An Investigation of the Performance of Hot Mix Asphalt (HMA) Binder Course Materials with High Percentage of Reclaimed Asphalt Pavement (RAP) and Rejuvenators

By

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Abstract

Use of high percentage of Reclaimed Asphalt Pavement (RAP) material in Hot Mix Asphalt is one of the several sustainable construction alternatives being considered by many Departments of Transportation (DOT). Use of RAP in HMA helps in reducing the consumption of virgin aggregates and binder and construction cost and conserving energy. Although most of the US state agencies allow the use of 30% or more RAP in the design of Hot Mix Asphalt (HMA), the current average RAP usage is only about 10 to 20%. This is because of the uncertainty about the performance of HMA mixes with a high RAP content. Several factors influence the performance of the HMA mixes with a high RAP content. Recent research has shown that the use of a high RAP content in HMA with rejuvenators is successful in reducing the stiffness of the RAP mixes, and thereby improving their performance. The present work is carried out to explore the feasibility of using a high RAP content of 50% in a binder layer HMA with the addition of rejuvenators.

Ultrasonic Pulse Velocity (UPV) test was carried out to compare the stiffness of the RAP mixes with and without the addition of rejuvenators. Moisture Induced Stress Test (MIST) was conducted to study the effect of moisture damage on the HMA mixes with high RAP content. The Indirect Tensile Strength Test (ITS) was used to determine the strength of the HMA mixes with high RAP content. In addition, creep compliance and Semicircular Bend (SCB) tests were carried out to determine the cracking potential and fracture strength of the mixes respectively. The addition of rejuvenators was found to significantly reduce the stiffness of the mix with high RAP content. The predicted complex shear modulus (G*) obtained from the Hirsch model and performance grading tests on extracted binders confirmed the effectiveness of the addition of rejuvenators in reducing the stiffness of recycled asphalt binder in the recycled mixes.

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1 INTRODUCTION

One of the most difficult challenges for the development of any road network is to execute projects in harmony with the concept of sustainable development. The road industry is therefore looking forward for alternative materials and construction technology, which are environment friendly, energy efficient and cost effective for the construction and maintenance of roads. Most of the current road construction practices are primarily dependent on naturally occurring aggregates that are obtained from quarries. The extraction of these aggregates from their natural sources results in the loss of forest cover and pollution on a large scale leading to environmental degradation. This, in turn, has raised environmental concerns in many parts of the world [1]. In order to sustain natural resources, sufficient reserves have to be ensured to meet the demands of aggregates at present and in the future, as these resources are depleting fast and are non-replenishable. On the other hand, the price of asphalt binder has also been fluctuating, and research is needed to reduce the consumption of virgin asphalt binder in rehabilitation strategies through alternate technologies and thereby reduce the cost of construction and maintenance. To cope up with the demand for aggregates to preserve and maintain the road infrastructure assets, many Departments of Transportation (DOT) are using Reclaimed Asphalt Pavement (RAP) material as an alternative [2], and considering their use at an increased percentage for Hot Mix Asphalt (HMA). Recycling of asphalt pavement materials has proved to be a valuable approach for both economic and environmental reasons.

1.1 Use of high RAP content in hot mix asphalt

The use of RAP in road construction can provide savings from 14% to 34% for RAP percentages varying from 10% to 50% of the total mix, [3]. Although it is generally accepted that the utilization of RAP in HMA can reduce cost, the percentage of RAP to be used in conventional HMA mixes is still debated. When using high RAP content in HMA, it is still unclear as how the aged asphalt binder from RAP interacts with virgin asphalt binder. It is generally assumed that the RAP material will not act like a black rock in the new mix and it will blend well with virgin binder during mixing [4] , but the question remains as to what extent will it blend. A constant effort is being made by the DOTs to adopt a higher RAP percentage for regular HMA production so as to reduce the consumption of virgin aggregates, cost and conserve energy.

1.2 Factors influencing the characterization of RAP

RAP is milled pavement material obtained from old and often distressed asphalt concrete pavement. This RAP material mainly consists of asphalt binder and aggregates. Of these two materials, the asphalt binder generally undergoes various physical and rheological changes during their service life. The binder properties in RAP are significantly affected by the rheological changes. There are two predominant factors which account for the severity of change in RAP binder properties: composition of the original binder used during its construction and amount of aging undergone during its service [5]. The asphalt binder in RAP, during its service period undergoes two stages of aging, i.e. short term aging (during construction) and long term aging (during service). During these two stages of aging, the viscosity of the binder gradually increases due to natural phenomena like oxidation, volatilization, polymerization and syneresis making it a hard and a stiff material [6]. This aged RAP asphalt binder significantly influences the property of the new blend.

1.3 Use of rejuvenators to improve the properties of RAP mixes

The four components of asphalt are: Saturates, Aromatics, Resins, and Asphaltenes (SARA) [7]. The asphalt in HMA mixes undergoes aging during the manufacturing process and this is known as short term aging. The binder in HMA layers when exposed to the atmosphere during the service life, undergo long term aging. During the aging process, the percentage of asphaltenes in the binder increases in proportion to the other components due to volatilization and oxidation. Higher percentage of asphaltenes in the binder stiffens the binder, causing cracks in the HMA layers. Therefore, the transformation in the components in the asphalt binder, causes stiffening of the HMA mixes and leads to cracking. The properties of the binder as obtained from the refinery is very different from the aged binder in the field due to short and long term aging.

Several factors have been identified as potential causes of aging [8] and they are as follows:

1. Oxidation; 2. Volatilization; 3. Steric or physical hardening; 4. Exudation of oils; 5. Photo-oxidation by direct light; 6. Photo-oxidation in reflected light; 7. Photochemical reaction

by direct light; 8. Photochemical reaction by reflected light; 9. Polymerization; 10. Changes by nuclear energy; 11. Action of water; 12. Absorption by solids; 13. Absorption of components at a solid surface; 14. Chemical reactions; 15. Microbiological deterioration.

The following four factors are considered to be the most significant factors that contribute to the aging process.

1. Oxidation: Due to oxidation, the components of the asphalt binder oxidize. They form heavier and more complex molecules. This results in increased stiffness and decreased flexibility. It is to be noted that the rate of oxidation is significantly affected by the temperature and the asphalt binder film thickness. Thinner films in HMA mixes when exposed to high temperature enhances oxidation. It is reported that at temperatures above 100°C, the rate of oxidation doubles for every 10°C increase in temperature.
2. Volatilization: Due to volatilization of the lighter components in the binder, the binder stiffens and gets aged.
3. Steric or physical hardening: The steric or physical hardening occurs due to reorientation of molecules and slow crystallization of waxes contributing to hardening of the binder, even at ambient temperatures.
4. Exudation of oils: Some of the aggregates are porous. Due to the porous nature of the aggregates, the oils from the asphalt binder are exuded into the aggregates in an asphalt mix to a different extent thereby resulting in aging of the binder.

Rejuvenating agents are added to RAP mixes to restore the physical and chemical properties of the aged RAP binder. Rejuvenating agents are additives, which are capable of restoring the original rheological properties of the aged RAP binder [9].These rejuvenating agents are believed to diffuse through the aged RAP binder up to a certain depth of the aged binder film and restore the original maltene to asphaltene ratio in it, making it a less stiff material or a more flexible material [10].This rejuvenated RAP binder is expected to blend with the virgin binder and contribute to the overall asphalt content of the mix. Recent research has shown that the use of a high (90% - 100%) RAP content in HMA with rejuvenators is successful in reducing the overall stiffness of the RAP mixes, and improving its performance. But research on the use of rejuvenators and its effects on performance of mid-high range RAP mixes has been so far very limited.

1.4 **Objectives**

The objective of this study is to investigate the performance of hot mix asphalt (HMA) binder course materials with 50% reclaimed asphalt pavement (RAP) with rejuvenators and compare test results with that of a control mix with 20 % RAP and to quantify the benefits of using HMA with 50% RAP content.

1.5 **Scope of work**

The scope of work consisted of preparation of HMA mixes with and without rejuvenators. Two rejuvenators, Waste Vegetable Oil and Sylvaroad were used in the present investigation. The various tests that were conducted on the HMA samples include non-destructive test (Ultrasonic pulse velocity), creep test, indirect tensile strength and semicircular bend test. The mixes were also subjected to Moisture Induced Stress Testing (MIST) to evaluate their moisture susceptibility. The extracted binders were tested for their stiffness at low, intermediate and high temperatures to evaluate their thermal, fatigue cracking and rutting potential respectively and determine the PG grade. Finally cost analysis was carried out to compute the savings in total construction cost, if HMA mixes with high RAP content are used.

2 LITERATURE REVIEW

2.1 Importance and need for conservation of natural resources

A literature review was carried out to determine the state of the art and practice for use of RAP in HMA, its properties and performance with addition of rejuvenators, and its susceptibility to moisture damage. The focus of the review was on the high percentage RAP use with rejuvenators in binder and surface HMA layers.

Recycling of RAP has proved to be one of the most cost effective solutions to help manage the rising cost of materials and increased demand of new aggregates. All roads need to be periodically replaced or repaired and this work would produce reclaimed materials, which have considerable value that can be reused. According to the National Asphalt Pavement Association [11] more than 500 million tons of reclaimed asphalt pavement are being produced each year in the US from milling or other breaking up of old surfaced roads, of which only 100 million tons are being re-used in pavement-related applications. This RAP material has good quality of mineral and filler material and they might have been unchanged in properties over the years except for the binder which would have age-hardened. It has been found that the most economical use of the RAP material is in the surface and intermediate layer of HMA pavements, where the binder from RAP can replace a portion of the more expensive virgin binder [12]. Even though RAP has been used for road construction since the 1930's in small percentages, there is a recent interest in using higher RAP content in mix design. Recent research has shown that recycling with 90% - 100% RAP content is possible with the addition of appropriate rejuvenators [2].

Milling operations generally result in production of fines in the RAP, which, from most wearing surface mixes, usually have 4.5-6% asphalt content. RAP materials generally contain aged binder with high stiffness, and as a result are believed to have inferior fatigue and thermal cracking properties [13].

Therefore, in order to utilize RAP in HMA, it is essential to characterize the aggregate and asphalt in RAP. The major factors that determine the final percentage of RAP to be used in HMA are mixture properties, aggregate requirements, RAP handling and homogeneity, and project economics [14]. It is very crucial to ensure that the RAP binder is capable of blending well with the virgin binder and that the final blend would meet all the binder requirement. The aggregates in RAP sometimes have some serious effect on the total mixture volumetric and performance. Therefore it is necessary to take into account the design aggregate structure, crushed coarse aggregate content, dust proportion and fine aggregate angularity of RAP aggregates. When the aged binder from RAP is combined with virgin binder, the resultant binder grade is affected [15]. While at low RAP percentages, this change in binder grade is negligible, at high RAP percentages the effect of RAP binder becomes significant.

Rejuvenators are chemical additives that are capable of restoring the physical and chemical characteristics of aged asphalt binder in RAP.

Chen et al., (2015) [16] studied the application of rejuvenators and soft asphalt cements as recycling agents in RAP mixes. Various dosages of recycling agents were added to aged binders recovered from field samples. It is found that the performance of hardened binders can be improved significantly with the addition of rejuvenators. The blends mixed with rejuvenators behaved better under fatigue than those with softening agents. The large molecular size was shown to be a characteristic of an asphalt blend. It is suggested that the changes in the carbonyl area may be used to estimate the viscosity value of the asphalt blend. It was reported that the formation of the carbonyl area in aged asphalt was reduced by adding recycling agents, which in turn changed the physical properties of the blended binder in a predictable manner. Chen et al (2015) also developed a model to detect the content of recycling agents.

Shen et al., (2007) [17] studied Superpave mixtures containing RAP with rejuvenating agents including a rejuvenator and a softer binder. They also carried out indirect tensile strength and evaluated the mixtures for rutting using the asphalt pavement analyzer. The results indicated, for the mixtures tested for this project, that the properties of the recycled mixtures using the rejuvenator were better than those containing the softer binder and that 10% more RAP could be incorporated in the Superpave mixtures by using the rejuvenator than using the softer binder. It was also reported that the blending charts established under the Superpave binder specifications can be used to determine the content of the rejuvenator for recycling.

Li et al., (2014) [18] studied the influence of aged modified asphalt in reclaimed asphalt pavement (RAP) mix. Styrene–butadiene rubber (SBR) latex, a polymer emulsion was used to blend modified asphalt with conventional asphalt and it was found that SBR latex enhances the low-temperature properties of RAP binder efficiently without causing any observable negative influence on RAP mix compaction. SBR latex was found to improve the viscoelastic characteristics and other performance of RAP mix, including the resistance to low-temperature cracking, rutting, and moisture damage.

Bennert et al., (2014) [19] evaluated the Plant-Produced High-Percentage RAP Mixtures in the Northeast. Three potential strategies were evaluated for incorporating higher RAP contents, using a softer asphalt binder grade to offset the stiff RAP asphalt binder, limiting the amount of RAP binder credited to the total asphalt content of the asphalt mixture, and using a performance based specification for the high-RAP content mixture. If a softer binder is specified, the availability of the softer binder and the cost implications are to be considered. A marginal improvement in low-temperature cracking properties were observed, when softer grade of binder was used. Softer grade of binder did not improve the intermediate temperature cracking performance. It was reported that 75% and 50% RAP mixtures achieved better intermediate fatigue performance when compared with the baseline 100% RAP mixture as shown in the overlay tester and flexural fatigue test.

Cooper et al., (2015) [20] studied the use of recycled asphalt shingles (RAS) as a partial replacement for aggregates and petroleum-based virgin asphalt cement binder. It is reported that 5% RAS without recycling agents had similar performance compared with the control asphalt mixture containing no RAS at high, intermediate, and low temperatures. The inclusion of RAS with and without recycling agents showed an improvement in rutting performance with no adverse effect on moisture sensitivity compared with the control mixture without RAS. It is interesting to note that as use of recycling agents was increased, the recycled binder ratio, and the intermediate- and low-temperature performances of the mixture were adversely affected.

Mogawer et al., (2016) [21] used softer binders to compensate the stiffness of reclaimed asphalt pavement (RAP) binders in mixtures. The effect of five asphalt rejuvenators on the performance of a 50% RAP surface-layer mixture was evaluated relative to rutting and cracking. It was found that the rejuvenators degraded the rutting resistance of the 50% RAP mixture, although the use of PMA binders remedied these degradations. The rejuvenators were found to improve the fatigue cracking resistance of the 50% RAP mixture to a level higher than that of all-virgin control mixture and also the 50% RAP mixture with softer binder. It was concluded that a combination of an asphalt rejuvenator and a PMA binder was required to yield a high RAP mixture with similar or better performance than a similar conventional mixture.

Diefenderfer et al., (2016) [22] reported the dynamic modulus of field-produced and field-cured recycled pavement materials from 24 projects constructed in the United States and Canada. It was found that the binder from the existing reclaimed asphalt pavement may play a role in their stiffness properties. The authors reported that the master curves showed that the use of chemical additives increased the stiffness and reduced the temperature dependency of the recycled materials. The master curves showed that the dynamic modulus values were similar when emulsified asphalt and foamed asphalt were used as the stabilizing and recycling agents.

Ding et al., (2016) [23] studied the effect of incorporation of recycled (aged) binder into virgin asphalt especially the mechanism of the diffusion process between virgin and aged binders. Molecular dynamics (MD) simulation was employed to investigate the diffusion between virgin and aged binders, while increasing the asphaltenes ratio on the basis of virgin binder. It was found that the diffusion of large molecules in asphalt was a critical factor for the diffusion of binders and that it was more susceptible to the changes of temperature. It was reported that adding rejuvenator into aged binder could accelerate the inter-diffusion rate between virgin and aged binder to maximum level and increase the efficiency of recycling.

Shen et al., (2007) **[24]** studied the performance-based properties of rejuvenated aged asphalt binders containing a rejuvenator at various percentages, under high, intermediate and low temperatures. The rejuvenator was found to affect the performance-based properties of both the rejuvenated aged binders and the mixtures containing the rejuvenated aged binders significantly. The properties of the asphalt paving mixtures with the rejuvenated binders were found to have improved or at the same level as the properties of the virgin mixtures.

Zaumanis et al., (2014) [2] studied the feasibility of producing 100% recycled mixtures. The mix design procedures and the best RAP management strategies were reported. A cradle-to-gate analysis of environmental effects was presented and it was shown that 18 kg or 35% CO_2 eq savings per ton of produced 100% recycled asphalt mixture is possible when compared to virgin mix, while cost analysis showed at least 50% savings in material related expenses.

Im et al., (2014) [25] studied the impacts of various rejuvenators on the performance and engineering properties of hot-mix asphalt (HMA) mixtures containing recycling materials (i.e., RAP and RAS). They found that the use of rejuvenators improved cracking resistance of the recycled mixes. They also found that incorporation of rejuvenators in the recycled materials improved their moisture susceptibility and rutting resistance. They concluded that the performance of the rejuvenators depend on degree of blending between the binder of the recycled materials and the virgin binder, aggregates, and the rejuvenator dosage.

Zaumanis et al., (2014) [26] reported the changes in Superpave performance grade (PG) of Reclaimed Asphalt Pavement (RAP) binder after addition of two doses of six rejuvenators. The high and low PG temperatures were found to reduce linearly with an increased dose while the penetration value was found to increase exponentially. It was found that the grade sum of rejuvenated RAP binder is always higher than that of the corresponding virgin binder.

Zaumanis et al., (2014) [27] carried out experiments with 100% recycled HMA laboratory samples with five generic and one proprietary rejuvenators at 12% dose and studied the binder and mixture properties. Waste Vegetable Oil, Waste Vegetable Grease, Organic Oil, Distilled Tall Oil, and Aromatic Extract were found to change the Superpave performance grade (PG) from 94–12 of extracted binder to PG 64-22 at similar doses while waste engine oil required higher dose to do the same. The mixes with all rejuvenators ensured excellent rutting resistance while providing longer fatigue life when compared to virgin mixtures and most lowered the critical cracking temperature. It was found that rejuvenated samples required more gyratory compaction to reach the design density compared to virgin samples and some oils reduced moisture resistance slightly.

Buss et al., (2015) [28] studied the rheological effects of warm mix asphalt (WMA) additives in RAP mixes. They explored if the reduction in the asphalt binder grade is still detectable after in-service aging. It was found that WMA facilitates the incorporation of higher amounts of recycled asphalt materials. The recycled binder was found to have a larger influence on binder properties compared to WMA additives.

Ongel and Hugener., (2015) [29] studied the potential reductions in construction costs and environmental emissions by the use of reclaimed asphalt pavement (RAP) as aggregates in HMA as an attractive alternative to the highway agencies. The aging behavior of rejuvenated 100% RAP binder was studied and compared with that of the virgin bitumen. Three types of rejuvenators were assessed in the study. It was found that the laboratory aging of a 70/100 Pen graded asphalt was slower than that of rejuvenated 40/50 Pen grade asphalt. No significant difference between the aging behaviors of the bitumen mixed with different types of rejuvenators was reported.

Xiao et al., (2015) [30] explored the rheological properties of the high percentage (up to 50%) of RAP binder with three base binders in terms of five RAP binder content, two RAP binder sources, one HMA and one warm mix additive (WMA) technologies at three aging states. The viscosity, failure temperature, rutting resistance, fatigue resistance of various asphalt binders were tested. Increasing the RAP binder concentration was found to improve the rutting resistance of asphalt binder but a reduction in the fatigue resistance was noticed. RAP source was found to affect the performance properties of combined asphalt binder.

Nazzal et al., (2015) [31] adopted Atomic Force Microscopy (AFM) techniques to study the effects of rejuvenators on the nanomechanical properties of the interfacial blending zone that forms between RAP and virgin asphalt binders in a high RAP content mixture. It was found that that the rejuvenators did not have a significant effect on the modulus of the virgin binder. However, the indentation modulus of the interface blending zones was found to have significantly decreased. The authors reported that AFM force spectroscopy results showed that the rejuvenators increased the interfacial blending zone adhesive bonding energy. The AFM indentation modulus of interfacial blending zone was found to be correlating well with the Hamburg Wheel Tracking test results of the high RAP content mixtures. The authors concluded that the interfacial blending zone bonding energy might be one of the factors dictating fatigue performance of high RAP mixtures.

Ma et al., (2015) [32] investigated the feasibility of using high-content reclaimed asphalt pavement (RAP) in high modulus asphalt concrete (HMAC). The effects of RAP content on performance of recycled high modulus asphalt concrete (RHMAC) is found to be dependent on the specific RAP content and the performance indicator. RAP content was found to have a significant influence on dynamic modulus and failure strain when the RAP content increased to 40%, while the RAP content showed significant impact on dynamic stability and tensile strength ratio when the RAP content increased to 50%. Considering the influences of RAP on low temperature performance and moisture stability, the authors suggest that RHMAC is not to be used in the surface layer with high RAP contents.

Ali et al., (2016) [33] investigated the ability of five asphalt binder rejuvenators to restore low and high temperature true performance grades of aged binders. The rejuvenators considered were: Naphthenic Oil, a Paraffinic Oil, an Aromatic Extracts, a Tall Oil, and an Oleic Acid. Several sets of asphalt mixtures containing different percentages (i.e. 25% and 45%) of RAP materials were prepared using PG 76-22 polymer-modified asphalt binder and blended with rejuvenators at manufacturers' recommended dosage. The authors concluded that rejuvenators helped in lowering the true grade of aged asphalt binders of RAP and that all of the rejuvenated binders had lower performance grade than that of the control binder. The rejuvenator's effectiveness was found to be not affected by aging (from 2 to 6 h) and by increasing the amount of RAP materials (up to 45%). The rejuvenators were also found to improve the fatigue resistance without substantially influencing rutting performance.

Lu and Saleh., (2016) [34] investigated the performance of WMA with RAP at different percentages, from 0 to 70% by mass of WMA. The performance of mixtures was compared with a control HMA. Mixtures with the chemical additive were found to perform better than other mixtures in terms of moisture resistance. WMA mixture with the rejuvenator showed a higher number of cycles to fatigue failure than the control HMA. The increase in RAP proportion was found to greatly improve the performance of rutting performance of WMA mixtures. All WMA-RAP mixtures were found to offer better rutting resistance than the HMA.

Moghaddam and Baaj (2016) [35] presented an overview of the potential of using RAP with rejuvenators. They concluded that the rejuvenating mechanism needs to be explored. The binder and mixture performance tests can to some extent provide the behavior of rejuvenated mixture. However, more advanced testing such as chemical tests should be performed to evaluate the chemical performance characteristics of the rejuvenated binders.

Yu et al. (2014) [36] have conducted research on rheological properties of virgin, aged and rejuvenator binders using dynamic shear rheometer and bending beam rheometer, and showed that the viscosity and complex modulus of the rejuvenated binder, were between those of virgin and aged binder.

Rojas et al., (1999) [37] evaluated asphalt mixes in the laboratory using ultrasonic pulse velocity tests and concluded that the seismic modulus increased with a decrease in the voids in the total mix (VTM). The seismic modulus decreased with a decrease in the binder viscosity; however, the impact of the viscosity was found to become less pronounced at higher void percentage (as close to 8% compared to 4% voids). Also at higher void levels the impact of binder viscosity on the seismic modulus would be significantly high. The UPV is a suitable test as it allows the testing of a sample before and after moisture conditioning due to its nondestructive nature.

The Semi-Circular Bending (SCB) test is a particularly attractive test because it uses a semicircular sample – half of a standard laboratory compacted HMA sample or field core (and hence two test samples could be obtained from one compacted sample or field core). Baoshan et al. (2005) conducted Semi-Circular Bend (SCB) test and compared its results with Indirect Tensile Strength (ITS) of the HMA mixes. Their research work concluded that SCB test, similar to ITS, can be used to characterize the tensile strength of asphalt mixtures with good repeatability. The results from their study showed that the tensile strengths of the SCB test and ITS were different because of difference in stress states under loading. They also concluded that SCB was a more suitable test for evaluating the tensile properties of HMA mixtures, because of smaller permanent deformation under the loading strip.

Kakar et al., (2015) [38] presented a review of various techniques and investigations for assessing the moisture damage so as to optimize the standard testing protocols. The authors concluded that introduction of new in-situ testing techniques and material selection criteria is required to address the moisture susceptibility of asphalt mixtures, which can improve the field assessment of moisture damage that appears during the design life of an asphalt pavement, and bridge the gap between field and laboratory investigations.

Tran et.al., (2012) [39] evaluated the effect of using a rejuvenator on mechanistic and performance properties of recycled binders and mixtures containing high RAP and RAS contents in the laboratory. Their research finding showed that the use of rejuvenator in the recycled mixtures improved the cracking resistance of the RAP mixtures without severely affecting their resistance to moisture damage and permanent deformation.

Willis et al., (2012) [40] conducted research to find whether the durability of mixtures containing high percentages of RAP is affected by increasing the volume of virgin binder or decreasing the performance grade of virgin asphalt. They compared the results of 0, 25 and 50 percent RAP mixes with PG67-22 and PG 58-28 virgin asphalt binders. Their research finding showed that the fatigue life of both 25 and 50 percent RAP improved when they used a soft binder grade. They observed that for 25 percent RAP mixes, by increasing effective virgin binder content the number of cycles to failure also increased but this trend was not seen for the 50 percent RAP binder blends.

2.2 Needed research

There has been limited research carried out on the effect of the addition of rejuvenators on the properties of aged binders in RAP and their influence on the performance of HMA with a high percentage of RAP content. There is a need to investigate the laboratory properties of HMA with a high RAP content with rejuvenators, and compare them to the properties of regularly used mixes with relatively low percentage of RAP. This present study is an attempt in this direction. One unique feature of this study was the use of non-destructive test for evaluation of recycled mixes before and after moisture conditioning. The creep compliance test was conducted to evaluate the cracking potential at low temperature and the SCB test was selected to investigate the fracture resistance of the mixes with high RAP. The Moisture Induced Stress Tester (MIST) was carried out to assess moisture susceptibility of the HMA mixes with high RAP. PG grading of asphalt extracted from recycled mixes was conducted to determine the relevant properties at low, intermediate and high temperatures.

3 EXPERIMENTAL INVESTIGATIONS

3.1 Experimental plan

Figure 1 shows the experimental plan adopted for this study. It involves preparation and testing of 150 mm diameter and 38.1mm height samples, determining seismic modulus with the UPV at two different temperatures of -10°C and 25°C for pre-MIST and post-MIST samples. This was performed to study the properties of rejuvenated and non-rejuvenated RAP mixes and their susceptibility towards moisture damage, and also to evaluate their effect on stiffness at low temperatures. The ITS and SCB test were conducted to study the strength and fracture energy of the recycled mixes at 25°C.

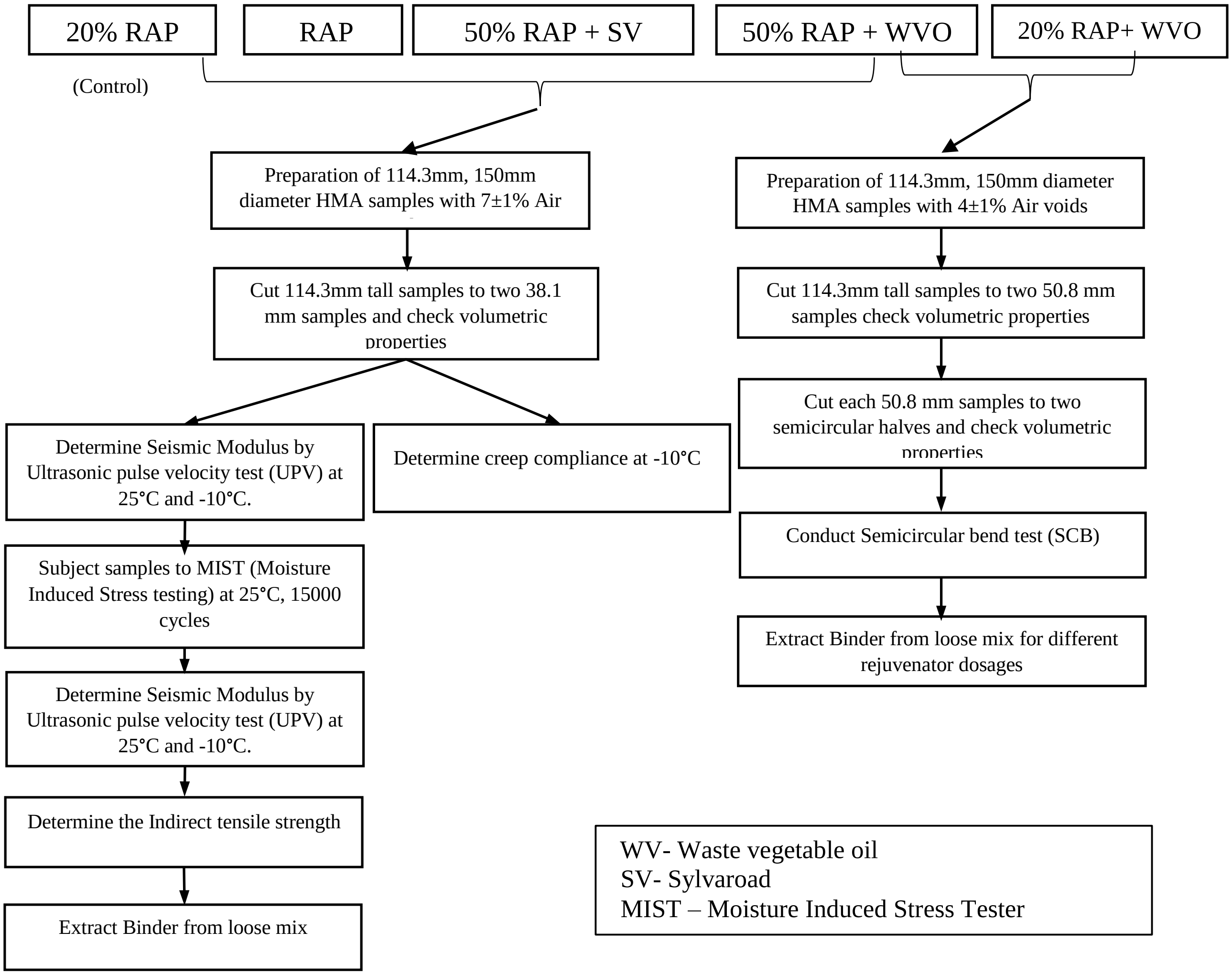


Figure 1: Experimental plan

Before framing this experimental plan, a plan was proposed in conducting dynamic modulus test in addition to ultrasonic pulse velocity test. But due to the problem of placing the LVDT (Linear

Variable Differential Transformer) mounts on the specimen, i.e. due to adhesion failure of LVDT mounts on the specimen, caused by the vacuum grease couplant used in the UPV test, the dynamic modulus test was not carried out, and the modulus values for the samples were computed from seismic modulus obtained from the UPV test.

4 MATERIALS AND METHODS

4.1 Gradation

The HMA mixes were prepared using RAP that was milled from in-service pavements in the city of West Brook, Maine, USA, and aggregates and asphalt binder provided by Maine DOT. The gradations adopted for the 20% RAP and 50% RAP mixes are shown in Table 1.The different stock pile materials used for this study consisted of 12.5mm, 9.5mm, Dry screen stone (DSS), Wet screen stone (WSS) and Sand and RAP. The percentages of these individual materials used for the samples are shown in Table 2.

Table 1: Gradation of materials used in the present Study

Sieve Size (mm)	Percent Passing		
	20% RAP	50% RAP	Specification Limits
19	100	100	100
12.5	99	99	92-100
9.5	87	89	80-90
4.75	59	57	52-66
2.36	45	44	41-49
1.18	34	34	30-38
600	22	23	19-25
300	12	13	10-14
150	6	8	5-9
75	4	6	2-6

Table 2: Individual aggregate proportions and asphalt content

Material	Aggregate Proportions	
	20% RAP	50%RAP
12.5mm	26	20
9.5mm	14	16
WSS	17	0
DSS	5	0
Sand	18	14
RAP	20	50
Virgin asphalt content (%)	4.7	3

4.2 Virgin Binder

The virgin binder used for preparing the mix was of grade PG 58-28 (provided by MDOT), which contained Evotherm (http://www.ingevity.com/markets/asphalt-and-paving/), a warm mix additive. A lower binder grade was selected by Maine DOT so as to compensate for the aged RAP binder. From binder extraction by ignition, the average binder content in the RAP mix was found to be 5.6 %. For 50% RAP mixes, the virgin binder content requirement was 3% of the total HMA mix [39], assuming the rest of the binder comes from the rejuvenated RAP material. Note that the NCAT recommendation (NCAT report No. 12-03) [40] of using slightly higher binder percentage when using higher RAP percentages was used. For 20% RAP mixes, the virgin binder content requirement was determined to be 4.7 % with 0.9% binder coming from RAP.

4.3 Rejuvenators

Rejuvenators are additives which are formulated to restore original properties like relaxation, ductility, cohesive and adhesive properties of aged (oxidized) asphalt binders, by restoring its original ratio of asphaltene to maltene. A rejuvenator usually contains high proportion of low viscosity maltene constituents to help restore the balance between maltene and asphaltenes of RAP binder that are changed during the aging process.

4.4 Waste vegetable oil (WV oil)

Waste vegetable oil, also known as cooking oil is derived from waste food frying oil. It is also sometimes referred to as “yellow grease”. The product used for this study consisted of peanut, sunflower, and canola oils, with large concentrations of oleic and linolic acids. It had low free fatty acids content and less than 2% moisture content in it. The optimum dosage of this rejuvenator was found to be 10.4 % by percentage weight of estimated asphalt binder from RAP, from penetration test results as shown in Figure 2. HMA with 20% and 50% recycled mixes for SCB samples were prepared using 2%, 6%, 10% and 15% rejuvenator dosages. Table 3 represents the SARA composition for Waste vegetable Oil.

Table 3: Saturates, Asphaltenes, Resins, Aromatics (SARA) table for waste vegetable oil (Frank, 2014 [41])

Rejuvenator	Asphaltenes	Saturates	Resins	Aromatics
Yellow Grease	-	0.01	32.4	67.5

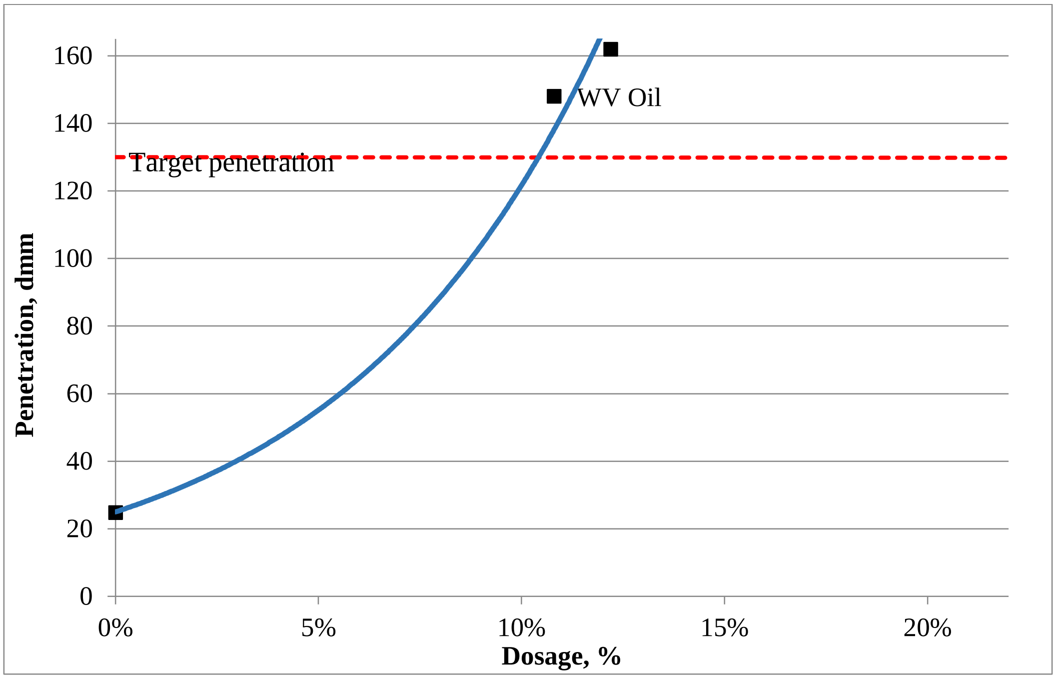


Figure 2: Optimum rejuvenator dosage for waste vegetable oil

4.5 Sylvaroad (SV)

Sylvaroad is a patented chemical additive produced from bio-renewable raw materials and marketed by Arizona Chemical (http://www.sylvaroad.com/). It is a pine chemical, derived from co-product of pulp and paper industry. This chemical is non-hazardous, bio-based and renewable. It has also been found that this rejuvenator is capable of reducing the stiffness of the RAP binder while using higher RAP percentages in the field (Rotterdam, NL). A rejuvenator dosage of 8% by weight of the estimated RAP binder was used according to the manufacturer’s recommendation.

5 MIX PROCEDURE

The mixing procedure adopted for this study were different for different mix types. The mixing procedures are explained in the following sections:

5.1 20% RAP and 50 % RAP without rejuvenators

The sequence of mixing for the 20% RAP and 50% RAP recycled mixes without rejuvenator involved drying and heating the virgin aggregates at 150^0C for 4 hours prior to mixing. The RAP was heated at a temperature of 150^0C for 1.5 hours. The virgin binder was heated to mixing temperature (150^0C) for 4 hours, with stirring to ensure homogeneous mixing. The RAP was added to the hot aggregates followed by the addition of binder and mixing for 2 minutes. The loose HMA mix was then aged at 150^0C for 4 hours prior to compaction. The binder content in RAP and the virgin binder content added to the mixes are shown in Table 4.

Table 4: Virgin and RAP Binder content in HMA Mixes

	20% RAP	50% RAP
RAP Binder Content, % (Ignition method)	5.6	5.6
Virgin Binder Content, %	4.7	3

5.2 50% RAP with waste vegetable oil rejuvenator

For recycled mixes with waste vegetable oil as rejuvenator, the virgin aggregates and virgin binder were heated at a temperature of 150°C for 4 hours prior to mixing. The RAP was warmed up to a temperature of 150°C for 1.5 hours before mixing. The mixing process involved addition of rejuvenator (kept at ambient temperature) to RAP and then mixing for 30 s. Virgin aggregates were then added and mixed for 60 s. This was followed by addition of hot virgin binder and mixing for another 90 s. The mix was aged at 150°C for 4 hours before compaction. Table 5 represents the Waste Vegetable Oil rejuvenator content calculation. For SCB test, the loose mix were prepared and aged as mentioned above using four rejuvenator dosages of 2%, 6%, 10% and 15%. The loose mixes with four rejuvenator contents were subjected to an additional long term aging at

135°C for 24 hours before compaction as they appeared to give more realistic results compared to the AASHTO R30 long-term aging procedure [42].

Table 5: Waste Vegetable Oil rejuvenator content calculation

RAP Binder Content,% (Ignition Method)	5.6
Virgin Binder Content, %	50% of Binder content available in RAP + 0.2% (NCAT Report No.12-05)[39]
	50% of 5.6% + 0.2% = 3
Rejuvenator content (% of RAP binder)	10.4

5.3 RAP with rejuvenator Sylvaroad (SV)

For recycled mixes with Sylvaroad as rejuvenator, the virgin aggregates were heated at a temperature of 180^{0}C (to compensate for the lower RAP temperature) for 8 hours prior to mixing. The RAP was warmed up at a temperature of 120^{0}C [110-130^{0}C] for 2.5 hours and the virgin binder was heated at the mixing temperature (150^{0}C) for 3 hours and stirred to have homogeneous mix before mixing. Sylvaroad rejuvenator (kept at ambient temperature) at a dosage of 8% by mass of RAP binder was added to the RAP and mixed for 30 seconds. The virgin aggregates were then added and mixed for 60 seconds. Hot virgin binder was then added and mixed for another 90 seconds. This loose mix was aged at 150°C for 4 hours before compaction. Table 6 shows the Sylvaroad rejuvenator content calculation

Table 6: Sylvaroad Rejuvenator Content Calculation

RAP Binder Content, % (Ignition Method)	5.6 %
Virgin Binder Content, %	50% of Binder content available in RAP + 0.2% (NCAT Report No.12-05)
	=50% of 5.6% + 0.2% = 3%
Rejuvenator content (% of RAP binder)	8% of RAP binder

6 COMPACTION

The compaction of the 20% and 50 % RAP mixes were carried out using a Superpave gyratory (ASTM D 4013). Figure 3a shows the Superpave gyratory compactor used for this study. The loose mixes after the required period, were compacted with target air void content of 7±1%, for non-SCB samples and 4±1% for SCB samples. The gyratory compactor was programmed such that the loose mix would be compacted with preset target height (114.3mm) or 100 gyrations, whichever is achieved first. The compacted samples had a diameter of 150mm and a height of 114.3mm. The compacted samples were then cut to 38.1mm thick samples for non-SCB testing and 50 mm thickness for SCB testing using saw cutter as shown in Figure 3b. The volumetric properties such as G_{mb} and G_{mm} were determined (ASTM D2041 and ASTM D2726) and air void contents of the each cut samples were calculated.

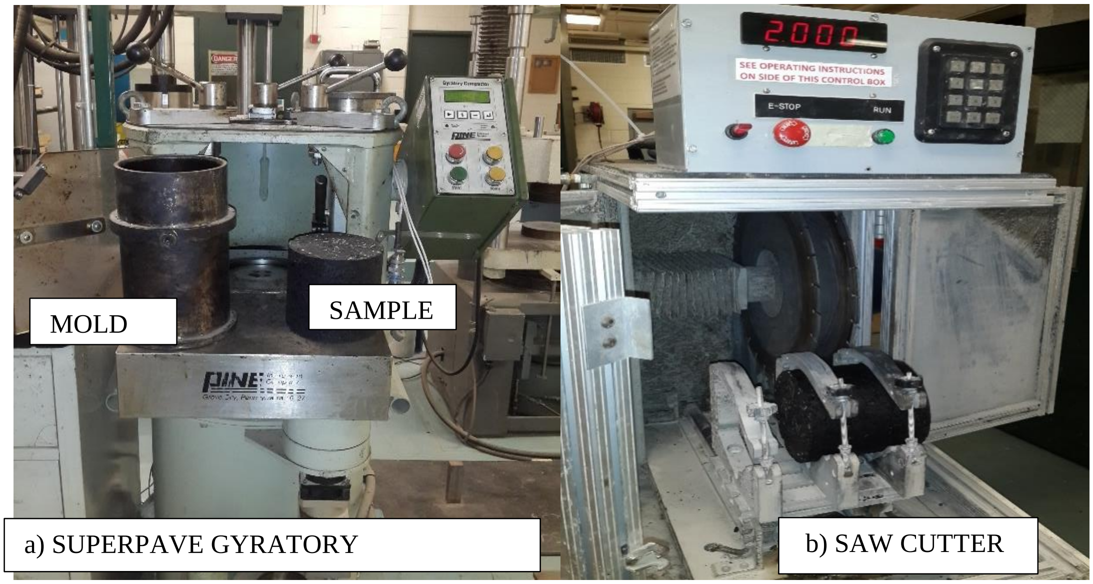


Figure 3: (a) Superpave Gyratory compactor and (b) Saw cutter

7 TEST METHODS

7.1 Ultrasonic pulse velocity

Ultrasonic Pulse Velocity test is a method of non-destructive evaluation of a HMA specimen based on wave propagation technique. In this test method, a piezoelectric crystal is used, which converts electrical energy to an ultrasonic shock wave. This shock wave or ultrasound is then transmitted from the transducer through the specimen and is then collected at the receiving transducer, which converts this shock wave back to an electrical pulse. The velocity of this pulse through a medium is dependent upon the material properties of the specimen such as its elastic properties and density of the medium. The test was conducted according to ASTM C597-09. For this study, six specimens were prepared for each mix type (24 specimens in total) of 150 mm diameter and 38 mm thickness. The equipment used in the study is a V-meter MK II, made by James Instruments, Inc, which generate ultrasonic pulse waves at a frequency of 54 KHz. The transducers were placed in direct transmission position for transmission and reception of these pulse waves. Damping pads and vacuum grease were used as couplant to ensure full contact between the transducer and specimen. A loading plate was placed on top of the transducer to ensure uniform pressure on the specimen. For calibration purposes, a specimen of known dimension was used. Figure 4 shows the apparatus used and experimental setup for the UPV test. The design modulus was obtained from seismic modulus (Nazarian et al., 2002) [43].

The specimen dimension was determined for each sample, and the compression wave (P-wave) velocity, Vp was then calculated from this equation:

$$Vp = H^* t_v \qquad (1)$$

Where H is the height of the specimen and t_v is the corresponding travel time (mean of four transmission time readings per sample). The constraint modulus, M_V, was then calculated using

$$Mv = \rho^* Vp \qquad (2)$$

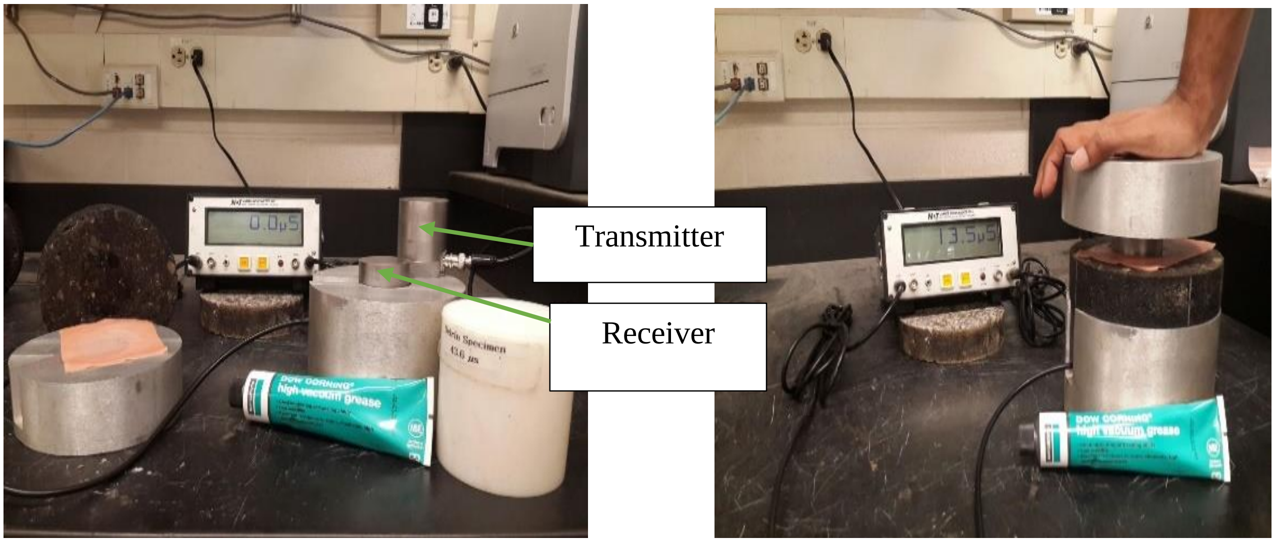
Where ρ is the bulk density of the specimen in g/cc.

The constraint modulus was then converted to Young's modulus, E_V through a theoretically corrected relationship in the form of

$$E_v = M_v * ((1+\mu) * (1-2\mu))/((1-\mu)) \qquad (3)$$

Where $E_v$is young’s modulus and μ is Poisson’s ratio. The Poisson’s ratio for all mixes was considered as 0.35.

In this study, the UPV test was conducted at two temperatures. 25°C and-10°C. These temperatures were selected to study the performance of the mix under expected fatigue cracking and low temperature cracking conditions respectively.



APPARATUS

EXPERIMENTAL SETUP

Figure 4: Ultrasonic device

7.2 Creep compliance and Indirect Tensile Strength test (ITS)

Creep compliance is a test method for characterizing the stiffness of material. It is used to determine the cracking potential of the asphalt mixes at low temperatures. For this study, the test was conducted according to AASHTO T322 and Indirect Tensile strength was performed according to ASTM D6931. These tests were used to evaluate the low temperature cracking potential and the strength of the recycled mixes. A total of three specimens for each mix type were used for each test. Figure 5 shows the experimental set up for creep compliance.

Creep compliance is defined as a ratio of time-dependent strain to the applied stress. It is determined by applying a static compression load to cause sufficient horizontal deformation in the sample between 0.00125 mm and 0.0190 mm (linear viscoelastic range). For a specimen with a gauge length of 38 mm, the corresponding strain range is recommended to be between $33\text{x}10^{-6}$ and $500\ \text{x}10^{-6}$ mm/mm (viscoelastic range) (AASHTO T322). The test is run for a period of 1,000 seconds at a temperature of -10°C, after a conditioning period of 3 hours. During the test, the horizontal and vertical deformations are measured on each face of the specimen using LVDT. For cases in which the strain on one face was higher (> allowable) than that in the other, the average strain value was chosen based on whichever face had a strain value within the viscoelastic range (33-500 µm).

Creep compliance was calculated by using the following equation:

$$D(t) = 1 + \frac{\Delta X_t \times d \times b}{P \times GL} \times C_{cmpl} \tag{4}$$

Where,

ΔX_t is the mean horizontal deflection (mm)
d is the diameter of the sample (mm)
b is the thickness of the sample (mm)
P is the creep load (kN)
GL is the gage length over which deformation is measured (mm)
C_{cmpl} is the compliance factor

$$C_{cmpl} = 0.6354\left(\frac{X}{Y}\right)^{-1} - 0.332 \tag{5}$$

Where X/Y is the ratio of horizontal to vertical deflection

The limits of C_{cmpl} are as follows:

$$\left[0.704 - 0.213\left(\frac{b}{d}\right)\right] \leq C_{cmpl} \leq \left[1.566 - 0.195\left(\frac{b}{d}\right)\right] \tag{6}$$

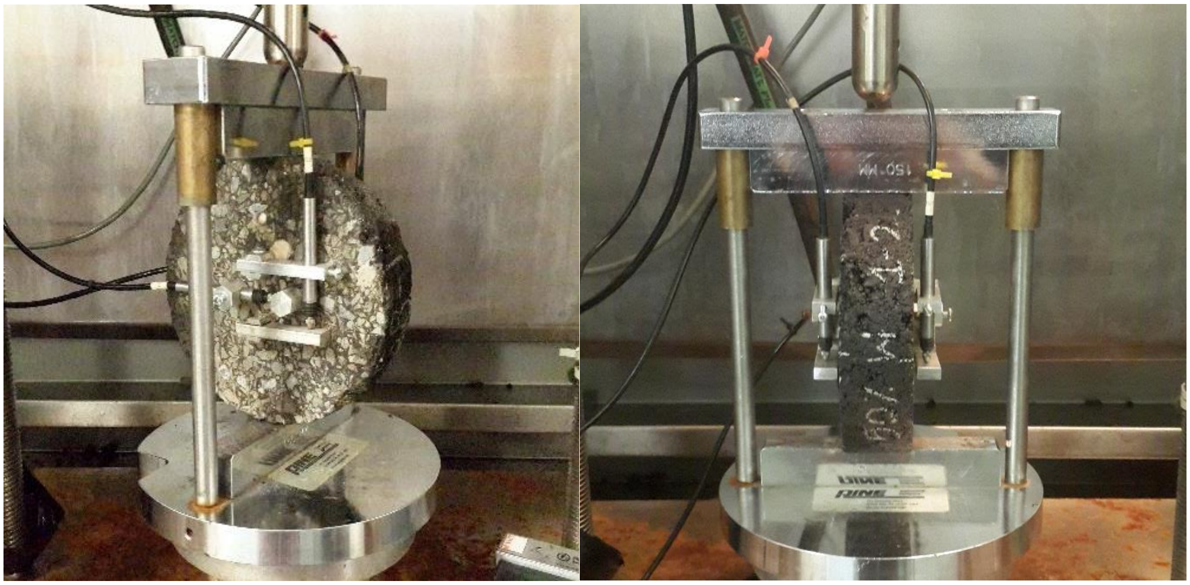


Figure 5: Creep compliance test setup

7.3 Indirect Tensile Strength (ITS)

The Indirect tensile test (ASTM D6931) was used to determine the strength of the asphalt mixes. The test was conducted by loading a cylindrical across its vertical diametric plane at a specified rate of deformation (50 mm per minute) and at a test temperature of 25°C. The peak load at failure was recorded and was used to calculate the ITS strength of the specimen. The Indirect Tensile strength of the specimen is given by equation 7:

$$Indirect\ Tensile\ Strength\ (ITS)\ =\ \frac{2P}{\pi dt} \tag{7}$$

Where,

ITS = Indirect Tensile Strength (kPa)

P = Peak Load applied under failure (N)

D = Diameter of the specimen (mm) and

t =Thickness of the specimen (mm)

7.4 Moisture Induced Stress Tester (MIST)

The Moisture Induced Stress Test (MIST) (equipment shown in Figure 6) simulates the generation of pore water pressure which is generated in a saturated pavement under repeated traffic loads. In this test, water is forced in and out of the samples by applying compressed air through a bladder assembly. The samples for this study were subjected to 15,000 cycles of loading with water pressure at 30 psi pressure and 25℃ test temperature. The above conditions were selected over an ASTM 7870 protocol of 60°C at 3,500 cycles and 40 psi to ensure the integrity of the specimen and the ability to test them after conditioning with the MIST.

Figure 6: Moisture Induced Stress Test equipment

7.5 Semi Circular Bend test (SCB)

The Semi Circular Bend Test (SCB) was used to determine the fracture energy and fracture toughness of the asphalt mixtures at intermediate temperature. The SCB test was performed according to the AASHTO standard (Al-Qadi et al., 2015) [44] at 25ºC. For this test, a semicircular disc of HMA, 150 mm in diameter and 25 mm thick, was tested in a 3-point bending mode as shown in Figure 7. Before conducting the test, a notch was created at the center for all samples, for a depth of 15 mm from the flat face of the specimen to initiate the crack propagation. The test was performed by imposing a small contact load of 0.1 ± 0.01 kN and then by loading at a rate of 50mm/min. The test was stopped once the load dropped below 0.1 kN.

The total work of fracture W_f was calculated by dividing the load-displacement data into two parts i.e. curve prior to peak load and the curve after the peak load and then numerically integrating the total area under the two parts.

The total work of fracture is calculated using the integral equation

$$\mathrm{W}_f = \int_0^{u_0} P_1(u)du + \int_{u_0}^{u_{final}} P_2(u)du \qquad (5)$$

Where U_{final} is the displacement at 0.1kN cut-off load

U_0 is the displacement at peak load (kN)

The fracture energy G_f was then found by dividing the work of fracture by the ligament area of the SCB specimen prior to testing

$$\mathrm{G}_f = \frac{W_f}{Area_{lig}} \times 10^6 \qquad (6)$$

Where:

G_f = fracture energy (Joules/m^2)

W_f = work of fracture (Joules)

P =load (kN)

Area $_{lig}$ = ligament length x×t

t = specimen thickness (mm)

The Flexibility Index (FI) is calculated from the parameters obtained from the load displacement curve.

$$FI = \frac{G_f}{|m|} \times A$$

Where

FI= Flexibility Index

|m|= absolute value of post-peak load slope m (kN/mm)

A= 0.01

Figure 7: Semicircular bend test (SCB) and specimen

7.6 Asphalt binder extraction

The binder from 20% RAP and 50 % RAP - rejuvenated and non-rejuvenated loose mix samples were extracted using solvent extraction procedure (ASTM D5405). For this method, toluene solution was used as a solvent to extract asphalt binder from the aggregates of the loose recycled mixes. This extracted asphalt with the toluene was transferred into a rotating distillation flask of the rotary evaporator, which was partially immersed in a heated oil bath. This solution was subjected to partial vacuum and a flow of nitrogen gas to separate asphalt binder from toluene. The recovered asphalt was then subjected to penetration test, Rolling Thin Film Oven (RTFO) test and Direct Shear Rheometer (DSR) test to find the penetration grade, high, low and intermediate temperatures of the extracted binder.

8 HIRSCH MODEL

The Hirsch model is a semi-empirical method of predicting modulus of HMA. Christensen et al. (2003) developed the application of the Hirsch model to HMA mixes. They had examined four different models based on the law of mixtures, parallel model and selected the model that incorporates the binder modulus, VMA, and VFA because it provides accurate results in the simplest form in the prediction of the modulus of HMA. For this study the Hirsch model was used to back calculate the shear complex modulus of the binder (G*), by using the design modulus values obtained from ultrasonic pulse velocity test and the volumetric properties by assuming that the bulk specific gravity of the aggregate (G_{sb}) is equal to effective specific gravity of the aggregate (G_{se}). The following equations were used to back calculate the complex modulus of the binder (G*) from Hirsch model.

$$E^* = P_c \times \left[4200000\left(1-\frac{VMA}{100}\right) + 3\,|G^*|_{binder}\left(\frac{VFA*VMA}{10000}\right) + \frac{1-P_c}{\left[\frac{\left(1-\frac{VMA}{100}\right)}{4200000} + \frac{VMA}{3\,|G^*|_{binder}\,VFA}\right]}\right. \tag{7}$$

$$P_c = \frac{20 + \frac{3\,|G^*|\,VFA}{VMA}^{\;0.58}}{650 + \left(\frac{3\,|G^*|\,VFA}{VMA}\right)} \tag{8}$$

Where

E*= Modulus (MPa) (Derived from Seismic Modulus [37])

G*= Shear Complex Modulus, (kPa)

VMA= Voids in Mineral Aggregates, %

VFA= Voids Filled with Asphalt, %

9 RESULTS AND ANALYSIS

A total of six samples were made for each mix type of 20% RAP (20R), 50% RAP (50R), 50% RAP with waste vegetable oil (50R-WV) and 50% RAP with Sylvaroad (50R-SV), of which three samples were used for ultrasonic pulse velocity test and the other three for creep compliance test. The air voids of the samples are shown in Table 7. Analysis of Variance (ANOVA), a statistical test used to determine the equality between the means of several groups, was carried out to determine if there is significant difference among the test properties of the different mix types using Stat tools software [44].

Table 7: Air Void Distribution among samples

Specimen No	Air Voids, %			
	20 R	**50 R**	**50R-WV**	**50 R-SV**
1	7.1	6.7	6.9	6.6
2	7.2	6.8	6.3	6.8
3	7.3	7	7.1	6.9
4	7.5	7.1	6.3	7.6
5	7.6	7.4	6.8	7.7
6	8	6	6.9	6

The following designation were used to denote the Mix type in this project: 20R - 20% RAP mix, 50R - 50% RAP mix, 50R-WV - 50% RAP mix with Waste Vegetable oil Rejuvenator 50R- SV - 50% RAP mix with Sylvaroad rejuvenator, 100R- 100% RAP.

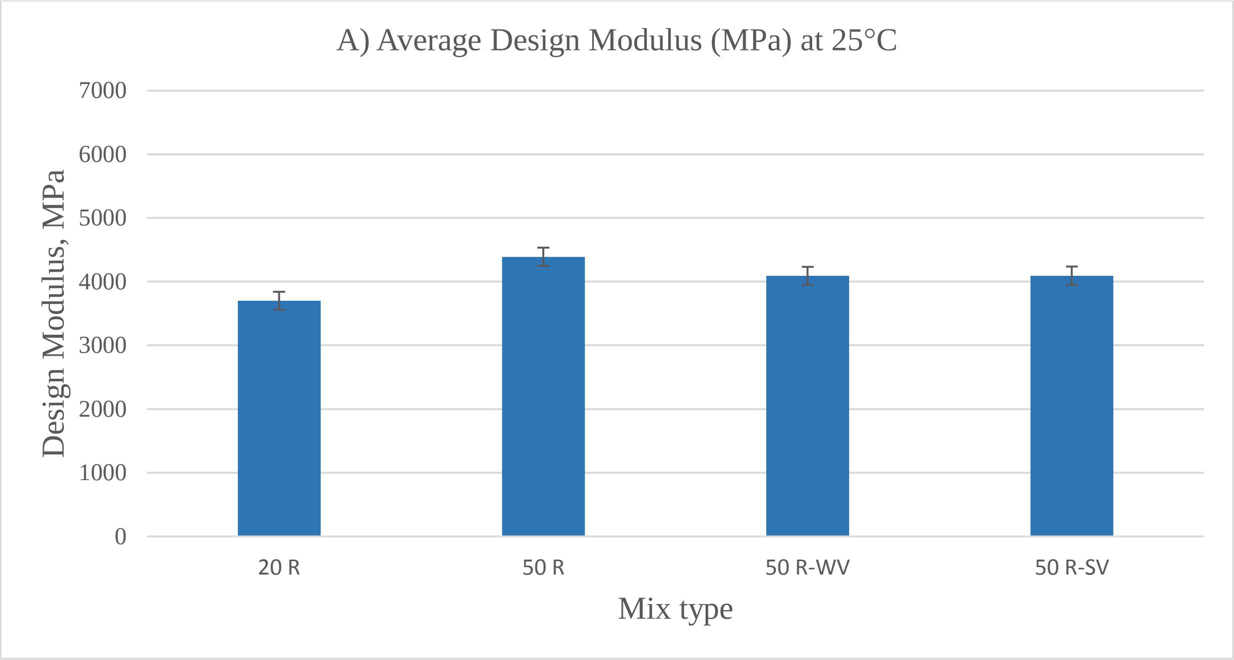
9.1 Ultrasonic Pulse Velocity (UPV) test result

The ultrasonic pulse velocity test was performed at two temperatures to study the effects of rejuvenated blends at low temperatures and intermediate temperatures. Seismic and the design moduli values obtained for the different mixes are shown in Table 8. The UPV test results reveal that the moduli values are higher at -10°C. Figure 8 shows the average Design moduli values at both 25°C and -10°C. Figure 9 shows the change in moduli values when the temperature was changed from 25°C to -10°C for the different mixes. While the trends in changes in moduli values with temperatures are similar, the plots do show that the rejuvenators are effective in lowering the stiffness of the 50R mix, and hence in rejuvenating the recycled mix. The results were analyzed to determine whether a significant difference between the different mixes exists. Table 8 shows that the 50% RAP mixes are ranked A (indicating a higher modulus) followed by the rejuvenator mixes which are ranked B, and the 20% RAP mixes, which are ranked as C.

Table 8: Seismic and Design Moduli at 25°C and -10°C

(Note: A higher rank indicates a higher Modulus)

Specimen ID	Avg. Travel Time at 25 °C (microsec)	Avg. Travel Time at -10 °C (microsec)	Seismic Modulus at 25 °C (MPa)	Seismic Modulus at -10 °C (MPa)	Design Modulus at 25 °C (MPa)	Design Modulus at -10 °C (MPa)	RANKING
ID	**t**	**t**	**SM**	**SM**	**DM**	**DM**	
20R-1	11.3	9.9	12036	15831	3761	4947	C
20R-2	11.6	9.9	11807	16152	3690	5048	
20R-3	11.4	9.8	12042	16284	3763	5089	
20R-4	11.4	9.8	12226	16483	3821	5151	
20R-5	11.7	9.9	11327	15808	3540	4940	
20R-6	11.6	9.8	11620	16519	3631	5162	
50R-1	10.8	9.4	13784	18221	4308	5694	A
50R-2	10.6	9.3	14416	18652	4505	5829	
50R-3	10.6	9.3	13996	18269	4374	5709	
50R-4	10.7	9.3	13950	18380	4359	5744	
50R-5	10.6	9.4	14117	18144	4412	5670	
50R-6	10.6	9.3	14019	18310	4381	5722	
50R-WV-1	11.0	9.5	13071	17792	4085	5560	B
50R-WV-2	10.9	9.3	13582	18388	4244	5746	
50R-WV-3	11.1	9.5	13047	17839	4077	5575	
50R-WV-4	11.0	9.4	13298	18391	4156	5747	
50R-WV-5	11.2	9.5	12740	17564	3981	5489	
50R-WV-6	11.0	9.4	12818	18020	4006	5631	
50R-SV-1	11.1	9.4	12937	18069	4043	5647	B
50R-SV-2	11.0	9.3	12979	18157	4056	5674	
50R-SV-3	11.0	9.3	13188	18268	4121	5709	
50R-SV-4	11.0	9.3	13184	18345	4120	5733	
50R-SV-5	11.0	9.4	13124	18054	4101	5642	
50R-SV-6	11.0	9.4	13177	18031	4118	5635	



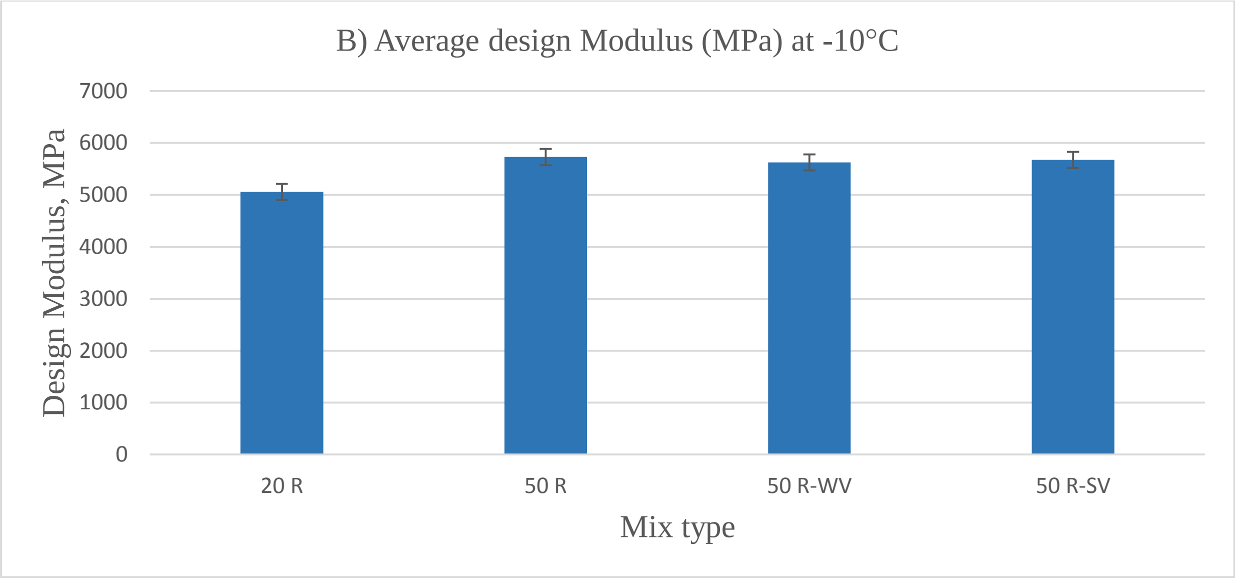


Figure 8: Average Design Modulus: A) 25°C; B) -10°C

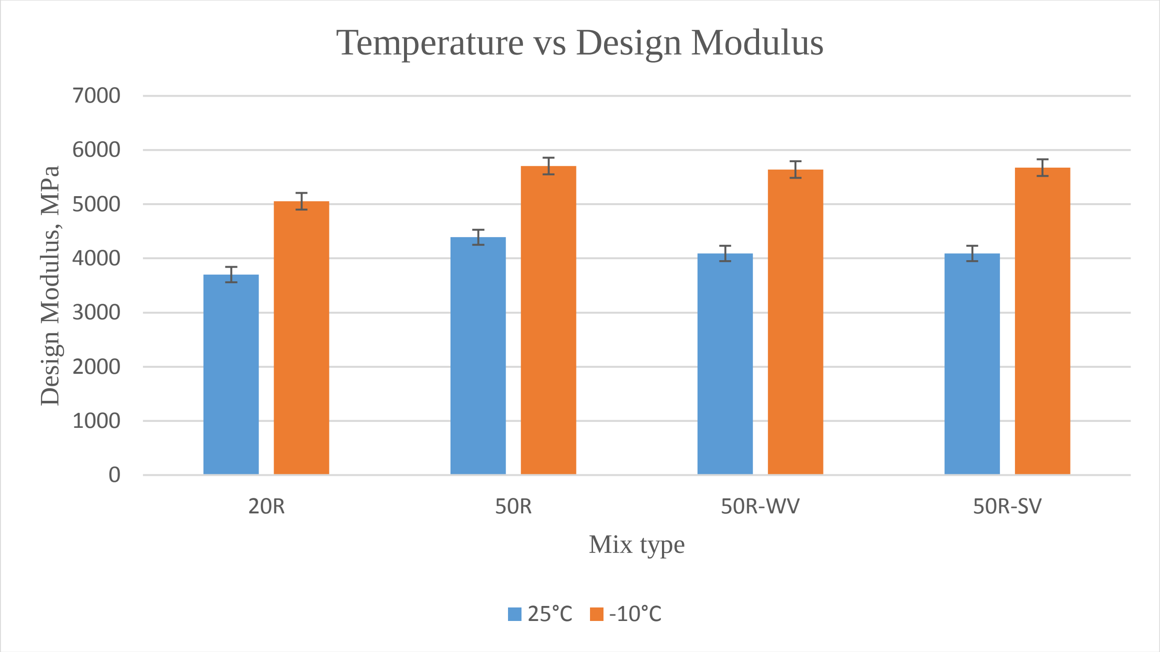


Figure 9: Plots of temperature versus modulus for the different mixes

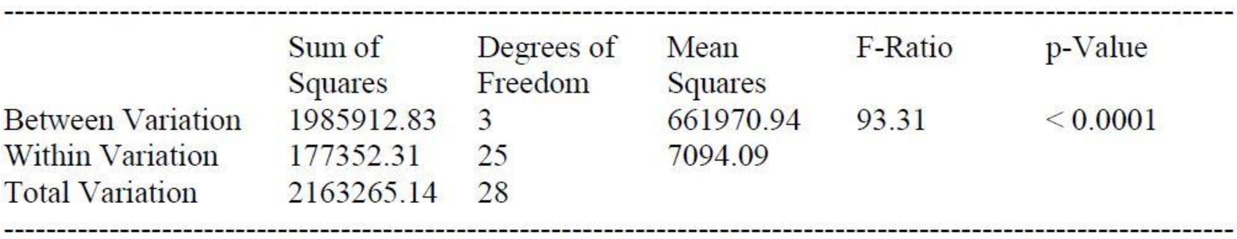
Table 9: ANOVA for Design Modulus (DM) at 25°C:

	Sum of Squares	Degrees of Freedom	Mean Squares	F-Ratio	p-Value
Between Variation	1567607.91	3	522535.97	70.60	< 0.0001
Within Variation	185026.32	25	7401.05		
Total Variation	1752634.23	28			

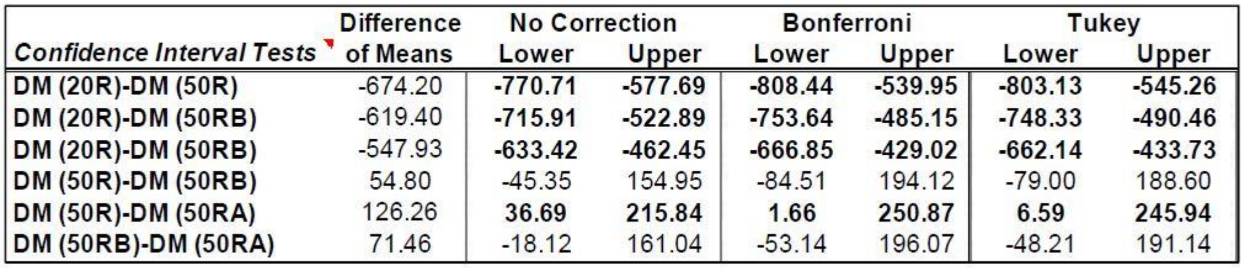
	Difference	No Correction		Bonferroni		Tukey	
Confidence Interval Tests	of Means	Lower	Upper	Lower	Upper	Lower	Upper
DM (20R)-DM (50R)	-689.29	**-787.87**	**-590.72**	**-826.41**	**-552.17**	**-820.98**	**-557.60**
DM (20R)-DM (50RB)	-392.72	**-491.29**	**-294.14**	**-529.84**	**-255.60**	**-524.41**	**-261.02**
DM (20R)-DM (50RA)	-380.29	**-467.60**	**-292.97**	**-501.74**	**-258.83**	**-496.94**	**-263.63**
DM (50R)-DM (50RB)	296.58	**194.28**	**398.87**	**154.28**	**438.87**	**159.91**	**433.24**
DM (50R)-DM (50RA)	309.01	**217.51**	**400.50**	**181.73**	**436.28**	**186.77**	**431.24**
DM (50RB)-DM (50RA)	12.43	-79.06	103.93	-114.84	139.70	-109.81	134.67

Where 50RA - 50% RAP Waste Vegetable Oil rejuvenator; 50RB - 50% RAP Sylvaroad rejuvenator.

Table 10: ANOVA for Design Modulus (DM) at -10°C



	Sum of Squares	Degrees of Freedom	Mean Squares	F-Ratio	p-Value
Between Variation	1985912.83	3	661970.94	93.31	< 0.0001
Within Variation	177352.31	25	7094.09		
Total Variation	2163265.14	28			



Confidence Interval Tests	Difference of Means	No Correction Lower	No Correction Upper	Bonferroni Lower	Bonferroni Upper	Tukey Lower	Tukey Upper
DM (20R)-DM (50R)	-674.20	**-770.71**	**-577.69**	**-808.44**	**-539.95**	**-803.13**	**-545.26**
DM (20R)-DM (50RB)	-619.40	**-715.91**	**-522.89**	**-753.64**	**-485.15**	**-748.33**	**-490.46**
DM (20R)-DM (50RB)	-547.93	**-633.42**	**-462.45**	**-666.85**	**-429.02**	**-662.14**	**-433.73**
DM (50R)-DM (50RB)	54.80	-45.35	154.95	-84.51	194.12	-79.00	188.60
DM (50R)-DM (50RA)	126.26	**36.69**	**215.84**	**1.66**	**250.87**	**6.59**	**245.94**
DM (50RB)-DM (50RA)	71.46	-18.12	161.04	-53.14	196.07	-48.21	191.14

Where 50RA - 50% RAP Waste Vegetable Oil rejuvenator; 50RB - 50% RAP Sylvaroad rejuvenator.

Table 9 and 10 confirms that the results are significantly different. Table 9 also shows that while there are differences between most of the mixes, there is no significant difference between the moduli of the 50R-WV and 50R-SV. Table 10 shows that at -10°C there is no significant difference between the moduli of 50R and 50R-SV and also 50R and 50R-WV

9.2 MIST test results

Three samples were chosen for each mix type with similar air void (7±1) content. These samples were then subjected to MIST. Table 11 shows the results of the UPV tests conducted before and after MIST test. An increase in the moduli values were observed after MIST test. Figure 10 shows the pre and post MIST modulus values, as well as the decrease in air voids for each of the samples of the different mixes. It is noted that even though the change in voids are the same or lower than the control and the 50R mixes, the rejuvenated mix samples have a comparatively higher change in modulus after the MIST process (that is, higher difference between pre and post MIST modulus). These could be due to either or both of two reasons. First, the presence of the rejuvenator could be facilitating the compaction of the mixes in such a way that the aggregate structure is improved, which leads to an increase in the modulus. The second possibility is that the action of the MIST conditioning process is reversing the effect of rejuvenation, and making the mix similar to the 50R mix. This possibility is being raised because it is noted that the post MIST modulus of the rejuvenated mix samples are almost at the same level as that of the post MIST modulus of the 50R samples. Table 12 shows the bulk specific gravity (BSG) and Air void (%) results before and after MIST test. We can see that there is an increase in density of the mix after MIST test. It can be seen from Table 11 that the difference between the pre and post-MIST samples were similar for the rejuvenated mixes, and higher than that of the other mixes. The 20R samples had the lowest difference between the pre and the post MIST samples. Further study is required to evaluate the change in modulus in rejuvenated samples due to the MIST process.

Table 11: Moisture Induced Sensitivity Tester (MIST) results on Moduli Values of RAP mixes

(Note: A higher rank indicates a higher moisture effect)

Sample ID	**Design Modulus, before moisture effect, MPa**	**Design Modulus after moisture effect, MPa**	**Difference between Pre and Post Moisture Test, %** $(\frac{Post - Pre}{Pre})\%$	**Ranking**
20R-2	3690	3956	7.21	B
20R-3	3778	3914	3.59	
20R-6	3631	3888	7.08	
50R-1	4291	4344	1.23	C
50R-3	4378	4407	0.65	
50R-5	4333	4374	0.95	
50R-WV-1	4085	4563	11.70	A
50R-WV-5	3981	4531	13.81	
50R-WV-6	4006	4579	14.32	
50R-SV-1	4043	4496	11.21	A
50R-SV-2	4056	4491	10.73	
50R-SV-5	4101	4596	12.07	

Table 12: Density comparison (PreMIST vs PostMIST)

Sample ID	Pre-MIST		Post-MIST		BSG Difference (Pre-Post) %
	BSG	AV (%)	BSG	AV (%)	
20R-2	2.293	7.08	2.312	6.3	0.8
20R-3	2.291	7.2	2.307	6.5	0.7
20R-6	2.287	7.3	2.300	6.8	0.5
50R-1	2.307	7.0	2.324	6.3	0.7
50R-3	2.305	7.1	2.318	6.6	0.5
50R-5	2.299	7.4	2.321	6.4	1.0
50R-WV-1	2.307	6.9	2.322	6.3	0.7
50R-WV-5	2.309	6.8	2.324	6.2	0.6
50R-WV-6	2.323	6.3	2.332	5.9	0.4
50R-SV-1	2.296	7.6	2.297	7.5	0.0
50R-SV-2	2.293	7.7	2.299	7.4	0.3
50R-SV-5	2.312	6.9	2.326	6.4	0.6

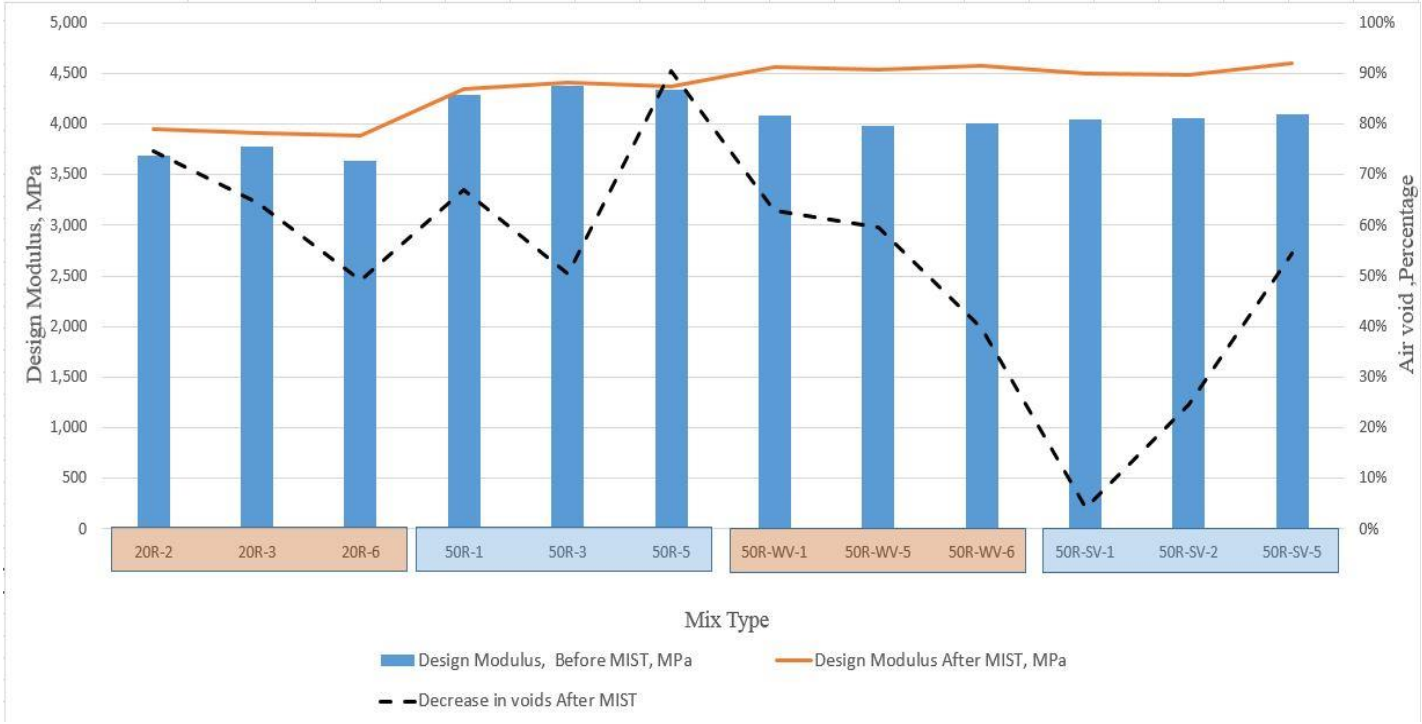
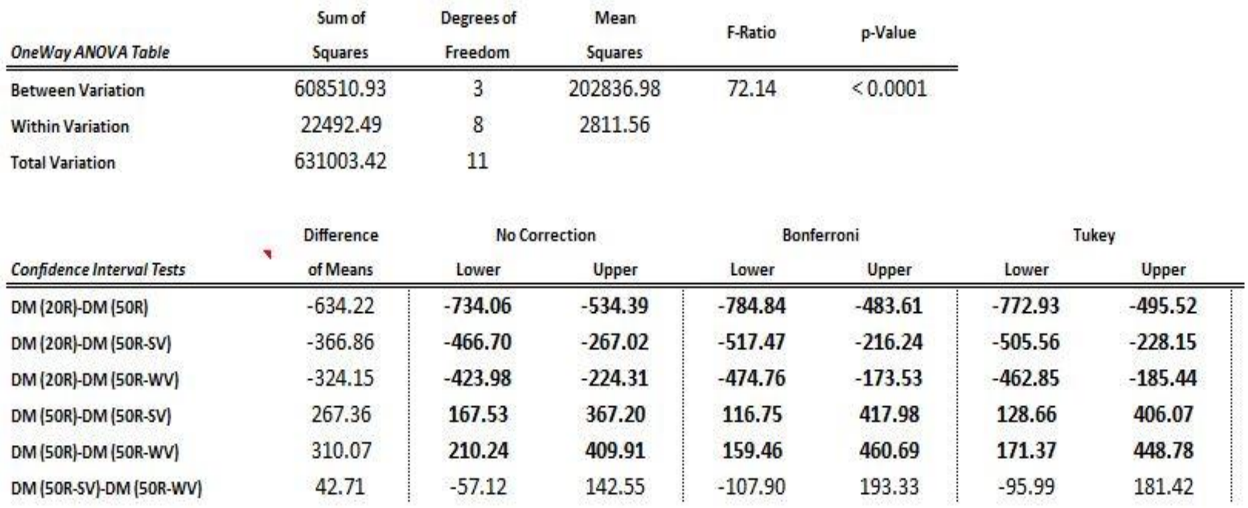


Figure 10: Comparison of Pre, Post MIST design Moduli and Air voids

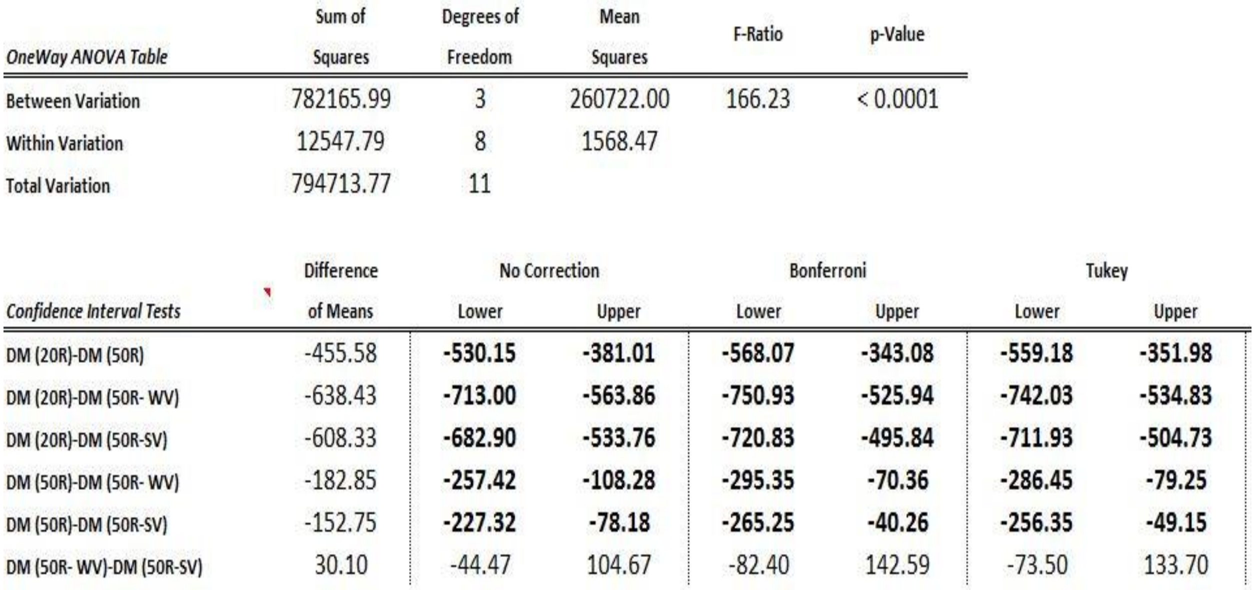
Table 13: ANOVA for Pre-MIST DM at 25C



OneWay ANOVA Table	Sum of Squares	Degrees of Freedom	Mean Squares	F-Ratio	p-Value
Between Variation	608510.93	3	202836.98	72.14	< 0.0001
Within Variation	22492.49	8	2811.56		
Total Variation	631003.42	11			

	Difference	No Correction		Bonferroni		Tukey	
Confidence Interval Tests	of Means	Lower	Upper	Lower	Upper	Lower	Upper
DM (20R)-DM (50R)	-634.22	**-734.06**	**-534.39**	**-784.84**	**-483.61**	**-772.93**	**-495.52**
DM (20R)-DM (50R-SV)	-366.86	**-466.70**	**-267.02**	**-517.47**	**-216.24**	**-505.56**	**-228.15**
DM (20R)-DM (50R-WV)	-324.15	**-423.98**	**-224.31**	**-474.76**	**-173.53**	**-462.85**	**-185.44**
DM (50R)-DM (50R-SV)	267.36	**167.53**	**367.20**	**116.75**	**417.98**	**128.66**	**406.07**
DM (50R)-DM (50R-WV)	310.07	**210.24**	**409.91**	**159.46**	**460.69**	**171.37**	**448.78**
DM (50R-SV)-DM (50R-WV)	42.71	-57.12	142.55	-107.90	193.33	-95.99	181.42

Table 14: ANOVA for Post-MIST DM at 25C



OneWay ANOVA Table	Sum of Squares	Degrees of Freedom	Mean Squares	F-Ratio	p-Value
Between Variation	782165.99	3	260722.00	166.23	< 0.0001
Within Variation	12547.79	8	1568.47		
Total Variation	794713.77	11			

	Difference	No Correction		Bonferroni		Tukey	
Confidence Interval Tests	of Means	Lower	Upper	Lower	Upper	Lower	Upper
DM (20R)-DM (50R)	-455.58	**-530.15**	**-381.01**	**-568.07**	**-343.08**	**-559.18**	**-351.98**
DM (20R)-DM (50R- WV)	-638.43	**-713.00**	**-563.86**	**-750.93**	**-525.94**	**-742.03**	**-534.83**
DM (20R)-DM (50R-SV)	-608.33	**-682.90**	**-533.76**	**-720.83**	**-495.84**	**-711.93**	**-504.73**
DM (50R)-DM (50R- WV)	-182.85	**-257.42**	**-108.28**	**-295.35**	**-70.36**	**-286.45**	**-79.25**
DM (50R)-DM (50R-SV)	-152.75	**-227.32**	**-78.18**	**-265.25**	**-40.26**	**-256.35**	**-49.15**
DM (50R- WV)-DM (50R-SV)	30.10	-44.47	104.67	-82.40	142.59	-73.50	133.70

From Table 13 and 14 we can see that the all the mixes are significantly different except the rejuvenator mixes. There is no significant difference observed between the 50R-SV samples and 50R-WV samples. This also tells us that both rejuvenated mixes are affected to the same extent by the MIST process.

9.3 Penetration test results

The extracted binder from the loose mix samples were tested for penetration (ASTM D5-06). Penetration test was performed to evaluate the effects of high percentages of RAP binder containing rejuvenators on the properties of virgin binder and overall binder properties. The results are presented in Table 15. The observed penetration values for the 100% RAP and the 50%RAP are low as expected. This indicates that 100 % RAP binder and 50 % RAP binder are stiffer compared to the 50% RAP rejuvenated binders and 20% RAP binders. The penetration results reveal that the rejuvenators are effective in reducing the overall stiffness of the aged RAP binders. Of the two rejuvenators, the Sylvaroad rejuvenator was found to be more effective in reducing the overall stiffness of the binder and hence resulted in a higher penetration values compared to the waste vegetable oil. Figure 11 represents the penetration values obtained for the different mix type. The results of Mean Separation test are also shown in Table 15. It can be seen from table that the 50R-SV mix is ranked A (which indicates more soft mix than others), the 50R-WV is ranked B, followed by the control mix (20R) which is ranked as C and 50% RAP and 100% RAP which are ranked as D.

Table 15: Penetration Test Results on Extracted Binder from HMA mixes

(Note: A higher rank indicates a higher penetration value)

Extracted Asphalt	**Temperature**	**Penetration 1/10mm**				**Ranking**
	°C	**Measurement 1**	**Measurement 2**	**Measurement 3**	**Mean**	
100% RAP	25	32	32	25	30	D
20% RAP	25	50	51	41	47	C
50% RAP	25	25	31	27	28	D
50%RAP+WVO	25	62	65	66	64	B
50%RAP+ SV	25	80	86	81	82	A

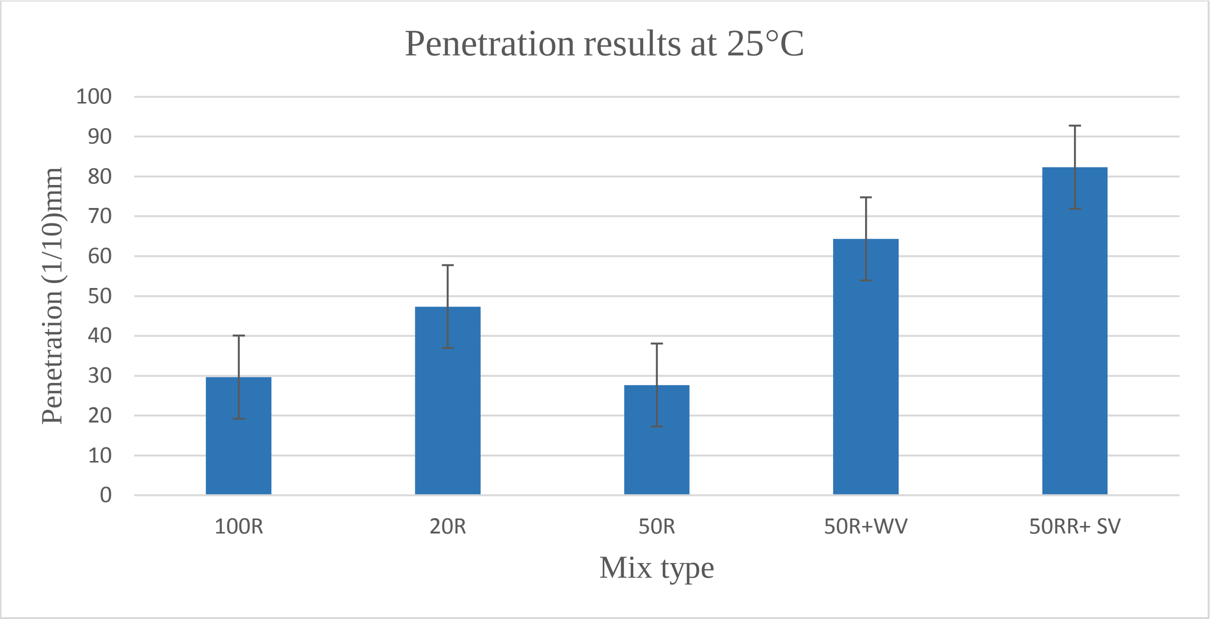
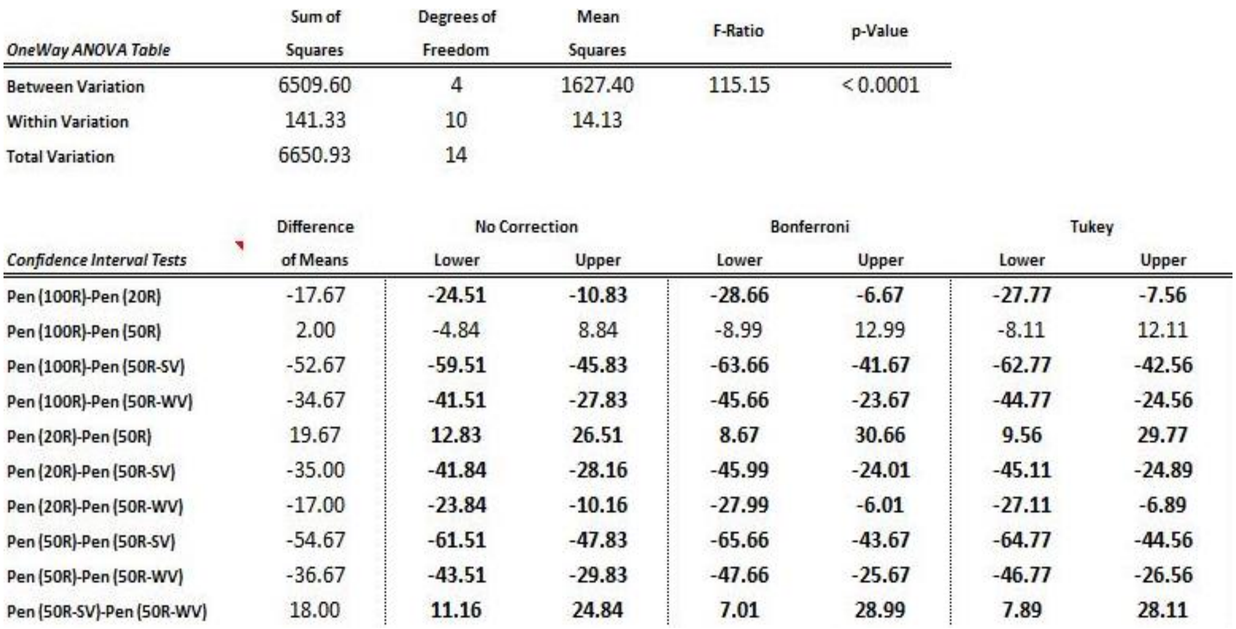


Figure 11: Penetration results

Table 16: ANOVA for Penetration at 25°C



OneWay ANOVA Table	Sum of Squares	Degrees of Freedom	Mean Squares	F-Ratio	p-Value
Between Variation	6509.60	4	1627.40	115.15	< 0.0001
Within Variation	141.33	10	14.13		
Total Variation	6650.93	14			

Confidence Interval Tests	Difference of Means	No Correction Lower	No Correction Upper	Bonferroni Lower	Bonferroni Upper	Tukey Lower	Tukey Upper
Pen (100R)-Pen (20R)	-17.67	**-24.51**	**-10.83**	**-28.66**	**-6.67**	**-27.77**	**-7.56**
Pen (100R)-Pen (50R)	2.00	-4.84	8.84	-8.99	12.99	-8.11	12.11
Pen (100R)-Pen (50R-SV)	-52.67	**-59.51**	**-45.83**	**-63.66**	**-41.67**	**-62.77**	**-42.56**
Pen (100R)-Pen (50R-WV)	-34.67	**-41.51**	**-27.83**	**-45.66**	**-23.67**	**-44.77**	**-24.56**
Pen (20R)-Pen (50R)	19.67	**12.83**	**26.51**	**8.67**	**30.66**	**9.56**	**29.77**
Pen (20R)-Pen (50R-SV)	-35.00	**-41.84**	**-28.16**	**-45.99**	**-24.01**	**-45.11**	**-24.89**
Pen (20R)-Pen (50R-WV)	-17.00	**-23.84**	**-10.16**	**-27.99**	**-6.01**	**-27.11**	**-6.89**
Pen (50R)-Pen (50R-SV)	-54.67	**-61.51**	**-47.83**	**-65.66**	**-43.67**	**-64.77**	**-44.56**
Pen (50R)-Pen (50R-WV)	-36.67	**-43.51**	**-29.83**	**-47.66**	**-25.67**	**-46.77**	**-26.56**
Pen (50R-SV)-Pen (50R-WV)	18.00	**11.16**	**24.84**	**7.01**	**28.99**	**7.89**	**28.11**

From Table 16 we can say that the mixes are significantly different except that we observe no significant difference between penetration values of 100% RAP and 50% RAP binders.

9.4 Performance Grade (PG) results:

The binder was extracted from the different mixes and tested for Performance Grade (PG). The results are tabulated in Table 17. It can be seen from the table, that 50% RAP binder and 100% RAP binder are severely aged and graded as PG 81-24 and PG 78-24 respectively, but with the addition of Waste vegetable oil and Sylvaroad rejuvenators, the binders were graded as PG-68-31 and PG 66-34 respectively. This indicates that the addition of these rejuvenators are capable of reducing the stiffness of the aged binder and probably restoring the original properties of RAP binder. From Figure 12, it can be inferred that of the two rejuvenators, Sylvaroad at the content used in this study, is more effective in reducing the stiffness of the aged binder compared to waste vegetable oil. The binders of the rejuvenated blend shows better characteristics (higher PG sum) in comparison to that of the control mix.

Table 17: Performance Grade (PG) -Low and High results

Binder State	Continuous high PG, ℃	Continuous low PG, ℃	PG sum,℃
Virgin binder	58.0	-28.0	86.0
20R	71.8	-27.1	98.9
50R-WV	68.1	-31.3	99.4
50R-SV	66.4	-34.0	100.4
50R	81.1	-24.0	105.0
RAP	78.2	-24.1	102.3

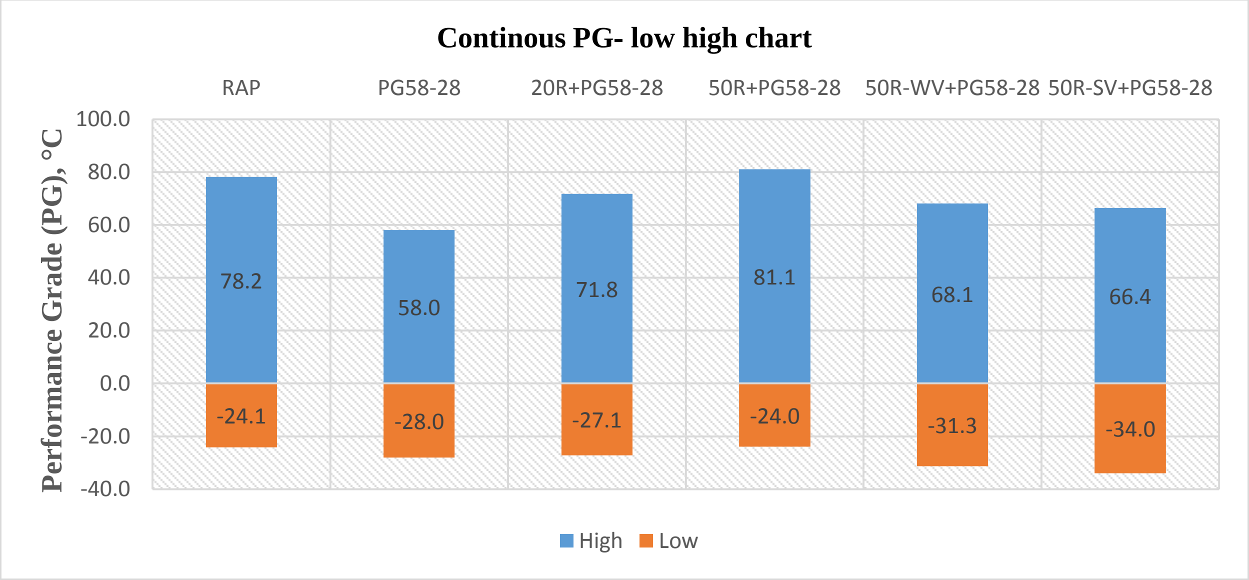
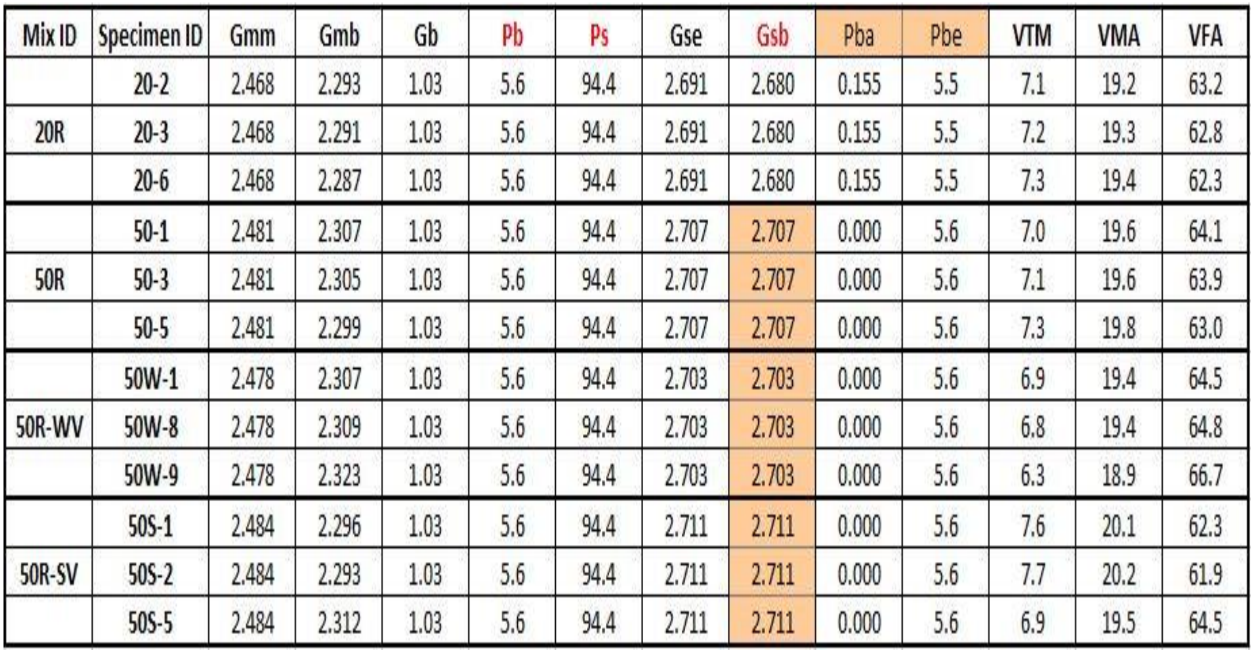


Figure 12: Continuous PG- Low High

9.5 Back calculated Hirsch model results

Hirsch model was used to back calculate the complex modulus (G*) from the design modulus values obtained from the Ultrasonic pulse velocity (UPV) test. The volumetric calculations were made to calculate the Voids in Mineral Aggregates (VMA) and Voids Filled with Asphalt (VFA) of the mix. For this calculation of volumetric properties, it was assumed that the bulk specific gravity (G_{sb}) and the effective specific gravity (G_{se}) are same. This assumption was made to bypass the problem of finding the G_{sb} of coated RAP particles. The volumetric properties of the different mixes are shown in Table 18. The back calculated values are tabulated in Table 19. From the table, it can be observed that there is difference in moduli values at 25 C and -10C between the different mixes. It can also be observed that there is significant difference in moduli value at two different temperatures for each of the rejuvenated mixes in comparison with the 50% RAP and 100% RAP mixes. This proves the significant influence of the rejuvenator on the moduli values. Table 20 shows the ANOVA results obtained from the G* data. It can be seen from Table 21 that the 50R mix is ranked as A, 50R-SV mix is ranked B followed by 50% RAP- WV, ranked C and finally 20% RAP which is ranked D. From Table 21 we can say that the mixes have significantly different back calculated complex modulus (G*)

Table 18: volumetric properties

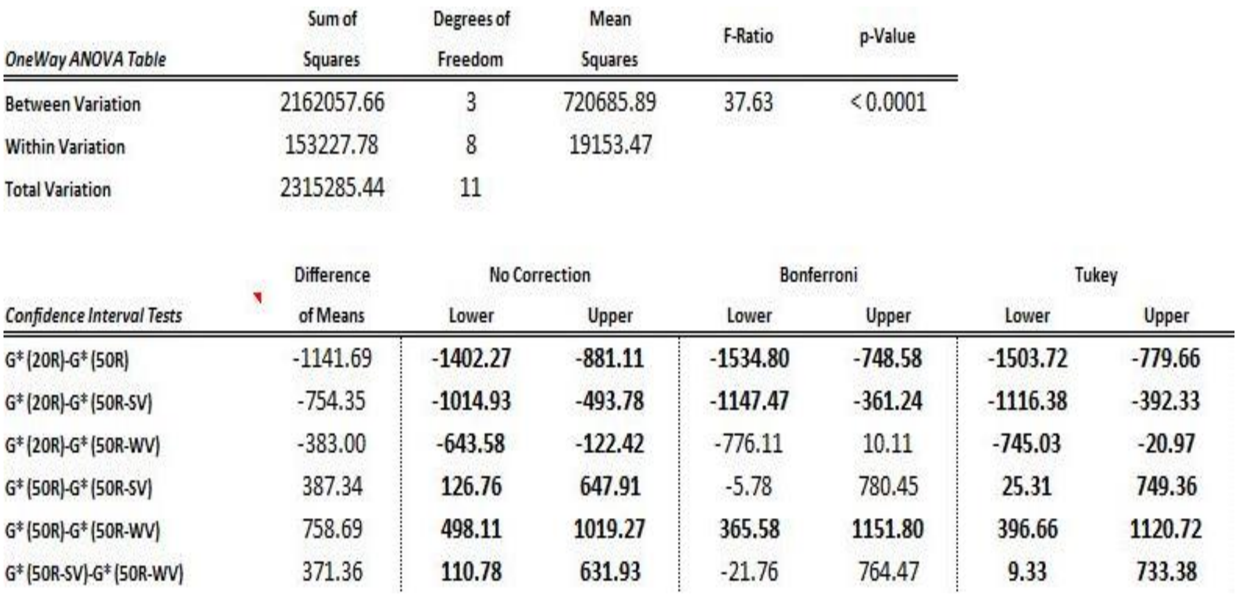


Mix ID	Specimen ID	Gmm	Gmb	Gb	Pb	Ps	Gse	Gsb	Pba	Pbe	VTM	VMA	VFA
20R	20-2	2.468	2.293	1.03	5.6	94.4	2.691	2.680	0.155	5.5	7.1	19.2	63.2
	20-3	2.468	2.291	1.03	5.6	94.4	2.691	2.680	0.155	5.5	7.2	19.3	62.8
	20-6	2.468	2.287	1.03	5.6	94.4	2.691	2.680	0.155	5.5	7.3	19.4	62.3
50R	50-1	2.481	2.307	1.03	5.6	94.4	2.707	2.707	0.000	5.6	7.0	19.6	64.1
	50-3	2.481	2.305	1.03	5.6	94.4	2.707	2.707	0.000	5.6	7.1	19.6	63.9
	50-5	2.481	2.299	1.03	5.6	94.4	2.707	2.707	0.000	5.6	7.3	19.8	63.0
50R-WV	50W-1	2.478	2.307	1.03	5.6	94.4	2.703	2.703	0.000	5.6	6.9	19.4	64.5
	50W-8	2.478	2.309	1.03	5.6	94.4	2.703	2.703	0.000	5.6	6.8	19.4	64.8
	50W-9	2.478	2.323	1.03	5.6	94.4	2.703	2.703	0.000	5.6	6.3	18.9	66.7
50R-SV	50S-1	2.484	2.296	1.03	5.6	94.4	2.711	2.711	0.000	5.6	7.6	20.1	62.3
	50S-2	2.484	2.293	1.03	5.6	94.4	2.711	2.711	0.000	5.6	7.7	20.2	61.9
	50S-5	2.484	2.312	1.03	5.6	94.4	2.711	2.711	0.000	5.6	6.9	19.5	64.5

Table 19: Back calculated G* using Hirsch Model

Mix ID	Back calculated G*, kPa at 25°C	Back calculated G*, kPa at -10°C
20R-2	2,732	5,308
20R-3	2,908	5,479
20R-6	2,722	5,745
50R-1	3,783	6,852
50R-3	3,988	7,059
50R-5	4,017	7,081
50R-WV-1	3,362	6,568
50R-WV-5	3,155	6,316
50R-WV-6	2,994	6,258
50R-SV-1	3,572	7,388
50R-SV-2	3,648	7,581
50R-SV-5	3,405	6,814

Table 20: ANOVA for back calculated G* at 25C



OneWay ANOVA Table	Sum of Squares	Degrees of Freedom	Mean Squares	F-Ratio	p-Value
Between Variation	2162057.66	3	720685.89	37.63	< 0.0001
Within Variation	153227.78	8	19153.47		
Total Variation	2315285.44	11			

	Difference	No Correction		Bonferroni		Tukey	
Confidence Interval Tests	of Means	Lower	Upper	Lower	Upper	Lower	Upper
G* (20R)-G* (50R)	-1141.69	**-1402.27**	**-881.11**	**-1534.80**	**-748.58**	**-1503.72**	**-779.66**
G* (20R)-G* (50R-SV)	-754.35	**-1014.93**	**-493.78**	**-1147.47**	**-361.24**	**-1116.38**	**-392.33**
G* (20R)-G* (50R-WV)	-383.00	**-643.58**	**-122.42**	-776.11	10.11	**-745.03**	**-20.97**
G* (50R)-G* (50R-SV)	387.34	**126.76**	**647.91**	-5.78	780.45	**25.31**	**749.36**
G* (50R)-G* (50R-WV)	758.69	**498.11**	**1019.27**	**365.58**	**1151.80**	**396.66**	**1120.72**
G* (50R-SV)-G* (50R-WV)	371.36	**110.78**	**631.93**	-21.76	764.47	**9.33**	**733.38**

Table 21: Ranking of Mix types

(Note: A higher rank indicates a higher complex moduli)

Mix ID	Backcalculated G*, kPa from E* AT 25C	Ranking (High to Low)
20%-RAP	2,732	D
	2,908	
	2,722	
50%-RAP	3,783	A
	3,987	
	4,016	
50%-RAP-WV	3,362	C
	3,155	
	2,994	
50%-RAP-SV	3,572	B
	3,648	
	3,405	

9.6 Indirect Tensile Strength (ITS) results

The ITS test results were obtained for samples tested at 25°C. From Table 22, it can be observed that the 50% RAP mixes show higher indirect tensile strength values compared to the other mixes.

Table 22: Indirect Tensile Strength Test (ITS) Results

S.No	SAMPLE ID	Peak Load (N)	Average specimen height(t) (mm)	Average dia of specimen (D) (mm)	ITS (kPa)
1	20R-2	6,130	38.9	152.4	659
2	20R-3	6,512	38.6	152.4	705
3	20R-6	6,868	38.6	152.4	743
-	**Average**	**6,503**	**38.7**	**152.4**	**702**
4	50R-1	8,469	38.9	152.4	910
5	50R-3	8,140	38.6	152.4	881
6	50R-5	8,928	38.6	152.4	966
-	**Average**	**8,512**	**38.7**	**152.4**	**919**
7	50R-WV-1	5,765	38.8	152.4	620
8	50R-WV-5	4,893	38.7	152.4	529
9	50R-WV-6	5,445	38.6	152.4	589
-	**Average**	**5,368**	**38.7**	**152.4**	**579**
10	50R-SV-1	5,222	38.9	152.4	561
11	50R-SV-2	4,875	38.6	152.4	527
12	50R-SV-5	5,792	38.6	152.4	627
-	**Average**	**5,296**	**38.7**	**152.4**	**572**

The rejuvenated mixes on the other hand show lower ITS values than the control and 50% RAP mixes. This indicates that rejuvenators are effective in reducing the overall stiffness of the mix at intermediate temperature which is relevant for evaluation of the potential of fatigue cracking. Figure 14 shows the Indirect Tensile Strength test results for the RAP samples with and without the addition of rejuvenators. Table 24 shows the Mean separation test results for the ITS data. From this table it can be seen that 50% RAP has been ranked A, followed by 20% RAP ranked as B and the rejuvenated mixes ranked as C.

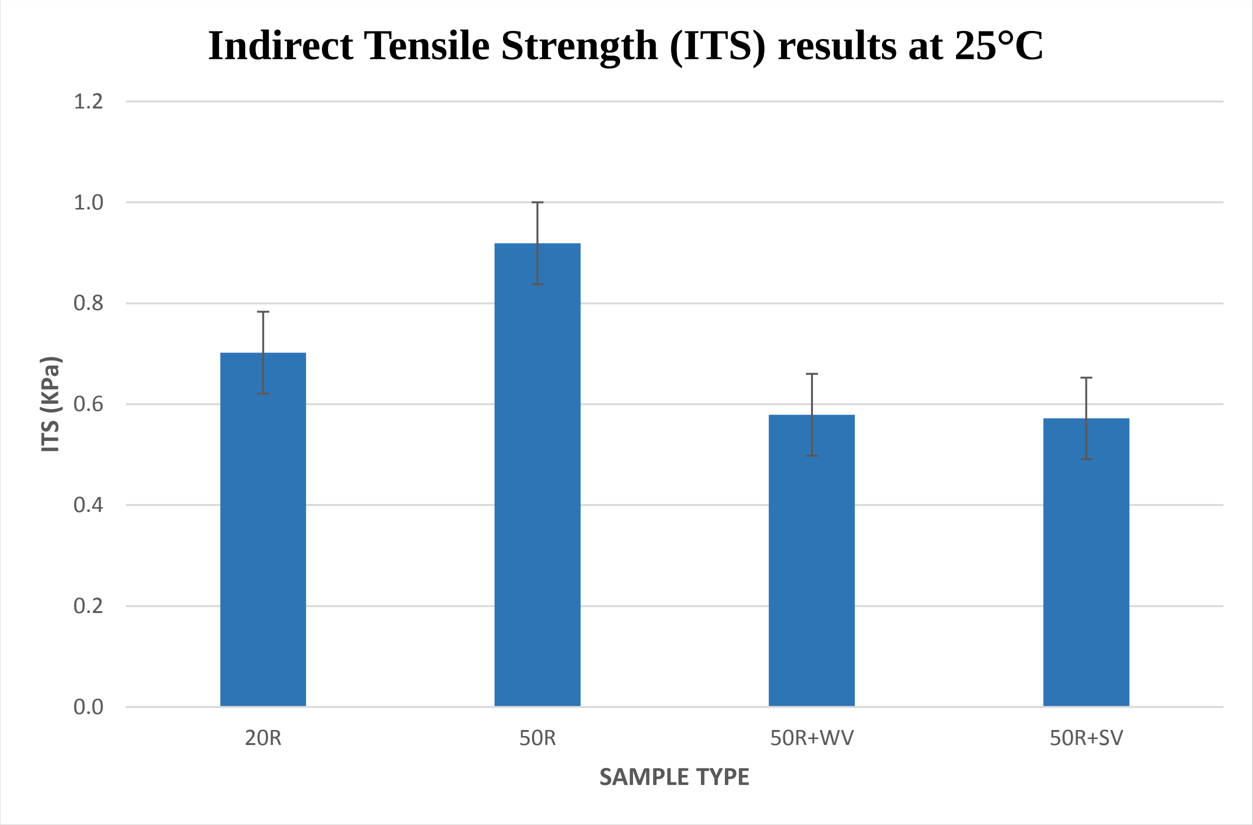
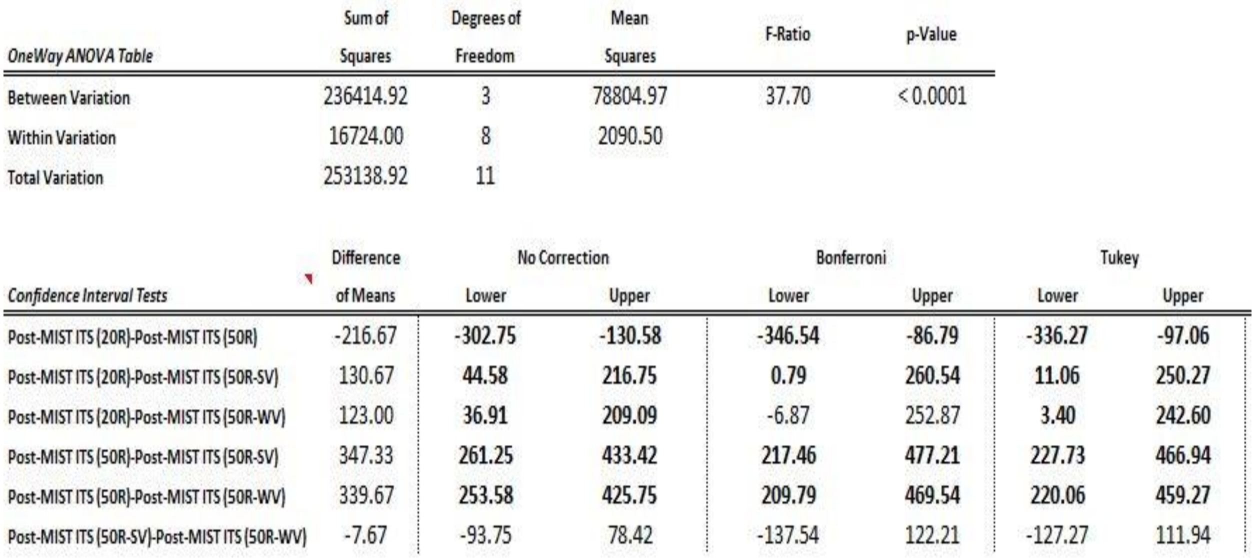


Figure 13: Indirect Tensile Strength (ITS) results

Table 23: ANOVA for ITS at 25 C



OneWay ANOVA Table	Sum of Squares	Degrees of Freedom	Mean Squares	F-Ratio	p-Value
Between Variation	236414.92	3	78804.97	37.70	< 0.0001
Within Variation	16724.00	8	2090.50		
Total Variation	253138.92	11			

Confidence Interval Tests	Difference of Means	No Correction		Bonferroni		Tukey	
		Lower	Upper	Lower	Upper	Lower	Upper
Post-MIST ITS (20R)-Post-MIST ITS (50R)	-216.67	**-302.75**	**-130.58**	**-346.54**	**-86.79**	**-336.27**	**-97.06**
Post-MIST ITS (20R)-Post-MIST ITS (50R-SV)	130.67	**44.58**	**216.75**	**0.79**	**260.54**	**11.06**	**250.27**
Post-MIST ITS (20R)-Post-MIST ITS (50R-WV)	123.00	**36.91**	**209.09**	-6.87	252.87	**3.40**	**242.60**
Post-MIST ITS (50R)-Post-MIST ITS (50R-SV)	347.33	**261.25**	**433.42**	**217.46**	**477.21**	**227.73**	**466.94**
Post-MIST ITS (50R)-Post-MIST ITS (50R-WV)	339.67	**253.58**	**425.75**	**209.79**	**469.54**	**220.06**	**459.27**
Post-MIST ITS (50R-SV)-Post-MIST ITS (50R-WV)	-7.67	-93.75	78.42	-137.54	122.21	-127.27	111.94

Table 23 shows the ANOVA test results for different mix types. We can see from the table that there is significant difference between all mixes except between 50R-WV and 50R-SV mixes.

Table 24: Ranking for ITS at 25°C

(Note: A higher rank indicates a higher tensile strength)

Mix ID	POST MIST Indirect Tensile Strength (ITS), KPa	Ranking
20R	659	**B**
	705	
	743	
50R	910	**A**
	881	
	966	
50R-WV	620	**C**
	529	
	589	
50R-SV	561	**C**
	527	
	627	

9.7 Creep compliance results

Creep compliance test is a way to characterize the stiffness of material. A higher stiffness or a low compliance at low temperature is indicative of a mix with potential of thermal cracking. Table 25 shows the results of the creep compliance test. The creep compliance results reveal that the 50% RAP rejuvenated mixes have better resistance to failure at low temperature in comparison to the 20% RAP and 50% RAP mixes. It can also be seen from Table 25 that the 50% RAP mixes show low creep compliance values which indicates that this mix has poor resistance to cracking at low temperature. Statistical analysis could not be done here as we require results of three specimens that are analyzed simultaneously to reduce variability in determining Poisson's ratio and creep compliance. Figure 14 shows the creep compliance value at -10°C.

Table 25: Creep compliance results

Mix type	Creep compliance (1/GPa)
20R	0.199
50R	0.113
50R-WV	0.223
50R-SV	0.248

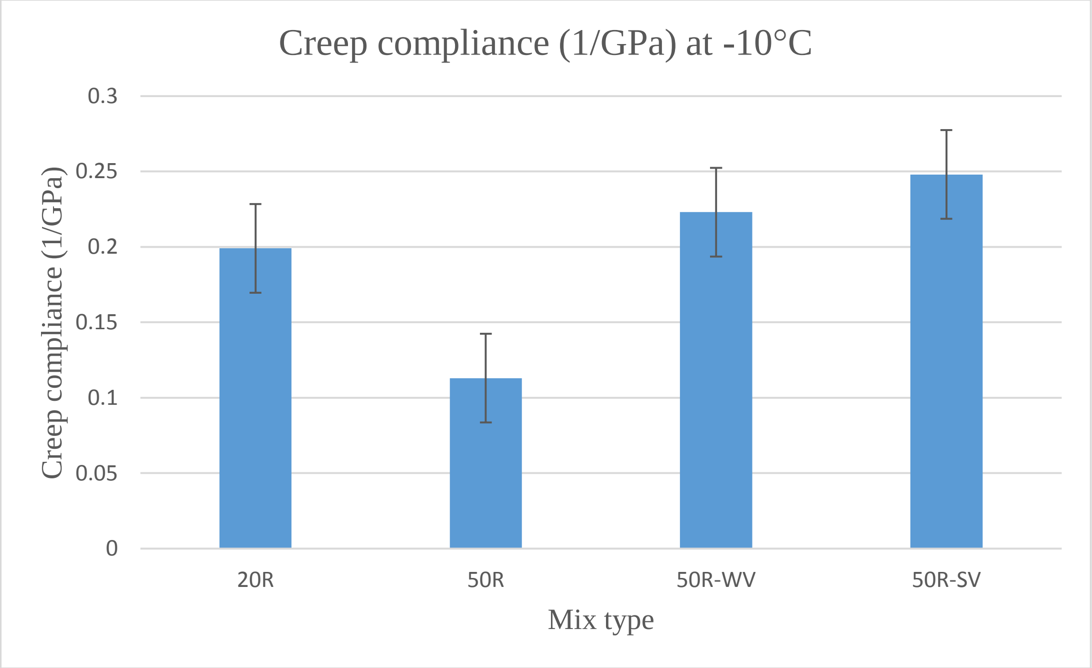


Figure 14: Creep compliance at -10C

9.8 Semi Circular Bend (SCB) test results

The SCB test results were obtained for samples with 4-5% air voids and at intermediate test temperature (25°C). Table 26 and Table 27 show the fracture energy results obtained for 20% RAP and 50% RAP samples with different waste vegetable oil rejuvenator dosages. From Table 26 we can infer from the mean values that addition of different rejuvenator dosages do not have significant influence over 20% RAP mix, whereas from Table 27 we can see that the Fracture energy drops for 50% RAP as the rejuvenator dosage increases. This indicates the effectiveness of the waste vegetable oil rejuvenator in softening the mix and thereby reducing the overall stiffness of 50% RAP mixes. Figure 15 shows the Fracture energy at different rejuvenator dosages for 20% RAP and 50% RAP. The flexibility index (FI) is a parameter that can indicate the cracking potential of asphalt concrete mix. A higher FI is desirable for greater resistance against cracking. We can see from Table 26 that the average flexibility index for 20% RAP remains fairly same for the different rejuvenator dosages except for 15% rejuvenator dosage where we can see it increases to 3. This also shows that at 15% rejuvenator dosage, the mix is less brittle in nature with respect to other dosages. Table 27 shows that for 50% RAP mixes, with the increase in rejuvenator dosage the flexibility index also increases specifically at 15% dosage. Overall a comparison of 20R and 50R mixes show a higher FI for the 20R (lower RAP content) mixes except at 15% rejuvenator dosage. This would indicate that the rejuvenators are capable of reducing the stiffness of the 50% RAP and thereby making it less brittle and more resistance to fatigue cracking. Figures 16 and 17 show the side by side comparison of 20% RAP and 50% RAP fracture energy and FI at different rejuvenator dosages.

Table 26: Fracture Energy test results of 20% RAP

Sample ID	Fracture Energy (Joules/m^2)							
	2% -WV	**FI**	**6% -WV**	**FI**	**10% -WV**	**FI**	**15% -WV**	**FI**
20R-1-1	1854	1.9	2019	3.2	1941	2.5	1898	2.2
20R-1-1A	1849	2.5	2686	3.9	2111	2.1	1841	2.5
20R-1-2	1984	3.9	2869	3.7	1521	1.1	1959	4.9
20R-1-2A	1545	1.5	2277	3.5	2047	1.4	1959	2.3
20R-2-1	1867	1.4	2407	1.8	1640	0.5	2254	2.1
20R-2-1A	1557	1.2	1585	0.8	1387	1.1	2466	2.4
20R-2-2	2000	2.7	2306	1.3	1609	1.4	2185	2.3
20R-2-2A	1827	0.7	2234	1.6	2028	1.8	2057	3.2
20R-3-1	2150	0.8	1634	0.8	2290	3.4	2997	4.3
20R-3-1A	1819	1.3	2478	1.1	2203	2.8	2318	3.9
20R-3-2	1823	1.1	1993	1.2	2903	5	2287	3.7
20R-3-2A	3371	6.1	1570	1.8	2036	1.2	1380	2
Average	**1971**	**2.1**	**2172**	**2.1**	**1976**	**2**	**2133**	**3**
SD	**471.92**	**1.56**	**424.67**	**1.18**	**409.21**	**1.24**	**393.92**	**0.99**
RANKING	**A**		**A**		**A**		**A**	

Table 27: Fracture energy test results for 50% RAP

Sample ID	Fracture Energy (Joules/m^2)							
	2% -WV	**FI**	**6% -WV**	**FI**	**10% -WV**	**FI**	**15% -WV**	**FI**
50R-1-1	1859	0.9	2289	1.5	2177	2.7	1796	4.2
50R-1-1A	2884	1.2	2068	2.5	1953	1.7	2978	5.4
50R-1-2	3600	1.0	2408	2.7	2006	1.4	1483	2.7
50R-1-2A	3164	4.0	2514	1.3	1930	1.5	1334	2.3
50R-2-1	1528	1.0	2142	1.2	1376	1.0	1772	2.9
50R-2-1A	2451	1.6	1709	1.2	1744	0.9	1613	1.9
50R-2-2	1745	0.8	2316	0.9	1719	1.0	1520	1.7
50R-2-2A	1815	1.1	1999	0.9	1565	1.1	1530	2.4
50R-3-1	2074	1.5	1630	1.0	2159	2.7	2344	4.0
50R-3-1A	2236	1.6	2939	1.5	1305	1.7	1855	5.4
50R-3-2	2862	2.1	2315	1.8	2661	2.2	1687	2.8
50R-3-2A	2036	1.5	1371	2.2	2158	1.2	2904	4.6
Average	**2354**	**1.5**	**2142**	**1.6**	**1896**	**1.6**	**1901**	**3.4**
SD	**642.38**	**1.03**	**426.03**	**0.61**	**381.65**	**0.62**	**547.71**	**1.31**
RANKING	**A**		**A**		**A**		**A**	

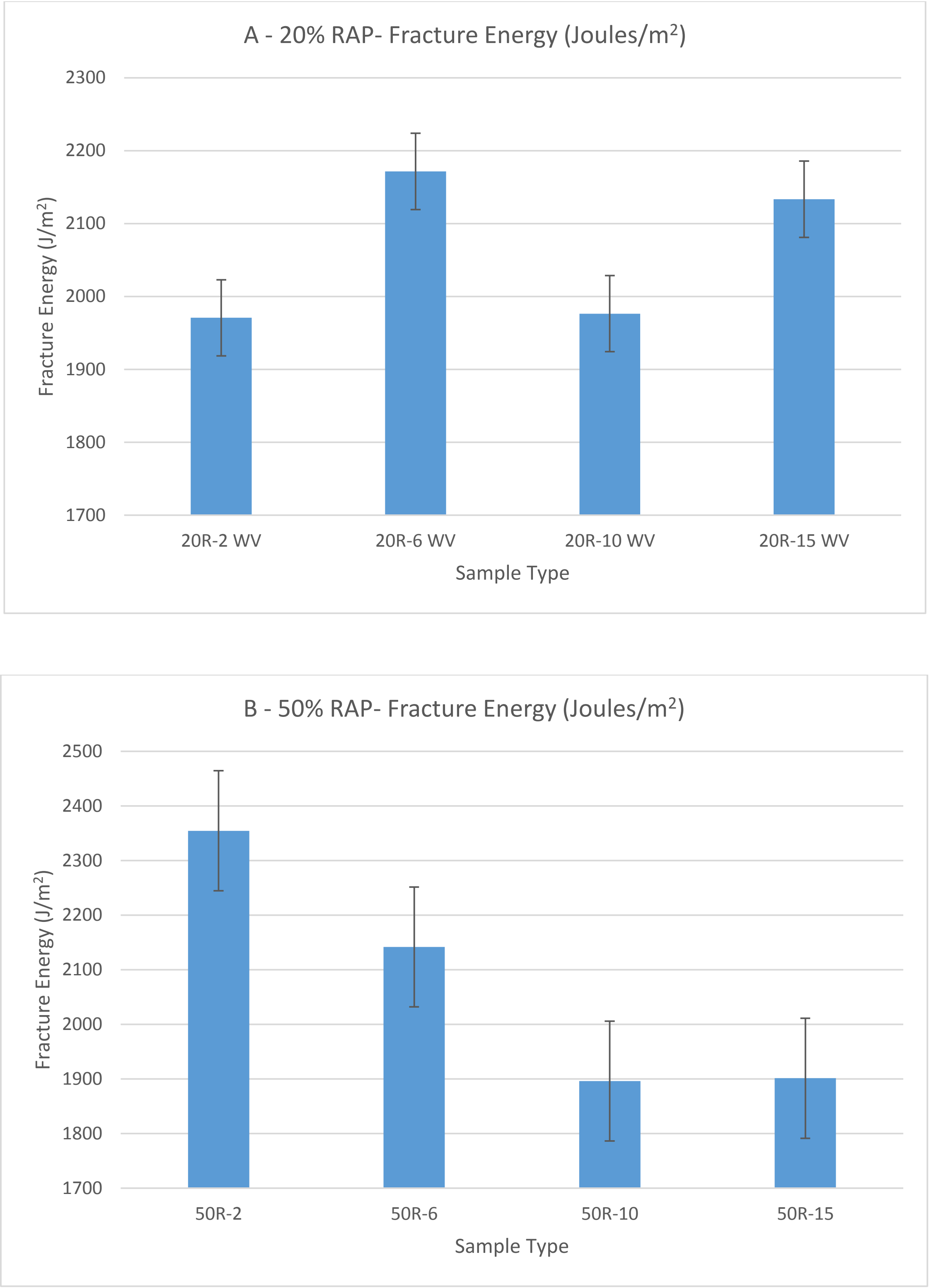


Figure 15: Fracture Energy at different rejuvenator dose for A-20% RAP; 50% RAP.

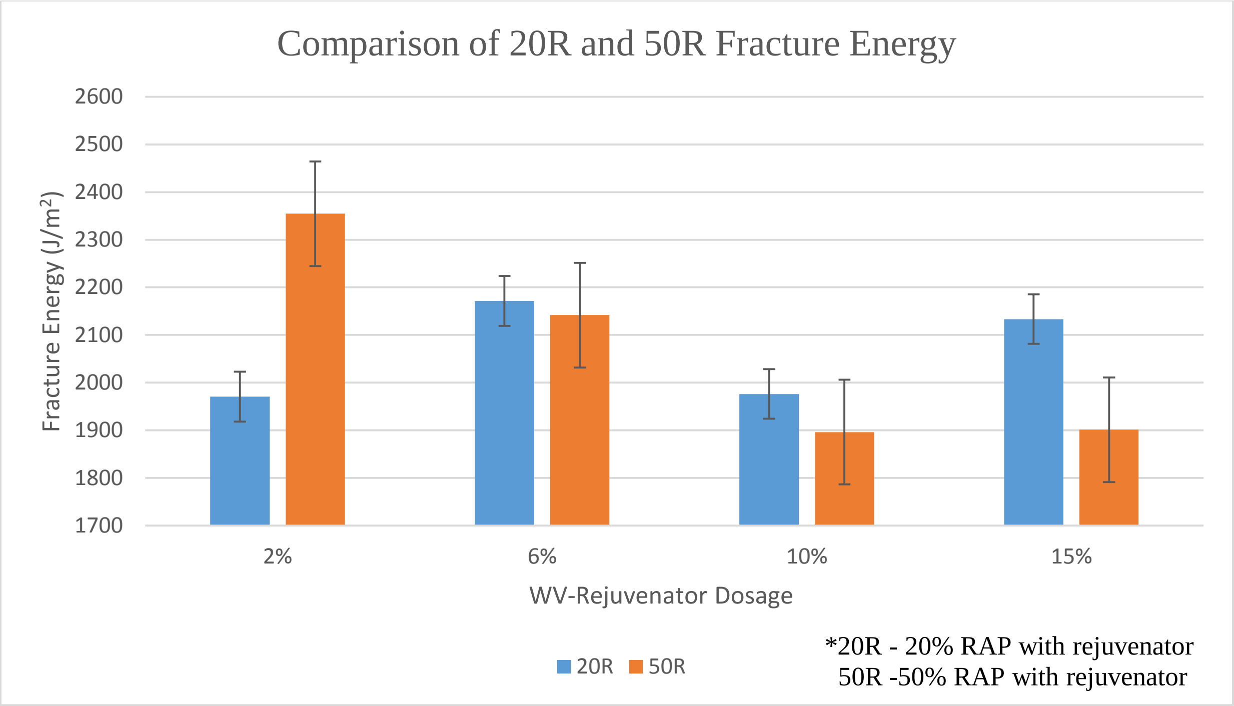


Figure 16: Comparison of Fracture Energy of 20% RAP and 50% RAP mixes

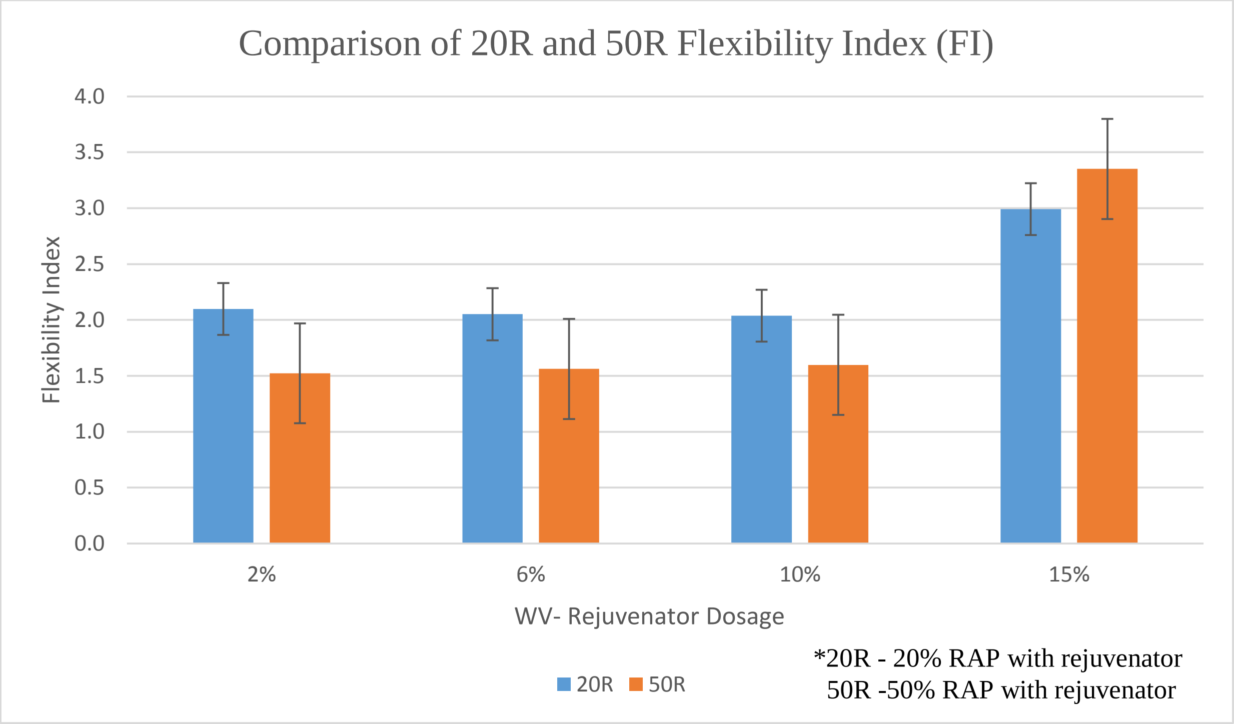
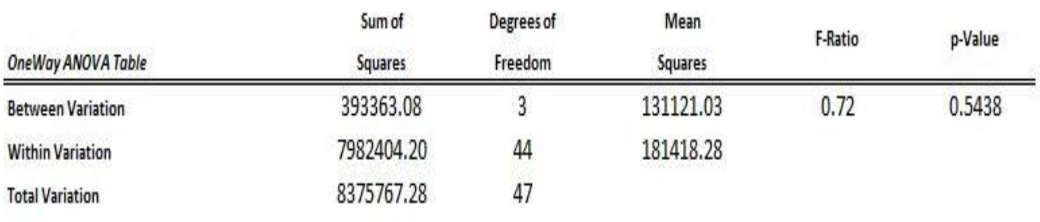
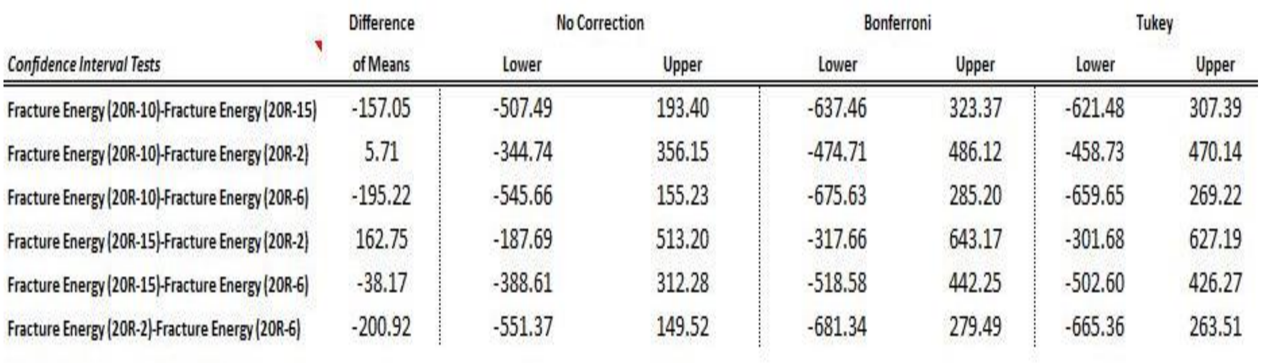


Figure 17: Comparison of Flexibility Index of 20% RAP and 50% RAP mixes

Table 28: ANOVA for Fracture Energy at 25°C for 20% RAP

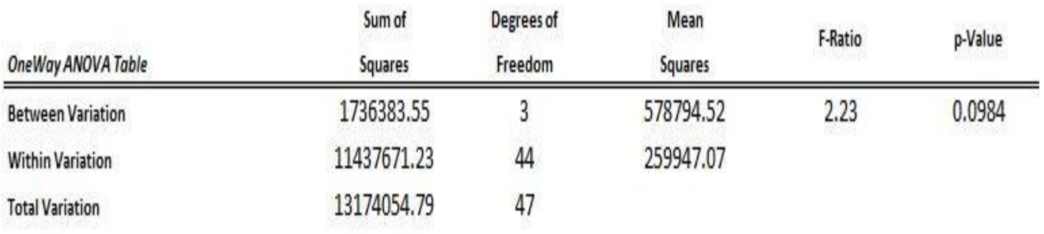


OneWay ANOVA Table	Sum of Squares	Degrees of Freedom	Mean Squares	F-Ratio	p-Value
Between Variation	393363.08	3	131121.03	0.72	0.5438
Within Variation	7982404.20	44	181418.28		
Total Variation	8375767.28	47			

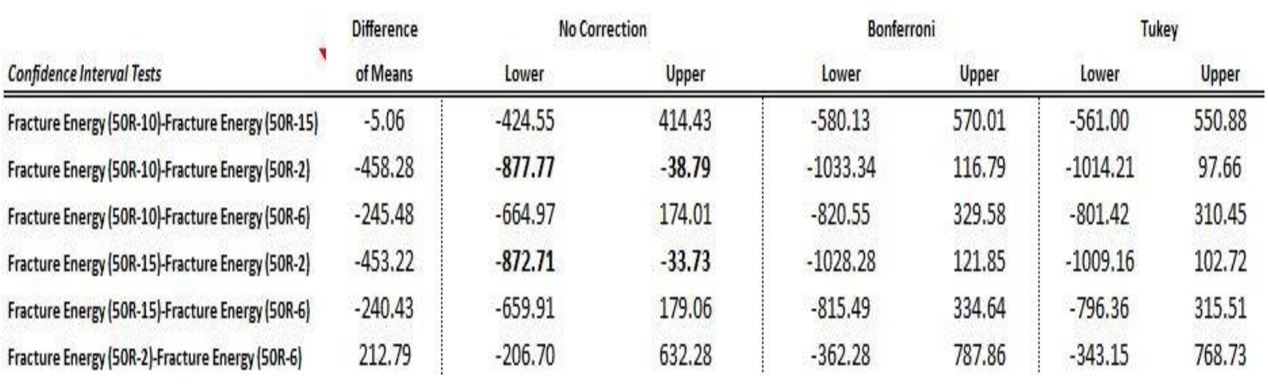


	Difference	No Correction		Bonferroni		Tukey	
Confidence Interval Tests	of Means	Lower	Upper	Lower	Upper	Lower	Upper
Fracture Energy (20R-10)-Fracture Energy (20R-15)	-157.05	-507.49	193.40	-637.46	323.37	-621.48	307.39
Fracture Energy (20R-10)-Fracture Energy (20R-2)	5.71	-344.74	356.15	-474.71	486.12	-458.73	470.14
Fracture Energy (20R-10)-Fracture Energy (20R-6)	-195.22	-545.66	155.23	-675.63	285.20	-659.65	269.22
Fracture Energy (20R-15)-Fracture Energy (20R-2)	162.75	-187.69	513.20	-317.66	643.17	-301.68	627.19
Fracture Energy (20R-15)-Fracture Energy (20R-6)	-38.17	-388.61	312.28	-518.58	442.25	-502.60	426.27
Fracture Energy (20R-2)-Fracture Energy (20R-6)	-200.92	-551.37	149.52	-681.34	279.49	-665.36	263.51

Table 29: ANOVA for Fracture Energy at 25°C for 50% RAP



OneWay ANOVA Table	Sum of Squares	Degrees of Freedom	Mean Squares	F-Ratio	p-Value
Between Variation	1736383.55	3	578794.52	2.23	0.0984
Within Variation	11437671.23	44	259947.07		
Total Variation	13174054.79	47			



	Difference	No Correction		Bonferroni		Tukey	
Confidence Interval Tests	of Means	Lower	Upper	Lower	Upper	Lower	Upper
Fracture Energy (50R-10)-Fracture Energy (50R-15)	-5.06	-424.55	414.43	-580.13	570.01	-561.00	550.88
Fracture Energy (50R-10)-Fracture Energy (50R-2)	-458.28	**-877.77**	**-38.79**	-1033.34	116.79	-1014.21	97.66
Fracture Energy (50R-10)-Fracture Energy (50R-6)	-245.48	-664.97	174.01	-820.55	329.58	-801.42	310.45
Fracture Energy (50R-15)-Fracture Energy (50R-2)	-453.22	**-872.71**	**-33.73**	-1028.28	121.85	-1009.16	102.72
Fracture Energy (50R-15)-Fracture Energy (50R-6)	-240.43	-659.91	179.06	-815.49	334.64	-796.36	315.51
Fracture Energy (50R-2)-Fracture Energy (50R-6)	212.79	-206.70	632.28	-362.28	787.86	-343.15	768.73

Table 28 and Table 29 show the ANOVA results obtained for 20 % RAP and 50 % RAP mixes. We can see from Table 28 that there is no significant difference between the groups of different mix type. Hence all the samples are ranked ‘A’ in Table 26. From Table 29 also we observe that there is no significant difference between the groups and they are all ranked as A in Table 27.

9.9 Cost analysis

A cost analysis was carried out to understand the relative cost economics of the HMA mixes with different percentages of RAP with and without rejuvenators. Table 30 shows the relative cost of each material per ton and the source. It can be seen from this table that major part of the costs come from the binder in comparison with other materials such as aggregates and RAP. Table 31 shows the relative cost of each rejuvenator based on their density. From Table 32 we can observe a savings of 40% in total cost when using waste vegetable oil as rejuvenator and 50% RAP in comparison with virgin mix and a savings of 34% when using Sylvaroad rejuvenator and 50% RAP in comparison with virgin mix. It can be concluded that a considerable savings in cost can be accomplished by using higher RAP percentages with rejuvenators. Note that these savings are based on the percentages of the rejuvenators used in this study

Table 30: Cost of materials

Unit	Material	Cost ($)	Source
per ton	Virgin AC	450	MDOT
per ton	Aggregate	20	MDOT
per ton	RAP	15	Assumed
per gallon	WV	3	Frank, 2014 [41]
per gallon	SV	9	Arizona Chemicals

Table 31: Density and cost of Rejuvenators

Unit	Material	Density	Cost ($)
lb. per gallon	WV, SV	7.6	
gallon per lb.		0.13158	
gallon per ton		263.158	
cost per ton	WV		789.47
	SV		2368.42

Table 32: Comparison of Cost

Unit	Mix	Cost($)	Savings with respect to 20% RAP mix	Savings with respect to all virgin mix
per ton	20% RAP	3		
per ton	80% new mix	32		
per ton	Total 20% RAP Mix	35		20
per ton	50% RAP	8		
per ton	50% new mix	16		
per ton	WV	2		
	50% RAP mix with WV	26	25	40
per ton	SV	5		
per ton	50% RAP mix with SV	29	17	34
per ton	all virgin mix	44		

9.10 **Summary of tests**

A radar chart (Figure 18) was plotted with all of the test results to compare the different types of mixes. We can see from Figure 18 that 50R-SV binder has a higher penetration value compared to that of 50R-WV. While comparing the complex modulus (G*) and Modulus (E_s) of different mixes we observe that both 50% RAP and the 50% RAP Sylvaroad mix have higher G* and E_s indicating that these mixes have greater resistance to rutting. The 50R-WV has lower G* and also lower E_S compared to the control and 50% RAP indicating a more flexible material even at low temperatures. The creep compliance test shows that the 50R-SV has higher creep compliance value compared to the waste vegetable and control mix, indicating a more flexible and durable material at low temperatures and better resistance to low temperature cracking. The ITS test results show that the 50% RAP mix has higher tensile strength due the presence of stiff and aged RAP binder in the mix. The rejuvenator mixes have lower ITS value indicating a less stiff material than the control mix. We can also see considerable savings in cost when using 50R in comparison with 20R. By using rejuvenators the cost increase marginally in comparison with 50R as the cost of rejuvenators is added. Huge savings in cost can be achieved by using 50% RAP with and without rejuvenators.

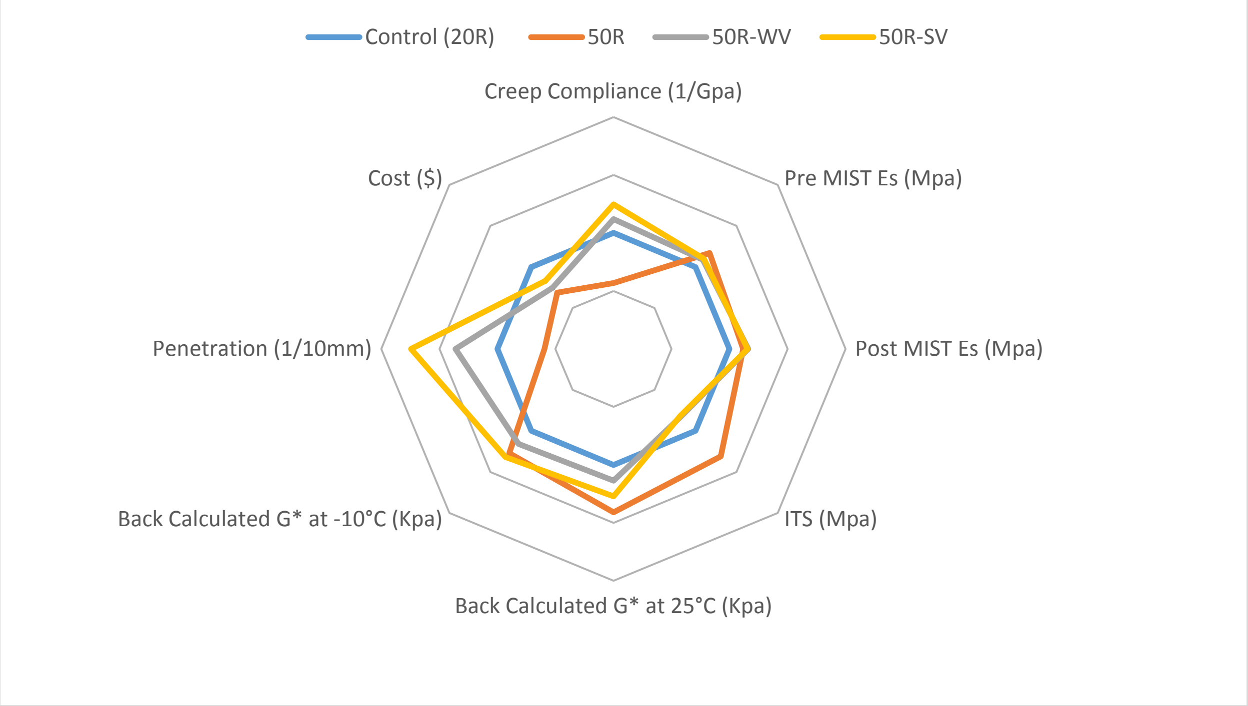


Figure 18: Radar chart of different test results in comparison with control mix (Values normalized against values of control mix, 20R)

10 CONCLUSIONS

The following conclusions can be drawn from this study:

1. The UPV test results at 25°C indicate that 50% RAP rejuvenated mixes have design moduli values in between that of 50% RAP and control mix. This indicates the effectiveness of the rejuvenators in reducing the overall stiffness of the 50% RAP mixes.
2. The MIST results indicate that the recycled mixes with rejuvenator are more prone to increase in modulus most likely because of increase in density with control mix and 50% RAP.
3. Binder extracted from 50% RAP mixes with rejuvenators have same or higher PG range compared to the regularly used binder. The PG sum of the rejuvenated mixes are higher than the virgin binder.
4. The presence of high recycled asphalt pavement (RAP) content in a mix tends to decrease the creep compliance and increase the tensile strength compared to a mix with low RAP content.
5. The addition of the two rejuvenators was found to be effective in increasing the low-temperature creep compliance value in comparison with the control mix and 50% RAP mix, therefore implying that rejuvenators are capable of improving low-temperature performance of RAP mixtures.
6. The SCB test results showed that by increasing the dosage of waste vegetable oil rejuvenator, the fracture energy of 50% RAP mixes could be reduced and the flexibility index could be increased, and most likely, resistance against fatigue cracking can be increased.
7. The savings in cost while using 50% RAP with waste vegetable oil as rejuvenator is around 40% in comparison with virgin mix and while using 50% RAP with Sylvaroad as rejuvenator it is around 34% in comparison with virgin mix.
8. Overall the properties of 50% RAP mixes with rejuvenator are not inferior in comparison with 20% RAP mixes.

11 RECOMMENDATIONS

The following recommendations are made on the basis of this study:

1. A detailed study with different percentages of rejuvenator (dosages) should be conducted to determine the most cost effective rejuvenator content.
2. In order to evaluate the relative performance of HMA mixes with 50% RAP, with and without rejuvenators, test section should be constructed. The performance of these mixes should be monitored under actual traffic, climate and environmental conditions.
3. The field performance data can be used to develop performance prediction models, which can be used in the calibration of M-E pavement design equations and life cycle cost can be determined.
4. Specifications for the use of High RAP mixes with and without rejuvenators may be developed, so that DoTs can adopt these mixes on a regular basis.

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