SUPERIOR AGING CHARACTERISTICS OF ASPHALT RUBBER

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ABSTRACT: This paper highlights the aging superiority of asphalt rubber and asphalt rubber hot mixes compared to conventional asphalts and mixes. The paper presents a review of the major studies available in the literature that demonstrated the improved aging resistance of asphalt rubber and asphalt rubber mixes. The paper provides results from standard tests conducted on unaged and laboratory-aged binders to evaluate the effect of rubber modification on the rheological properties of the binders and resistance to aging. Test results pertaining to engineering properties and performance behavior (fatigue cracking, permanent deformation, and low-temperature cracking) of aged and unaged asphalt rubber mixes are also provided for both laboratory-aged and field-aged specimens. The paper concludes that asphalt rubber hot mix offers an excellent product that surpasses the conventional unmodified mix with regard to long-term performance and long-lasting aging resistance superiority. Finally, the paper presents a few areas where additional work would be needed to quantify the benefits of asphalt rubber aging superiority more effectively and improve damage and performance models to capture these benefits more accurately in pavement design and rehabilitation.

KEY WORDS: asphalt rubber, aging, hot mixes, gap-graded, dense graded, open graded, performance, rehabilitation, fatigue, permanent deformation, thermal cracking, reflective cracking.

1. Introduction

This paper focuses on the aging characteristics of rubberized asphalt rubber binders and mixes. Asphalt rubber mixes (also called rubberized hot mix asphalt, RHMAs per the Caltrans Highway Design Manual [1] are produced by blending an asphalt rubber binder with aggregates to form a material suitable for constructing asphaltic layers such as overlays. The high viscosity of the CRM modified binders allows for a significant increase in binder content (up to 2% by total weight of the mix), without the potential of binder drain down or bleeding, compared to conventional asphalt concrete mixtures with similar aggregate gradation [2]. Because the modified binder contains the CRM particles, the aggregate matrix must have sufficient void space to accommodate these particles, and an appropriately-determined amount of the high-viscosity binder to improve the mix performance. As such, gap graded mixtures (RHMA-G) are the most suitable type of all RHMA mixes. RHMA-G tends to have a relatively lower stiffness than the conventional dense graded mix (also called hot mix asphalt, HMA), thus of fering two significant performance benefits to pavement: (i) higher resistance to fatigue and thermal (low-temperature) cracking, and (ii) higher resistance to asphalt permanent deformation due to its relatively higher elastic response to loading compared to unmodified mixes especially at high temperature. Dense graded aggregates are not suitable for use with high-viscosity CRM binders because they do not provide the void space to accommodate the CRM particles. Appropriate mixture design procedures must be performed to determine the mixture volumetric properties such as binder content and air voids content. The enhanced performance characteristics that an RHMA can provide include [3]:

- Improved resistance to surface initiated and fatigue/reflection cracking due to higher binder content and elasticity.
- Reduced temperature susceptibility.
- Improved low-temperature cracking resistance.
- Improved aging and oxidation resistance due to higher binder content, thicker binder film, and presence of anti-oxidants in the tire rubber.
- Improved resistance to asphalt rutting (permanent deformation) due to binder higher viscosity, softening point, and resilience (i.e., the binder is stiffer and more elastic at high temperature).
- Improved self-healing characteristics for fatigue damage recovery [4], [5], [6].
- Lower pavement maintenance costs due to improved pavement durability and performance.

Besides the above benefits, many studies on asphalt rubber binders and rubberized hot mix asphalts have concluded that such materials have superior aging characteristics compared to conventional binders and mixtures. It was found that aging is not as detrimental to performance of CRM modified binders and mixtures as to conventional counterparts. This paper will provide a review of major studies that compared the aging characteristics of CRM modified and unmodified binders and mixes with regard to aging effect

on the rheological properties of the asphalt binders and the engineering performance properties of HMA mixes in-service pavements.

2. Asphalt Aging

It is well known that bituminous materials can undergo two substantially different aging phases leading to their hardening or stiffening (or increase in viscosity). The causes of asphalt binder aging include [7]: progressive oxidation, evaporation, exudation, and steric hardening (molecular re-structuring). The two major aging processes (phases) that affect the asphalt and consequently its properties and performance are:

- **Short-term aging:** This occurs during production, transportation, and placement of the bituminous material. During this phase, the asphalt binder is subjected to elevated temperatures (during its mixing) and high degree of exposure to air in a relatively short period of time (during its placement). As a result, volatilization of the low-molecular components of the asphalt occurs accompanied by oxidation causing asphalt hardening. This is a relatively rapid process.
- **Long-term aging:.** This occurs due to exposure of the in-place asphalt to solar radiation and heating in addition to progressive oxidation over several years in the life of the pavement. Other factors that can contribute to aging of in-place asphalt materials include steric hardening (molecular re-structuring) and actinic light (mainly ultraviolet radiation). These processes are rather slow and tend to take place over a relatively long time. Additionally, they can be affected by the mix volumetric properties such as air voids content (e.g., higher air voids content results in higher oxidation and more hardening of the mix), and even the location of the asphalt layer in the pavement system (e.g., asphalt layers placed deeper in the pavement section age considerably much slower than a surface layer directly exposed to air).

While the long-term aging is a complex process, laboratory accelerated aging has been used and found to be effective in simulating field aging of asphalt binders and evaluating the aging characteristics of both modified and unmodified asphalt mixtures [8],[9]. Additionally, the use of rheological properties of the asphalt binders has been found to be adequate for characterizing the performance of asphalt-aggregate mixtures [10],[4]. Further details on asphalt binders aging can be found in the *Shell Bitumen Handbook* [8] and the *SHRP-A-390 report: Laboratory aging of asphalt-aggregate mixtures* [9].

3. Laboratory Accelerated Aging

There are several methods designed to simulate field aging in the laboratory. These procedures aim at simulating field hardening that occurs to asphalt binders and mixtures using accelerated methods. In the laboratory, asphalt aging is primarily conducted using extended heating for binders, or loose

bituminous materials prior to compaction. Other aging methods include a combination of extended oven aging, high and low pressure oxidation, and ultraviolet and infrared light treatment. In 2003, Airey presented a comprehensive review of the numerous test methods routinely used for accelerated laboratory aging of bituminous pavement materials; both binders and mixtures [11].

3.1 Asphalt Binder Aging

Short-term aging (hardening) of asphalt binder occurs primarily due to volatilization of the asphalt within the asphalt mixture during production and placement. The most commonly used accelerated laboratory tests to simulate the hardening that takes place during asphalt production are the extended high-temperature heating tests; namely the thin film oven test (TFOT) and the rolling thin film oven test (RTFOT). These two tests are able to simulate hardening of conventional unmodified asphalt binders [11]. The RTFOT was developed by the California Division of Highways [12] in which a sample of 35g of asphalt binder is added to a set of 8 vertically-rotating glass bottles (at 15 rev/min) while air is blown in each sample (at a rate of 4000 ml/min) at its lowest travel position. The test is run for 75 minutes at a temperature of 163 ^{o}C to form a 1.25 mm thin film around the inner surfaces of each bottle that mimics the asphalt coating on aggregate. This way, the bitumen film is exposed to both heating and oxidation while the continuous movement ensures that no skin develops that would otherwise shield and protect the binder [12]. Several modifications including changing the film thickness, and exposure duration have been made [11]. For example, for modified asphalt binders exhibiting higher viscosities (such as rubber-modified binders), many modifications of the RTFOT apparatus have been implemented (e.g., Bahia et al. 1998) [13] to allow for proper aging of these binders by reducing binder films and preventing roll-out. In Bahia et al.'s apparatus, a set of steel rods each 127 mm long and 6.4 mm in diameter are installed inside each glass bottle during oven aging to effectively spread the higher-viscosity binder into thin film by creating shear forces within the binder as it rotates in the bottles [13]. The RTFOT method has been standardized as ASTM D2872-04 and AASHTO T240-00: *Standard Test Method for Effect of Heat and Air on a Moving Film of Asphalt (Rolling Thin-Film Oven Test)*. The equivalent California standard test is Test Method 374: *Method for determining asphalt durability using the California tilt-oven durability test*.

Long-term aging of the asphalt binder in the mixture occurs after placement and while the pavement is in service as a result of oxidation and steric hardening over a long period of time. The SHRP-A-370 project (*Binder Characterization and Evaluation: Test Methods*) developed the pressure aging vessel (PAV) method to simulate the long-term aging of in-place asphalt binder by oxidation [14], [15]. In this method, the asphalt binder is first hardened (aged) in the RTFOT or TFOT, then the asphalt aged residue is transferred to the PAV to subject it to oxidation. A sample of 50g of bitumen is placed in a 140 mm diameter pan to form a 3.2 mm film within the heated vessel, then air-pressurized to 2.07 MPa for 20 hours at a temperature of 90-110 ^{o}C. The PAV method has been standardized as AASHTO R28-02 or ASTM D6521-08: *Standard Practice for Accelerated Aging of Asphalt Binder Using a Pressurized Aging*

Vessel (PAV). It is reported in the test procedure that this test when conducted on RTFOT residues can provide an estimate of the physical and chemical properties of asphalt binders after five to ten years in service. Many studies, however, pointed out the limitations of this test method; for example ignoring the influence of air voids on asphalt aging [16]. Additional tests that have been also used to simulate the long-term aging involve subjecting RTFOT-aged binder residues to ultraviolet (UV) and infrared (IR) light to mimic the contribution of sun radiation to asphalt mixtures aging [17],[18]. The UV radiation affects the upper 1-2 mm of the surface asphalt layer, which could be neglected, whereas the IR radiation effect can be greater resulting in dramatic increase of the asphalt mean temperature [19].

In summary, laboratory accelerated aging is most commonly performed by RTFOT to simulate short-term aging that occurs during asphalt mixture production and using RTFOT/PAV to simulate the long-term aging by oxidation that occurs over long period of time during pavement service life.

3.2 Asphalt Mixture Aging

Similar to asphalt binder accelerated aging, asphalt mixtures have also been aged artificially in the laboratory using extended heating, oxidation, UV/IR exposure, and steric hardening [11]. The purpose of aging the mixture is to evaluate the effect of aging on key material parameters such as stiffness, or performance indicators as asphalt fatigue and permanent deformation (rutting). Extended heating subjects the loose mixture to high temperature for specified period of time before testing. The oxidation test subjects the mixture or laboratory specimens to a combination of extended heating and pressure oxidation, whereas the UV/IR treatment exposes the specimen or mixture to UV and IR radiation. In these tests, the loose mixture material may be aged first, then compacted to simulate the short-term aging and its effect on specimen performance and strength. Von Quintus et al. (1991) [20] investigated the use of forced draft oven aging in which loose mixture samples are heated at 135 ^{o}C for 4 hrs prior to compaction, to simulate short-term aging that occurs during production of asphalt mixtures. This method, named the short-term oven aging (STOA), is described in AASHTO PP2: *Standard Practice for Mixture Conditioning of Hot Mix Asphalt (HMA)*.

To simulate the long-term aging of asphalt concrete, compacted asphalt mixture specimens are subjected to aging (extended heating, oxidation, UV/IR radiation) then evaluated for performance and other key parameters. Von Quintus et al. (1991) [20] also investigated the long-term aging of compacted specimens in a forced draft oven by aging the specimen for 2 days at 60 ^{o}C followed by 3 days at 107 ^{o}C. This method is called long-term oven aging (LTOA). Another variation of the LTOA procedure involves aging the loose asphalt mixture using the STOA method, then compacting the aged mixture, followed by additional aging in a forced draft oven at 85 ^{o}C for 5 days [21]. Some modifications to the SHRP STOA and LTOA methods have been made. Oxidation of compacted specimens has been performed in a modified triaxial cell using the method of low pressure oxidation (LPO).

4. Aging Performance of Asphalt Binders

Because it is the binder that ages in the mix, most studies on aging have focused on studying the aging performance characteristics of the binder. However, some studies have also investigated the aging properties of asphalt mixtures which provide a more realistic investigation that considers the influence of all variables (e.g., air voids) on aging, and will be presented in a subsequent section of this paper. In the following, a review of major studies on accelerated laboratory aging of crumb rubber modified and unmodified asphalt binders is provided to demonstrate on the beneficial impact of rubber modifications on aging characteristics.

4.1 Testing of Binder Rheological Properties

Short-term and long-term aged asphalt binders (respectively, RTFTO-aged and RTFTO/PAV-aged residues], both modified or unmodified, are tested in many different ways to evaluate the impact of aging on their rheological characteristics. The use of rheological properties of asphalt binders provides for an efficient means for characterizing the asphalt mixtures [10],[4]. The same tests are usually run on the unaged binders to serve as "Controls" for comparison purposes. The following are the most commonly used laboratory tests conducted on asphalt binders along with brief discussion of the parameters that are quantified with the test:

4.1.1 Dynamic Shear Rheometer (DSR) Test

This test is designated as *AASHTO T 315: Standard Method of Test for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)]*. This test measures the viscoelastic properties of the asphalt binder including complex shear modulus (G*) and phase angle (δ) of the aged and unaged modified and unmodified binders. G* provides a measure of the total resistance of the binder to deformation due to repeated shearing forces and consists of two components: (1) the elastic (or storage) modulus (G'), and (2) the viscous (or loss) modulus (G''). Both G' and G'' are related to G* and to each other through the phase angle. The phase angle, δ, represents the phase or time difference between the applied stress and the strain response, and therefore serves as an indicator of the relative amount of recoverable and non-recoverable deformation. The phase angle is an important parameter for characterizing the flow properties or the level of viscoelasticity that exists in the asphalt [22]. The lower the phase angle, the more elastic is the binder. A perfectly elastic material exhibits a zero lag time as the strain response immediately coincides with the applied stress, whereas a viscous material (e.g., asphalt binder) exhibits a large time lag approaching 90 degrees (Liang and Lee 1996) [23]. Both G* and δ are basic parameters that can affect the performance of the HMA mix, and are highly dependent on temperature and loading frequency. The rutting resistance of the asphalt mixture is strongly associated with the term (G*/sin δ) and the fatigue resistance with the term (G*.sin δ). To resist rutting, and asphalt binder should be both stiff and elastic, therefore, the complex shear modulus elastic portion, (G*/sin δ)

should be large. Superpave specifies a minimum value for (G*/sin δ) ≥1.0 kPa for unaged binder, and ≥2.2 kPa for RTFO-aged binder. In order to resist fatigue cracking, an asphalt binder should be elastic but not too stiff, therefore, the viscous portion of the complex modulus (G*.sin δ) should be small. Superpave recommended a maximum value of (G*.sin δ)≤5 MPa for PAV-aged binder. Polymer-modified asphalt binders generally have a higher G* (stiffer) and a lower δ (more elastic) than their corresponding unmodified binders. Additionally, the ratio (G'/G'') has also been used to describe the elastic behavior of the binder; the higher the ratio the more elastic is the binder and the better the rutting resistance of the asphalt.

4.1.2 Bending Beam Rheometer (BBR) Test

This test is designated as *AASHTO T 313: Standard Method of Test for Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer (BBR*). This test provides a measure of low temperature stiffness and relaxation properties, which give an indication of the binder's ability to resist low temperature cracking. The creep loading simulates the thermal stresses that build up gradually in asphalt pavement as temperature drops. The test can be run at any temperature between -36 ^{o}C and 0°C, the selection of which depends on the lowest temperature anticipated for the project site. The test provides an estimate of the creep stiffness and m-value representing the slope of the stiffness-vs.-time curve (log-log scales) at 60 seconds. Low m-values indicate lower ability of the binder to relax stress built up at low temperature (slower stress relaxation). Therefore, Superpave specifies a BBR creep stiffness of less than 300 MPa at 60 seconds for PAV-aged binder residue and a minimum m-value of 0.300.

4.1.3 Penetration Index (PI) Test

This test is designated as *AASHTO T 49-06 or ASTM D 5: Standard Method of Test for Penetration of Bituminous Materials*). This test measures the penetration index of asphalt binder which provides an indication of its temperature sensitivity.

4.1.4 Viscosity Test

This test is designated as *AASHTO T 316: Standard Method of Test for Viscosity Determination of Asphalt Binder Using Rotational Viscometer, or ASTM D4402- 06: Standard Test Method for Viscosity Determination of Asphalt at Elevated Temperatures Using a Rotational Viscometer)*. This test measures the viscosity of modified and unmodified asphalt binder at elevated temperature in the range from 60°C to over 200°C. Viscosity provides an indication of the workability of the hot asphalt concrete mixes containing the tested binder. Superpave specifies a viscosity of 3 Pa.s at 135 ^{o}C (Shen et al. 2005) [24].

4.1.5 Direct Tension Tester (DTT) Test

This test is designated as *AASHTO T 314 and ASTM D 6723 Test Method for Determining the Fracture Properties of Asphalt Binder in Direct Tension DT)*. This test is designed to measure the strength and relaxation of the asphalt binder at the critical cracking temperature (low temperature). The test can be run on both aged and unaged binders to determine their resistance to low temperature cracking. The basic DTT test pulls apart (at a constant rate of elongation) a specimen of the asphalt binder and determines its stress and strain at failure. The DTT is used in conjunction with the BBR test to determine the binder's low temperature PG grade.

4.1.6 High Pressure-Gel Permeation Chromatographic (HP-GPC) Test

This test is used to determine the molecular size distribution (MSD) of asphalt binders (aged, unaged, modified and unmodified). This test is adopted from the polymer industry and includes the classification of the chemical composition of the bitumen into three groups based on molecular size by analyzing the HP-GPC chromatographic profiles (chromatograms) of the binders [25]. These groups are the large molecular size (LMS), medium molecular size (MMS), and small molecular size (SMS). The molecular size distribution can have a significant effect on the physical properties of the binder [26],[27]. Additionally, this classification was found to be effective in analyzing the aging process that affects asphalt binders [28],[29]. The chromatograms provide some insight about what fractions of the asphalt binder were aged after a long-term aging [25]. Upon aging, the LMS fraction tends to increase, whereas the MMS and SMS percentages decrease. The changes in the molecular size distribution can significantly influence the asphalt binder consistency and consequently its physical properties (Shen et al. 2006) [29]. Aging tends to generate a greater number of LMS particles for unmodified binders compared to modified binders. Therefore, CRM modification tends to extend the long-term performance of asphalt binders through decelerating the generation of LMS particles [25].

4.2 Performance Studies

4.2.1 Huang (2008)[22]

Huang (2008) [22] studied the effect of rubber addition and PAV-aging duration on the rheological properties of neat (unmodified) and rubber-modified asphalt binders for both unaged and aged samples. Figure 1 shows the viscosity-phase angle plots for two asphalt binders (AAD-1 and ABD) and their corresponding rubber treatment. AAD binder is a gel-type binder (less compatible containing higher amount of asphaltene) and ABD is sol-type binder (more compatible containing lower amount of asphaltene). The lower the phase angle at the same viscosity, the higher the susceptibility of the asphalt binder to thermal and fatigue cracking at low temperatures. Alternatively, the higher the phase angle at the same viscosity, the better is the (viscous) flow properties of the asphalt. In order to provide for stress relaxation, an aged oxidized asphalt must maintain a certain level of viscous flow behavior at low temperature [22]. Figure 1 shows the following:

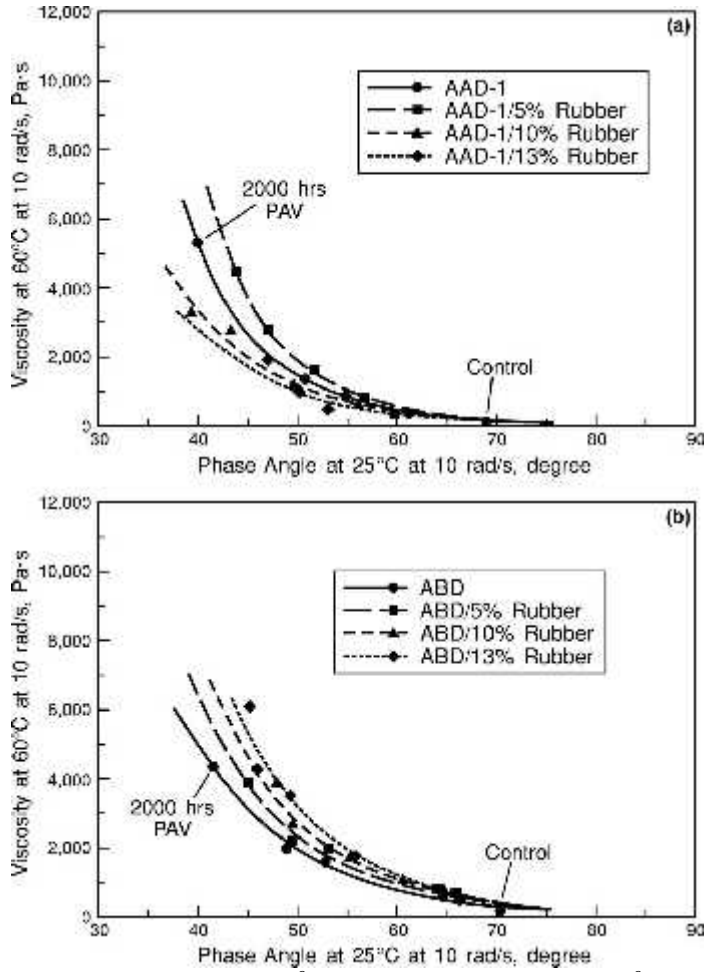
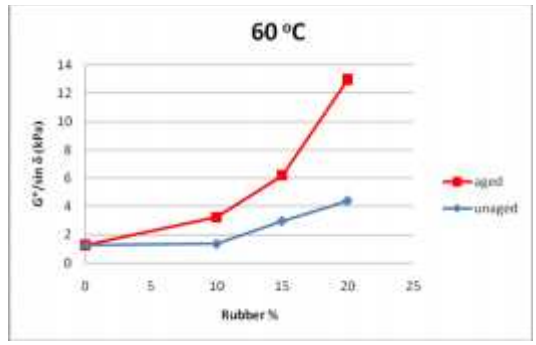


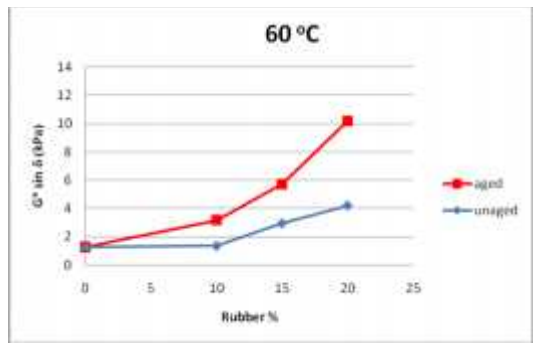
Figure 1. *Viscosity at 60 °C versus phase angle at 25 °C for CRM-modified and unmodified asphalt binders after various PAV aging durations: (a) binder AAD-1, and (b) binder ABD (from Huang 2008) [22].*

- As aging time increase, the viscosity increases and phase angle decreases exponentially. The decrease in phase angle at same viscosity indicates the less resistance of the binder to thermal and fatigue cracking at low temperature, as mentioned above.

- Rubber-modified binders exhibit higher phase angle than unmodified binders, thus lower susceptibility to thermal and fatigue cracking. However, this behavior can be highly binder specific. For the less-compatible binder as AAD1, rubber improves resistance to cracking for the 5% concentration, whereas higher concentrations of rubber were detrimental. On the contrary, the highly-compatible asphalt ABD consistently increased phase angle at the same viscosity with increasing rubber content for all aging durations.
- Rubber modification increases phase angle for a given viscosity (or a given aging duration). That is, aging is less detrimental to the degree of resistance of the binder to thermal and fatigue cracking for the rubber-modified binders than for the unmodified neat binders. The "highly-compatible" ABD asphalt aged to 4000 Pa.s viscosity (see Figure 1-b) from the "Control" unaged values of viscosity and phase angle, would exhibit δ of 48° for the 13% aged rubber-modified binder compared to δ of 42° for the aged unmodified binder. This 6°-increase in δ due to rubber modification of the aged binder can result in dramatic improvement in cracking resistance. Huang (2008) [22] concluded that rubber modification of asphalt binders generally increased the binder viscosity, improved their resistance to oxidative aging, and imparted elasticity to the binder thus improving its fatigue cracking resistance.



(a)



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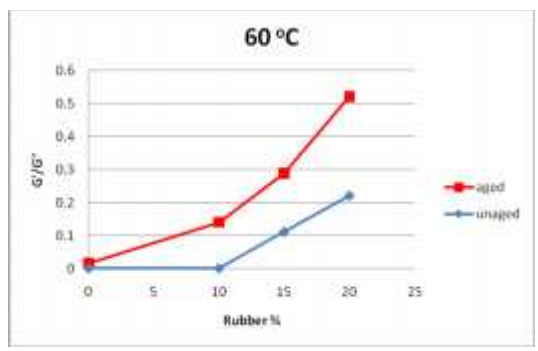


(c)

Figure 2. *Effect of CRM content and aging on the rheological properties of DSR tested binders at 60 ^{o}C. Data obtained from Liang and Lee (1996) [23].*

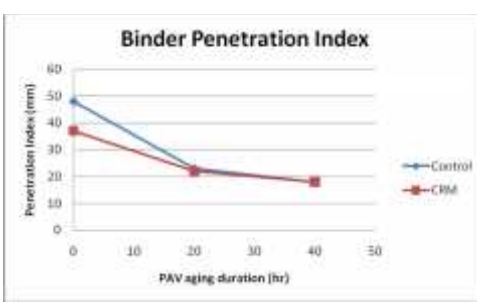
4.2.2 Liang and Lee (1996) [23]

Liang and Lee (1996) [23] studied the effect of short-term aging (STA) and long-term aging (LTA) of crumb rubber modified asphalt paving materials on a number of rheological parameters of the binder and engineering properties of the HMA mixes. Various crumb rubber contents were used. The various binders (unaged, TFOT-aged, modified and unmodified) were tested using the DSR (AASHTO TP5) for both G* and δ at three temperatures of 40 ^{o}C, 50 ^{o}C, and 60 ^{o}C. Figure 2 shows results for DSR tests conducted at 60 ^{o}C. The following can be observed:

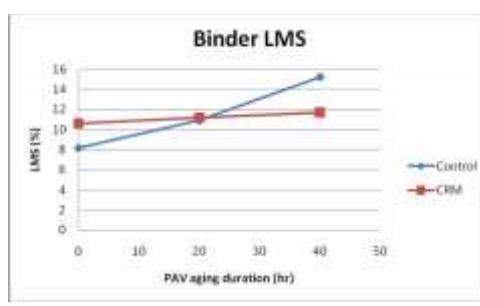
- STA increased the viscosity of CRM modified binder more significantly than the unmodified binders,
- STA increased G* (and its components G'and G''), and the increase was more significant for the modified binders, and
- STA increased the parameters (G*/sin δ), (G*.sin δ), and (G'/G''). The increases became more significant as the crumb rubber content increased, as shown in Figure 2. Interestingly, as can be seen from Figure 2 the higher the crumb rubber content the better are the aging characteristics of the modified binder compared to the unaged counterpart with respect to fatigue (G*.sin δ, and permanent deformation (G*/sin δ and G'/G''). The rheological characteristics of rubber modified binders seem to improve with aging and with increasing crumb rubber content.

4.2.3 Xiao et al. (2010) [30]

Xiao et al (2010) [30] investigated aging effect on the rheological characteristics of CRM modified and unmodified binders. A PG 64-22 binder was used as the neat (unmodified, base) binder and rubber modification was performed using 10% (by weight of the base binder). The CRM was prepared in the laboratory using the wet process with rubber particles passing #40 mesh. Modified and unmodified binders were first RTFO-aged at 163 ^{o}C for 85 minutes, then the RTFO-residues were further long-term aged in PAV at 100 ^{o}C for two aging durations of 20 and 40 hrs. After they have been PAV-aged, the binders were subjected to a number of tests including DSR, penetration, BBR, and high pressure-gel permeation chromatography (HP-GPC). The unaged binders were also tested, however only for the penetration index and HP-GPC molecular size classification. Figure 3 show the rheological properties of



(a)



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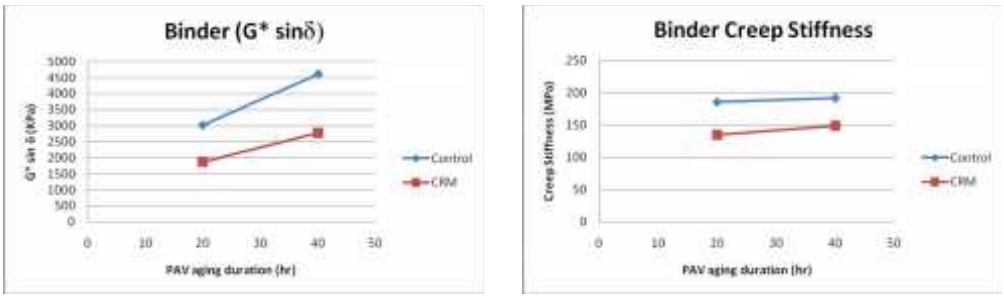


(c) (d)

Figure 3. *Accelerated long-term aging effect on rheological properties of unmodified (control) and CRM modified binder (PG64-10) with 10% CRM. Data were obtained from Xiao et al. (2010).*

the binders for the three aging states (unaged, 20 hr-PAV, and 40 hr-PAV) based on data provided by Xiao et al. (2010) [30]. The following can be concluded:

- In general, the CRM modified binder shows lower values of the main rheological parameters measured at the three aging states, compared to the unmodified (Control) binder. The reduced values of penetration index, (G*.sin δ), creep stiffness, and %LMS are beneficial in improving the binder fatigue resistance and extending its fatigue life. This in turn can extend the fatigue life of the CRM modified mix.
- The CRM modified binder is more resistant to aging than the unmodified binder as evidenced from the smaller slopes of the modified binder's property-versus-aging duration lines shown in Figure 3. The higher slopes exhibited by the unmodified binder indicate its higher susceptibility to aging than the modified binder (rheological properties more sensitive to changes in aging duration). Therefore, changes in the rheological properties tend to be more significant for the unmodified binder in response to aging than the modified binder. Modification of binders with the use of crumb rubber improves their aging resistance [25].

4.2.4 Shen et al. (2005)[24]

Shen et al. (2005) [24] studied the influence of CRM incorporation on the effectiveness of using rejuvenating agents in changing the performance and rheological properties of aged binders in recycled asphalt pavements (RAP) applications. Two CRM binders and one base (Control) binder of PG76-22 were RTFO-aged then restored by blending the aged binders with one of two selected rejuvenating agents: commercial agent and a softer binder PG52-28. Several percentages of each of the rejuvenating agents were used. The blends (including those without rejuvenating agent) were subsequently RTFO/PAV-aged prior to testing for viscosity (at 135 ^{o}C), DSR, and BBR.

The viscosity of the un-rejuvenated CRM-modified and unmodified binders at both the unaged and RTFO-aged states is summarized in Table 1. As expected, aging increased the viscosity for all binders; however, more significantly for the unmodified (Control) binder. As shown in Table 1, the higher rate of increase in viscosity of the Control PG76-22 binder due to aging (439%) compared to that of CRM-modified binders Type I (124%) or Type C (241%) suggests that the unmodified binder experienced more severe aging under the same RTFO aging conditions than the CRM-modified binders. Therefore, CRM modification of asphalt binders is beneficial in enhancing their aging resistance.

Binder type	Unaged viscosity (Pa.s)	RTFO-aged viscosity (Pa.s)	% increase
Unmodified PG76-22 (Control)	1.80	9.71	439
CRM modified binder (target PG76-22) Type I	1.95	4.37	124
CRM modified binder (target PG76-22) Type C	2.50	8.52	241

Table 1. *Data obtained from Shen et al. (2005) [24]*

The economic benefits of recycling are greater when recycling is performed with rubberized hot mix asphalt pavements than with conventional pavements. This is demonstrated in the following findings from Shen et al.'s [24] study:

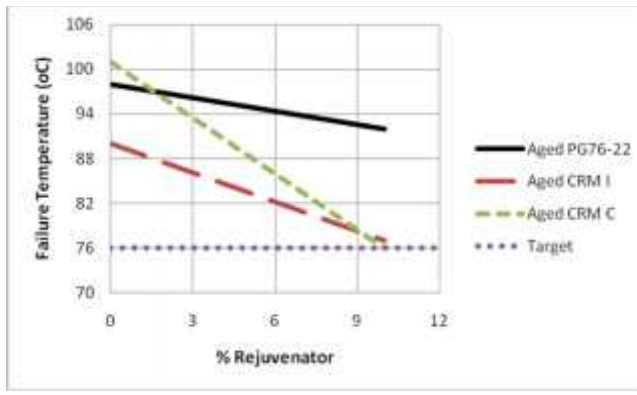
- Figure 4-a shows the effect of rejuvenator content on failure temperature (the upper value of the PG76-22 unmodified binder of 76 ^{o}C) of unmodified and modified binders measured with DSR at high temperature. The *blends* comprising the original binder, the rejuvenating agent (if any), and crumb rubber (if any) were not aged. It is obvious that aged CRM modified binders as well as the aged unmodified (control) binder can be rejuvenated back to a targeted PG grade using the proper rejuvenating agent. However, the CRM modified aged binders required less amounts of rejuvenating agents (~11%) than the aged control binder which requires a much higher amount to reach the target temperature.
- Figure 4-b shows effect of rejuvenator content on failure temperature of binders tested with DSR at intermediate temperature. The blends were RTFO/PAV-aged. Superpave specifies a failure intermediate temperature of 28 ^{o}C or less for PG76-22. As can be seen, the blends with unmodified binder required about 2.8% rejuvenating agent to meet the Superpave criterion, however, the blends with modified binders required no rejuvenation to obtain the temperature requirement in the intermediate temperature range.
- Figure 4-c shows the m-value results obtained from testing the blends with the BBR at low temperatures of -12 ^{o}C and -18 ^{o}C. The blends where RTFO/PAV-aged. The creep stiffness for all

- blends met the Superpave criterion of maximum 300 MPa (not shown). However, the m-values of the blends varied. In order to meet the m-value criterion (a minimum of 0.30), the blends with unmodified binder required ~10% rejuvenating agent, whereas blends with CRM C required only ~2.5%, and the blends with CRM I required no rejuvenation.

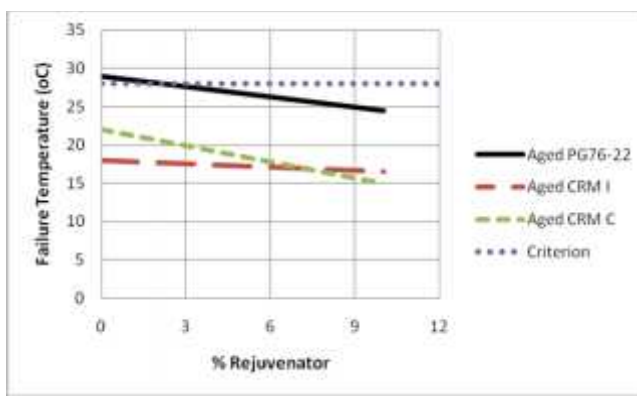
This proves the cost effectiveness in using asphalt rubber mixes in flexible pavements construction not only with regard to its improved performance and aging superiority, but also in cost savings associated with using smaller amounts of rejuvenators in recycling.

4.3 Self-Healing of Asphalt Binder

Only a few studies used crumb rubber modified binders in evaluating the healing properties of asphalt binders. Cheng et al. (2002) [31] evaluated with the use of surface energy concept one rubber modified binder aged in the laboratory for 3 and 6 months. Surface energy of the asphalt binders, which is used to assess their healing characteristics, vary considerably between asphalt binders and is a property commonly used in physical chemistry of surfaces [32]. The asphalt surface energy was determined for this type of binder in addition to other conventional binders using the Wilhelmy plate method [32],[31]. The Wilhelmy plate method measures surface energy of asphalt by obtaining the dynamic contact angles between the asphalt plate and liquid solvent whose surface energies are known [31]. The total surface energy of an asphalt binder or aggregate is composed of a non-polar component and an acid-base (A-B) component [33]. The non-polar component is termed the Lifshitz-van der Waals (L-W) component. The lower the L-W component of the surface energy and the higher the A-B component of the surface energy the better is the healing potential of the binder. Results

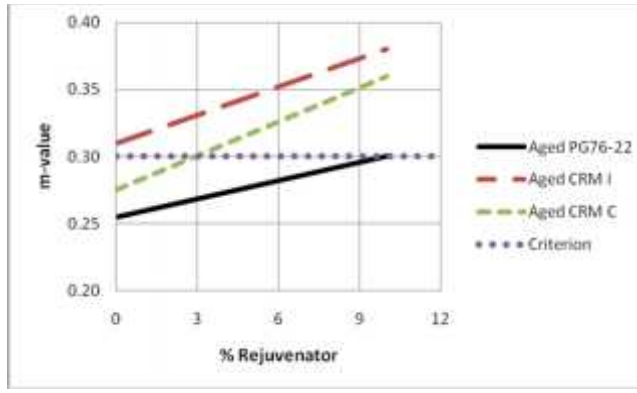


(a)



(b)

from Cheng et al. (2002) [31] indicated that aging can significantly affect the surface energy properties of the asphalt. Aging significantly increases the L-W component of the surface energy and decreases the A-B component of the surface energy. The healing ability of the crumb rubber modified binder was found to drop significantly with aging. Unfortunately, the conventional binders studied by Cheng et al. (2002) [31] were not aged. Therefore, a comparison between the rate of deterioration in the healing of the crumb rubber modified binder and its base (unmodified) binder could not be made. However, since many studies reported in this White Paper and elsewhere confirmed the superior aging characteristics of rubber modified binders compared to their corresponding base binders, it is expected that rubber modified binders would have a longer-lasting healing characteristics against fatigue damage compared to unmodified binders.



(c)

Figure 4. *Effect of rejuvenator on rheological properties of modified and unmodified binders. (a) Failure temperature of unaged blends, (b) Failure temperature of RTFO/PAV aged blends, and (c) BBR m-value of RTFO/PAV aged blends. Data obtained from Shen et al. (2005) [24].*

5. Aging Performance of Compacted Mixtures

A fewer studies on aging characterization of compacted crumb rubber modified and unmodified mixtures are available in the literature. In this section, the superiority of asphalt mixtures produced with crumb rubber modified binders is demonstrated by testing accelerated laboratory-aged specimens and long-term field-aged specimens for a number of mechanical properties and performance behavior (fatigue cracking, rutting, and low-temperature cracking).

5.1 Performance of Laboratory-Aged Mixes

Liang and Lee [23] aged compacted asphalt mixtures using procedure described by Von Quintus et al. (1991) [20]. The aging of asphalt mixtures (both CRM modified and unmodified) was performed in a forced-draft oven. The short-term aging (STA) was done by heating the compacted specimens at 275 ^{o}C for 8 hrs, and the long-term aging (LTA) was performed by heating the specimens at 140 ^{o}C for 2 days, then at 225 ^{o}C for an additional 5 days. All unaged and aged specimens were tested for resilient modulus at three temperatures; namely 5 ^{o}C, 25 ^{o}C, and 40 ^{o}C. It was found, as expected, that aging tends to

increase the resilient modulus of asphalt mixes. Table 2 shows ratio of aged to unaged modulus for both STA and LTA cases. As can be seen in Table 2, aging generally has a greater effect on CRM-modified HMA mixes than on the conventional mixes, as evident from the higher modulus ratios for the asphalt rubber mixes. Therefore, modified binders tend to be advantageous to the HMA mix performance in response to aging when compared to conventional HMA mixes.

	Ratio=(Mr_{STA}/Mr_{unaged})			**Ratio=(Mr_{LTA}/Mr_{unaged})**		
Mixture	Mr test at 5°C	Test at 25°C	Test at 40°C	Test at 5°C	Test at 25°C	Test at 40°C
Conventional HMA (AC-20) mix	1.061	1.074	2.222	1.041	1.095	1.047
Modified binder: (AC-5)+15% crumb rubber. Dense graded mix	1.094	3.12	1.583	1.130	3.038	1.522

Table 2. *Effect of aging on total resilient modulus (Mr) of unmodified and CRM modified mixes (Data obtained from Liang and Lee 1996) [23]*

5.2 Performance of Field-aged Mixes

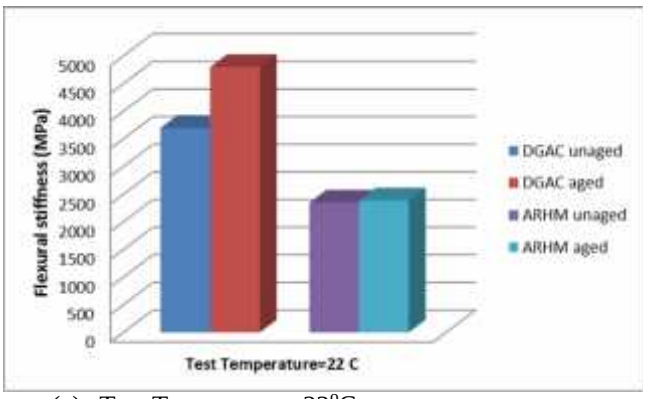
Unlike accelerated aging performed in the laboratory, studies comparing long-term field aging between asphalt rubber and conventional asphalt mixtures are quite few in the literature. Prominent among those few studies is the work done by Shatnawi (1997) [34], Raad et al. (2001) [35] and Saboundjian et al. (2004) [36].

5.2.1 Raad et al (2001) and Sbounjian (2004)

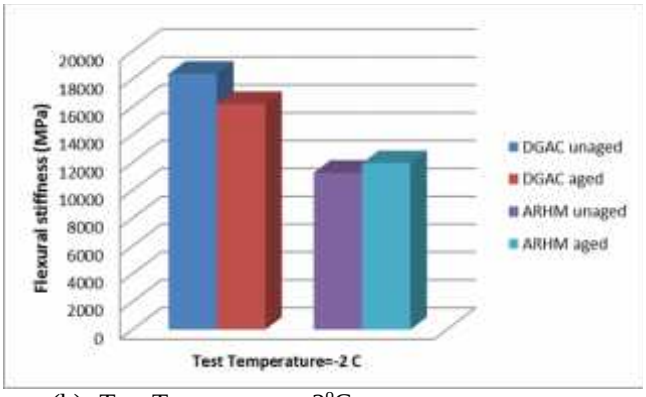
Raad et al (2001) [35] and Sabounjian (2004) [36] evaluated the fatigue, rutting, and thermal (low temperature) cracking resistances of field-aged conventional dense graded asphalt (DGAC) and gap graded asphalt rubber hot (ARHM-GG) mixes by conducting a series of laboratory tests. In those two studies, specimens were obtained from a field test section consisting of asphalt rubber and conventional asphalt mixes, both right after construction in 1990 (unaged) and 10 years later in 2000 (aged). The test section was constructed in a parking lot in southern California, so the materials were not subjected to a substantial traffic during the 10-year aging period. Therefore, performance differences between specimens can be solely attributed to the effect of aging on the materials without any contribution from traffic. The DGAC consisted of the standard Caltrans ¾” aggregate mix (1998 Caltrans Satndard Specifications, Section 39-2.02) with 5.7% (by weight) AR-4000 binder, and 1.6% air voids. The ARHM-GG consisted of the ¾” mix according to the then-proposed Standard Specifications for Public Works Construction (Section 203-11.3), and AR-4000 asphalt binder modified with 4% asphalt modifier and 20% rubber (by weight of asphalt binder), 7.3% binder content (by weight of total mix) and 1.6% air voids. Results from the two studies are presented in the following sections.

5.2.1.1 Fatigue Cracking

Laboratory strain-controlled beam fatigue tests were performed at 22 ^{o}C and -2 ^{o}C using MTS closed-loop hydraulic testing equipment and a haversine displacement pulse having a width of 0.1 second and 60 cpm frequency. In all beam fatigue tests, it was assumed that (i) the initial stiffness corresponds to stiffness measured from the beam center deflection at the 50th load repetitions, and (ii) fatigue failure occurs when the stiffness drops by 50% from the initial stiffness value. The results of the strain-controlled beam fatigue experiments on aged and unaged DGAC and ARHM-GG specimens are shown in Figures 5 and 6. The following was observed from this study:



(a) Test Temperature=22°C

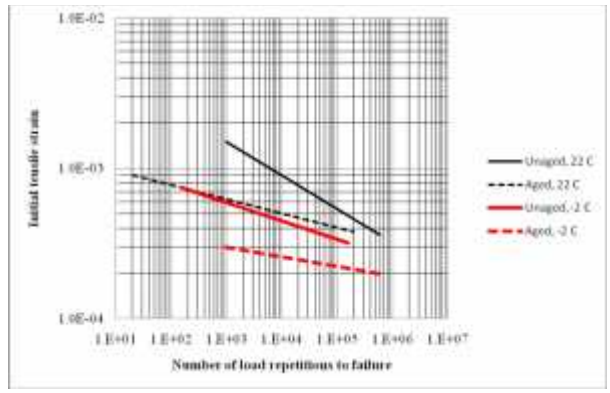


(b) Test Temperature=-2°C

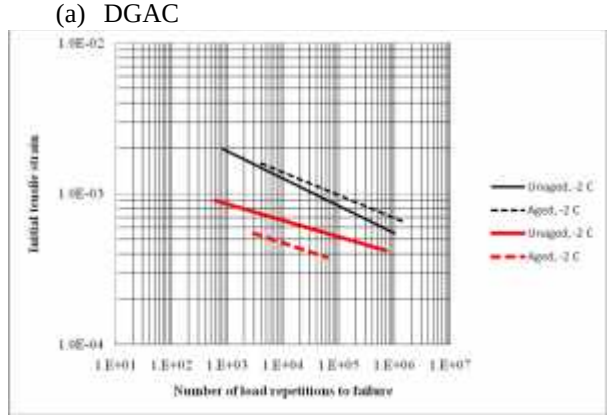
Figure 5. *Effect of aging on flexural stiffness of DGAC and ARHM at test temperature of (a) 22 ^{o}C and (b) -2 ^{o}C. Data obtained from Raad et al. (2001).*

- DGAC mixes exhibited larger difference in flexural stiffness between unaged and aged states compared to ARHM-GG mixes, as can be seen in Figure 5. The *average* flexural stiffness of DGAC beams increased by aging when tested at 22 ^{o}C, whereas the average stiffness dropped when testing was done at -2 ^{o}C. Raad et al. (2001) explained this rather unexpected trend as the influence of decreasing temperature on increasing stiffness is less significant for aged than unaged DGAC specimens. The ARHM-GG specimens showed slight variation in stiffness between aged and unaged conditions indicating the better resistance of ARHM-GG material to aging. The superior performance of ARHM mixes is primarily due to the improved rheological properties of the asphalt rubber binder against aging.

- The fatigue behavior of DGAC specimens indicates that aging reduces beam fatigue life, and the reduction is more significant for tests performed at -2 ^{o}C than at 22 ^{o}C, as shown in Figure 6-a. In comparison, the ARHM-GG specimens exhibited a much smaller sensitivity to aging than the DGAC specimens as demonstrated by the minimal reduction in fatigue life upon aging, as shown in Figure 6-b. When tested at-2 ^{o}C, the reduction in fatigue life was more evident, however, less significant than that of the DGAC beams. These trends demonstrate that aging has a negligible influence on asphalt rubber mixes compared to conventional hot mixes.



(a) DGAC



(b) ARHM-GG

Figure 6. *Fatigue behavior of aged and unaged asphalt mixtures at two test temperatures. (a) DGAC specimens, and (b) ARHM-GG specimens. Data obtained from Raad et al. (2001) [35].*

5.2.1.2 Permanent Deformation (Rutting)

Saboundjian et al. (2004) [36] tested another set of unaged (original) and 10-year field aged specimens (obtained from the same test section mentioned above) for permanent deformation performance under accelerated repeated loading using the Georgia Loaded Wheel Test, GLWT [37]. Each specimen is comprised of a slab 5" wide by 3" thick by 12" long conditioned for 24 hrs at 40 ^{o}C prior to loading. Figure 7 shows the rut accumulation with loading cycles for both the DGAC and ARHM-GG mixes. The following can be noted from Figure 7:

- Unaged DGAC mix exhibit lesser rut accumulation compared to the asphalt rubber mix. However, for aged specimens, the rut accumulation for both mixes becomes nearly equal.
- The effect of aging on rutting performance differs between the DGAC and ARHM-GG mixes. Whereas the DGAC resistance to rutting deteriorated with aging (aged conventional specimens exhibited higher rut accumulation compared to unaged specimens), the rutting resistance of ARHM-GG specimens improved with aging (aged specimens exhibited lower rut accumulation than the unaged specimens).

5.2.1.1 Thermal Cracking

Thermal (low-temperature) cracking is a major distress in flexible pavements constructed in cold regions characterized by very low temperatures and/or very rapid cooling between day and night. The susceptibility of asphalt concrete mixtures to cracking at low temperature is commonly assessed using the thermal stress restrained specimen test (TSRST) developed as part of a SHRP project [38]. The test is conducted using AASHTO TP-10: *Test Method for Thermal Stress Restrained Specimen Test*. In this test, a prismatic specimen (5cm×5cm×15cm) is subjected to controlled temperature drop at a cooling rate of approximately 10°C/hr while restrained at both ends until fracture occurs. The specimen develops tensile stress as it attempts to contract due to decreasing temperature. Both the temperature and the stress at which the specimen fractures are recorded and referred to as fracture temperature and fracture strength.

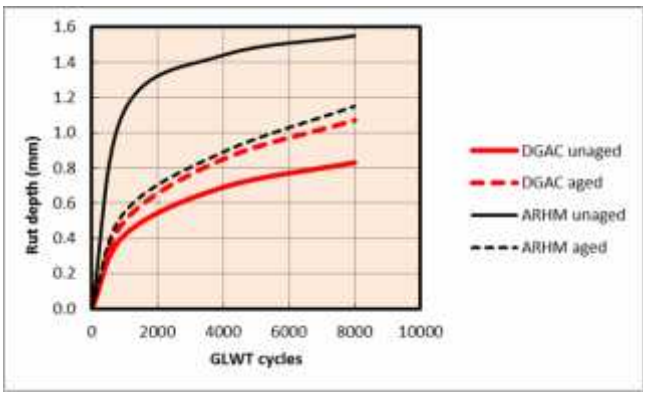


Figure 7. *Permanent deformation of asphalt mixtures tested with the accelerated Georgia Load Wheel Test (GLWT). Data obtained from Saboundjian et al. (2004) [36].*

Saboundijian et al. (2004) [36] evaluated the low-temperature cracking behavior of aged and unaged asphalt mixtures with and without rubber modifier obtained from the California test section described earlier. Figure 8 shows the fracture temperature and fracture strength of the aged (10 yrs old) and unaged DGAC and ARHM-GG mixes. The following can be noted from Figure 8:

- Asphalt rubber modified mixes (both aged and unaged) exhibited lower (colder) fracture temperature than the conventional mixes (Figure 8-a). The unaged ARHM specimens were able to resist at least 12 ^{o}C less than the DGAC mixes before fracture occurred. The aged ARHM mixes resisted up to 9 ^{o}C lower temperature than the DGAC mixes before breaking. The improved performance of ARHM mixes has also been observed from testing specimens obtained from pavements-in-services in Alaska by Saboundjian and Raad [39]. The superior thermal cracking resistance of the ARHM mixes is attributed to improving the rheological properties of the binder through rubber modification.
- Aging resulted in increased (warmer) fracture temperature of both the ARHM and DGAC mixes. This was especially evident in the ARHM specimens where aging increased the fracture temperature from an average of -32 ^{o}C for the original specimens to -26 ^{o}C for the aged specimens.
- Both the aged and unaged ARHM mixes have a lower average fracture strength than the corresponding conventional mixes.
- Aging increased fracture strength of both the ARHM and conventional mixes. However, increased fracture strength also means increased stiffness as evidenced from the increased (warmer) fracture temperature [40]. This increased stiffness renders the mix less

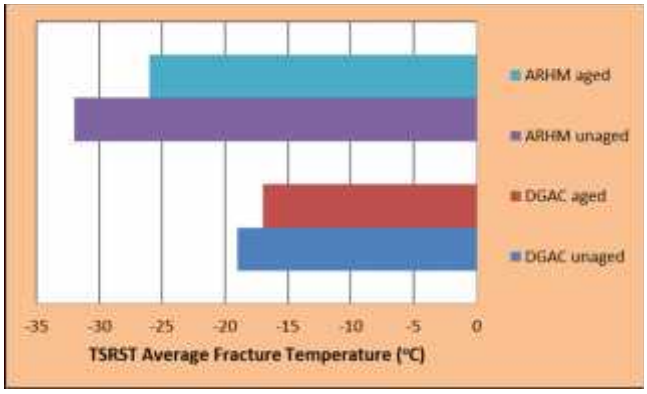


Figure 8-a. *TSRST results of aged and unaged conventional and rubber-modified mixes for fracture temperature. Data obtained from Saboundjian et al. (2004).*

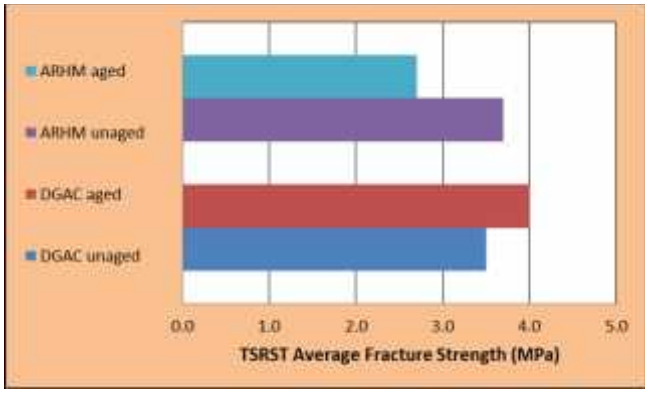


Figure 8-b. *TSRST results of aged and unaged conventional and rubber-modified mixes for racture strength. Data obtained from Saboundjian et al. (2004).*

resistant to fatigue and fracture under low temperature conditions. Therefore, aging causes mix fracture resistance to decrease. The lower fracture strength of ARHM mixes shown in Figure 8-b indicates that the rubber modified asphalt mix has superior thermal cracking resistance over the life of the pavement compared to the conventional mix [36].

5.2.2 Shatnawi (1997)[34]

Shatnawi evaluated the fatigue behavior of field aged specimens obtained from various lifts (overlays) of asphalt rubber and conventional dense graded mixes. The specimens were obtained from the center of the wheel path five years after placement. The location of the project was on Interstate 40 near Newberry Springs, California which is a hot climate desert region where the 7-day maximum pavement temperature at 50 mm pavement depth was found to be 60°C. The project was constructed in 1992 and consisted of various sections. One section consisted of a rehabilitation strategy composed of an ARHM-GG layer at a reduced thickness over a new conventional DGAC layer, and another section consisted of a rehabilitation strategy composed of 3 layers of conventional DGAC (Figure 11).

Figure 11 shows the various overlays that were tested for fatigue. As shown, Section 2 has two lifts; an ARHM-GG with Valley asphalt (top lift), and a DGAC with Coastal asphalt (second lift). These lifts were designated as S2L1 and S2L2, respectively.

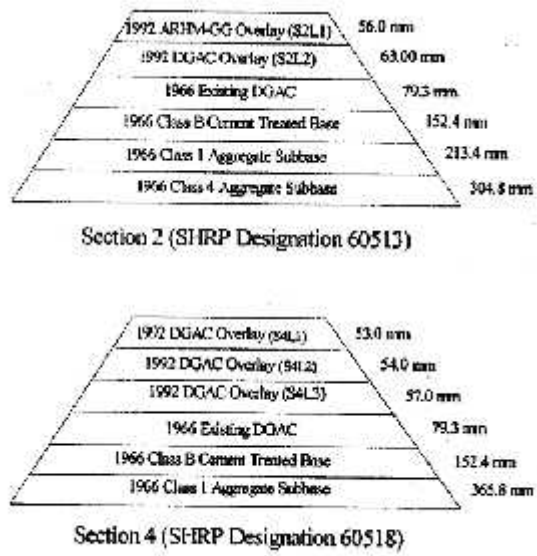


Figure 12. *Pavement Structures Evaluated by Shatnawi (1997 [34]).*

Section 4 has three conventional DGAC lifts; a DGAC overlay with Coastal asphalt (top lift), a DGAC with Coastal asphalt (second lift), and a DGAC with Valley asphalt (third lift). These lifts were designated as S4L1, S4L2 and S4L3, respectively.

Fatigue tests were conducted on beams taken from the two sections using a repetitive direct tension test with a test temperature of 20°C and a frequency of 10 Hz under controlled-strain mode of loading. Two asphalt sources were used on the project; Coastal (soft) and Valley (hard). The fatigue results revealed that the asphalt rubber mix containing the hard asphalt source performed better in fatigue than the conventional mixes containing either hard or soft binders (Figure 12) [34]. The conventional DGAC mixes with the hard asphalt resulted in higher stiffness values and lower fatigue lives than the conventional DGAC mixes with the soft asphalt. The asphalt rubber mix containing the hard asphalt outperformed all of the conventional DGAC mixes containing both asphalt sources (hard and soft) in the fatigue test.

Figure 12 shows two distinct fatigue curves for the coastal mixes indicating the effect of aging on the top lift as compared to the second lift. Field reviews after 5 years of traffic showed comparable fatigue performance in both the DGAC and the asphalt rubber sections. The laboratory fatigue performance showed the superior aging characteristics of asphalt rubber as it outperformed not only the top lift DGAC layer but the lower DGAC layers which are less exposed to oxidation and hardening. This aging superiority of asphalt rubber is shown even when a harder asphalt base (Valley) was used when compared with the softer asphalt (Coastal) for DGAC surface layer.

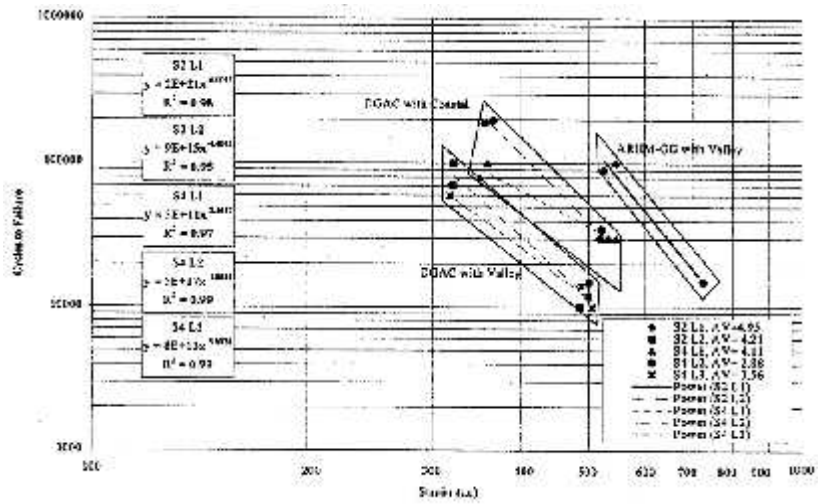


Figure 11. *Repetitive Direct Tension Fatigue Test Results. Data obtained from Shatnawi (1997) [34].*

5.3 Self-Healing Potential

Numerous studies exist in the literature that report on the self healing properties of asphalt concrete mixtures with regard to fatigue damage. Also, a number of studies compared performance of conventional and crumb rubber modified mixtures using the direct tensile fatigue test [31],[5],[6],[41]. These studies showed that the extension in fatigue life due to healing (fatigue damage recovery) of the modified mixtures was significantly greater than that of unmodified mixtures. However, no study was focused on evaluating the aging effect on healing potential. Although the degree of healing is mixture dependent, it is largely related to the binder properties.

6. Conclusions

Crumb rubber modified binders, and mixtures prepared with such binders exhibit improved aging resistance than their corresponding base binders and conventional mixes. This has been confirmed by numerous experimental investigations on the binders rheological characteristics and mixture engineering properties and performance behavior, which all demonstrated the superior aging of the modified binder and mixtures over their conventional counterparts. Whereas the benefits of using rubberized hot mix asphalt for flexible pavement construction and rehabilitation have been realized at many fronts including environmental impact, the deterioration of rubberized asphalt properties by aging is significantly reduced due to rubber modification compared to conventional asphalt concrete. In summary, the rubberized hot mix asphalt should be the material of choice for all flexible pavement construction activities and in all climatic regions.

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