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Rejuvenating Agents with RAP in Hot Mix Asphalt (HMA)

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16. Abstract

One potential method to aid in the blending of the RAP and virgin binders, as well as the general softening of the RAP binder, is to utilize a rejuvenating agent. An asphalt rejuvenator is a manufactured product which has the ability to absorb or penetrate into the asphalt mixture/material and potentially restore those reactive components, or rebalance them, which have been lost due to oxidation. The benefit of utilizing the rejuvenating agent is that it can be either preblended with the virgin asphalt binder, or added during the mixing process, instead of requiring the use of a softer PG graded binder that would require an additional storage tank on site. Therefore, to look at potentially adopting rejuvenating agents for use in higher RAP mixtures, the NJDOT needs guidance as to which rejuvenating agents are more practical, environmentally friendly, and work best in obtaining the NJDOT specified properties while being used in conjunction with higher RAP percentages.

A research study was conducted to evaluate the effectiveness of various rejuvenators currently on the market. The research looked at how the rejuvenator impacted the virgin binder used in the asphalt mixture, as well as the resultant asphalt binder properties of the high RAP asphalt mixture. Mixture performance tests were used to evaluate the rutting and fatigue cracking performance of the high RAP mixtures within the limits of the NJDOT High RAP specification. Testing of the rejuvenator blended in the virgin binder showed that a significant softening occurs, sometimes lowering the PG grade by as much as three grades. This is concerning when most rejuvenators are blended at the refinery, resulting in a significantly softer asphalt binder in the plant's storage tank. The study developed a new procedure, using the analysis of the asphalt binder master curves, to evaluate how effective the different rejuvenators are at "rejuvenating" the asphalt binder blended with RAP binder. Although the rejuvenators did improve the fatigue performance of the high RAP mixtures, a majority of the rejuvenators were not able to achieve passing fatigue performance within the NJDOT High RAP specification. This is most likely attributed to the asphalt mixture being under-asphalted when assuming 100% of RAP binder is contributing to the total asphalt content of the asphalt mixture. The methodology developed during the study was also applied in a joint effort with the University of Massachusetts, evaluating the same practice of using rejuvenators for high RAP asphalt mixtures. Similar mixture performance and conclusions were drawn with the Massachusetts materials. Both studies indicated that the best performing rejuvenator (i.e. – the one that was most effective at softening the RAP mixture and provided the best fatigue cracking resistance), were the paraffinic oil based rejuvenators.

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INTRODUCTION

The New Jersey Department of Transportation (NJDOT) has been investigating various options to utilize higher percentages of recycled asphalt pavement (RAP) in hot mix asphalt (HMA). Research efforts ranging from controlled laboratory studies to field pilot projects have clearly indicated that RAP mixtures are stiffer and more prone to cracking than virgin asphalt mixtures. These efforts have also suggested that one of the major causes of the higher stiffness and cracking potential is the lack of blending between the RAP and virgin asphalt binders. Although the true degree of blending is highly production dependent (i.e. – plant type, production temperature, storage time, etc.) studies conducted by Rutgers University and Rowan University have indicated that at percentages as low as 15% RAP, blending begins to become an issue. The lack of blending would clearly become more of an issue as RAP contents increased.

Another general issue found with increased RAP contents is ensuring the final PG grade of the mixture meets that specified by the NJDOT. Currently, the Superpave mixture design system recommends selecting a virgin binder grade one grade softer than normal when using 15 to 25% RAP, while blending charts are to be used when utilizing RAP at percentages greater than 25%. Obviously, different percentages of RAP used in conjunction with different NJDOT mixtures could require a variety of asphalt binder PG grades for the asphalt supplier to maintain. In most cases, this would not be practical. Not to mention, the New Jersey asphalt industry has already told the NJDOT that it is not in favor of increasing the number of asphalt binder storage tanks on site.

One potential method to aid in the blending of the RAP and virgin binders, as well as the general softening of the RAP binder, is to utilize a rejuvenating agent. An asphalt rejuvenator is a manufactured product which has the ability to absorb or penetrate into the asphalt mixture/material and potentially restore those reactive components, or rebalance them, which have been lost due to oxidation. The benefit of utilizing the rejuvenating agent is that it can be either preblended with the virgin asphalt binder, or added during the mixing process, instead of requiring the use of a softer PG graded binder that would require an additional storage tank on site. Therefore, to look at potentially adopting rejuvenating agents for use in higher RAP mixtures, the NJDOT needs guidance as to which rejuvenating agents are more practical, environmentally friendly, and work best in obtaining the NJDOT specified properties while being used in conjunction with higher RAP percentages.

OBJECTIVES

The objective of NJDOT 2011-04, *Rejuvenating Agents with RAP in HMA*, is to evaluate the potential use of rejuvenating agents in conjunction with higher RAP content asphalt mixtures. With the multitude of rejuvenating agents on the market, all claiming to soften RAP, a research study is required to determine which agents are the most advantageous for the NJDOT. The research objectives are proposed to be met combining a thorough literature review and interview process and an extensive laboratory testing program consisting of both asphalt binder and mixture characterization of asphalt mixtures containing RAP at different percentages and modified with various rejuvenating agents.

PHASE 1 – LITERATURE REVIEW

Introduction of How Rejuvenators Work

The effectiveness of a rejuvenator should be judged on how well the product reverses the aging of the recycled asphalt binder – whether this is recycled asphalt pavement (RAP) or recycled asphalt shingles (RAS). The rejuvenator should make the RAP binder available for blending with the virgin asphalt binder in the asphalt mixture, while also restoring aged and oxidized asphalt binder into something that behaves rheologically more like virgin asphalt material. Rejuvenators that have faster levels of diffusion, or penetration of the rejuvenator into the recycled asphalt, will be more effective during the rejuvenating process since mixing times at asphalt plants are generally small. The diffusion process of a rejuvenator into aged asphalt is hypothesized to occur sequentially in the following four steps (Carpenter and Wolosick, 1980; Tran et al., 2012):

1. The rejuvenator forms a very low viscosity layer surrounding the asphalt-coated aggregate.
2. The rejuvenator starts to penetrate into the aged asphalt binder layer, decreasing the amount of raw rejuvenator surrounding the aggregate and softening the aged binder.
3. When the rejuvenator is no longer present on the outside of the aged binder, the penetration of the rejuvenator continues, decreasing the viscosity of the inner layer, causing the viscosity of the outer layer to gradually increase.
4. After a certain time period, equilibrium between the inner and outer layers is relatively achieved.

It should be noted that rate and amount of diffusion of the rejuvenator into the aged asphalt is dependent on a number of factors that include; compatibility of the RAP and virgin binders, temperature of mixing, stiffness of the RAP and virgin binders, and the amount of the recycled asphalt binder in the total blend (Karlsson, R. and U. Isacsson, 2003).

Carpenter and Wolosick (1980) verified the above diffusion process by conducting staged solvent extractions. Figure 1 shows the researchers test results using the Penetration test at 25^{o}C as a means of measuring the performance of the recovered asphalt binder. Additional studies that confirmed this generalized diffusion process can be found in Noureldin and Wood (1987), and Huang et al. (2005).

Along with the importance of the diffusion time, the stability of the rejuvenator is important as well. A rejuvenator that may begin to penetrate into the recycled asphalt binder, but quickly volatizes as it is introduced to oxygen and/or high temperatures for extended time periods, provides very limited rejuvenating qualities.

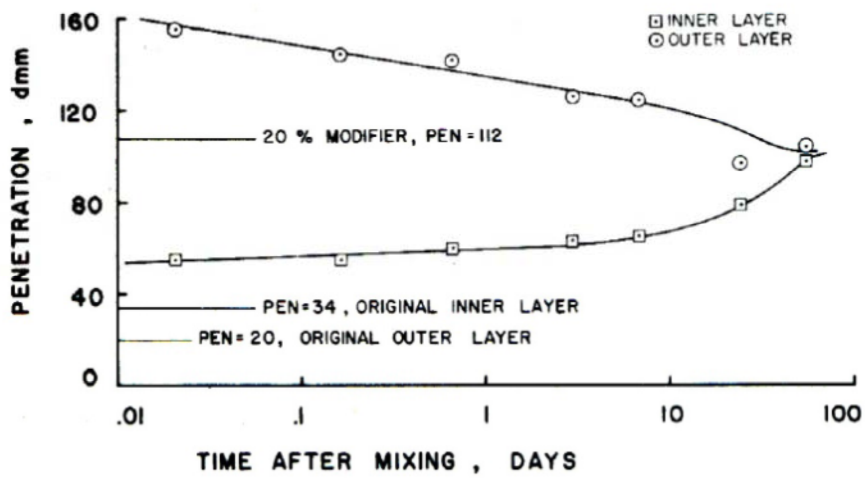

Figure 1 – Penetration of Rejuvenator into the Inner and Outer Layers of Recycled Asphalt (After Carpenter and Wolosick, 1980)

Aging of Asphalt Binders

The understanding of the chemistry of an asphalt binder is still in its infancy and it not fully understood. The current state of knowledge indicates that asphalt binder models generally describe the asphalt as containing two different fractions; 1) A viscosity-building fraction (asphaltenes) and 2) A low viscosity oil fraction (maltenes). The maltene fraction is a collection of non-polar and polar molecules and can be classified into four principle bodies (Boyer, 2000);

1. Polar compounds or Nitrogen bases (N) – components of highly reactive resins, which act as a peptizer for the asphaltenes.
2. First acidiffins (A_1) – compounds of resinous hydrocarbons which function as a solvent for the peptized asphaltenes.
3. Second acidiffins (A_2) – compounds of slightly unsaturated hydrocarbons that also serve as a solvent for the peptized asphaltenes.
4. Saturated hydrocarbons or paraffins (P) – compounds of hydrocarbons, which function as a jelling agent for the asphalt components.

Asphalt binder, being a suspension of viscous asphaltene assemblies is a less viscous maltene media, ages primarily in the maltene fraction. Rostler and White (1970) reported that the Asphaltenes fraction is the most stable components of the asphalt binder, while the Maltene fraction was more subject to aging, in particular, oxidative aging. During the process of aging, the ratio of maltenes to asphaltenes decreases, resulting in the hardening and embrittlement of the asphalt pavement.

To help understand the makeup of crude oil and asphalt, Figure 2 shows the general makeup of crude oil after a SARA (Saturate, Aromatics, Resins, Asphaltenes) Extraction procedure. As noted earlier and shown in Figure 2, the Maltene and Asphaltene fraction are the 2 major components of the asphalt base. The Maltenes are made up primarily of three components; Saturates, Aromatics, and Resins. The exact percentages of each of the components are highly dependent on the crude source the asphalt binder was produced from. As noted earlier, with the Maltene portion of the asphalt binder being the major contributor to aging, it is apparent that utilizing rejuvenators that replace or improve the properties of the Saturates, Aromatics and Resins is required for proper rejuvenation to take place. Unfortunately, as will be noted, different aging mechanisms affect the asphalt components differently.

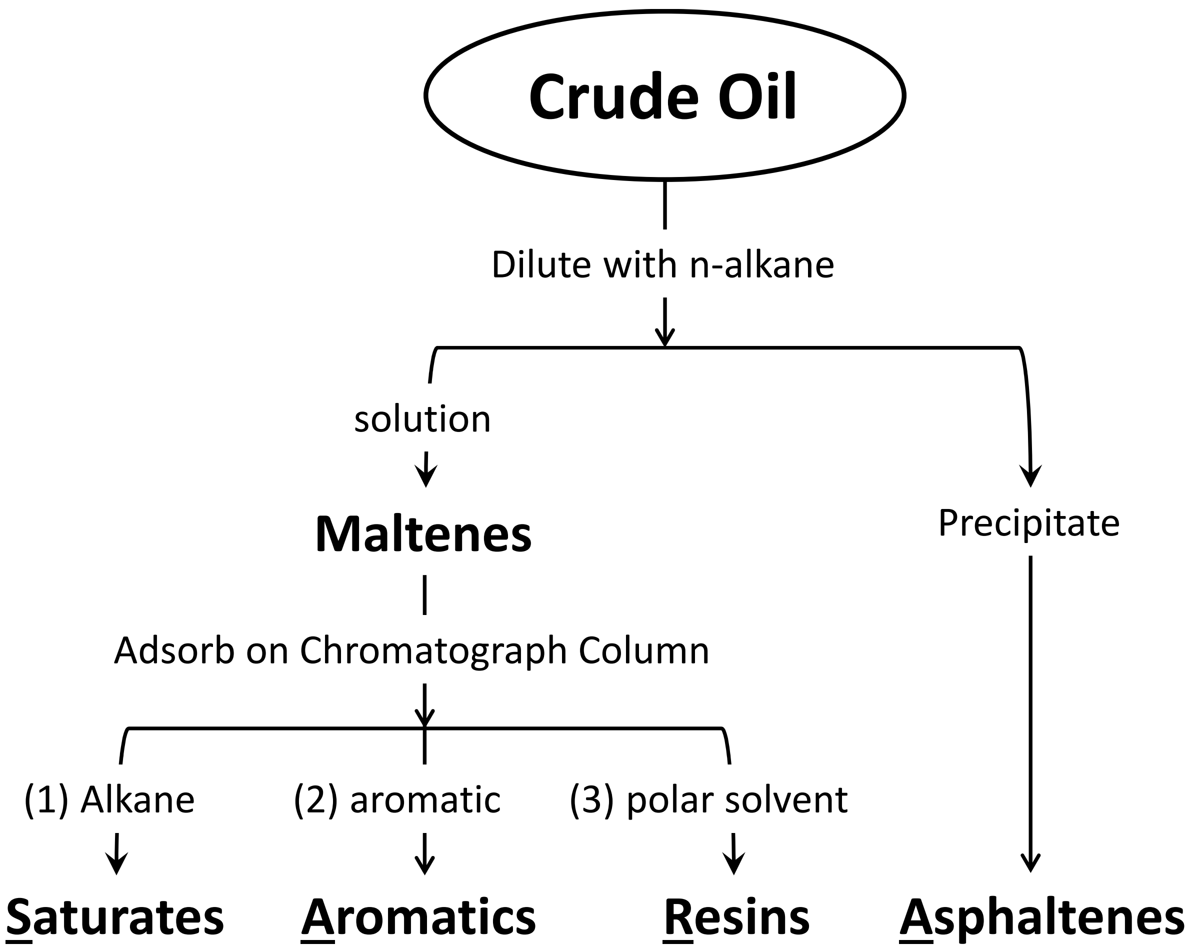

Figure 2 – Major Components of Crude Oil After SARA Extraction

Different Mechanisms of Asphalt Binder Aging

Although the working mechanisms of asphalt binder aging is not fully understood, it is fairly agreed upon that there are generally four processes that work in conjunction which cause an asphalt binder to age.

Oxidation: An irreversible process by which oxygen that diffuses into the asphalt binder from voids in the asphalt mixture react with non-polar maltenes to form polar functional groups that increase the intermolecular network interactions and viscosity (i.e. – an increase in stiffness).

Evaporation: The evaporation of volatile compounds in fresh asphalt binder is accelerated by temperature, surface area, and turbulence. Most evaporation can occur during manufacturing since all three accelerants are present simultaneously. Evaporative loss is best controlled by minimizing quantities of volatile compounds in fresh asphalt binder.

Exudation: Some maltene chains will absorb into aggregate pores due to the chemical reaction between the aggregate mineralogy and the asphalt binder chemistry. On average, it is a relatively minor contributor to binder aging.

Physical Hardening: Physical hardening of asphalt binders take place as asphaltene molecules compact over time displacing the maltene oils that provided viscoelastic behavior. Physical hardening is theoretically "reversible" by the reintroduction of displaced maltenes during recycling and mechanical mixing.

As per the definitions of the various aging mechanisms of asphalt binder, rejuvenators are most effective in reversing the Physical Hardening and Oxidation aging mechanisms associated with the properties of recycled asphalt pavement (RAP) asphalt binder as they are able to aid in replacing some of the chemical compound deficiencies of the aged asphalt.

Use of Rejuvenators in Pavement Applications

The first published document describing the use of an asphalt rejuvenator was by the Gold Bear Oil Company in 1960 (Brownridge and Grady, 2000). However, the Literature Review only contains information published within the past 10 years in an effort to only present current testing procedures and analytical concepts. Interesting to note that there was a "gap" in the published literature regarding rejuvenators from early 1990's until mid 2000's (approximately 15 years). And even prior to the 1990's, available literature was limited. It would appear that the main driving force behind the recent interest in the use of rejuvenators is the "sustainability" push within the transportation industry. Higher use of recycled asphalt, with a stiffer asphalt binder, would require the incorporation of an additive to soften the asphalt binder and make it viable and available for blending with the virgin asphalt components.

Shen et al., (2007) – Effects of Rejuvenating Agents on Superpave Mixtures Containing Reclaimed Asphalt Pavement

The researchers evaluated Superpave mixtures containing RAP and different rejuvenator agents, as well as the simple use of a softer asphalt binder. The researchers utilized volumetric results, Indirect Tensile Testing (ITS), and the Asphalt Pavement Analyzer (APA) to rank the performance of the various mixtures/additives. The researchers noted that for the mixtures and additives evaluated in the study;

- The ITS and APA properties of the recycled mixtures using the rejuvenator were better than the performance of the softer asphalt binder;
- Only 10% more RAP could be incorporated in the asphalt mixtures when using a rejuvenator and still perform as well as the virgin mixtures; and
- The blending charts established under the Superpave binder specification can be used to help determined the content of the rejuvenator for the recycling.

Gordon et al., (2009) – Comparison of Renewable Oil, Recycled Oil, and Commercial Rejuvenating Agent Derived from Crude Oil in Paving Asphalt Modification

The researchers looked at different oily materials to modify Canadian paving asphalt and determine their effectiveness at improving the Superpave low-temperature PG grade of the asphalt binder. The different additives were blended with the asphalt binder at various percentages and then tested using Superpave performance grading tests. The researchers evaluated Cyclogen L (a crude oil-dervied material), a vegetable wax, and recycled cooking oil. The researchers found that the Cyclogen L reduced the low temperature PG grade while having negligible effect on the high temperature PG grade. The soy-bean derived wax (a sustainable, renewable material) performed well when low amounts were added. However, it is more expensive than the Cyclogen L product described earlier. The best candidate for an effective, economic asphalt softening agent out of the materials tested was the recycled cooking oil. It outperformed the Cyclogen L oil in terms of improving the low temperature PG grade and is far less expensive, contains no crude oil and can be collected from restaurants. However, the researchers noted that other variables such as consistency of the material, availability, and field trials should all be investigated before it becomes a viable alternative to current commercial products.

Santagata et al., (2009) – Rheological and Chemical Investigation on the Damage and Healing Properties of Bituminous Binders

The researchers conducted an experimental program that focused on the correlation between asphalt binder chemistry and the damage and healing properties of six different penetration grade asphalt binders. The chemical characterization consisted of elemental analysis and fractionation of the asphalt binder into its SARA components (Saturates, Aromatics, Resins, and Asphaltenes). The chemical properties were then compared to asphalt binder testing consisting of constant stress amplitude oscillatory tests, with and without rest periods, in the Dynamic Shear Rheometer (DSR). The researchers reported that the microstructural parameters from the SARA analysis can be correlated to damage and healing parameters determined for the asphalt binders tested. In particular, while damage resistance seemed to be governed by the balance of all four fractions which compose an asphalt binder, the healing appeared to be more directly linked to the microstructure of just the oil phase, noted in the paper as the ratio between the Saturate (S) and Aromatic (Ar) fractions (i.e. – S/Ar) (Figure 3).

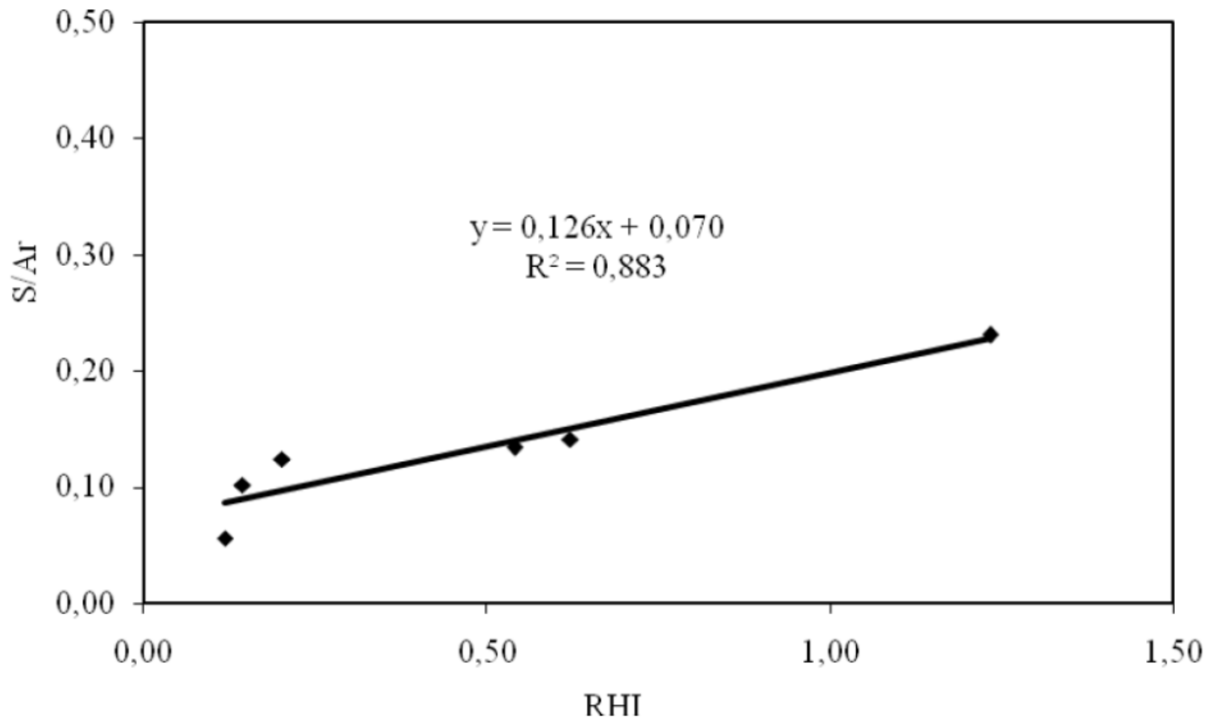

Figure 3 – Saturate to Aromatic Ratio Relationship to Healing Index (Santagata et al., 2009)

Tran et al., (2012) – Effect of Rejuvenator on Performance Properties of HMA Mixtures with High RAP and RAS Contents

The researchers looked at the performance of five (5) asphalt mixtures containing different percentages of RAP and RAS. Cyclogen L, a rejuvenating product supplied by Tricor Refining LLC was utilized in the study. The results showed that the use of the rejuvenator in the recycled mixtures improved the cracking resistance of the mixtures without adversely affecting the moisture damage and permanent deformation properties. Along with the performance testing, a cost comparison analysis was conducted using the different mixtures evaluated in the study. The cost analysis indicated that up to a 36% cost savings can be achieved, even when incorporating the rejuvenating additive. Table 1 shows the cost comparison.

Table 1 – Cost Comparison of High Recycled Asphalt Mixtures with a Rejuvenator (Tran et al., 2012)

Component		Cost per ton of Material (USD)	Cost per ton of Mix (USD)				
			Virgin Mix	50% RAP	50% RAP + RA	20% RAP + 5% RAS	20% RAP + 5% RAS + RA
Binder	PG 67-22	600	36.6	21.0	21.0	27.0	27.0
	RAP AC***	0	0.0	0.0	0.0	0.0	0.0
	RAS AC*	25	0.0	0.0	0.0	0.2	0.2
	RA**	1200	0.0	0.0	3.6	0.0	2.4
Aggregate	Virgin Agg	15	14.1	7.0	7.0	11.2	11.2
	RAP Agg***	9	0.0	4.2	4.2	1.7	1.7
Total			50.7	32.3	35.9	40.1	42.5
Percent of Virgin Mix				63.6	70.7	79.2	83.9
Percent Savings				36.4	29.3	20.8	16.1

* Total RAS AC = effective RAS AC*100/73
** $4/gallon at facility in CA, $5/gallon at a plant in Alabama
*** Including costs for both RAP AC and RAP aggregate

Hajj et al., (2013) – Influence of Hydrogreen Bio-asphalt on Viscoelastic Properties of Reclaimed Asphalt Mixtures

The researchers conducted a study that looked at the effectiveness of a non-crude source rejuvenator, called BituTech. BituTech is an alternative to the more effective carcinogenic aromatic oil rejuvenants and is a unique combination of selected natural plant extracts reacted in a distinct process to create an asphaltene dispersant. Generally it has been found to reduce the high and low PG grade temperature when preblended with a base asphalt binder, which helps to offset the stiffer RAP asphalt binder. The results of the study summarized by the researchers indicated that:

- The addition of BituTech helps to improve the mixtures resistance to moisture damage after extended freeze-thaw cycling;
- The addition of BituTech restored the low temperature properties of RAP mixtures. A reduction in the relaxation modulus was observed with a shift in the fracture temperature, micro-cracking initiation temperature, and viscous-glassy transition temperature to the colder side; and
- A brief cost analysis showed potential savings for using BituTech with RAP percentages as low as 15%. Maximum cost effectiveness was found at the maximum RAP level evaluated in the study (50%) (Table 2).

Table 2 – Cost Effectiveness Using a Rejuvenating Additive (After Hajj et al., 2013)

Costs	RAP obtained from millings*	RAP purchased
Value of RAP	$46.5/ton	$46.5/ton
RAP cost		- $5.00/ton
Plant cost for extra equipment	- $0.85/ton	- $0.85/ton
Trucking cost	- $3.50/ton	
Processing and handling cost	- $5.80/ton	- $5.80/ton
Extra quality control cost	- $0.60/ton	- $0.60/ton
BituTech RAP cost[1]	- $21.49/ton	- $21.49/ton
Total savings	$35.74/ton	$34.24/ton
Saving per 15% RAP in mix (without BituTech RAP)[2]	$5.36/ton	$5.14/ton
Saving per 50% RAP in mix (without BituTech RAP)[2]	$17.87/ton	$17.12/ton
Saving per 50% RAP in mix (without BituTech RAP) with softer binder (PG52-34)	$14.57/ton	$13.82/ton
Saving per 15% RAP in mix (with BituTech RAP)[2]	$2.14/ton	$1.91/ton
Saving per 50% RAP in mix (with BituTech RAP)[2]	$7.12/ton	$6.37/ton

* Cost of millings included in the contract
[1] kg of BituTech RAP costs $1.43. BituTech RAP was added at 1.5% of the weight of RAP.
[2] Using PG58-28.

Hill et al., (2013) – Low Temperature Performance Characterization of Bio-Modified Asphalt Mixtures Containing Reclaimed Asphalt Pavement

The researchers utilized the Disk-Shaped Compact Tension (DC(T)), Indirect Tension, and Acoustic Emission tests to characterize the low temperature properties of asphalt mixtures with higher RAP contents, with and without a Bio-modified asphalt. The low temperature test procedures employed by the researchers showed that in all cases, the addition of the Bio-modified asphalt improved the low temperature cracking performance properties of the RAP mixtures. Figure 4 illustrates some of the finding the researchers provided using the Acoustic Emission test procedure.

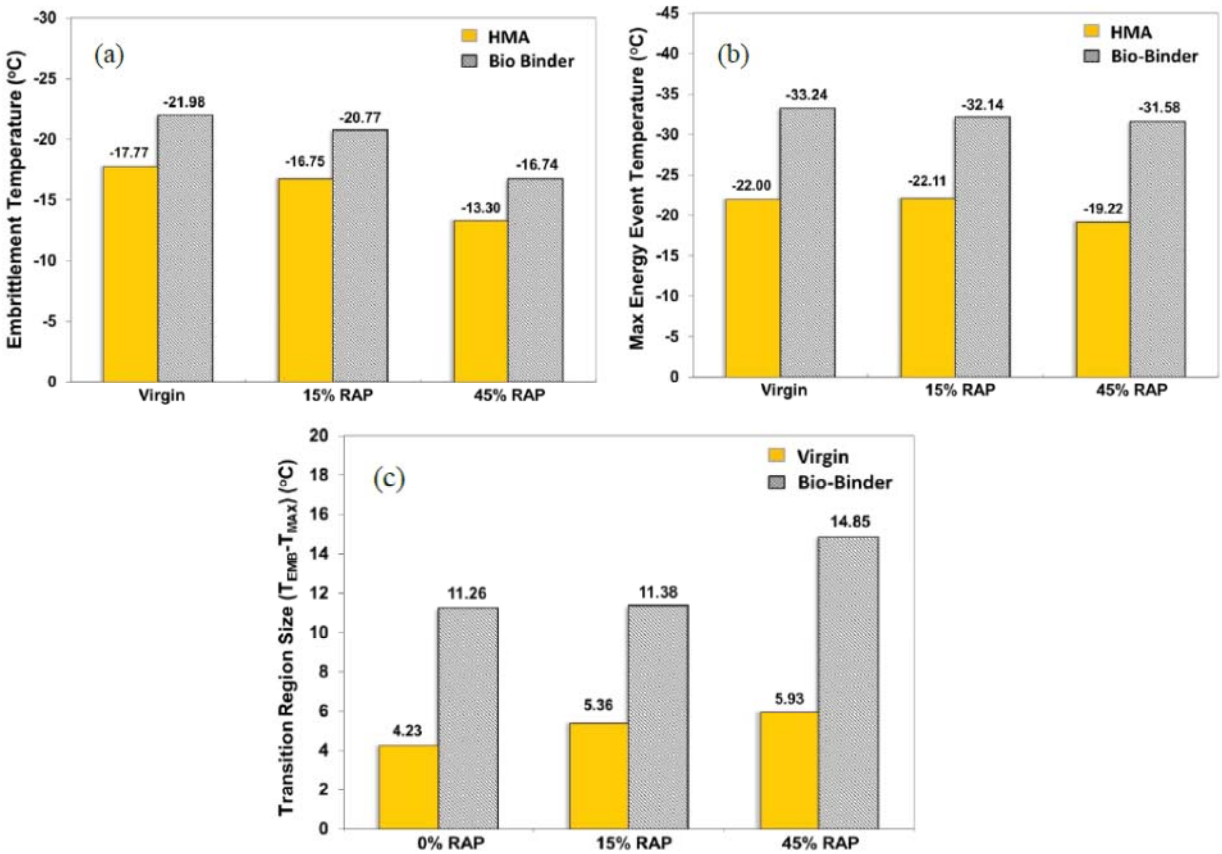

Figure 4 – Acoustic Emissions Test Results and Characterization for (a) Embrittlement Temperatures, (b) Max Energy Event Temperature, and (c) Transition Region Size (After Hill et al., 2013)

Im, S. et al. (2014) - "Impacts of Rejuvenators on Performance and Engineering Properties of Asphalt Mixtures Containing Recycled Materials"

The researchers evaluated three rejuvenating agents currently on the market and blended them in a PG64-22 asphalt binder. The rejuvenators were used in conjunction with a 19% RAP, 13% RAP/5% RAS, and 5% RAS mixture. Laboratory testing encompassed Hamburg Wheel Tracking, Overlay Tester, Repeated Load Permanent Deformation and Dynamic Modulus tests. The researchers also conducted a brief cost benefit analysis to determine if the combined use of higher recycled asphalt contents with the additional cost of the rejuvenators were cost effective. The results of the laboratory evaluation showed that all of the mixtures that utilized the rejuvenators exhibited improved cracking and moisture damage resistance compared to the control mixtures (Figure 5). The general performance ranking of the rejuvenators depended on the mixture type evaluated. The researchers concluded that this was due to the degree of blending between the recycled asphalt binder, the virgin asphalt binder, and the rejuvenator agent. The cost analysis results showed that using rejuvenators may be a cost effective way to enhance the overall performance of asphalt mixtures containing high amounts of recycled asphalt (Table 3).

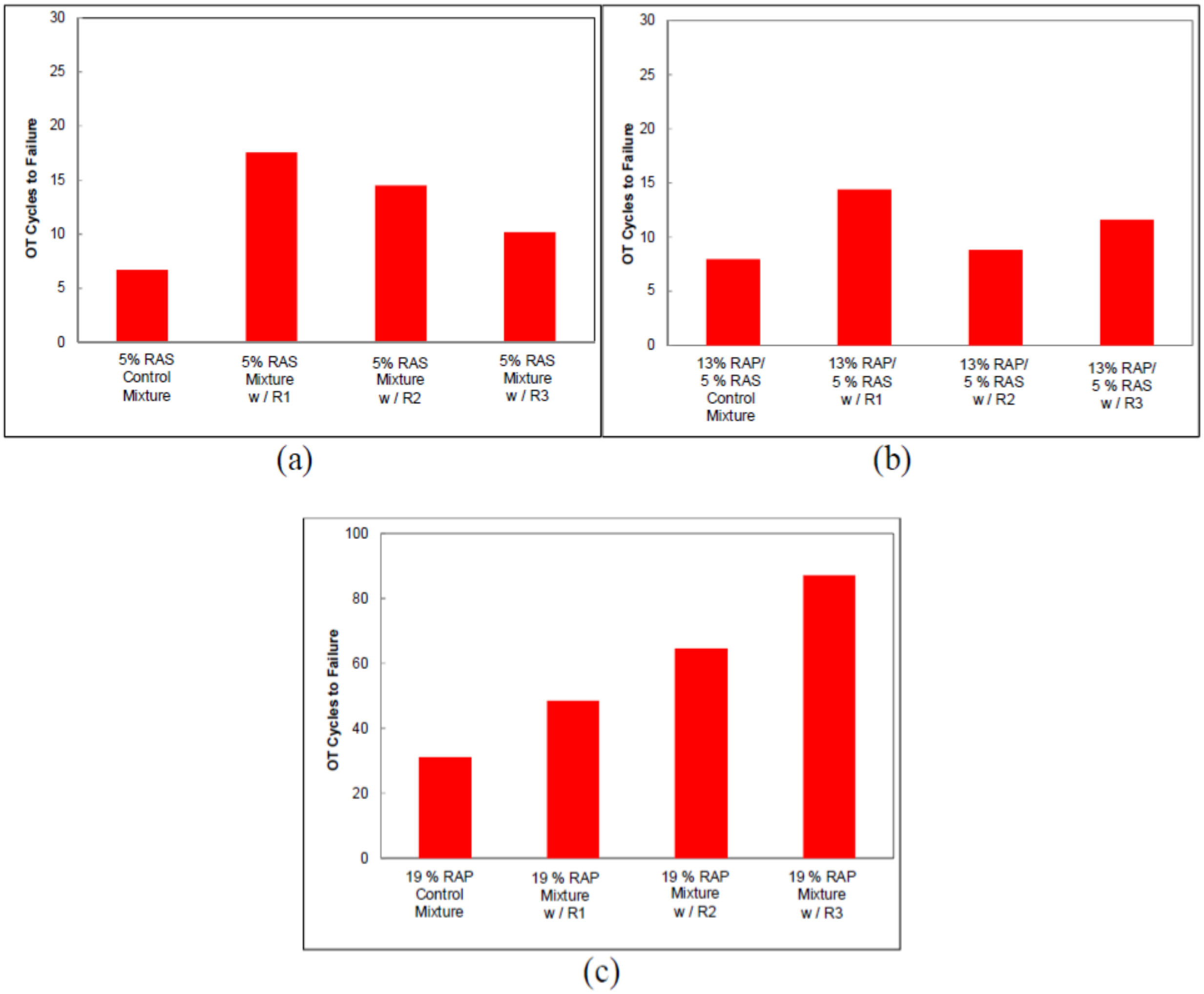

Figure 5 – Overlay Tester Results for Each Asphalt Type (a) 5% RAS Mixtures, (b) 13% RAP/5% RAS Mixtures, and (c) 19% RAP Mixtures (After Im et al., 2014)

Table 3 – Example of Cost Savings Using Rejuvenators

Case 1. Virgin aggregates and virgin binder	
Total weight of asphalt mixture	1,000 (kg)
4.8 % asphalt by total weight (virgin binder)	48 (kg)
Total weight of aggregate (virgin aggregates)	952 (kg)
Total cost = (952×0.015)+(48×0.685)	**47.2 ($/1,000 kg)**
Case 2. Virgin aggregates plus 19 % RAP and virgin binder	
Total weight of asphalt mixture	1,000 (kg)
19 % RAP	190 (kg)
Asphalt content of RAP (5 %) =(190×0.05)	9.5 (kg)
4.8 % asphalt by total weight (virgin binder)	48 (kg)
Actual virgin binder needed = (48-9.5)	38.5 (kg)
Total weight of aggregate (virgin aggregates)	771.5 (kg)
Total cost = (771.5×0.015)+(190×0.005)+(38.5×0.685)	**38.9 ($/1,000 kg)**
Case 3. Virgin aggregates plus 19 % RAP and virgin binder plus 0.6 % R1	
Total weight of asphalt mixture	1,000 (kg)
19 % RAP	190 (kg)
Asphalt content of RAP (5 %) =(190×0.05)	9.5 (kg)
4.8 % asphalt by total weight (virgin binder)	48 (kg)
0.6 % R1 on total binder	0.288 (kg)
Actual virgin binder needed = (48-9.5-0.288)	38.2 (kg)
Total weight of aggregate (virgin aggregates)	771.5 (kg)
Total cost = (771.5×0.015)+(190×0.005)+(38.2×0.685)+(0.288×1.67)	**39.2 ($/1,000 kg)**

Oldham et al., (2014) – Investigating the Rejuvenating Effect of Bio-Binder on Recycled Asphalt Shingles

The researchers presented findings of a study looking at the effect of a bio-based additive, produced from swine manure, on asphalt mixtures containing recycled asphalt shingles (RAS). The asphalt binder in RAS is significantly harder than RAP binder, and therefore, if the bio-based additive is effective on RAS mixtures, it should provide similar benefits to RAP mixtures. The researchers noted that the addition of the bio-based additive helped to reduce the rotational viscosity of the RAS asphalt, which should in turn provide a more workable asphalt mixture. The viscosity reduction was also noted in RAS percentages as high as 30%. Low temperature cracking performance, measured using Fracture Energy testing, showed that the introduction of the bio-based additive improved the low temperature performance of the RAS asphalt mixtures (Figure 6).

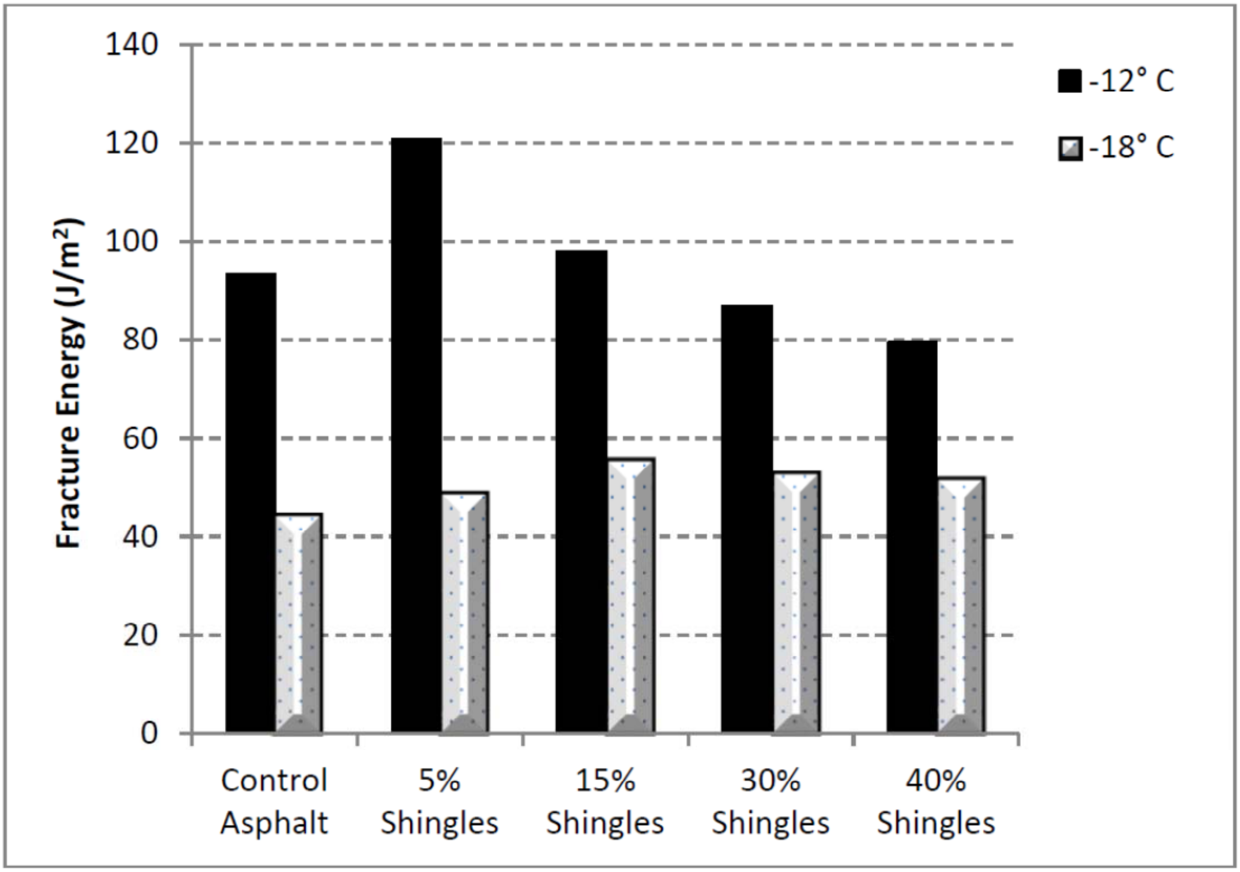

Figure 6 – Comparison of RAS Asphalt Fracture Energy at -12 and -18°C (After Oldham et al., 2014)

Naher et al.,(2014) – Turning Back Time: Rheological and Microstructural Assessment of Rejuvenated Bitumen

The researchers evaluated two different rejuvenators, an emulsion-based and liquid-based additive, using rheological and microstructural testing techniques. The researchers noted that the use of master curves shifted upward towards stiffer values as aging increased and shifted downward towards softer values as the rejuvenators were introduced (Figure 7). This suggests that rheological testing may provide a means for assessing the rejuvenator's potency in softening the aged asphalt.

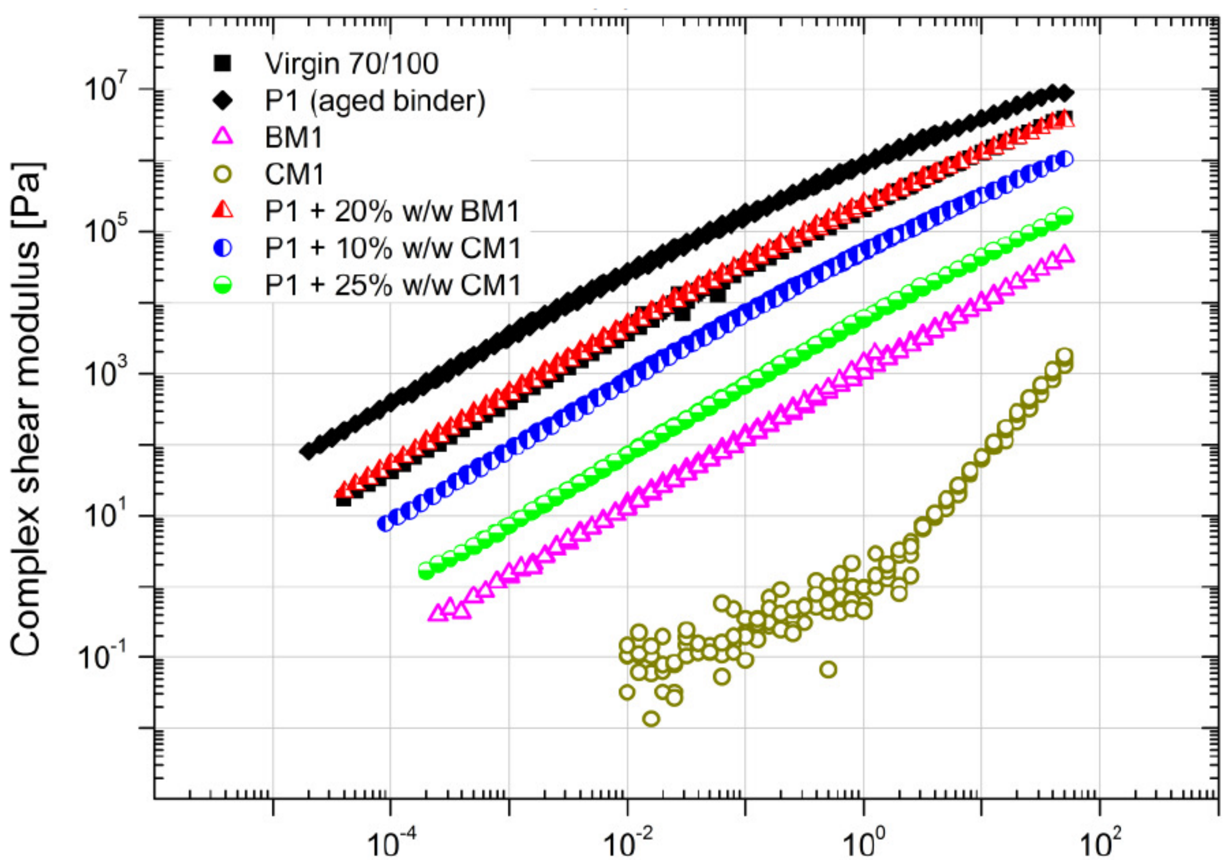

Figure 7 – Shear Modulus Stiffness Curves for Asphalt Binders with and without Rejuvenators (After Naher et al., 2014)

Literature Review Findings

A literature review was conducted to look at what the current state of practice was regarding the use of rejuvenating additives for asphalt mixtures with higher recycled asphalt contents. The literature review would suggest that:

- As the asphalt binder ages, the maltene fraction of the asphalt binder is the most affected and breaks down. During the process of aging, the ratio of maltenes to asphaltenes decreases, resulting in the hardening and brittlement of the asphalt pavement. An effective rejuvenating strategy should help to reverse this process, or aid in supplementing the asphalt with additional maltenes.
- Aged asphalt binders are more sensitive to fatigue/durability related distresses due to their reduced flexibility and lack of potential for "healing". The application of rejuvenators appear to help the aged asphalt binder overcome some of these deficiencies and perform better in fatigue-related conditions.
- The Literature Review suggests that additives advertised as "rejuvenating agents" do not provide the same level of rejuvenation, and therefore, results are mixed among the various materials.

- A procedure for evaluating the effectiveness of “rejuvenating agents” currently does not exist, although from the available research published, it would appear that fatigue testing of asphalt mixtures provides the best means of evaluating their effectiveness.

SELECTION OF REJUVENATING AGENTS FOR STUDY

As noted earlier, there are a number of additives in the asphalt industry marketed as an asphalt rejuvenating agent. All of these additives are promised to soften the aged asphalt to something that better resembles the original asphalt binder. Unfortunately, due to the limited information published, the selection process of which rejuvenator to use is difficult. Therefore, a step-wise approach was used in the selection of rejuvenators for further researching. First, Mr. Bob Frank, owner and president of Compliance Monitoring, as well as RAP Technologies, was contacted. Mr. Frank owns and operates a 100% RAP asphalt plant in northern New Jersey, where he produces asphalt mixtures for pothole repair, as well as small commercial work. Mr. Frank has an extensive, practical knowledge on which rejuvenators appear to work best, as well as their relative costs. Mr. Frank graciously provided his opinion on what he perceived were good performing rejuvenators, as well as rejuvenators that were cost effective.

After meeting with Mr. Frank, the list of rejuvenators was further reduced to 5 additives based on the criteria of petroleum-based vs non-petroleum-based rejuvenators. The third and final criteria used for the selection of rejuvenators to include in the study was the research published by Santagata et al. (2009). The researchers indicated that the ratio between the Saturates and Aromatics (S/Ar) of the asphalt binder was related to a Healing Index parameter developed in their study. Their results suggested that as the S/Ar ratio increased, the asphalt binder showed a greater potential to “heal” during rest periods in fatigue-based asphalt binder testing.

Based on the step-wise methodology, five rejuvenators were chosen for the laboratory study (Table 4). The Hyprene L150 is a naphthenic oil that is advertised to have a low pour point, a low odor level and a resistance to discoloration by heat or UV light. The Hyprene L150 had a Saturate to Aromatic (S/Ar) ratio of 1.733. The Valero VP165 is a dewaxed, parafinnic oil. The S/Ar ratio of the Valero VP165 is 0.453. The Valero 130A is an aromatic extract oil with a S/Ar ratio of 0.169. The Oleic Acid is a fatty acid from vegetable oil production and the Akzo Nobel product is advertised to be derived from renewable raw materials (bio-based). Neither the Oleic Acid nor the Akzo Nobel product are petroleum based products.

Table 4 – Rejuvenators Used in NJDOT Study

Rejuvenator Type	Composition/Active Ingredients
Hyprene 150 Flux	Saturates = 63.1%; Aromatics = 36.4%; S/Ar = 1.733
Valero VP165	Saturates = 31.1%; Aromatics = 68.8%; S/Ar = 0.453
Valero 130A	Saturates = 13%; Aromatics = 77.1%; S/Ar = 0.169
Oleic Acid	Fatty Acid from Vegetable Oil
Akzo Nobel	Tall Oil Derivative

The dosage rate of each of the rejuvenators was based on the recommendations of each of the respective manufacturers. According to the manufacturers, the dosage rate is a function of the proposed recycled product (RAP or RAS) by total weight of the mixture. In the case of this project, RAP was used at 25% and 45% of the total weight of the asphalt mixture. Each of the respective rejuvenators was preblended with a PG76-22 asphalt binder at a blending temperature of 330^{o}F using a high shear mixer for 1 hour.

It should be noted that although the manufacturers' recommendations were followed in the study, in theory, the rejuvenator dosage rate should not be a function of the weight of RAP by total weight, but instead, should be a function of the virgin binder replaced by the recycled binder in the asphalt mixture. Also, by preblending the rejuvenator in the virgin asphalt binder, there is a potential to dilute the rejuvenator, as well as the potency be reduced as the rejuvenator-dosed asphalt binder must coat the RAP and virgin aggregate.

RESEARCH WORKPLAN

A laboratory workplan was developed to evaluate the effectiveness of different rejuvenators utilized with RAP mixtures. Two different mixtures, a 25% and 45% RAP mixtures, were evaluated under a variety of asphalt binder and mixture performance tests. The mixtures were also evaluated using two different short-term aged conditioning protocols to determine if short-term aging affects the effectiveness of the rejuvenators.

Laboratory Materials

Performance Grading of PG76-22 Asphalt Binder Dosed with Rejuvenators

A polymer-modified PG76-22 was used in the study as the virgin asphalt binder in the mixtures. The NJDOT requested the use of the PG76-22 asphalt binder as their belief was that the rejuvenator-dosed asphalt mixtures would most often be utilized in surface course mixtures. Currently, over 50% of all surface course mixtures placed in New Jersey utilize a polymer-modified PG76-22 asphalt binder.

As noted earlier, the rejuvenators were preblended in the asphalt binder at a dosage rate recommended by the respective manufacturer. The resultant PG grade of the PG76-22 and PG76-22 rejuvenator-dosed asphalt binders are shown in Table 5. The results show that the different rejuvenators clearly soften the PG grade of the PG76-22 asphalt binder and that the magnitude of change differs with the various rejuvenators. For example, when comparing the resultant PG grades at the identical RAP content dosage, the Valero 165 rejuvenator had the greatest “softening” effect when compared to the other rejuvenator-dosed asphalt binders. In the case of the Valero 165, when the asphalt binder was dosed for 45% RAP, it reduced the PG76-22 asphalt binder to a PG58-34. This is of great concern when considering that a majority of the rejuvenator-dosed asphalt binders will be preblended at the refinery and delivered directly to the storage tank at the asphalt plant. If there is an unexpected change in the RAP content, or the job needs to be shut down for extended periods of time, the asphalt plant will have a significantly softer asphalt binder in than storage tank.

The PG grade of the RAP used in the study is also shown in Table 5. The measured PG grade of the RAP was a PG82-16, with the low temperature grade controlled by the m-slope.

Table 5 – Performance Grade of PG76-22 Dosed with Various Rejuvenators and Dosage Rates

Rejuvenator/Binder Type	RAP Content (%)	Continuous PG Grade (°C)					
		High Temp		Low Temp		Intermediate Temp	Final PG Grade
		Original	RTFO	Stiffness	m-slope		
PG76-22	0%	78.9	77.8	-25.0	-26.1	22.8	76-22
RAP	100%	90.8	84.1	-24.6	-17.9	28.8	82-16
Binders below represent PG76-22 "dosed" for the noted RAP content - No RAP Binder included							
Valero 130	25%	74.5	74.2	-26.8	-28.6	20.8	70-22
	45%	68.4	67.7	-29.4	-32.2	16.5	64-28
Valero 165	25%	70.7	71.9	-31.7	-31.5	16.9	70-28
	45%	62	63.5	-38.9	-38.7	9.5	58-34
Hyprene 150	25%	74.2	73.8	-27.7	-28.3	20.2	70-22
	45%	74.7	68.5	-31.8	-33.0	15.4	64-28
Oleic Acid	25%	74.1	74.1	-27.5	-29.4	20.0	70-22
	45%	65.2	67.5	-33.1	-35.2	11.8	64-28
Azko Nobel	25%	74.4	74.3	-28.6	-26.8	20.7	70-22
	45%	69.1	68.4	-32.0	-30.1	15.7	64-28

Aggregates and Mixture Design

The asphalt mixture used in the study was a NJDOT approved, 9.5 mm nominal maximum aggregate size (NMAS), PG76-22 asphalt mixture from Tilcon Keasby, NJ (currently owned and operated by Trap Rock Industries). The NJDOT 9.5M76 asphalt mixture had an optimum asphalt content of 5.5%. The RAP used in the study was also from the Tilcon Keasby facility, although the true source of the screened RAP was from various locations in northern and central New Jersey. The asphalt content of the RAP, determined by solvent extraction and recovery, was 5.0%. Due to the lower asphalt content in the RAP, and the fact that the NJDOT utilizes RAP by total weight of the asphalt mixture, additional virgin asphalt binder was required to be added to maintain the optimum asphalt content of 5.6%. Table 6 and Figure 8 present the aggregate gradation and asphalt content of the mixtures in the study.

Table 6 – Gradation and Asphalt Content of Mixtures

Sieve Size (mm)	Virgin Mix	25% RAP	45% RAP
50.00	100.00	100.00	100.00
37.50	100.00	100.00	100.00
25.00	100.00	100.00	100.00
19.00	100.00	100.00	100.00
12.50	99.95	99.96	99.97
9.50	92.31	92.11	91.99
4.75	55.29	55.35	55.36
2.36	37.11	36.94	36.57
1.18	25.94	26.16	26.45
0.60	18.45	18.56	19.05
0.30	12.60	12.34	12.63
0.15	7.94	7.95	8.32
0.075	5.18	5.30	5.65
Virgin AC%	5.6	4.35	3.35
RAP AC%	0.0	1.25	2.25

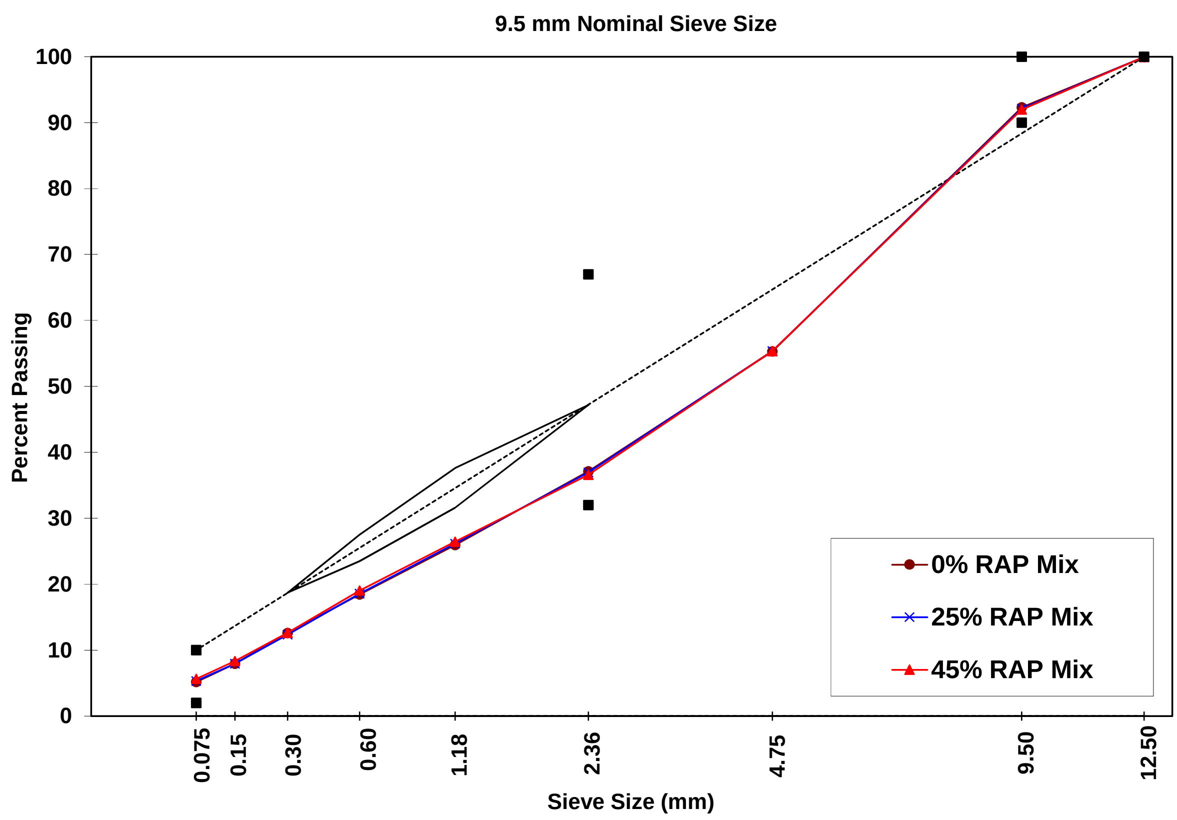

Figure 8 – Gradation Chart of Asphalt Mixtures in Study

The asphalt mixtures were conditioned at two different short-term oven conditions; 2 hours at compaction temperature and 6 hours of additional loose mix aging at 135^{o}C. The purpose of evaluating the mixtures at two different conditioning levels was to evaluate if changes in the rejuvenators' effectiveness occurred when the rejuvenated mixture was held at elevated temperatures for extended time periods. After the respective conditioning had occurred, the loose mix was then compacted into test specimens.

Phase 1 Testing – Asphalt Binder Analysis

The performance grade (PG) system uses the Dynamic Shear Rheometer (DSR) to measure high and intermediate binder performances. It provides a shear modulus (G*) and a phase angle (δ) which is used to measure the elastic (recoverable) and viscous (non-recoverable) behaviors of binders at high temperatures, and elastic (recoverable) and cracking (non-recoverable) behaviors of binders at intermediate temperatures. Creep stiffness (S) and creep slope (m-value) from a Bending Beam Rheometer are used to measure low-temperature performance along with the critical cracking temperature provided by a Direct Tension test. The PG's provided by these tests and also the Multiple Stress Creep Recovery (MSCR) test were used in this study to evaluate changes in binder rheology due to aging and the effect of the rejuvenators.

Recently, G* and δ have also been used to generate a rheological plot commonly referred to as Black Space Diagram. Researchers have illustrated the use of Black Space Diagram to evaluate the changes in binder rheology due to aging (King et al., 2012) (Anderson et al., 2011). Another analysis that can be used to evaluate these changes is the Christensen-Anderson Model (CAM). The two methodologies were the focus of this study.

Black Space Diagram and the Glover - Rowe Damage Parameter

Figure 9 illustrates a Black Space Diagram that shows the current performance grade (PG) parameter for fatigue cracking (G*sinδ), in addition to a new Black Space function defined by a new parameter, named the Glover-Rowe parameter, in the form of $G^*(\cos\delta)^2/(\sin\delta)$ (Anderson et al., 2011). This parameter was developed based on the Glover fatigue cracking parameter, $G'/(\eta'/G')$, which was found to have a high correlation to the ductility of the asphalt binder (Glover et al., 2005). It is determined from intermediate temperature DSR testing. The advantage of this Glover-Rowe parameter is that as long as the test frequency (ω) is known, variables G* and δ can be plotted to create a damage curve in black space. Based on the work of Anderson et al., (2011) and Rowe (2014), preliminary thresholds have been proposed to determine when non-load associated cracking, specifically block cracking, may begin (Damage Onset) and when there will be definite cracking problems (Significant Cracking). A typical cause of block cracking is the inability of asphalt binder to expand and contract with temperature cycles because of the aging of the asphalt binder. These thresholds have $G^*(\cos\delta)^2/(\sin\delta)$ values of 180 kPa and 450 kPa, respectively, when tested at 15°C (59°F) and a loading frequency of 0.005 radians/sec.

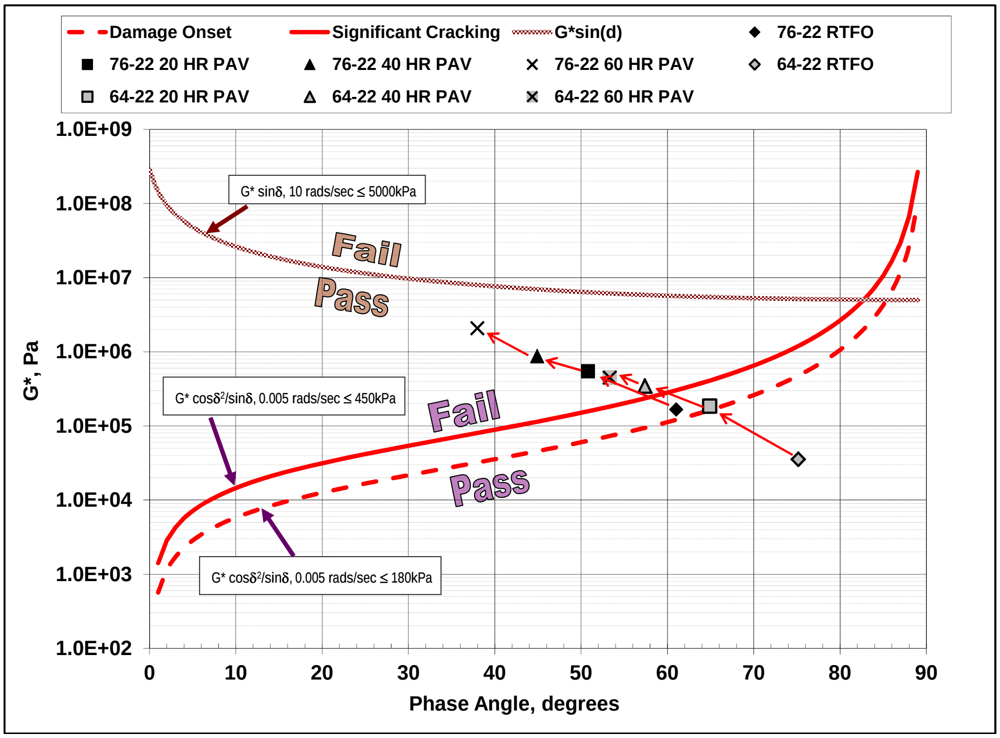

Figure 9 – PAV-aged Asphalt Binders Passing Through the Glover-Rowe Damage Zone

Similar to the work described by Anderson et al. (2011), Figure 9 illustrates data for two different binders (PG64-22 & PG76-22) that were aged in a pressure aging vessel (PAV) for 0, 20, 40, and 80 hours. The PAV aging was done after all binders were short term aged in a rolling thin film oven (RTFO). The purpose of the longer PAV aging times was to create a more highly-aged sample in the laboratory. Using the new Glover-Rowe parameter and presenting the data in Figure 8, the RTFO aging for each binder started at the lower right location in the Black Space diagram; each additional aging period caused the rheological properties to move to the upper left of the diagram (increase in the stiffness and reduced phase angle for each binder). It should be noted that even after 60 hours of PAV aging, the asphalt binders still “Pass” the current G*sinδ Superpave specification. For extracted and recovered binders from high RAP content mixtures with consequently higher amounts of aged binder in a mixture, binder testing data is expected to follow the same trend illustrated in Figure 9. This trend is a rheological response to move towards the upper left of the Black Space diagram. Daniel (2013) confirmed this trend on extracted and recovered asphalt binder from plant produced mixtures in Vermont.

The trend in the Black Space Diagram indicated that as RAP percentage increases for the same mixture, the G* and δ data migrates from the lower right to the upper left of the Black Space. Therefore, if a rejuvenator is assisting in restoring the rheological properties of aged RAP binder, the trend should be reversed on the Black Space Diagram (movement toward lower right of the diagram). This movement in Black Space, combined with the Glover-Rowe damage parameters, will be utilized in this study to understand if rejuvenators can assist in mitigating the aging experienced by binders extracted and recovered from high RAP mixtures. Additionally, using the Glover-Rowe damage parameter alone a quantification of the binders resistance to non-load associated cracking can be made.

Christensen-Anderson Model (CAM) Master Curve Parameters

Another tool that can be used to investigate the effect of rejuvenators on the rheological properties of aged binders is to use traditional rheological master curves of G* versus loading frequency. The Christensen-Anderson Model (CAM) is a very useful tool because the master curve parameters (ω_o, R, and T_d) have specific physical significance. The Cross-over Frequency, ω_o, is a measure of the overall hardness of the binder. As this frequency increases, the hardness of the binder decreases which is desirable for rejuvenated binders. The Rheological Index, R-value, is an indicator of the rheological type. It is defined as the difference between the log of the glassy modulus and the log of the dynamic modulus at the cross-over frequency. As R-value increases, the master curve becomes flatter indicating a more gradual transition from elastic behavior to steady-state flow. Normally, R-value is higher for oxidized asphalt. Accordingly, the R-value is expected to increase with oxidization. Therefore, for rejuvenators to be effective, the R-value for the overall aged plus virgin binder should decrease. Figure 10 shows the parameters used to define the shape of the binder master curve.

Figure 11 shows the ω_o and R-value for the same test data presented earlier in Figure 9. In this case, ω_o and R-value are plotted in their own space (ω_o – R-value Space). The PG64-22 and PG76-22 asphalt binders migrate from the upper left to the lower right of the ω_o – R-value Space as the magnitude of aging increases. The same trend can be expected as the RAP content of the asphalt mixture increases.

The master curve test results and analysis indicate that G* and δ, as well as the functional form of the master curve itself (ω_o and R-value), can be utilized to evaluate aging in an asphalt binder. Since aging can be clearly identified using this method, it is hypothesized that the same testing and analysis procedures can be utilized to evaluate the effectiveness of rejuvenators for mitigating the effects of aged asphalt binder in high RAP mixtures.

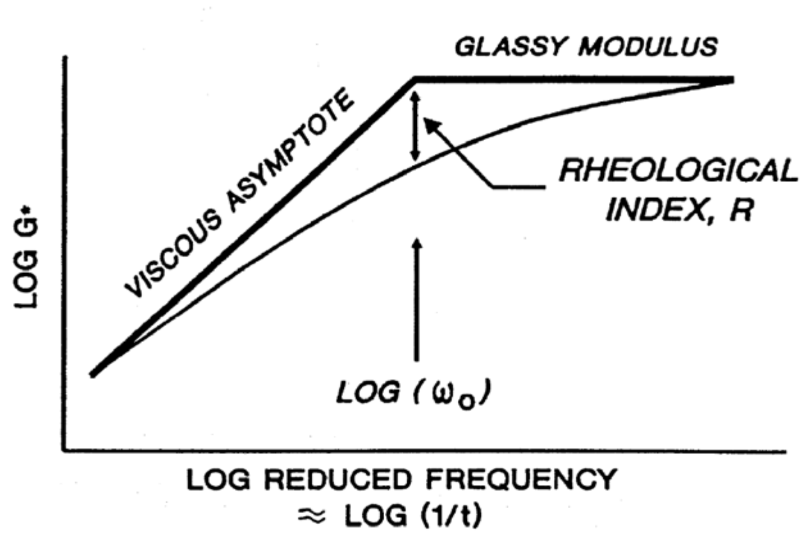

Figure 10 – Functional Form of Christensen-Anderson Asphalt Binder Master Curve Model (Christensen and Anderson, 1992)

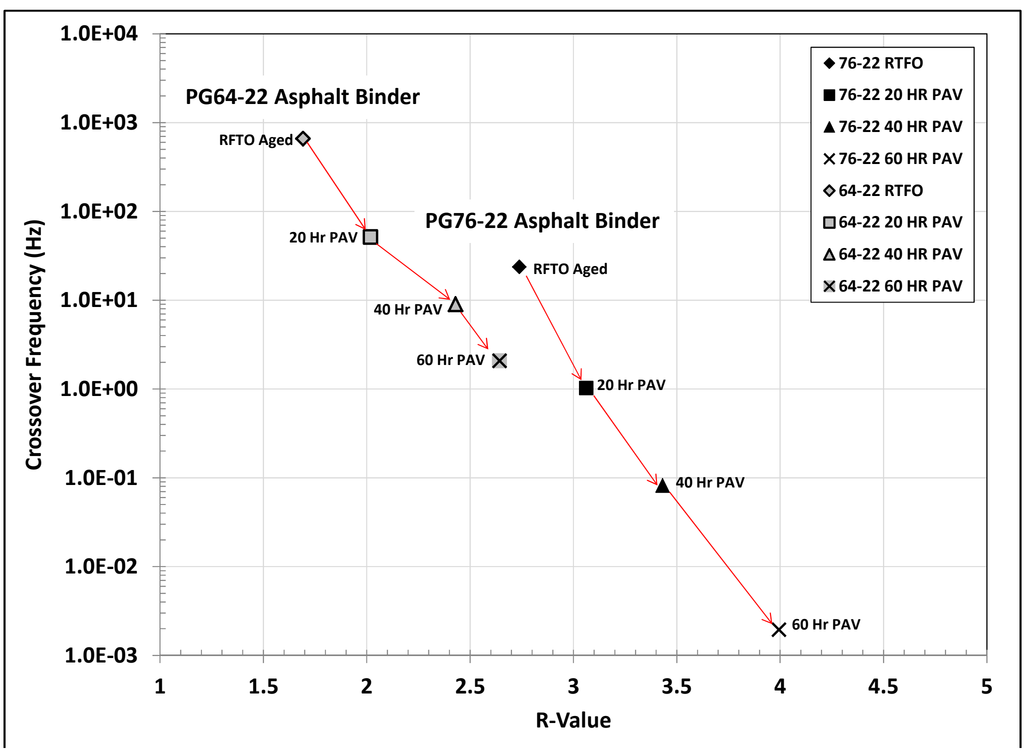

Figure 11 – Crossover Frequency – R-value Space: PG64-22 and PG76-22 Asphalt Binders After Different Aging Levels

Performance Grade Results of Extracted/Recovered Binders

Prior to the rheological testing and analysis described earlier, the performance grade of the extracted and recovered asphalt binders were determined in accordance with AASHTO M320, *Standard Specification for Performance-Graded Asphalt Binder*. The asphalt binder from compacted test specimens was extracted and recovered in accordance with AASHTO T164, Method A, *Procedure for Asphalt Extraction and Recovery Process.* The extraction/recovery, PG grading, and generation of master curves was conducted at the asphalt binder laboratory at Rowan University.

The Performance Grade results for the recovered asphalt binders are shown in Table 7 and Figures 12 and 13. In general, the test results indicate that the addition of the different rejuvenators, at the manufacturer's recommended dosage rate, were able to maintain the low temperature PG grade of the RAP mixture to a -22^{o}C. In a few instances, the rejuvenator was actually able to drop the low temperature PG grade to a -28^{o}C. This is important as a major concern in utilizing recycled asphalt (RAP or RAS) is that it will detrimentally affect the low temperature PG grade of the asphalt binder. The high temperature PG grade typically graded out somewhere between a PG88 to a PG76, indicating that the rejuvenator and dosage rate used did not overly soften the asphalt mixture, resulting in a mixture that may be prone to permanent deformation.

Using the low temperature PG grade as an indicator of which rejuvenator worked the best at softening the RAP mixture, it would appear that both Valaro products worked the best, with the Valaro 165 (Paraffinic base) rejuvenator providing the best rejuvenation.

Table 7 – Performance Grading Results of Extracted/Recovered Asphalt Binders from Compacted Specimens

Rejuvenator/ Binder Type	RAP Content (%)	Aging Condition	Continuous PG Grade Results		
			High Temp (^oC)	Low Temp (^oC)	Final PG Grade
PG76-22 (No Rejuvenator)	0%	2 Hr	88.2	-21.8	88-16
	25%	2 Hr	89.0	-24.0	88-22
	45%	2 Hr	92.7	-22.3	88-22
	0%	6 Hr	101.0	-18.6	100-16
	25%	6 Hr	91.5	-22.0	88-22
	45%	6 Hr	89.1	-22.4	88-22
Valaro 130	25%	2 Hr	82.8	-25.7	82-22
	45%	2 Hr	78.4	-29.6	76-28
	25%	6 Hr	81.8	-26.5	76-22
	45%	6 Hr	83.0	-26.2	82-22
Valaro 165	25%	2 Hr	79.4	-28.9	76-28
	45%	2 Hr	80.1	-30.3	76-28
	25%	6 Hr	81.5	-27.5	76-22
	45%	6 Hr	77.3	-30.2	76-28
Hyprene	25%	2 Hr	83.4	-26.3	82-22
	45%	2 Hr	81.1	-27.0	76-22
	25%	6 Hr	88.6	-24.5	88-22
	45%	6 Hr	82.7	-25.8	82-22
Oleic Acid	25%	2 Hr	85.2	-27.2	82-22
	45%	2 Hr	82.7	-27.5	82-22
	25%	6 Hr	84.7	-24.8	82-22
	45%	6 Hr	87.1	-26.8	82-22
Akzo Nobel	25%	2 Hr	82.9	-26.6	82-22
	45%	2 Hr	79.7	-25.9	76-22
	25%	6 Hr	82.1	-26.2	82-22
	45%	6 Hr	84.4	-24.5	82-22

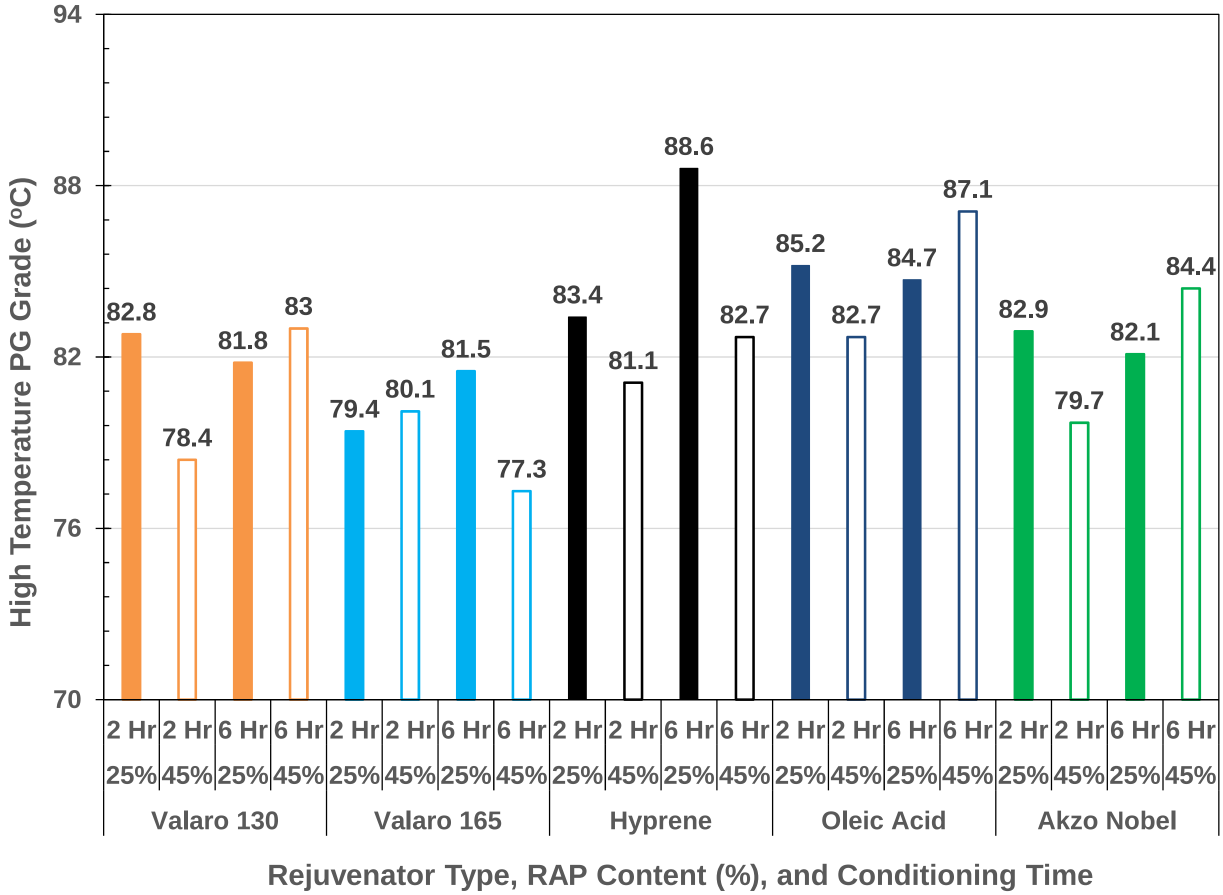

Figure 12 – High Temperature Performance Grade of Extracted/Recovered Asphalt Binders

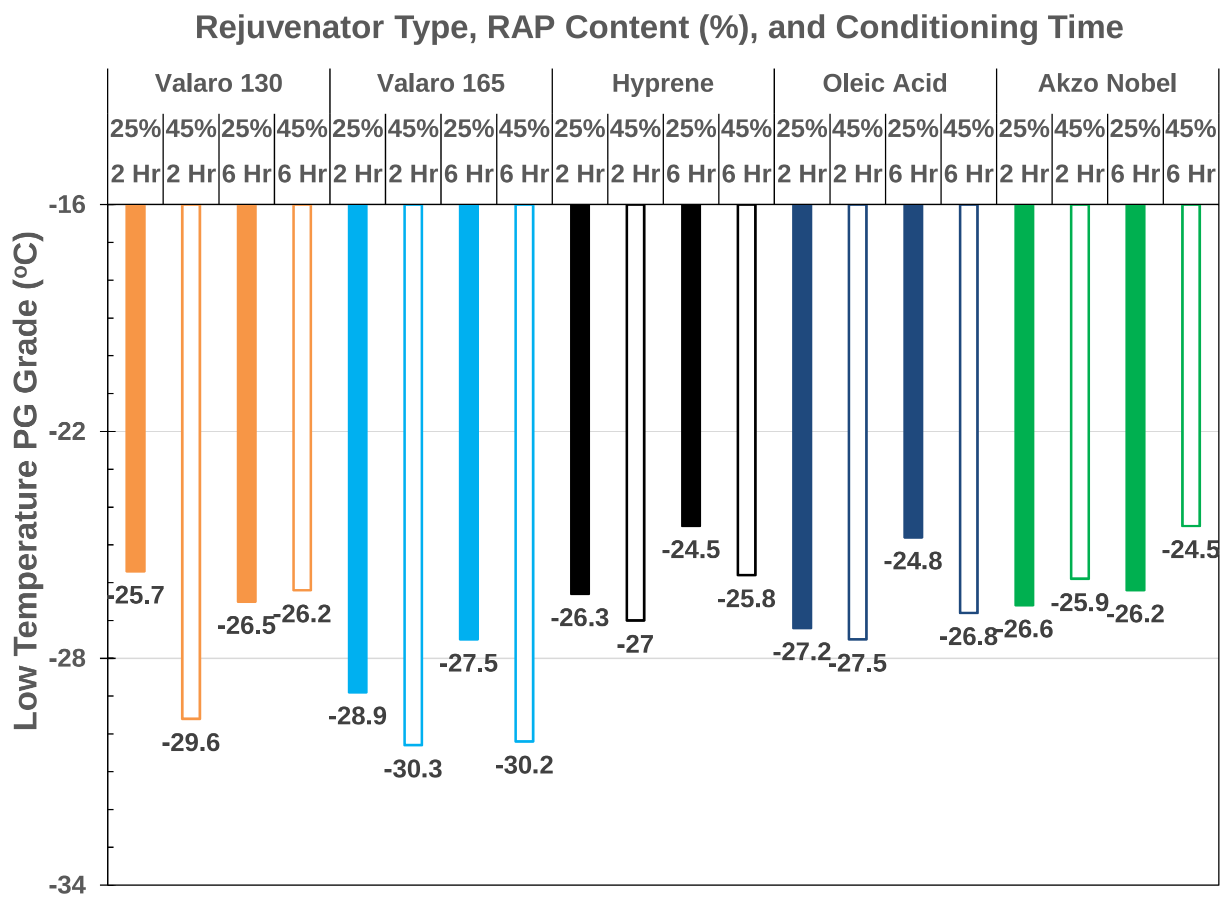

Figure 13 – Low Temperature Performance Grade of Extracted/Recovered Asphalt Binders

Black Space Diagram and the Glover - Rowe Damage Parameter – Results

As described earlier, the information generated during the construction of the recovered asphalt binder master stiffness curve can be utilized to evaluate the cracking potential and aging potential of the asphalt binder. Glover et al. (2005) proposed the rheological parameter, G'/(η'/ G'), as an indicator of ductility based on a derivation of a mechanical analog to represent the ductility test consisting of springs and dashpots. It has been well demonstrated that the Glover parameter is directly correlated to measured ductility. The Glover parameter can be calculated based on DSR frequency sweep testing results, making it much more practical than directly measuring ductility using traditional methods. Rowe (2011) re-defined the Glover parameter in terms of |G*| and δ based on analysis of a black space diagram as shown in Equation (1) and suggested use of the parameter $|G^*|\cdot(\cos\delta)^2/\sin\delta$, termed the Glover-Rowe (G-R) parameter in place of the original Glover parameter.

$$\frac{G'}{\eta'/G'} = \frac{|G^*|\cdot(\cos\delta)^2}{\sin\delta}\cdot\omega \qquad \textbf{(1)}$$

Rowe proposed measuring the G-R parameter based on construction of a master curve from frequency sweep testing at 5°C, 15°C, and 25°C in the DSR and interpolating to find the value of G-R at 15°C and 0.005 rad/sec to assess binder brittleness (Rowe et al. 2014). A higher G-R value indicates increased brittleness. It has been proposed that a G-R parameter value of 180 kPa corresponds to damage onset whereas a G-R value exceeding 450 kPa corresponds to significant cracking based on a study relating binder ductility to field block cracking and surface raveling by Anderson et al. (2011).

By plotting the recovered asphalt binders in Black Space, before and after the rejuvenators have been added, one can observed whether or not the rejuvenator is capable of rejuvenating the asphalt binder enough where the potential for cracking does not exist.

Figures 14 to 18 show the Black Space analysis for the different rejuvenators evaluated. Using the G-R parameter value of 180 kPa as a PASS/FAIL line for comparison, Figures 14 and 15 show that the Hyprene and Valaro 165 rejuvenators were capable of rejuvenating RAP mixtures from a condition of "Damage Onset" to a condition where fatigue cracking potential in minimal. Figure 16 shows that the Valaro 130 was able to rejuvenate most of the mixtures to a "PASSING" area, while Figures 17 and 18 show mixed results with the Akzo Nobel and Oleic Acid rejuvenators, respectively.

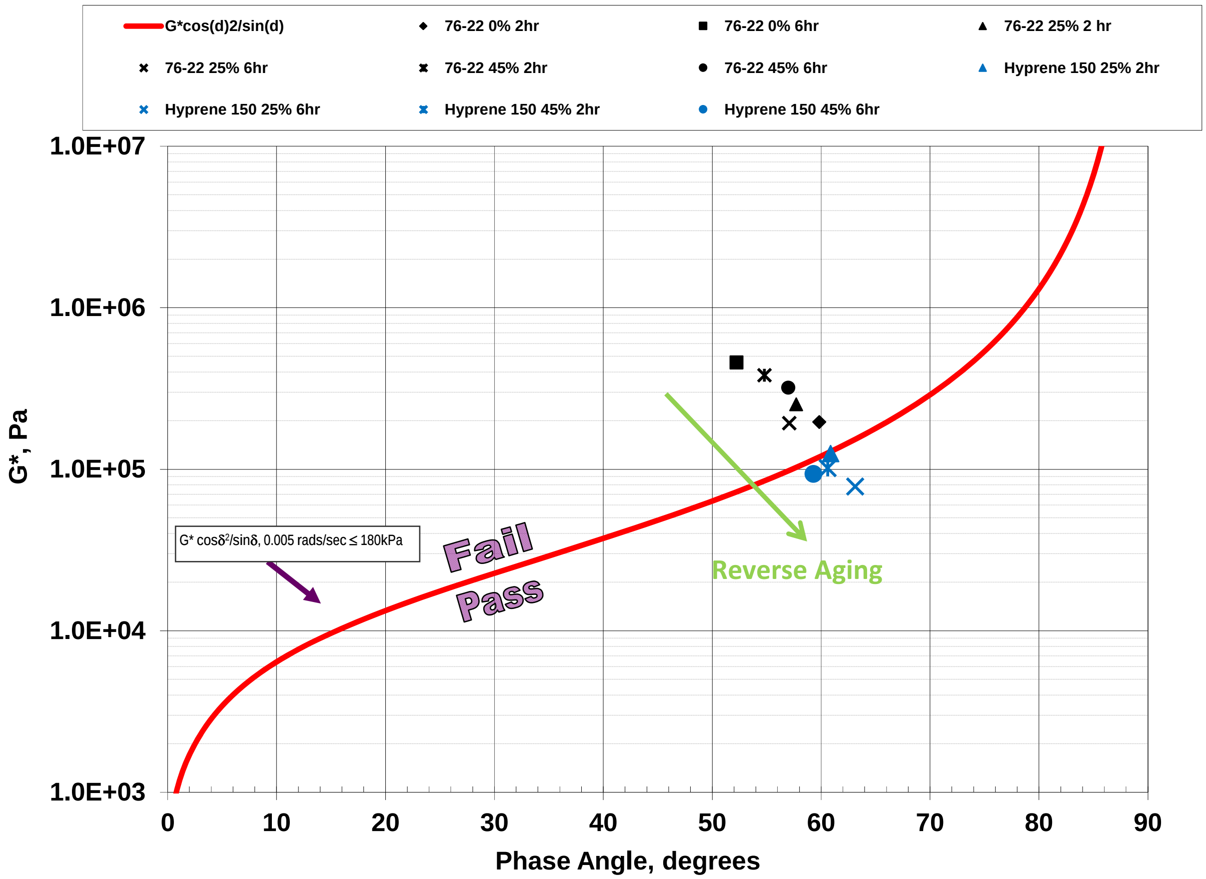

Figure 14 – Black Space Analysis for Hyprene Rejuvenator

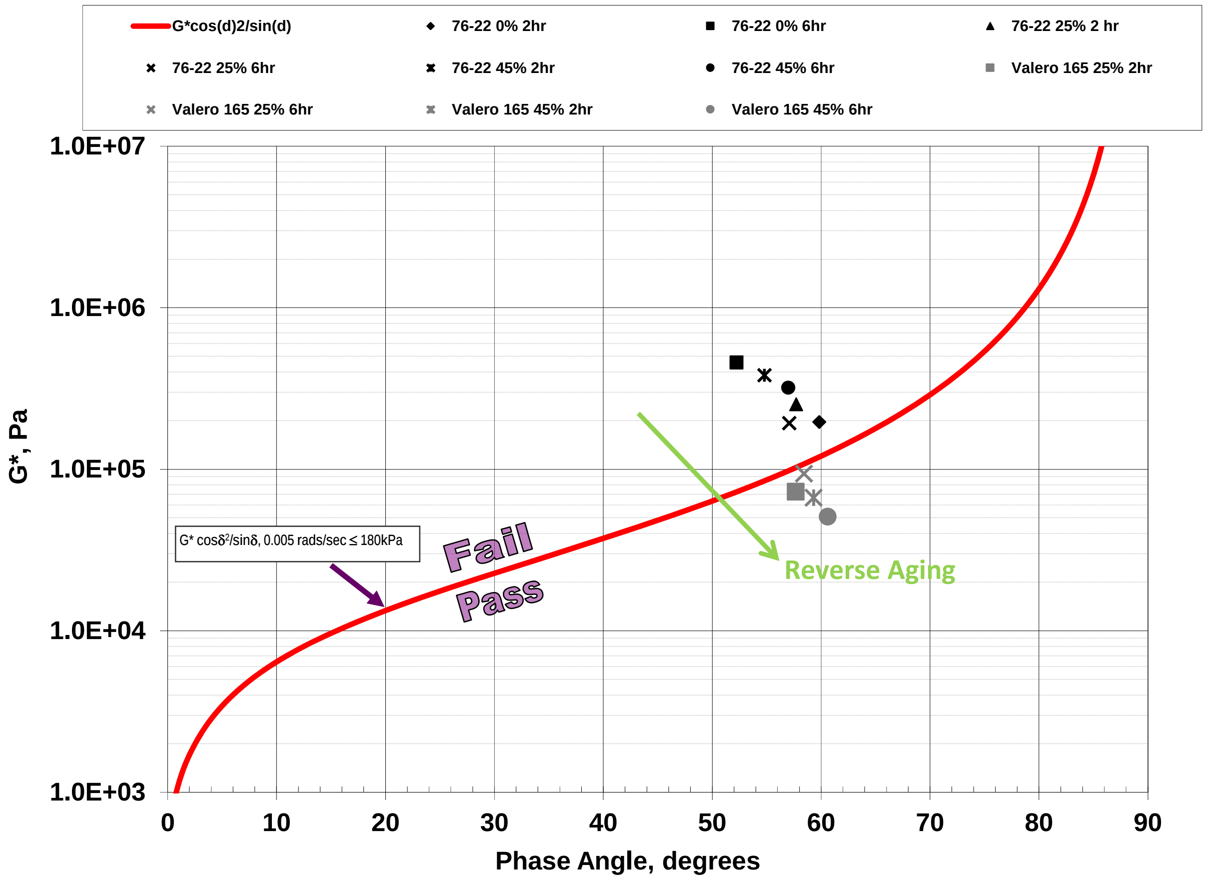

Figure 15 – Black Space Analysis for Valero 165 (Paraffinic Base) Rejuvenator

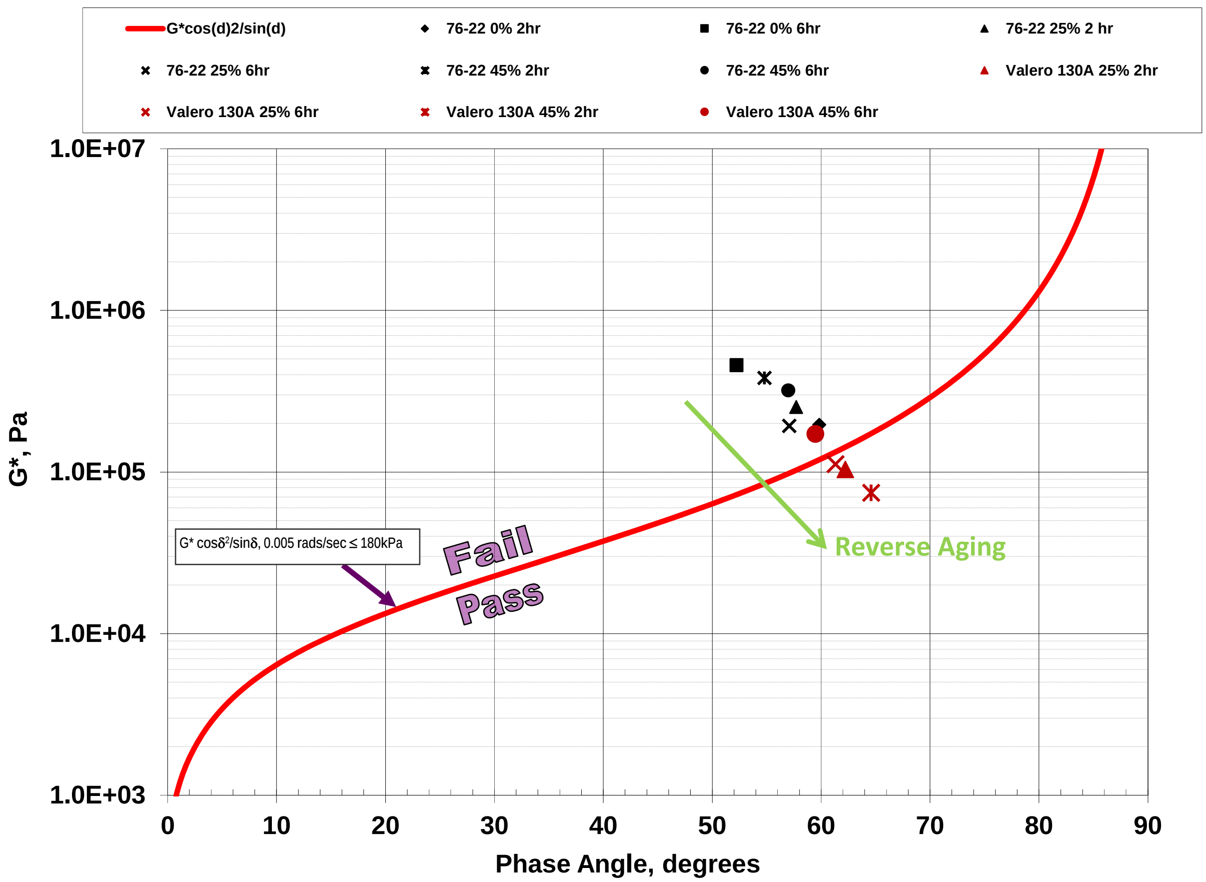

Figure 16 – Black Space Analysis for Valero 130 (Aromatic Oil) Rejuvenator

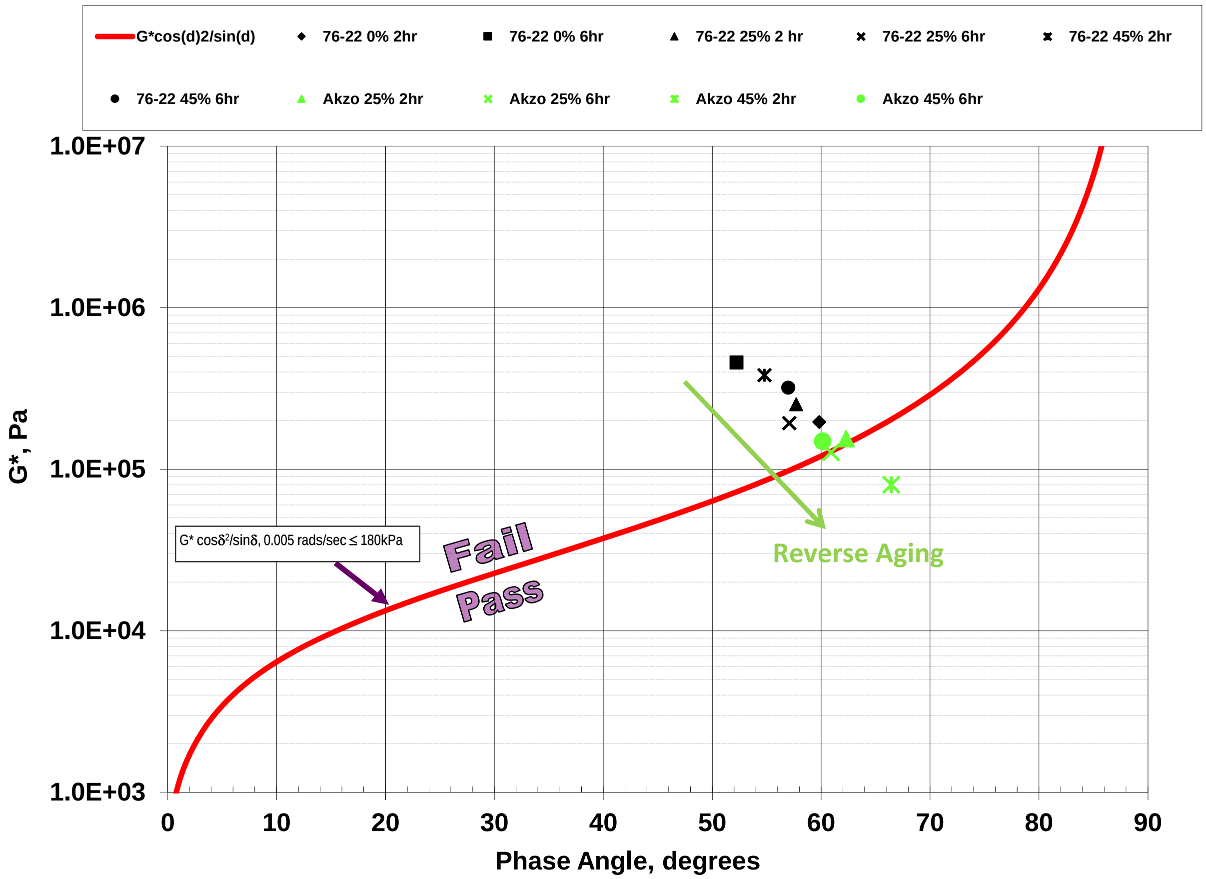

Figure 17 – Black Space Analysis for Akzo Nobel Rejuvenator

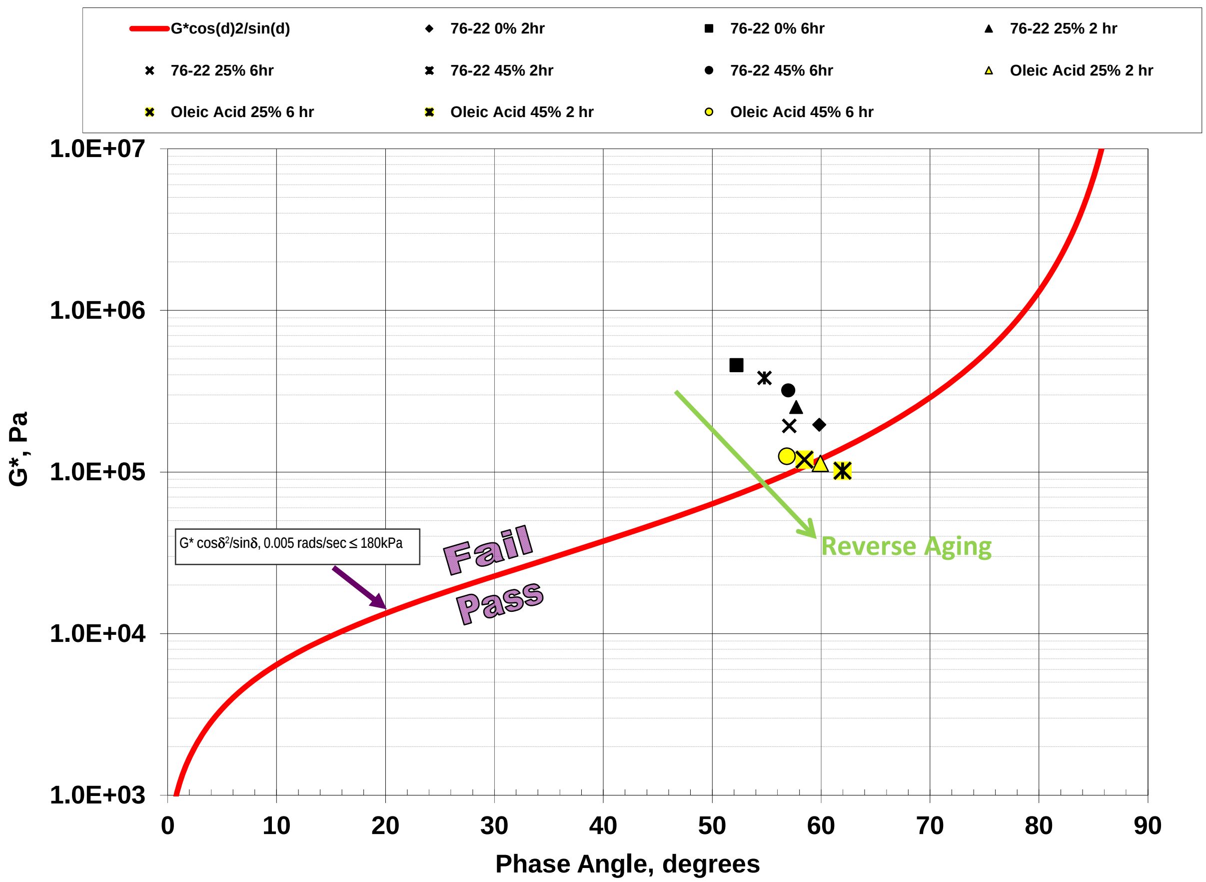

Figure 18 – Black Space Analysis of Oleic Acid Rejuvenator

As mentioned earlier, Anderson et al., (2011) and Rowe (2011) proposed the value of 180 kPa at 15°C and 0.005 rad/sec as a threshold value for when the onset of cracking is likely. Using Equation (1) to determine the Glover-Rowe (G-R) parameter for the various extracted and recovered asphalt binders, Figures 19 and 20 were generated. Figure 19 contains the test results for the asphalt mixtures that contained 25% RAP. The results clearly show that the two mixtures without rejuvenators resulted in the highest G-R parameter; meaning that those mixtures were more susceptible to fatigue cracking than the mixtures containing the rejuvenators. On average, the rejuvenated 25% RAP mixtures had approximately one half of the G-R parameter when compared to the No Rejuvenator mixtures. No real difference is observed between the 2 hour and 6 hour conditioning times.

Figure 20 shows the test results for the 45% RAP mixtures. The difference between the mixtures with and without rejuvenators is even greater at the 45% RAP content. In fact, both of the No Rejuvenator mixtures comes somewhat close to the G-R Damage Onset Value of 180 kPa. For the 45% RAP mixtures, it appears that conditioning time does influence the results, as there is a clear increase in the G-R parameter for the rejuvenator mixtures due to the additional conditioning time.

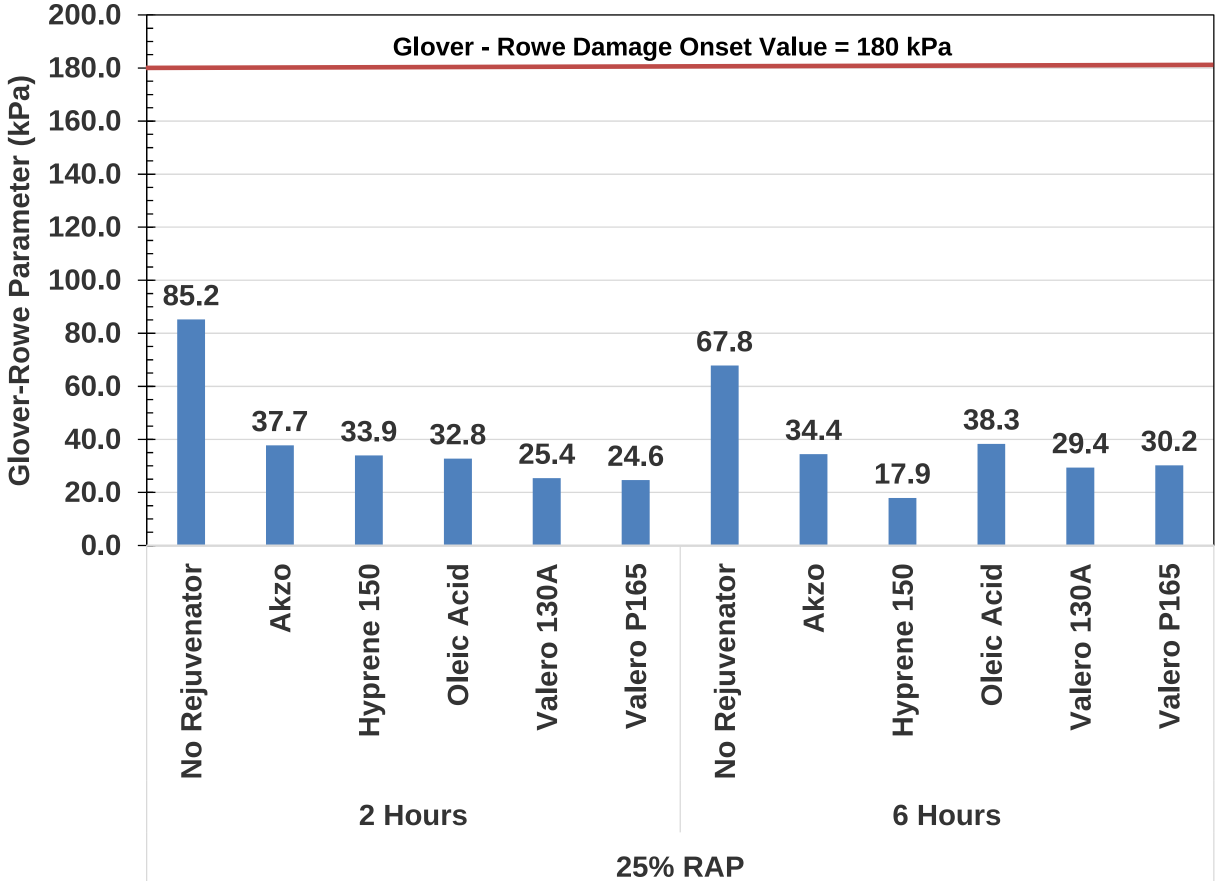

Figure 19 – Glover-Rowe Parameter Results for 2 Hour Conditioned Mixtures

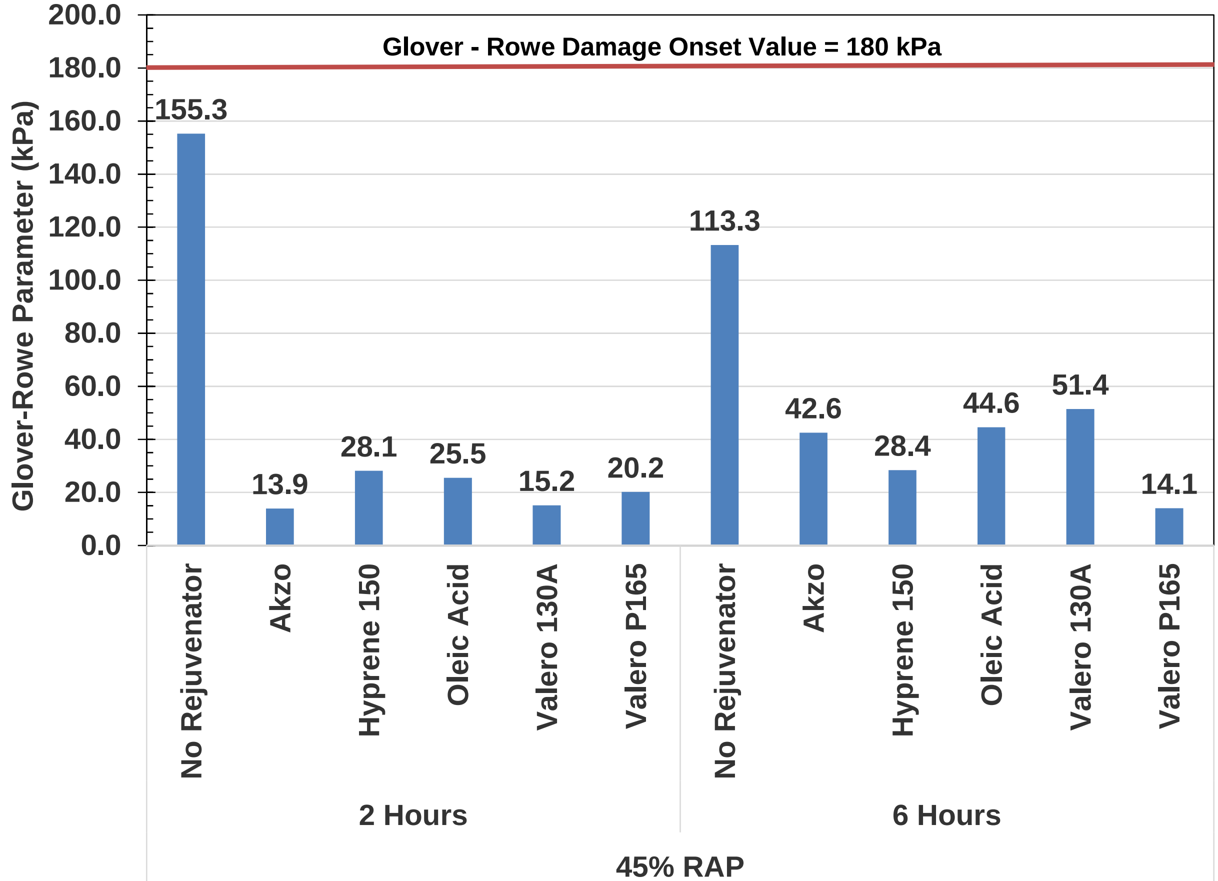

Figure 20 – Glover-Rowe Results for 6 Hour Conditioned Mixtures

Christensen-Anderson Model (CAM) Master Curve Parameters - Results

The rheological index, R, has been proposed to assess oxidation sensitivity as related cracking resistance of binder based on the rheological model proposed for asphalt binders during the SHRP program (Christensen and Anderson 1992). The R value is the distance between the |G*| master curve and glassy modulus ($|G^*|_g$) at the frequency where δ equals 45°, termed the cross-over frequency (ω_c). The cross over frequency corresponds to the frequency where loss and storage moduli are equal. The R value is related to the relaxation spectra and chemical composition of the binder. R values increase with oxidation and thus, high R values are anticipated to indicate increased cracking susceptibility. The cross over frequency (ω_c) has also been proposed as an index to assess cracking susceptibility. Harder, more brittle asphalts generally have lower cross over frequencies. Therefore, the cross-over frequency would be sensitive to the amount of age asphalt binder, as well as the effectiveness of rejuvenators to soften the aged asphalt binder.

It is proposed in this study that the R-value and the ω_C can be used to construct a ω_C – R-value Space, similar to Black Space shown earlier. In the ω_C – R-value Space, as asphalt binders exhibit aging, the data will move from the upper left area of the space to the lower right area of the space, noted earlier in Figure 11. Therefore, for the asphalt binders to have exhibited rejuvenation, the data should move from the lower right to the upper left area in the space.

Figures 21 through 25 show the ω_C – R-value Space analysis results for the different rejuvenators. As the figures clearly shows, the addition of the rejuvenators beings to shift the data towards the upper left area of the space. However, the magnitude of movement was dependent on the rejuvenator type used. The Hyprene, Valero 130, and Akzo Nobel all appeared to able to rejuvenate the RAP mixtures in a very similar manner. However, the Valero 165 and Oleic Acid shifted the mixture properties upwards and slightly right. It is not understood if this was a testing error or the general performance of those particular rejuvenators. The Crossover Frequency (ω_C) is generally considered as a “hardness parameter”, while the Rheological Index (R-value) is directly proportional to the relaxation spectrum, and is an indicator temperature susceptibility of the asphalt binder. When there is no change in the R-value, as shown for the Valero 165 and Oleic Acid, it would indicate that a change in temperature susceptibility is not occurring due to the addition of the rejuvenator.

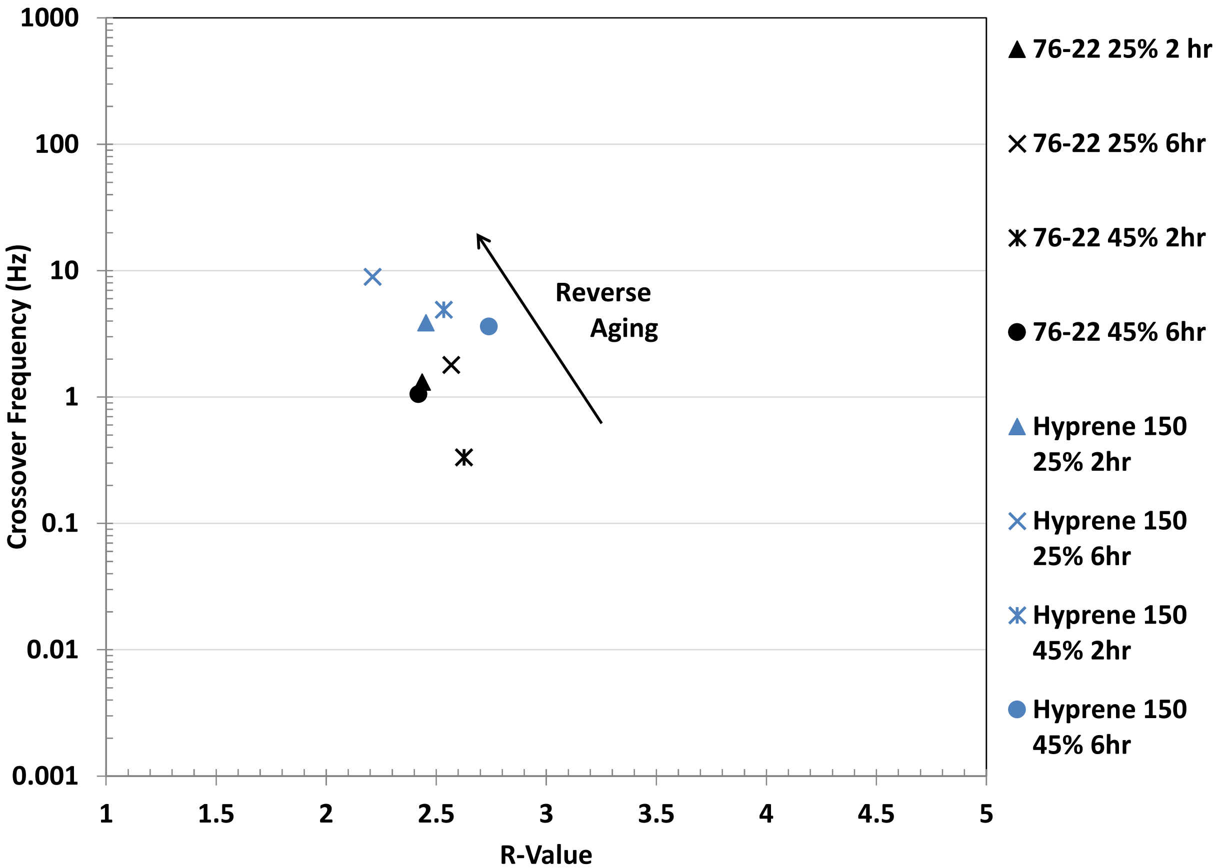

Figure 21 – ω_C – R-value Space Analysis for Hyprene Rejuvenator

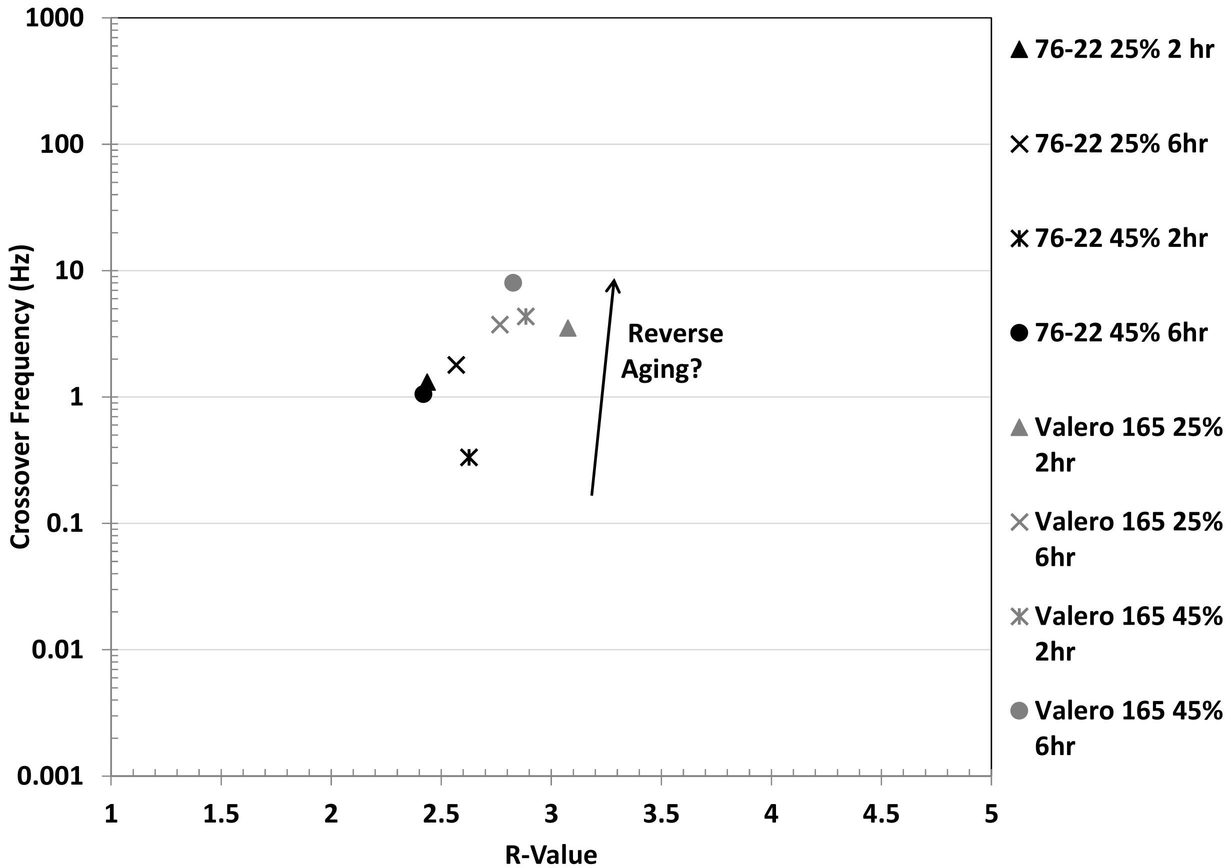

Figure 22 - ω_C – R-value Space Analysis for Valaro 165 Rejuvenator

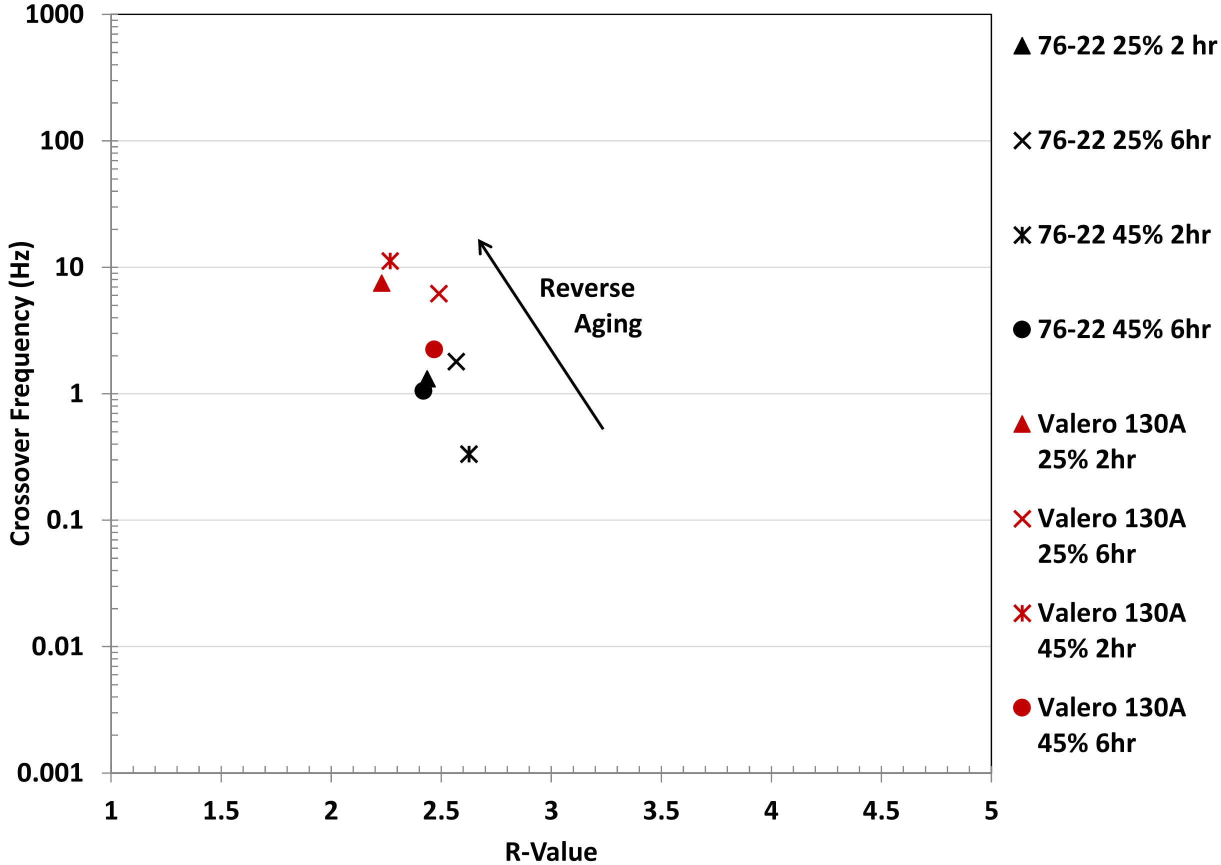

Figure 23 - ω_C – R-value Space Analysis for Valero 130 Rejuvenator

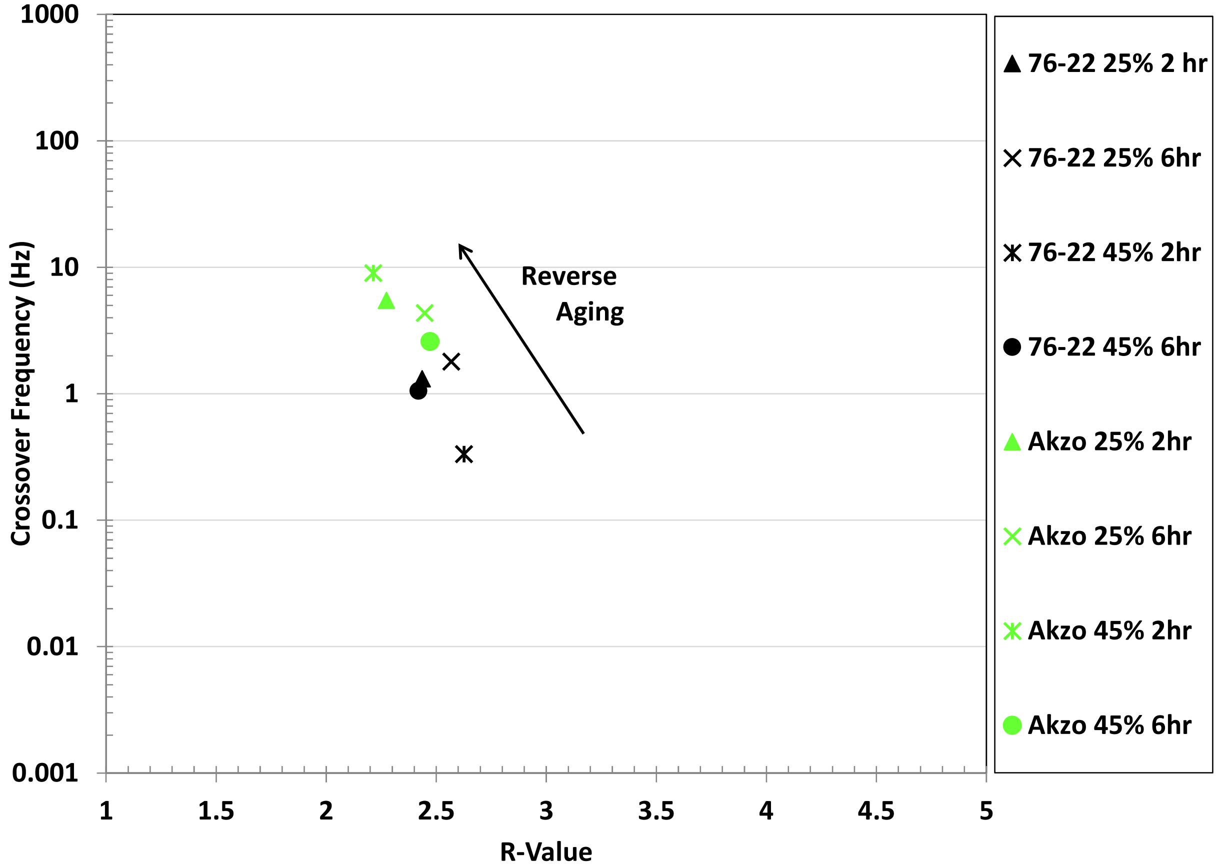

Figure 24 - ω_C – R-value Space Analysis for Akzo Nobel Rejuvenator

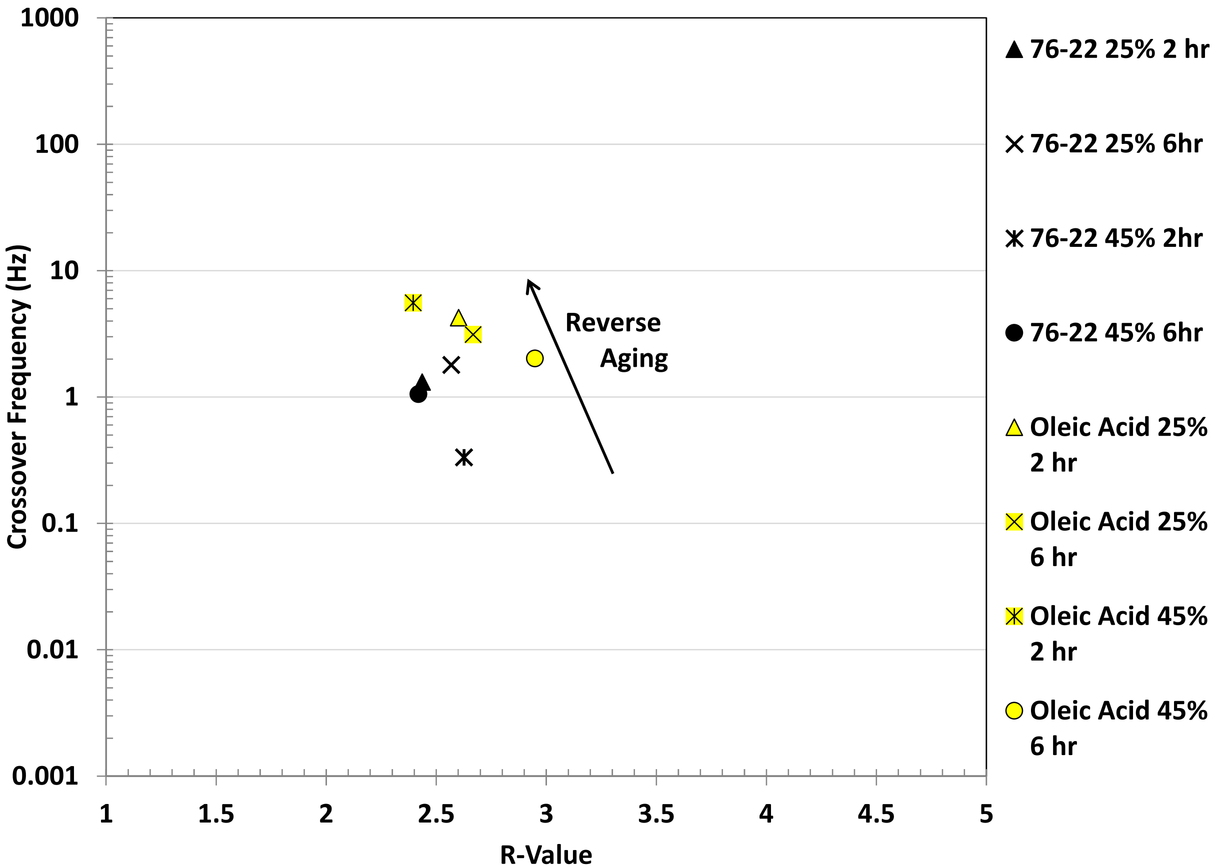

Figure 25 - ω_C – R-value Space Analysis for Oleic Acid Rejuvenator

Asphalt Binder Testing – Conclusions

Asphalt binder characterization, consisting of PG grading and master curve generation and analysis, was conducted on extracted and recovered asphalt binders from compacted asphalt mixtures produced in the laboratory with varying RAP percentages and short-term conditioning times. The laboratory characterization indicated that:

- The various rejuvenators used at the dosage rate recommended by the respective manufacturer, resulted in maintaining the low temperature PG grade of a -22^{o}C or lower for each mixture evaluated. This illustrates that each of the rejuvenators was capable of softening the blend of the RAP and virgin asphalt binders.
- The use of the G* master curves was found to have the potential to track the rejuvenating magnitude of the different rejuvenators. The Glover-Rowe (G-R) parameter appears to have the greatest potential as there are tentative criteria for “cracking limit and potential” that could be used as guidance as to whether or not the dosage rate and/or rejuvenator type is sufficient.

Comparison with NJDOT High RAP (HRAP) Specification

The NJDOT has recently developed at high RAP (HRAP) specification for use with asphalt mixtures containing more than 20% RAP in surface course mixtures and more than 30% RAP in intermediate and base mixtures. The specification is a performance-based specification, requiring the asphalt mixture to meet fatigue cracking and rutting performance criteria during the mixture design and plant production. A copy of the specification can be found in the Appendix of the report, however, a table containing performance requirements are shown in Table 8.

Table 8 – NJDOT's High RAP (HRAP) Performance Requirements

Table 902.11.03-2 Performance Testing Requirements for HMA HIGH RAP Design				
	Requirement			
	Surface Course		**Intermediate Course**	
Test	**PG 64-22**	**PG 76-22**	**PG 64-22**	**PG 76-22**
APA @ 8,000 loading cycles (AASHTO T 340)	< 7 mm	< 4 mm	< 7 mm	< 4 mm
Overlay Tester (NJDOT B-10)	> 150 cycles	> 175 cycles	> 100 cycles	> 125 cycles

The High RAP specification uses the Overlay Tester for the fatigue cracking performance, while using the Asphalt Pavement Analyzer for the rutting potential. Brief descriptions of both test procedures are below.

<u>Overlay Tester (TxDOT TEX-248F)</u>

The Overlay Tester, described by Zhou and Scullion (2007), has shown to provide an excellent correlation to field cracking for both composite pavements (Zhou and Scullion, 2007; Bennert et al., 2009) as well as flexible pavements (Zhou et al., 2007). Figure 26 shows a picture of the Overlay Tester used in this study. Sample preparation and test parameters used in this study followed that of TxDOT TEX-248F, *Overlay Test for Determining Crack Resistance of HMA*. These included:

- o 25^{o}C (77^{o}F) test temperature;
- o Opening width of 0.025 inches;
- o Cycle time of 10 seconds (5 seconds loading, 5 seconds unloading); and
- o Specimen failure defined as 93% reduction in Initial Load.

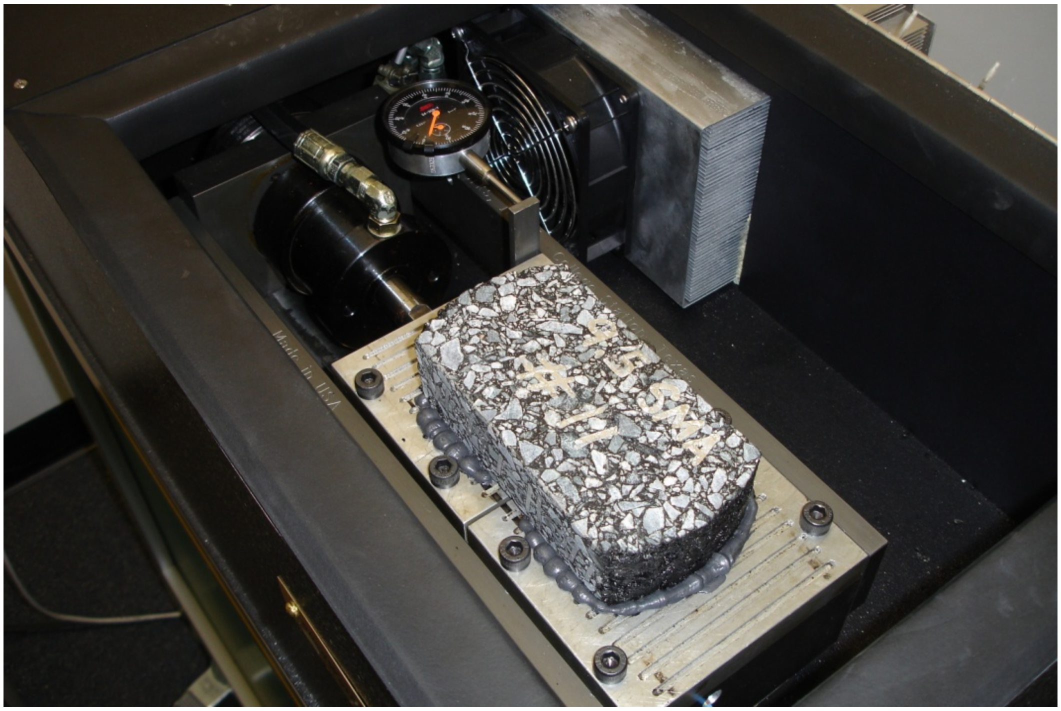

Figure 26 - Picture of the Overlay Tester (Chamber Door Open)

<u>Asphalt Pavement Analyzer (AASHTO T340)</u>

The Asphalt Pavement Analyzer (APA) was conducted in accordance with AASHTO T340, *Determining Rutting Susceptibility of Asphalt Paving Mixtures Using the Asphalt Pavement Analyzer (APA).* A hose pressure of 100 psi and a wheel load of 100 lb were used in the testing. Testing was continued until 8,000 loading cycles and APA rutting deformation was recorded at each cycle. The APA device used for testing at Rutgers University is shown in Figure 27.

Prior to testing, each sample was heated for 6 hours (+/- 15 minutes) at the testing temperature to ensure temperature equilibrium within the test specimen was achieved. Testing started with 25 cycles used as a seating load to eliminate any sample movement during testing. After the 25 seating cycles completed, the data acquisition began recording test information until a final 8,000 loading cycles was reached. Samples were tested at a test temperature of 64^{o}C.


(a)

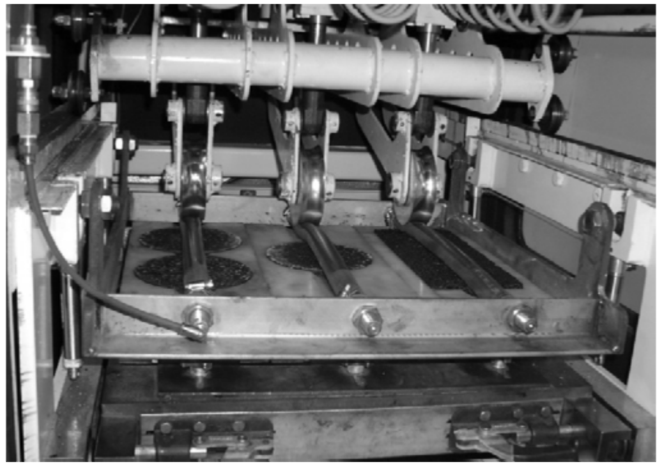
(b)

Figure 27 – Asphalt Pavement Analyzer; a) Front of the APA, 2) Inside Testing Chamber of the APA

2 Hour Conditioning – Test Results

The asphalt mixtures were conditioned at two different short-term oven conditions; 2 hours at compaction temperature and 6 hours of additional loose mix aging at 135°C. The purpose of evaluating the mixtures at two different conditioning levels was to evaluate if changes in the rejuvenators' effectiveness occurred when the rejuvenated mixture was held at elevated temperatures for extended time periods. After the respective conditioning had occurred, the loose mix was then compacted into test specimens.

The Overlay Tester fatigue cracking results for the 2 hour conditioning are shown in Figure 28. In almost all cases, the addition of the rejuvenator helped to increase the Overlay Tester fatigue cracking results. In some cases, Hyprene 25% RAP and Valero 130 45% RAP, it appears that no improvement was found when the rejuvenator was added. Meanwhile, in cases like the Valero 165, marked improvements in the fatigue cracking performance was noted at both the 25% and 45% RAP contents.

The Asphalt Pavement Analyzer (APA) rutting results for the 2 hour conditioned test specimens are shown in Figure 29. The test results are rather consistent, falling between 2.2 to 4.7 mm of rutting. The general trend in test data indicates that when the Overlay Tester cycles was higher (i.e. – better fatigue life), it was followed by an increase in the APA rutting (i.e. – greater potential for rutting). The would be somewhat expected as the rejuvenator is reducing the overall stiffness of the asphalt mixture by either softening the RAP binder and/or lower the PG grade of the asphalt binder it was preblended in.

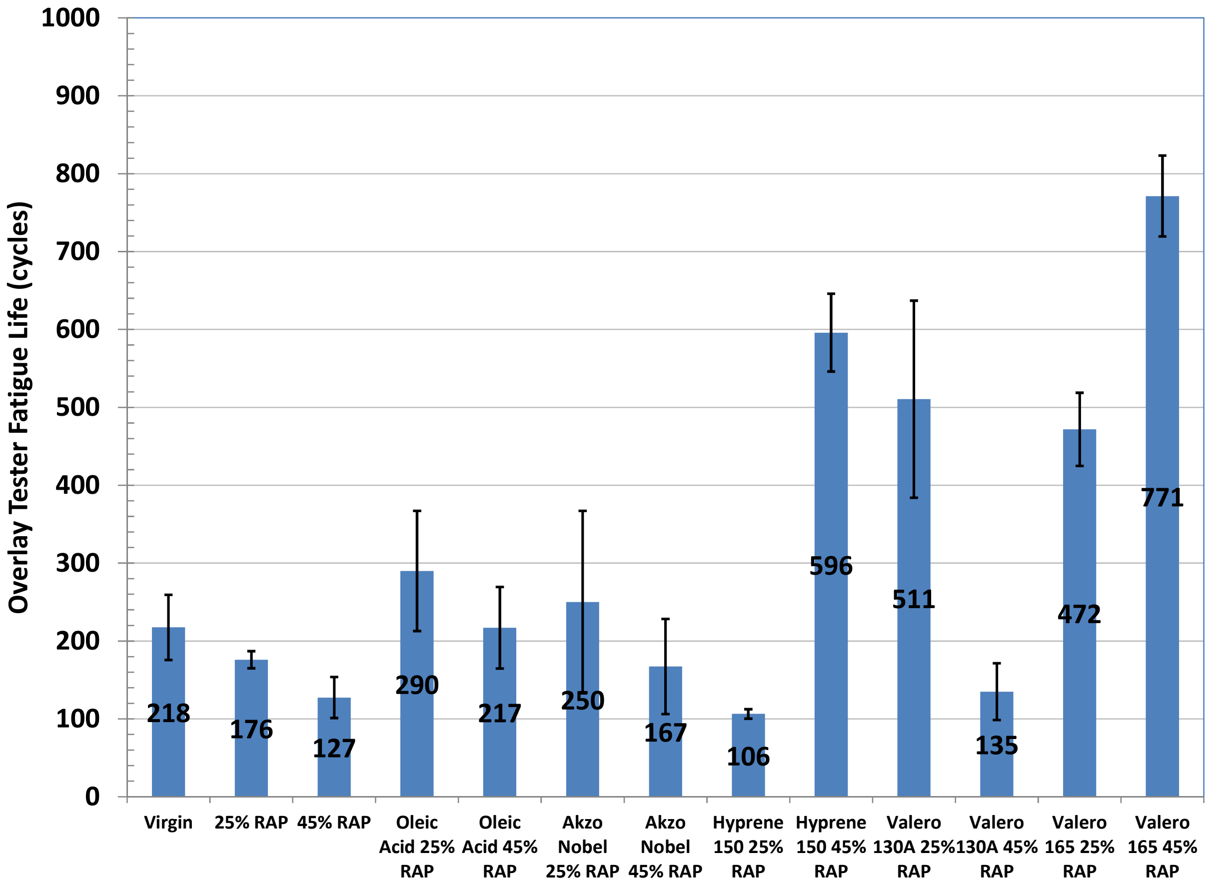

Figure 28 – Overlay Tester Results for 2 Hour Laboratory Conditioning

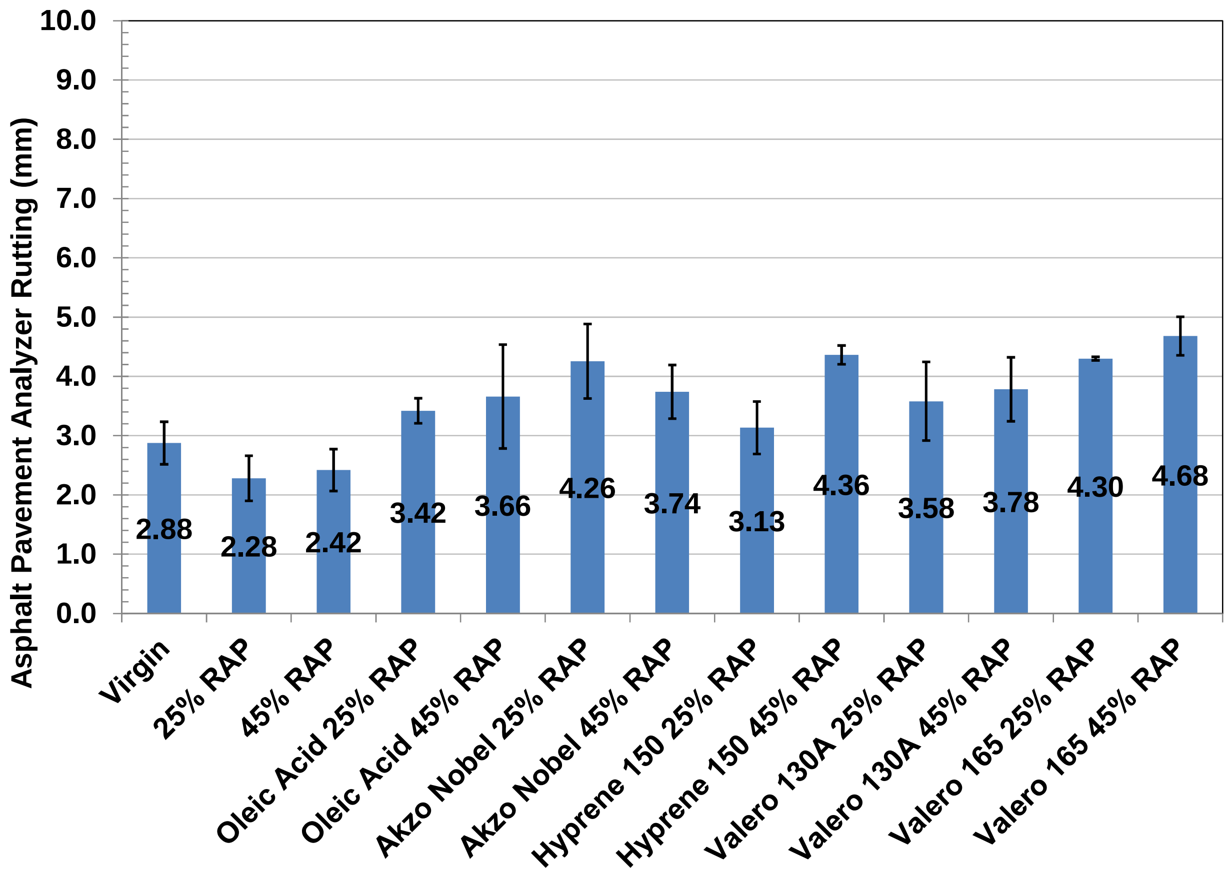

Figure 29 – Asphalt Pavement Analyzer Results for the 2 Hour Laboratory Conditioning

6 Hour Conditioning – Test Results

The Overlay Tester and Asphalt Pavement Analyzer test results are shown and compared with the 2 hour conditioning test specimens in Figures 30 and 31. In Figure 30, there is a general trend for the Overlay Tester cycles to failure to decrease due to the additional 4 hours of loose mix conditioning. This would be expected as the additional loose mix aging will oxidize the asphalt binder, resulting in a stiffer asphalt mixture. This is clearly shown with the virgin mix data, as well as the RAP mixtures not containing rejuvenators. However, the reduction in the Overlay Tester cycles to failure due to the additional loose mix conditioning time is much greater for the mixture with the rejuvenators than the mixtures without rejuvenators.

As discussed earlier, there are two characteristics that are important for rejuvenators to be effective; 1) Diffusion and 2) Stability. There is a clear improvement in the fatigue resistance when the rejuvenators are added, as shown with the 2 hour conditioning test data. However, the reduction in the fatigue resistance due to the additional conditioning time may indicate that the rejuvenators selected in the study may not have the stability characteristics necessary to continue to diffuse into the recycled asphalt when subjected to elevated temperature for extended time periods. For the 6 hour conditioned test specimens, this resulted in a stiffer asphalt mixture that ultimately reduced the resistance to fatigue cracking.

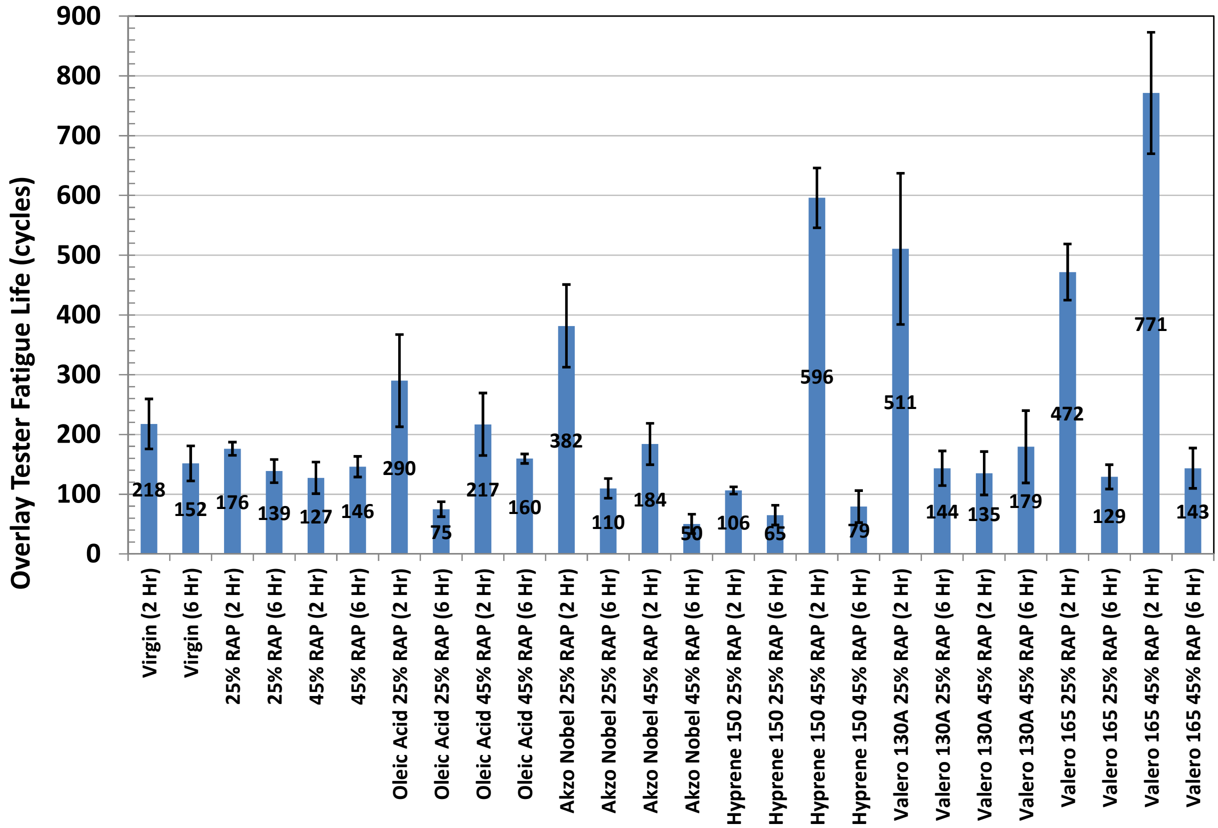

Figure 30 – Overlay Tester Results for 2 and 6 Hour Conditioning

A similar affect is observed in the APA rutting test results in Figure 31. In this case, as the conditioning time increased from 2 to 6 hours, the APA rutting decreased, which would indicate a stiffening of some kind has occurred. Once again, it is believed that during the additional 4 hours of loose mix conditioning, the rejuvenators utilized in the study may have volatized and reduced their effectiveness.

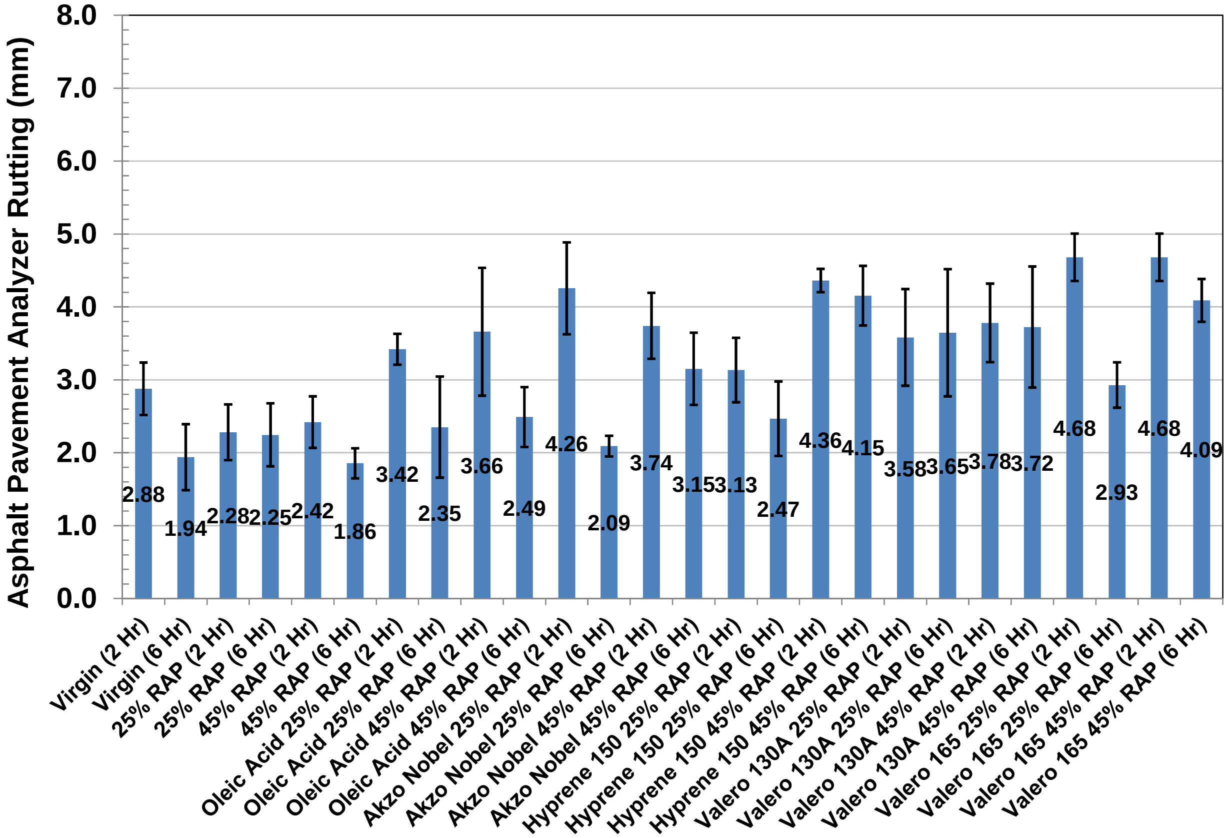

Figure 31 – Asphalt Pavement Analyzer Results for 2 and 6 Hour Laboratory Conditioning

Rejuvenated Mixtures within the NJDOT High RAP Specification Criteria

The generated Overlay Tester and APA test results were compared to the required performance of he NJDOT High RAP specification to determine whether or not the rejuvenators can help in producing a well-balanced, high RAP asphalt mixture. The resultant test results are shown in Figure 32. Figure 32 indicates that the Virgin and 25% RAP mixtures, evaluated without rejuvenators, do meet the High RAP balanced performance requirements. However, as the RAP content increased to 45% RAP, the non-rejuvenator mixture did not meet the balanced performance, failing the Overlay Tester fatigue cracking. A few of the rejuvenated asphalt mixtures met the High RAP specification, including the Oleic Acid 25% and 45% RAP mixtures, as well as the Valero 130 25% RAP mixture. Some of the asphalt mixtures were not “rejuvenated” enough and did not meet the Overlay Tester requirement (45% RAP, Valero 130 45% RAP, Akzo Nobel 45% RAP, Hyprene 150 25% RAP), while other mixtures appearred to be “over-softened” and failed the APA rutting requirement (Akzo Nobel 25% RAP, Valero 165 25% and 45% RAP, and Hyprene 150 45% RAP).

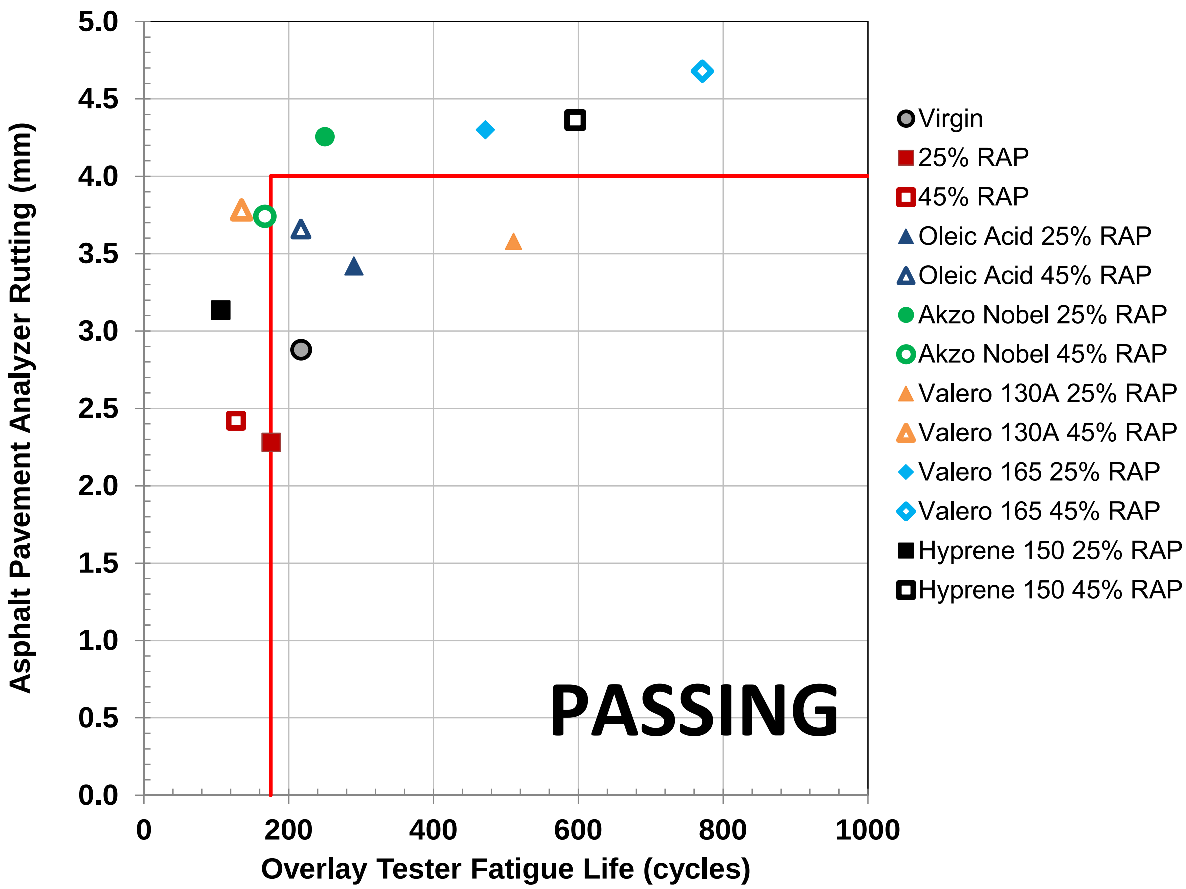

Figure 32 – 2 Hour Conditioning Rejuvenator Mixture Test Results within the NJDOT High RAP Specification

The results for the 6 hour loose mix conditioning is shown as Figure 33. As the test figure indicates, the additional 4 hours of loose mix conditioning has actually resulted in all but one of the mixtures failing the Overlay Tester requirement of 175 cycles until failure. The results in Figure 33 further indicate that extended hold times at elevated temperatures may result in the possible volatizing of some rejuvenators.

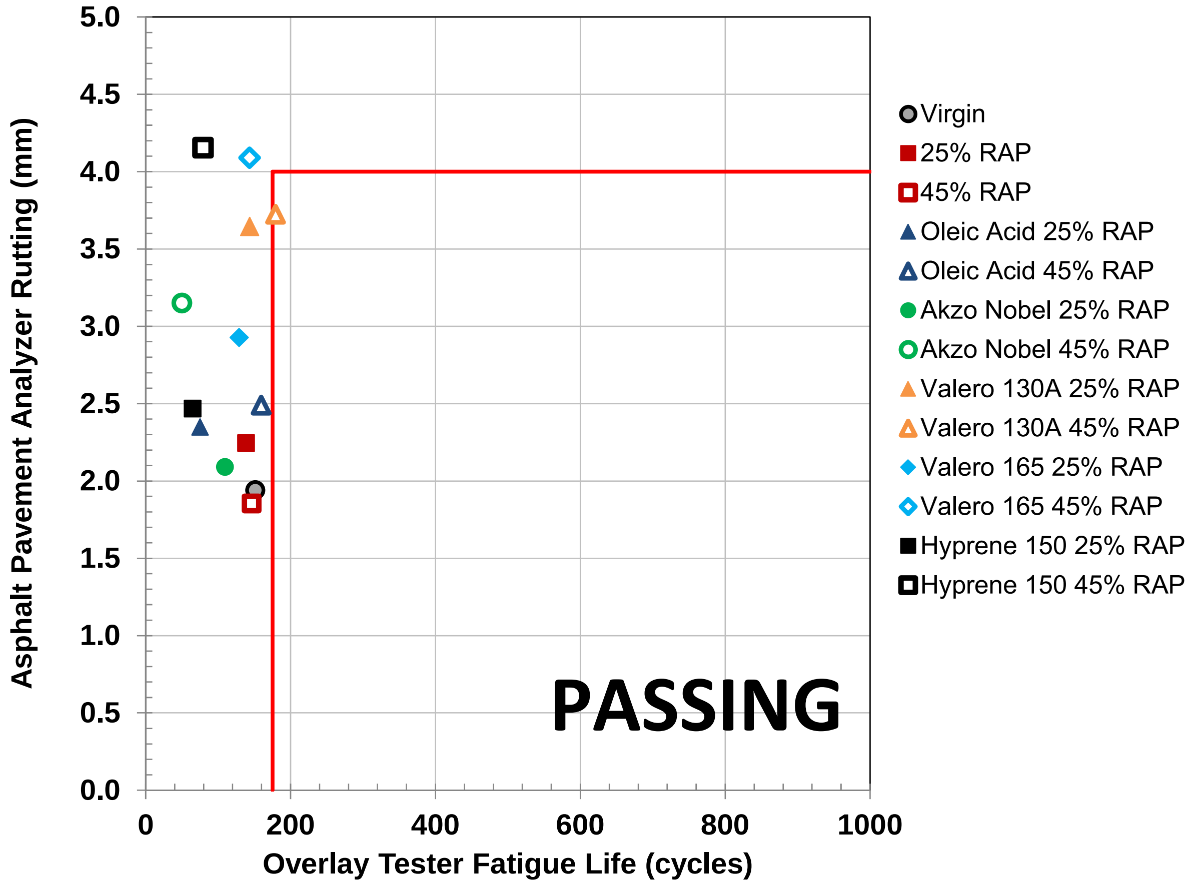

Figure 33 – 6 Hour Conditioning Rejuvenator Mixture Test Results within the NJDOT High RAP Specification

Mixture Healing - Modified Flexural Beam Fatigue Testing

As described earlier, research has suggested that the chemical make-up of the rejuvenator may provide additional healing properties lacking with aged, recycled asphalt. Santagata et al. (2009) suggested the ratio of the Saturates to Aromatics (S/Ar) provided an indication of rejuvenators that are better at "healing" the initial stages of cracking. However, testing was conducted solely on asphalt binders, where it is guaranteed that complete blending between the aged asphalt binder, virgin asphalt binder, and rejuvenator takes place. However, this scenario most likely does not occur in mixtures and therefore the effectiveness of the rejuvenator to heal the initial stages of cracking may be minimized.

An effort was undertaken to try and assess whether asphalt mixtures could be tested and ranked after some type of pre-stressing had occurred. The Flexural Beam Fatigue test (AASHTO T321) was used in an attempt to produce a pre-stressed asphalt mixture specimen, loaded just to the point where micro-cracking is assumed to begin to initiate. In AASHTO T321, the crack initiation is measured at the point where 50% of the initial stiffness of the asphalt mixture has been achieved due to cyclic loading. Therefore, testing the asphalt mixture specimen to a point before 50% should act as a pre-stressing affect, loading the specimen just before micro-cracking occurs.

In this study, the Flexural Beam Fatigue specimens were loaded to a point where only 40% of the initial stiffness was lost (i.e. – 60% of the initial stiffness remaining). This was able to be set in the computer controlled software to ensure loading did not go beyond this point. After 40% of the initial stiffness was lost, the test was stopped and the specimen allowed to rest and recover for 12 hours. After the 12 hour rest period, the test specimen was once again loaded until it reached 33% of its initial stiffness. The fatigue life of the test specimen is then determined using an exponential model (Equation 2) for the calculation of cycles to 50% initial stiffness, as follows:

$$S = Ae^{bn} \tag{2}$$

where,

S = sample flexural stiffness
A = constant
B = constant, and
n = number of load cycles

The constants are determined by regression analysis of loading cycles versus the natural logarithm of the flexural stiffness. The number of cycles to failure is determined by solving Equation (2) for 50% of initial stiffness.

The Flexural Beam Fatigue testing was conducted at a test temperature of 15^{o}C using a strain-controlled sinusoidal waveform. The asphalt mixtures were tested at three tensile strain levels; 350, 500, and 650 micro-strains (ms).

The Flexural Beam Fatigue healing experiment test results are shown in Figures 34 to 37. The test results are interesting as the behavior of the No Rejuvenator mixture appears to be more dependent on the strain level than the mixtures containing rejuvenators. In most cases, at the 350 micro-strain level, the No Rejuvenator mixture achieves a fatigue life that compares favorable, and sometime even better, than the mixtures with the rejuvenators. However, at the 500 micro-strain, and especially the 650 micro-strain level, the No Rejuvenator mixtures clearly underperform when compared to the rejuvenator mixtures. This would indicate that the rejuvenators have softened the asphalt mixtures to some degree that is capable of withstanding higher straining without early failure. It may also indicate that the rejuvenators are providing better resistance to micro-crack development by aiding in the healing process during the rest period provided. It would be difficult to uncouple which of these characteristics are the driving force behind the better performance at higher tensile strains. However, both are important for fatigue cracking resistance and the rejuvenators clearly show to provide a benefit at the higher tensile strains.

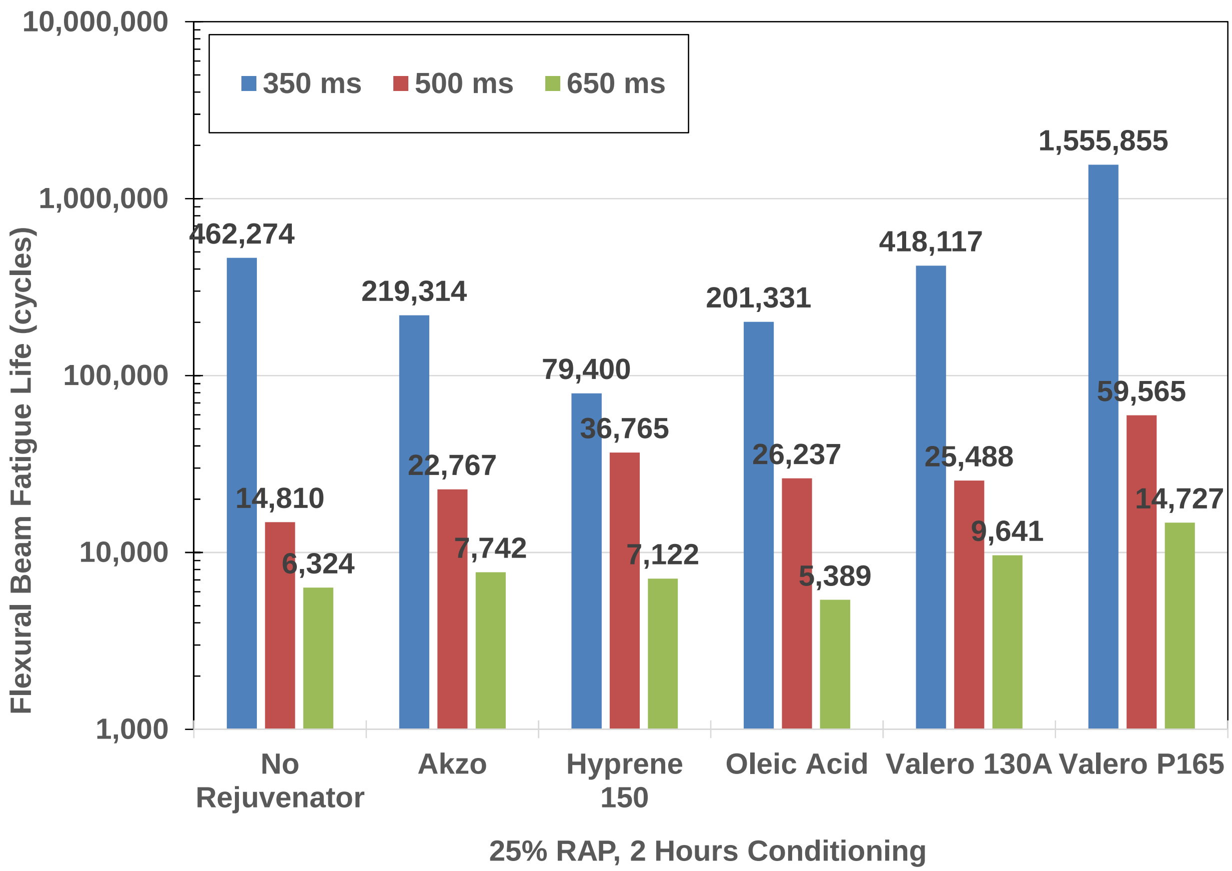

Figure 34 – Flexural Beam Fatigue Results for "Healing" Performance – 25% RAP, 2 Hours Conditioning

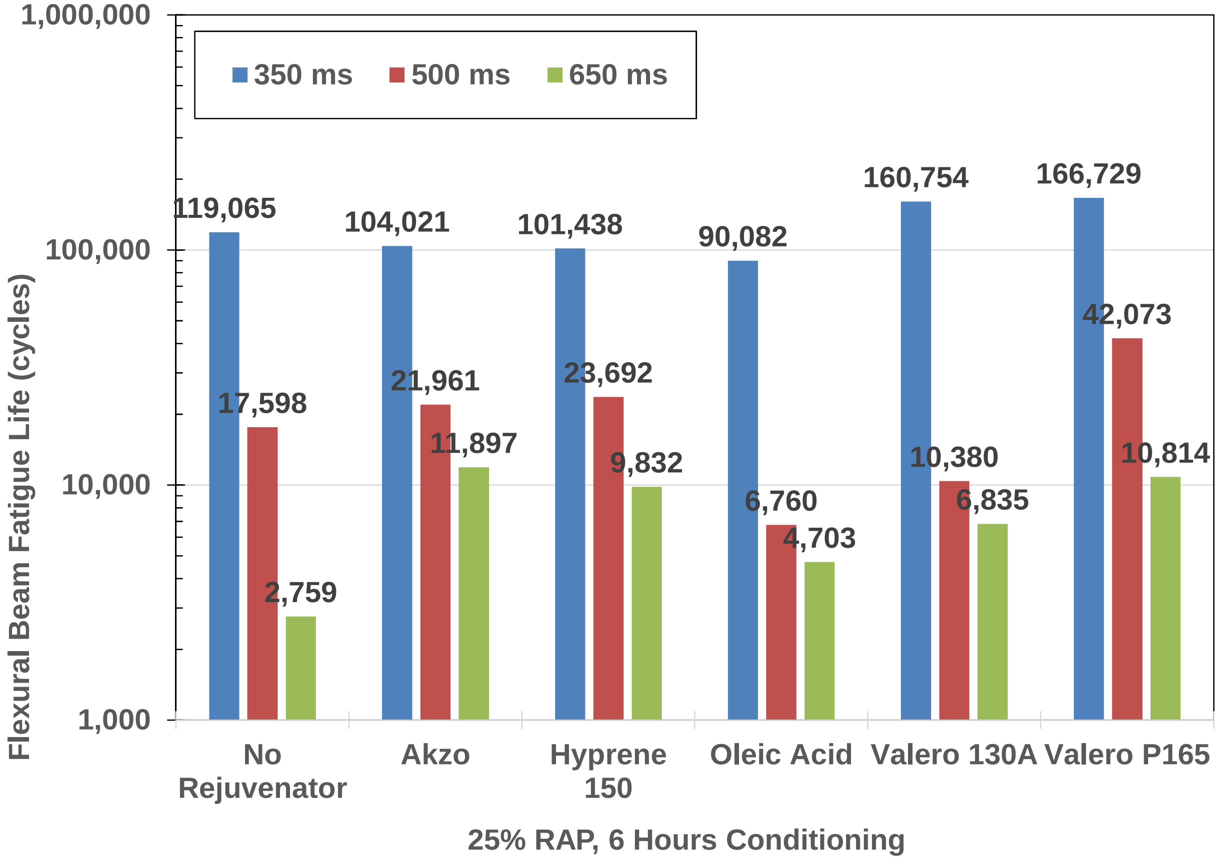

Figure 35 – Flexural Beam Fatigue Results for "Healing" Performance – 25% RAP, 6 Hours Conditioning

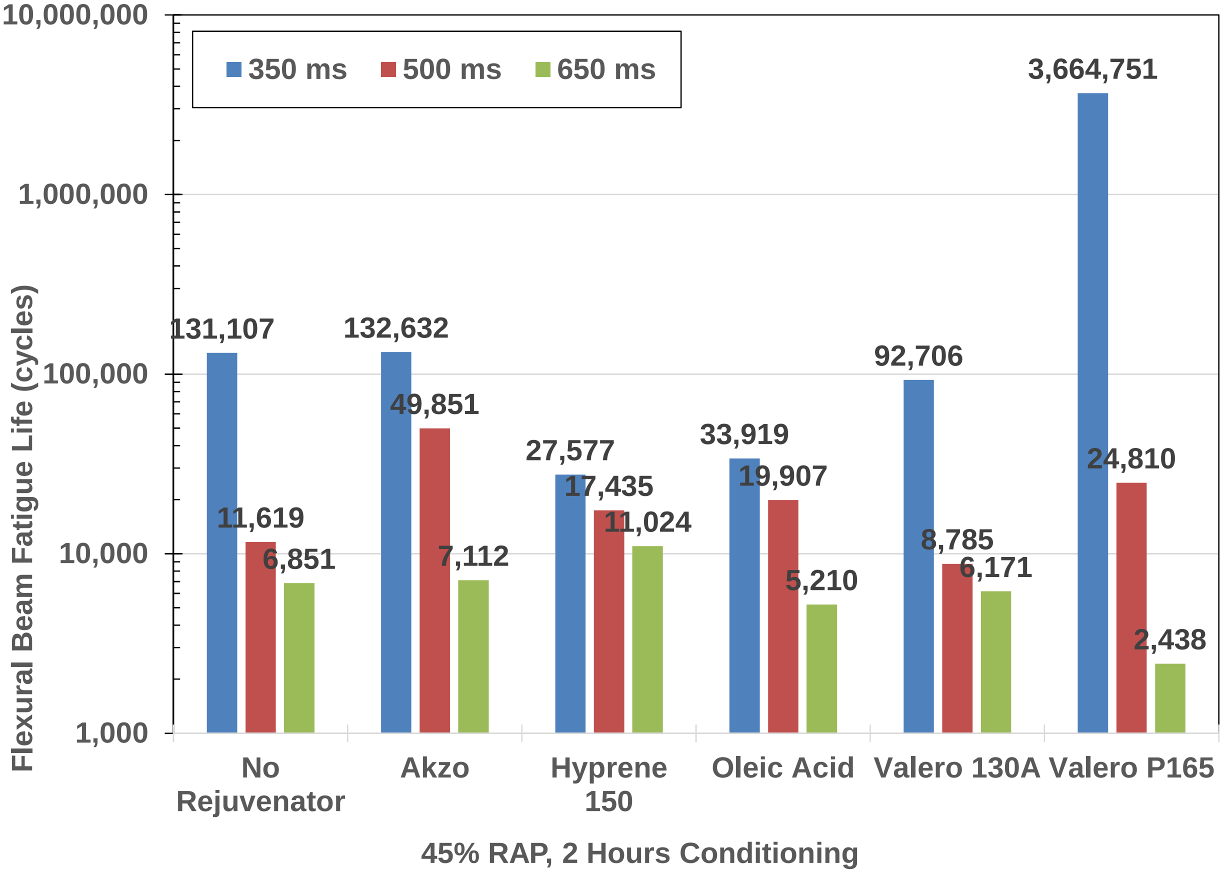

Figure 36 – Flexural Beam Fatigue Results for "Healing" Performance – 45% RAP, 2 Hours Conditioning

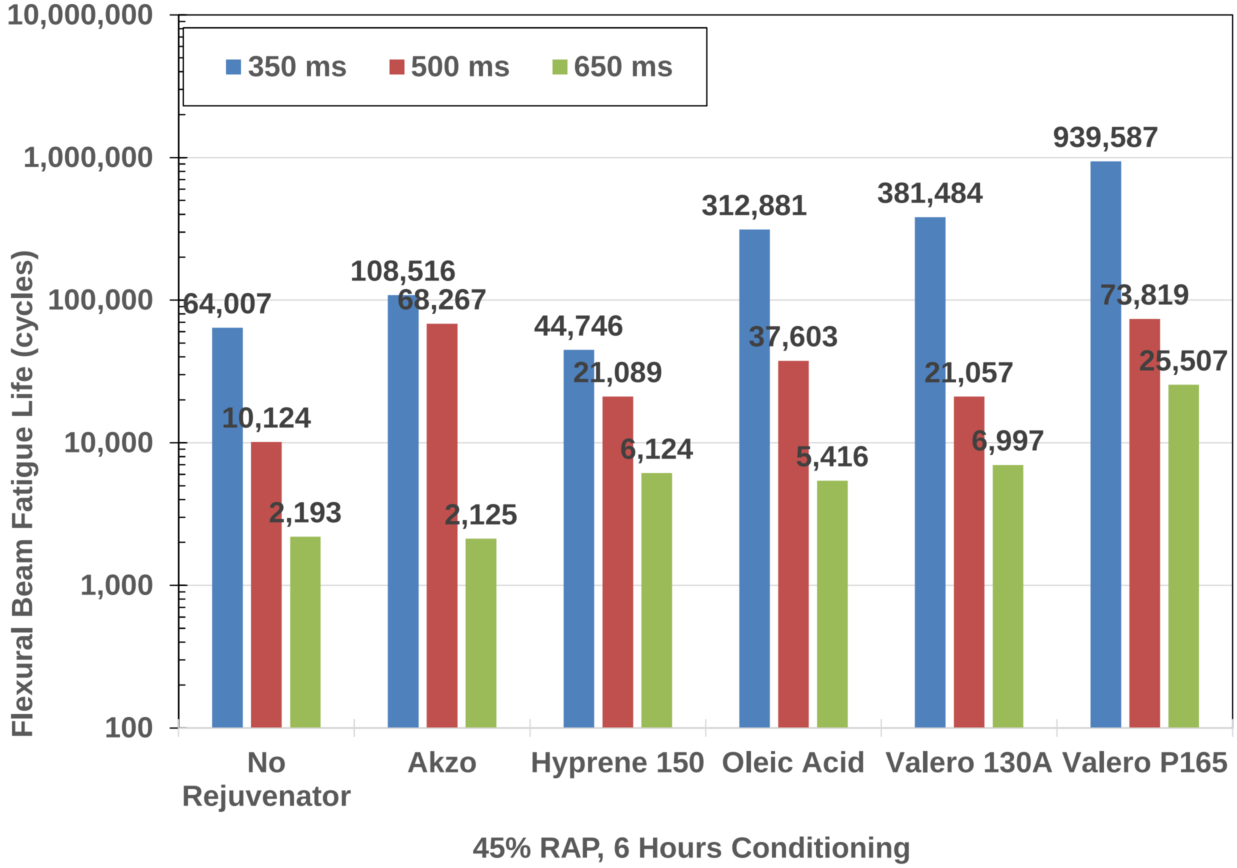

Figure 37 – Flexural Beam Fatigue Results for "Healing" Performance – 45% RAP, 6 Hours Conditioning

Comparison of Asphalt Binder and Mixture Fatigue Properties

The asphalt binder properties, Glover – Rowe Parameter and Cross-over Frequency, which have been shown to compare favorably to fatigue properties of virgin asphalt mixtures, were compared with the Overlay Tester fatigue cracking results of the RAP mixtures with and without rejuvenators. The concept here was to evaluate if the rankings/trends in the asphalt binder fatigue performance matched that of the asphalt mixtures. If indeed the trends did match, one could conclude that full blending of the virgin binder, RAP binder and rejuvenator (which occurs during extraction and recovery) is occurring in the asphalt mixture. Poor correlation between the mixtures and extracted/recovered asphalt binders would suggest that blending is not occurring in the asphalt mixtures and the rejuvenators may not be fully reactive with the recycled asphalt binder of the RAP. This general concept has been used by others to evaluate the relative blending in RAP and RAS mixtures (Bonaquist, 2005; Bennert and Dongre, 2010; Mogawer et al., 2012).

Figure 38 shows the comparison of the extracted and recovered asphalt binder properties to one another. As mentioned earlier, the Cross-over Frequency has been known to be an indicator of mixture aging/stiffening, while the Glover – Rowe parameter has been recently verified to observations of cracking in the field. The fact that both parameters show good agreement with one another indicates that aging/stiffening and cracking are highly related to one another. Figure 39 shows the same relationship, although broken out by RAP content.

Figures 40 and 41 show the Overlay Tester mixture fatigue properties compared to the Glover – Rowe fatigue index asphalt binder property. As the figures indicate, there appears to be a minor relationship between the mixture and asphalt binder properties. A similar observation was made in Figures 42 and 43 when the Overlay Tester was compared with the Cross-over Frequency of the extracted/recovered asphalt binders. This clearly indicates that the asphalt binders and asphalt mixtures are not behaving in the same manner. It is hypothesized that the main reason for this is the lack of blending that is occurring between the virgin binder, RAP binder, and rejuvenator in the asphalt mixture phase. Once extracted and recovered, all three of these components are fully blended. However, in the mixture phase, the mixture is dependent on the mixing temperature, mixing energy, and rejuvenator to mobilize the RAP asphalt binder to a condition where it can thoroughly blend with the virgin binder.

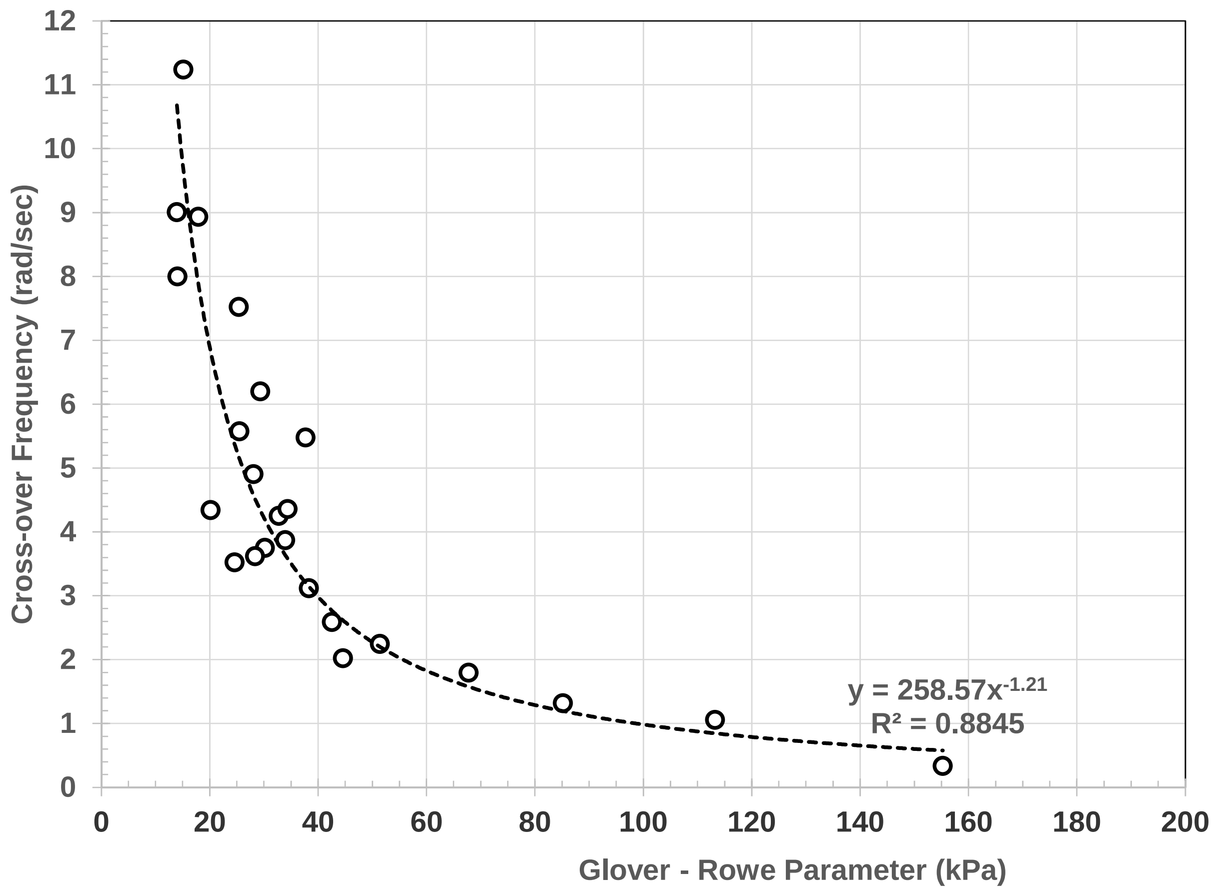

Figure 38 – Relationship Between Asphalt Binder Fatigue Indices – Cross-over Frequency and Glover-Rowe Parameter

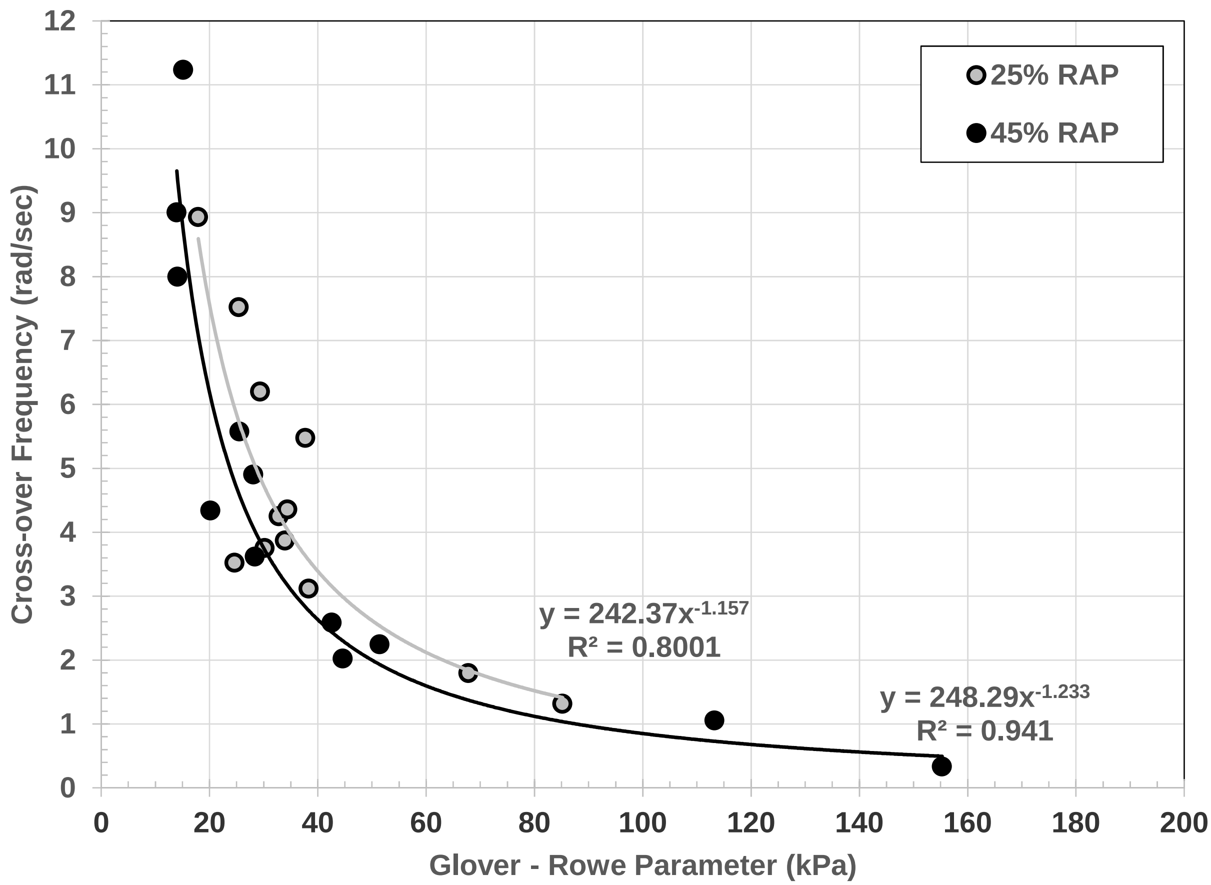

Figure 39 - Relationship Between Asphalt Binder Fatigue Indices – Cross-over Frequency and Glover-Rowe Parameter Based on RAP Content

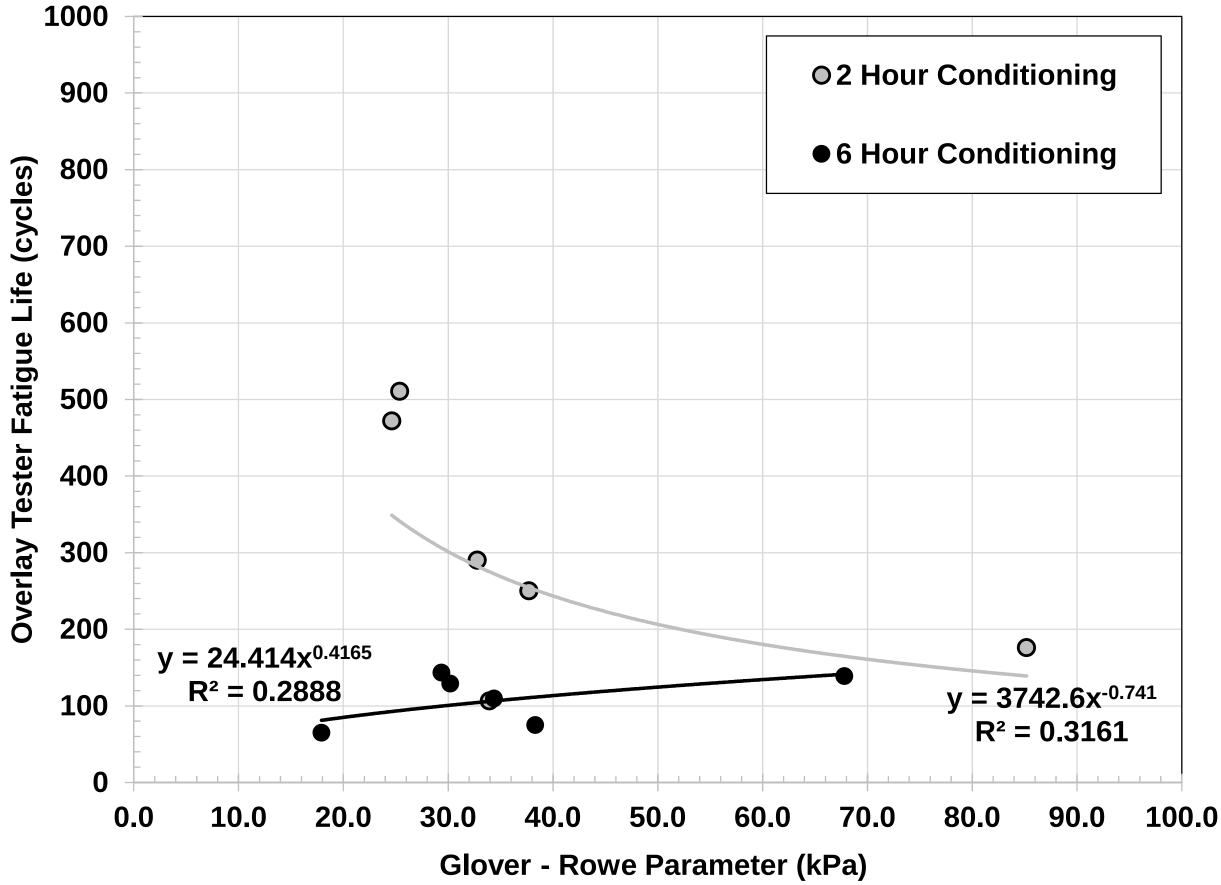

Figure 40 – Mixture Fatigue (Overlay Tester) vs Binder Fatigue (Glover-Rowe) for 25% RAP Mixtures with and without Rejuvenators

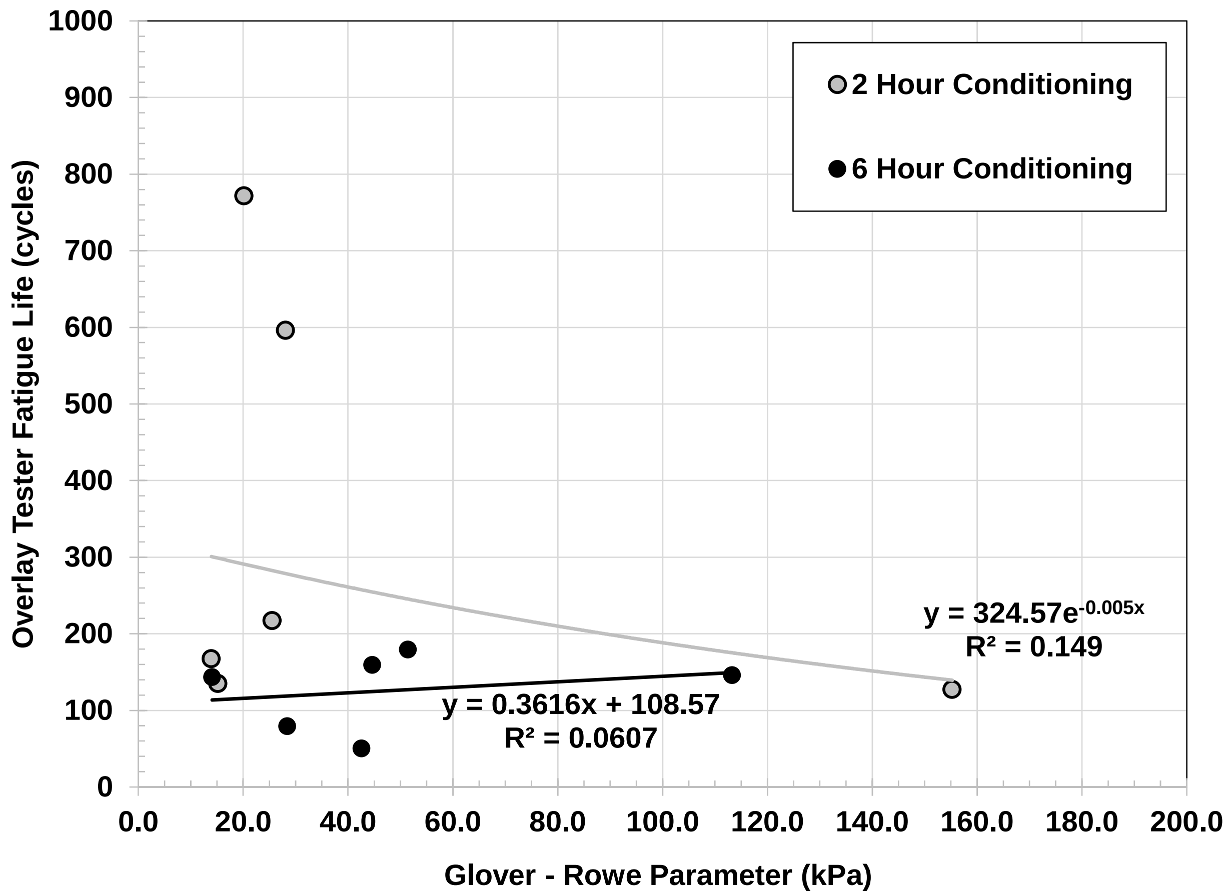

Figure 41 - Mixture Fatigue (Overlay Tester) vs Binder Fatigue (Glover-Rowe) for 45% RAP Mixtures with and without Rejuvenators

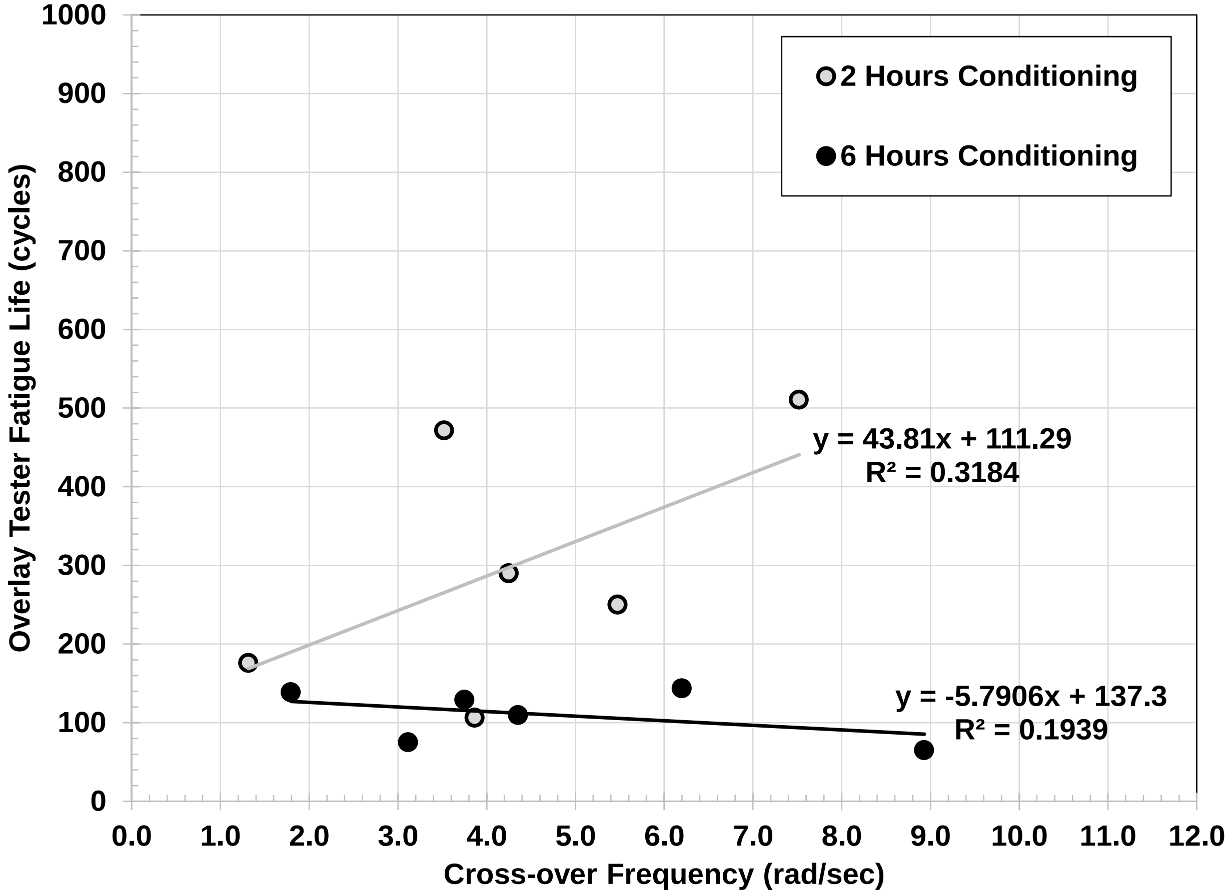

Figure 42 - Mixture Fatigue (Overlay Tester) vs Binder Fatigue (Cross-over Frequency) for 25% RAP Mixtures with and without Rejuvenators

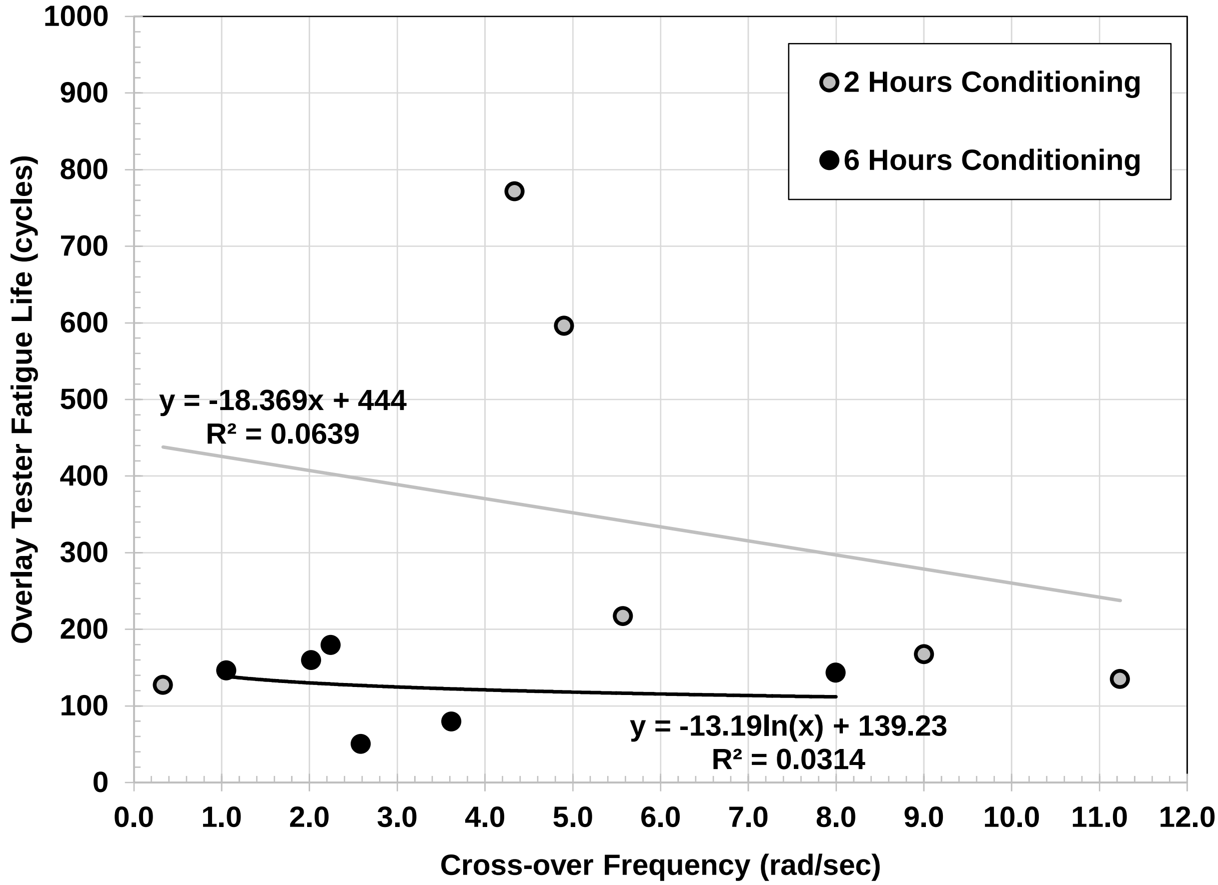

Figure 43 - Mixture Fatigue (Overlay Tester) vs Binder Fatigue (Cross-over Frequency) for 45% RAP Mixtures with and without Rejuvenators

UNIVERSITY OF MASSACHUSETTS – RUTGERS UNIVERSITY REJUVENATOR STUDY – MASSACHUSETTS MIXTURES

During the NJDOT Rejuvenator study, the University of Massachusetts-Dartmouth began a similar study to look at the influence of different rejuvenators on the performance of a higher RAP mixture. The additional set of mixtures provided additional test data to validate the binder procedure for evaluating asphalt binder rejuvenation, as well as another comparison of the effectiveness of different rejuvenator types. This study was undertaken in an effort to better understand the effects of rejuvenators on RAP mixtures with 50% RAP by weight of mixture, and it examined these effects after both short- and long-term aging to determine if rejuvenators can assist in mitigating aging in high RAP mixtures. A two tier evaluation was undertaken: (1) examine the rheology of extracted and recovered binders and (2) mixture performance tests. Tests performed on extracted and recovered binders included rheological plots of shear modulus (G*) versus phase angle (δ) (commonly known as a Black Space Diagram), rheological parameters derived from master curves using the Christensen-Anderson model, Superpave Performance Grading (PG) results, critical cracking temperatures, and Multiple Stress Creep Recovery (MSCR) results. The results from these tests were compared to mixture test results for rutting and moisture damage susceptibility, fatigue cracking and low temperature cracking to determine if they correlate. Overall, the results of the study provide a better understanding of the interrelationship between rejuvenators and aging in high RAP mixtures.

Study Experimental Plan and Materials

The experimental plan of the study is shown as Figure 44. The study used a 9.5 NMAS surface course mixture with 50% RAP. All of the asphalt mixtures were prepared at the asphalt mixture laboratory at the University of Massachusetts, Dartmouth. Mixture testing, except for the Overlay Tester, was conducted at the University of Massachusetts, while the Overlay Tester and all asphalt binder related work was conducted at Rutgers University.

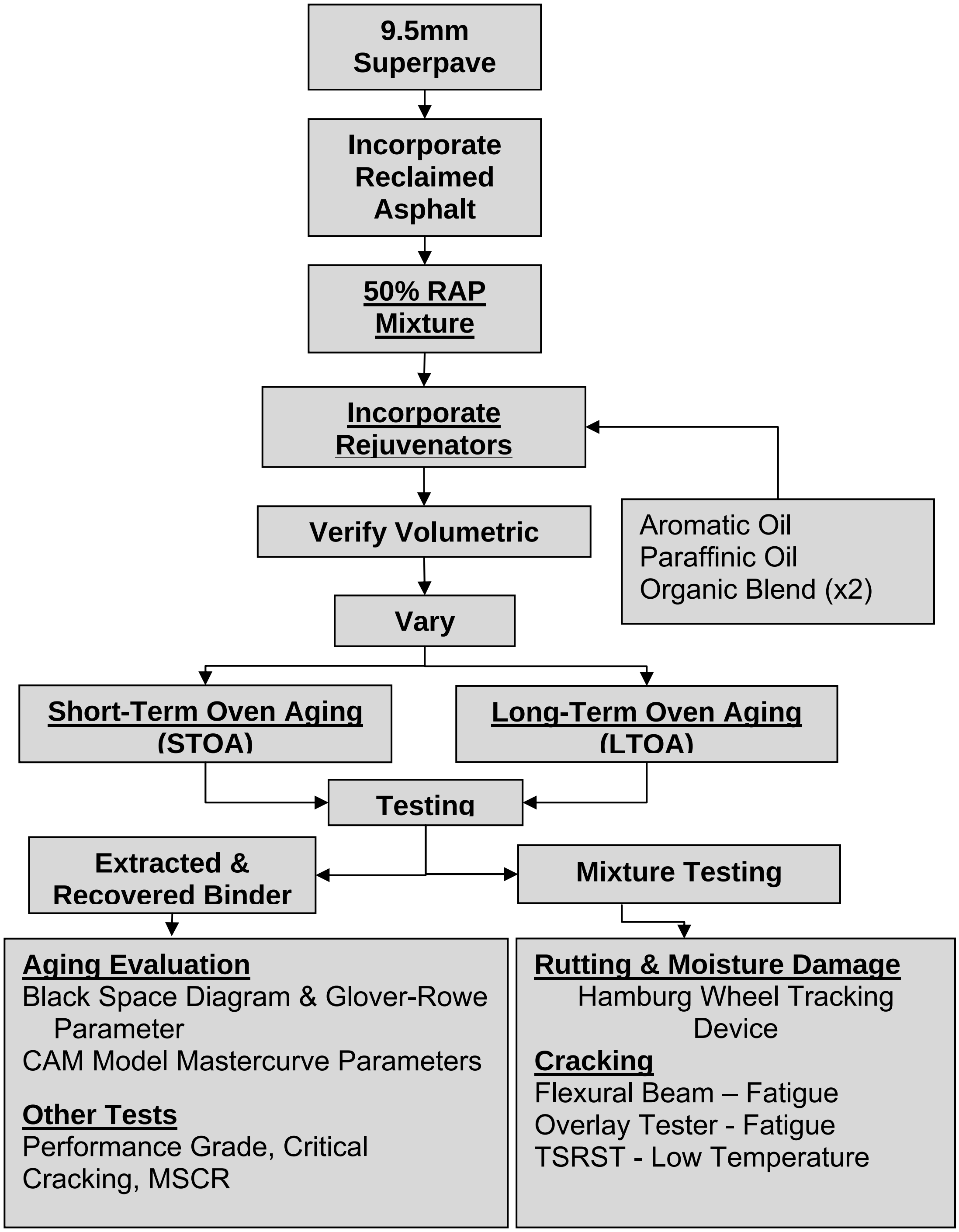

Figure 44 – Experimental Plan for UMass – Rutgers Rejuvenator Study

Asphalt Rejuvenators

Four asphalt rejuvenators were selected so that different types were represented including those already commonly used and those based on emerging green technologies. Details about each rejuvenator are outlined in Table 9.

Table 9 – Rejuvenator Descriptions and Details

Rejuvenator ID	Description	Details
AO	Aromatic Oil	Commonly Used in Pavement Preservation Activities
PO	Paraffinic Oil	Commonly Used in Pavement Preservation Activities
OB1	Organic Blend	Green Chemistry Product
OB2	Organic Blend	Organic Oils Based

The proposed dosage of each asphalt rejuvenator was based on a previous study (Mogawer et al., 2013) and recommendations of the rejuvenator manufacturers which suggested a dosage of 0.5% by weight of total RAP in the mixture. Based on the design binder content and percent asphalt binder in the RAP, this dosage equaled 9.0% rejuvenator by weight of recycled binder. This dosage was utilized throughout the study. Each rejuvenator was added directly to the pool of heated binder immediately prior to mixing for each specimen fabricated.

Asphalt Binder

A PG58-28 binder was utilized for designing and evaluating the high RAP mixtures. As outlined previously, the conventional method for introducing higher RAP contents into asphalt mixtures is to use a softer PG grade binder. A PG58-28 asphalt binder was used in the Control mix, as well as the RAP mixtures. The PG58-28 binder was used in an attempt to offset the potential mixture stiffening due to the use of high percentage of RAP in the mixtures. The PG58-28 was selected because it was the softest grade available. Based on the viscosity of the binder, the mixture mixing temperature was 150ºC (300ºF) and the compaction temperature was 138ºC (280ºF).

Aggregates

The aggregates utilized were from a crushed stone source in Wrentham, Massachusetts. Two aggregate stockpiles were obtained: 9.5 mm crushed stone and stone dust. Each aggregate stockpile was tested to determine their properties which are shown in Table 10. Sieve analysis was completed in accordance with American Association of State Highway and Transportation Officials (AASHTO) test method T11 “Standard Method of Test for Materials Finer Than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing” and T27 “Standard Method of Test for Sieve Analysis of Fine and Coarse Aggregates” (AASHTO, 2011).

Table 10 – Virgin Aggregate Stockpile and Post Ignition RAP Aggregate Properties

Sieve Size	9.5 mm	Stone Dust	RAP Aggregates Post Ignition
19.0 mm	100	100	100
12.5 mm	99.4	100	100
9.5 mm	93.8	100	100
4.75 mm	29.7	99.7	76.8
2.36 mm	5.2	83.7	57.6
1.18 mm	2.8	57.1	43.3
0.600 mm	2.3	38.6	31.1
0.300 mm	2.1	24.9	19.8
0.150 mm	1.8	15.9	12.1
0.075 mm	1.5	10.9	8.3
Binder Content, % (AASHTO T308) =			5.6%

Reclaimed Asphalt Pavement (RAP)

RAP was obtained from the same contractor as the aggregates. The RAP stockpile was fractioned in the laboratory in order to meet the gradation requirements for this study. The binder content of the RAP was determined using the ignition oven in accordance with AASHTO T308 "Determining the Asphalt Binder Content of Hot Mix Asphalt (HMA) by the Ignition Method" (AASHTO, 2011). The aggregates in the RAP remaining post ignition were tested to determine their gradations, which are shown in Table 10.

Description of Mixture Aging Procedures

For this study, the major variable under investigation is the impact of rejuvenators on the aging properties of high RAP mixtures and their binders after different periods of aging. The three aging schemes utilized are described below. For the binder and mixture performance evaluations, testing and analysis was conducted after the short-term and long-term aging.

Mixture Design & Volumetric Verification Aging

For mixture design and volumetric property verification, specimens of each mixture were batched, mixed and aged at the respective compaction temperature previously noted for 2 hours ± 5 minutes in a loose state in accordance with AASHTO R30 "Standard Practice for Mixture Conditioning of Hot Mix Asphalt (HMA)" Section 7.1 "Mixture Conditioning for Volumetric Mixture Design" (AASHTO, 2011). Specimens were stirred after 60 ± 5 minutes to maintain uniform conditioning. After aging, specimens were immediately compacted.

Short-Term Oven Aging (STOA)

STOA was conducted in accordance with AASHTO R30 “Standard Practice for Mixture Conditioning of Hot Mix Asphalt (HMA)” Section 7.2 “Short-Term Conditioning for Mixture Mechanical Property Testing” (AASHTO, 2011). For STOA aging, specimens of each mixture were batched, mixed and aged at 135 ± 3°C (275± 5°F) for 4 hours ± 5 minutes in a loose state. Specimens were stirred after 60 ± 5 minutes to maintain uniform conditioning. After aging, specimens were returned to the compaction temperature and immediately compacted.

Long-Term Oven Aging (LTOA)

LTOA was conducted in accordance with AASHTO R30 “Standard Practice for Mixture Conditioning of Hot Mix Asphalt (HMA)” Section 7.3 “Long-Term Conditioning for Mixture Mechanical Property Testing” (AASHTO, 2011). For LTOA aging, specimens were first subjected to STOA. Next, the compacted STOA specimens were cooled for 16 ± 1 hour. In accordance with AASHTO R30 Subsection 7.3.4 “Long-term Conditioning of Prepared Test Specimens” the compacted specimens were conditioned in an 85 ± 3°C (185 ± 5°F) oven for 120 ± 0.5 hours (5 days). After aging, the specimens were allowed to cool at room temperature which took approximately 16 hours. The specimens were not handled or disturbed until after completely cooled to room temperature.

Mixture Design

The target gradation for the mixtures utilized in this study is shown in Table 11. This target gradation met the requirements for a 9.5 mm Superpave mixture in accordance with AASHTO M323 “Superpave Volumetric Mix Design” and AASHTO R35 “Superpave Volumetric Design for Hot Mix Asphalt” (AASHTO, 2011).

Table 11 – Target Mixture Gradation and Specification

Sieve Size	Sieve Size (mm)	Target Gradation for All Mixtures	Superpave 9.5mm Specification
3/4"	19.0 mm	100	-
1/2"	12.5 mm	100	100 min
3/8"	9.5 mm	98	90-100
No. 4	4.75 mm	85	90 max
No. 8	2.36 mm	58	32-67
No. 16	1.18 mm	42	-
No. 30	0.600 mm	27	-
No. 50	0.300 mm	15	-
No. 100	0.150 mm	9	-
No. 200	0.075 mm	6.0	2-10
Binder Content		6.5%	-

A control mixture utilizing all virgin materials was designed using the PG58-28 binder. RAP was then used to replace 50% of the virgin aggregates with RAP aggregates. The aggregate gradations for the control mixture and the 50% RAP mixture were identical. Because they were identical, mixture design verifications for the 50% RAP mixtures incorporating each rejuvenator were performed at the design binder content determined for the control mixture. Verifications were completed assuming 100% contribution of the RAP binder.

The design Equivalent Single Axle Loads (ESALs) for this project was selected as 0.3 to <3 million which is consistent with surface course mixtures in New England. The design Superpave gyratory compactive effort for this ESALs level was Ndesign = 75 gyrations.

To incorporate the RAP into the mixtures, a procedure that was used in a prior study utilizing similar materials was followed (Mogawer et al., 2011). This procedure was utilized to eliminate moisture in the RAP stockpile material and to optimize the blending between the aged and virgin binders in the mixture. The procedure steps were:

1. The RAP was air dried until a constant mass was achieved.
2. The RAP was further dried for two days at 60ºC (140ºF).
3. The RAP was added to heated aggregates two hours prior to adding the binder during the mixing process.

The results of the mixture design and volumetric verifications are shown in Table 12. Relative to the control mixture, the 50% RAP mixture with no rejuvenator had higher air voids (+ 1.1%) and a lower Voids Filled with Asphalt (VFA). This may be an indication that good blending is occurring between the virgin and RAP binders and subsequently the mixture is stiffer and more difficult to compact. Conversely, the discrepancies in volumetric properties could also be an indicator that incomplete blending is occurring between the virgin and RAP binders leading to lower effective asphalt content and thus higher air voids. The addition of the rejuvenators did improve the volumetric properties by decreasing the difference in the air voids between the control and the 50% RAP mixture from +1.1% to a maximum difference of +0.48%. The effect of these rejuvenators on the rheological properties of the binders described in the next few sections might provide insights into the reasons for this improvement. Also note, the Voids in Mineral Aggregate (VMA) percentage for the 50% RAP mixtures with rejuvenators were slightly below the minimum of 15.0% but deemed acceptable for further study because they were within typical allowable production tolerances. It is hypothesized that the lower VMA was due to errors in the calculation procedure. The G_{sb}, used to calculate VMA, was based on the virgin aggregate blend. The G_{sb} did not take into consideration the RAP aggregate G_{sb}, and therefore, it appears that this may have influenced the design VMA values shown in Table 12.

Table 12 – Mixture Design and Volumetric Verification Results

Mixture	Air Voids, %	Voids in Mineral Aggregate VMA, %	Voids Filled with Asphalt VFA, %
Specification	*4.0%*	*15% min.*	*65-78*
Control – PG58-28	3.63	15.9	77.2
50% RAP + No Rejuvenator	4.77	15.3	68.7
50% RAP + Aromatic Oil	3.90	14.9	73.8
50% RAP + Paraffinic Oil	4.11	14.7	72.0
50% RAP + Organic Blend 1	3.95	14.3	72.3
50% RAP + Organic Blend 2	4.06	14.5	72.0

Binder Testing & Results

The asphalt binders of the various mixtures were extracted and recovered in accordance with AASHTO T164 “Standard Method of Test for Quantitative Extraction of Asphalt Binder from Hot Mix Asphalt (HMA)” (AASHTO, 2011) and ASTM D5404 “Standard Practice for Recovery of Asphalt from Solution Using the Rotary Evaporator” (ASTM, 2012). After the recovery process, each asphalt binder was tested for its performance grade (PG) in accordance with AASHTO M320 “Standard Specification for Performance-Graded Asphalt Binder” (AASHTO, 2011) and by the Multiple Stress Creep Recovery (MSCR) in accordance with AASHTO T350-14 “Standard Method of Test for Multiple Stress Creep Recovery (MSCR) Test of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)” (AASHTO, 2014). Critical cracking temperatures were determined in accordance with AASHTO R49 “Determination of Low-Temperature

Performance Grade (PG) of Asphalt Binders" (AASHTO, 2011). G* master curves were also measured and utilized to evaluate the overall stiffness properties of the asphalt binders as well as their relative aging characteristics. The G* master curve data was generated using the 4.0 mm geometry for the DSR as per the recommendations by Sui et al. (2010); Sui et al. (2011); Farrar et al. (2013). The G* master curves were shifted and generated using the RHEA© software.

Aging Mitigation/Reversal Evaluation

As discussed earlier, the Glover-Rowe parameter, defined as $G^*(\cos\delta)^2/(\sin\delta)$, has been found to be sensitive to the aging of asphalt binders. Based on work conducted by Anderson et al. (2011), as well as additional analysis by Rowe (2014), thresholds have been found that correlate well to non-load associated cracking (i.e. – Block Cracking). One of the causes for block cracking is the aging of the asphalt binder. Figure 45 shows the Glover-Rowe parameter plotted in Black Space at a test temperature of 15°C (59 °F) and loading frequency of 0.005 rad/sec for the control mixtures. As indicated in the figure, as the Control mixtures were aged from STOA to LTOA, the test data migrates from the lower right of the Black Space towards the upper left. The figure also shows that the virgin PG58-28 Control mixture aged more than the 50% RAP mixture based on the magnitude of the movement in Black Space. This would be expected as the 50% RAP mixture already has a significant amount of aged/oxidized asphalt binder that would be minimally aged due to the laboratory aging procedure. It is also interesting to note that the 50% RAP mixture at LTOA condition passes the initial "Onset of Cracking" threshold shown in the figure, while the virgin PG58-28 mixture stays below the threshold in the "PASS" zone. A summary of all of the Black Space and Master Curve parameters can be found in Table 13.

Table 13 – Black Space and Master Curve Parameters

Mixture	Aging	G* @ 15°C and 0.005 rad/sec (Pa)	δ @ 15°C and 0.005 rad/sec (degrees)	Crossover Frequency (ω_o)	Rheological Index (R-value)
Control PG58-28	STOA	23,320	72.9	732.2	1.92
	LTOA	80,780	66.7	103.0	2.04
50% RAP – No Rejuvenator	STOA	74,840	66.6	113.4	2.15
	LTOA	136,830	62.2	31.6	2.27
50% RAP + Aromatic Oil	STOA	41,689	68.8	234.7	2.09
	LTOA	69,730	66.2	98.5	2.15
50% RAP + Paraffinic Oil	STOA	22,320	70.4	405.5	2.08
	LTOA	79,550	63.2	44.0	2.20
50% RAP + Organic Blend 1	STOA	59,070	67.8	136.6	2.06
	LTOA	65,260	65.8	79.8	2.15
50% RAP + Organic Blend 2	STOA	25,890	68.8	205.4	2.04
	LTOA	75,220	63.7	56.5	2.27

The Black Space diagram for the STOA and LTOA rejuvenator mixtures is shown in Figure 46. The results again show a migration of the test data. However, the magnitude of the aging is less severe for the 50% RAP mixtures with Rejuvenator AO (Aromatic Oil) and OB1 (Organic Blend #1), respectively. The larger change in location in Black Space for the 50% RAP mixtures with Rejuvenator PO (Paraffinic Oil) and OB2 (Organic Blend #2) would indicate that the asphalt binder is stiffening more due to the LTOA aging process. However, it should be noted that for neither the STOA nor LTOA aged conditions do the 50% RAP mixtures with the rejuvenators fail either of the proposed cracking thresholds shown in the figure.

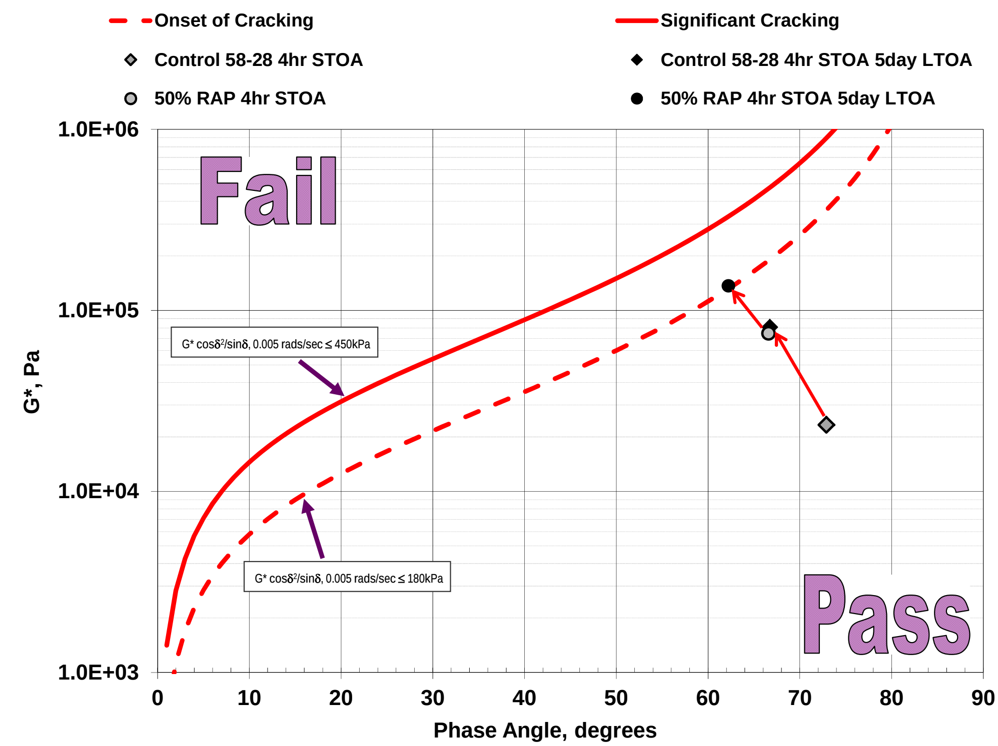

Figure 45 – Black Space Diagram for Control and 50% RAP Mixtures – Short-term and Long-term Aging

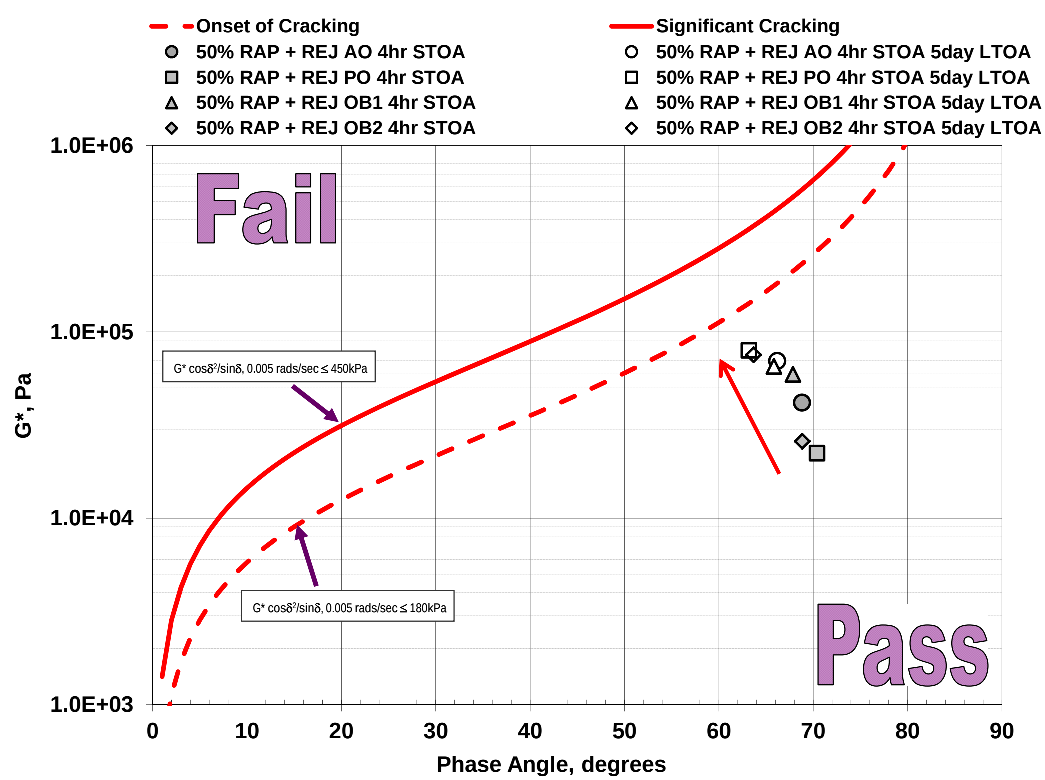

Figure 46 – Black Space Diagram for Rejuvenator Mixtures – Short-Term and Long-term Aging

Figures 47 and 48 show the Black Space diagrams for the STOA and LTOA conditions, respectively. Along with the rejuvenator mixtures, the figures also contain the virgin PG58-28 Control mixture and the 50% RAP with no rejuvenator mixture. When comparing the relative aging in the figures, the more effective rejuvenator would result in Black Space parameters closer to virgin PG58-28 Control mixture. Meanwhile, rejuvenators that are less effective would result in Black Space parameters closer to the 50% RAP mixture. As indicated by the "green" arrow in Figure 47, each of the rejuvenators used provides some aging mitigation of the aged binder associated with the 50% RAP mixture and moves the respective samples away from the cracking thresholds. Based on the STOA condition, Figure 47 indicates that Rejuvenator PO (Paraffinic Oil) provides the largest mitigation of aging as its Black Space parameters are very similar to the virgin PG58-28 Control sample and moved furthest away from the 50% RAP sample.

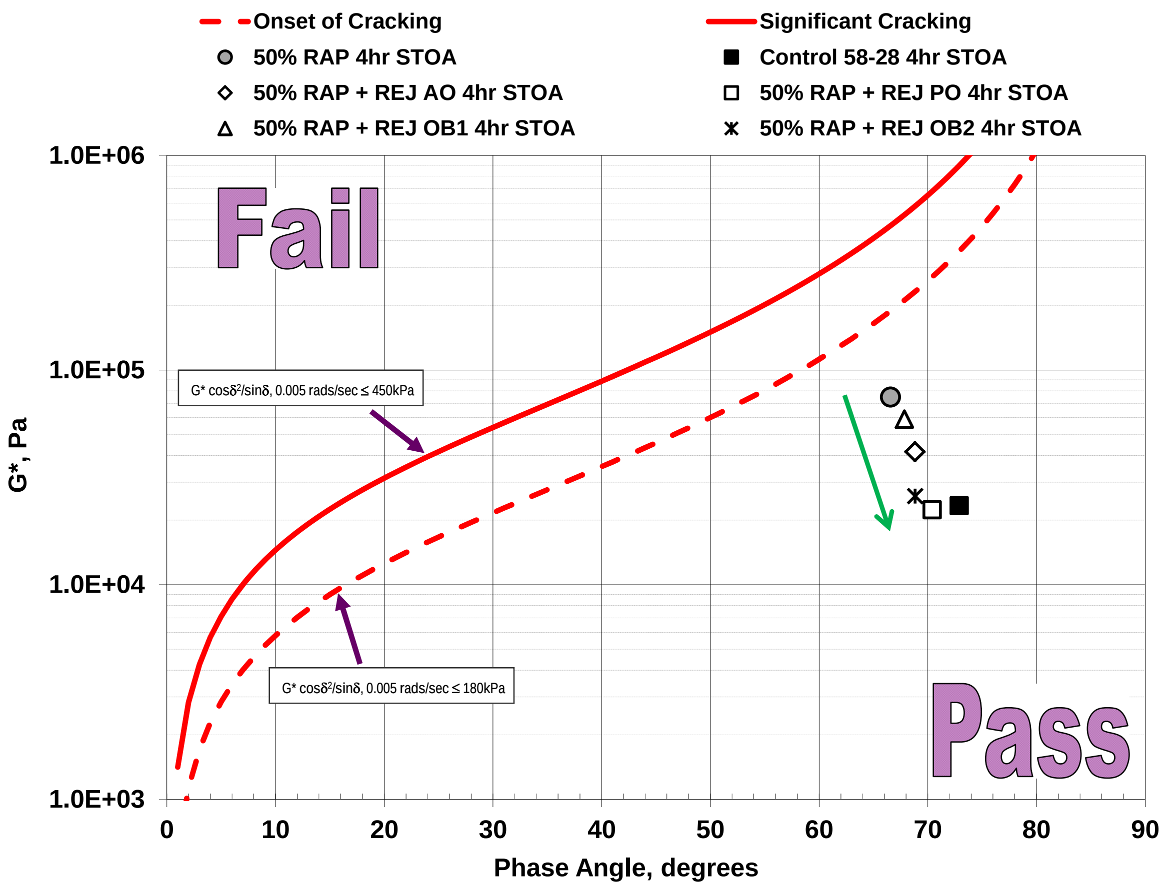

Figure 47 – Black Space Diagram for Short-term Aging – Rejuvenator Mixes Compared to Control and 50% RAP No Rejuvenator Mixtures

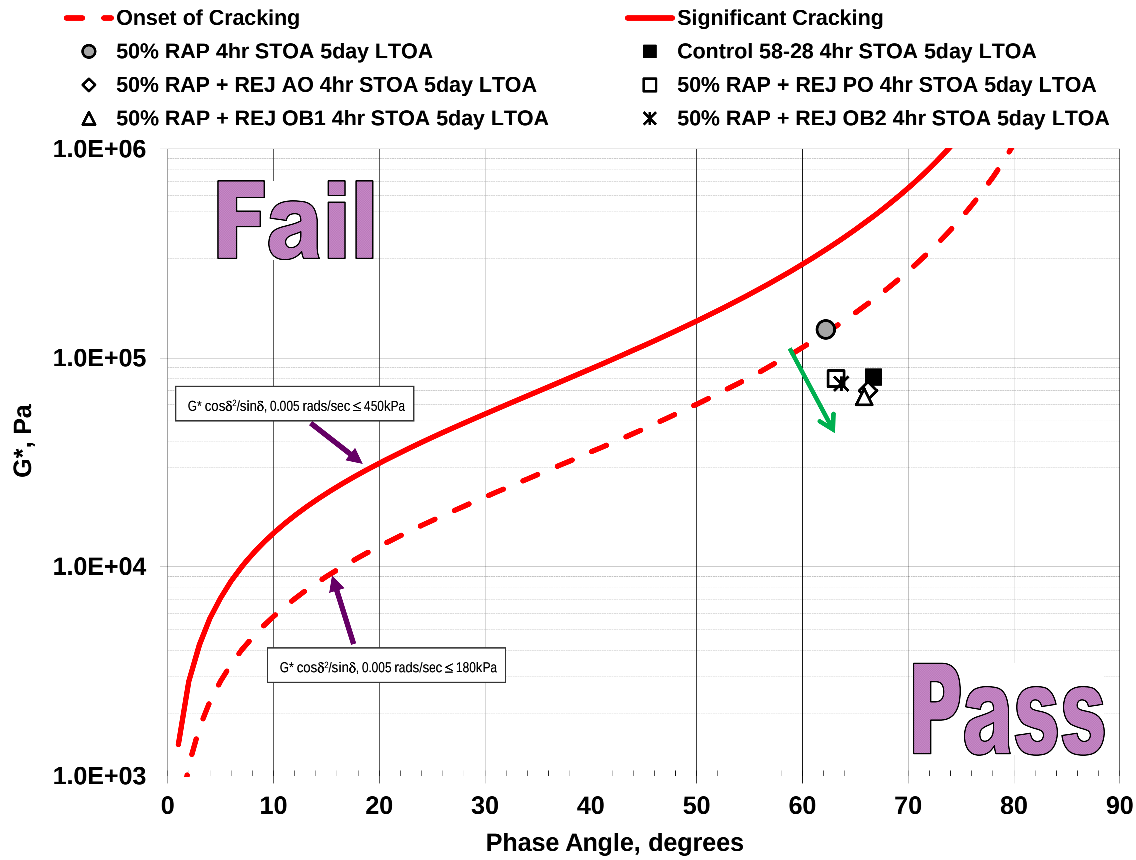

Figure 48 – Black Space Diagram for Long-term Aging – Rejuvenator Mixes Compared to Control and 50% RAP No Rejuvenator Mixtures

Figure 48 contains the Black Space diagram for the LTOA conditioned mixtures. Similar to the dataset shown previously, each of the rejuvenators provides some degree of improved aging mitigation when compared to the 50% RAP mixture. In the case of the LTOA conditioned mixtures, Rejuvenators AO (Aromatic Oil) and OB1 (Organic Blend #1) resulted in the best performance as both of these mixtures were closer; if not slightly better, than the virgin PG58-28 Control. This would indicate that Rejuvenators AO (Aromatic Oil) and OB1(Organic Blend #1) are still providing a level of rejuvenating even after long term aging conditions – something that Rejuvenators PO (Paraffinic Oil) and OB2 (Organic Blend #2) appear to be limited at accomplishing.

<u>CAM Model – Crossover Frequency – R-value Space as an Aging Index</u>

Another proposed method for assessing aging and aging mitigation of asphalt binders is through the evaluation of the CAM model parameters Cross-over Frequency (ω_o) and Rheological Index (R-value). As presented earlier, as the parameters plotted in ω_o – R-value Space migrate from the upper left to the lower right of the space, it clearly tracks the aging of the asphalt binder. Therefore, asphalt binders that have undergone a rejuvenation, or aging mitigation, should migrate back towards the upper left.

Figure 49 shows the ω_o – R-value Space for the control and 50% RAP no rejuvenator mixtures. As one would expect, as aging increased from STOA to LTOA, the test data moves downward and towards the right, indicating that aging of the asphalt binder has taken place. The magnitude of the change in the virgin PG58-28 Control mixture is greater than the 50% RAP mixture as approximately half of the asphalt binder in the 50% RAP mixture has already been highly oxidized.

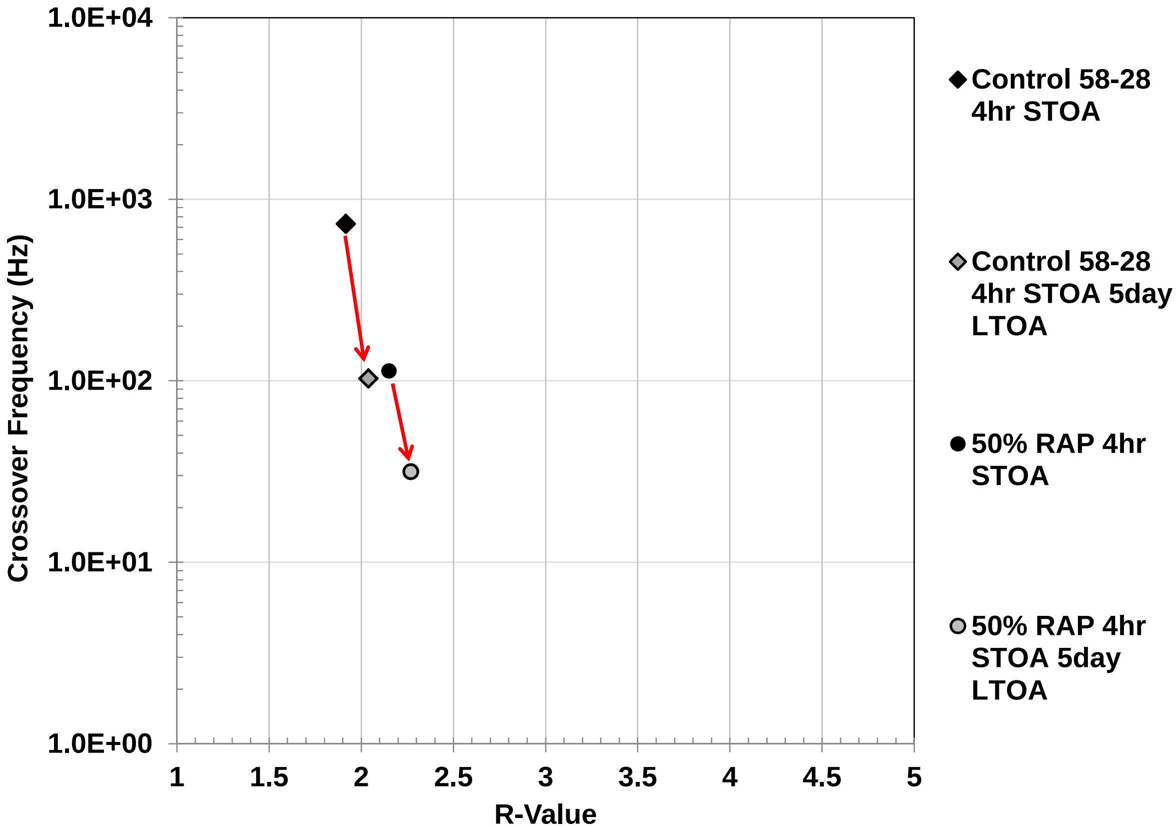

Figure 49 - ω_o – R-value Space Diagram for Control and 50% RAP No Rejuvenators Mixtures – Short-term and Long-term Aging

The rejuvenator test samples are shown in Figure 50. Again, a downward right movement is observed in the test data, indicating that binder aging has taken place. However, different magnitudes in the downward movement are observed between the different rejuvenated samples. The greatest change was found when using Rejuvenator PO (Paraffinic Oil), which would indicate that this particular rejuvenator may not maintain the same rejuvenating potency over the long-term performance of the asphalt mixture. Meanwhile, the mixtures using Rejuvenator AO (Aromatic Oil) and OB1 (Organic Blend #1) show the least change in aging between the STOA and LTOA conditions.

Figures 51 and 52 show the mitigation of aging when using the different rejuvenators and comparing the rejuvenators in the ω_o – R-value Space with the virgin PG58-28

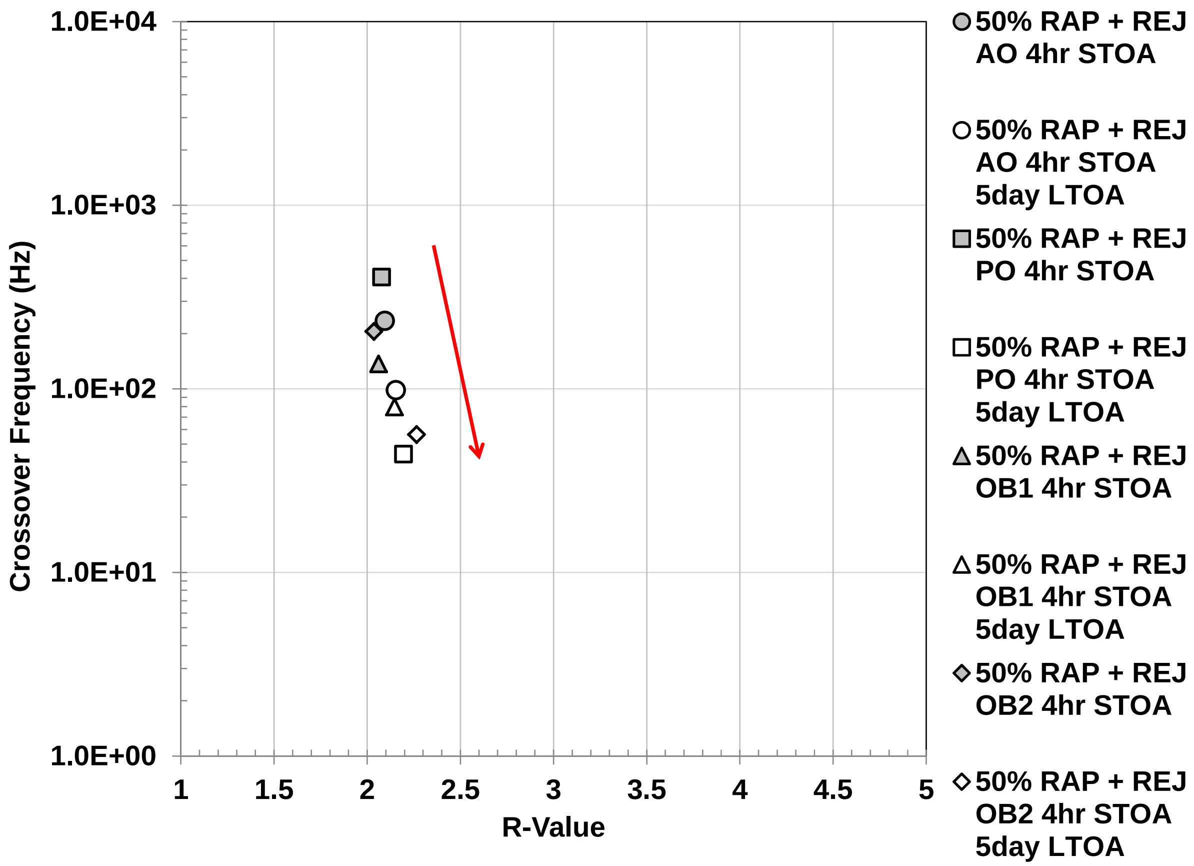

Figure 50 - ω_o – R-value Space Diagram for Rejuvenator Mixtures – Short-term and Long-term Aging

Control and the 50% RAP mixture. In Figure 51, the STOA samples show an upward left movement away from the 50% RAP sample (no rejuvenator) and towards the virgin PG58-28 Control sample. The same type of change in the ω_o – R-value Space is also observed in Figure 52 for the LTOA samples; however, the magnitude of the movement away from the 50% RAP (no rejuvenator) sample is not as great. The results shown in Figures 51 and 52 indicate that all four of the rejuvenators evaluated in the study provide some type of aging mitigation to the 50% RAP mixture. However, the amount of aging mitigation witnessed varies among the different rejuvenators, as well as the degree of mixture aging.

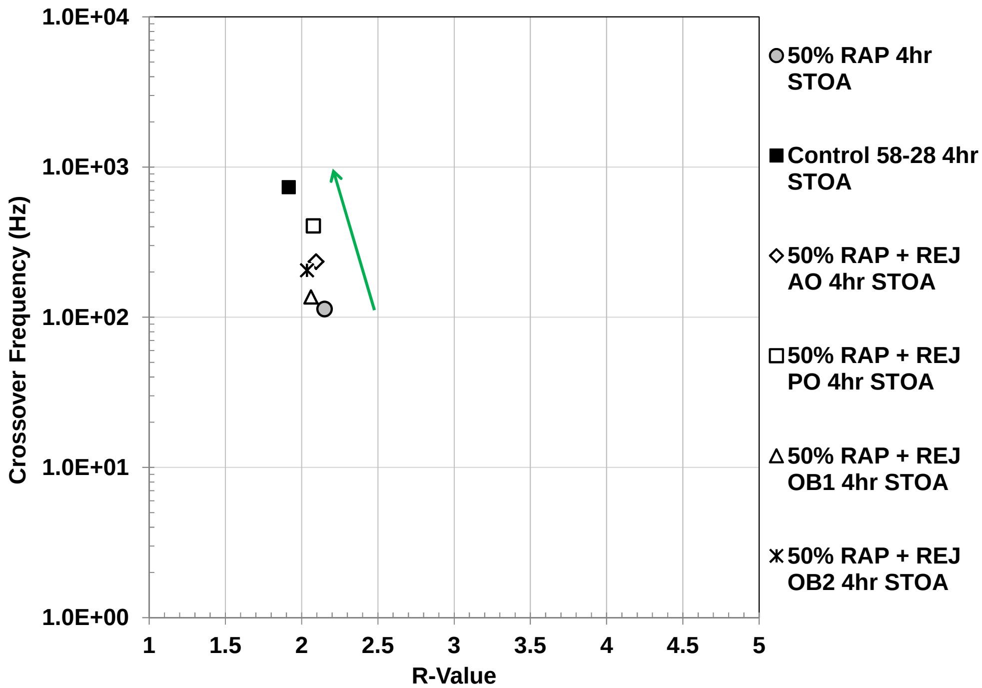

Figure 51 - ω_o – R-value Space Diagram for Short-term Aging – Rejuvenator Mixes Compared to the Control and 50% RAP No Rejuvenators Mixtures

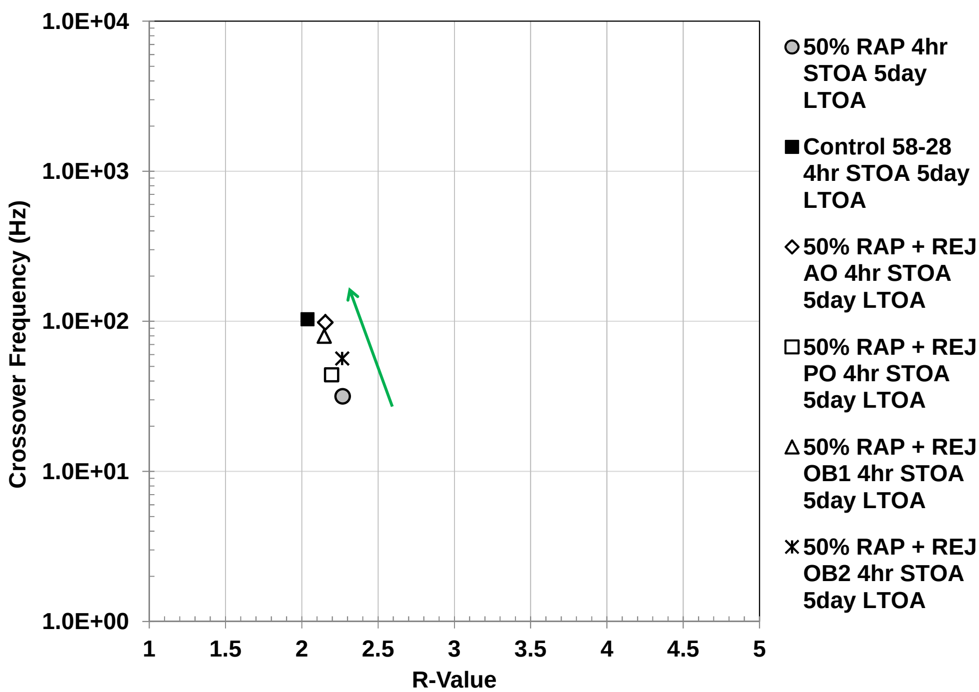

Figure 52 - ω_o – R-value Space Diagram for Long-term Aging – Rejuvenator Mixes Compared to the Control and 50% RAP No Rejuvenators Mixtures

Performance Grading of Recovered Asphalt Binders

Performance Grading Results

The performance grades (PG) including the continuous PG's of the asphalt binders are summarized in Table 14. From a practical standpoint, most if not all state agencies would be willing to utilize a rejuvenating product if it; (1) is cost effective, (2) is not a health risk, and (3) produces a recycled asphalt mixture with properties equivalent to a virgin mixture. Therefore, when comparing the effectiveness of the rejuvenators, their PG's were compared to the control mixture and the 50% RAP mixture without rejuvenator. A rejuvenator that is capable of "rejuvenating" the aged RAP binder should result in PG's very similar to the control mixture or fall in between it and 50% RAP mixture without rejuvenator. Rejuvenators that are not effective in rejuvenating the aged RAP binder will result in PG's very similar to the 50% RAP mixture.

Recovered Asphalt Binder High Temperature Performance

As would be expected Table 14 shows that the control mixture had the lowest high temperature PG, as well as the largest non-recoverable creep compliance (J_{nr}) at both STOA and LTOA. Rejuvenator PO (Paraffinic Oil) provided high temperature properties very similar to the control mixture including the J_{nr}'s.

Recovered Asphalt Binder Low Temperature Performance

It is often the fatigue and low temperature properties that are of concern with high RAP content mixtures. As noted previously, a rejuvenator utilized in the 50% RAP mixture should provide low temperature properties similar to or better than the Control mixture. Based on Table 14, the low temperature PG from AASHTO R29 indicates that Rejuvenator AO (Aromatic Oil) restored the low temperature properties of the 50% RAP mixture to those of the control mixture. The low temperature PG, determined using AASHTO R49, indicates that three 50% RAP mixtures with rejuvenators provided critical cracking temperatures similar to or better than the control mixture. The rejuvenators were AO (Aromatic Oil), PO (Paraffinic Oil), and OB2 (Organic Blend #2).

Table 14 – Recovered Asphalt Binder PG Grade Results

Mixture	Aging	Continuous Grade (°C) High	Continuous Grade (°C) Low	Continuous Grade (°C) Intermediate	PG Using AASHTO R29 & M320
Control – PG58-28	STOA	64.5	-29.4	16.5	64-28
	LTOA	69.7	-27.7	17.8	64-22
50% RAP + No Rejuvenator	STOA	71.4	-27.8	18.8	70-22
	LTOA	75.5	-25.5	21.3	70-22
50% RAP + Aromatic Oil	STOA	68.0	-28.4	16.7	64-28
	LTOA	71.6	-28.7	17.8	70-28
50% RAP + Paraffinic Oil	STOA	65.2	-29.5	15.3	64-28
	LTOA	71.7	-25.0	17.7	70-22
50% RAP + Organic Blend 1	STOA	75.5	-27.7	19.8	70-22
	LTOA	73.0	-25.4	18.4	70-22
50% RAP + Organic Blend 2	STOA	67.5	-28.4	16.3	64-28
	LTOA	71.9	-27.1	17.5	70-22

Mixture	Aging	Critical Cracking Temperature (°C) AASHTO R49	Multiple Stress Creep Recovery (MSCR) @64°C J_{nr} (1/kPa)	Multiple Stress Creep Recovery (MSCR) @64°C % Recovery
Control – PG58-28	STOA	-28.1	4.21	0.7
	LTOA	-26.8	1.80	3.0
50% RAP + No Rejuvenator	STOA	-26.9	1.47	4.6
	LTOA	-25.1	0.71	10.1
50% RAP + Aromatic Oil	STOA	-28.6	2.38	2.3
	LTOA	-28.3	1.37	4.8
50% RAP + Paraffinic Oil	STOA	-30.1	3.77	0.6
	LTOA	-28.8	1.37	5.1
50% RAP + Organic Blend 1	STOA	-26.5	1.76	2.6
	LTOA	-27.9	1.23	5.8
50% RAP + Organic Blend 2	STOA	-30.6	2.69	2.0
	LTOA	-27.9	1.30	5.2

Mixture Tests

The results from the binder evaluation were compared to mixture test results for rutting and moisture damage susceptibility, fatigue cracking and low temperature cracking to determine if they correlate.

Rutting and Moisture Damage

Rutting and moisture damage testing was conducted in accordance with AASHTO T324 "Hamburg Wheel-Track Testing of Compacted Hot-Mix Asphalt (HMA)" (AASHTO, 2011). This test is utilized to determine the failure susceptibility of a mixture due to weakness in the aggregate structure, inadequate binder stiffness, or moisture damage (AASHTO, 2011). In this test, a mixture is submerged in heated water (typically 40-50ºC) and subjected to repeated loading provided by a 705N (158lb) steel wheel. As the steel wheel loads the specimen, the corresponding rut depth of the specimen is recorded. The rut depth versus numbers of passes of the wheel is plotted to determine the Stripping Inflection Point (SIP) as shown in Figure 53. The SIP gives an indication of when the test specimen begins to exhibit moisture damage (stripping).

Gyratory specimens for this test were fabricated using the Superpave gyratory compactor (SGC) to an air void level of 7.0±1.0% as required by AASHTO T324. Mixtures were tested after undergoing both STOA and LTOA aging. Testing was conducted at a test temperature of 50ºC (122ºF). The specimens were tested at a rate of 52 passes per minute after a soak time of 30 minutes at the test temperature. Testing terminated at 20,000 wheel passes or when visible stripping was noted. Table 15 presents the HWTD results.

The data in Table 15 illustrated, for mixtures with STOA aging, that the control mixture failed the HWTD test fairly quickly while the 50% RAP mixture with no rejuvenator passed the test with no inflection point and minimal rutting (□ 2 mm). If the rejuvenators used in this study are effective in mitigating the aging of the aged RAP binder, it would be expected that the performances of the 50% RAP mixtures with rejuvenators fall between the performance of the control mixture and 50% RAP mixture with no rejuvenator. This is expected because the overall binder in 50% RAP mixtures with rejuvenators should be stiffer than the control binder (PG58-28) and softer than the overall binder in the 50% RAP mixture without rejuvenator. After STOA and LTOA the data indicated, as presented in Table 15, that stripping inflection points and the rut depth of the 50% RAP mixtures with the rejuvenators did fall between them, and it agrees with the Black Space and ω_o – R-value Space diagrams that suggested these rejuvenators are mitigating the aging of the RAP binder. Generally, the mixture rutting data did not agree with the MSCR binder data except that rutting generally decreased as the aging period increased.

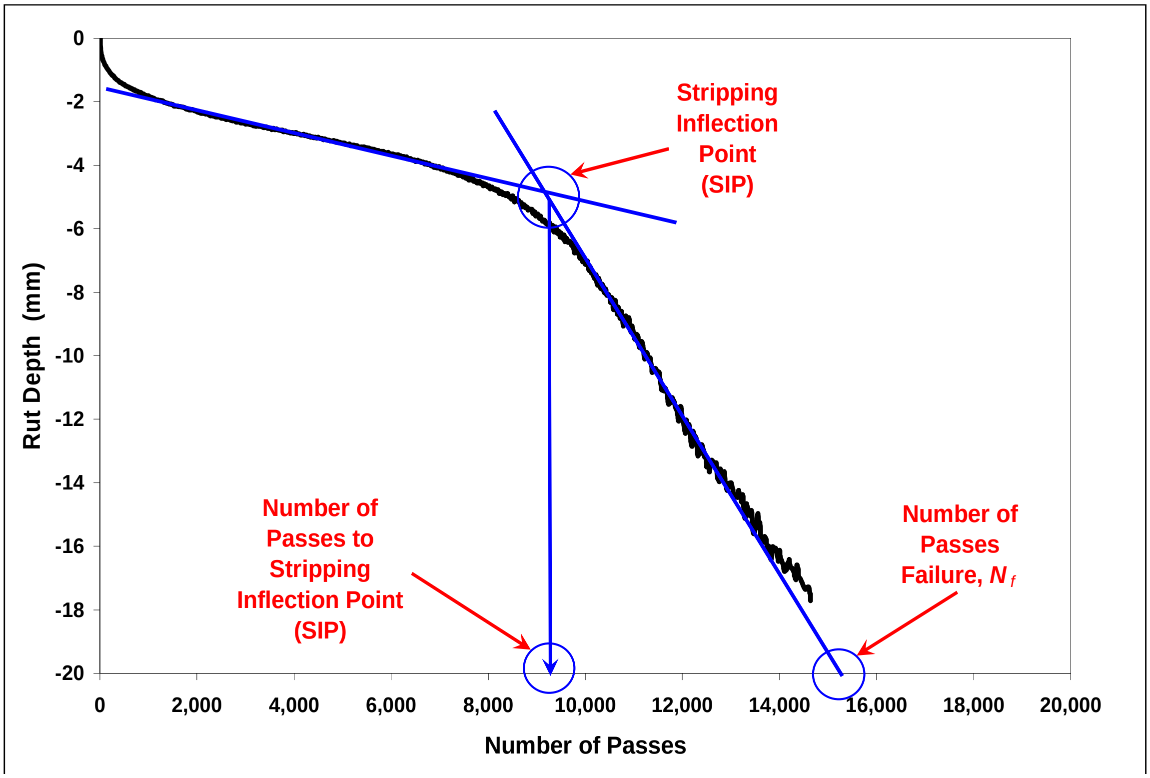

Figure 53 – Determination of HWTD Stripping Inflection Point (SIP)

Table 15 – Rutting and Moisture Susceptibility HWTD Results

Mixture	Aging	Stripping Inflection Point	Rut Depth at 10,000 Passes (mm)	Rut Depth at 20,000 Passes (mm)
Control PG58-28	STOA	5,900	>20	>20
	LTOA	12,000	3.00	>20
50% RAP - No Rejuvenator	STOA	NONE	1.09	1.80
	LTOA	NONE	0.91	1.45
50% RAP + Aromatic Oil	STOA	9,800	5.06	>20
	LTOA	14,700	1.65	12.21
50% RAP + Paraffinic Oil	STOA	14,500	1.46	12.76
	LTOA	15,200	3.13	14.15
50% RAP + Organic Blend 1	STOA	8,500	7.61	>20
	LTOA	13,600	1.92	5.20
50% RAP + Organic Blend 2	STOA	12,900	1.92	16.70
	LTOA	12,500	3.10	17.73

Fatigue Cracking Evaluation

Fatigue Cracking - Four-Point Flexural Bending Beam AASHTO T321

One of the most common and historically used laboratory test procedure to evaluate the fatigue cracking performances of asphalt mixtures is the four-point flexural beam fatigue test, and it is the only standard procedure. The AASHTO test protocol is AASHTO T321 "Determining the Fatigue Life of Compacted Hot Mix Asphalt (HMA) Subjected to Repeated Flexural Bending" (AASHTO, 2011). In order to investigate the relative fatigue cracking performances of the mixtures used in this study, the four point bending beam fatigue tests were conducted following this procedure.

Slabs with dimensions of 150 mm wide, 180 mm tall, and 450 mm long (6 in. wide, 6 in. tall, and 17.5 in. long) were fabricated for each mixture using the IPC Global Pressbox slab compactor. From each slab, beams with dimensions of 63 mm wide, 50 mm tall, and 380 mm (2.5 in. wide, 2 in. tall, and 15 in. long) long were cut such that the sides had smooth faces. The air voids of the final cut specimens were 7±1%. Beam specimens were conditioned at the test temperature of 15°C (59ºF) for at least two hours prior to testing. A 15°C (59ºF) test temperature was selected as it represents the intermediate temperature for the Northeast.

Each beam fatigue test was conducted in strain control at a loading frequency of 10Hz applied using a sinusoidal waveform. Specimens were tested at strain levels of 250 $\mu\varepsilon$, 500 $\mu\varepsilon$, and 750 $\mu\varepsilon$. Initially, all mixtures were tested at the 250 $\mu\varepsilon$. However, at this strain level, the 50% RAP mixture with the rejuvenators reached over six million cycles with less than 20% loss in the initial stiffness measured at 50 cycles. Therefore, the two higher strain levels were selected based on trial and error with the aim of achieving more than 10,000 cycles at failure. At 500 $\mu\varepsilon$ and 750 $\mu\varepsilon$, all mixtures lost 50 percent of their initial stiffness closely after at least 10,000 cycles. The number of cycles to failure was determined by fitting an exponential function to the flexural stiffness versus number of cycles relationships and then evaluating the number cycles that it took to decrease the initial stiffness by 50%. The beam fatigue testing results are shown in Figures 54 and 55.

The data in Figures 54 and 55 indicated, for the majority, that the number of cycles to failure for the 50% RAP mixtures with rejuvenators improved as compared to the 50% RAP mixture without rejuvenator. This occurred for both aging conditions. In one case (50% RAP + Aromatic Oil LTOA) at 750 $\mu\varepsilon$, the average cycles to failure marginally decreased. Overall, the data suggested that the rejuvenators are helping in "rejuvenating" the aged RAP asphalt binder, leading to an overall binder softer than the overall binder in the 50% RAP mixture without rejuvenator. This agrees with the Black Space and the ω_o – R-value Space diagrams that suggested these rejuvenators are softening the aged RAP binder. It should be noted that these observations are made based on the fact that the fatigue characteristics of mixtures are function of the overall binder stiffness.

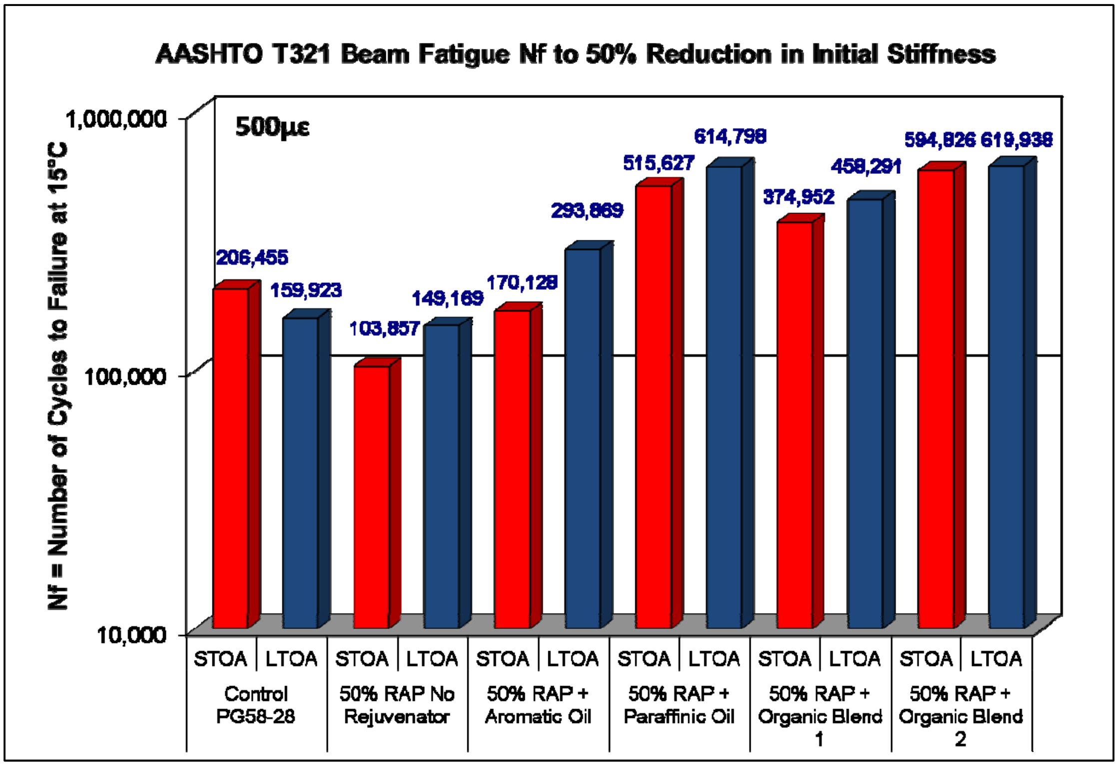

Figure 54 – Fatigue Cracking Results from Flexural Beam Fatigue – 500 microstrains

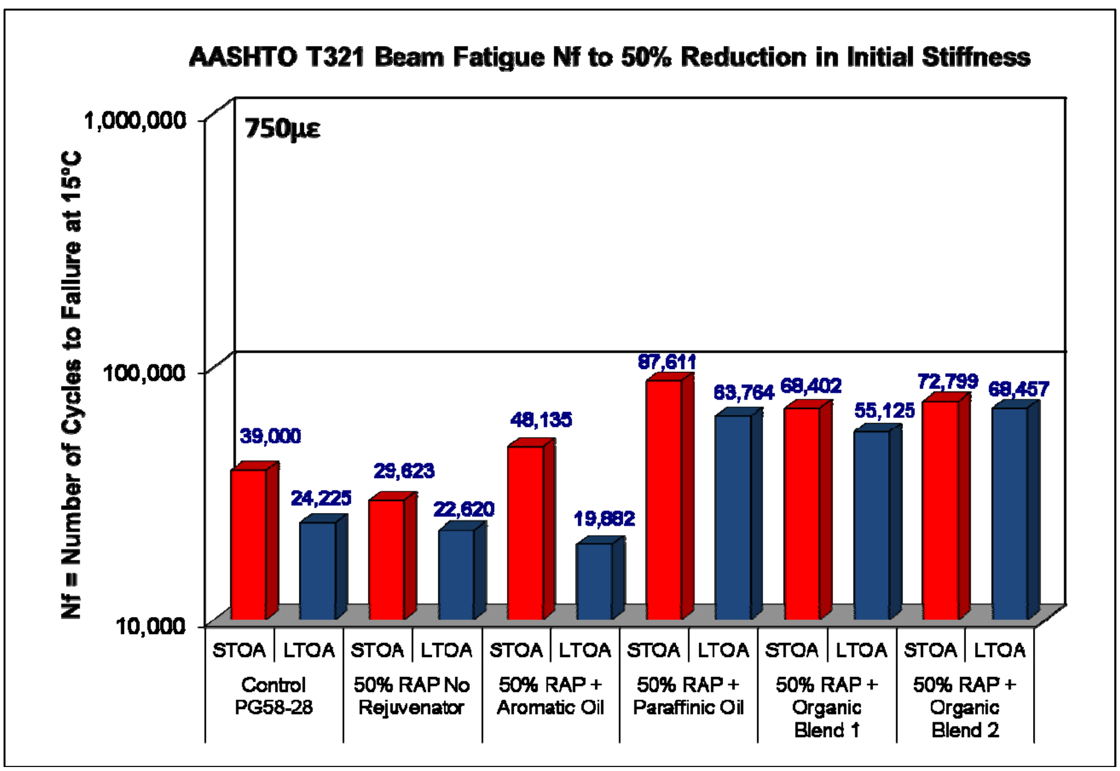

Figure 55 – Fatigue Cracking Results from Flexural Beam Fatigue – 750 microstrains

Fatigue Cracking - Overlay Tester

The Overlay Tester, described by Zhou and Scullion (2007), has shown to provide an excellent correlation to field cracking for both composite pavements (Zhou and Scullion, 2007; Bennert et al., 2009) as well as flexible pavements (Zhou et al., 2007). Sample preparation and test parameters used in this study followed that of TxDOT TEX-248F, *Overlay Test for Determining Crack Resistance of HMA*. These included:

- 25°C (77°F) test temperature;
- Opening width of 0.025 inches;
- Cycle time of 10 seconds (5 seconds loading, 5 seconds unloading); and
- Specimen failure defined as 93% reduction in Initial Load.

The Overlay Tester fatigue cracking results are shown in Figure 56. At first observation, one can see the benefit of a virgin asphalt mixture containing the PG58-28 asphalt binder. However, after long-term aging, the fatigue resistance drops dramatically. Similar to the Overlay Tester results shown earlier, there is an improvement in the Overlay Tester when rejuvenators are used, as there is an improvement in the fatigue cracking results from the 50% RAP No Rejuvenator mix. And although the short-term aged fatigue results are better for the Control PG58-28 (No RAP), after long-term aging, similar results can be found to that of the rejuvenated 50% RAP mixtures. This would indicate that the rejuvenators appear to continue to add benefit to the fatigue resistance as the pavement ages.

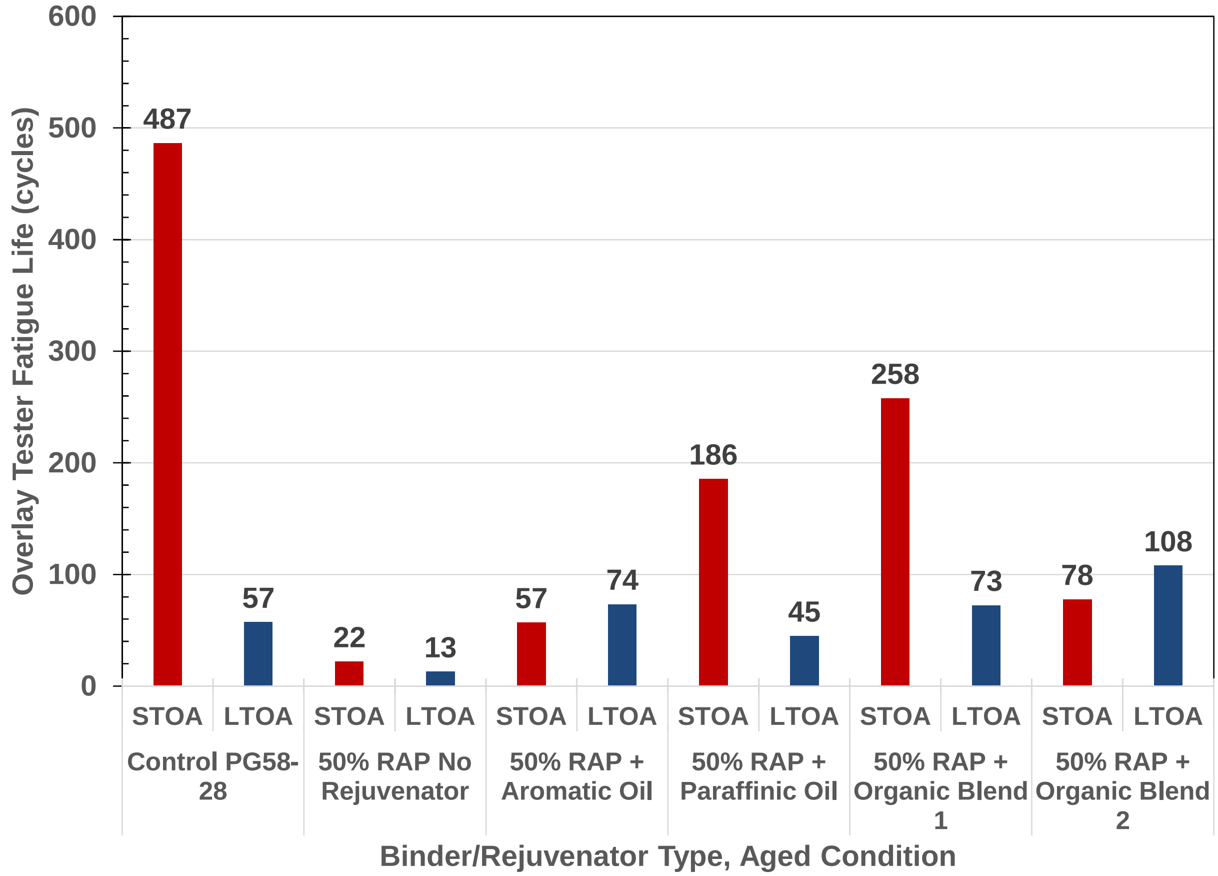

Figure 56 – Overlay Tester Fatigue Cracking Results for UMass – Rutgers Mixtures

Low Temperature Cracking - Thermal Stress Restrained Specimen Test (TSRST)

To assess the effect of aging and rejuvenators on the low temperature cracking susceptibilities of the mixtures, each mixture was tested in the Thermal Stress Restrained Specimen Test (TSRST) device in accordance with AASHTO TP10-93 (AASHTO, 1993) with the exception that Superpave gyratory compacted specimens were utilized.

In the TSRST test, an asphalt mixture specimen is cooled at a constant rate (-10ºC/hour) while its original length is held constant by the TSRST device. As the specimen gets colder, it tries to contract but cannot which results in the accumulation of thermal stresses. Eventually the thermal stresses exceed the tensile strength capacity of the specimen resulting in specimen fracture (crack). The temperature at which this fracture occurs is recorded and noted as the low cracking temperature of the mixture.

SGC specimens 185 mm (7.3 in) tall by 150 mm (5.9 in) in diameter were fabricated for each mixture. TSRST specimens were then cored and cut to a final height of 160 mm tall (6.3 in) by 54 mm (2.1 in) in diameter. The air voids of the final cut specimens were 7±1%. The TSRST results are presented in Figure 57.

The incorporation of the 50% RAP into the mixture made the low cracking temperature warmer relative to the control mixture by 4°C and 3°C after STOA and LTOA, respectively. The incorporation of the rejuvenators helped improve the low temperature cracking susceptibilities of the mixtures after STOA and LTOA as compared to both the control mixture and 50% RAP mixture without rejuvenator. This improvement is an indication that rejuvenators are causing a reduction in the stiffness of the aged RAP binder (mitigation of aging) leading to an overall binder with lower stiffness relative to the 50% RAP mixture with no rejuvenator. Furthermore, by comparing the LTOA data to the STOA data, it can be seen that any additional aging of the RAP binder caused by LTOA did not have a significant impact on the low cracking temperatures when these rejuvenators were used. In fact, LTOA had little to no effect on any of the TSRST cracking temperatures compared to STOA. The low cracking temperatures from the mixture tests did not agree well with the critical cracking temperatures of the binders, as these values were much colder.

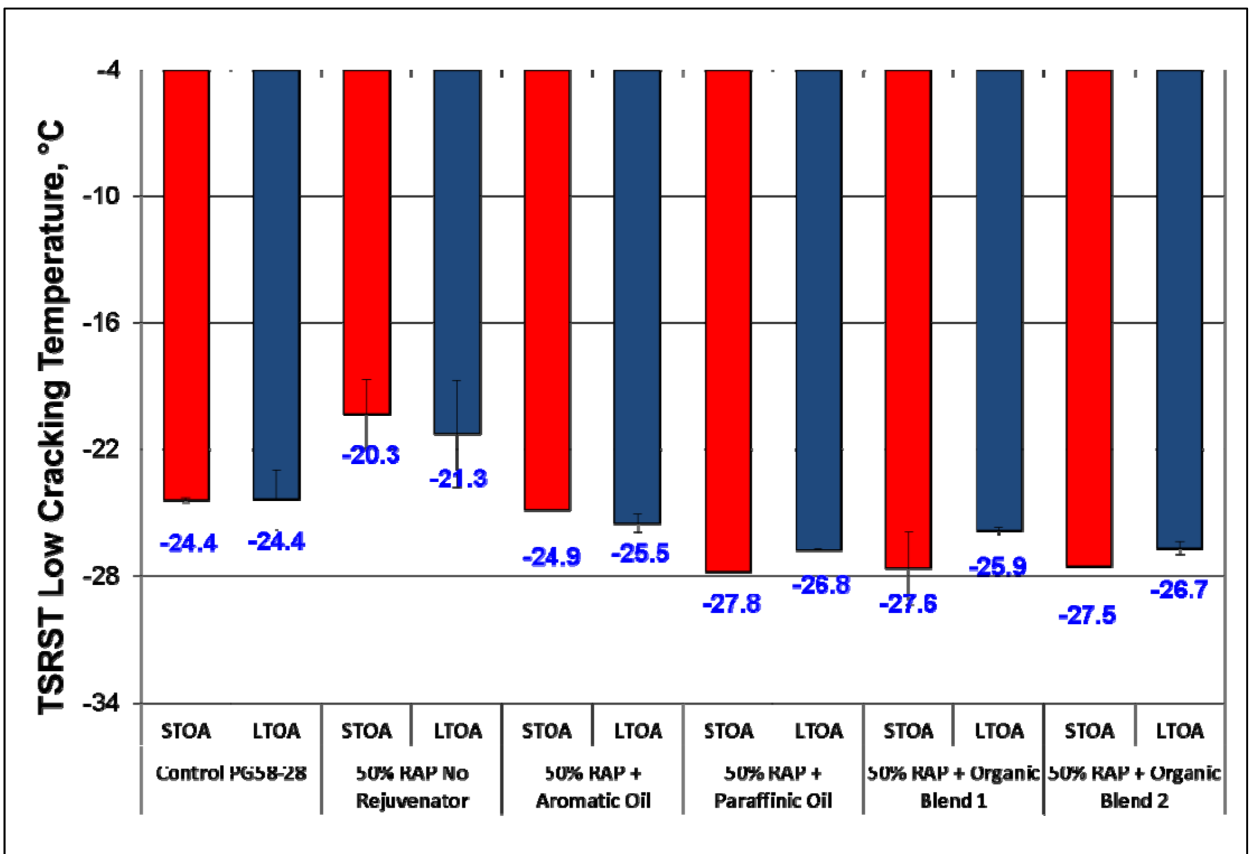

Figure 57 – Low Temperature Cracking Results from the TSRST

Comparisons of Asphalt Binder and Mixture Fatigue Performance

Similar to the earlier test data, the asphalt binder fatigue property indices (Glover-Rowe Parameter and Cross-over Frequency) were compared with the asphalt mixture fatigue cracking properties of the Overlay Tester and Flexural Beam Fatigue. The low temperature thermal cracking properties were also compared using the low temperature PG grading (AASHTO R29 and AASHTO R49) for the asphalt binders and the TSRST thermal cracking properties of the asphalt mixtures. Again, the hypothesis being that since full blending is occurring in the extracted/recovered asphalt binders, if the trend in asphalt binder and mixture properties is strong, then full blending is also occurring in the asphalt mixtures. Meanwhile, if a poor relationship exists, than blending is most likely limited or not occurring in the asphalt mixture phase.

Figure 58 shows the relationship between the Cross-over Frequency and the Glover-Rowe Parameter. A strong relationship exists between the two parameters, again emphasizing the inter-relationship between aging and cracking thresholds.

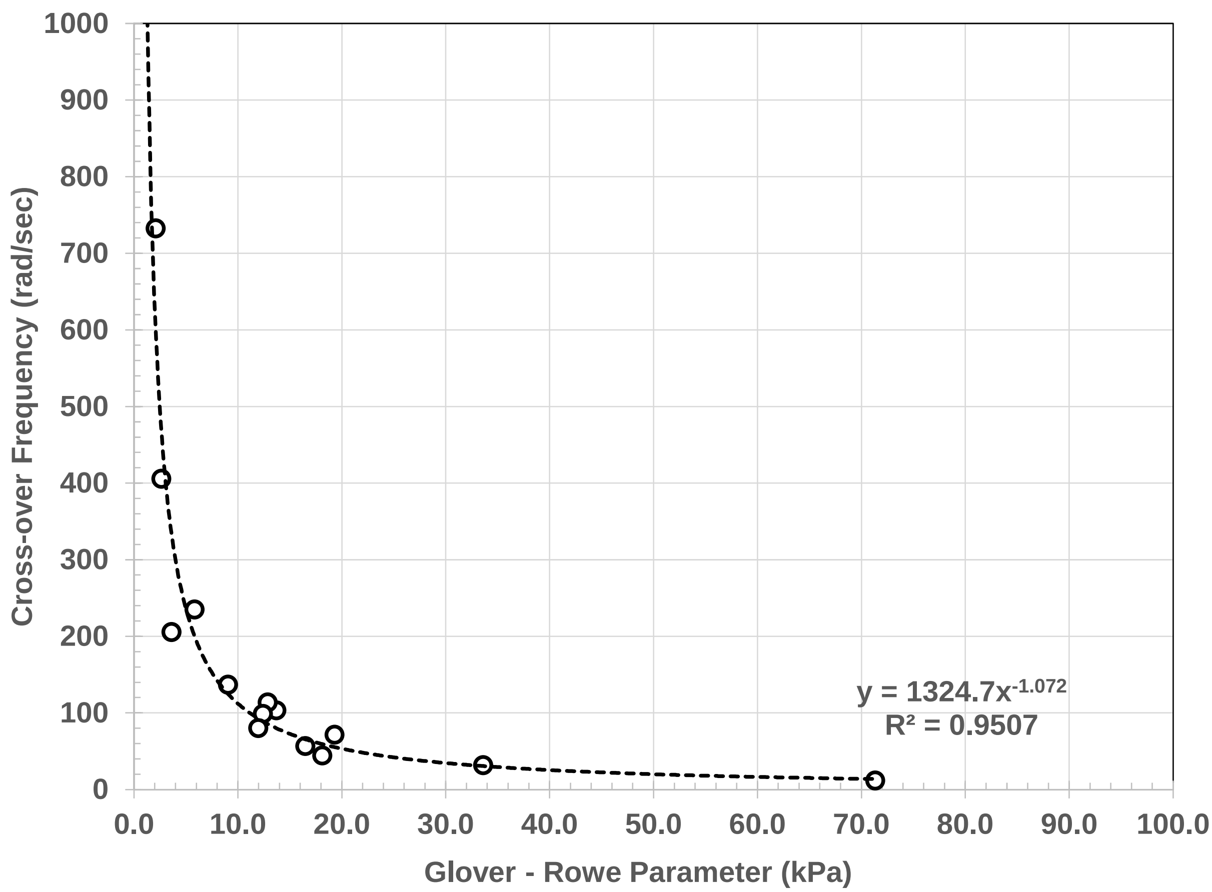

Figure 58 – Relationship Between Asphalt Binder Properties – Glover-Rowe Parameter & Cross-over Frequency

Figures 59 and 60 show the correlation between the asphalt binder fatigue cracking indices (Glover-Rowe Parameter and Cross-over Frequency) and the asphalt mixture fatigue cracking in the Overlay Tester. A moderate relationship between the asphalt mixture and binders properties exists in Figures 59 and 60, indicating the perhaps better blending was achieved in this set of asphalt mixtures when compared to the ones shown earlier. Another factor that needs to be considered is the property of the different RAP used in the two separate studies. If a much more oxidized and harder RAP was used, it would be more difficult to mobilize regardless of whether or not a rejuvenator was utilized. Although the RAP properties from the UMass-Rutgers mixtures were not known, it is clear from the figures that a better relationship exists between the performance of the asphalt binders and mixture than shown in the New Jersey mixtures earlier.

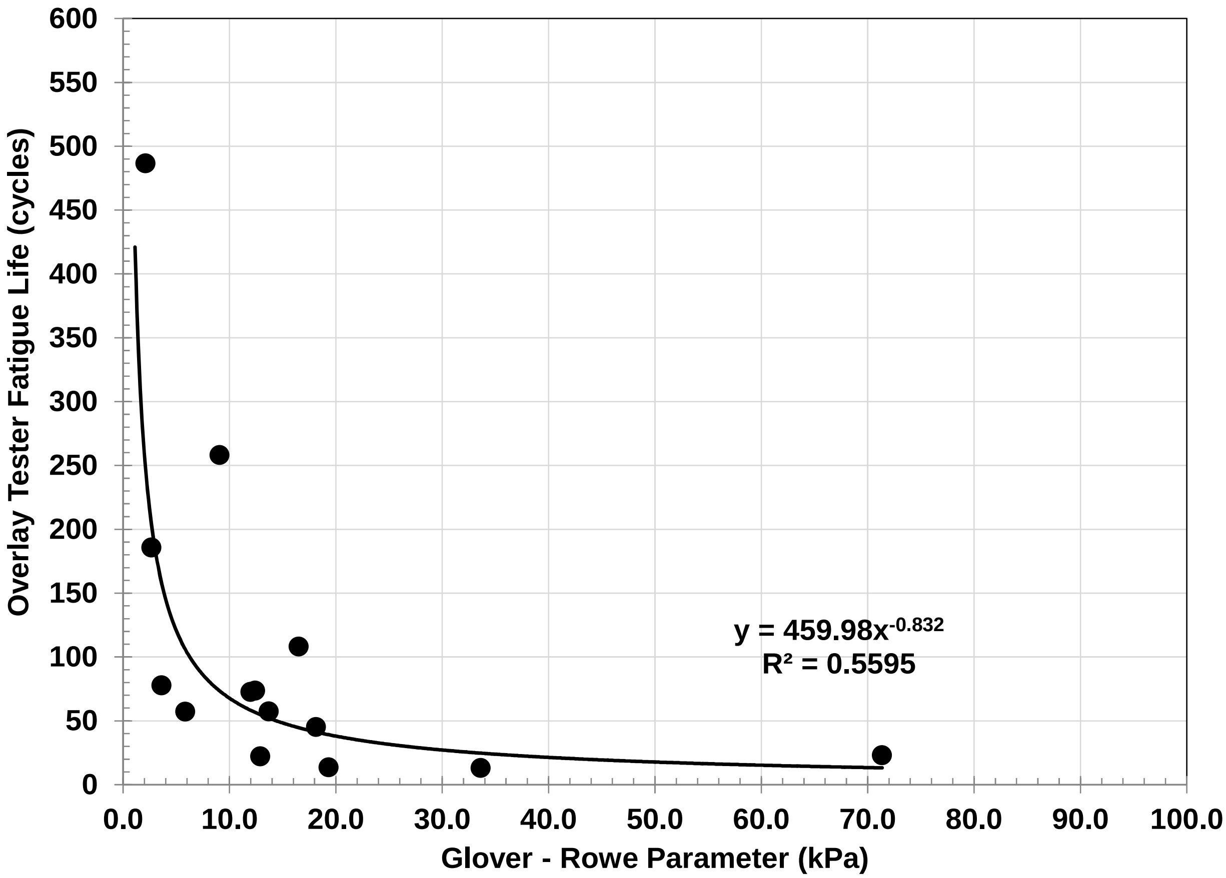

Figure 59 – Asphalt Mixture (Overlay Tester) vs Asphalt Binder (Glover-Rowe) Fatigue Cracking Relationships

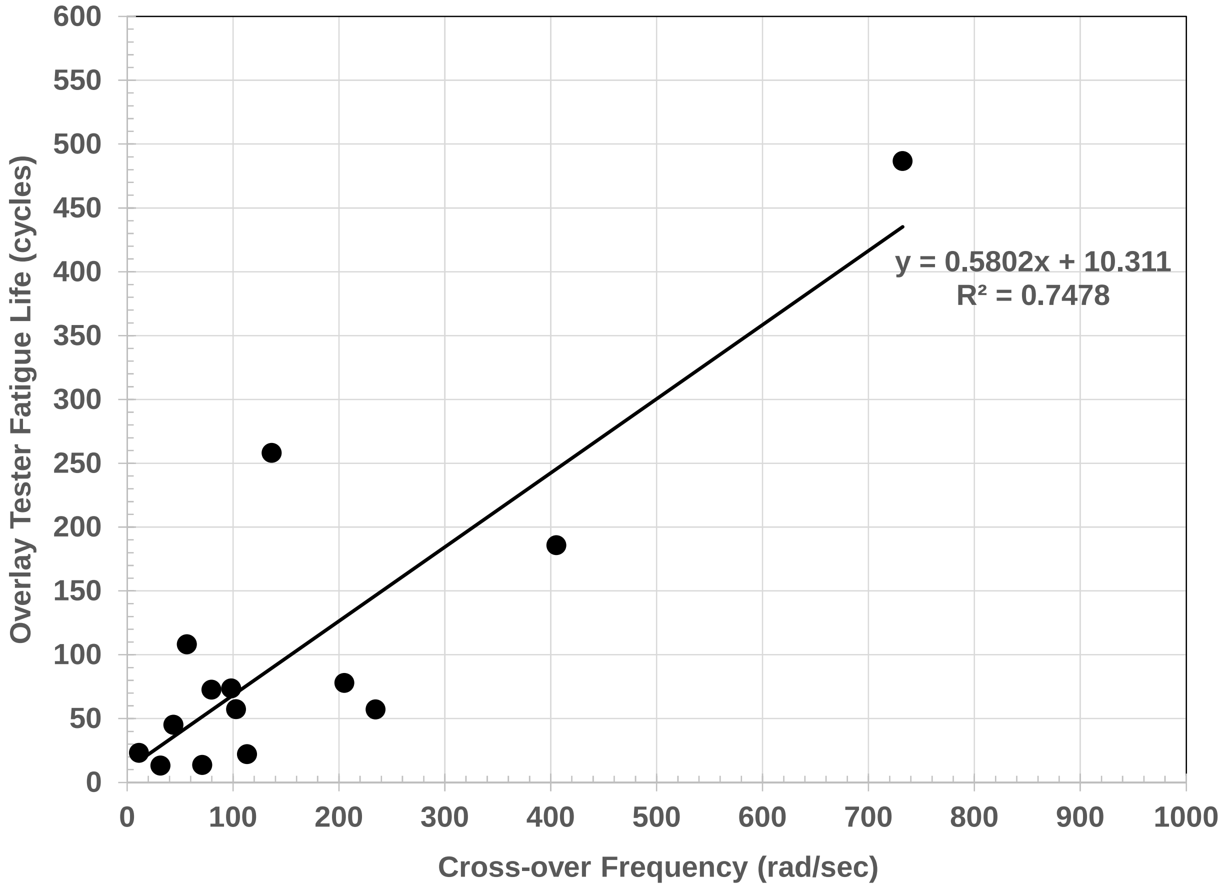

Figure 60 – Asphalt Mixture (Overlay Tester) vs Asphalt Binder (Cross-over Frequency) Fatigue Cracking Relationships

The same asphalt binder properties were also compared to the fatigue resistance properties measured in the Flexural Beam Fatigue test at two different tensile strain levels; 500 and 750 micro-strains. The results of the comparisons are shown in Figures 61 through 64. As shown in the test results, the relationship between the asphalt mixture and asphalt binder properties is not as strong as shown earlier for the Overlay Tester.

Upon further observation, it is clear that the fatigue properties between the crack initiation test (Flexural Beam Fatigue) and the crack propagation test (Overlay Tester) do not correlate between one another (Figure 65). This is an important finding as the term “cracking resistance” is often used broadly without defining the mode of cracking associated with the test. The test data from the UMass-Rutgers mixtures would suggest that the asphalt binder fatigue properties best relate to the crack propagation properties of the Overlay Tester, as opposed to the crack initiation properties of the Flexural Beam Fatigue test. This may be due to the larger strains commonly associated with asphalt binder testing best match the larger deformation associated with most crack propagation tests, including the Overlay Tester.

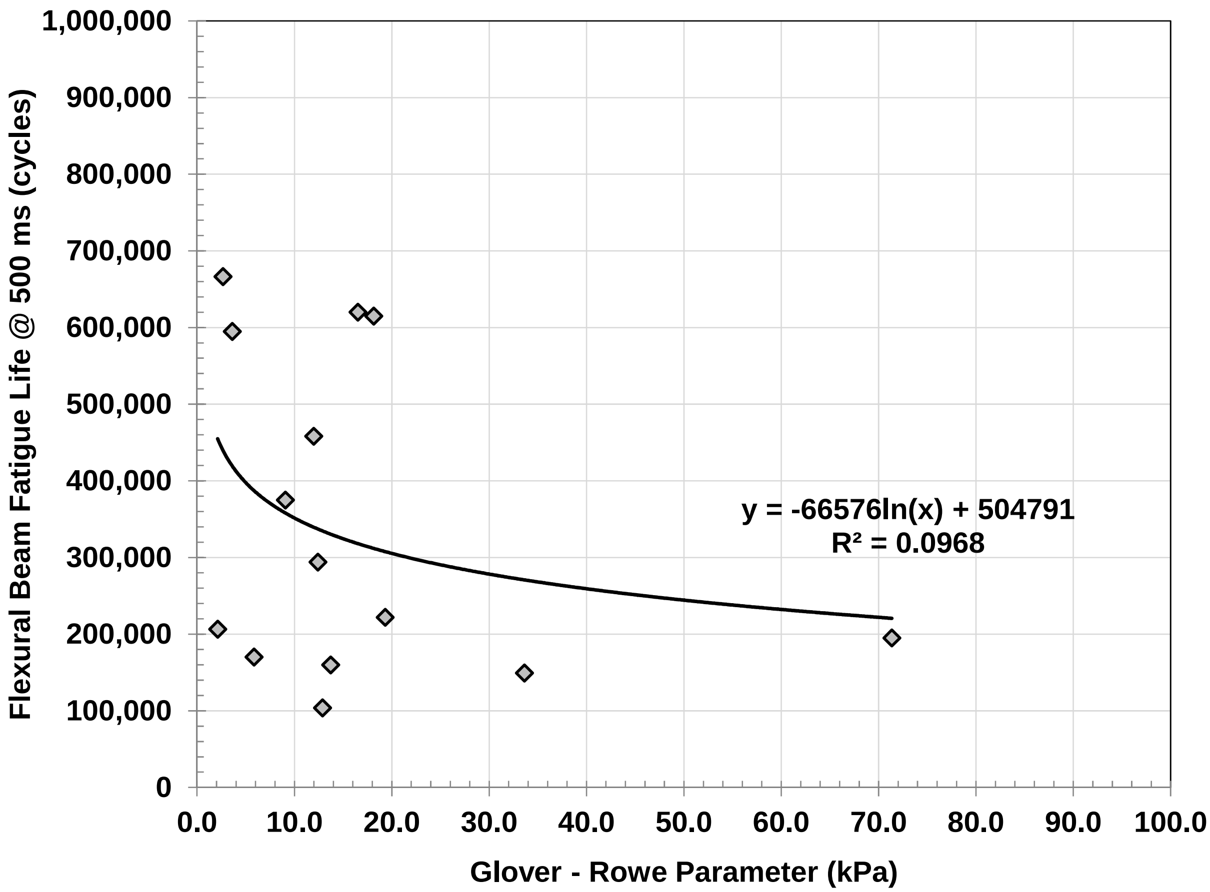

Figure 61 - Asphalt Mixture (Flexural Beam Fatigue @ 500 micro-strains) vs Asphalt Binder (Glover-Rowe) Fatigue Cracking Relationships

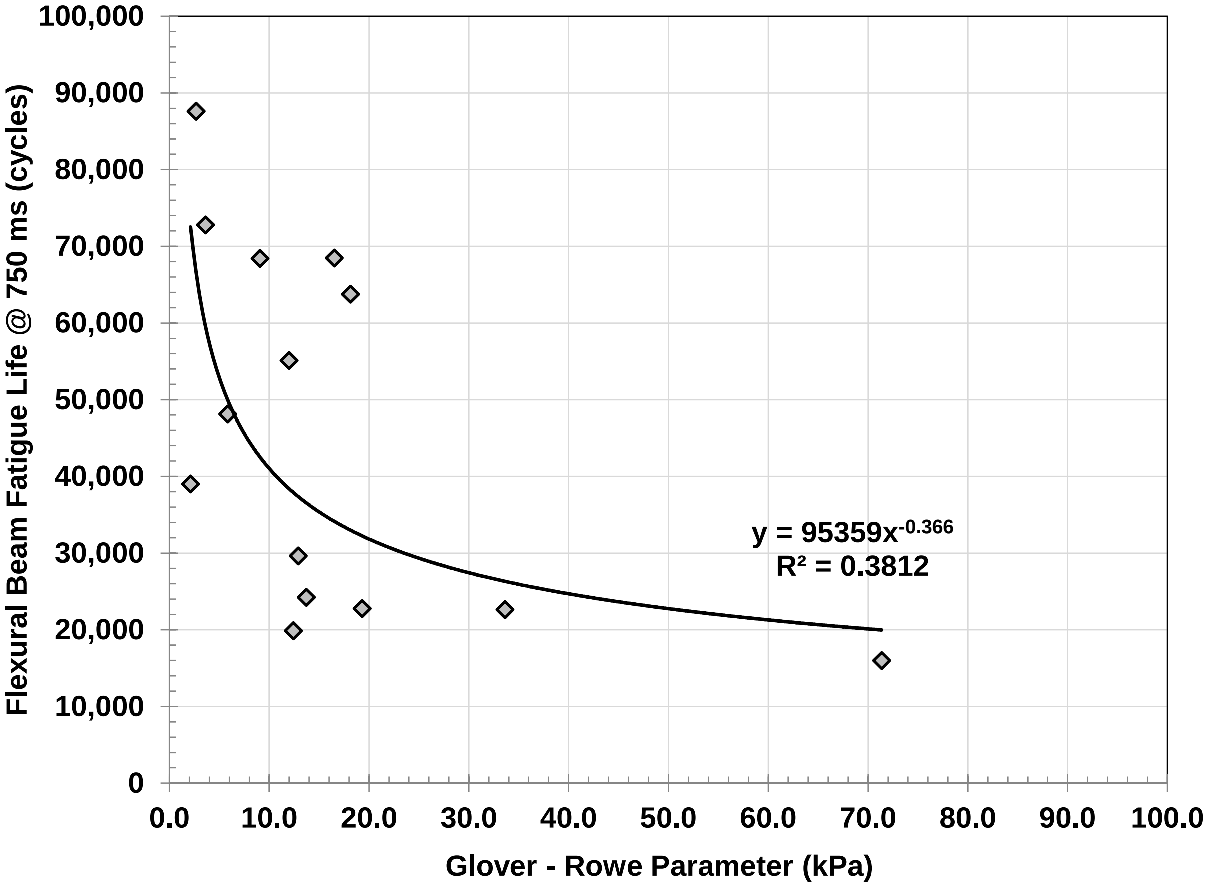

Figure 62 - Asphalt Mixture (Flexural Beam Fatigue @ 750 micro-strains) vs Asphalt Binder (Glover-Rowe) Fatigue Cracking Relationships

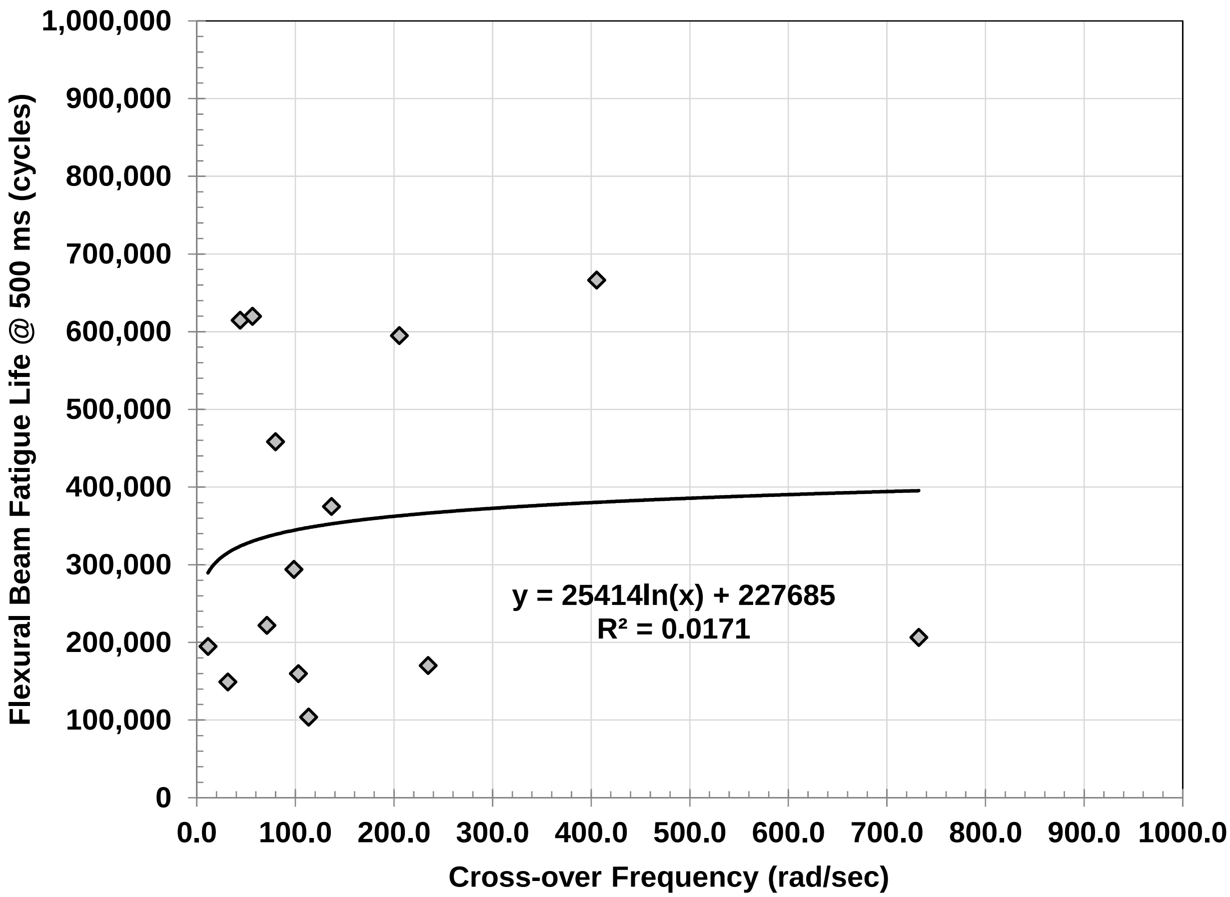

Figure 63 - Asphalt Mixture (Flexural Beam Fatigue @ 500 micro-strains) vs Asphalt Binder (Cross-over Frequency) Fatigue Cracking Relationships

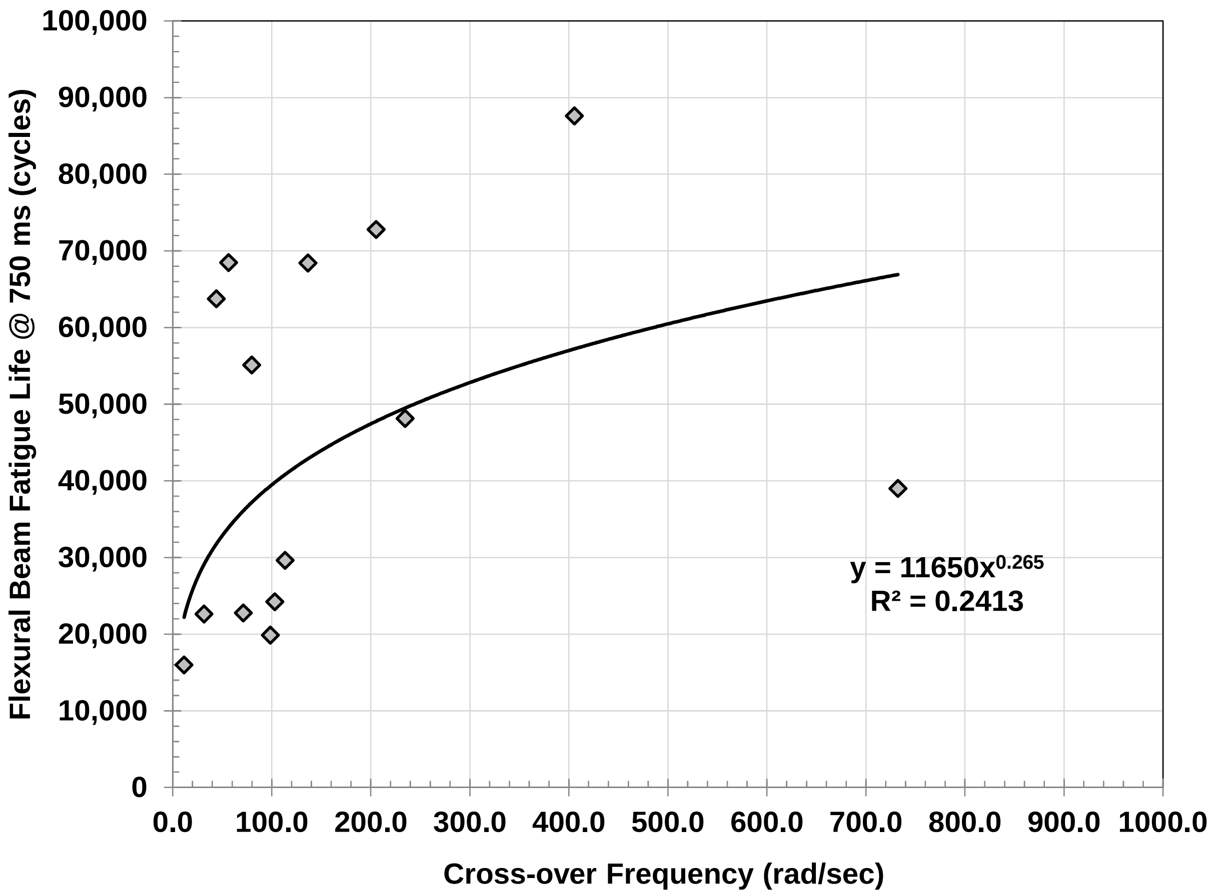

Figure 64 - Asphalt Mixture (Flexural Beam Fatigue @ 750 micro-strains) vs Asphalt Binder (Glover-Rowe) Fatigue Cracking Relationships

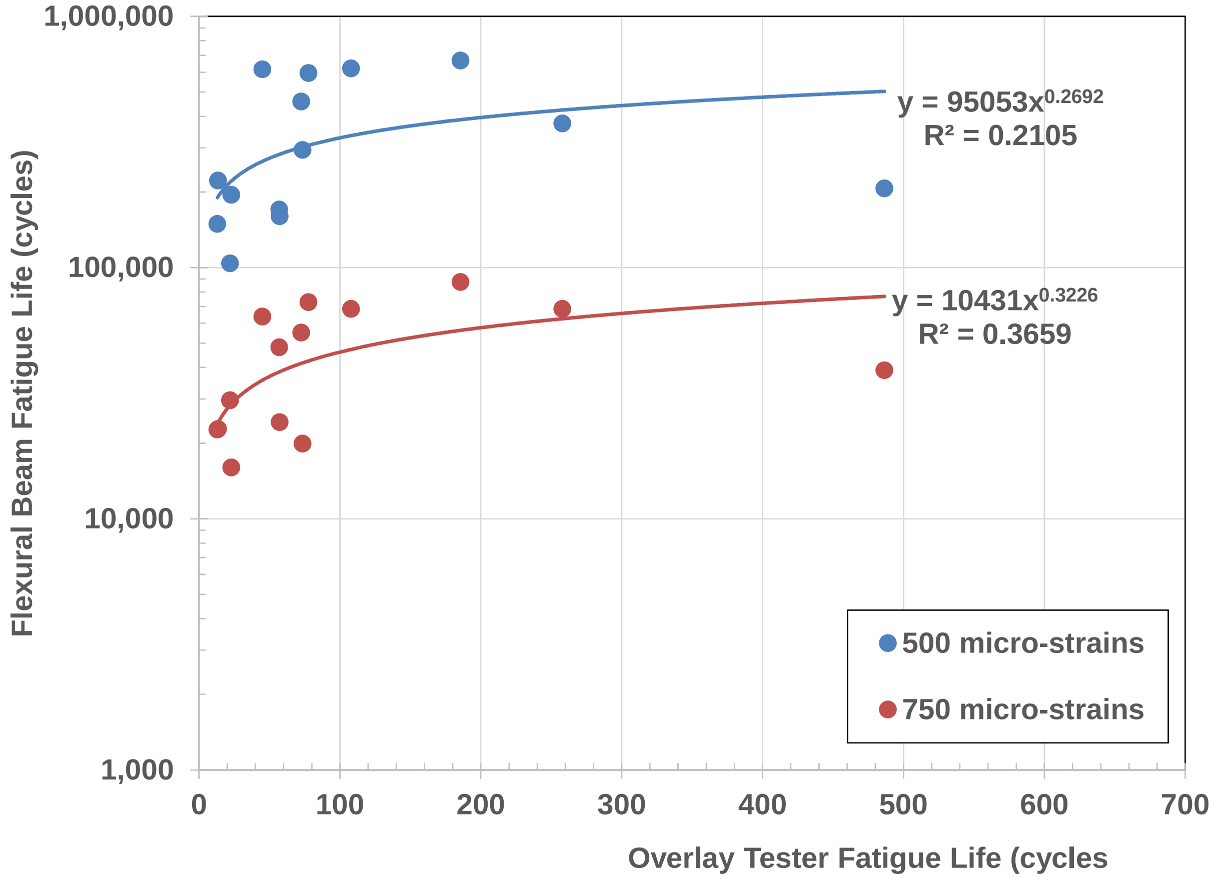

Figure 65 – Fatigue Life Measured by Crack Initiation (Flexural Beam Fatigue) and Crack Propagation (Overlay Tester) Test Methods

Low Temperature Asphalt Binder and Mixture Performance Comparisons

After the recovery process, the asphalt binder was tested for the respective PG grade, in accordance with AASHTO R29 & M320, *Standard Specification for Performance-Graded Asphalt Binder*. The low temperature cracking properties of the asphalt binders were also evaluated in accordance with AASHTO R49, *Determination of Low-Temperature Performance Grade (PG) of Asphalt Binders.* The analysis procedure utilizes the test data from the Bending Beam Rheometer (BBR) and Direct Tension Test (DTT). The BBR data is used to compute the thermal stress in the pavement using User-Specified cooling rates and other material parameters, such as coefficient of liner expansion. The plot of thermal stress vs temperature is then developed. Also plotted on the graph is the DTT failure stress vs temperature. The location at which these two graphs intersect (BBR thermal stress and DTT failure stress) is noted as the low temperature critical cracking temperature. An example of this is shown in Figure 66.

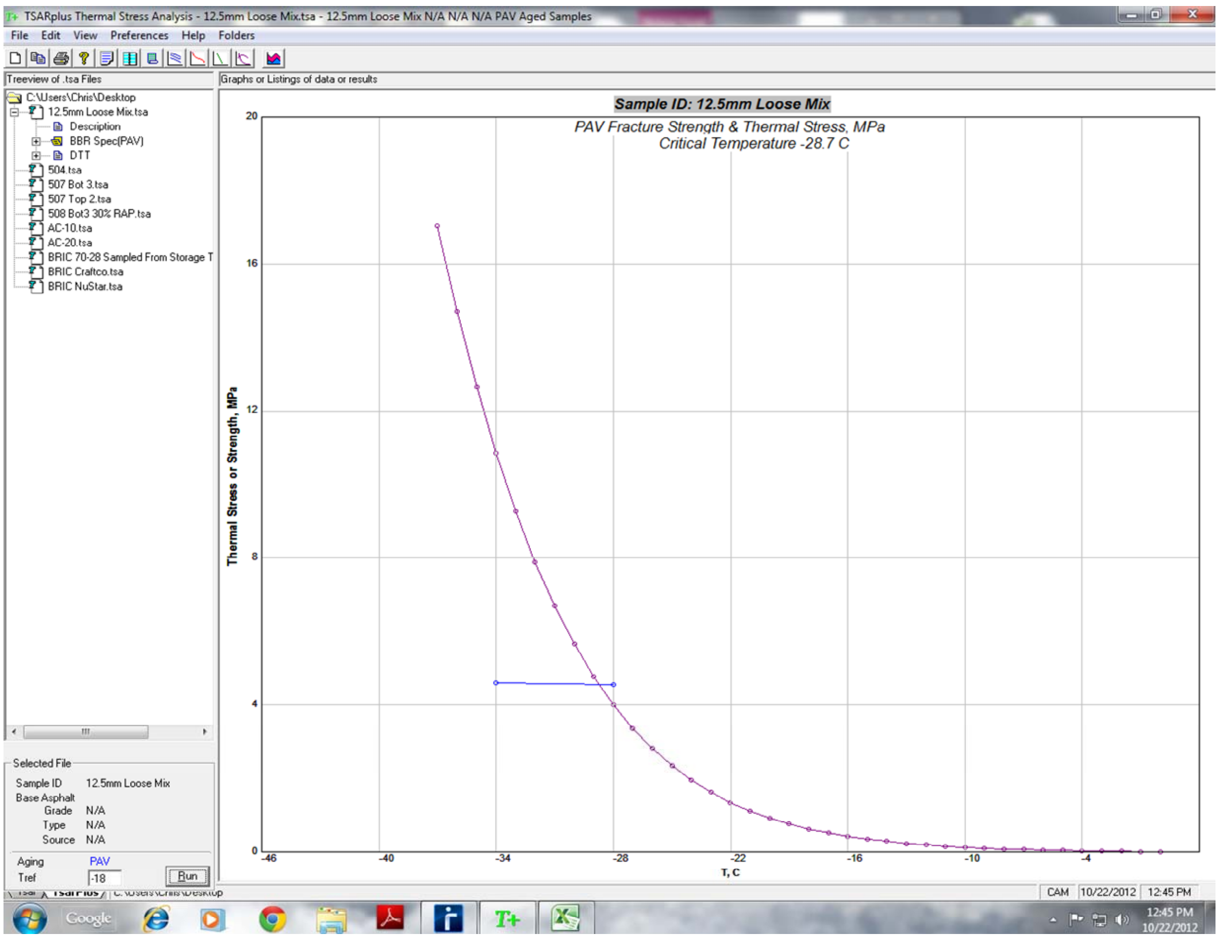

Figure 66 - Screenshot from TSAR™ Program Calculating Low Temperature Critical Cracking Temperature in Accordance with AASHTO R49

The low temperature PG grade determined used the AASHTO R29 and R49 test procedures were compared with the low temperature thermal cracking temperatures from the TSRST. The comparisons are shown in Figure 67. For all but three of the mixtures evaluated, the asphalt binder testing results in a lower (better) low temperature PG grade when compared to the TSRST mixture test. On average, the asphalt binder test procedures are determining a -2.5°C lower critical cracking temperature than the TSRST mixture test. Although the visual data in Figure 67 show a scatter of test results, the fact that the average different is -2.5°C does indicate a relatively good agreement between the asphalt binder and mixture tests considering the precision and bias of the different test methods involved.

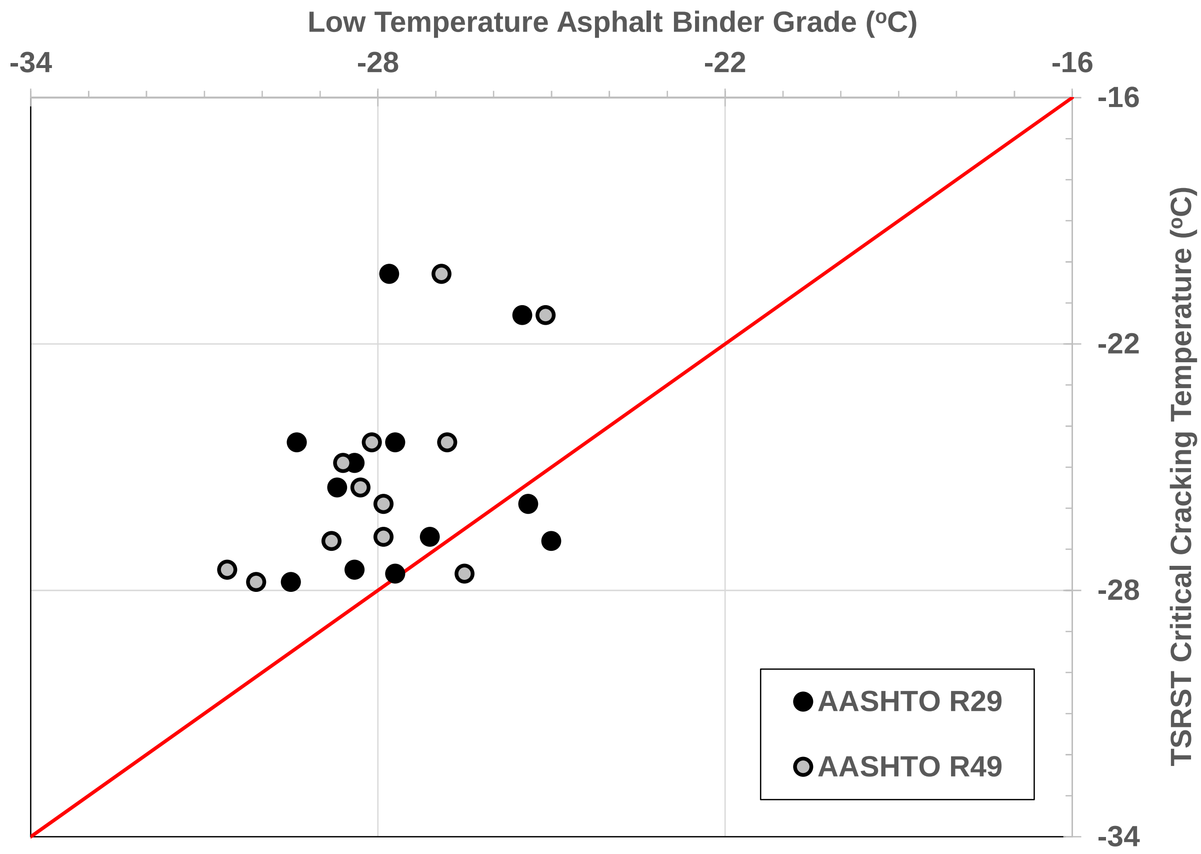

Figure 67 – Low Temperature Thermal Cracking Properties from Asphalt Binder Testing (AASHTO R29 and R49) and Asphalt Mixture Testing (TSRST)

Conclusions from UMass – Rutgers Study

This study was undertaken to better understand the effects of rejuvenators on high RAP mixtures (50% RAP), and it examined these effects after both short- and long-term aging to determine if rejuvenators can assist in mitigating aging in high RAP mixtures. A two tier evaluation was undertaken: (1) examine the rheology of extracted and recovered binders and (2) mixture performance tests. Based on the testing and analysis the following conclusions were made:

- The Black Space parameters for the virgin PG58-28 control mixture and the 50% RAP mixture with no rejuvenator showed that when these mixtures were aged from STOA to LTOA, the test data migrated from the lower right of the Black Space towards the upper left, indicating that aging of the asphalt binder had taken place. The same trend was observed when rejuvenators were used. However, the magnitude of the aging was less severe for certain rejuvenators. This indicates that the type of rejuvenator can play a role in the degree of mitigation of aged binder.
- For STOA conditioned mixtures, Rejuvenator PO (Paraffinic Oil) provided the largest mitigation of aging as its Black Space parameters were very similar to the virgin PG58-28 control mixture and was furthest away from the 50% RAP mixture without rejuvenator.
- For LTOA conditioned mixtures, Rejuvenators AO (Aromatic Oil) and OB1(Organic Blend #1) provided the largest mitigation of aging as their Black Space parameters were closer to, if not slightly better, than the virgin PG58-28 control mixture. This indicates that these two rejuvenators are still providing an effective level of rejuvenation even after long-term aging – something that Rejuvenators PO (Paraffinic Oil) and OB2 (Organic Blend #2) appear to be limited at accomplishing.
- The ω_o – R-value Space parameters for the virgin PG58-28 control mixture and the 50% RAP mixture with no rejuvenator showed that when these mixtures were aged from STOA to LTOA, the test data migrated downward and towards the right, indicating that aging of the asphalt binder had taken place. The magnitude of the change in the virgin PG58-28 control mixture was greater than for the 50% RAP mixture because approximately half of the asphalt binder in the 50% RAP mixture had already been highly oxidized.
- The ω_o – R-value Space indicated that all four rejuvenators provided some type of aging mitigation. However, similar to the Black Space diagram, the amount of aging mitigation varied among the different types of rejuvenators.
- The binder grading results exhibited subtle variances based on the rejuvenator used and aging period. These variances were not always consistent and may be due in part to variability in the test procedures. This indicates that PG tests may not have been as sensitive to aging. Since Black Space analysis did show sensitivity to aging, it may provide more beneficial information about aging mitigation for these types of mixtures. Additionally, the smaller sample size (about 1 gram of binder) required to develop the Black Space diagrams require less effort and time to complete than standardized PG grading tests. This could

allow for easier field aging evaluation as a single core would be required to obtain the test sample, whereas PG tests would require multiple cores.

- After both STOA and LTOA, the HWTD stripping inflection points and the rut depths for the 50% RAP mixtures with the rejuvenators fell between the values for the 50% RAP mixture with no rejuvenator and the virgin PG58-28 control mixture. This shows that the rejuvenators are helping in mitigating the aging of the RAP binder which agreed with the Black Space Diagram and the ω_o – R-value Space diagrams.
- After both STOA and LTOA, the higher fatigue lives provided by the beam fatigue test for the 50% RAP mixtures with the rejuvenators showed that the rejuvenators are helping in mitigating the aging of the RAP binder, and agreed with the Black Space and ω_o – R-value Space diagrams. Most of the fatigue lives of the 50% RAP mixtures with the rejuvenators were even higher than for the virgin PG58-28 control mixture.
- After both STOA and LTOA, the lower TSRST cracking temperatures for the 50% RAP mixtures with the rejuvenators compared to both the 50% RAP mixture without rejuvenator and virgin PG58-28 control mixture showed that the rejuvenators are helping in mitigating the aging of the RAP binder. This improvement is an indication that rejuvenators are causing a reduction in the stiffness of the aged RAP binder at low temperatures. Furthermore, by comparing the LTOA data to the STOA data, it was found the any additional aging of the RAP binder caused by LTOA did not have a significant impact on low temperature cracking when these rejuvenators were used. In fact, LTOA had little to no effect on any of the TSRST cracking temperatures compared to STOA. The low cracking temperatures from the mixture tests did not agree well with the critical cracking temperatures of the binders, as these values were much colder.
- Overall, the data indicated that the Black Space diagram and the ω_o – R-value Space diagram have the potential to be used as tools to evaluate the effect of rejuvenators on the mitigation of aging of high RAP mixtures. These two diagrams agreed with the mixture tests for rutting and moisture damage, fatigue cracking and low temperature cracking. Further work using chemical analysis of the binders is needed to reinforce the work presented here and add to the understanding of the ability of each rejuvenator to restore the properties of an aged asphalt binder after different periods of aging.

CONCLUSIONS

Asphalt mixture and binder testing was conducted on a variety of asphalt mixtures containing different RAP contents and rejuvenator types. Asphalt binder testing was conducted on virgin binders dosed with different rejuvenators, as well as testing conducted on asphalt binders extracted and recovered from RAP mixtures conditioned at different levels of aging – both short-term and long-term. Along with fatigue and low temperature asphalt binder characterization, asphalt mixture fatigue and low temperature cracking were conducted on mixtures containing identical asphalt binders. With the goal of the study to evaluate the effectiveness of rejuvenators when used with high RAP mixtures, the following conclusions can be drawn:

1. The addition of the rejuvenators, commonly dosed based on the weight of the RAP by total weight of the mixture, should be dosed based on the actual asphalt binder replacement by the RAP binder, as well as the general stiffness properties of the RAP itself. The current method of dosage assumes the RAP binder content is identical to the virgin binder, as well as assuming all RAP binder is identical in its stiffness. Although different RAP sources were not utilized in the study, common sense dictates that these RAP properties would highly influence the effectiveness of the rejuvenator used.
2. The typical means of introducing the rejuvenator to the asphalt binder is by preblending the rejuvenator in the virgin binder. This significantly softens the virgin asphalt binder. In the case of one of the rejuvenators, the dosed PG76-22 resulted in a final PG grade of PG58-34. If for some reason production on that construction job was significantly delayed after production had started, the asphalt supplier now has a very soft asphalt binder in its storage tanks – rendering that storage tank useless for any other work except for that high RAP project. A separate introduction and metering system that would allow dosing the asphalt binder on demand would provide the asphalt supplier greater flexibility when using rejuvenators.
3. The research study developed and introduced a new means for evaluating the maximum effectiveness of the rejuvenator on the RAP mixture. The procedure requires the extraction and recovery of the asphalt binder from the mixture with a shear modulus master curve being developed with the recovered binder. Using the shape of the master curve, the Rheological Index (R-value) and Cross-over Frequency can be determined. Work in this study clearly showed the trends with aging when the test data is plotted in R-value – Cross-over Frequency Space. As asphalt binder age, they move from the upper left portion of the space to the lower right area in this space. Although additional research is needed to continue to understand what the magnitude of these changes mean, comparison testing of different materials clearly shows which additives best mitigate and reverse the aging associated with oxidized asphalt binder.
4. The set of New Jersey mixtures were evaluated using the NJDOT High RAP specification that incorporates balancing the fatigue cracking and rutting properties using the Overlay Tester and Asphalt Pavement Analyzer, respectively. The minimum requirements of the High RAP specification were

developed using virgin asphalt mixtures. This means that the NJDOT would accept a high RAP mixture with a rejuvenator as long as it performs as well as a virgin mixture. The results of the testing showed that only a few of the asphalt mixtures would have met the specification when conditioned in the oven for 2 hours at compaction temperature. Meanwhile, it was found that only 1 mixture would have met the minimum requirements if they mixture was conditioned loose for 6 hours at compaction temperature. This indicates that the rejuvenators may volatize and lose their effectiveness if held at elevated temperature in the presence of oxygen for too long of a period.

5. Asphalt binder fatigue performance indicators, Glover-Rowe Parameter and the Cross-over Frequency, were compared to the asphalt mixture fatigue properties using the Overlay Tester for the New Jersey mixtures. The results showed a poor correlation between asphalt binders and asphalt mixtures, lending to the belief that poor blending in the asphalt mixtures had occurred.
6. Based on the mixture and asphalt binder testing conducted on the New Jersey mixes, it would appear that two best rejuvenators used in the study were; 1) De-waxed, Paraffinic Oil from Valero; and 2) Aromatic oil from Valero.
7. A companion mixture and binder study using rejuvenators was also conducted using asphalt mixtures from Massachusetts. Although the New Jersey mixtures utilized two different RAP contents (25% and 45%), the Massachusetts mixtures only used one RAP content, but it was slightly higher than the New Jersey mixtures (50%). The Massachusetts mixtures were evaluated using four different rejuvenators; paraffinic oil, aromatic oil, and 2 organic-based oils. The Massachusetts mixtures also included a long-term aging component, where the New Jersey mixtures included two different short-term aging components. Very similar testing protocols were used to evaluate the Massachusetts mixtures, allowing for a good comparison of performance with a slightly different set of virgin materials.
8. The R-value – Cross-over Frequency Space method, developed with the New Jersey mixtures, was able to show the reversal of aging that was occurring due to the addition of the different rejuvenators. It also indicated that even after long-term aging on the compacted specimens had occurred, the rejuvenators still offered some type of rejuvenating property. In fact, the aromatic oil rejuvenator used in the study was capable of bringing the 50% RAP mixture to a similar aged condition as the virgin asphalt mixture after long-term aging had occurred.
9. The Overlay Tester and Flexural Beam Fatigue tests ranked the fatigue cracking performance differently among the rejuvenator mixtures. This shows that crack propagation tests (Overlay Tester) and crack initiation tests (Flexural Beam Fatigue) capture different mixture and binder properties. Therefore, it is important that the mode of cracking be noted whenever describing the “fatigue resistance” of asphalt mixtures. On average, the paraffinic oil rejuvenator performed the best in the Flexural Beam Fatigue test with the Organic Blend #2 resulting in the second best Flexural Beam Fatigue results. Meanwhile, the Organic Blend #1 resulted in the best results for the Overlay Tester, with the paraffinic oil resulting in the second best results.

10. The asphalt binder fatigue properties best correlated to the Overlay Tester crack propagation testing. This indicates that the larger straining involved with the Overlay Tester more closely mirrors the strain magnitudes associated in the binder tests, as the Flexural Beam Fatigue is most often used at lower strains. Since there existed a moderate correlation between the asphalt binder fatigue performance and the asphalt mixture fatigue performance in the Overlay Tester, it is hypothesized that the degree of blending between the virgin binder, RAP binder, and rejuvenators were better in the Massachusetts mixtures than the New Jersey mixtures.
11. The critical low temperature thermal cracking properties of the asphalt binders were compared with the critical low temperature thermal cracking properties of the asphalt mixtures using the TSRST test. A relatively good agreement was found between the asphalt binder and mixtures, with the average difference between the asphalt binders and mixtures being -2.5°C. On average, the Paraffinic Oil provided the best low temperature thermal cracking properties as measured in the TSRST with the Organic Blend #2 resulting in the second best low temperature cracking results of the rejuvenated mixtures.
12. In evaluating the two different sets of RAP mixtures using asphalt binder and mixture testing protocol, the testing indicates that the Paraffinic Oil rejuvenator provided the best rejuvenating properties.

RECOMMENDATIONS/IMPLEMENTATION PLAN

The research study clearly showed that the use of rejuvenators is a viable means of producing high RAP asphalt mixtures that are capable of performing relatively well in fatigue cracking. However, not all rejuvenators provided the same level of rejuvenation. Also, as shown in the difference between the New Jersey asphalt mixtures and the Massachusetts asphalt mixtures, the asphalt mixture design, amount and quality of the RAP (RAP binder more importantly). Also, the production process at the asphalt plant will also have a significant influence on how well a high RAP asphalt mixture can be produced. Therefore, it would make it very difficult to specify a rejuvenator type or manufacturer.

Therefore, it is recommended that the NJDOT should simply evaluate the respective asphalt plant's high RAP mixture using the current NJDOT HRAP specification. The specification currently allows the use of rejuvenators, however, it does not specify which rejuvenator to use. This is left up to the asphalt plant to decide. However, the HRAP specification does include necessary performance testing on the plant produced high RAP mixture to ensure that the material can meet both rutting and fatigue cracking minimum criteria. By testing the final asphalt mixture, it is taking into account all of the possible variables noted earlier (i.e. – plant production, RAP quality, mixture design, rejuvenator type and dosage, etc.).

With respect to implementation, some of the findings generated during the course of this research study have already been implemented. For example, the NJDOT HRAP specification began during the beginning of the study. Rejuvenators have been evaluated and utilized in the HRAP mix produced by Tilcon, Mt Hope. Also, findings from the study have been utilized and presented at the Northeast Asphalt User Producer Group (NEAUPG), as well as the Association of Asphalt Paving Technologists (AAPT) regarding the use of rejuvenators and addressing their effectiveness. Therefore, findings from this study have already been implemented and disseminated to other agencies and the asphalt industry.

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APPENDIX A – NJDOT HRAP SPECIFICATION

SECTION 401 – HOT MIX ASPHALT (HMA) COURSES

ADD THE FOLLOWING TO 401.01:

401.01 DESCRIPTION

This Section also describes the requirements for constructing a Hot Mix Asphalt (HMA) course with required minimum amounts of Reclaimed Asphalt Pavement (RAP).

ADD THE FOLLOWING TO 401.02.01:

401.02.01 Materials

Hot Mix Asphalt HIGH RAP 902.11

ADD THE FOLLOWING SUBSECTION TO 401.03:

401.03.07 Hot Mix Asphalt (HMA) HIGH RAP

A. Paving Plan. At least 20 days before beginning placing the HMA HIGH RAP, submit a detailed plan of operation as specified in 401.03.03.A to the RE for approval. Include in the paving plan a proposed location for the test strip. Submit for Department approval a plan of the location for the HMA HIGH RAP on the project.

B. Weather Limitations. Place HMA HIGH RAP according to the weather limitations in 401.03.03.B.

C. Test Strip. Construct a test strip as specified in 401.03.03.C.

D. Transportation and Delivery of HMA. Deliver HMA HIGH RAP as specified in 401.03.03.D.

E. Spreading and Grading. Spread and grade HMA HIGH RAP as specified in 401.03.03.E. Record the laydown temperature (temperature immediately behind the paver) at least once per hour during paving. Submit the temperatures to the RE and to the HMA Plant producing the HMA HIGH RAP.

F. Compacting. Compact HMA HIGH RAP as specified in 401.03.03.F.

G. Opening to Traffic. Follow the requirements of 401.03.03.G for opening HMA HIGH RAP to traffic.

H. Air Void Requirements. Ensure that the HMA HIGH RAP is compacted to meet the air void requirements as specified in 401.03.03.H.

I. Thickness Requirements. Ensure that the HMA HIGH RAP is paved to meet the thickness requirements as specified in 401.03.03.I.

J. Ride Quality Requirements. Ensure that the HMA HIGH RAP is paved to meet the ride quality requirements as specified in 401.03.03.J

ADD THE FOLLOWING TO 401.04:

401.04 MEASUREMENT AND PAYMENT

The Department will measure and make payment for Items as follows:

Item	*Pay Unit*
HOT MIX ASPHALT ___ ___ ___ SURFACE COURSE HIGH RAP	TON
HOT MIX ASPHALT ___ ___ ___ INTERMEDIATE COURSE HIGH RAP	TON
HOT MIX ASPHALT ___ ___ ___ BASE COURSE HIGH RAP	TON

ADD THE FOLLOWING TO 902:

902.11 HOT MIX ASPHALT RAP

902.11.01 Mix Designations

The requirements for specific HMA mixtures with required minimum amounts of RAP are identified by the abbreviated fields in the Item description as defined as follows:

HOT MIX ASPHALT 12.5H64 SURFACE COURSE HIGH RAP

1. "HOT MIX ASPHALT" "Hot Mix Asphalt" is located in the first field in the Item description for the purpose of identifying the mixture requirements.
2. "12.5" The second field in the Item description designates the nominal maximum size aggregate (in millimeters) for the job mix formula (sizes are 4.75, 9.5, 12.5, 19, 25, and 37.5 mm).
3. "H" The third field in the Item description designates the design compaction level for the job mix formula based on traffic forecasts as listed in Table 902.02.03-2 (levels are L=low, M=medium, and H=high).
4. "64" The fourth field in the Item description normally designates the high temperature (in °C) of the performance-graded binder (options are 64, 70, and 76 °C). In the High RAP mixes this field will designate the mix performance requirements.
5. "SURFACE COURSE" The last field in the Item description designates the intended use and location within the pavement structure (options are surface, intermediate, or base course).
6. "HIGH RAP" This additional field designates that there will be a minimum percentage of RAP required for the mixture in 902.011.02.

902.11.02 Composition of Mixture

Provide materials as specified:

Aggregates for Hot Mix Asphalt.. 901.05

Use a virgin asphalt binder that will result in a mix that meets the performance requirements specified in Table 902.11.03-2. Ensure that the virgin asphalt binder meets the requirements of 902.01.01 except the performance grade. Use a performance grade of asphalt binder as determined by the mix design and mix performance testing.

Mix HMA HIGH RAP in a plant that is listed on the QPL for HMA Plants and conforms to the requirements for HMA Plants as specified in 1009.01.

Composition of the mixture for HMA HIGH RAP surface course is coarse aggregate, fine aggregate, asphalt binder, and a minimum of 20 percent Reclaimed Asphalt Pavement (RAP), and may also include mineral filler, asphalt rejuvenator and Warm Mix Asphalt (WMA) additives or processes as specified in 902.01.05. When WMA is used it must meet the requirements as specified in 902.10. Ensure that the finished mix does not contain more than a total of 1 percent by weight contamination from Crushed Recycled Container Glass (CRCG).

The composition of the mixture for HMA HIGH RAP base or intermediate course is coarse aggregate, fine aggregate, asphalt binder, and a minimum of 30 percent Reclaimed Asphalt Pavement (RAP), and may also include mineral filler, up to 10 percent of additional recycled materials, asphalt rejuvenator, and Warm Mix Asphalt (WMA) additives or processes as specified in 902.01.05. When WMA is used it must meet the requirements as specified in 902.10. The recycled materials may consist of a combination of RAP, CRCG, Ground Bituminous Shingle Material (GBSM), and RPCSA, with the following individual limits:

Table 902.11.02-1 Use of Recycled Materials in Base or Intermediate Course

Recycled Material	Minimum Percentage	Maximum Percentage
RAP	30	
CRCG		10
GBSM		5

Combine the aggregates to ensure that the resulting mixture meets the grading requirements specified in Table 902.02.03-1. In determining the percentage of aggregates of the various sizes necessary to meet gradation requirements, exclude the asphalt binder.

Ensure that the combined coarse aggregate, when tested according to ASTM D 4791, has less than 10 percent flat and elongated pieces retained on the No. 4 sieve and larger. Measure aggregate using the ratio of 5:1, comparing the length (longest dimension) to the thickness (smallest dimension) of the aggregate particles.

Ensure that the combined fine aggregate in the mixture conforms to the requirements specified in Table 902.02.02-2. Ensure that the material passing the No. 40 sieve is non-plastic when tested according to AASHTO T 90.

902.11.03 Mix Design

At least 45 days before initial production, submit a job mix formula for the HMA HIGH RAP on forms supplied by the Department, to include a statement naming the source of each component and a report showing that the results meet the criteria specified in Tables 902.02.03-1 and 902.11.03-1.

Include in the mix design the following based on the weight of the total mixture:

1. Percentage of RAP or GBSM.
2. Percentage of asphalt binder in the RAP or GBSM.
3. Percentage of new asphalt binder.
4. Total percentage of asphalt binder.
5. Percentage of each type of virgin aggregate.

Table 902.11.03-1 HMA HIGH RAP Requirements for Design

Compaction Levels	Required Density (% of Theoretical Max. Specific Gravity)		Voids in Mineral Aggregate (VMA)[2], % (minimum) Nominal Max. Aggregate Size, mm					Voids Filled With Asphalt (VFA) %	Dust-to-Binder Ratio
	@N_{des}[1]	@N_{max}	25.0	19.0	12.5	9.5	4.75		
L	96.0	≤ 98.0	13.0	14.0	15.0	16.0	17.0	70 - 85	0.6 - 1.2
M	96.0	≤ 98.0	13.0	14.0	15.0	16.0	17.0	65 - 85	0.6 - 1.2

1. As determined from the values for the maximum specific gravity of the mix and the bulk specific gravity of the compacted mixture. Maximum specific gravity of the mix is determined according to AASHTO T 209. Bulk specific gravity of the compacted mixture is determined according to AASHTO T 166. For verification, specimens must be between 95.0 and 97.0 percent of maximum specific gravity at N_{des}.
2. For calculation of VMA, use bulk specific gravity of the combined aggregate including aggregate extracted from the RAP.

The job mix formula for the HMA HIGH RAP mixture establishes the percentage of dry weight of aggregate, including the aggregate from the RAP, passing each required sieve size and an optimum percentage of asphalt binder based upon the weight of the total mix. Determine the optimum percentage of asphalt binder according to AASHTO R 35 and M 323 with an N_{des} as required in Table 902.02.03-2. Before maximum specific gravity testing or compaction of specimens, condition the mix for 2 hours according to the requirements for conditioning for volumetric mix design in AASHTO R 30, Section 7.1. If the absorption of the combined aggregate is more than 1.5 percent according to AASHTO T 84 and T 85, ensure that the mix is short term conditioned for 4 hours according to AASHTO R 30, Section 7.2 prior to compaction of specimens (AASHTO T 312) and determination of maximum specific gravity (AASHTO T 209). Ensure that the job mix formula is within the master range specified in Table 902.02.03-1.

Ensure that the job mix formula provides a mixture that meets a minimum tensile strength ratio (TSR) of 80% when prepared according to AASHTO T 312 and tested according to AASHTO T 283. Submit the TSR results with the mix design.

Determine the correction factor of the mix including the RAP by using extracted aggregate from the RAP in the proposed proportions when testing is done to determine the correction factor as specified in AASHTO T 308. Use extracted aggregate from the RAP in determining the bulk specific gravity of the aggregate blend for the mix design.

For each mix design, submit with the mix design forms 3 gyratory specimens and 1 loose sample corresponding to the composition of the JMF. Ensure that the samples include the percentage of RAP that is being proposed for the mix. The ME will use these to verify the properties of the JMF. Compact the specimens to the design number of gyrations (N_{des}). For the mix design to be acceptable, all gyratory specimens must comply with the requirements specified in Tables 902.02.03-1 and 902.11.03-1. The ME reserves the right to be present at the time the gyratory specimens are molded.

In addition, submit nine gyratory specimens and five 5-gallon buckets of loose mix to the ME. The ME will use these additional samples for performance testing of the HMA HIGH RAP mix. The ME reserves the right to be present at the time of molding the gyratory specimens. Ensure that the additional gyratory specimens are compacted according to AASHTO T 312, are 77 mm high, and have an air void content of 6.5 ± 0.5 percent. The ME will test six (6) specimens using an Asphalt Pavement Analyzer (APA) according to AASHTO T 340 at 64°C, 100 psi hose pressure, and 100 lb. wheel load. The ME will use the remaining three (3) specimens to test using an Overlay Tester (NJDOT B-10) at 25°C and a joint opening of 0.025 inch.

The ME will approve the JMF if the results meet the criteria in Table 902.11.03-2.

Table 902.11.03-2 Performance Testing Requirements for HMA HIGH RAP Design

Test	Requirement			
	Surface Course		Intermediate Course	
	PG 64-22	PG 76-22	PG 64-22	PG 76-22
APA @ 8,000 loading cycles (AASHTO T 340)	< 7 mm	< 4 mm	< 7 mm	< 4 mm
Overlay Tester (NJDOT B-10)	> 150 cycles	> 175 cycles	> 100 cycles	> 125 cycles

If the JMF does not meet the APA and Overlay Tester criteria, redesign the HMA HIGH RAP mix and submit for retesting. The JMF for the HMA HIGH RAP mixture is in effect until modification is approved by the ME.

When unsatisfactory results for any specified characteristic of the work make it necessary, the Contractor may establish a new JMF for approval. In such instances, if corrective action is not taken, the ME may require an appropriate adjustment to the JMF.

Should a change in sources be made or any changes in the properties of materials occur, the ME will require that a new JMF be established and approved before production can continue.

902.11.04 Sampling and Testing

A. General Acceptance Requirements. The RE or ME may reject and require disposal of any batch or shipment that is rendered unfit for its intended use due to contamination, segregation, improper temperature, lumps of cold material, or incomplete coating of the aggregate. For other than improper temperature, visual inspection of the material by the RE or ME is considered sufficient grounds for such rejection.

Ensure that the temperature of the mix at discharge from the plant or storage silo meets the recommendation of the supplier of the asphalt binder, supplier of the asphalt modifier and WMA manufacturer. For HMA, do not allow the mixture temperature to exceed 330°F at discharge from the plant. For WMA, do not allow the mixture temperature to exceed 300°F at discharge from the plant.

Combine and mix the aggregates and asphalt binder to ensure that at least 95 percent of the coarse aggregate particles are entirely coated with asphalt binder as determined according to AASHTO T 195. If the ME determines that there is an on-going problem with coating, the ME may obtain random samples from 5 trucks and will determine the adequacy of the mixing on the average of particle counts made on these 5 test portions. If the requirement for 95 percent coating is not met on each sample, modify plant operations, as necessary, to obtain the required degree of coating.

B. Sampling. The ME will take 5 stratified random samples of HMA HIGH RAP for volumetric acceptance testing from each lot of approximately 3500 tons of a mix. When a lot of HMA HIGH RAP is less than 3500 tons, the ME will take samples at random for each mix at the rate of one sample for each 700 tons. The ME will perform sampling according to AASHTO T 168, NJDOT B-2, or ASTM D 3665.

Use a portion of the samples taken for volumetric acceptance testing for composition testing.

C. Quality Control Testing. The HMA HIGH RAP producer shall provide a quality control (QC) technician who is certified by the Society of Asphalt Technologists of New Jersey as an Asphalt Technologist, Level 2. The QC technician may substitute equivalent technician certification by the Mid-Atlantic Region Technician Certification Program (MARTCP). Ensure that the QC technician is present during periods of mix production for the sole purpose of quality control testing and to assist the ME. The ME will not perform the quality control testing or other routine test functions in the absence of, or instead of, the QC technician.

The QC technician shall perform sampling and testing according to the approved quality control plan, to keep the mix within the limits specified for the mix being produced. The QC technician may use acceptance test results or perform additional testing as necessary to control the mix.

To determine the composition, perform ignition oven testing according to AASHTO T 308.

For each acceptance test, perform maximum specific gravity testing according to AASHTO T 209 on a test portion of the sample taken by the ME. Sample and test coarse aggregate, fine aggregate, mineral filler, and RAP according to the approved quality control plan for the plant.

Ensure that the supplier has in operation an ongoing daily quality control program to evaluate the RAP. As a minimum, this program shall consist of the following:

1. An evaluation performed to ensure that the material conforms to 901.05.04 and compares favorably with the design submittal.
2. An evaluation of the RAP material performed using a solvent or an ignition oven to qualitatively evaluate the aggregate components to determine conformance to 901.05.
3. Quality control reports as directed by the ME.

D. Acceptance Testing and Requirements. The ME will determine volumetric properties at N_{des} for acceptance from samples taken, compacted, and tested at the HMA plant. The ME will compact HMA HIGH RAP to the number of design gyrations (N_{des}) specified in Table 902.02.03-2, using equipment according to AASHTO T 312. The ME will determine bulk specific gravity of the compacted sample according to AASHTO T 166. The ME will use the most current QC maximum specific gravity test result in calculating the volumetric properties of the HMA HIGH RAP.

The ME will determine the dust-to-binder ratio from the composition results as tested by the QC technician.

Ensure that the HMA HIGH RAP mixture conforms to the requirements specified in Table 902.11.04-1, and to the gradation requirements in Table 902.02.03-1. If 2 samples in a lot fail to conform to the gradation or volumetric requirements, immediately initiate corrective action.

The ME will test a minimum of 1 sample per lot for moisture, basing moisture determinations on the weight loss of an approximately 1600-gram sample of mixture heated for 1 hour in an oven at 280 ± 5°F. Ensure that the moisture content of the mixture at discharge from the plant does not exceed 1.0 percent.

Table 902.11.04-1 HMA HIGH RAP Requirements for Control

Compaction Levels	Required Density (% of Theoretical Max. Specific Gravity)	Voids in Mineral Aggregate (VMA), % (minimum)					Dust-to-Binder Ratio
		Nominal Max. Aggregate Size, mm					
	@Ndes[1]	25.0	19.0	12.5	9.5	4.75	
L, M	95.0 – 98.5	13.0	14.0	15.0	16.0	17.0	0.6 - 1.3

1. As determined from the values for the maximum specific gravity of the mix and the bulk specific gravity of the compacted mixture. Maximum specific gravity of the mix is determined according to AASHTO T 209. Bulk specific gravity of the compacted mixture is determined according to AASHTO T 166.

E. Performance Testing for HMA HIGH RAP. Provide five (5) 5-gallon buckets of loose mix to the ME for testing in the Asphalt Pavement Analyzer (APA) and the Overlay Tester device. Ensure that the first sample is taken during the construction of the test strip as specified in 401.03.07.C. Thereafter, sample every lot or as directed by the ME. If a sample does not meet the design criteria for performance testing as specified in Table 902.11.03-2, the Department will assess a pay adjustment as specified in Table 902.11.04-2. If a lot fails to meet requirements for both APA and Overlay Tester, the Department will assess pay adjustments for both parameters. The Department will calculate the pay adjustment by multiplying the percent pay adjustment (PPA) by the quantity in the lot and the bid price for the HMA High RAP item.

Table 902.11.04-2 Performance Testing Pay Adjustments for HMA HIGH RAP

	Surface Course		**Intermediate Course**		**PPA**
	PG 64-22	**PG 76-22**	**PG 64-22**	**PG 76-22**	
APA @ 8,000 loading cycles, mm (AASHTO T 340)	t ≤ 7 7 > t > 10 t ≥ 10	t ≤ 4 4 > t > 7 t ≥ 7	t ≤ 7 7 > t > 10 t ≥ 10	t ≤ 4 4 > t > 7 t ≥ 7	0 – 1 – 5
Overlay Tester, cycles (NJDOT B-10)	t ≥ 150 150 > t > 100 t ≤ 100	t ≥ 175 175 > t > 125 t ≤ 125	t ≥ 100 100 > t > 75 t ≤ 75	t ≥ 125 125 > t > 90 t ≤ 90	0 – 1 – 5