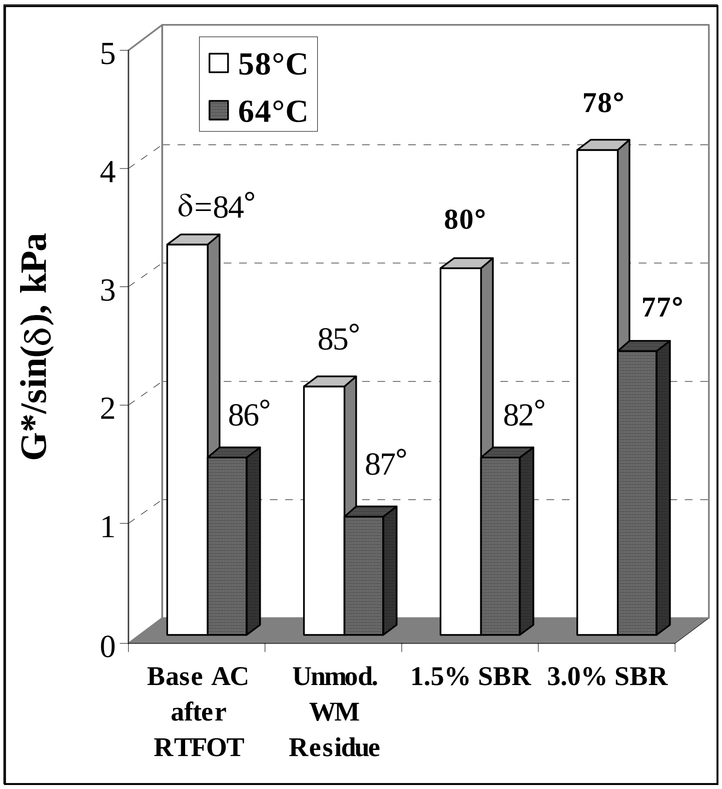
Figure 11. Results of fatigue resistance testing at 7°C at 1%, 5%, and 10% strains with relaxation period (0.1% strain) between each strain increase. (a) Base AC after RTFO-aging looses its strength (complex modulus) immediately after application of 5% strain, (b) Evotherm® residue tolerates repeated 5% strain cycles without sharp reduction in strength, (c) Evotherm® residue after PAV-aging has similar fatigue resistance as the base PG 58-28 asphalt after RTFO-aging, suggesting improved fatigue resistance of the composite Evotherm® warm mix pavement

5.0 SBR LATEX -MODIFIED EVOTHERM® BINDER

5.1 Rutting Resistance Temperature

G*/sin(δ) values at 58 and 64°C for the recovered, unmodified and SBR latex-modified Evotherm® residues are summarized in Figure 12. The measured phase angle is also indicated in the same figure above the bars. G*/sin(δ) values of the base asphalt after RTFO-aging were 3.3 and 1.5 kPa at 58 and 64°C, respectively. Those of the unmodified Evotherm® residue were 2.1 and 1.0 kPa, respectively. The phase angle of the base AC and unmodified Evotherm® residue is approximately 85 degrees at 58°C, indicating limited elasticity of these binders. If the recovered, unmodified Evotherm® residue is treated as a conventional hot mix binder subjected to RTFO-aging, as defined in the Superpave binder specifications, it would grade out at just below the PG 58 specification minimum of G*/sin(δ)>2.2 kPa.

G*/sin(δ) values increased to 3.1 and 4.1 kPa at 58°C and 1.5 and 2.4 kPa at 64°C with addition of 1.5 percent and 3.0 percent Butonal® NX1118, respectively. These SBR latex-modified Evotherm® residues also show improved elasticity as shown by δ<80° at 58°C. The addition of 3 percent Butonal® NX1118 results in one PG grade improvement of the base asphalt from PG 58 to PG 64.



Note: RTFOT is Rolling Thin Film Oven Test.
PAV is Pressure Aging Vessel.
AC is Asphalt Cement.
WM is Warm Mix.
SBR is Styrene-Butadiene-Rubber.

Figure 12. Superpave G*/sin(δ) values of base AC, unmodified Evotherm®, and SBR latex-modified Evotherm® residues at 58 and 64°C. The unmodified residue is just below the PG 58 specification of G*/sin(δ)>2.2kPa. 3.0% Butonal® NX1118 modified Evotherm® residue meets the PG 64 specification through improved elasticity as evidenced by δ=77°.

5.2 Dynamic Shear Rheometry at Wide Temperature Range

Quantities defined by Road Pavement – Bituminous Bound Materials, Clause 928 of the European Union Specifications were determined (see Section 4.2) and summarized in Table 3 for the 1.5 and 3.0 percent Butonal® NX1118-modified Evotherm® residues. The as-recovered residues as well as those after PAV-aging were examined.

Figure 13 compares the estimated temperature at G*=2.2 kPa for the neat asphalt, unmodified, and SBR latex-modified Evotherm® residues. As discussed earlier, the unmodified Evotherm® binder is consistently softer and slightly more elastic (lower δ values) even after PAV-aging. Modification with 3.0 percent Butonal® NX1118 is necessary to provide a similar G* to the base asphalt cement used to produce a standard hot mix pavement (since Evotherm® binders are not subjected to high temperatures during mixing with the aggregate at the hot mix plant). Alternatively, a harder base asphalt could be used to produce the Evotherm® warm mix emulsion binder.

Table 3. Physical properties of 1.5% and 3.0% Butonal® NX1118-modified Evotherm® residue as defined by EU Clause 928. The glass transition temperature, T_g, as estimated from the maximum in G" is also included.

	1.5% NX1118		3% NX1118	
	Residue	PAV	Residue	PAV
T_{2kPa}, °C	53	61	57	66
T_{2MPa}, °C	12	18	14	18
$G^*_{(5°C)}$, MPa	9	18	12	13
$G^*_{(pen)}$, kPa	170	500	210	700
$G^*_{(60°C)}$, kPa	0.8	2	0.9	2
$\delta_{(low)}$, degree	51	41	48	38
$\delta_{(high)}$, degree	70	60	66	53
T_g, °C	-17	-18	-17	-21

Figure 13 also demonstrates that the 1.5 and 3.0 percent SBR latex-modified Evotherm® residues produce a 4 to 8°C reduction in the phase angle at the same equi-stiffness temperature. This demonstrates that polymer modification with SBR increases G* mostly though improved elasticity, in contrast to the viscosity increase of hot AC that is hardened through heat and oxidation (during mixing, laydown, and compaction in a standard HMA process).

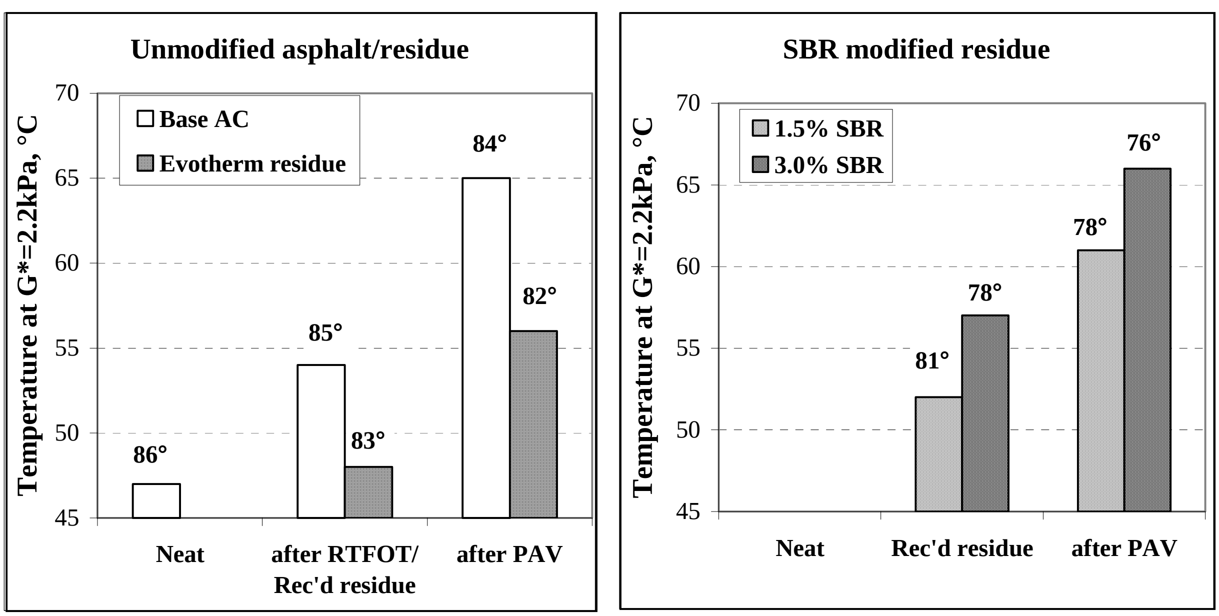


Figure 13. Estimated temperatures at G* = 2.2 kPa for the base PG 58-28 asphalt, unmodified, and SBR latex-modified Evotherm® binders. Modification with 1.5% and 3.0% Butonal® NX1118 results in a phase angle δ<80° after PAV-aging, demonstrating that the polymer-modified Evotherm® binder could maintain its elasticity even after extensive oxidative hardening has occurred in the pavement.

Further benefits of this enhanced elasticity through polymer modification can be demonstrated through cold fracture (BBR) and fatigue resistance testing (see Sections 5.4 and 5.5).

5.3 Glass Transition Temperature

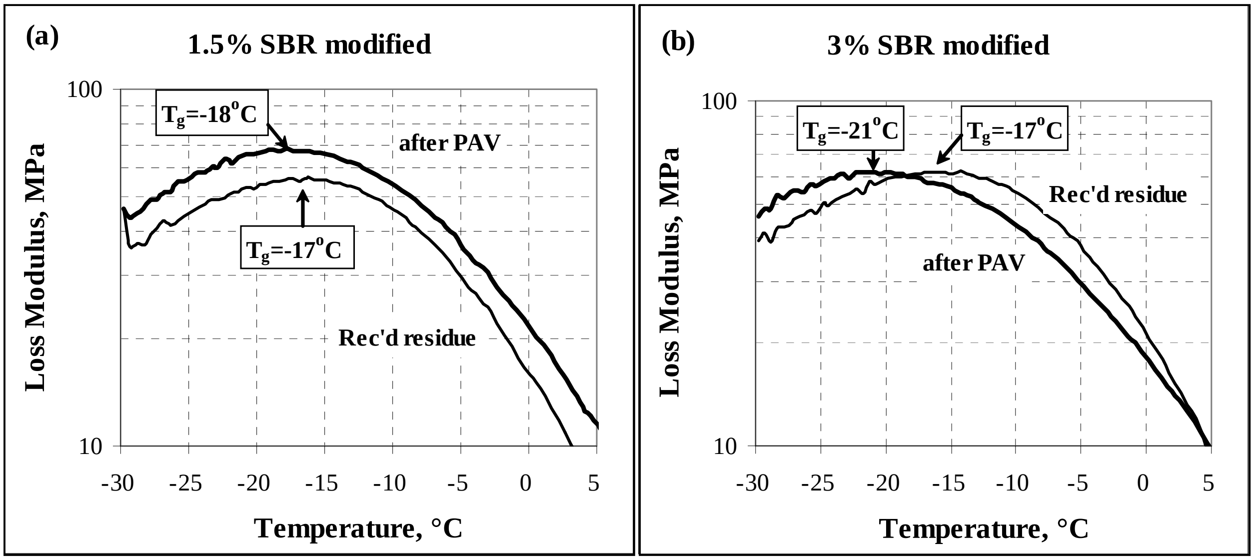
As discussed in Section 4.3, the maximum value in loss modulus, G" corresponds to the glass transition temperature, T_g of the asphalt binder. An increase in T_g of the unmodified Evotherm® binder was observed with Valero PG 64-22 asphalt after PAV-aging [15]. This was not the case with the PG 58-28 asphalt used in this study. The glass transition temperature of the base AC and unmodified Evotherm® binders were consistently measured at -14°C for all samples tested even after RTFO- and PAV-aging.

A five degree reduction in T_g was observed with 3.0 percent SBR latex-modified Evotherm® residue made with Valero PG 64-22 asphalt [15]. Figure 14 illustrates measured G" as a function of temperature for 1.5 and 3.0 percent Butonal® NX1118-modified Evotherm® residues produced from PG 58-28 base asphalt before and after PAV-aging. The estimated T_g values for these samples are included in Table 3. Modification with 1.5 and 3.0 percent Butonal® NX1118 resulted in a 3°C reduction in T_g in the as-recovered residues to -17°C. PAV-aging of these as-recovered residues actually caused a further 1 and 4°C reduction in T_g for 1.5 and 3.0 percent SBR latex-modified residues, respectively. An explanation for this unexpected reduction in T_g after PAV-aging is not clear and is in strong contrast to the measured T_g of the unmodified and SBR latex-modified Evotherm® residues recovered from the Valero PG 64-22 base asphalt [15], which showed a 5°C increase in T_g in both cases. The heat applied (100°C) to the emulsion during PAV-aging could cause improved integration of the SBR polymer network with the asphalt as observed by hot stage microscopy.

5.4 Cold Fracture Resistance

Bending Beam Rheometry (BBR) was performed on the SBR latex-modified Evotherm® residues after PAV-aging at –24 and –18°C, and the measured creep stiffness, S, was plotted as a function of time in Figure 15. The m-values at 60 seconds are also indicated in the figure. In Figure 7, S(60) of the unmodified Evotherm® binder was 172 MPa with an m-value of 0.35. In Figure 15a, the 1.5 percent SBR latex-modified Evotherm® residue has almost identical values of S(60) of 175 MPa and an m-value of 0.33. These S(60) values are 60 MPa lower than that of the base asphalt (S(60) = 235 MPa with m-value of 0.31). A further reduction in S(60) to 129 MPa with m-value = 0.37 was observed when increasing the polymer loading level to 3.0 percent Butonal® NX1118. Superpave low temperature binder specifications require S(60) < 300 MPa and m-value < 0.30. Thus, the SBR latex-modified Evotherm® residues easily satisfy the PG -28 grade requirement.

The creep stiffness of the Butonal® NX 1118-modified residues was also determined at -24°C, and results are shown in Figure 15b. Measured S(60) values are 289 and 256 MPa for residues modified with 1.5 and 3.0 percent SBR latex polymer, respectively. These S(60) values meet the PG -34 requirement, but measured m-values of these residues are 0.28 and 0.27, respectively, which are slightly below the required specification minimum of m-value >0.30. Although modification with 3.0 percent Butonal® NX1118 significantly improves the low temperature flexibility of the recovered Evotherm® residue as demonstrated by the DSR and creep stiffness data discussed above, it does not reduce the m-value, which is predominately controlled by the viscous component of the base asphalt.



Note: RTFOT is Rolling Thin Film Oven Test, PAV is Pressure Aging Vessel, SBR is Styrene-Butadiene-Rubber.

Figure 14. Loss modulus, G" vs. temperature of the (a) 1.5% and (b) 3.0% Butonal® NX1118-modified Evotherm® residues. The maximum in G" corresponds to the glass transition temperature, T_g of the residue. In contrast to the unmodified Evotherm® residues whose T_g was –14°C as-recovered and after PAV-aging, polymer modification results in a 3° C reduction in T_g in the as-recovered residues and as much as 4 and 7° C reduction after PAV-aging for 1.5 and 3.0% Butonal® NX1118-modified residues, respectively.

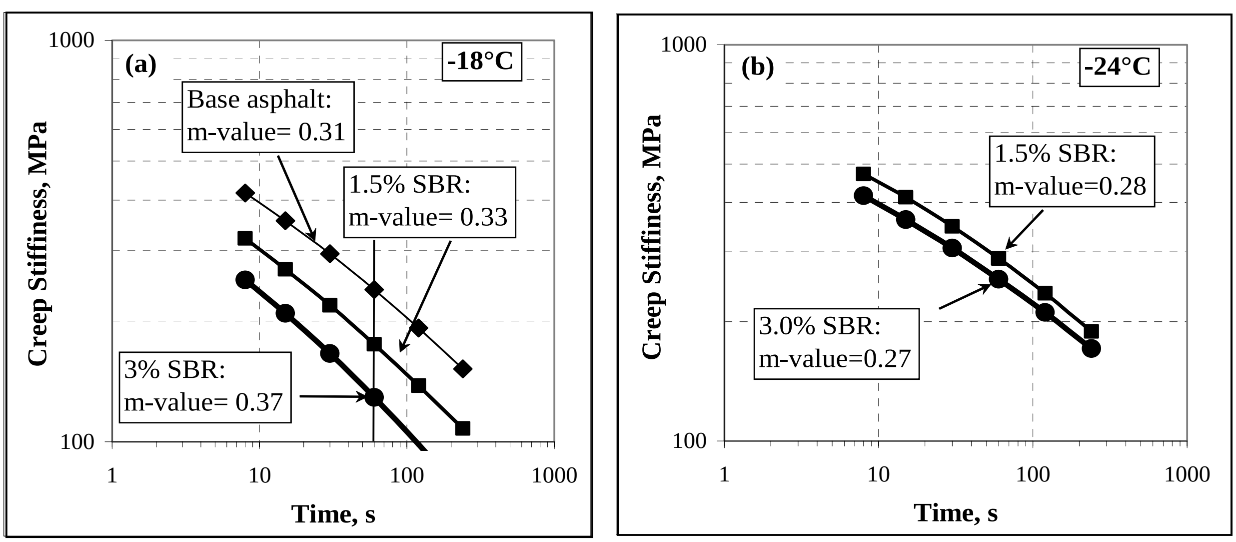
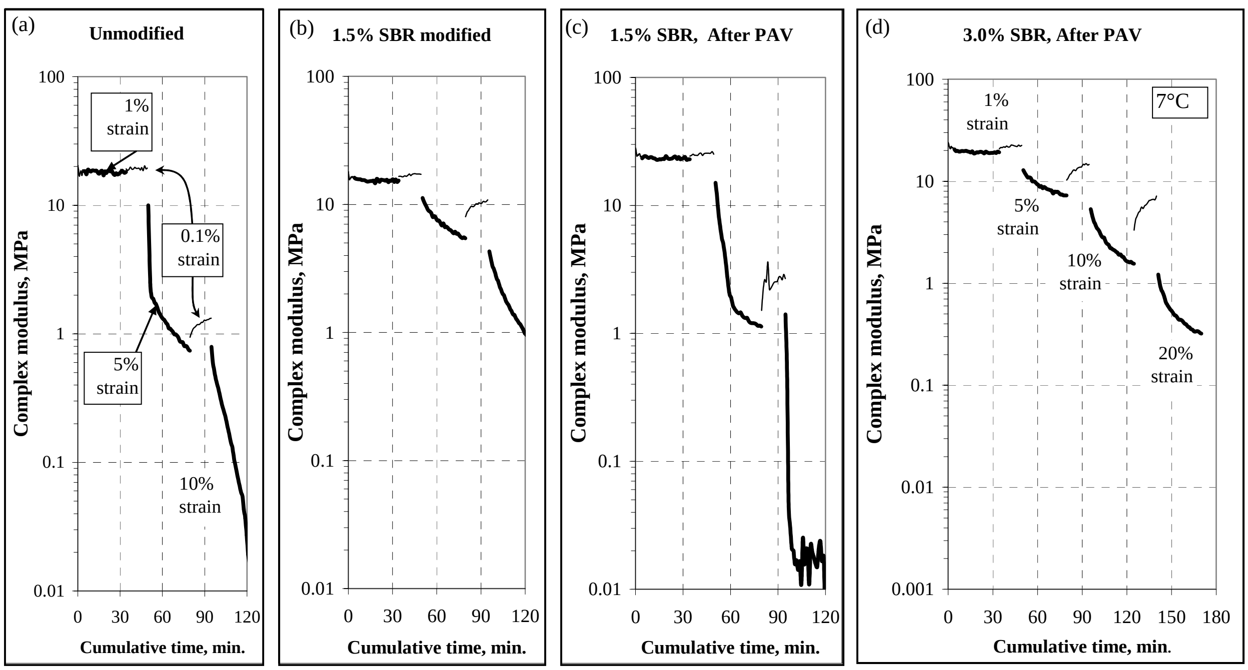


Figure 15. Creep stiffness for SBR latex-modified Evotherm® residues after PAV-aging. (a) S(60) of the Evotherm residues with 1.5 and 3.0% Butonal NX1118 are 60 and 106 MPa lower than the base asphalt at -18°C, respectively. (b) S(6) of these Styrene-Butadiene-Rubber (SBR) latex-modified Evotherm residues meet PG-34 specification of <300MPa, but m-values are slightly below the specification. of >0.30.

5.5 Fatigue Resistance

Figure 11 showed that the unmodified Evotherm® binder after PAV-aging maintained similar fatigue resistance properties when compared to the base asphalt after RTFO-aging. Figures 16a and 16b compare the fatigue resistance at 7°C of the unmodified and 1.5 percent SBR latex-modified Evotherm® binders as-recovered. The complex modulus, G* of the unmodified residue sharply drops with repeated 5 percent strain-stresses. In contrast, the residue modified with 1.5 percent Butonal® NX1118 maintains the same or higher G* values even at the end of 10 percent strain cycles. However, as seen in Figure 16c, a sharp reduction in the fatigue resistance is noted when the 1.5 percent SBR latex-modified Evotherm® residue is subjected to PAV-aging. By comparing Figures 16a and 16c, it may also be suggested that modification with 1.5 percent SBR latex polymer can mitigate the reduction in fatigue resistance of the unmodified Evotherm® binder after prolonged oxidative aging in the field.



Note: PAV is Pressure Aging Vessel, SBR is Styrene-Butadiene-Rubber.

Figure 16. Results of fatigue resistance test at 7°C at 1, 5, 10 and 20% strains with relaxation period (0.1% strain) between each strain increase for the 1.5 and 3.0% SBR latex-modified Evotherm® residues. (a) Results for the unmodified Evotherm® residue are also included for comparison; (b) and (c) Results demonstrate that the Evotherm® residue modified with 1.5% Butonal® NX1118 after PAV-aging maintains similar fatigue resistance when compared to the as-recovered unmodified Evotherm® residue (d) Significantly improved fatigue resistance at 3.0% SBR latex loading level.

The fatigue resistance of the Evotherm® warm mix residue modified with 3.0 percent SBR latex polymer is also included in Figure 16d. The excellent fatigue resistance of this binder even after PAV-aging can be clearly seen in this figure. This residue shows no sharp reduction in G* even under repeated 20 percent strain cycles. This 3.0 percent SBR latex-modified Evotherm® residue provides better fatigue resistance than the freshly recovered Evotherm® binder modified with 1.5 percent SBR latex polymer. In total, this data suggests that the 1.5 percent SBR latex-modified Evotherm® warm mix pavement would provide similar fatigue resistance after 10 to 15 years of in-service life as freshly-placed unmodified Evotherm® warm mix pavement. Increasing the SBR latex loading level from 1.5 percent to 3.0 percent could potentially further double the service life of the Evotherm® warm mix pavement.

6.0 LONG TERM PAV-AGING

The results discussed in Section 5.5 concerning the reduced oxidative hardening of the SBR latex-modified Evotherm® residues are limited to samples subjected to the standard Superpave PAV-aging condition of 20 hours at 100°C. To try and elucidate the mechanism for this observed reduced oxidative hardening of the SBR latex-modified Evotherm® binders during PAV-aging, the residues were subjected to a series of PAV-aging times ranging from 6 to 94 hours. Chemical, as well as rheological, measurements were then conducted on these residue samples as a function of PAV-aging time.

6.1 Chemical Analysis of Oxidative Hardening

The oxidation of asphalt by reaction with atmospheric oxygen is a major factor contributing to the age hardening and embrittlement of asphalt pavements in service [18]. Figure 17 compares the infrared spectra of unmodified and 3.0 percent SBR latex-modified Evotherm® binders after 6, 20, 44 and 94 hours of PAV-aging. The spectrum for the neat asphalt (base AC prior to PAV-aging) is also included for reference. The standard PAV-aging procedure (20 hours at 100°C) is expected to simulate 7 to 10 years of in-service oxidation of the asphalt pavement. As seen in Figure 17a, intensity of absorption peaks related to sulfoxide (R-SO-R') formation at 1030 cm^{-1} and carbonyl segments (RCOOH, R-CO-R' and RCHO) at 1690-1710 cm^{-1} in the unmodified Evotherm® residue increases continuously during the prolonged PAV-aging process.

The spectra for the 3.0 percent Butonal® NX1118-modified Evotherm® residue shows a clear butadiene absorption at 970 cm^{-1} even after 94 hours of PAV-aging. The intensity of this peak is almost identical after 6, 44, and 94 hour PAV-aging times, suggesting that the SBR polymer did not decompose after long-term exposure in this severe oxidative environment. A continuous increase in the intensity of the neat asphalt related peaks at 1030 cm^{-1} and 1690-1710 cm^{-1} after long-term PAV-aging up to 44 hours suggests that polymer modification has no significant effect on the kinetics and extent of oxidation of the base PG 58-28 asphalt. The reduced intensity of the 1690-1710 cm^{-1} peak relative to the 1600 cm^{-1} peak of the 3.0 percent SBR latex-modified Evotherm® residue when compared to the intensities of the same peaks for the unmodified Evotherm® residue after 94 hour PAV-aging time may suggest that the SBR latex polymer can reduce the oxidatin kinetics in the base asphalt at late pavement service lifetimes (>>10-15 years).

6.2 Rheological Measurements

The various Evotherm® binders after 44 and 94 hours PAV-aging were too brittle to prepare for BBR testing. The complex modulus and phase angle of these residues after PAV-aging were measured near ambient temperature (similar to Superpave binder fatigue resistance testing [13]). G* at 19°C and δ of the base asphalt, unmodified Evotherm®, and 3 percent SBR latex-modified Evotherm® residues are plotted in Figure 18 as a function of PAV-aging time. The complex modulus of the base asphalt and unmodified Evotherm® binder sharply increase from below 2 MPa after 6 hours PAV-aging time to 18 and 13 MPa, respectively, after 94 hours PAV-aging. The phase angles of these binders drop sharply to below 45 degrees with long term PAV-aging, suggesting reduced resistance to brittle fracture at above 20 hour PAV-aging due to effects of oxidative hardening.

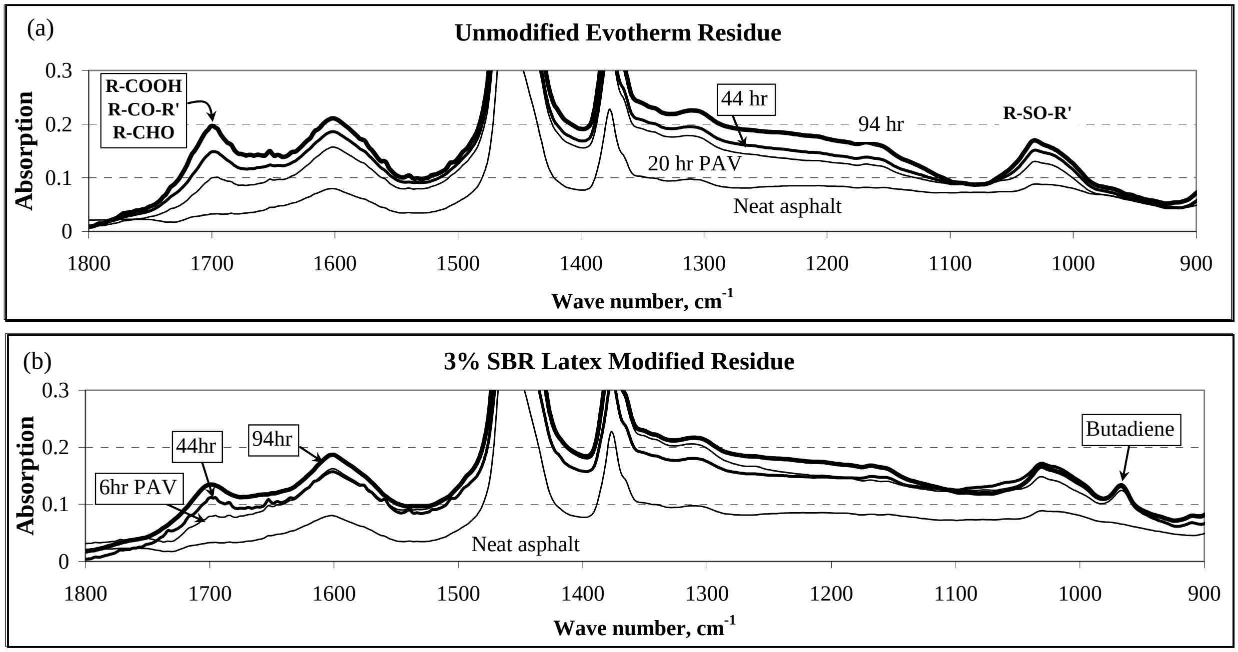


Figure 17. Infrared spectra of the (a) unmodified and (b) SBR latex-modified Evotherm® residues after 6, 20, 44 and 94 hour PAV-aging. Absorption peaks relating to sulfoxide and carbonyl segments increased continuously during prolonged PAV-aging. SBR latex polymer modification does not prevent asphalt oxidation, but the absorption intensity for butadiene at 970 cm^{-1} does not change even after 94 hour PAV-aging.

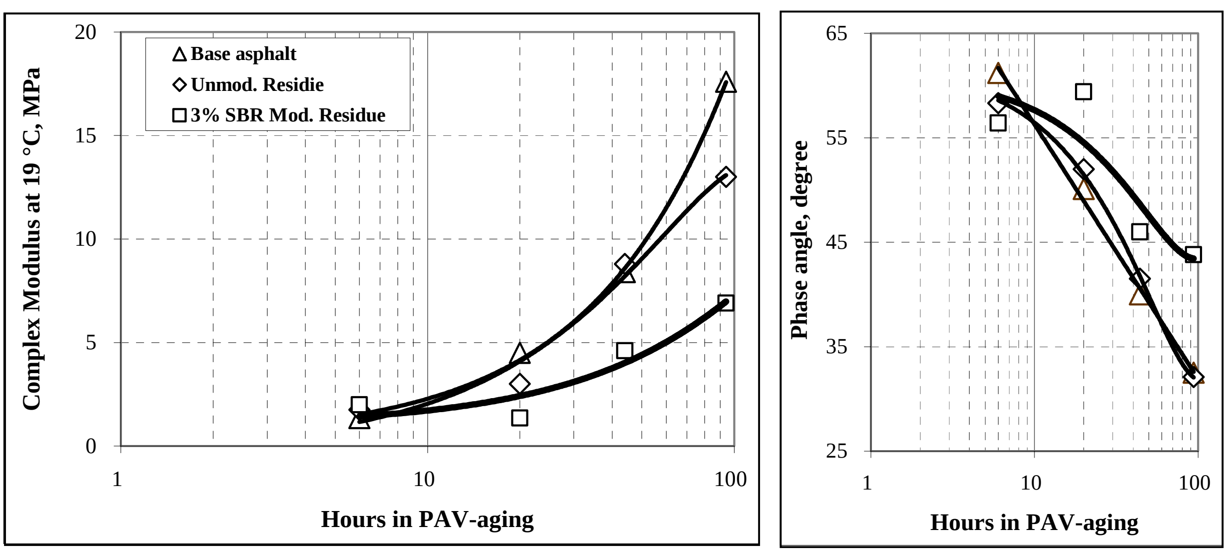
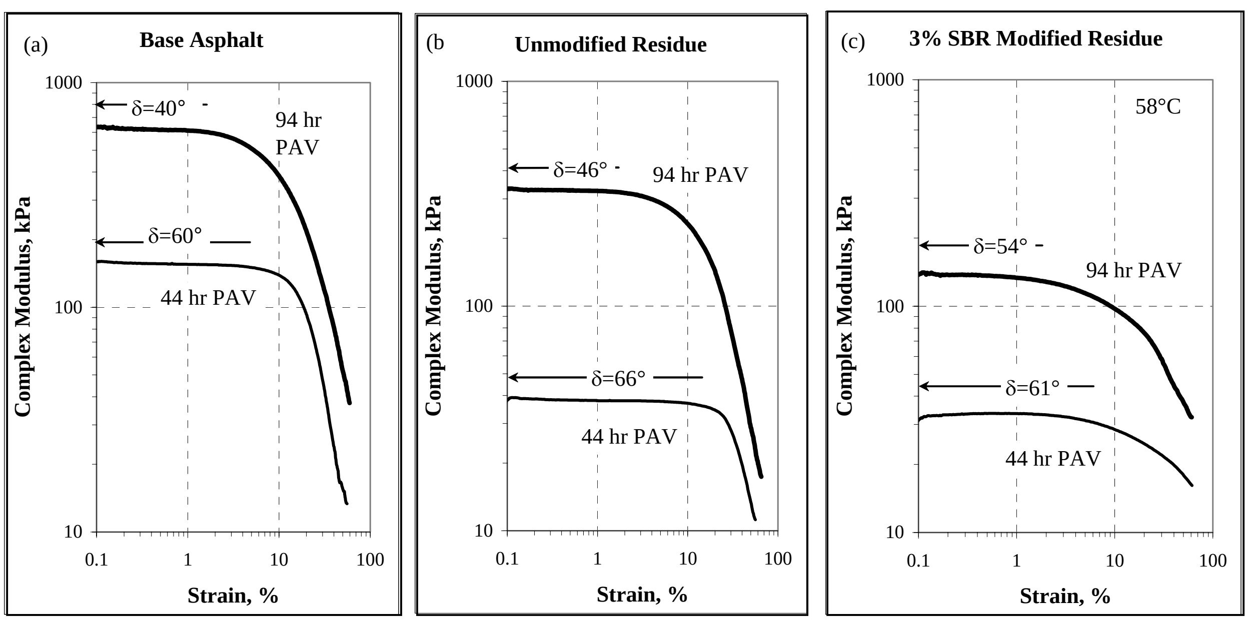


Figure 18. (a) Complex modulus and (b) phase angle of the base asphalt, unmodified Evotherm®, and 3% Styrene-Butadiene-Rubber (SBR) latex-modified Evotherm® binders as a function of PAV-aging. The SBR latex-modified Evotherm® residue shows only limited increase in G* after 44 and 94 hour PAV-aging time. The phase angle of the 3.0% SBR latex-modified residue also remain above 45° even up to 44 hours PAV-aging time.

In comparison, the Evotherm® binder modified with 3 percent SBR latex polymer shows only limited increase in G* to 4.5 and 7.9 MPa after 44 and 94 hours PAV-aging, respectively. The measured phase angles of this residue remain above or near 45° (44° after 94 hour PAV-aging time), indicating that the SBR latex- modified Evotherm® residue maintains balanced visco-elastic properties and can withstand applied strain without causing permanent binder damage.

Figure 19 shows the complex modulus, G*, of the base asphalt, unmodified Evotherm®, and 3.0 percent Butonal® NX1118-modified Evotherm® residues as a function of the applied strain at 58°C after prolonged PAV-aging time. The complex moduli of the base asphalt were 160 and 630 kPa at below 1 percent strain after 44 and 94 hour PAV-aging, respectively (Figure 19a). The phase angle of the neat asphalt after 94 hours PAV-aging is only 40 degrees, even at this elevated temperature. G* of this base AC after RTFO-aging at 58°C was only 2.5 kPa with δ=86 degrees, so the extremely high complex modulus (630 kPa) and very low phase angle (40 degrees) after 94 hours PAV-aging clearly demonstrate the susceptibility of the base asphalt to severe oxidative hardening upon prolonged PAV-aging time. The G* values of the neat asphalt after 44 and 94 hours PAV-aging times drop sharply at around 10 to 20 percent strain. The G* vs strain relationship for the unmodified Evotherm® residue is similar to the base asphalt except that the unmodified Evotherm® residue appears to show a lesser degree of oxidative hardening as indicated by lower G* and higher δ values after prolonged PAV-aging (Figure 19b). The G* vs strain relationship for the 3.0 percent Butonal® NX1118- modified Evotherm® residue shown in Figure 19c demonstrates reduced oxidative hardening of this binder; G*=33 and 140 kPa after 44 and 94 hours PAV-aging, respectively, and no sharp reduction in G* between 2 to 60 percent strain.



Note: PAV is Pressure Aging Vessel.

Figure 19. The complex modulus of (a) base asphalt, (b) unmodified, and (c) 3.0% Styrene-Butadiene-Rubber (SBR) latex- modified Evotherm® residues as a function of applied strain at 58°C. The phase angle, δ, at low strain (G* ~ constant) is also indicated in the figure.

7.0 DISCUSSION

In contrast to other warm mix systems, which artificially reduce the base asphalt viscosity at mixing and compaction temperatures, the emulsion-basedEvotherm® system does not directly alter the rheological properties of the base AC. The Superpave PG binder specification requires that the asphalt viscosity must be below 3 Pa·s at 135°C. For the unmodified asphalt binder, it is recommended to select mixing and compaction temperatures corresponding to binder viscosities of 0.17±0.02 Pa·s and 0.28±0.03 Pa·s, respectively [19]. The viscosity of an asphalt emulsion is independent of the base asphalt viscosity (rheology determined primarily by the water phase, not the asphalt phase) and meets these viscosity requirements even at below 80°C.

The study by McAsphalt [8] indicates that more than 50 percent of water in the Evotherm® emulsion was retained in the mix prior to compaction. The retained water forms a thin water film between asphalt-coated aggregate and acts as an effective lubricant to improve the workability of the mix during laydown and compaction. Even though the aggregate has to be above a minimum critical temperature to allow for adequate asphalt coating, workability of the Evotherm® mix is less sensitive to the aggregate temperature since the viscosity of water only increases 1.7x from 0.28 to 0.47 mPa·s when cooled from 100 to 60°C. The viscosity of a typical paving grade asphalt increases nearly 1000x over the same temperature range.

Data from the McAsphalt Evotherm® warm mix trials [8-10] show the penetration value of the recovered asphalt binder from the control hot mix pavement cores is generally 60 percent of the base AC value, but the recovered Evotherm® warm mix binder maintains 80 percent of the original asphalt penetration. The measured penetration of the unmodified Evotherm® emulsion residue, recovered by the procedure developed in this study, was 89 percent of the original PG 58-28 base asphalt penetration. The softening point and G*/sin(δ) values also confirm that the residue recovery procedure developed here closely simulates the heat aging history of the Evotherm® emulsion binder during mixing, laydown, and compaction in the field.

D. Newcomb, Vice President-Research & Technology, National Asphalt Pavement Association, states [2]: ”Binder aging is directly related to the production temperature of the mixture. In fact, the majority of binder hardening due to aging takes place in the hot-mix plant. If the plant temperature is reduced, the oxidative hardening of the binder will be reduced. Less hardening of the binder during construction could mean more flexibility and resistance to cracking in service. This could have implications concerning the specification of the low-temperature level for PG binders as well as better potential resistance to top-down and bottom-up fatigue cracking.”

In addition to the reduced mixing, laydown, and compaction temperature realized with the Evotherm® warm mix system, the thin water film present during mixing with the aggregate would reduce/prevent direct contact of the hot asphalt cement with air, further reducing the potential for oxidative hardening of the base AC. Penetration, softening point, Superpave dynamic shear rheometry and bending beam rheometry data, as well as fatigue resistance testing consistently demonstrate that the asphalt cement in the Evotherm® warm mix pavement could maintain the same or better flexibility after 10 to 15 years of in-service life when compared to a freshly-placed hot mix pavement. Addition of 1.0 to 3.0 percent SBR latex polymer could further prolong the service life of the Evotherm® warm mix pavement by enhancing the elasticity of the asphalt cement, especially at low temperature.

The concept of perpetual asphalt pavement is gaining acceptance in the United States [20] since it can extend the 20-year life expectancy of hot-mix asphalt pavement to greater than 50 years. M. Buncher and

C. Rosenberger of the Asphalt Institute [21] recently demonstrated that a perpetual pavement constructed with polymer-modified asphalt would result in a 14 percent reduction in overall life cycle cost when compared to a conventional unmodified asphalt pavement over a 40 year lifetime. The study assumes that polymer-modified asphalt is used for all base and wearing layers up to a total pavement thickness of 368 mm (14.5"). The study further assumes that the top 50 mm (2") wearing layer would be milled and resurfaced every 18 years for the polymer-modified pavement. The unmodified pavement requires resurfacing after 10 years, and a structural overlay of the top 165 mm (6.5") of the pavement after 18 years. Use of the SBR latex-modified Evotherm® warm mix pavement system in conjunction with microsurfacing as a periodic preventative maintenance treatment could provide even more significant savings in the life cycle cost of a perpetual asphalt pavement than incorporating standard polymer-modified hot mix asphalt alone.

8.0 CONCLUSIONS

Trial data generated by McAsphalt [8-10] demonstrate that a nearly 50 percent reduction in energy consumption and 60 to 80 percent reduction in CO, NO_x and SO_2 emissions can be achieved by using the Evotherm® warm mix system. The reduction in mixing temperature also leads to reduced heat hardening of the asphalt binder. Binder extracted from warm mix field cores maintained nearly 80 percent of the original base AC penetration value compared to only 60 percent penetration retention on binder recovered from the control hot mix cores.

The recovery procedure developed here closely simulates the heat history that the Evotherm® emulsion is exposed to during actual field mixing and paving processes. Superpave binder characterization of the Evotherm® residue suggests that Evotherm® warm mix pavement after 10 to 15 years of service would still have the same cold fracture and fatigue resistance as a freshly-placed hot mix pavement. FTIR data demonstrate that modification with SBR latex polymer does not prevent oxidation of the asphalt binder, but rather reduces the impact of undesired changes in rheological properties of the asphalt binder at low temperature. This would be expected to further prolong the service life of the Evotherm® warm mix pavement.

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