STUDY OF RECLAIMED ASPHALT PAVEMENT MATERIALS WITH WASTE ENGINE OIL AS REJUVENATOR USING DYNAMIC SHEAR RHEOMETER

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ABSTRACT

Developing countries requires large quantities of materials, where continues development of infrastructure is necessary, requirement of construction materials is continuously increases exponentially. The transportation development can be profitable by using the recycled aggregates acquired form existing pavement practices. When an asphalt pavement needs to be replaced, the existing pavement is removed. This acquired material, known as reclaimed asphalt pavement (RAP), is then used with new asphalt roads. The reuse of RAP needs to be treated before using it with new asphalt. RAP are weathered during their course of use. Repeated exposure of RAP to ultraviolet rays and moisture deteriorates the properties of the aggregates and binders. It is adequate to treat RAP before using with new asphalt. This study focuses on the possibility of using waste engine oil as a rejuvenator for the higher percentage of reclaimed asphalt pavement that could meet the increasing demand in a more sustainable way. Testing was conducted for asphalt binder testing and laboratory mixture testing. Asphalt binder testing consisted of dynamic shear rheometer.

Keywords: *Reclaimed Asphalt Pavement (RAP), Waste Engine Oil, Asphalt, Recycled Aggregate, Bitumen*

1.0 INTRODUCTION

Asphalt concrete is one of the most common types of pavement surface materials used in the world. It is a porous material made at a very high temperature of about 180°C that consists of mixture of asphalt binder (bitumen), aggregate particles, and air voids. After some years of usage, the stiffness of asphalt concrete increases, and its relaxation capacity decreases. The binder becomes more brittle, then micro-cracks develop in it and cracking of the interface between aggregates and binder occurs (*Yildirim, 2007*). It is prone to go fragile and stiff due to exposing to heat, oxygen, and ultraviolet light during storage, mixing, transport, and laying down, as well as during service life (*Yu et al., 2009; Juyal et al., 2005; Masson et al., 2008*). Asphalt has been used to seal ship hulls since 6,000 B.C. in ancient Samaria. From there, natural asphalts were employed by numerous ancient civilizations for anything from waterproofing masonry used for public baths in the Indus Valley to Egypt (*NCAT 1996*). Natural rock asphalt was used to build sidewalks in France and the United States in the early 1800s.

Despite the fact that asphalt has been a part of human society for over 6,000 years and contemporary society for over a century, many of its complexity remain a mystery to scholars. The ability to recycle wasted asphalt pavement into new pavements is the topic of this study. When an old asphalt pavement needs to be repaired or replaced, the old material can be mechanically ground and utilized as a raw material in new roads. Reclaimed asphalt pavement is an old, recyclable material (RAP). Because the old material has oxidized and is stiffer and more brittle than unaged asphalt pavements, a chemical recycling agent must be applied to counteract the ageing in order to use RAP (*Lins et al. 2008*). The use of RAP and its effects on the performance of new pavements has been thoroughly studied, and it is known that using RAP without modification results in a stiffer asphalt pavement overall (*Widyatmoko 2008; Zaumanis et al 2019*). Waste motor oil from vehicles and trucks is one waste resource that may be able to revive RAP (*Villanueva et al. 2008; Liu et al 2018*). During a typical oil change, this is the oil that is extracted from the car. Engine oil in large quantities on pavements causes harm to the asphalt. When coupled with RAP, however, modest volumes of waste oil thoroughly integrated in the mix may prove useful by countering the increased stiffness to provide a pavement with performance comparable to that of virgin and unused materials before in any structure.

The asphalt paving industry has had great success with recycling deteriorated asphalt pavements in the early twentieth century. The successful introduction of reclaimed asphalt pavement (RAP) in road construction has reduced the amount of virgin asphalt and aggregate needed and subsequently has made the industry's operations more sustainable. However, one of the main challenges of using RAP in road construction is the stiffness of RAP. The use of unmodified RAP can make the mix too stiff, and difficult to compact, which can result in premature failure of the pavement (*Faheem et al 2018, Mirhosseini et al 2019, Wang et al 2019*). Increased stiffness is a consequence of gradual oxidation which alters the constituents of asphalt and consequently erodes the viscoelastic properties (*Hosseinnezhad et al 2019*, *Pakenari et al 2021*). Therefore, to use the RAP in road construction, the lost properties of oxidized asphalt must be regained using a feasible rejuvenation technique.

2.0 STATEMENT OF THE PROBLEM

This study focuses on to investigate the feasibility of using waste engine oil as an asphalt rejuvenator to improve asphalt pavement recyclability. Several testing approaches were utilized to investigate this issue. Traditional asphalt binder testing and scale asphalt mixed performance testing were done.

- To determine the change in rheological properties of asphalt binder mixed with waste motor oil using traditional dynamic shear rheometer and rotating viscometer.
- To investigated the moisture susceptibility of the mixtures with waste engine oil

3.0 LITERATURE REVIEW

Environmentalists say that used oil is insoluble and contains toxic chemicals and heavy metals. Used or waste engine oil obtained from single car service can contaminate around 37 lakh litres of water, if released to water. Large quantity of used engine oils from different places is uncountable disposed of in various water bodies. At any given time in the India, an estimated 295 million registered automobiles are travelling on 5 million miles of public road (FHWA 2008). Used motor oil from highway vehicles may be able to assist in the recycling of asphalt pavement material. Previous research has revealed that when RAP is recycled in pavements, the stiffness of the pavement increases and the low temperature cracking resistance decreases (*Kandhal et al. 1995; Chen et al. 2007a; Ma et al. 2010*).

The addition of waste engine oil to asphalt binder has been found to minimize stiffness and increase fatigue resistance in pavements without RAP (*Villanueva et al. 2008*). Waste engine oil, when mixed with RAP, may help to offset the stiffening caused by the RAP and improve the pavement's low-temperature performance. These two waste streams could be combined to make a pavement that performs similarly to one composed completely of virgin materials.

3.1 ASPHALT PAVEMENT

Hot-mix asphalt mixtures containing RAP has been proven to perform as well as or even better than mixtures made with virgin material (*McDaniel and Anderson, 2001*). Many literatures have examined from mix design to performance of HMA containing RAP (*Al-Bayati et al., 2018; Tanty et al., 2018; Ma et al., 2019; Zhu et al., 2020a*) and studied effects of increased content of RAP in the new asphalt mixtures (*Nazzal et al., 2015; Shannon et al., 2017; Stimilli et al., 2016; Tang et al., 2017*). Effects of rejuvenator on performance of mixture containing RAP has also been examined in literature. With increasing concerns on rutting damage, application on high-modulus asphalt mixture (HMAM) is receiving increasing attention, both in new pavement construction and existing pavement rehabilitation (*Ban'kowski & Wiman, 2009*). RAP have been evaluated to save material resources, construction costs and energy, since the high stiffness of aged binder in RAP is similar to high modulus asphalt binder.

The subbase, base, and asphalt layer, all of which sit on top of the subgrade, make up a standard asphalt pavement. A schematic of a typical asphalt pavement structure is shown in Figure 1. The existing soil on which the pavement construction is built is referred to as the subgrade. A layer of coarse grained rock is laid on top of the subgrade beneath the base and subbase layers. The two base layers are 4 to 12 inches thick, and their principal function is to give structure for the asphalt pavement. In the case of permanent pavements, the asphalt pavement layer might be as thin as four inches or as thick as two feet (*Huang 1993*).

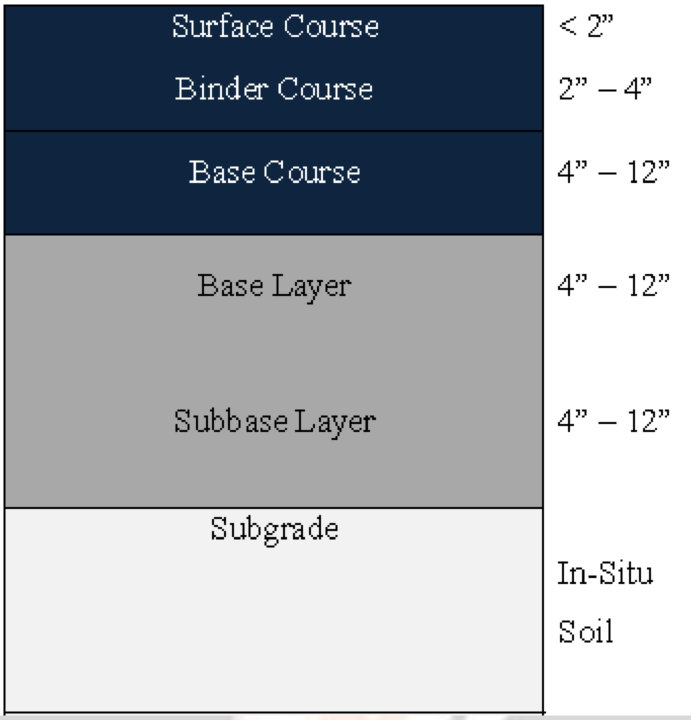

Figure 1 Typical Asphalt Pavement Cross Section (*Katamine, 2000)*

The base course, binder course, and surface course are the three sublayers of the asphalt pavement layer. The surface or wearing course is the top layer of asphalt concrete that is exposed to traffic. The surface course, which is rarely thicker than two inches, is primarily responsible for pavement friction and smoothness. Smaller aggregates are frequently used in this layer than in the two layers of asphalt beneath it. Most significantly, this layer can be replaced at the first sign of distress to prevent harm to the surrounding support layers. The binder coarse, also known as the levelling course, acts as a layer between the surface course and the base course, transferring loads.

This layer is also utilized to smooth out any irregularities and guarantee a uniform thickness of the surface course. The average binder course is 2-4 inches thick. The base course, the final layer, is made up of bigger aggregates that help to distribute load through the pavement and into the aggregate layers below. The base course can be anywhere from 4 to 12 inches thick, and it's usually the thickest pavement layer because it needs less asphalt binder than the two levels above it (*Institute 1960; Huang 1993*)

Asphalt pavement is made up of three ingredients in terms of volume: aggregate, asphalt binder, and air. Although aggregate makes up the majority of asphalt pavement (about 90%), the two remaining components are critical to the pavement's resilience. The percentage of air spaces in the pavement is fixed at 4% by volume as a standard. This trapped air is necessary for freezing water to escape into the void structure rather than shatter the pavement. Asphalt binder, the final component, is the "glue" that ties the pavement together. Even though it only accounts for around 5% of the total weight, the binder is by far the most complex component of the pavement system.

3.2 SUPERPAVER

Over the years, several methods of characterization for asphalt binder have been developed to satisfy the necessity for asphalt binder to manage high and low temperature failure causes. The Superior Performing Asphalt Pavements system is the most recent materials characterization system. Asphalt binder performance is graded using two temperatures: a high temperature and a low temperature. The maximum seven-day average temperature that the pavement will see during its design life is referred to as the high temperature. The low temperature represents the pavement's lowest single-day temperature during its design life. This range is indicated by a binder classification of PG XX-YY, where XX denotes the permissible high temperature in degrees Celsius and YY denotes the binder's low temperature rating in negative degrees Celsius. To measure the performance grade (PG) temperature of asphalt binder, several tests have been established. Two of the typical tests used are the dynamic shear rheometer (DSR) and rotational viscometer.

3.3 DYNAMIC SHEAR RHEOMETER

When an asphalt binder is subjected to a sinusoidal load, the Dynamic Shear Rheometer (DSR) is used to measure its engineering qualities. ASTM D 7175 is the standard that best describes the tests (*ASTM 2008c*). The DSR test includes placing a sample of asphalt binder between circular parallel plates that are subjected to a sinusoidal force and measuring the binder's response. The test is performed in two ways, depending on whether the binder is old or not. The plates measuring 25 mm in diameter and 1000 microns apart are used for unaged binder. The plates for aged binder are 10 mm in diameter and 2000 microns apart. On stiffened binder, the lower sample size is employed due to a mechanical constraint of the DSR's ability to accurately shear the stiffened binder.

The binder is submerged in a water bath at a predetermined temperature equivalent to the PG high temperature grade to conduct the test. The binder is added after ten minutes of temperature acclimatization, and the DSR measures each sample's Complex Modulus (G*) and phase angle (δ). The link between complex modulus and phase angle is depicted in Figure 2.

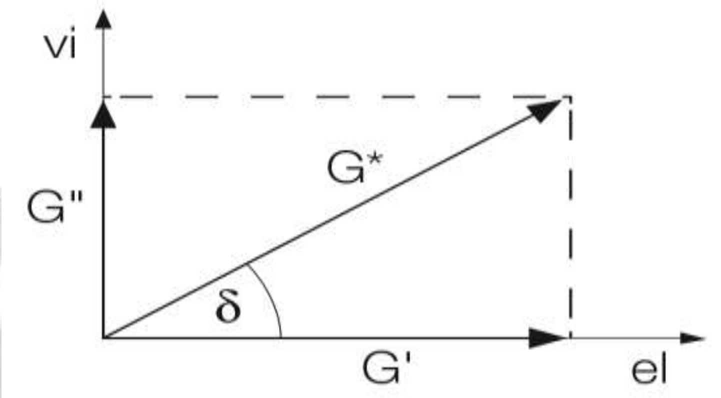

Figure 2 Complex Modulus & Phase Angle

The G*/Sin (δ) parameter indicates the rutting or permanent deformation standard performance criterion, whereas G*/Sin(δ) indicates the cracking resistance for low temperatures.

The binder meets the rutting criterion for performance when the G*/Sin (δ) parameter is greater than 1000 Pa for unaged binder and greater than 2200 Pa for Rolling Thin-Film Oven (RTFO) aged binder at a certain PG temperature. Binder is tested at increasing PG temperatures until it exceeds or fails the test parameter. The G*/Sin(δ) has a ceiling of 5000 kPa for Pressure Aging Vessel (PAV) aged binder, and if the binder surpasses that limit, it fails specification. The parameter G*/Sin (δ) as an indication of the rutting or permanent deformation standard performance criterion and G*·Sin(δ) as an indication of the resistance to cracking for the low temperatures.

4.0 EXPERIMENTAL SET-UP AND METHODOLOGY

Previous research has suggested that the inclusion of reclaimed asphalt pavement (RAP) will make asphalt pavements stiffer in nature and increase performance grade (PG) (*Kandhal et al. 1995*). Research into the feasibility of waste engine oil as an asphalt modifier have concluded that waste engine oil will soften virgin binder and cause a reduction in PG (*Villanueva et al. 2008*). These two findings could be combined to utilize both the cost savings of RAP with the softening properties of waste engine oil to offset the unavoidable stiffening inherent with using RAP. In order to test the theory that waste engine oil can be combined with RAP as a recycling agent, small scale binder testing was performed. In this phase of research, asphalt binder recovered from the RAP stockpile was blended with virgin binder. The resultant blend of asphalt binder was combined with four and eight percent waste engine oil to produce three different modified samples in addition to the pure virgin control binder. The four types of binder were tested for viscosity, aged dynamic modulus and unaged dynamic modulus.

Methods

The virgin binder chosen for this study was a PG 70-22 neat binder obtained from a pavement project in Grand Rapids, Michigan. This binder was combined with RAP- recovered binder at the ratio of 75% neat binder to 25% RAP-recovered binder. The RAP-recovered binder was extracted from a RAP stockpile in

Hancock, Michigan. In extracting the RAP binder, the ASTM D 2172 procedure was followed (*ASTM 2005b*). The extraction process involved soaking the RAP in trichloroethylene, then centrifuging the solution of asphalt binder and trichloroethylene from the aggregates. Once extracted, the binder was recovered using the rotary evaporation process as described in ASTM D 1856 (*ASTM 2005a*). The recovery process involved distilling the solution of trichloroethylene and asphalt binder. The solution was heated until the trichloroethylene boiled out of solution, leaving only the recovered asphalt binder (RAB). The extraction process yielded 88 grams of RAB from 2800 grams of the sample of RAP.

A second source of aged asphalt was created in the laboratory by open air aging a PG 58-28 binder in a 100°C oven for several weeks. A thin layer of the PG 58-28 binder was placed in a laboratory pan inside of on oven. Inside the oven, hot air was circulated over the binder to encourage oxidation. In-house air aging was chosen to supplement RAB testing because a second source of RAB was unavailable for testing. There is a known variability in RAP stockpiles, so a second source of RAB is important for broad applicability.

The used engine oil was collected from Modern Maruti service station in Hisar. Due to perceived environmental concerns, there is some stigma over the idea of mixing used engine oil into asphalt pavements. To counter this opposition, Summit Environmental Technologies, INC. tested the oil waste stream for potentially hazardous contents. Both EPA and ASTM test methods were utilized for the testing of the oil. The results of the test show the contaminants Arsenic, Cadmium, and Polychlorinated biphenyls (PCBs) at concentrations of less than 1 part per million (ppm) and chromium at less than 4 ppm, is below the restrictions placed on hazardous waste by the EPA (e-CFR 2006). A complete table of the hazard content test results can be found in Table 1.

All of the contents of the waste engine oil, with the exception of lead, are below the EPA admissible limits for hazardous waste. However, if the waste engine oil remains locked inside the asphalt binder while inside the pavement, it may be possible to achieve permitting to use waste engine oil as a recycling agent. Previous research by Herrington examined the leachate potential of oil contained inside asphalt pavements that were subjected to laboratory-simulated environmental weathering (*Herrington et al. 1993*). In this experiment, the oil had a lead concentration of 29,000 mg/kg. At 5 percent oil blended with the binder, the leachate test yielded a lead concentration of less than 0.05 mg/L. The oil used in the above study had a concentration significantly higher than that obtained for this report, and was shown to leach at a concentration much lower than the EPA acceptable level.

The waste engine oil was blended with the asphalt blends in two concentrations; 4% and 8% by total weight of binder. With the aid of a glass rod and under continuous stirring action, the binders were mixed homogenously in a standard specimen can over a hot plate at temperatures around 150°C. The percentages were chosen based on a review of literature on recycling agents in which the authors advocate against using high concentrations of recycling agent because of the potential damage to the asphalt pavement (*Villanueva et al. 2008; Widyatmoko 2008*). With the blends, seven types of binder were tested: original binder (Original Binder), 25% RAP blended with original binder at three percentages of oil, 0, 4, and 8 percent (RAP-0%, RAP-4%, RAP-8% respectively), and in-house oven aged asphalt blended with 0, 4 and 8% Oil (OA-0%, OA-4%, OA-8%, respectively). Table 2 shows the breakdown of sample compositions.

Table 1 Waste Engine Oil Chemical Composition

Parameter	Waste Oil Test Results	Allowable Level
Flash Point	>95° C	140 ° F
Lead	14.0 ppm	5.56 ppm
PCB	< 1.0 ppm	1.11 ppm
pH	6.69 @ 22.7 °C	2-12
Arsenic	< 1.2 ppm	5.56 ppm
Ash	0.56%	--
BTU/Gal	149795 / gal	--
Cadmium	0.31 ppm	1.11 ppm

Chromium	< 3.0 ppm	5.56 ppm
Sulfur, Wt%	0.19%	--
Total Halogen, ppm	396 ppm	--

Table 2 Composition of asphalt blends

	Original Binder	RAP-0%	RAP-4%	RAP-8%	OA-0%	OA-4%	OA-8%
Percentage Aged	0	25	25	25	100	100	100
Percentage Oil	0	0	4	8	0	4	8

After the samples had been prepared, rotational viscometer testing was performed according to ASTM D 4402. The tests were performed on a Brookfield model DV-II Viscometer. The viscosity readings were taken at four temperatures: 100°C, 125°C, 140°C and 160°C.

The binder was tested on a Bolhin CVO 120 Dynamic Shear Rheometer (DSR). Standard Strategic Highway Research Program (SHRP) Pass/Fail testing was conducted at various temperatures. SHRP Pass/Fail testing involves testing samples at low temperatures then progressively testing at the next highest PG until the sample fails by testing below the established Superpave control limits. At the point of failure, the test is discontinued since subsequent tests will fail at every temperature above the initial failure temperature.

The DSR measured the Complex Modulus (G*) and phase angle (δ) of each sample. The Super pave system uses the parameter G*/Sin(δ) as an indication of the rutting or permanent deformation standard performance criterion. When the G*/Sin (δ) parameter is greater than 1000 Pa for unaged binder or 2200 Pa for RTFO aged binder at a given PG temperature, the binder meets the Super pave rutting criterion for performance and is then progressively tested at the next grade temperature until it fails, that is until the testing parameter is not met. For PAV aged binder, the G*·Sin(δ) has a ceiling of 5000 kPa. Asphalt binder is tested at progressively lower temperatures inside the DSR until the G*·Sin(δ) reads above 5000 kPa, at that time the binder is said to have failed to meet specification and the test is discontinued.

4.1 RESULT AND ANALYSIS

Asphalt Binder Testing

From the DSR testing, the following data was obtained. Figure 3 is a plot of the viscosity results of the original binder, and then the original binder with 25% RAB and increasing amounts of engine oil. From this graph, it is shown that the binder blended with RAB experienced an upward shift in viscosity when compared to the control with no RAB. This shift corresponds to a stiffening of the binder once RAB has been added. The binders containing 4% and 8% waste engine oil then caused a downward shift in viscosity, which corresponds to a softening when the oil was added.

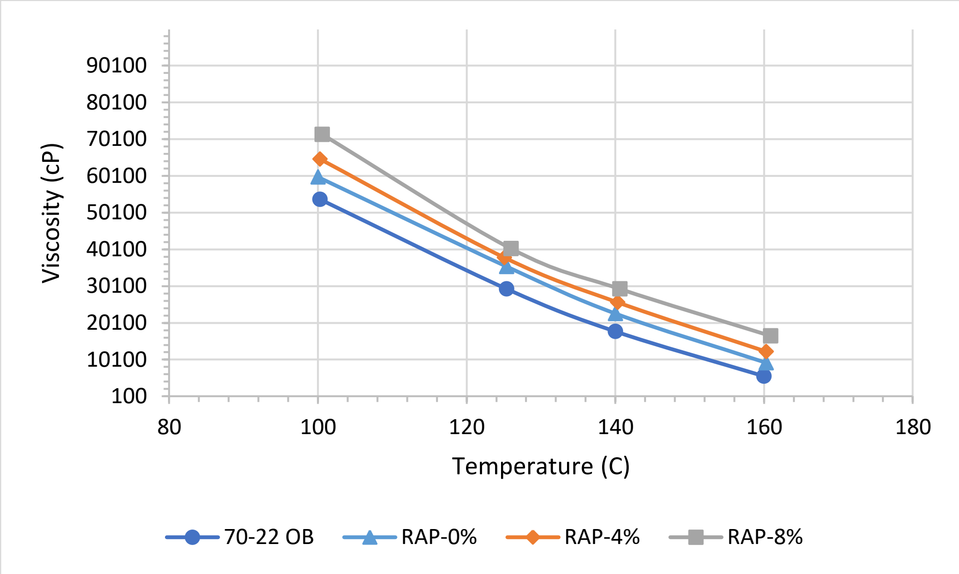

Figure 3 Viscosity of PG 70-22 original binder blended with 25% RAP and waste engine oil

Figure 4 is a plot of the G*/Sin(δ) parameters obtained from the DSR test results. These results are for the PG 70-22 binder that was then blended with 25% RAB and then four and eight percent waste engine oil for subsequent testing. The original binder, shown in gray, fails specification at 76ºC, which is expected for a PG 70 binder. The blend with 25% RAB and 0% waste engine oil experienced an upward shift for all data points, and had an overall PG increase to PG 76, indicating an improved resistance to rutting. The binder with RAB and 4% oil performed almost identically to the original binder, while 8% waste engine oil proved to reduce the PG to a 64, as indicated by the G*/Sin(δ) less than the specification of 1000 Pa at 70º

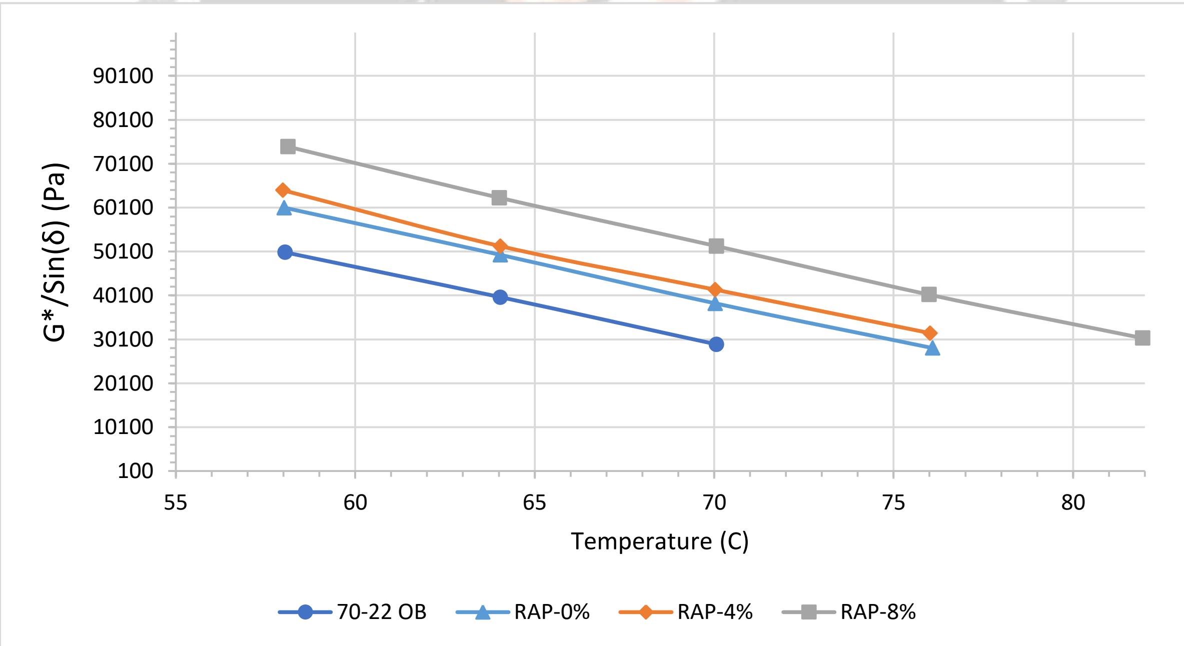

Figure 4 DSR results of PG 70-22 original binder blended with 25% RAP and waste engine oil

Figure 5 is a plot of the DSR results from the in house aged asphalt binder. Since the entire binder was oven aged and not blended with original binder, the original PG of this binder becomes irrelevant. What is important from these tests is the ability to replicate aged binder in the laboratory, then to test the aged binder with waste engine oil to compare these results to the PG 70-22 test results. The graph shows a PG 76 binder experiencing a downward shift as increasing amounts of waste engine oil is added.

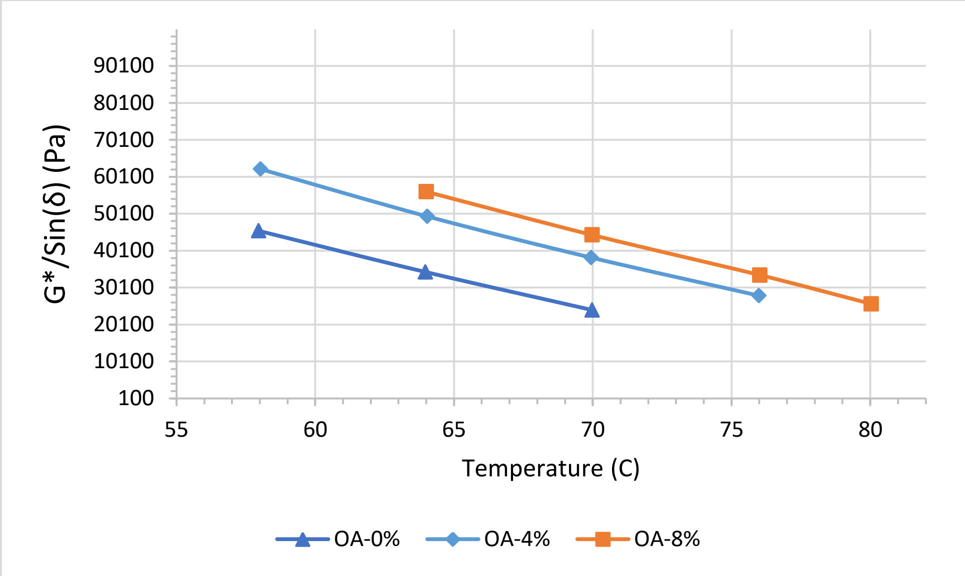

Figure 5 DSR Results for Oven Aged binder blended with waste engine oil

Figure 6 is of DSR results for a PG 70-22 binder that has undergone RTFO testing to see how binder blended with waste engine oil behaves. This experiment shows a two-grade decrease in high temperature acceptable binder with 8 % waste engine oil.

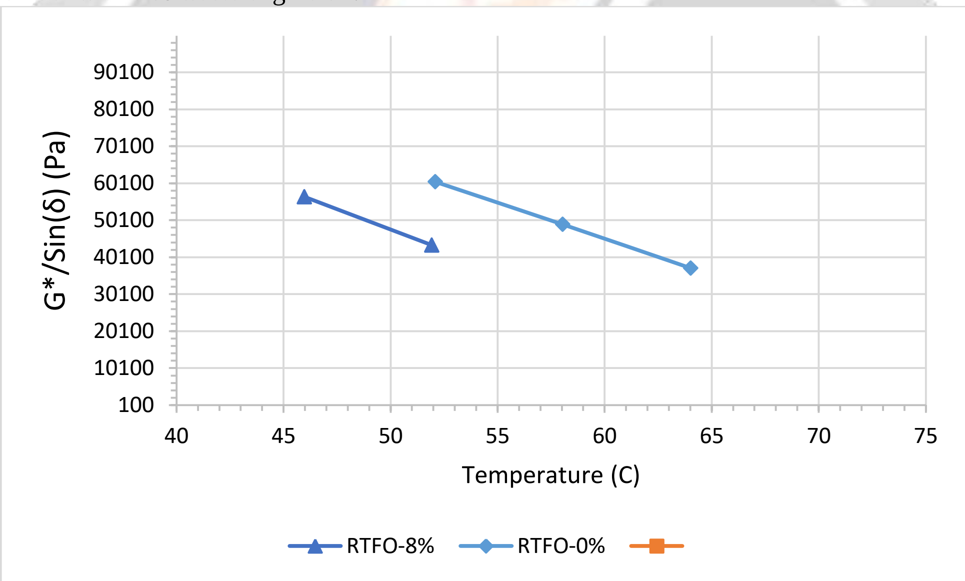

Figure 6 DSR Results for RTFO aged binder blended with RAP and waste engine oil

PAV testing was also performed on the PG 70-22 asphalt binder blended with 25% RAB and then blended with 0% and 8% waste engine oil. Based on the Superpave performance criterion maximum of 5000 kPa for the G*·Sin(δ) the 8% binder underwent a downward shift after PAV aging, indicative of softening. The plot of this shift can be seen in Figure 7

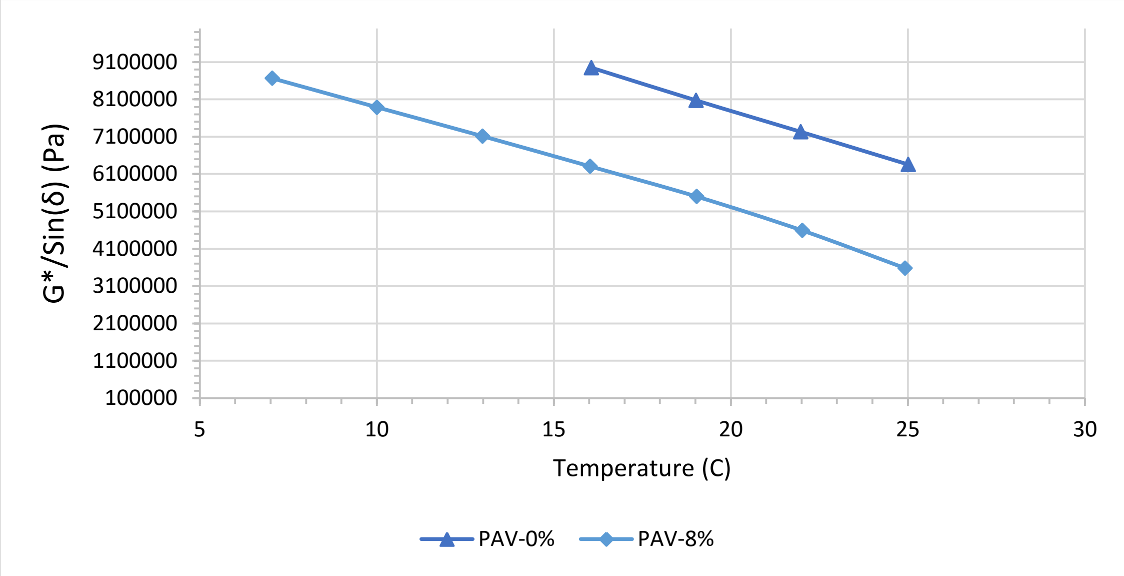

Figure 7 DSR Results for PAV aged binder blended with RAP and waste engine oil

From the data gathered in DSR testing of the PG 70-22 binder and the blends of RAP and oil, a comparison of the high temperature performance grades of the asphalt binders can be made, as shown in Figure 8. Initially the RAP caused an increase in PG because it increased the G*/Sin(δ) parameter to a point where it was less than 1.0 kPa at the test temperature. The increase in PG corresponds to an increase in stiffness and rutting resistance. With subsequent percentages of oil added, that stiffening was reduced and ultimately the binder was softened beyond the initial PG before RAP was added.

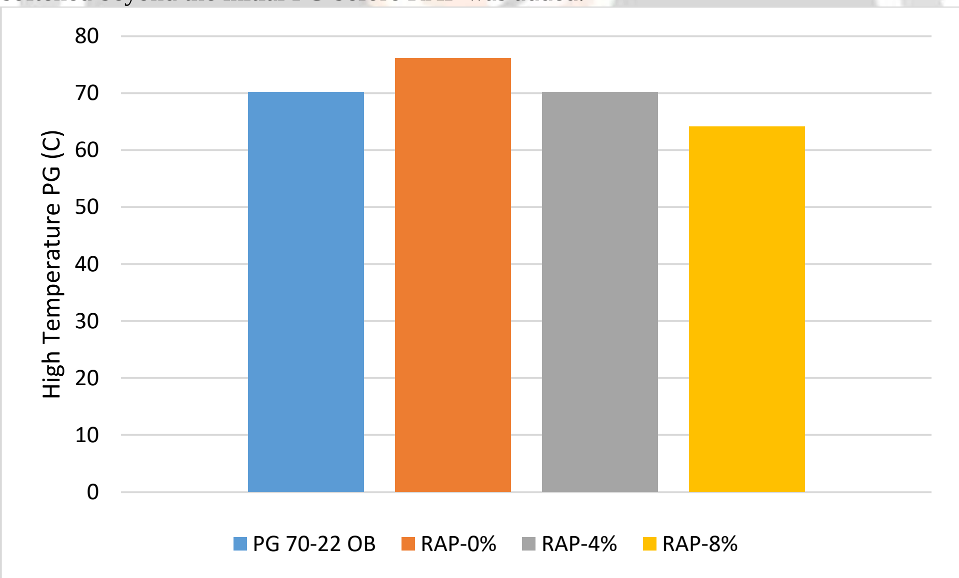

Figure 8 Results from DSR Testing with PG 70-22 Asphalt Binder

The results from the in house oven aged experiments are summarized in Figure 9. There was also an increase in the G*/Sin(δ) parameter when comparing the virgin binder to the aged binder. This finding is significant because it shows oven aged binder has an increased stiffness, similar to the increased stiffness with the RAP tested previously. The addition of waste engine oil into the aged binder led to a drop in high temperature PG, which means the rutting resistance is moving toward the virgin binders PG. This drop in PG was one successive grade for 4% waste engine oil, and two grades for the 8%.

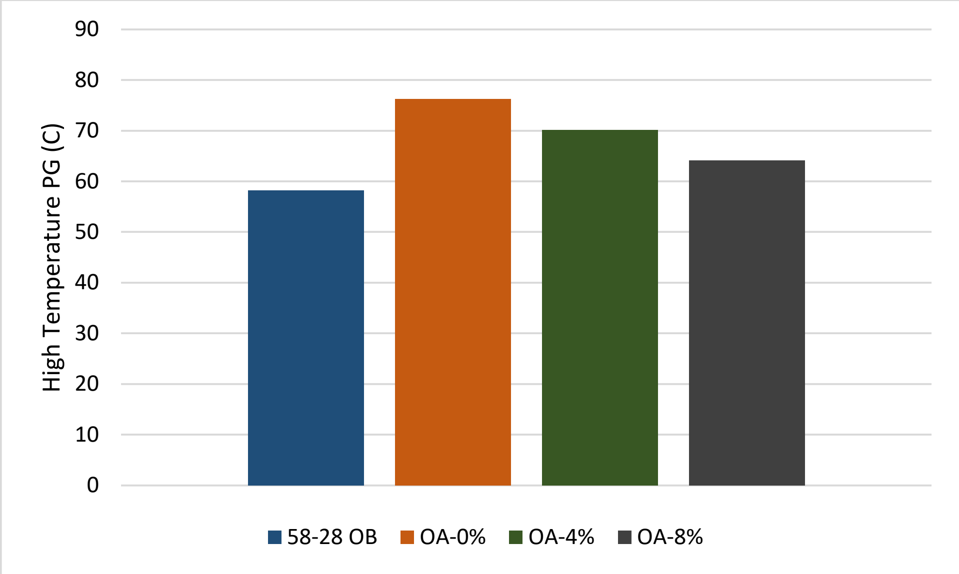

Figure 9 Results from DSR Testing with Oven Aged Asphalt Binder

The graphical results of the DSR tests performed on RFTO aged binder are seen in Figure 10. The aged binder exhibited a PG drop with 8% waste engine oil added. This result is the same as the unaged samples tested in the DSR. Due to the low smoke point of waste engine oil, the aging tests are a point of controversy. At small percentages of oil, however, the aging test returned the same two PG drop as unaged binder blended with waste engine oil, implying excessive aging did not take place with the waste engine oil.

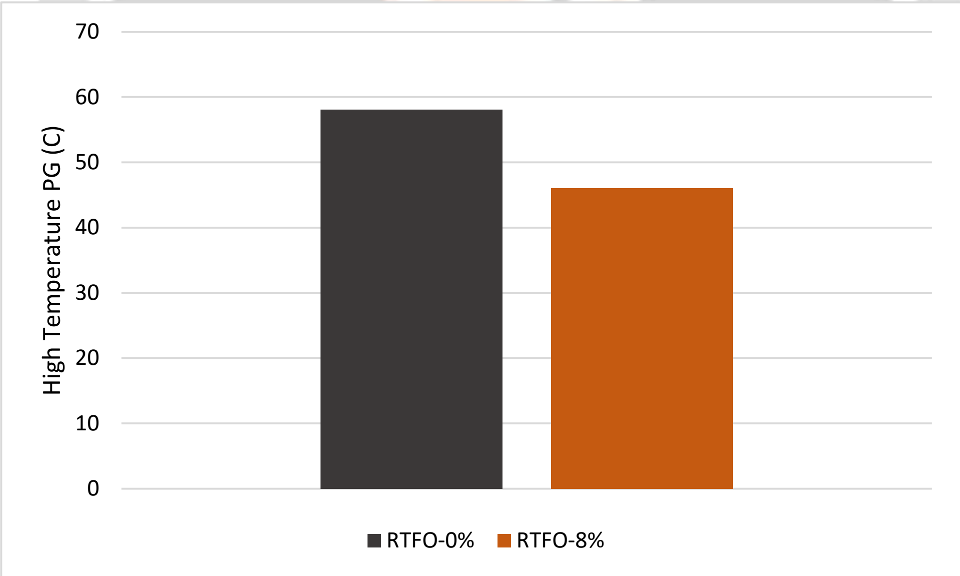

Figure 10 Results from DSR Testing with RTFO Aged Asphalt Binder

When the PAV aged binder was tested in the DSR for G*·Sin(δ) the binder underwent a two PG increase to low temperature cracking resistance. Figure 11 shows the two PG increase caused by the waste engine oil. This result matches what has been said in the literature about waste engine oil acting to reduce fatigue and extend the cracking life of asphalt pavements (Villanueva et al. 2008).

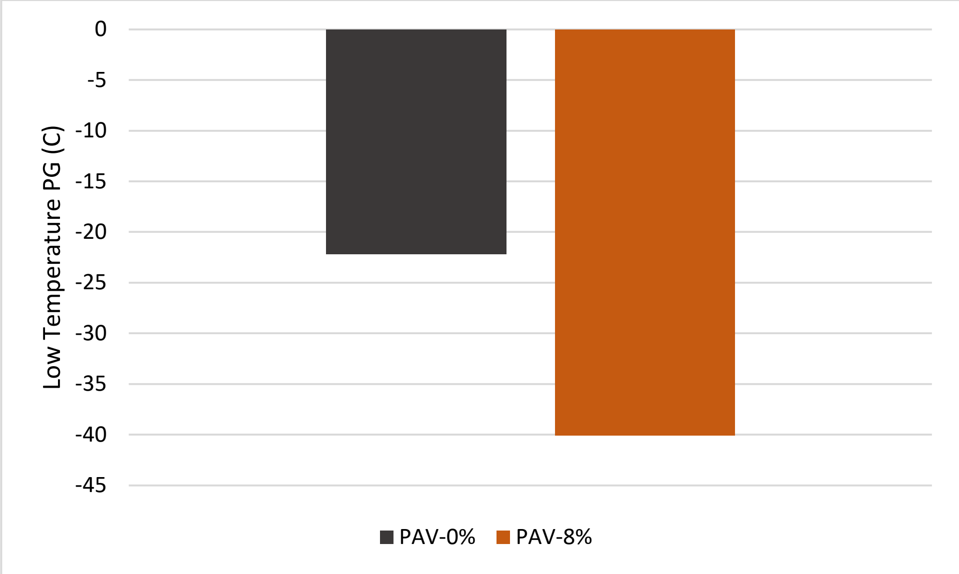

Figure 11 Results from DSR Testing with PAV Aged Asphalt Binder

5.0 CONCLUSIONS

Super pave asphalt binder testing is the accepted standard for establishing a usable service range of temperatures for which different asphalt binders are acceptable. Aged asphalt binder was tested in the same fashion as the virgin binder. Then waste engine oil was added to the aged binder in the hopes of showing the aging effects can be offset with the oil acting as a softening agent.

The DSR results for asphalt blended with RAB showed an increase in the G*/Sin(δ) parameter, which is indicative of an increased resistance to rutting. This supports the claim that RAP inside asphalt pavements will increase the rutting resistance. A similar increase in G*/Sin(δ) is obtained by oven aging virgin binder. Both oven aged binder and RAB were progressively softened with the addition of waste engine oil to the mixture. This proves that waste engine oil has the potential to counteract the stiffening from using RAP in new asphalt pavements.

By oven aging in the shallow dish, asphalt binder similar to field aged, recovered binder could be mimicked in the laboratory. Once simulated RAB was created, the addition of 4% and 8% waste engine oil caused equal softening to that seen by the RAB recovered by traditional means. This result is useful because it shows waste engine oil works as a softening agent on different RAB sources.

At some point the binder blended with waste engine oil becomes softer than the virgin binder being used. Further testing should be conducted to determine at what point excessive softening occurs. Excessive softening may damage asphalt pavements, and care should be taken not to use too much waste engine oil.

At 8% waste engine oil, the aged properties of the blended binder are less than desirable. There was a two PG decrease in high temperature grade, but an extension of two PG’s on the low temperature end. A lack of aged binder was the reason for the limited number of tests performed on aged binders. It is recommended in the future to acquire more aged binder and test concentrations other than 8% waste engine oil. Also, bending beam rheometer (BBR) testing is a common test for measuring the creep stiffness of PAV aged binder at low temperatures. It is highly recommended this test be conducted in the future to determine a definitive low temperature PG grading.

REFERENCES

ASTM. 2005a. ASTM D 1856 - 95a: Standard Test Method for Recovery of Asphalt from Solution by Abson Method. 2008 Annual Book of ASTM Standards. West Conshohocken, PA: ASTM International. p. 166-167.

ASTM. 2005b. ASTM D 2172 - 05: Standard Test Methods for Quantities Extraction of Bitumen from Bituminous Paving Mixtures (Method A). 2008 Annual Book of ASTM Standards. West Conshohocken, PA: ASTM International. p. 203-214.

ASTM. 2008c. ASTM D 7175 - 08 Standard Test Method for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer. 2008 Annual Book of ASTM Standards. West Conshohocken, PA: ASTM International.

ASTM. 2008d. ASTM D 4402 - 06 Standard Test Method for Viscosity Determination of Asphalt at Elevated Temperatures Using a Rotational Viscometer. 2008 Annual Book of ASTM Standards. West Conshohocken, PA: ASTM International.

Aurangzeb, Q., Al-Qadi, I. L., Ozer, H., & Yang, R. (2014). Hybrid life cycle assessment for asphalt mixtures with high RAP content. *Resources, conservation and recycling*, *83*, 77-86.

Borhan, M. N., Suja, F., Ismail, A., & Rahmat, R. A. O. K. (2009). The effects of used cylinder oil on asphalt mixes. *European Journal of Scientific Research*, *28*(3), 398-411.

Button, J. W., Little, D. N., & Estakhri, C. K. (1994). *Hot in-place recycling of asphalt concrete* (No. 193).

Chen, J. S., Huang, C. C., Chu, P. Y., & Lin, K. Y. (2007). Engineering characterization of recycled asphalt concrete and aged bitumen mixed recycling agent. *Journal of Materials Science*, *42*(23), 9867-9876.

Chen, J. S., Huang, C. C., Chu, P. Y., & Lin, K. Y. (2007). Engineering characterization of recycled asphalt concrete and aged bitumen mixed recycling agent. *Journal of Materials Science*, *42*(23), 9867-9876.

Cortizo MS, Larsen DO, Bianchetto H, Alessandrini JL. 2004. Effect of the thermal degradation of SBS copolymers during the ageing of modified asphalts. Polymer Degradation and Stability 86(2):275-282.

Dong, M., Hao, Y., Zhang, C., & Li, L. (2017). Failure mechanism analysis of asphalt–aggregate systems subjected to direct shear loading. *Materials and Structures*, *50*(5), 1-13.

Dunning RL, Mendenhall RL. 1978. Design of Recycled Asphalt Pavements and Selection of Modifiers. ASTM Special Technical Publication:35-46.

Faheem, A., Abboud, B., Coe, J., & Alsalihi, M. (2018). *Effect of warm mix asphalt (WMA) low mixing and compaction temperatures on recycled asphalt pavement (RAP) binder replacement* (No. FHWA-PA-2018-002-TEM WO 008). Pennsylvania. Dept. of Transportation. Bureau of Planning and Research.

Hosseinnezhad, S., Zadshir, M., Yu, X., Yin, H., Sharma, B. K., & Fini, E. (2019). Differential effects of ultraviolet radiation and oxidative aging on bio-modified binders. *Fuel*, *251*, 45-56.

Kandahl, P. S., Rao, S. S., Watson, D. E., & Young, B. (1995). Performance of recycled hot mix asphalt mixtures.

Kandhal, P. S., Rao, S. S., Watson, D. E., & Young, B. (1995). Performance of recycled hot-mix asphalt mixtures in Georgia. *Transportation Research Record*, (1507).

Katamine NM. 2000. Physical and mechanical properties of bituminous mixtures containing oil shales. Journal of Transportation Engineering-Asce 126(2):178- 184.

Kiggundu BM, Nusser BJ, Newcomb DE, Zallen DM. Correlations Between Physical and Chemical Properties in Recycled-Asphalt Binder Studies. Proceedings of the Paving and Transportation Conference. 1984; Albuquerque, NM, USA: Univ of New Mexico, Dep of Civil Engineering. p. 178-200.

Lin, P. S., Wu, T. L., Chang, C. W., & Chou, B. Y. (2011). Effects of recycling agents on aged asphalt binders and reclaimed asphalt concrete. *Materials and structures*, *44*(5), 911-921.

Lins, V. F. C., Araújo, M. F. A. S., Yoshida, M. I., Ferraz, V. P., Andrada, D. M., & Lameiras, F. S. (2008). Photodegradation of hot-mix asphalt. *Fuel*, *87*(15-16), 3254-3261.

Liu, S., Peng, A., Wu, J., & Zhou, S. B. (2018). Waste engine oil influences on chemical and rheological properties of different asphalt binders. *Construction and Building Materials*, *191*, 1210-1220.

Ma, T., Huang, X., Bahia, H. U., & Zhao, Y. (2010). Estimation of rheological properties of RAP binder. *Journal of Wuhan University of Technology-Mater. Sci. Ed.*, *25*(5), 866-870.

Ma, T., Wang, H., He, L., Zhao, Y., Huang, X., & Chen, J. (2017). Property characterization of asphalt binders and mixtures modified by different crumb rubbers. *Journal of Materials in Civil Engineering*, *29*(7), 04017036.

Mamlouk MS, Zaniewski JP. 2006. Materials for Civil and Construction Engineers. Upper Saddle River, NJ 07458: Pearson Prentice Hall.

Mandula, J., & Olexa, T. (2017). Study of the visco-elastic parameters of asphalt concrete. *Procedia engineering*, *190*, 207-214.

Masson, J. F., & Gagné, M. (2008). Polyphosphoric acid (PPA)-modified bitumen: disruption of the asphaltenes network based on the reaction of nonbasic nitrogen with PPA. *Energy & fuels*, *22*(5), 3402-3406.

McDaniel, R. S., & Anderson, R. M. (2001). *Recommended use of reclaimed asphalt pavement in the Superpave mix design method: technician's manual* (No. Project D9-12 FY'97). National Research Council (US). Transportation Research Board.

Mirhosseini, A. F., Tahami, S. A., Hoff, I., Dessouky, S., & Ho, C. H. (2019). Performance evaluation of asphalt mixtures containing high-RAP binder content and bio-oil rejuvenator. *Construction and Building Materials*, *227*, 116465.

Nazzal, M. D., Mogawer, W., Austerman, A., Qtaish, L. A., & Kaya, S. (2015). Multi-scale evaluation of the effect of rejuvenators on the performance of high RAP content mixtures. *Construction and Building Materials*, *101*, 50-56.

Nguyen, H. T., Tu, T. V., Phan, V. R., & Phan, B. G. (2019, November). Analysis of stress and strain in flexible pavement structures comprised of conventional and high modulus asphalt using viscoelastic theory. In *International Conference on Critical Thinking in Sustainable Rehabilitation and Risk Management of the Built Environment* (pp. 207-219). Springer, Cham.

Pakenari, M. M., & Hamedi, G. H. (2021). Investigating the effective laboratory parameters on the stiffness modulus and fatigue cracking of warm mix asphalt. *International Journal of Civil Engineering*, *19*(6), 685-698.

Shannon, C., Mokhtari, A., Lee, H. D., Tang, S., Williams, C., & Schram, S. (2017). Effects of high reclaimed asphalt-pavement content on the binder grade, fatigue performance, fractionation process, and mix design. *Journal of Materials in Civil Engineering*, *29*(2), 04016218.

Soleimani A, Walsh S, Hesp SAM. 2009. Asphalt cement loss tangent as surrogate performance indicator for control of thermal cracking. Transportation Research Record(2126):39-46.

Stimilli, A., Virgili, A., Giuliani, F., & Canestrari, F. (2017). Mix design validation through performance-related analysis of in plant asphalt mixtures containing high RAP content. *International Journal of Pavement Research and Technology*, *10*(1), 23-37.

Tang, S., Williams, R. C., & Cascione, A. A. (2017). Reconsideration of the fatigue tests for asphalt mixtures and binders containing high percentage RAP. *International Journal of Pavement Engineering*, *18*(5), 443-449.

Tanty, K., Mukharjee, B. B., & Das, S. S. (2018). A factorial design approach to analyse the effect of coarse recycled concrete aggregates on the properties of hot mix asphalt. *Journal of The Institution of Engineers (India): Series A*, *99*(2), 165-181.

Villanueva, A., Ho, S., & Zanzotto, L. (2008). Asphalt modification with used lubricating oil. *Canadian Journal of Civil Engineering*, *35*(2), 148-157.

Villanueva, A., Ho, S., & Zanzotto, L. (2008). Asphalt modification with used lubricating oil. *Canadian Journal of Civil Engineering*, *35*(2), 148-157.

Wang, D., Falchetto, A. C., Moon, K. H., Riccardi, C., Pei, J., & Wen, Y. (2019). Artificially prepared Reclaimed Asphalt Pavement (RAP)—an experimental investigation on re-recycling. *Environmental Science and Pollution Research*, *26*(35), 35620-35628.

Wang, H., Li, X., Xiao, J., You, Z., Yang, X., & Irfan, M. (2018). High-temperature performance and workability of crumb rubber–modified warm-mix asphalt. *Journal of Testing and Evaluation*, *48*(4), 2946-2962.

Widyatmoko, I. (2008). Mechanistic-empirical mixture design for hot mix asphalt pavement recycling. *Construction and Building materials*, *22*(2), 77-87.

Widyatmoko, I. (2008). Mechanistic-empirical mixture design for hot mix asphalt pavement recycling. *Construction and Building materials*, *22*(2), 77-87.

Yildirim, Y. (2007). Polymer modified asphalt binders. *Construction and Building Materials*, *21*(1), 66-72.

Yu, J. Y., Feng, P. C., Zhang, H. L., & Wu, S. P. (2009). Effect of organo-montmorillonite on aging properties of asphalt. *Construction and Building Materials*, *23*(7), 2636-2640.

Zhao, X., Yan, K., He, W., & Cai, C. (2017). Effects of Sasobit/Deurex on amorphous poly alpha olefin (APAO) modified asphalt binder. *Construction and Building Materials*, *154*, 323-330.

Zhu, J., Ma, T., & Dong, Z. (2020). Evaluation of optimum mixing conditions for rubberized asphalt mixture containing reclaimed asphalt pavement. *Construction and Building Materials*, *234*, 117426.