Rejuvenation of Reclaimed Asphalt Pavement (RAP) in Hot Mix Asphalt Recycling with High RAP Content

by

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Abstract

This study aims to understand intermingling process between rejuvenators and aged asphalt binders in reclaimed asphalt pavement (RAP) materials during RAP recycling operations in pavement construction. This study presents results of a laboratory study on the use of rejuvenators to recycle age hardened asphalt binders in RAP. Laboratory Hot Mix Asphalt (HMA) samples were prepared with RAP millings from one specific pavement and a commercial rejuvenator, with 80 to 90 percent RAP content. The following mixes with various amount of the rejuvenator were evaluated: a control mix prepared from burned RAP aggregate and virgin asphalt binder, another control mix prepared with heated RAP, a recycled RAP mix with 1% rejuvenator (at the weight of the total mix), a recycled RAP mix with 0.5% rejuvenator, and a recycled RAP mix with 0.5% rejuvenator and 0.5% virgin asphalt binder. Dynamic modulus test results of laboratory prepared samples were obtained for a range of temperatures over an eleven-week period of accelerated aging at 60ºC in an inert gas oven and a conventional convection oven. Accelerated aging protocol was used to evaluate the intermingling process associated with diffusion mechanism between the rejuvenator and aged asphalt binder while an argon inert gas oven provides an environment where oxidation-related ageing and hardening in rejuvenated asphalt binders can be eliminated. The dynamic modulus data of six distinct mixes were statistically analyzed and compared to the results reported in the literature for virgin and low percentage recycled mixes. Collected data suggest that the use of rejuvenator is a viable option for recycling HMA with high RAP material content.

1 Introduction

An increased use of reclaimed asphalt pavement (RAP) material can have a significant positive impact on the economics and environmental sustainability of pavement construction. Unfortunately current RAP recycling practices don't support the evolution of high RAP mixes. The FHWA reports that national RAP utilization remains an abysmal 13% in the US [1] with many agencies limiting RAP content in all pavement layers. With the specter of long term deficits restricting public spending what can be done to facilitate recycling more RAP? Is it possible to recycle 80 to 100% of the mix binder using existing hot mix asphalt (HMA) plants?

Following the 1974 Oil Embargo FHWA sponsored pilot RAP projects across the nation that by coincidence were a minimum70% recycled content [2]. These mixes were evaluated with the pre-SHRP analytical tools available at the time that indicated the RAP mixes were consistently superior to the original source pavements. [3]. RAP use exploded following FHWA's demonstration projects with many states accepting 50% recycled content in base layers. That is until the Superpave mix design method replaced the Marshall mix design method.

In the post-SHRP/Superpave era, material managers need to know the blended binder grade prior to accepting vendor mixes. At first, standard procedure had been to limit RAP content such that it had minimal impact on the blended binder properties. Ultimately laboratory investigations were conducted to determine how the Performance Grade of the liquid asphalt added to a mix should be adjusted to accommodate higher RAP percentages. These investigations have been carried out on the basis of blended binder properties - viscosity, $G^*/\sin(\delta)$, and later on the basis of mix properties such as dynamic modulus.

The guidance provided by these studies was sufficient for most of the past decade. While the recommendations vary in their specific steps, in essence they are as follows: no change in binder grade for mixes with 15-20% RAP, one grade lower up to 40%, and two grades lower above that, and so on [4]. These recommendations have provided a rational method that supports recycled contents approaching 40% but have done little to prepare for higher rates of recycle needed in today's market.

Perhaps of greater significance, this method of correcting recycled binder hardness with softer grades of liquid asphalt is not producer friendly and discourages widespread adoption by industry. The amount of RAP that can be utilized depends on the availability of the specific binder grade that produces the desired blended grade at that RAP percentage. Obviously, to produce mixes with different percentages of RAP, one needs several different PG grades of binder. This practice has effectively limited the use of RAP to minimum levels, or worse caused producers to use the wrong binder grade on a routine basis. From a practical point of view, it is not possible for producers to maintain a large number of binders of different grades to produce mix with different percentages of RAP.

In the post SHRP-Superpave era, the large majority of funded research has been in support of low RAP percentages, less than 40%. Too many of those studies were distracted by the age old black rock debate and attempted to determine the short term interactions of the aged binder with the new liquid asphalt. Few researchers recognized that when testing RAP mixes, results will change over time due to the slow paced mixing of the two binders [5]. The properties obtained at any point during a typical laboratory study are at best a snapshot of an ongoing mixing process. Consequently a recycled mix can exhibit much softer properties initially than would be predicted by extraction and recovery testing. While dynamic blending is of little concern at low RAP contents, higher RAP contents with binder grade bumped more than one step could be susceptible to rutting failures until the old and new binders blend sufficiently.

1.1 Need for a different approach

Use of softer PG binders has not been widely adopted by either refineries or producers even at low RAP contents. In order for industry to be successful when recycling at increasingly higher RAP contents a new approach is needed to correct for age hardened RAP binders. That approach should accommodate a wide range of RAP contents using one material and require little change from existing practice. Following is a discussion of an old pre-SHRP recycling strategy that at one time was widely accepted but still holds promise for wider use in the future.

Strategy: Use industrial process oils, rejuvenators, to soften age hardened RAP binders. Liquid asphalt remains the PG 64-22 or equivalent binder used for a virgin mix.

Rejuvenators are actually used by some refineries to create the softer binder grades called for by current practice. When used at the plant, a rejuvenator delivers the same softening as different PG binders but with far fewer products and storage tanks. Multiple tanks containing different PG binders can be replaced by a single tank and a single rejuvenator.

This approach is suitable for all levels of recycling right up to 100% recycled content. Rejuvenators have the ability to match exactly the recycled binder content while only requiring producers to store one new product in an unheated storage tank. Most existing drum plants are already capable of recycling 80% of mix binder requirements with a combination of fractionated RAP and recycled asphalt shingles. Industry is ready for a new way to increase recycled content. The current practice of binder grade bumping isn’t adequate as producers start pushing the envelope with recycled contents greater than 40%.

1.2 Objective

The objective of this project was to investigate the rejuvenation process between industrial process oil rejuvenators and age hardened asphalt binder within RAP material. This study reports on the time dependent effects of the rejuvenation process on laboratory samples.

2 Literature Review

A literature review was conducted to establish the level of applicable theory development, laboratory experiments, and field investigations that is available on the effects of recycling on the stiffness of asphalt pavement. This literature review is presented in two parts. Part 1 presents the effects of hot-mix recycling on the stiffness of a mix. Part 2 discusses the significance of asphalt rejuvenation on this vital issue within recycling asphalt pavement materials.

2.1 Asphalt Pavement Recycling: Effects on Stiffness

2.1.1 Age Hardened Asphalt

When reclaimed asphalt pavement (RAP) is included in a mix design there is an automatic concern regarding the inherent asphalt binder that the mix receives from the RAP. The asphalt has been significantly aged through its initial production (short-term) and then through-out its life (long-term) as a pavement structure. The asphalt is referred to as age hardened asphalt due to its deteriorated rheological properties from extensive oxidation. There are two things that need to be addressed by designers when including RAP in a mix design, first of which is to make a decision regarding the availability of binder in RAP material and second of which being the issue of stiffness.

The first issue, binder availability, tends to be addressed through one of three accepted concepts. The three concepts are 1. *black rock* (all aged hardened asphalt acts as aggregate); 2. *fully blendable* (all age hardened asphalt becomes fluid and totally blends with virgin asphalt binder); 3. *partially reusable* (some age hardened asphalt is reusable in the new mixture with the extent being dependent on several factors including aged binder properties, temperature, aging time, and additives) [6]. There is no well accepted concept, which ultimately leads to inconsistent mix design developments and only increases variability when analyzing mixes. For the purpose of ease the fully blendable approach is considered due to the difficulty in predicting the percentage of partially reusable binder.

The second issue to be addressed, more commonly considered by pavement engineers, is the stiffness of the age hardened asphalt in the RAP. The aged hardened asphalt experiences a loss in ductility as it hardens, resulting in cracking and raveling of a pavement structure containing high RAP contents where stiffness of the mix was not properly addressed [7]. Particularly when the Superpave method was adopted, RAP usage became very conservative due to the difficult and limiting procedures associated with the incorporation of RAP in a Superpave mix design.

To fully understand the effects of the two issues on the overall performance of a mix the process of aging and blending must be explored. Chemically, asphalt contains three distinct components, asphaltenes, resins, and oils [8]. Asphaltenes are insoluble and maltenes (the resin and oils) are soluble in n-pentane (n-heptane). The maltene component can be further classified as saturates, naphthene-aromatics, polar-aromatics-1, and polar-aromatics-2. During oxidation, the maltene fraction is affected and causes the hardening of the binder. When the asphalt oxidizes the maltene fraction dissipates and causes the ratio of asphaltene to maltene ratio to alter and effect the stiffness properties of the asphalt.

The Superpave method effectively limits RAP content in HMA to 40%. The adoption of the Superpave method discredited many of the advances of the pre-SHRP generation in RAP practices developed through the 1970's. It is recommended that no more than 15 to 30% RAP content should be included in a mix design without additional specialized testing. Common practice includes the use of binder bumping and blending charts to achieve desired binder properties.

However, it has been shown that high RAP content mixes, all the way to 100% RAP content, are achievable. In 2009, a study conducted at WPI in conjunction with RAP Technologies in Linwood, NJ concluded that 100% recycled mixes with good performance can be produced with existing quality control procedures in a suitable plant [24]. The study employed dynamic modulus and creep compliance testing and compared the results of the high-RAP content mixes to published parameters of virgin or low-RAP content mixes to validate the performance.

2.1.2 Performance

The most obvious benefit to using RAP is economical but there is also a benefit in terms of performance, the binder in RAP has already been aged and further aging during production and its second life is less extensive [9]. This resistance to further aging in mixes containing RAP leads to a decrease increased stiffness over the life of the structure, extending the expected service life. It has also been reported that up-to 20% RAP content the performance of the mix is not affected, but from 20-40% RAP content it is indicated that modification to the mix needs to occur for an acceptable mix to be developed [10]. These findings support the SHRP requirements for additional testing beyond 15 or 20% RAP content.

There is an obvious trend of available work supporting the inclusion of RAP in mix designs - data is readily available for mixes containing up to the Superpave accepted 40% RAP content. Due to the constraints of current dictating specifications there hasn't been a significant push for more extensive development of high RAP content mix designs. Although, there is increasingly more awareness for the need in the asphalt community, primarily due to the current economic conditions in the United States.

Current methods employed to include high RAP contents are not representative of the actual mix that will be achieved, which discourages mix designers from working with high RAP contents. Extraction is used to determine the effects of the age hardened binder on the total binder properties; however extraction is not fully representative of the literal binder properties. The blending of the extracted and virgin binders is too controlled to associate to realistic mix properties, particularly if the black rock or partial availability notion is considered.

2.2 Asphalt Rejuvenation: Possible Solution to Stiffness?

Asphalt rejuvenation is the process by which age hardened asphalt's rheological properties are restored to a point that the binder can be considered comparable to a virgin material. The restoration of rheological properties is facilitated by the use of recycling agents. A recycling agent is defined as "hydrocarbon products with physical characteristics selected to restore aged asphalt to the requirements of current asphalt specifications" [11]. Recycling agents are also referred to a softening agents, "soft" asphalt, recycling oil, and aromatic oil [12]. In order to be classified as a recycling agent, in addition to having the chemical composition required to restore the necessary components of the aged binder, a material must have a high flash point, be easy to disperse, have a low volatile loss during hot mixing, resist hardening, and be uniform from batch to batch [7].

Examples of recycling agents are industrial process oil, "softer" PG binders, asphalt flux oil, lube stock, and slurry oil [13]. The industrial process oils (lubricating and extender oils) are commonly used due to the high proportion of maltene constituents [14]. The high maltene content restores the rheological properties of the oxidized RAP binder. Industrial process oils can be used applied to achieve the appropriate binder grade by varying the content. SHRP specifications can be satisfied through blending charts, justifying the removal of the unnecessary stocking of multiple PG binders to satisfy different mix designs [15].

With the recent increase in recycling interest in the United States has come the development of new products to the market of asphalt rejuvenators. Particularly, products like Hydrogreen, by Asphalt & Wax Innovations, LLC, aim to offer maltenes without an aromatic content in order to eliminate environmental concerns associated with using oil based products [16]. It is important that with the introduction of new products the compatibility of the rejuvenator and the aged binder remain high in order to ensure diffusion and restoration.

2.2.1 Evaluation of Diffusion and Performance Indicators

The diffusion process between age hardened RAP binder and rejuvenator and virgin binders has been evaluated through binder interaction extensively. The rejuvenation process can be evaluated through extraction of the binder from a mix. Binder tests such as DSR and BBR can give indications of acceptable binder properties of a rejuvenated RAP material [17]. The diffusion process occurring in a mix has been theorized as occurring gradually through the layers of aged binder on the exterior of aggregates [13]. This suggests that the relationship between extracted binder diffusion and diffusion in a mix is not exchangeable and mixes should be evaluated to gain a better understanding of the diffusion process.

In order to best evaluate the diffusion process and ultimately the restoration of the rheological properties of RAP binder, mixes should be evaluated rather than binders. The use of dynamic modulus testing to evaluate the diffusion process can give indication to the performance of the mix. It has been suggested that dynamic modulus is a good performance indicator to achieve a general indication of the mix performance, allowing the potential of rutting and fatigue cracking to be addressed in a single test [18].

Conventionally dynamic modulus testing is determined at a range of temperatures and frequencies. Current specifications call for testing between 14ºF (-10ºC) to 130ºF (54.4ºC), however a recent study conducted at Rutgers University in New Jersey concluded that the lower and upper extremes of the test temperatures should be removed. It was found that the extremes produced the most significant variability and least adequate representation of the mixes performance [22]. The report recommended that room temperature, 70ºC (20ºC), could best correlate to fatigue cracking potential of a mix and a more moderate temperature, 113ºF (45ºC), could best indicate rutting potential.

3 Methodology

The goal of this research was to evaluate the influence of long-term diffusion process on the properties of high Recycled Asphalt Pavement (RAP) material content HMA mixes that were with recycled with a rejuvenator. To achieve this, the dynamic modulus of several mixes was determined periodically during a moderate temperature oven aging protocol. The research methodology is presented in Figure 1.

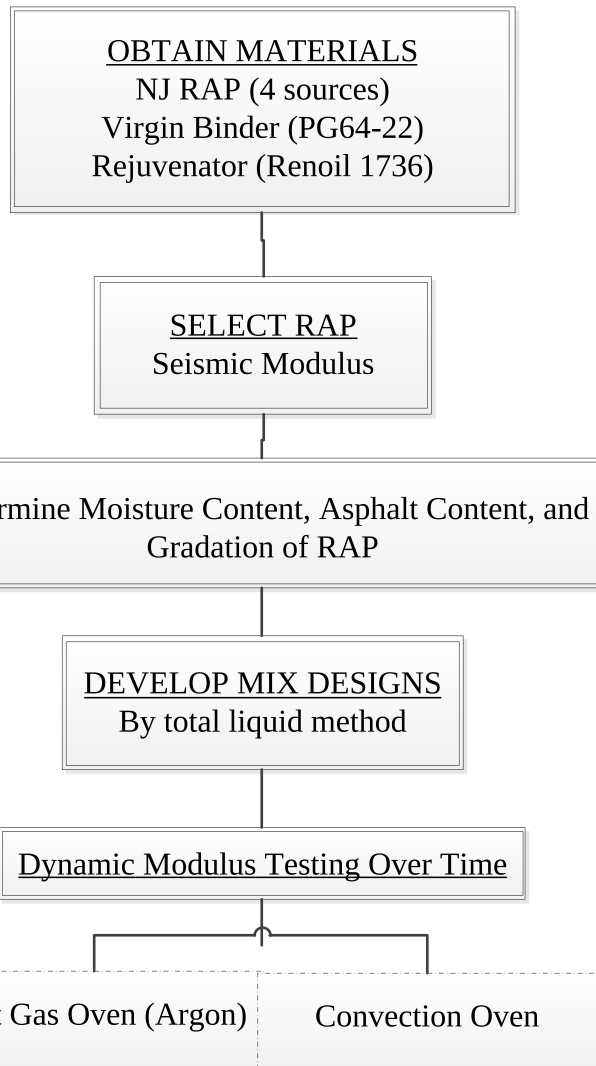

Figure 1. Methodology Flow Chart

3.1 Material Selection

Initially small quantities of RAP from nine stockpiles were acquired. Of the nine stockpiles where the RAP was pulled from, four were to known as large and well maintained stockpiles. This means that if additional RAP were to be pulled from these piles the material would be most similar to the originally acquired material. To select one RAP source, seismic modulus testing was carried out. The aim was to obtain the RAP that had the most extensively aged asphalt binder; this would allow the rejuvenator to rehabilitate the RAP more extensively making the diffusion process more apparent. The seismic modulus testing was selected for initial characterization due to its need for only small quantities of material and its speed and ease of use.

To carry out the seismic testing, three samples of each type of RAP were compacted from the RAP as it was received. Initially the theoretical maximum specific gravity (TMD) was determined and the RAP was compacted by means of a gyratory compactor to achieve a 6" diameter sample with a height of 2.75" and voids in total mix (VTM) of 7±1%. Figure 2 shows the volumetric properties of the twelve samples tested.

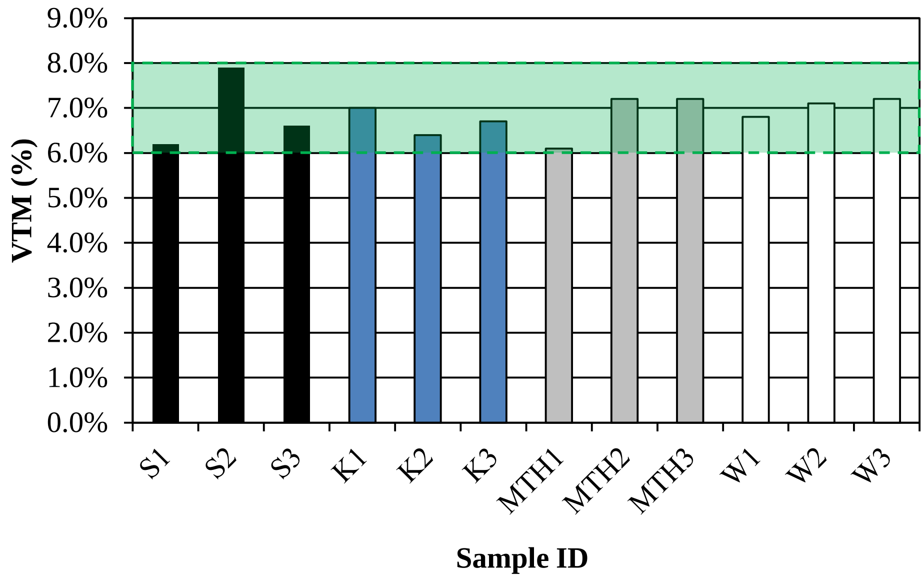

Figure 2. Seismic Modulus Test Sample Volumetric Results

In order to get the most extreme results, allowing the difference in moduli to be more identifiable, the samples were conditioned to -10°C overnight before testing. The seismic testing was carried out using an Ultrasonic Pulse Velocity Device (V-meter) and the modulus was reduced by means of an excel workbook developed by the Center of Transportation Infrastructure Systems (CTIS) [19]. The reduction sheet can be found in the Appendix, and the results are summarized in Figure 3. The seismic modulus results would give indication to which stockpile had the stiffest material, or the material with "hardest" aged asphalt binder.

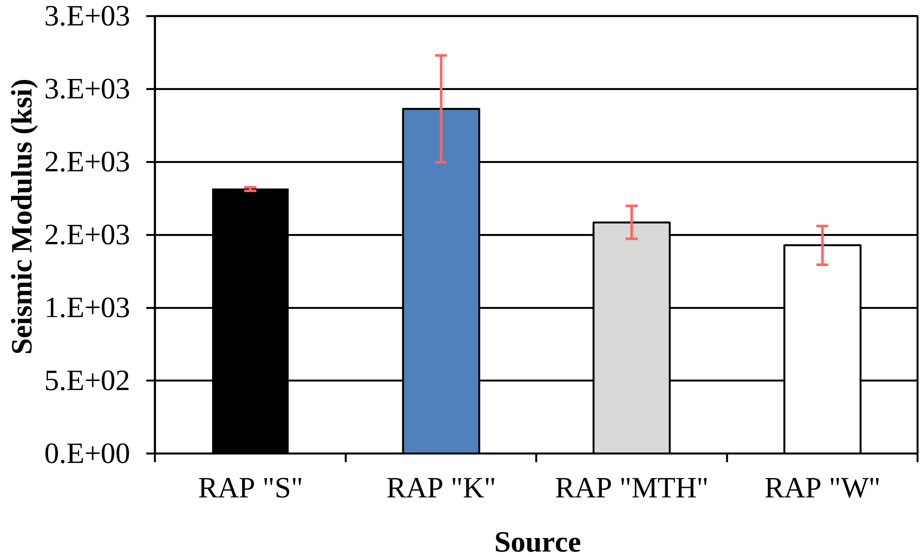

Figure 3. Seismic Modulus Results by RAP Source

Based on the results of the ultrasonic testing, and the fact that it has the highest stiffness, the RAP from Keasbey (K), NJ was selected and the necessary quantity of material for the study was obtained from the Keasbey, NJ stockpile. Once the source was selected the RAP was fully characterized - the moisture content, asphalt content, and gradation were determined. The moisture content was determined and the asphalt content was determined by ignition oven method in accordance with *ASTM D 6307 – 98: Standard Test Method for Asphalt Content of Hot-Mix Asphalt by Ignition Method*. The washed gradation of the RAP was determined using the burnt aggregates from the asphalt content determination in accordance with *AASHTO T 27-93: Sieve Analysis of Fine and Coarse Aggregate*. The results of the characterization are presented in Figure 4 and 4.

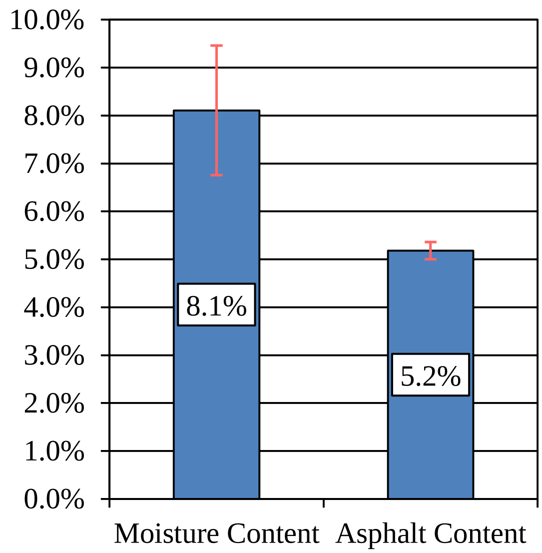

Figure 4. Keasbey, NJ RAP Characterization

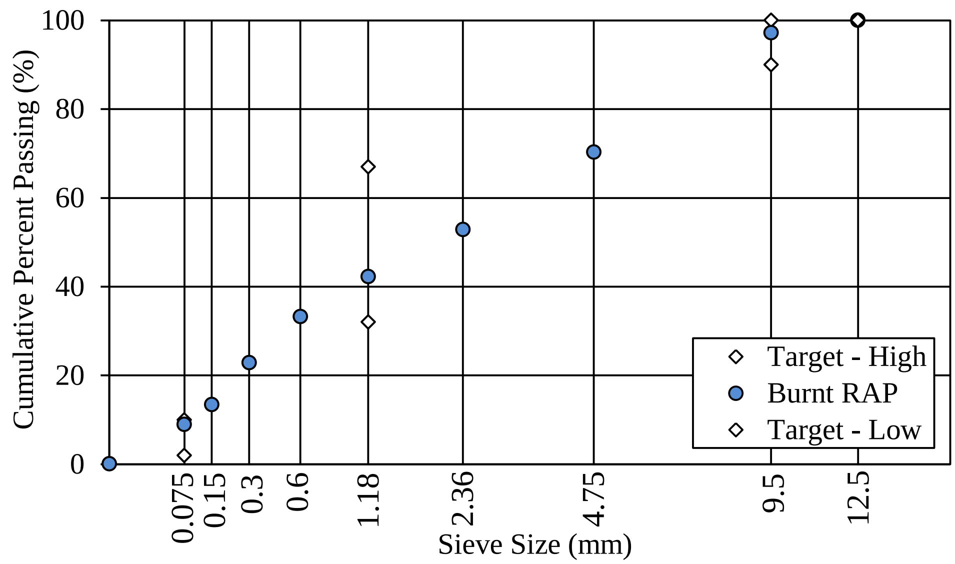

Figure 5. Natural Gradation of RAP, Burnt Aggregates from Ignition Method

In summary, the asphalt content of the RAP was 5.2% and the natural gradation was within the limits of a NJ 9.5 mm NMAS (nominal maximum aggregate size) mix. Once the RAP was characterized, the rejuvenator needed to be selected. Industrial process oil was selected as the type of rejuvenator to be used. To select a particular product the aromatic content was considered. A middle ground material was selected to offer the most conclusive diffusion insight. The material selected for this study was Renoil 1736, comprised of 65.3% Alkyl Aromatic Oil and 27.7% Saturate Oil [20].

3.2 Mix Design

Superpave mix design methods were considered when developing the mix designs for this study. Additionally a constant total liquid content was considered. The natural asphalt content of the RAP was 5.2% and this became the target liquid content for all mixes evaluated. The materials to be classified as “liquid” in this concept were age hardened asphalt binder (existing in the RAP), virgin asphalt binder (PG64-22), and rejuvenator (Renoil 1736). All mixes utilized RAP material and/or burnt aggregates obtained from the RAP material in order to maintain a consistent gradation and aggregate properties between the mixes.

In order to gain the most comprehensive understanding of the diffusion process five mix designs were developed. Two controls were considered, the first mix was a conventional hot-mix asphalt (HMA) using aggregates burnt by the ignition oven method. The second control mix was a 100% RAP mix that was simply the Keasbey, NJ RAP as it was received; the samples were compacted at conventional HMA temperatures for a PG 64-22 binder - 150°C. Three investigative mix designs were developed. The rejuvenator content as determined on the basis of the formula suggested by the producer. The formula is:

$$P = \frac{(4R + 7S + 12F) * 1.1}{100}$$

Where,
P = asphalt content of RAP plus recycling agent (required) content
R = percent retained on 2.36 mm sieve
S = percent passing 2.36 mm sieve and retained on 0.075 mm sieve
F = percent passing 0.075 mm sieve
The 1.1/1.2 factor compensates for base or soil contamination in the mix

The formula estimates the rejuvenator content to be 0.8%, for investigative purposes range of lower and higher contents was selected. The mixes contained 0.5% and 1.0% rejuvenator. A third mix contained 0.5% rejuvenator and 0.5% virgin binder. The complete proportions for each of the five mix designs are presented in Table 1.

Table 1. Mix Designs, Percent of Total Mix by Mass

Mix Component	Control (HMA)	Control (RAP)	0.5% RJ, 0.5% VB	0.5% RJ	1.0% RJ
Rejuvenator (Renoil 1736)	0.0%	0.0%	0.5%	0.5%	1.0%
Virgin Binder (PG64-22)	5.2%	0.0%	0.5%	0.0%	0.0%
RAP (Keasbey, NJ)	0.0%	100.0%	80.8%	90.4%	80.8%
Burnt Aggregate (Assumed as virgin aggregate)	94.8%	0.0%	18.2%	9.1%	18.2%
Aged Binder (Assumed in RAP)	0.0%	5.2%	4.2%	4.7%	4.2%
Aggregate (Assumed in RAP)	0.0%	94.8%	76.6%	85.7%	76.6%
Total Aggregate (RAP + Burnt)	**94.8%**	**94.8%**	**94.8%**	**94.8%**	**94.8%**
Total Liquid (RJ, VB, AB)	**5.2%**	**5.2%**	**5.2%**	**5.2%**	**5.2%**
Total Mix	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**

The 1.0%RJ mix design was used for two separate sets to distinguish between diffusion and aging, discussed fully in the next section. Ultimately this study included six mix sets, to be abbreviated in accordance with Table 1 throughout this paper.

3.3 Dynamic Modulus

In order to determine the dynamic modulus for the six different mixes, samples were prepared in accordance with *Appendix 2* of *|E*| - DYNAMIC MODULUS: Test Protocol – Problems and Solutions* [21]. The test was performed in a Universal Testing Machine, equipped with a loading cell and a computer containing a ShedWorks® software package for data collection, following the modified procedure that follows.

1. Three to four specimens were compacted for each mix, 150 mm (6 in) diameter by 170 mm (6.69 in) tall specimens were prepared in a Superpave Gyratory Compactor using the height-control mode in accordance with *AASHTO T 312 Standard Method of Test for Preparing and Determining the Density of Hot Mix Asphalt (HMA) Specimens by Means of the Superpave Gyratory Compactor*. Essentially the TMD of each mix was used to estimate the amount of material needed for the desired volume to contain 7±1% VTM.
2. All mixes were prepared using Superpave HMA methods, targeting 150°C.
3. Each sample was cored using a 4 inch coring rig.
4. The BSG of each sample was determined using the CoreLok®.
5. The rough ends of the cylindrical specimen were sawed off using a double blade saw to reach a smooth height of 152.4 mm (6.00 in).
6. Mounting studs for the axial Linear Variable Differential Transformers (LVDTs) were attached using quick setting epoxy in accordance with the mounting specifications provided by ShedWorks, Inc. for the Dynamic Modulus testing using the UTM.
7. The samples were tested at five temperatures. At each temperature the samples were tested under four loading frequencies, with a different specified load applied at each temperature to achieve appropriate amount of elastic deformation in the samples. The testing conditions are summarized in Table 2.

Table 2. Dynamic Modulus Testing Parameters

Temperature (ºC (ºF))	Frequency (Hz)	Peak Load (lb)	Contact Load (lb)
-10 (14)	10, 5, 1, 0.1	3000	150
4.4 (40)	10, 5, 1, 0.1	1500	75
21.1 (70)	10, 5, 1, 0.1	1000	50
37.8 (100)	10, 5, 1, 0.1	400	20
54.4 (130)	10, 5, 1, 0.1	100	5

8. The samples were tested periodically over approximately 10 weeks. Between testing days the samples were then kept in an oven at 60^{o}C (to facilitate the action of the rejuvenating agent). Two ovens were employed; initially a conventional oven was used. The Control (HMA), Control (RAP), 0.5%RJ, 0.5RJ/0.5%VB, and 1.0%RJ mixes were aged in the conventional oven. An Inert Gas Oven was then used for a second set of 1.0%RJ in order to distinguish between aging of the asphalt binder and diffusion of rejuvenator with the asphalt binder over time.
9. The results of the test are presented by the ShedWorks® software in a Microsoft Office Excel2007® worksheet containing the deformation readings of the LVDTs at each frequency. This data were then organized by frequency and interpreted by a MatLAB® program developed at WPI. The dynamic modulus and phase angle were then transferred to an Excel® workbook for analysis.
10. After the series of dynamic modulus results were compiled a statistical analysis of the moduli overtime was carried out to evaluate the change in values over time.

4 Results

The long term effects of rejuvenation was determined through periodic testing of dynamic modulus through-out an accelerated oven aging protocol that exposed gyratory compacted samples to moderate temperatures (60°C) to facilitate the mingling process of the rejuvenator and/or virgin binder into the age hardened asphalt binder in the RAP. Two ovens were utilized, all five mixes were aged in a conventional oven and a second set of 1.0%RJ was aged in an inert gas oven. The inert gas oven was continuously fed with Argon; this allowed the change in dynamic modulus over time to be separated from the oxidative aging of the binder (both of which would tend to cause a change in modulus of the mix).

The dynamic modulus samples were produced targeting 7±1% voids in total mix. The volumetric results for the samples tested are presented in Figure 6 by type of mix. All six sets of samples were within the targeted VTM.

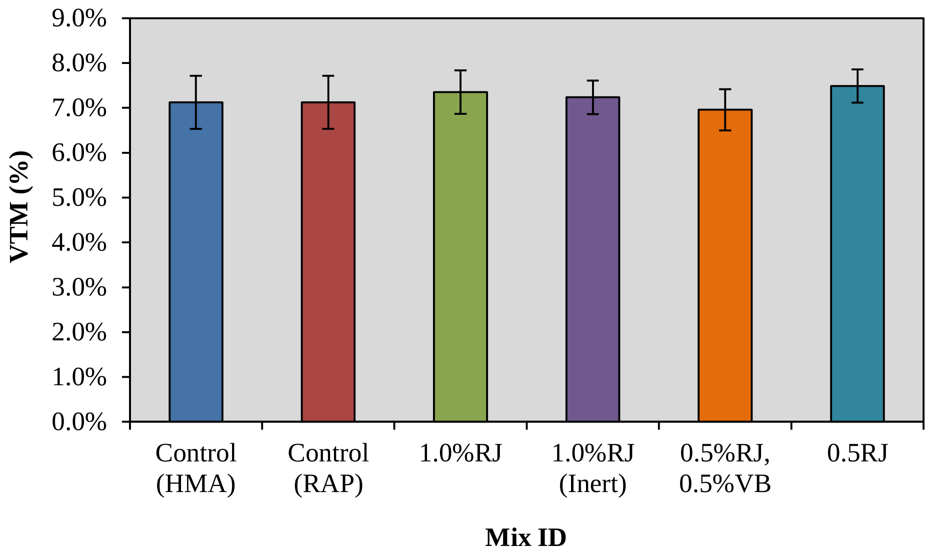

Figure 6. Voids in Total Mix (VTM) for Dynamic Modulus Samples, by Mix

The results of the dynamic modulus and phase angle test data over time are presented in Tables 3 through 9 by average values. Data was collected at five temperatures (-10°C, 4.4°C, 21.1°C, 37.8°C, and 54.4°C) with four frequencies tested at each temperature (10Hz, 5Hz, 1Hz, and 0.1Hz).

Table 3. Average |E*| and Phase Angle for Control (HMA)

	T(C)	F(Hz)	|E*| (ksi)							Phase Angle						
			0	5	35	54	69	76	148	0	5	35	54	69	76	148
Average	-10	10	2.5E+03	2.6E+03	2.4E+03	2.9E+03	3.7E+03	3.3E+03	3.5E+03	5.429	5.271	6.956	4.903	4.649	4.557	4.315
	-10	5	3.5E+03	3.1E+03	2.8E+03	3.0E+03	4.4E+03	3.9E+03	4.5E+03	5.281	4.572	6.471	4.166	3.843	4.197	3.345
	-10	1	3.0E+03	2.8E+03	2.0E+03	2.7E+03	4.5E+03	3.4E+03	3.5E+03	4.813	5.007	7.789	4.302	4.571	5.097	3.647
	-10	0.1	2.2E+03	2.3E+03	1.5E+03	3.6E+03	8.4E+03	3.6E+03	3.9E+03	7.124	6.226	10.449	5.305	6.681	4.135	4.586
	4.4	10	1.7E+03	2.6E+03	2.8E+03	3.0E+03	3.0E+03	2.6E+03	2.8E+03	9.881	9.703	9.976	8.378	7.252	6.658	7.443
	4.4	5	1.6E+03	2.8E+03	3.0E+03	3.0E+03	3.4E+03	3.2E+03	2.7E+03	10.296	8.321	8.500	7.467	6.750	5.722	8.411
	4.4	1	1.3E+03	2.6E+03	2.7E+03	2.8E+03	2.7E+03	3.9E+03	2.5E+03	12.323	9.961	9.825	8.435	6.432	5.607	6.420
	4.4	0.1	8.6E+02	1.5E+03	1.7E+03	1.5E+03	2.3E+03	3.1E+03	3.4E+03	16.811	14.671	14.212	18.414	10.129	9.687	7.162
	21.1	10	8.1E+02	1.0E+03	9.9E+02	1.3E+03	1.6E+03	1.3E+03	1.1E+03	21.800	21.437	21.151	17.506	14.620	14.326	13.385
	21.1	5	7.0E+02	8.6E+02	1.0E+03	1.2E+03	1.4E+03	1.2E+03	9.8E+02	22.265	20.073	18.795	17.476	15.242	16.088	12.995
	21.1	1	4.6E+02	5.9E+02	7.0E+02	8.0E+02	1.0E+03	8.7E+02	7.7E+02	25.949	23.904	22.888	21.440	18.762	19.099	15.182
	21.1	0.1	2.4E+02	3.1E+02	3.8E+02	4.5E+02	6.0E+02	5.1E+02	4.9E+02	30.493	28.408	28.138	27.178	24.645	24.317	20.982
	37.8	10	2.5E+02	2.9E+02	2.9E+02	4.7E+02	4.2E+02	4.8E+02	6.9E+02	32.301	30.550	29.286	28.450	26.136	26.959	22.985
	37.8	5	2.0E+02	2.3E+02	2.3E+02	4.0E+02	3.5E+02	3.9E+02	5.9E+02	30.607	29.597	28.775	27.477	26.226	26.539	23.097
	37.8	1	1.2E+02	1.3E+02	1.4E+02	2.3E+02	2.2E+02	2.4E+02	4.1E+02	29.365	28.861	27.607	29.688	27.469	27.894	26.395
	37.8	0.1	6.5E+01	7.0E+01	7.6E+01	1.1E+02	1.1E+02	1.2E+02	2.2E+02	25.661	24.903	23.927	26.666	25.838	26.568	30.007
	54.4	10	6.4E+01	8.3E+01	7.9E+01	1.6E+02	1.3E+02	1.6E+02	2.0E+02	31.766	28.820	33.741	36.205	31.621	34.036	28.698
	54.4	5	5.6E+01	6.7E+01	6.3E+01	1.1E+02	1.0E+02	1.2E+02	1.5E+02	28.051	26.293	30.908	33.449	31.596	32.424	30.880
	54.4	1	4.6E+01	6.7E+01	6.4E+01	7.5E+01	5.5E+01	1.0E+02	9.5E+01	24.308	24.196	24.741	30.596	36.908	31.741	29.275
	54.4	0.1	2.3E+01	3.7E+01	2.8E+01	5.1E+01	3.7E+01	4.3E+01	4.3E+01	20.218	14.050	20.518	28.720	21.131	24.275	26.537

Table 4. Average |E*| and Phase Angle Results for Control (RAP)

	T (C)	F(Hz)	|E*| (ksi)					Phase Angle				
			0	7	19	29	79	0	7	19	29	79
Average	-10	10	2.05E+03	2.77E+03	2.65E+03	3.25E+03	2.89E+03	4.280	4.343	4.562	4.446	4.534
	-10	5	2.11E+03	3.01E+03	3.25E+03	3.37E+03	3.11E+03	3.463	3.570	3.573	3.543	3.456
	-10	1	2.14E+03	2.80E+03	3.00E+03	2.97E+03	3.22E+03	3.598	3.250	3.434	3.304	2.938
	-10	0.1	3.06E+03	2.70E+03	2.87E+03	4.88E+03	4.56E+03	5.245	4.289	4.830	4.660	6.452
	4.4	10	2.05E+03	1.93E+03	2.19E+03	2.16E+03	2.36E+03	8.646	5.140	5.645	6.479	5.440
	4.4	5	2.41E+03	2.22E+03	2.73E+03	2.22E+03	2.39E+03	4.353	5.283	4.368	5.688	4.767
	4.4	1	1.95E+03	2.05E+03	2.59E+03	2.12E+03	2.21E+03	5.782	5.442	5.357	5.631	4.585
	4.4	0.1	1.84E+03	1.75E+03	1.91E+03	2.09E+03	4.39E+03	7.241	6.631	6.227	6.773	5.958
	21.1	10	1.55E+03	1.28E+03	1.38E+03	1.38E+03	1.43E+03	11.872	11.473	10.548	10.481	9.135
	21.1	5	1.63E+03	1.18E+03	1.32E+03	1.49E+03	1.41E+03	9.841	10.111	10.152	9.369	8.553
	21.1	1	1.32E+03	1.05E+03	1.14E+03	1.11E+03	1.37E+03	10.758	11.307	11.160	10.770	9.426
	21.1	0.1	1.15E+03	7.47E+02	8.37E+02	9.37E+02	1.10E+03	14.568	15.623	14.621	13.570	11.931
	37.8	10	5.69E+02	7.40E+02	7.13E+02	7.27E+02	7.70E+02	19.653	17.085	16.839	17.087	15.290
	37.8	5	5.02E+02	6.65E+02	6.84E+02	6.57E+02	7.10E+02	20.219	17.180	16.868	17.126	14.942
	37.8	1	3.53E+02	5.00E+02	5.00E+02	4.94E+02	5.80E+02	23.151	19.657	19.133	19.184	16.337
	37.8	0.1	2.01E+02	2.98E+02	3.06E+02	3.00E+02	3.56E+02	27.960	24.444	23.676	23.689	21.995
	54.4	10	3.07E+02	5.80E+02	3.16E+02	3.68E+02	4.48E+02	36.679	23.084	25.169	36.217	8.064
	54.4	5	2.40E+02	4.83E+02	2.67E+02	3.69E+02	3.88E+02	28.590	25.852	25.051	23.725	21.118
	54.4	1	1.48E+02	3.07E+02	1.72E+02	2.23E+02	2.54E+02	28.678	24.685	27.029	25.280	23.255
	54.4	0.1	7.31E+01	1.49E+02	8.91E+01	1.02E+02	1.48E+02	30.062	27.523	28.686	29.100	26.774

Table 5. Average |E*| and Phase Angle Results with for 1.0%RJ

	T (C)	F(Hz)	E*							phase angle						
			0	5	10	20	27	37	69	0	5	10	20	27	37	69
Average	-10	10	1.5E+03	1.8E+03	1.9E+03	2.0E+03	1.9E+03	2.0E+03	1.5E+03	13.176	9.223	9.402	8.569	9.227	9.180	10.533
	-10	5	1.3E+03	1.7E+03	1.7E+03	2.5E+03	1.8E+03	1.9E+03	1.4E+03	13.029	9.650	9.175	5.646	8.752	8.602	10.774
	-10	1	1.1E+03	1.8E+03	1.7E+03	1.8E+03	1.6E+03	1.6E+03	1.2E+03	15.183	9.045	9.684	8.225	9.521	9.277	11.907
	-10	0.1	6.8E+02	1.0E+03	1.3E+03	1.6E+03	1.2E+03	1.3E+03	8.7E+02	20.413	13.088	12.678	10.452	12.409	11.600	15.434
	4.4	10	8.1E+02	9.9E+02		1.2E+03	1.1E+03	1.3E+03	1.2E+03	18.345	15.817		13.124	14.235	13.196	12.798
	4.4	5	7.2E+02	8.8E+02		1.3E+03	1.0E+03	1.2E+03	1.1E+03	18.052	15.940		12.147	14.295	12.991	12.735
	4.4	1	5.4E+02	6.7E+02		1.1E+03	8.1E+02	9.6E+02	9.2E+02	20.104	17.817		13.444	15.858	14.248	13.792
	4.4	0.1	3.2E+02	4.2E+02		6.7E+02	5.3E+02	6.6E+02	6.6E+02	24.347	21.712		17.165	19.587	17.767	16.646
	21.1	10	2.8E+02	4.1E+02		5.0E+02	5.0E+02	5.4E+02	6.5E+02	25.028	22.666		20.239	20.471	20.873	17.373
	21.1	5	2.4E+02	3.6E+02		4.4E+02	4.4E+02	4.7E+02	5.8E+02	24.381	22.097		20.448	20.136	19.804	18.019
	21.1	1	1.6E+02	2.5E+02		3.1E+02	3.2E+02	3.5E+02	4.4E+02	25.497	23.331		21.989	20.858	20.530	19.285
	21.1	0.1	9.4E+01	1.5E+02		1.8E+02	2.1E+02	2.3E+02	2.9E+02	26.670	24.362		24.127	21.680	21.631	21.396
	37.8	10	1.1E+02	1.7E+02		2.2E+02	2.0E+02	2.2E+02	2.7E+02	26.710	23.554		23.771	24.518	24.042	23.039
	37.8	5	8.8E+01	1.4E+02		1.8E+02	1.7E+02	1.9E+02	2.3E+02	24.974	22.273		22.073	22.892	22.571	22.065
	37.8	1	5.8E+01	1.0E+02		1.3E+02	1.3E+02	1.5E+02	1.7E+02	24.204	21.228		21.759	21.680	21.537	21.761
	37.8	0.1	3.7E+01	7.0E+01		8.4E+01	8.3E+01	8.8E+01	1.1E+02	22.975	19.867		20.437	20.117	20.185	21.090
	54.4	10	4.6E+01	7.0E+01		7.8E+01	7.7E+01	8.6E+01	8.5E+01	23.849	33.281		25.798	26.349	25.920	26.041
	54.4	5	3.9E+01	6.4E+01		8.0E+01	7.0E+01	7.5E+01	8.1E+01	21.556	22.053		21.692	24.345	24.214	24.012
	54.4	1	3.6E+01	6.3E+01		6.5E+01	6.3E+01	7.0E+01	6.0E+01	23.556	19.087		19.871	21.788	22.416	22.977
	54.4	0.1	2.0E+01	2.8E+01		5.0E+01	3.2E+01	3.6E+01	3.1E+01	17.821	18.614		22.093	19.672	20.331	21.068

Table 6. Average |E*| and Phase Angle Results for 1.0%RJ (Inert)

	T (C)	F(Hz)	E*					phase angle				
			0	5	12	22	72	0	5	12	22	72
Average	-10	10	1.86E+03	1.83E+03	1.88E+03	1.93E+03	1.87E+03	10.34977	7.697733	8.245967	7.828867	8.412733
	-10	5	1.86E+03	1.77E+03	1.80E+03	2.25E+03	1.91E+03	10.154	7.2773	7.7162	7.067333	7.496467
	-10	1	1.52E+03	1.60E+03	1.80E+03	1.67E+03	1.98E+03	11.24647	7.6973	8.1795	7.5738	7.7177
	-10	0.1	1.09E+03	1.22E+03	1.19E+03	1.57E+03	1.69E+03	15.1458	10.17003	10.4063	9.497967	9.2767
	4.4	10	1.09E+03	1.43E+03	1.52E+03	1.92E+03	1.51E+03	15.23603	13.0873	13.3359	13.0772	10.7977
	4.4	5	9.95E+02	1.34E+03	1.83E+03	1.65E+03	1.54E+03	15.0412	11.70757	11.74027	10.58557	10.32567
	4.4	1	7.76E+02	1.23E+03	1.18E+03	1.30E+03	1.24E+03	16.95923	13.4606	12.89133	12.28137	11.40067
	4.4	0.1	5.20E+02	8.22E+02	8.23E+02	9.53E+02	8.90E+02	21.0007	17.3853	15.99243	15.4886	14.5866
	21.1	10	3.14E+02	6.12E+02	6.46E+02	6.54E+02	7.84E+02	21.41025	19.73753	19.59883	18.45503	19.7629
	21.1	5	4.12E+02	5.39E+02	5.73E+02	5.84E+02	7.16E+02	22.3085	19.24817	18.8601	18.1719	16.78903
	21.1	1	2.89E+02	3.97E+02	4.34E+02	4.34E+02	5.32E+02	23.94107	20.57177	20.2526	19.5573	18.60163
	21.1	0.1	1.64E+02	2.52E+02	2.72E+02	2.81E+02	3.51E+02	19.5467	22.6298	22.12817	21.75077	21.01157
	37.8	10	2.00E+02	2.47E+02	2.57E+02	2.53E+02	2.95E+02	25.51027	23.45827	22.30497	22.16497	22.52943
	37.8	5	1.71E+02	2.13E+02	2.27E+02	2.21E+02	2.58E+02	24.26183	22.33353	21.9631	21.07427	22.6299
	37.8	1	1.18E+02	1.56E+02	1.69E+02	1.74E+02	2.02E+02	23.85217	21.8165	20.80177	20.45887	21.81613
	37.8	0.1	7.60E+01	1.40E+02	1.04E+02	1.07E+02	1.16E+02	23.29587	22.64217	17.2059	20.68283	21.75813
	54.4	10	9.98E+01	9.46E+01	9.58E+01	8.23E+01	1.15E+02	26.64207	26.17293	25.60187	41.68083	25.32973
	54.4	5	8.28E+01	7.89E+01	9.38E+01	7.95E+01	9.82E+01	25.02807	24.50373	23.08427	19.11623	23.27697
	54.4	1	5.93E+01	6.57E+01	7.14E+01	6.91E+01	1.34E+02	23.86343	22.35023	21.80407	14.33047	20.3105
	54.4	0.1	3.40E+01	3.56E+01	3.71E+01	3.74E+01	4.64E+01	22.5059	21.058	20.95157	19.14303	21.01937

Table 7. Average |E*| and Phase Angle Results for 0.5%RJ

	Temperature	Frequency	E*					phase angle				
			0	5	12	22	72	0	5	12	22	72
Average	-10	10	2.72E+03	2.03E+03	3.04E+03	3.95E+03	2.69E+03	5.867	5.287	5.724	6.020	4.432
	-10	5	3.21E+03	1.94E+03	3.00E+03	3.46E+03	2.72E+03	5.347	9.898	4.873	3.858	3.561
	-10	1	2.54E+03	1.84E+03	2.92E+03	3.35E+03	2.60E+03	5.405	11.097	4.897	4.453	3.985
	-10	0.1	2.18E+03	1.67E+03	2.95E+03	3.56E+03	2.81E+03	6.339	12.303	5.851	4.691	6.555
	4.4	10	1.93E+03	1.57E+03	2.90E+03	2.15E+03	2.99E+03	8.394	7.970	13.094	5.574	7.908
	4.4	5	2.02E+03	1.57E+03	2.37E+03	2.31E+03	3.79E+03	7.880	6.806	6.909	6.228	5.174
	4.4	1	1.76E+03	1.52E+03	2.20E+03	2.20E+03	2.90E+03	8.420	5.845	7.312	6.816	4.803
	4.4	0.1	1.48E+03	1.10E+03	1.71E+03	1.62E+03	2.28E+03	10.985	8.816	9.337	8.268	7.658
	21.1	10	1.04E+03	1.21E+03	1.26E+03	1.30E+03	1.70E+03	15.139	13.901	12.913	11.633	8.082
	21.1	5	9.55E+02	1.11E+03	1.17E+03	1.22E+03	1.53E+03	15.197	13.141	12.980	12.256	10.674
	21.1	1	7.50E+02	9.41E+02	9.48E+02	1.02E+03	1.26E+03	17.408	14.705	14.706	13.903	12.007
	21.1	0.1	4.84E+02	6.04E+02	6.44E+02	6.89E+02	8.75E+02	21.961	19.262	18.355	17.848	15.848
	37.8	10	4.87E+02	6.46E+02	6.13E+02	7.90E+02	8.70E+02	23.100	19.935	19.435	19.406	17.458
	37.8	5	4.26E+02	5.69E+02	5.55E+02	7.70E+02	7.04E+02	22.952	20.068	19.284	18.774	16.724
	37.8	1	2.94E+02	4.04E+02	4.46E+02	4.99E+02	5.30E+02	24.827	22.114	26.993	21.819	19.741
	37.8	0.1	1.70E+02	2.38E+02	2.40E+02	2.99E+02	3.22E+02	27.699	25.347	24.498	24.867	23.642
	54.4	10	2.19E+02	2.70E+02	2.86E+02	3.47E+02	4.52E+02	26.264	25.916	25.819	22.100	22.884
	54.4	5	1.45E+02	2.28E+02	2.32E+02	2.76E+02	4.52E+02	24.771	25.444	24.788	25.257	25.850
	54.4	1	1.23E+02	1.50E+02	1.68E+02	1.76E+02	3.02E+02	26.430	26.299	21.177	24.891	23.300
	54.4	0.1	6.56E+01	7.85E+01	8.36E+01	8.55E+01	1.28E+02	27.018	27.881	25.543	29.983	26.613

Table 8. Average |E*| and Phase Angle Results for 0.5%RJ, 0.5%VB

	T (C)	F(Hz)	E*							phase angle						
			0	5	10	20	27	37	69	0	5	10	20	27	37	69
Average	-10	10	1.4E+03	2.1E+03	1.9E+03	1.6E+03	1.5E+03	2.9E+03	1.8E+03	8.138	6.637	7.008	5.991	6.489	5.698	6.469
	-10	5	1.5E+03	2.2E+03	2.3E+03	2.5E+03	1.8E+03	4.3E+03	1.8E+03	7.944	5.646	5.547	4.516	5.229	5.329	6.280
	-10	1	1.4E+03	2.1E+03	2.6E+03	2.2E+03	1.5E+03	2.2E+03	1.6E+03	9.102	4.466	6.125	5.782	6.198	5.737	6.600
	-10	0.1	9.6E+02	2.4E+03	2.1E+03	1.6E+03	1.2E+03	1.8E+03	1.3E+03	11.518	7.552	9.559	6.024	7.751	6.228	8.552
	4.4	10	9.1E+02	1.4E+03		1.6E+03	1.4E+03	1.5E+03	1.6E+03	12.860	9.866		8.581	8.724	8.016	10.253
	4.4	5	8.8E+02	1.5E+03		1.8E+03	1.5E+03	1.5E+03	1.7E+03	12.601	9.207		7.270	8.000	7.988	5.935
	4.4	1	4.8E+02	1.6E+03		2.1E+03	1.4E+03	1.4E+03	1.4E+03	14.232	10.308		8.615	8.582	8.164	7.744
	4.4	0.1	3.2E+02	9.5E+02		1.4E+03	1.0E+03	1.1E+03	1.2E+03	18.956	13.624		11.161	10.750	10.517	9.633
	21.1	10	4.3E+02	6.4E+02		7.6E+02	8.1E+02	6.5E+02	9.8E+02	20.632	16.702		14.799	15.243	14.374	12.557
	21.1	5	3.8E+02	6.2E+02		7.0E+02	7.4E+02	5.9E+02	9.3E+02	20.755	16.678		14.469	15.291	14.132	12.343
	21.1	1	2.6E+02	4.7E+02		5.8E+02	5.8E+02	4.7E+02	7.7E+02	23.342	18.628		15.686	17.183	15.968	13.548
	21.1	0.1	1.6E+02	2.9E+02		4.0E+02	3.8E+02	3.2E+02	5.5E+02	27.889	22.940		18.931	21.088	19.597	17.033
	37.8	10	1.7E+02	3.3E+02		3.8E+02	3.8E+02	3.9E+02	4.8E+02	27.807	23.352		22.305	22.229	21.617	20.142
	37.8	5	1.4E+02	2.8E+02		3.2E+02	3.2E+02	3.4E+02	4.2E+02	27.283	22.929		21.930	31.183	21.280	19.688
	37.8	1	8.7E+01	1.9E+02		2.2E+02	2.3E+02	2.4E+02	3.1E+02	29.100	24.048		23.308	22.921	22.651	21.438
	37.8	0.1	4.7E+01	1.2E+02		1.3E+02	1.4E+02	1.4E+02	1.9E+02	30.499	24.776		24.587	23.960	23.971	23.856
	54.4	10	6.0E+01	1.3E+02		1.3E+02	1.5E+02	1.6E+02	2.0E+02	33.960	26.625		26.155	25.869	26.561	25.968
	54.4	5	4.9E+01	1.0E+02		1.1E+02	1.2E+02	1.3E+02	1.7E+02	34.844	25.919		24.685	25.088	25.175	24.238
	54.4	1	3.1E+01	7.0E+01		8.2E+01	9.0E+01	8.9E+01	1.2E+02	25.933	25.598		24.368	23.918	25.621	26.103
	54.4	0.1	1.7E+01	3.9E+01		4.4E+01	4.8E+01	5.3E+01	6.2E+01	24.641	24.007		23.592	23.801	24.239	25.899

The results presented in Figures 7 and 8 are for each temperature at 10Hz and a linear trend line represents the data in order to clearly show the change in dynamic modulus over time, as a result of rejuvenation and aging. Generally the mixes were in two groups of dynamic modulus responses, the two control mixes (HMA and RAP) and the 0.5%RJ mix resulted in similar dynamic modulus values. The second cluster, which reportedly had lower moduli results, was the 1.0%RJ (conventional and inert ovens) and 0.5%RJ, 0.5%VB mixes. The observation is that the rejuvenator is effective in lowering the stiffness of the aged RAP binder, and hence produces mixes with dynamic modulus values that are lower than those of virgin or non-rejuvenated RAP mixes. Also, over time, the increase in stiffness is much lower for rejuvenated mixes than RAP or HMA mixes (without any rejuvenator or with lower rejuvenator content).

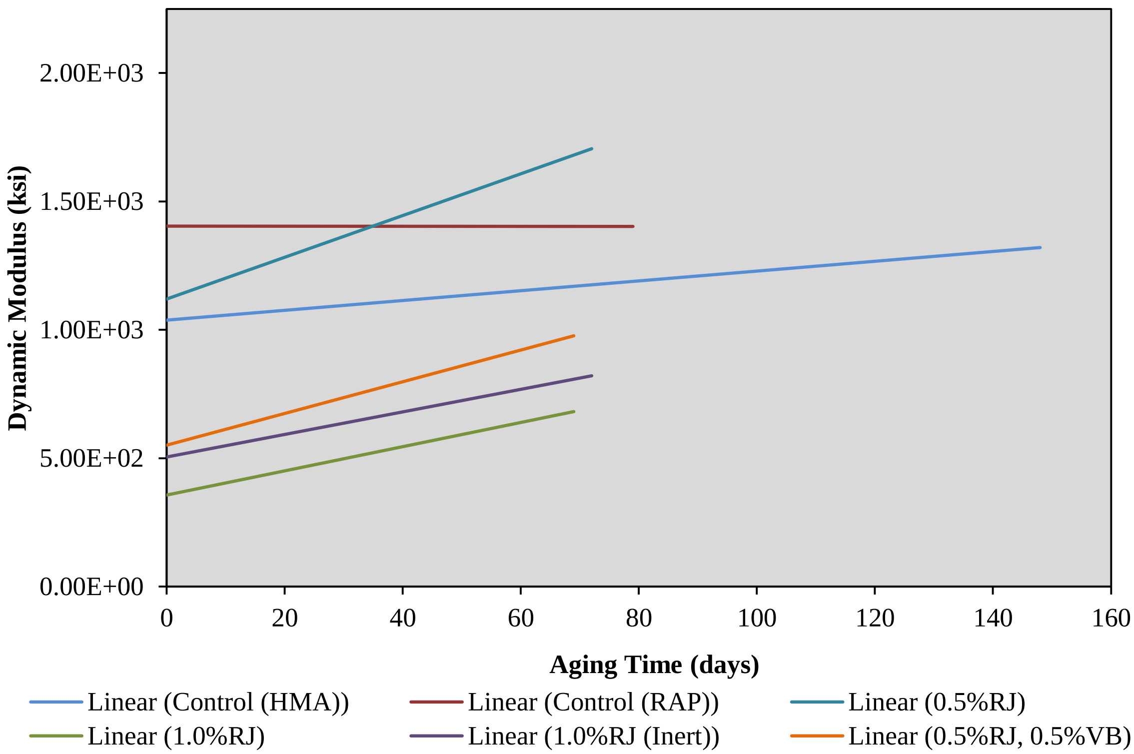

Figure 7. Dynamic Modulus Results for 21.1°C, 10Hz

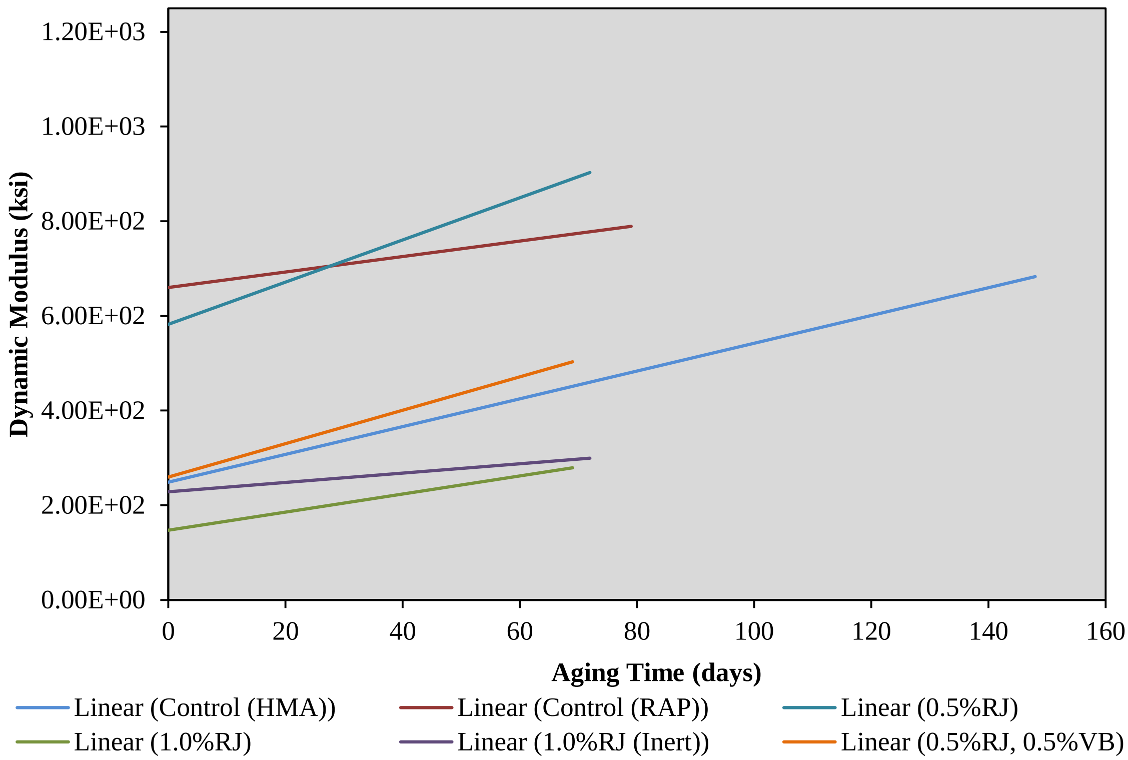

Figure 8. Dynamic Modulus Results for 37.8°C, 10Hz

It is apparent that at higher temperatures, 37.8°C and 54.4°C, the Control (HMA) mix begins to respond as a softer (i.e. rejuvenated) mix. This could be due to the virgin binder in the mix being more susceptible to increased temperatures then the stiffer RAP mixes (Control (RAP) and 0.5%RJ).

During the dynamic modulus testing the phase angle was recorded to develop an understanding of the binder properties of the mixes. The phase angle is a parameter that quantifies the response time between applied stress and experienced strain. It is essentially the lag between stress and strain that is experienced by viscoelastic materials (e.g. asphalt). The phase angle results are presented by test temperature for each of the six mixes, in Figures 9 through 13. The average data for each mix tested at 10Hz is presented, while the complete data can be found in the Appendix.

Generally, all six mixes experienced a decrease in phase angle throughout the aging protocol. This indicates that over time in the 60°C oven the asphalt binder was reacting more as an elastic material. It is of interest that the 1.0%RJ mix that was aged in the inert oven rather than the conventional oven follows the same trend as the other five mixes, suggesting the same chemical diffusion behavior was occurring in both ovens.

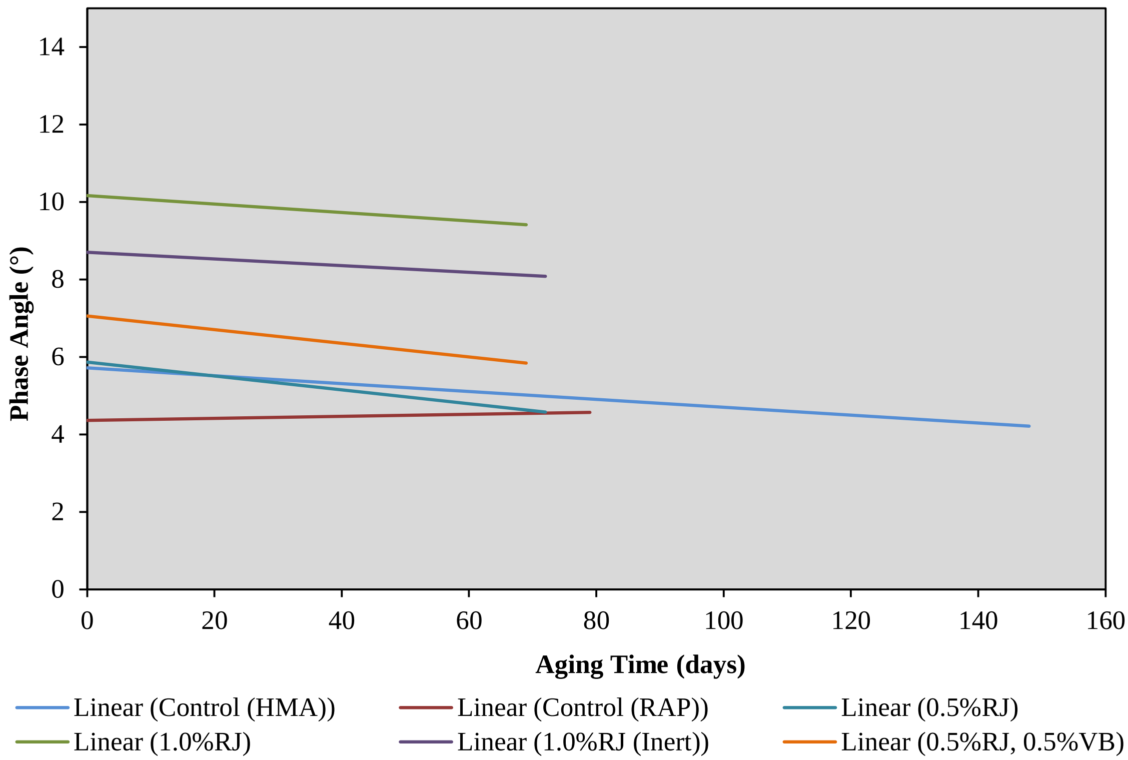

Figure 9. Phase Angle Results for -10°C, 10Hz

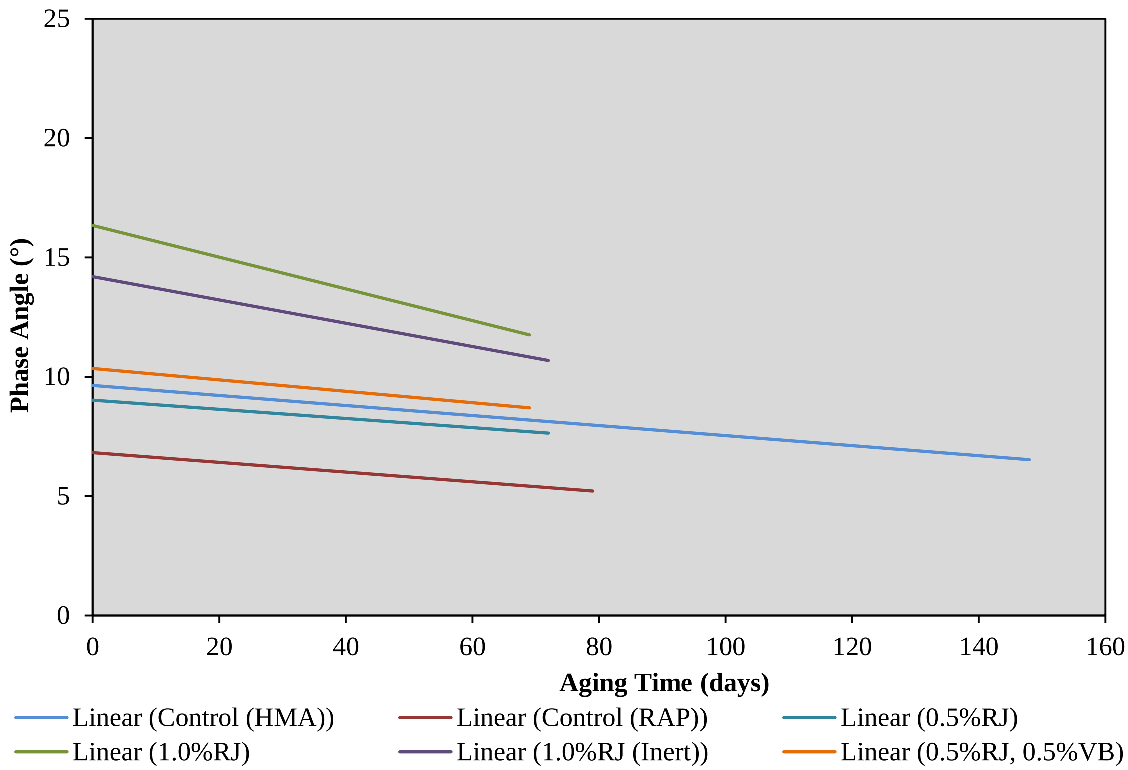

Figure 10. Phase Angle Results for 4.4°C, 10Hz

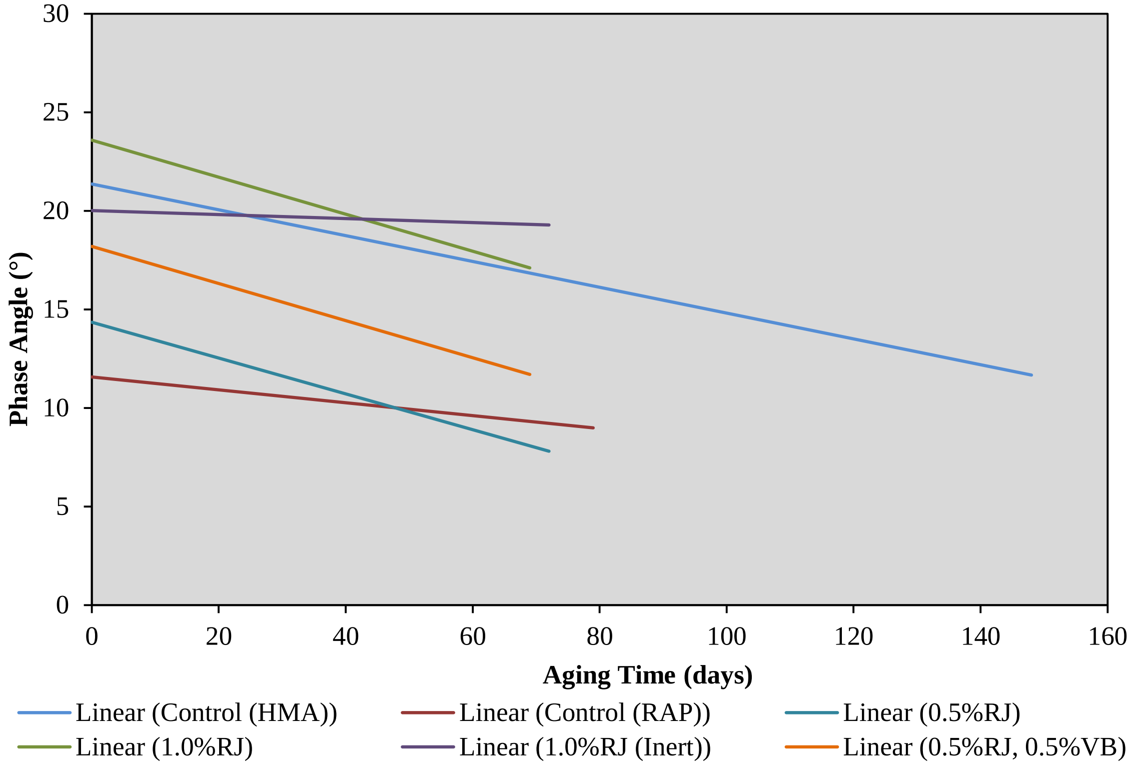

Figure 11. Phase Angle Results for 21.1°C, 10Hz

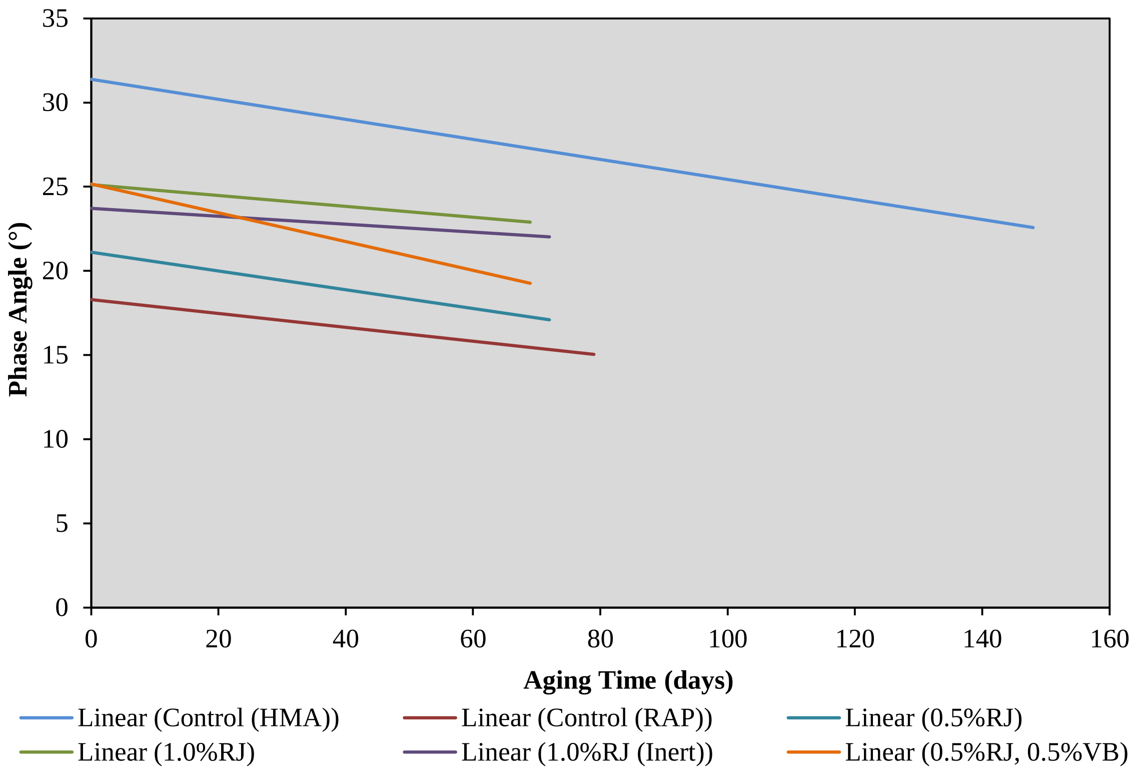

Figure 12. Phase Angle Results for 37.8°C, 10Hz

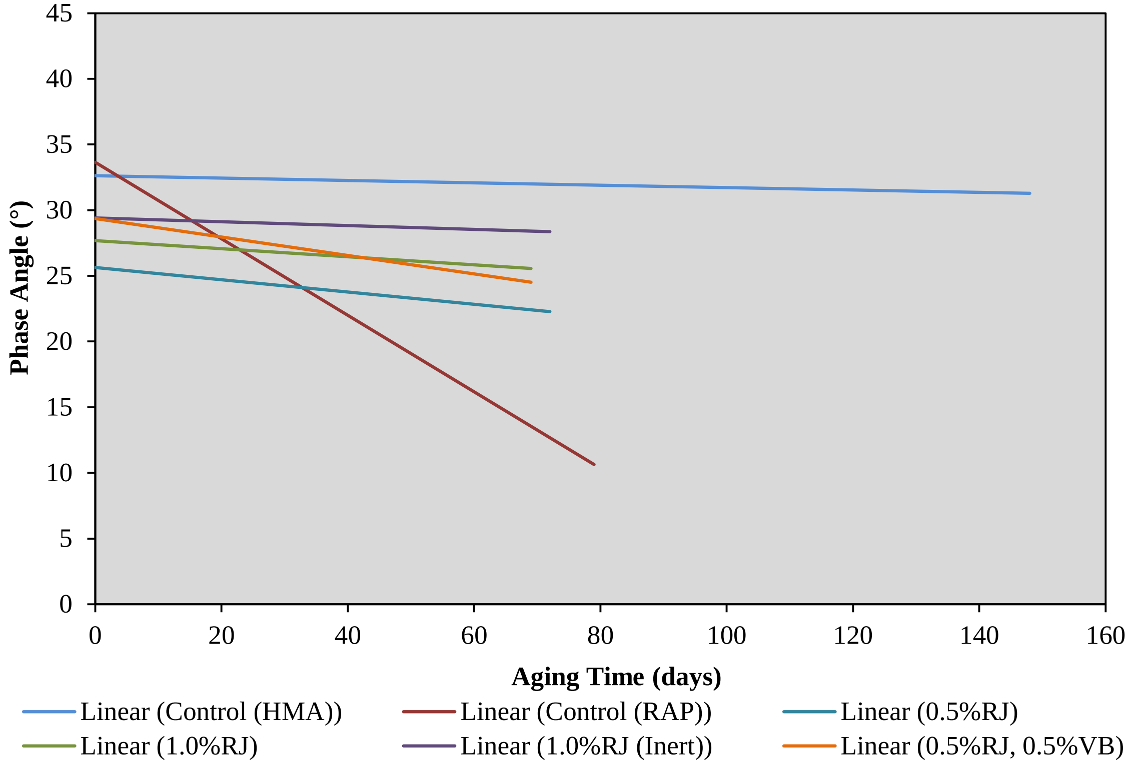

Figure 13. Phase Angle Results for 54.4°C, 10Hz

Figures 14 through 18 present |E*||/sin(δ) for varying temperatures computed using the average dynamic modulus and phase angle data at 10Hz. This parameter was developed to give insight to the effect of binder properties on the dynamic modulus results. Due to the visco-elastic behaviors of asphalt it is important to look at this parameter. A second parameter, |E*|*sin(δ), was developed at room temperature to give insight into the fatigue behavior of the mixes tested and is presented in Figure 19.

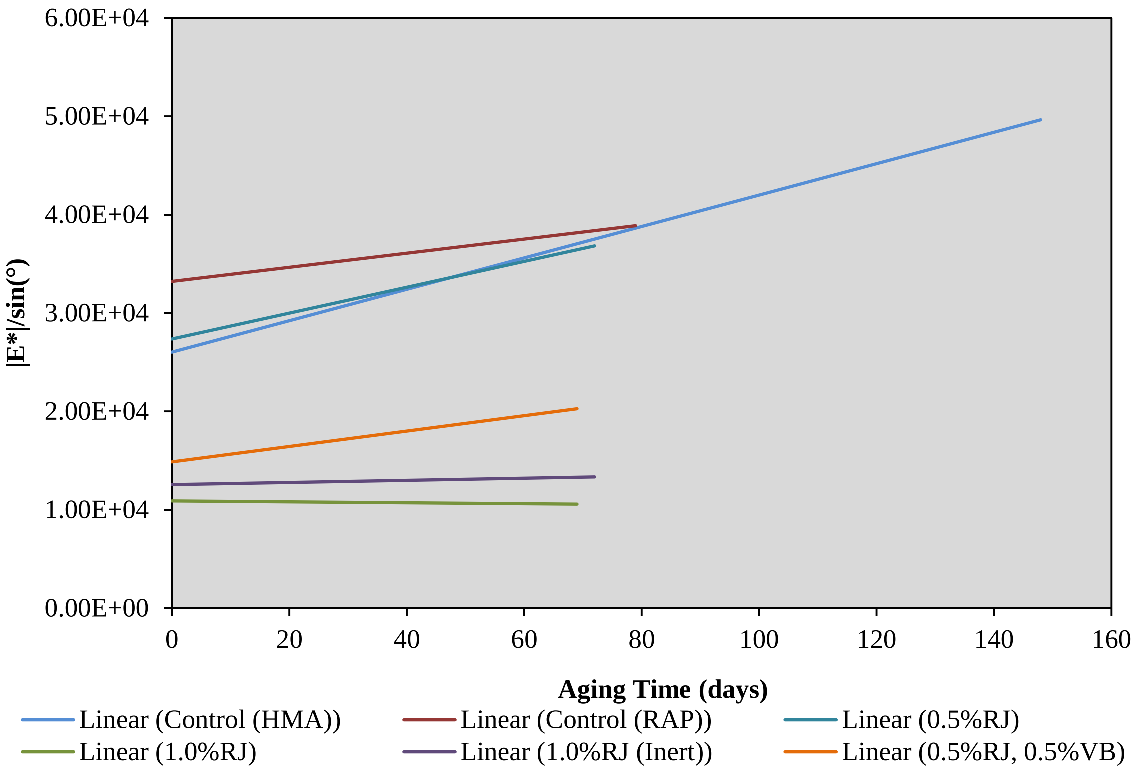

Figure 14. |E*|/sin(δ) Results for -10°C, 10Hz

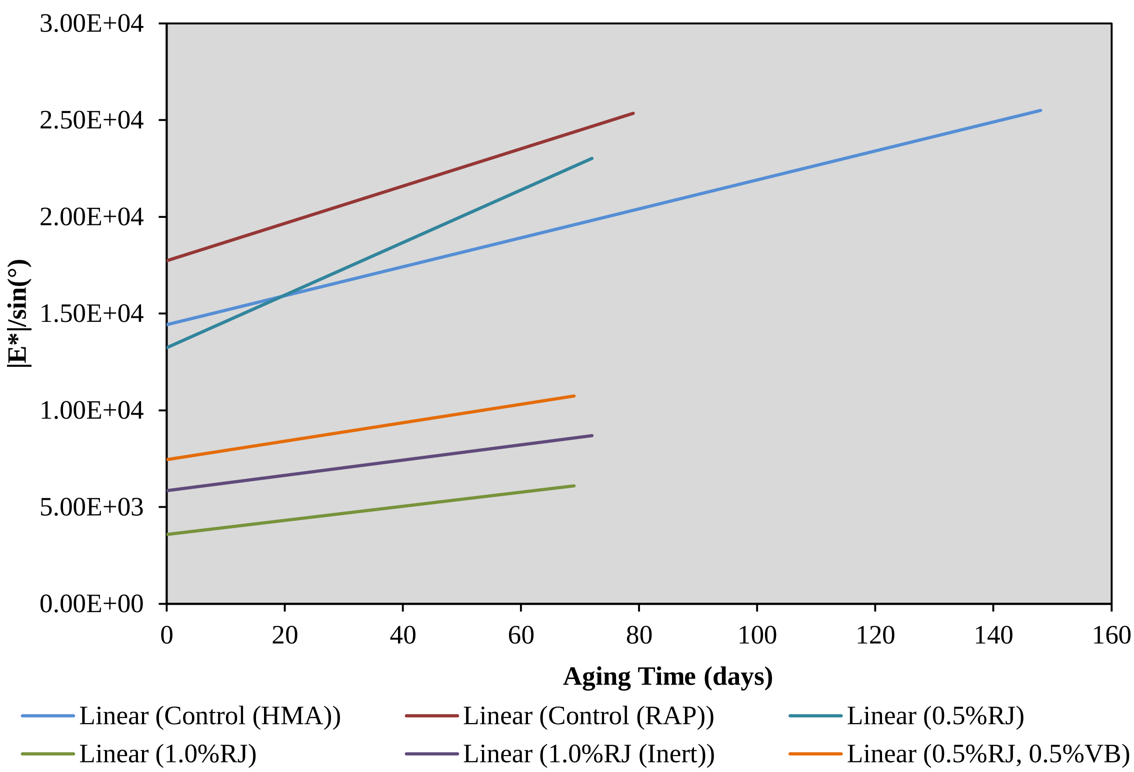

Figure 15. |E*|/sin(δ) Results for 4.4°C, 10Hz

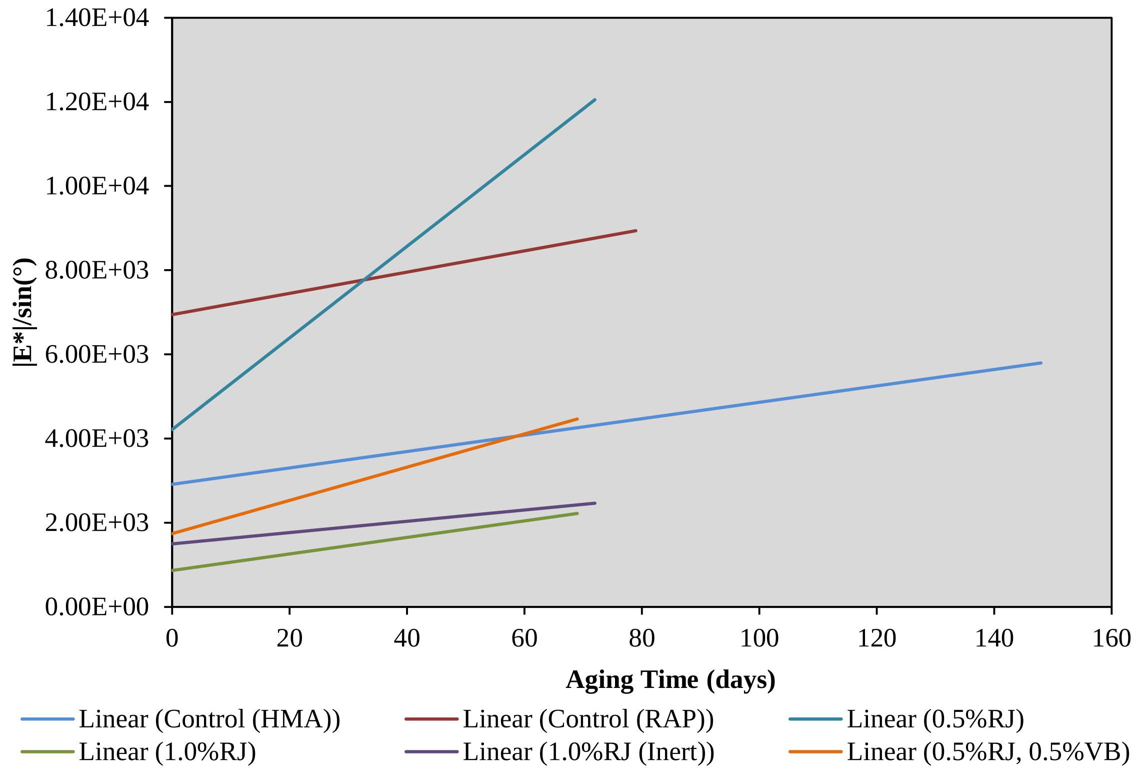

Figure 16. |E*|/sin(δ) Results for 21.1°C, 10Hz

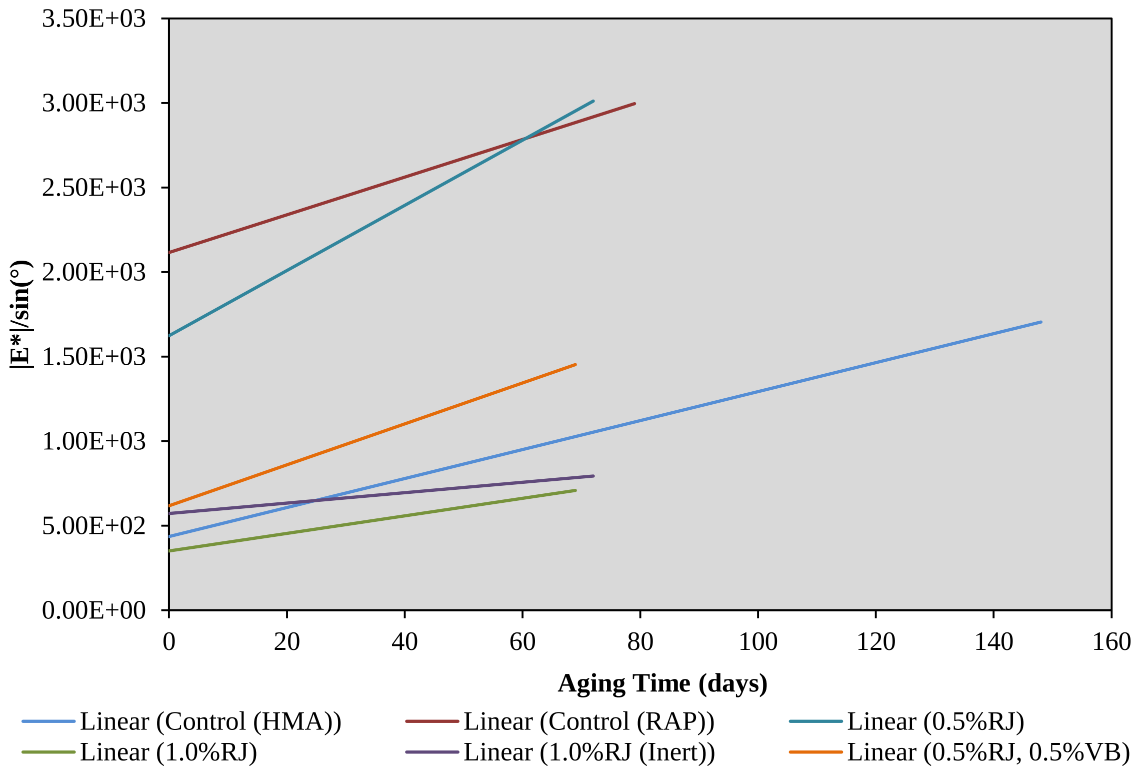

Figure 17. |E*|/sin(δ) Results for 37.8°C, 10Hz

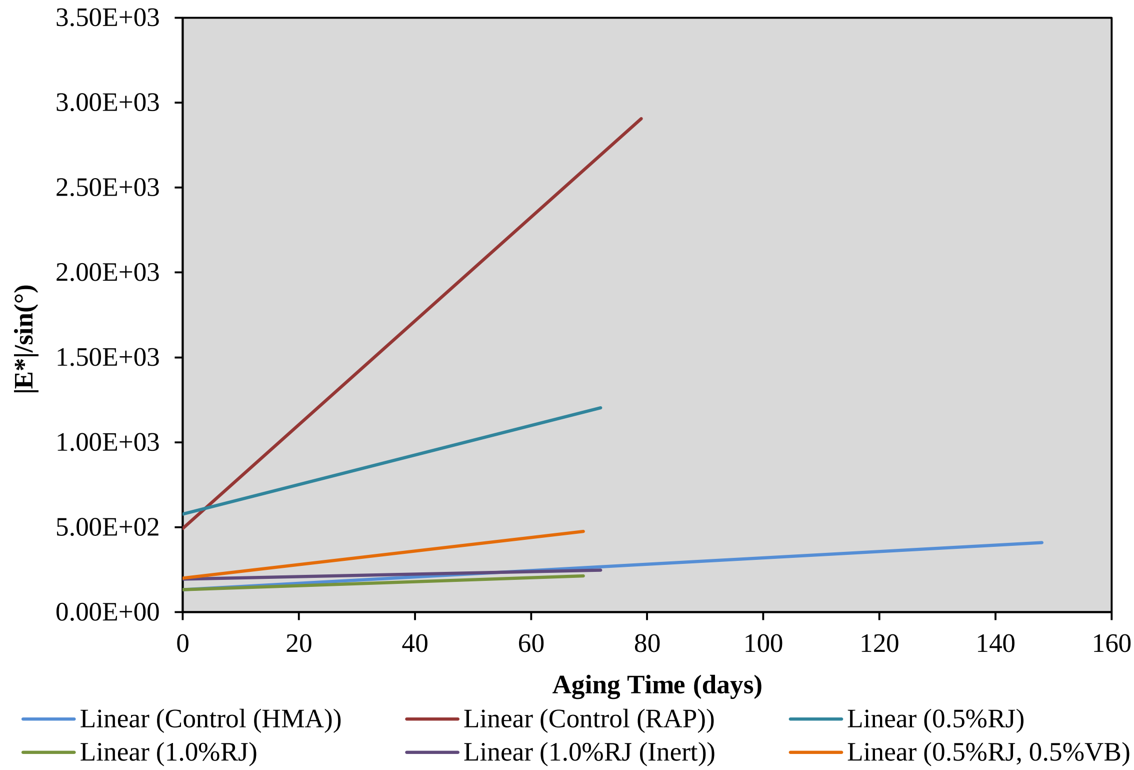

Figure 18. |E*|/sin(δ) Results for 54.4°C, 10Hz

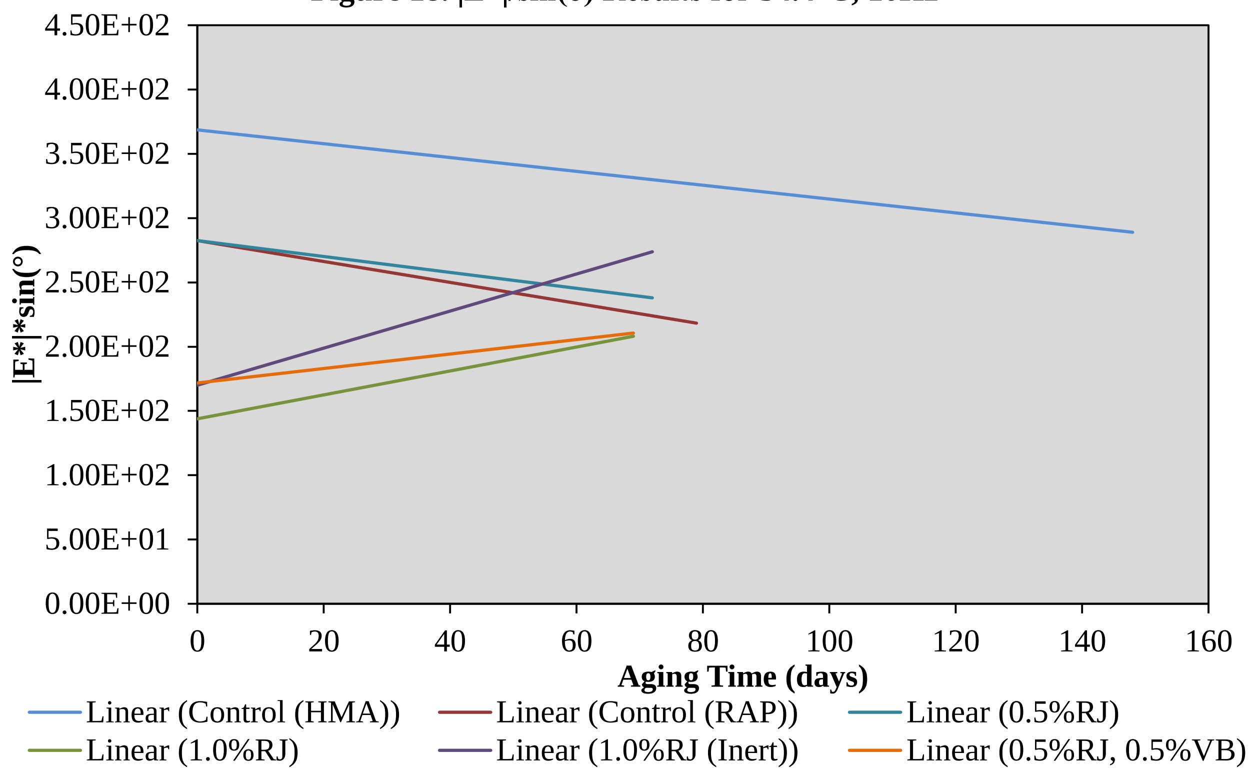

Figure 19. |E*|*sin(δ) Results for 21.1°C, 10Hz

5 Analysis of Results

5.1 Analysis of Variance (ANOVA)

In order to determine whether the variation of the dynamic modulus results over time was significant, an Analysis of Variance (ANOVA) with the utilization of *post hoc* testing was conducted. An ANOVA is a statistical test used to determine the equality between the means of several groups. The ANOVA was carried out using SPSS Statistics 11.5 software, IBM, Somers, NY, USA [23]. In order to best select a *post hoc* method, Levene's test was first utilized to determine the homogeneity of variance within the groups. The results of the Levene's test are present in Table 9. The results show a clear trend of heterogeneity within the sample groups. Due to the heterogeneous nature of the group variances and small sample sizes; the Games-Howell method was selected. Additionally, the Games-Howell method offered a more conservative protection against Type I errors or errors of rejecting the null hypothesis when it is actually true, also known as an "error of the first kind." The purpose of the *post hoc* testing was to find patterns in the subgroups of the ANOVA data.

For the purpose of this analysis the dynamic modulus data was organized by mix type, and temperature and frequency that the modulus was computed at. This allowed the independent variable or "factor" to be aging time and the dependent variables to be the dynamic modulus of the samples at varying aging times. The subgroups are the sample sets (either 3 or 4 samples depending on the mix). The ANOVA could determine the temperature and frequency combinations that experienced statistically significant changes of modulus throughout the aging protocol. The Games-Howell method could then specify at what time in aging this statistically significant change occurred.

Table 9a. Levene Homogeneity Results by Mix

		Control (HMA)				1.0%RJ				0.5%RJ, 0.5%VB			
Temperature	**Frequency**	**Levene Statistic**	**df1**	**df2**	**Sig.**	**Levene Statistic**	**df1**	**df2**	**Sig.**	**Levene Statistic**	**df1**	**df2**	**Sig.**
(-10C)	**10Hz**	1.615	6	14	0.215	4.058	6	21	0.007	2.825	6	21	0.035
	5Hz	0.820	6	14	0.573	3.413	6	21	0.016	5.710	6	21	0.001
	1Hz	1.252	6	14	0.339	4.988	6	21	0.003	2.507	6	21	0.055
	0.1Hz	2.204	6	14	0.105	3.690	6	21	0.012	1.426	6	21	0.251
(4.4C)	**10Hz**	5.162	6	14	0.005	2.444	5	18	0.074	0.524	5	17	0.755
	5Hz	3.441	6	14	0.027	2.671	5	18	0.056	0.266	5	17	0.926
	1Hz	9.593	6	14	0.000	0.953	5	18	0.471	4.558	5	17	0.008
	0.1Hz	6.342	6	14	0.002	1.434	5	18	0.260	3.263	5	17	0.030
(21.1C)	**10Hz**	8.985	6	14	0.000	1.396	5	18	0.273	0.597	5	17	0.702
	5Hz	8.810	6	14	0.000	2.096	5	18	0.113	0.719	5	17	0.618
	1Hz	9.912	6	14	0.000	1.598	5	18	0.211	1.103	5	17	0.395
	0.1Hz	10.570	6	14	0.000	0.657	5	18	0.660	2.936	5	17	0.043
(37.8C)	**10Hz**	5.376	6	14	0.005	1.066	5	18	0.411	1.166	5	17	0.366
	5Hz	6.927	6	14	0.001	0.604	5	18	0.698	0.962	5	17	0.468
	1Hz	9.468	6	14	0.000	0.827	5	18	0.547	1.101	5	17	0.396
	0.1Hz	11.029	6	14	0.000	0.665	5	18	0.655	1.209	5	17	0.347
(54.4C)	**10Hz**	4.304	6	14	0.011	6.452	5	18	0.001	0.724	5	17	0.615
	5Hz	2.628	6	14	0.064	2.458	5	18	0.073	0.461	5	17	0.800
	1Hz	2.214	6	14	0.103	3.787	5	18	0.016	1.368	5	17	0.285
	0.1Hz	6.282	6	14	0.002	6.928	5	18	0.001	0.782	5	17	0.576

Table 1b. Levene Homogeneity Results by Mix

		Control (RAP)				1.0%RJ (Inert)				0.5%RJ			
Temperature	**Frequency**	**Levene Statistic**	**df1**	**df2**	**Sig.**	**Levene Statistic**	**df1**	**df2**	**Sig.**	**Levene Statistic**	**df1**	**df2**	**Sig.**
(-10C)	**10Hz**	4.595	4	10	0.023	2.450	4	10	0.114	4.903	4	10	0.019
	5Hz	2.424	4	10	0.117	3.645	4	10	0.044	4.537	4	10	0.024
	1Hz	2.745	4	10	0.089	2.564	4	10	0.104	4.452	4	10	0.025
	0.1Hz	4.724	4	10	0.021	3.480	4	10	0.050	2.239	4	10	0.137
(4.4C)	**10Hz**	0.162	4	10	0.953	3.887	4	10	0.037	1.947	4	10	0.179
	5Hz	1.501	4	10	0.274	5.738	4	10	0.012	7.399	4	10	0.005
	1Hz	1.688	4	10	0.228	3.347	4	10	0.055	1.708	4	10	0.224
	0.1Hz	1.536	4	10	0.265	6.402	4	10	0.008	1.853	4	10	0.195
(21.1C)	**10Hz**	3.345	4	10	0.055	3.703	4	10	0.042	0.347	4	10	0.840
	5Hz	6.804	4	10	0.007	3.406	4	10	0.053	0.233	4	10	0.914
	1Hz	10.348	4	10	0.001	2.273	4	10	0.133	0.075	4	10	0.988
	0.1Hz	7.259	4	10	0.005	3.259	4	10	0.059	0.251	4	10	0.903
(37.8C)	**10Hz**	0.573	4	10	0.689	1.098	4	10	0.409	0.274	4	10	0.888
	5Hz	1.371	4	10	0.311	1.244	4	10	0.353	1.764	4	10	0.213
	1Hz	2.109	4	10	0.154	1.892	4	10	0.188	0.087	4	10	0.985
	0.1Hz	0.843	4	10	0.529	1.369	4	10	0.312	0.101	4	10	0.980
(54.4C)	**10Hz**	4.296	4	10	0.028	0.532	4	10	0.716	0.462	4	10	0.762
	5Hz	2.527	4	10	0.107	0.520	4	10	0.723	2.416	4	10	0.118
	1Hz	2.722	4	10	0.091	5.910	4	10	0.010	1.077	4	10	0.418
	0.1Hz	1.506	4	10	0.273	1.783	4	10	0.209	2.263	4	10	0.135

The complete statistical data can be found in the Appendix; for the purpose of ease of interpretation of the meaningful data an example of analysis will be presented. The ANOVA and Games-Howell data were extensive, and in order to interpret the data more conclusively the results were organized to be more easily understood. Table 10 presents the results of the ANOVA analysis for the Control (HMA) mix at 21.1°C.

Table 10. ANOVA Results for Control (HMA) at 21.1°C

Temperature	Frequency		Sum of Squares	df	Mean Square	F	Sig.
(21.1°C)	10Hz	Between Groups	1.129E+12	6	1.882E+11	3.079	0.039
		Within Groups	8.556E+11	14	6.111E+10		
		Total	1.985E+12	20			
	5Hz	Between Groups	1.074E+12	6	1.79E+11	3.682	0.021
		Within Groups	6.804E+11	14	4.86E+10		
		Total	1.754E+12	20			
	1Hz	Between Groups	6.239E+11	6	1.04E+11	3.951	0.016
		Within Groups	3.685E+11	14	2.632E+10		
		Total	9.924E+11	20			
	0.1Hz	Between Groups	2.78E+11	6	4.633E+10	4.461	0.01
		Within Groups	1.454E+11	14	1.039E+10		
		Total	4.234E+11	20			

Statistical analyses of the data obtained at all temperature-frequency (temp-freq) combinations were conducted to determine whether the values changed over time or not. Some of these temp-freq combinations were able to detect the change and the others were not. Which of them would be able to catch the change? The answer is that most likely the ones at which the effect of the binder is most pronounced.

The Games-Howell results for the Control (HMA) mix at 21.1C, 5Hz is presented in Table 11. Using The Games-Howell results, the timeline of change in modulus can be determined. A lettering distinction was applied to the moduli at different times, so at time zero the modulus is considered to be an “A” modulus and when a statistically significant change occurs, the modulus is then considered a “B” modulus and so on and so forth to the end of the conditioning time. Therefore, for the Control (HMA) mix at 21.1°C, 5 Hz the modulus is considered an “A” modulus up to day 35 where a significant change occurs (significance = 0.006) and the modulus becomes a “B” modulus. When considering the Games-Howell results, it’s important to look at the entirety of the results and not simply sequential results. For example, in this case the change does not happen from 0 to 5 days or 5 to 35 days but from 0 to 35 days. There is also a statistically significant change from 0 to 76 days but not from 35 to 76 days so the change at 76 days is accounted for in the recognition of the 35th day change. This process was carried for every temperature and frequency combination for each mix, the statistical analysis is summarized by temperature in Tables 12 to 17.

It is interesting to see that the more change (A to B to C to D) happens in the 1% RJ or the 0.5% RJ+0.5%VB mixes than in the control HMA mix (A to B only). This indicates that sufficient amount of interaction/mingling of old and new asphalt is happening, in addition to aging, during the conditioning process to cause changes in the modulus. This observation is encouraging as it reinforces the concept of rejuvenation of the recycled mixes.

Table 11. Games-Howell Results for Control (HMA) at 21.1C, 5Hz

Temperature	Frequency	(I) TIME	(J) TIME	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
							Lower Bound	Upper Bound
(21.1°C)	5Hz	0	5	-1.55E+05	2.78E+04	0.051	-3.10E+05	1.15E+03
			35	-3.02E+05	2.81E+04	0.006	-4.57E+05	-1.47E+05
			54	-4.71E+05	7.08E+04	0.056	-9.65E+05	2.25E+04
			69	-7.42E+05	1.21E+05	0.088	-1.72E+06	2.36E+05
			76	-4.96E+05	5.04E+04	0.012	-7.93E+05	-1.98E+05
			148	-2.79E+05	3.04E+05	0.938	-2.91E+06	2.36E+06
		5	0	1.55E+05	2.78E+04	0.051	-1.15E+03	3.10E+05
			35	-1.47E+05	2.09E+04	0.015	-2.52E+05	-4.34E+04
			54	-3.17E+05	6.83E+04	0.148	-8.60E+05	2.27E+05
			69	-5.88E+05	1.20E+05	0.144	-1.61E+06	4.31E+05
			76	-3.41E+05	4.67E+04	0.048	-6.77E+05	-4.95E+03
			148	-1.24E+05	3.03E+05	0.998	-2.78E+06	2.53E+06
		35	0	3.02E+05	2.81E+04	0.006	1.47E+05	4.57E+05
			5	1.47E+05	2.09E+04	0.015	4.34E+04	2.52E+05
			54	-1.69E+05	6.84E+04	0.429	-7.09E+05	3.70E+05
			69	-4.40E+05	1.20E+05	0.239	-1.46E+06	5.76E+05
			76	-1.93E+05	4.69E+04	0.164	-5.26E+05	1.39E+05
			148	2.32E+04	3.03E+05	1.000	-2.63E+06	2.68E+06
		54	0	4.71E+05	7.08E+04	0.056	-2.25E+04	9.65E+05
			5	3.17E+05	6.83E+04	0.148	-2.27E+05	8.60E+05
			35	1.69E+05	6.84E+04	0.429	-3.70E+05	7.09E+05
			69	-2.71E+05	1.36E+05	0.541	-1.06E+06	5.19E+05
			76	-2.42E+04	8.01E+04	1.000	-4.58E+05	4.09E+05
			148	1.92E+05	3.10E+05	0.988	-2.27E+06	2.65E+06
		69	0	7.42E+05	1.21E+05	0.088	-2.36E+05	1.72E+06
			5	5.88E+05	1.20E+05	0.144	-4.31E+05	1.61E+06
			35	4.40E+05	1.20E+05	0.239	-5.76E+05	1.46E+06
			54	2.71E+05	1.36E+05	0.541	-5.19E+05	1.06E+06
			76	2.47E+05	1.27E+05	0.573	-6.23E+05	1.12E+06
			148	4.63E+05	3.26E+05	0.773	-1.73E+06	2.65E+06
		76	0	4.96E+05	5.04E+04	0.012	1.98E+05	7.93E+05
			5	3.41E+05	4.67E+04	0.048	4.95E+03	6.77E+05
			35	1.93E+05	4.69E+04	0.164	-1.39E+05	5.26E+05
			54	2.42E+04	8.01E+04	1.000	-4.09E+05	4.58E+05
			69	-2.47E+05	1.27E+05	0.573	-1.12E+06	6.23E+05
			148	2.17E+05	3.06E+05	0.978	-2.35E+06	2.78E+06
		148	0	2.79E+05	3.04E+05	0.938	-2.36E+06	2.91E+06
			5	1.24E+05	3.03E+05	0.998	-2.53E+06	2.78E+06
			35	-2.32E+04	3.03E+05	1.000	-2.68E+06	2.63E+06
			54	-1.92E+05	3.10E+05	0.988	-2.65E+06	2.27E+06
			69	-4.63E+05	3.26E+05	0.773	-2.65E+06	1.73E+06
			76	-2.17E+05	3.06E+05	0.978	-2.78E+06	2.35E+06

Table 12. Games-Howell Moduli Grouping for -10°C

Control (HMA)				
Time (days)	10Hz	5Hz	1Hz	0.1Hz
0	A	A	A	A
5	A	A	A	A
35	A	A	A	A
54	A	A	A	A
69	A	A	A	A
76	A	A	A	A
148	A	A	A	A

1.0% RJ				
Time (days)	10Hz	5Hz	1Hz	0.1Hz
0	A	A	A	A
5	A	A	A	A
10	A	A	A	B
20	A	A	B	B
27	A	A	B	B
37	A	A	B	B
69	B	B	C	C

0.5% RJ, 0.5% VB				
Time (days)	10Hz	5Hz	1Hz	0.1Hz
0	A	A	A	A
5	A	A	A	A
10	A	A	A	A
20	A	A	A	A
27	A	A	A	A
37	A	A	A	A
69	A	A	A	A

Control (RAP)				
Time (days)	10Hz	5Hz	1Hz	0.1Hz
0	A	A	A	A
7	A	A	A	A
19	A	A	A	A
29	A	A	A	A
79	A	A	A	B

1.0% RJ (Inert)				
Time (days)	10Hz	5Hz	1Hz	0.1Hz
0	A	A	A	A
5	A	A	A	A
12	A	A	A	A
22	A	A	A	A
72	A	A	A	A

0.5% RJ				
Time (days)	10Hz	5Hz	1Hz	0.1Hz
0	A	A	A	A
5	A	A	A	A
12	A	A	A	A
22	A	A	A	A
72	A	A	A	A

Table 13. Games-Howell Moduli Grouping for 4.4°C

Control (HMA)				
Time (days)	10Hz	5Hz	1Hz	0.1Hz
0	A	A	A	A
5	A	A	A	A
35	A	A	A	A
54	A	A	A	A
69	A	A	A	A
76	A	A	A	A
148	A	A	B	A

1.0% RJ				
Time (days)	10Hz	5Hz	1Hz	0.1Hz
0	A	A	A	A
5	A	A	A	B
20	B	B	B	C
27	B	B	B	C
37	B	B	B	C
69	B	B	B	C

0.5% RJ, 0.5% VB				
Time (days)	10Hz	5Hz	1Hz	0.1Hz
0	A	A	A	A
5	A	A	A	B
20	A	B	A	B
27	A	B	A	B
37	A	B	A	B
69	A	B	B	B

Control (RAP)				
Time (days)	10Hz	5Hz	1Hz	0.1Hz
0	A	A	A	A
7	A	A	A	A
19	A	A	A	A
29	A	A	A	A
79	A	A	A	B

1.0% RJ (Inert)				
Time (days)	10Hz	5Hz	1Hz	0.1Hz
0	A	A	A	A
5	A	A	A	A
12	A	A	B	B
22	A	A	B	B
72	A	B	B	B

0.5% RJ				
Time (days)	10Hz	5Hz	1Hz	0.1Hz
0	A	A	A	A
5	A	A	A	A
12	A	A	A	A
22	A	A	A	A
72	A	A	A	A

Table 14. Games-Howell Moduli Grouping for 21.1°C

Control (HMA)				
Time (days)	10Hz	5Hz	1Hz	0.1Hz
0	A	A	A	A
5	A	A	A	B
35	A	B	B	C
54	B	B	B	C
69	B	B	B	C
76	B	B	C	D
148	B	B	C	D

1.0% RJ				
Time (days)	10Hz	5Hz	1Hz	0.1Hz
0	A	A	A	A
5	B	B	B	B
20	B	B	B	C
27	B	C	C	C
37	C	C	C	D
69	D	D	D	E

0.5% RJ, 0.5% VB				
Time (days)	10Hz	5Hz	1Hz	0.1Hz
0	A	A	A	A
5	A	B	B	B
20	B	B	B	B
27	B	B	B	B
37	B	B	B	B
69	B	C	C	B

Control (RAP)				
Time (days)	10Hz	5Hz	1Hz	0.1Hz
0	A	A	A	A
7	A	A	A	A
19	A	A	A	A
29	A	A	A	A
79	A	A	A	A

1.0% RJ (Inert)				
Time (days)	10Hz	5Hz	1Hz	0.1Hz
0	A	A	A	A
5	A	A	A	A
12	A	A	A	A
22	B	A	A	A
72	B	A	A	A

0.5% RJ				
Time (days)	10Hz	5Hz	1Hz	0.1Hz
0	A	A	A	A
5	A	A	A	A
12	A	A	A	A
22	A	A	A	A
72	A	A	A	A

Table 15. Games-Howell Moduli Grouping for 37.8°C

Control (HMA)				
Time (days)	10Hz	5Hz	1Hz	0.1Hz
0	A	A	A	A
5	A	A	A	A
35	A	A	A	A
54	A	A	A	A
69	A	A	A	A
76	B	B	B	B
148	B	B	B	B

1.0% RJ				
Time (days)	10Hz	5Hz	1Hz	0.1Hz
0	A	A	A	A
5	B	B	B	B
20	B	B	C	C
27	B	C	C	C
37	C	C	C	C
69	D	D	D	D

0.5% RJ, 0.5% VB				
Time (days)	10Hz	5Hz	1Hz	0.1Hz
0	A	A	A	A
5	B	B	B	B
20	B	B	B	B
27	B	B	B	B
37	B	B	B	B
69	B	C	C	B

Control (RAP)				
Time (days)	10Hz	5Hz	1Hz	0.1Hz
0	A	A	A	A
7	A	A	A	A
19	A	A	A	A
29	A	A	A	A
79	A	B	B	B

1.0% RJ (Inert)				
Time (days)	10Hz	5Hz	1Hz	0.1Hz
0	A	A	A	A
5	A	A	A	A
12	A	A	A	A
22	A	A	A	A
72	A	A	A	A

0.5% RJ				
Time (days)	10Hz	5Hz	1Hz	0.1Hz
0	A	A	A	A
5	A	A	A	A
12	A	A	A	A
22	A	A	A	A
72	A	A	A	A

Table 16. Games-Howell Moduli Grouping for 54.4°C

Control (HMA)				
Time (days)	10Hz	5Hz	1Hz	0.1Hz
0	A	A	A	A
5	A	A	A	A
35	A	A	A	A
54	A	A	B	A
69	B	B	B	A
76	B	B	B	A
148	B	B	B	A

1.0% RJ				
Time (days)	10Hz	5Hz	1Hz	0.1Hz
0	A	A	A	A
5	B	B	B	A
20	B	B	B	A
27	B	B	B	B
37	C	B	B	B
69	C	B	B	B

0.5% RJ, 0.5% VB				
Time (days)	10Hz	5Hz	1Hz	0.1Hz
0	A	A	A	A
5	A	A	B	B
20	B	B	B	B
27	B	B	B	B
37	B	B	B	B
69	B	B	C	B

Control (RAP)				
Time (days)	10Hz	5Hz	1Hz	0.1Hz
0	A	A	A	A
7	A	A	A	A
19	A	A	A	A
29	A	A	A	A
79	A	A	A	A

1.0% RJ (Inert)				
Time (days)	10Hz	5Hz	1Hz	0.1Hz
0	A	A	A	A
5	A	A	A	A
12	A	A	A	A
22	A	A	A	A
72	A	A	A	A

0.5% RJ				
Time (days)	10Hz	5Hz	1Hz	0.1Hz
0	A	A	A	A
5	A	A	A	A
12	A	A	A	A
22	A	A	A	A
72	A	A	A	A

The Games-Howell grouping results presented completely above are presented in Figure 20 and 20 superimposed over a plot of the average dynamic modulus values over time for each mix at 21.1ºC, 10Hz and 37.8ºC, 10Hz. The only mix that experienced multiple significant changes in modulus over-time was the 1.0%RJ mix that was aged in the conventional oven. The results of the 1.0%RJ mix aged in the inert gas oven only experience one significant change in dynamic modulus.

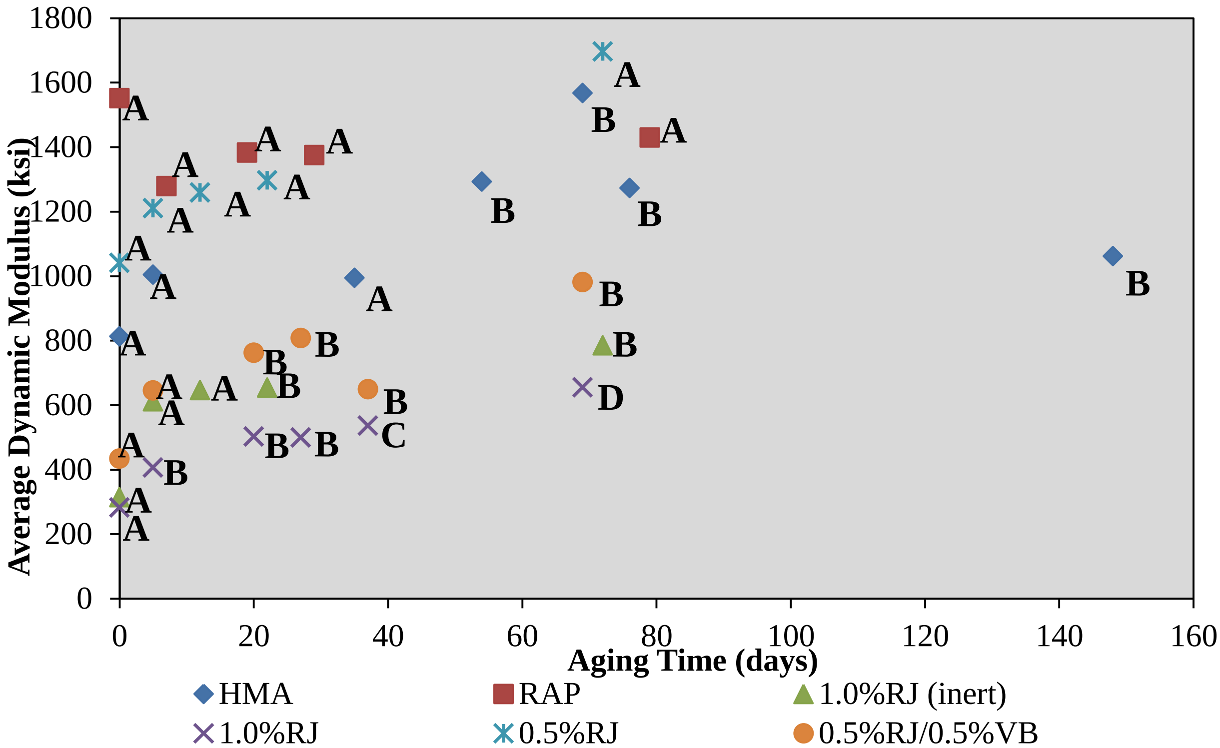

Figure 20. Games-Howell ANOVA Grouping of Average Dynamic Modulus Values, 21.1ºC, 10Hz

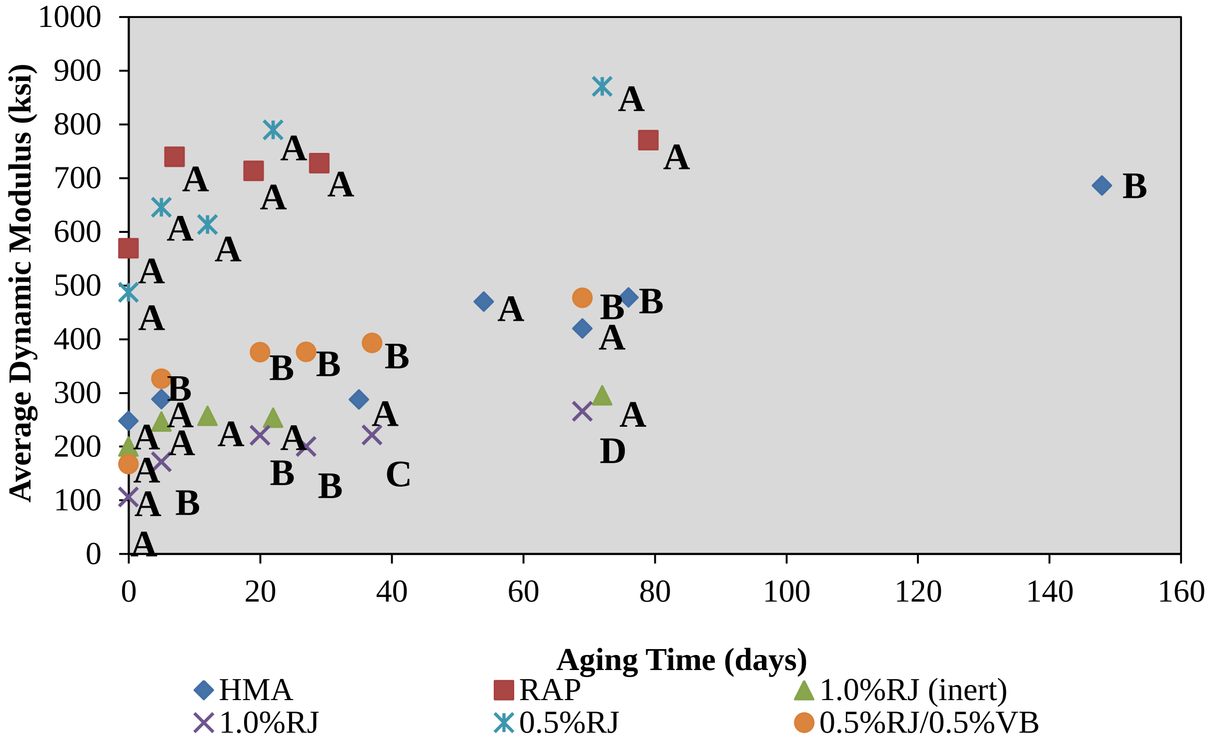

Figure 21. Games-Howell ANOVA Grouping of Average Dynamic Modulus Values, 37.8ºC, 10Hz

The percent change in dynamic modulus values experienced when a statistically significant change in modulus occurred was determined by considering the average dynamic modulus value at within each Games-Howell group (e.g. "A"). The severity of the change in modulus is more clearly evaluated by the bar charts presented in Figures 21 and 22 below.

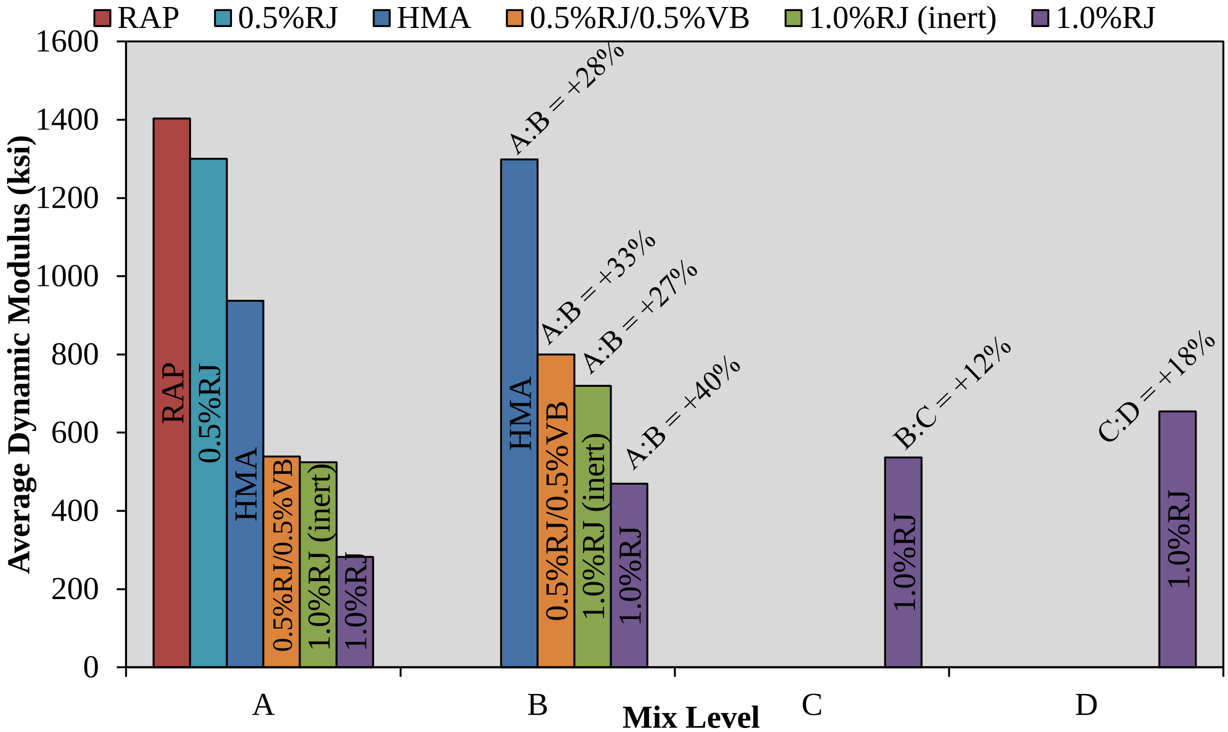

Figure 22. Percent change between Games-Howell Groupings, 21.1ºC, 10Hz

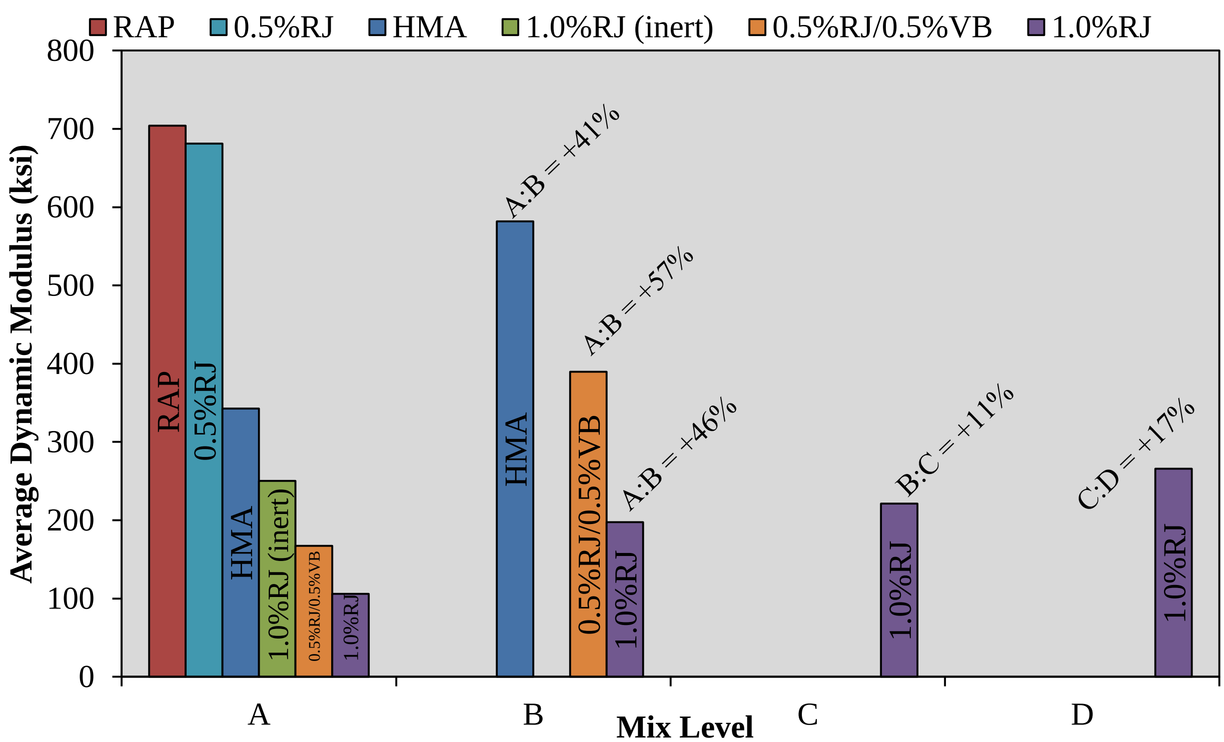

Figure 23. Percent change between Games-Howell Groupings, 37.8ºC, 10Hz

6 Conclusions

This study aimed to evaluate the long term relationship between asphalt rejuvenator and age hardened asphalt binder in reclaimed asphalt pavement (RAP) materials. It can be concluded that:

1. Seismic modulus testing is a fast and simple way to perform initial screening of RAP materials. The results are easy to obtain and quick comparisons of several materials, based on their estimated stiffness, can be made without needed much material.
2. The accelerated aging protocol implemented resulted in varying severity and indications of changes in dynamic modulus results through-out the aging protocol.
3. The changes can be attributed to either oxidation or diffusion of the rejuvenator into the age hardened binder.
4. The use of an inert gas oven for aging can remove the concern of oxidation of the asphalt binder when aged in a conventional over.
5. The mix exposed to the inert gas oven experienced either no or only one statistically significant change in dynamic modulus values over time, whereas the mix exposed to the conventional oven experienced up to four. The increase in changes can be attributed to oxidation of the binder rather than diffusion, but the inert mix suggested some long term diffusion was occurring.

7 Recommendations

The following recommendations are suggested for future work pertaining to the diffusion of rejuvenator into age hardened asphalt binder in RAP.

1. The changes can be attributed to either oxidation or diffusion of the rejuvenator into the age hardened binder, more work and analysis should be conducted to correctly isolate the cause when changes were identified.
2. The different reaction of the 1.0%RJ mixes when exposed to the accelerated aging protocol in varying atmospheres (inert and conventional) indicates a need for additional investigation of the diffusion process.
3. Proof testing should be conducted to fully evaluate the expected performance of the mixes, including TTI's balanced mix design which employs the overlay tester and Hamburg rut test is recommended.

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