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Asphalt Rheology and Strengthening Through Polymer Binders

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16. Abstract
This term paper investigates the influences of polymer modifications to asphalt rheology as compared to conventional asphalt pavement sections. The addition of 2% to 3% of polymers into the wearing and base courses of asphalt (flexible) pavements have been known to enhance the engineering characteristics of traditional asphalt as a binder which offers longer life expectancy and increased capacity, increased resistance to fatigue cracking, increased resistance to rutting (permanent deformation), improved thermal-stiffness performance at high and low extreme temperatures, increased resistance to tension cracking, increased resistance to stripping, and reduce binder drain down. Polymers are classified in this paper into their major respective categories with the most common types presented and described in detail. Challenges related to the usage, rheology, and practical implementation of polymer modified asphalt are discussed. Standardized and non-standardized tests and experiments related to the physical and rheological characterization of asphalts and polymer-modified are also presented. Recent research has focused on the sustainability concepts for the application of polymer modified asphalt for high-recycled asphalt mixtures to achieve similar or better engineering characteristics as compared to conventional asphalt pavement mixtures. The sustainable benefits of using high-reclaimed asphalt pavement with the addition of polymer and rejuvenator modifications include reduced landfill / stockpile dependence, reduced greenhouse gas emissions from less required virgin binder from oil barrels, and possible economic benefits depending on the true-costs of the project. To achieve comparable or better rheological properties for high-recycled asphalt pavement high-polymer modified asphalt can be used with between 7% and 8% polymer additions. Furthermore, high-polymer modified asphalt is shown to be applicable to applications such as highly traveled highways, when thinner layers of pavement is required and long-life expectancy is critical when combined with increasing traffic intensities and loads.

17. Key Words
Asphalt Rheology; Pavements; Polymers; Binders

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1. DESCRIPTION OF THE PROBLEM

Asphalt is a sticky, dark brown, and highly viscous liquid or semisolid as a hydrocarbon produced from petroleum distillation residue. This distillation can occur naturally in asphalt lakes or occur in a petroleum refinery. Due to its adhesive characteristics, asphalt is commonly used as an aggregate binder to create asphalt concrete (AC) mixture which is a composite material employed in the construction of flexible highway pavements (Chen and Xu, 2000). Asphalt (bitumen) is a thermoplastic material widely used as an adhesive or binder in paving industry. Desired characteristics of asphalt include flexibility to withstand low temperature cracking due to sudden stress and resistance to permanent deformation (or viscous flow) at high temperatures thereby resisting load stresses at both extremum temperatures (Bulatovic et al., 2013). Bitumen emulsified binders (asphalt binders) are commonly employed in various surface treatment applications including micro-surfacing, slurry seal and chip seals (Khadivar and Kavussi, 2013).

Polymers are widely used to enhance the characteristics of asphalt as a binder in asphaltic concrete. Polymer modified asphalt generally offer longer life and enhanced pavement performance of the asphalt. Polymers enhance temperature susceptibility of asphalt by improving its stiffness at high service temperatures and decreasing its stiffness at low service temperatures (Bulatovic et al., 2013). Asphalt rheology properties such as fatigue cracking, rutting, hardening of asphalt binder, and temperature cracking potential affect the pavement performance. Addition of polymers in asphalt improves resistance to fatigue, rutting, temperature cracking and stripping (Khattak and Baladi, 1998) and considerably enhance the mechanical characteristics of asphalt mixtures and relatively reduce the binder drain down (Mokhtari and Nejad, 2012). Polymers can be categorized into four main classes namely plastics (or plastomers), elastomers (rubbers), fibers and additives/coatings. The use of polymer modifiers in PMAs give rise to several challenges including high production costs, miscibility and storage issues (Polacco et al., 2005) as well as effects of oxidative ageing (Šušteršic et al., 2013). Polymer modification has been found to double the cost of asphalt binders even for small proportions of the additive (Isacsson and Lu, 1995, Polacco et al., 2005, Šušteršic et al., 2013). Incompatibility or low compatibility of such polymers utilized in the asphalt binder may result in phase separation with separation into polymer-rich and asphalt rich phases occurring during storage at high temperatures in the absence of stirring.

According to the American Society of Civil Engineering (ASCE) 2009 infrastructure assessment report, the United States of America infrastructure achieved a D+ condition rating. This poor rating, coupled with tight DOT budgets, climate change and emission of greenhouse gasses, and the need to continuously expand our nation's infrastructure results in the requirement for innovative and sustainable techniques for infrastructure rehabilitation and construction projects to meet the tightening economic and environmental goals (Bowers, 2016). Furthermore, traffic intensities and loading on pavement continues to increase with time, and when coupled with DOT's tight budgets there is a need for "value engineering" for maintaining highway infrastructure. There is potential for highly polymer modified asphalt mixtures to meet the increasing demand for greater and more intense traffic loading on highways (Willis, 2016). As a result, there has been several recent research projects investigating the application of using recycled asphalt aggregate to create a mixture of virgin aggregate and binder, recycled aggregate and binder, and polymer modifiers to improve or rehabilitate existing roadways and build new roadways.

For the recycled asphalt mixtures to be feasible and applicable to wide scale projects the recycled asphalt mixture must perform as well as conventional asphalt with virgin aggregate in terms of structural performance, capacity and longevity. Many state DOT's allow for up to 30% recycled asphalt aggregate and binder in mix designs; however, most states use only between 10% and 20% in actual practice. AASHTO fatigue cracking tests showed that the use of rejuvenators in the recycled asphalt pavement mixtures improved the cracking resistance when compared to the virgin aggregate and binder asphalt control mixture. Most importantly, when the 7.5% styrene-butadiene-styrene (SBS), PG 64-28E (heavy traffic greater than 30 million ESAL, AASHTO M 332), and PG 58-28 plus low temperature Rosphalt 50-LT were added the fatigue cracking resistance significantly improved as well. It is shown that the number of cycles to fatigue failure is 50% less for the recycled asphalt mixture with no rejuvenator and no polymer modification, when compared to the virgin aggregate and binder control group, refer to Figure A.1.1 (Mogawer, 2016).

Highly polymer modified asphalt binders contains 7% to 8% of polymer to create a highly integrated polymer chain network (Willis, 2016). Also, highly polymer modified pavements improve the rutting and fatigue performance of asphalt. The results of the research study show that after 20 million equivalent single axle loads of traffic and six years of environmental effects the highly polymer modified test section shows less rutting and less cracking when compared to the conventional asphalt section control group; furthermore, the highly polymer modified section did not diminish in ride quality over time when compared to the control even though the cross section was 1.25 inches less than the conventional section (Willis, 2016).

2. APPROACH

2.1 ASPHALT MODIFICATION

Road performance can be enhanced through modification of the asphalt. Asphalt modification is the introduction of an additive with desired characteristics to enhance the asphalt. Modified asphalts tend to provide longer life and better pavement performance than conventional pavements (Brovelli et al., 2013). There are generally three major types of asphalt modification: polymer modification, non-polymer additive modification and chemical reaction modifications. Non-polymer additives employed in asphalt modification include use of fillers, anti-stripping additives, extenders, anti-oxidants, organo-metal compounds, and other materials such as shale oil, gilsonite, silicone and inorganic fibers. Polymer additives include plastics, elastomers, reclaimed rubbers and fibers. Chemical reaction modifications include addition reaction (asphaltic reaction with monomer), vulcanization (asphaltic reaction with sulfur) and nitration reaction (asphaltic reaction with nitric acid) (Isacsson and Lu, 1995).

2.2 POLYMER MODIFICATION

Asphalt rheology properties such as fatigue cracking, rutting, hardening of asphalt binder, and temperature cracking potential affect the pavement performance. Addition of polymers in asphalt improves resistance to fatigue, rutting, temperature cracking and stripping (Khattak and Baladi, 1998) and considerably enhance the mechanical characteristics of asphalt mixtures and relatively reduce the binder drain down (Mokhtari and Nejad, 2012). In surface treatment applications, polymer binders have been found to enhance aggregate bonding, thermal susceptibility, abrasion resistance and bleeding resistance (Khadivar and Kavussi, 2013).

2.3 TYPES OF POLYMER

Polymers can be categorized into four main classes namely plastics (or plastomers), elastomers (rubbers), fibers and additives/coatings. Plastics can be further classified into thermoplastics and thermosets (or thermosetting resins) whereas elastomers can be classified into natural and synthetic rubber (Isacsson and Lu, 1995). Polymers can also be categorized into three main classes related to their behavior upon addition to the asphalt namely elastomers, non-reactive plastomers and reactive polymers (or reactive plastomers). Plastomers form a rigid three-dimensional network improving rigidity and providing permanent deformation resistance under loading whereas elastomers induce higher elasticity and recovery. Reactive polymers are similar to plastomers but have the additional functionality of chemically bonding with asphalt molecules (Brovelli et al., 2013, Gama et al., 2016).

Thermoplastics tend to harden during cooling and soften during heating whereas thermosets cannot revert to a fluid state upon heating. Thermoplastics increase the viscosity and stiffness of asphalt (bitumen) at service temperatures. Common thermoplastics used in asphalt modification include polyethylene (PE), polypropylene (PP), poly(vinyl chloride) (PVC), polystyrene (PS) and ethylene vinyl acetate (EVA). Thermosets are formed through the direct creation of polymers from monomers or the crosslinking of linear prepolymers resulting in a strong three-dimensional structure. The resulting products are insoluble, infusible and do not flow. Common (important) thermosets used in asphalt modification include alkyds, amino and phenolic resins, epoxies, unsaturated polyesters and polyurethanes.

Elastomers used in asphalt modification include styrene-butadiene-styrene (SBS) block copolymer, styrene-butadiene copolymer (SBR), natural rubber (NR), polybutadiene (BR), polyisoprene (IR), isobutene-isoprene copolymer (IIR) and polychloroprene (CR). Styrene-butadiene-styrene (SBS) block copolymer, however is highly popular due to its thermoplastic and elastic characteristics are popularly called thermoplastic rubbers (TR) (Isacsson and Lu, 1995) or thermoplastic elastomer with multiphase structure comprising of polystyrene (S) block at the double ends and polybutadiene (B) block in the middle (Weizen et al., 2001). This unsaturated thermoplastic elastomer is probably the most widely used polymer in asphalt modification (Polacco et al., 2005) and has been widely used in the paving industry to enhance endurance life and pavement performance (Weizen et al., 2001).

SBR and NR polymers are thermoset elastomers which are employed as dispersed additives in water phase (latex) and have been commonly used in modified asphalt binders. They have been found to primarily improve the elastic characteristics of the asphalt. SBR is a random copolymer of styrene and butadiene which have been found to considerably enhance the elastic recovery and ductility of modified asphalt at all temperature permitting flexibility and crack resistance at low temperatures. SBR also enhance elastic, adhesive and cohesive characteristics of asphalt and decreases the rate of oxidation. NR latex on the other hand is an elastic hydrocarbon polymer of Isoprene monomers which is milk-like in nature (natural milk-like liquid). However, it is incompatible with some asphalt binders due to its high molecular weight (Khadivar and Kavussi, 2013).

Fibers are threadlike in nature without restriction on composition and can be categorized into natural and synthetic fibers. Synthetic fibers can be further classified into organic and inorganic fibers. Polymer fibers are hydrogen-carbon or heterochain polymers which can be either natural or synthetic (Isacsson and Lu, 1995). Fibers have been found to enhance a vast array of engineering properties of asphalt matrix. These properties include moisture susceptibility, viscoelasticity, creep compliance, rutting resistance, low-temperature anti-cracking properties, fatigue life, durability of asphalt concrete mixtures, material toughness, tensile strength, dynamic modulus, elasticity, wear resistance (of AC mixtures that are employed as pavement wearing course) and reflective anti-cracking properties of AC mixtures and pavements. Fibers also increase the optimum asphalt content in the mixture design and absorbs asphalts preventing asphalt leakage. However, a disadvantage of the use of fibers is the need for higher compaction effort due to the increase in air voids of the asphalt concrete mixture (Chen and Wu, 2010). Fibers alter the viscoelasticity of mixtures and enhance dynamic modulus, tensile strength and moisture susceptibility, creep compliance, rutting resistance and fatigue life while considerably reducing binder drain down (Mokhtari and Nejad, 2012).

2.4 CHALLENGES RELATED TO USE OF POLYMER MODIFIERS IN PMAs

The use of polymer modifiers in PMAs give rise to several challenges including high production costs, miscibility and storage issues (Polacco et al., 2005) as well as effects of oxidative ageing (Šušteršic et al., 2013). Polymer modification has been found to double the cost of asphalt binders even for small proportions of the additive (Isacsson and Lu, 1995, Polacco et al., 2005, Šušteršic et al., 2013). This is most notable for SBS block copolymers which are applied as virgin polymers due to degradation when subjected to atmospheric agents and mechanical stress thus cheaper polymers such as olefinic polymers like Polyethylene (PE) and polypropylene (PP) are employed. However, these plastomers have also been found to be incompatible with asphalt due to their non-polarity. Incompatibility or low compatibility of such polymers utilized in the asphalt binder may result in phase separation with separation into polymer-rich and asphalt rich phases occurring during storage at high temperatures in the absence of stirring. The polymer-rich phase tends to migrate above the asphalt-rich phase leading to an inhomogeneous substance which is ineffective for paving applications with additional issues due to the remarkably high viscosity of the polymer-rich phase (Polacco et al., 2005). This and other disadvantages of using polymers however can be decreased through the functionalization of polymers. Functionalization during asphalt polymer modification is the chemical addition of specific polymers to achieve specific modified properties of the asphalt. These properties ideal in hot climatic conditions include good storage stability, excellent ageing resistance, strong adhesion with aggregates, high stiffness at high temperatures and good cracking resistance at low temperatures. Functionalization enhances the quality of polymer-modified asphalt invariably improving the long-term durability and serviceability. Reactive polymers are polymer modifiers which chemically react with components of asphalt resulting in the creation of new desired asphalt-modified mixes by means of functionalization (Gama et al., 2016). However, in some cases functionalization (such as modification of olefinic chain) has been found to enhance the miscibility of the polymer in asphalt but has not resulted in improved stability of the mix (Polacco et al., 2005).

Ageing of asphalt is induced by chemical and/or physical changes and occurs in three different stages: storage; mixing, transport and laying and finally during service life (Isacsson and Lu, 1995). The principal cause of asphalt ageing and embrittlement in service is the atmospheric oxidation of molecules with the formation of highly polar and strongly interacting functional groups containing oxygen (Li et al., 2016). Despite the notable improvement of high-temperature properties by polymer-modified asphalts (PMAs), oxidative ageing has been found to have a significant effect on the pavement performance. Also, many PMAs soften quickly at high temperatures (Šušteršic et al., 2013). Oxidative aging also causes hardening of asphalt binders and contributes to the deterioration of asphalt pavements (Li et al., 2016). Ageing causes alterations in chemical composition as well as rheological and mechanical characteristics of the modified asphalt (Bulatovic et al., 2013) resulting in polymer degradation and increase in viscosity of binders. Hence, the resulting restructuring of a binder due to polymer degradation affects the mechanical and rheological characteristics of modified asphalt. Polarity of the polymer however can improve its solubility and compatibility with base asphalt through the reaction of the polar groups present in polymer molecules with polar elements of the asphalt. This leads to the prevention of phase separation which invariably improves the consistency of the asphalt and reduces oxidative ageing (Šušteršic et al., 2013).

3. METHODOLOGY

3.1 PREVIOUS RESEARCH FINDINGS

Several studies have been conducted on the effect of polymer modifiers on the performance of modified asphalt mixtures. Mokhtari and Nejad (2012) examined the effect of additives such as styrene–butadiene–styrene (SBS), mineral fiber and cellulose fiber employed as modifiers in stone matrix asphalt (SMA) mixtures. The modifiers were added to the SMA mixtures as drain down inhibitors. SBS was found to be more effective in enhancing the performance of SMA in comparison to the fibers. SBS was found to the best at prolonging the service life of the pavement as well as reducing the pavement layer thickness with mineral fibers providing the least improvement. SBS was also found to best at improving moisture damage resistance (moisture susceptibility) however mineral fibers produced negligible improvement with cellulose fiber performing better However SBS was found to be a less effective drain down inhibitor.

Chen and Wu (2010) investigated the physical characteristics, reinforcing effects and mechanisms of fibers for stabilizing and reinforcing asphalt binder. Laboratory experiments were formulated to examine the physical properties of fibers. The tests include laboratory tests of water absorption, mesh-basket drain down, and oven heating which were employed to evaluate the wettability, asphalt absorption and stabilization, and thermostability of the fibers respectively. These formulated tests were conducted on five fiber types comprising three polymer fibers (two polyesters, one polyacrylonitrile) and two non-polymer fibers (one lignin and one asbestos). Scanning Electron Microscopy was also employed to observe the microstructures of fibers and their spatial network in asphalt binder in order to gain a better comprehension of fiber reinforcing mechanisms. Mechanisms tests on fiber modified asphalt were conducted as supplementary tests. A mesh-basket drain down experiment was conducted to examine the fiber's absorption and stabilization of the asphalt. A cone sink experiment was conducted to evaluate fiber-modified asphalt's resistance to flow and shear. The dynamic shear rheometer (DSR) test was designed to measure the shear modulus and phase angle of asphalt binder, and examine its rheological properties and rutting resistance.

The polymer fibers (polyester and polyacrylonitrile) were found to have stronger networking effect than the non-polymer fibers (lignin and asbestos). However, the polymer fibers were found to present lower effects of asphalt absorption and stabilization than the non-polymer fibers. The lignin fiber (a non-polymer fiber) was found to have the highest water absorption but the lowest thermostability.

Sustersic et al. (2013) examined the effect of Waste composite poly-methyl methacrylate filled with a fine dispersion aluminum trihydrate (PMMA/ATH) and Fischer–Tropsch wax as an asphalt modifier on asphaltic concrete. The authors investigated the effect of modifying agent content, primary ageing and long-term oxidative ageing on rheological and mechanical properties of base and modified asphalt.

Oruc and Yilmaz (2016) investigated the effect of cyclic borate ester (CBE), a novel boron-containing additive chemically synthesized in laboratory conditions, on the improvement in the performance characteristics of asphalt. The CBE additive was found to increase the hardness, softening point, viscosity, flash-point value and rutting resistance of asphalt binder and decreased temperature sensitivity. CBE was found to improve elastic responses (increased complex shear modulus and decreased phase angle), aging resistance and low-temperature cracking resistance and did not change the cohesion property.

Gama et al. (2016) investigated the rheological characteristics of asphalt binders modified with polymers such as Ethylene–Methyl-Acrylate–Glycidyl-Methacrylate (EMA-GMA) (an elastomeric polymer), High-Density Polyethylene (HDPE) and Polyphosphoric Acid (PPA 116%). Polymer addition resulted in elastic characteristic enhancement of modified asphalt subjected to high traffic loadings. Penetration, softening point and elastic recovery results indicated an improvement in the elastic characteristics of the modified asphalt producing suitable paving material. Improvements in softening point and complex modulus indicated an increased resistance to permanent deformation. The improvement in performance grade (PG) indicate improvement in asphalt binder performance at high temperatures. In general, the modifiers resulted in an improvement in elastic behavior of the asphalt resulting in high-working performance at medium and high temperatures.

Brovelli et al (2015) assessed the effect of amorphous polyolefin polymer and a polymer obtained by combining LDPE (low density polyethylene) and EVA (ethyl-vinyl-acetate) on enhancing rutting resistance of asphaltic concrete. Rutting tests were conducted using a wheel tracking device to evaluate the rut depth and wheel-tracking slope (WTS). Stiffness and fatigue were performed to verify the performance of the polymer modified asphalt. Results indicated the improvement of the rutting resistance of the asphalt due to polymer modification without compromising the stiffness and fatigue characteristics.

Yan et al. (2016) assessed the effects of alternative polymer modifications on intermediate temperature cracking performance of asphalt binders and resultant mixtures using the energy ratio (ER) parameter which is related to field pavement cracking performance. Four alternative polymer-modified asphalt (PMA) binders were compared to the styrene-butadiene-styrene (SBS) PMA binder which has been widely used due to its enhancement of rutting resistance and improvement of pavement cracking performance. The aim of the study is to establish whether alternative binders could achieve equivalent or better performance as standard SBS PMA binder (binders with SBS alone). The four alternative PMA binders which were previously found to have excellent elastomeric binder and fracture characteristics were binders produced SBS plus polypropylene composite, terpolymer plus polypropylene composite, SBS plus oxidized polyethylene wax and a non-SBS polymer of unknown composition.

Khadiar and Kavussi (2013) examined the effects of Butadiene Rubber (SBR) and Natural Rubber (NR) latexes on the rheological characteristics of Polymer Modified Bitumen Emulsions (PMBE) (modified asphalt binders). They were examined at three different additive contents (3%,4% and 5%). Standard empirical and rheological tests were used to test the asphalt binders. Physical properties of the PMBE residues was analyzed using conventional tests such as penetration, softening point and ductility. Temperature sweep, dynamic shear rheometer (DSR) testing and Multiple Stress Creep and Recovery (MSCR) testing were conducted to characterize the rheological properties in linear and non-linear modes. Conventional test results indicated that the introduction of the polymer modifiers significantly improved the stiffness and elastic properties of the modified residual asphalt mixture in the linear region. The modifiers also led to the reduction in temperature susceptibility of the binder. However, this was more evident in higher proportions of SBR. Temperature sweep test results indicated a considerable increase in the complex and phase angle values of the binder residues for both polymers. SBR was found to be more sensitive to applied stresses in the non-linear region. NR latex resulted in significant increase in the stiffness of the asphalt but did not alter the elastic properties of the asphalt mixture.

Edwards et al (2007) investigated the rheological effects of polyphosphoric acid (PPA) and three commercial waxes on bitumen (asphalt) of 160/200 penetration grade at medium and high temperature. The study was conducted to examine the rutting performance of the modified asphalt concrete pavement. The three waxes are FT paraffin wax (Sasobit), Montan Wax and Polyethylene Wax. Tests such as Dynamic Shear Rheometer (DSR), Differential Scanning Calorimeter (DSC) and Force Ductilometer (FD) as well as empirical binder (conventional) tests for penetration, softening point and Fraass breaking point were conducted. Ageing of samples were performed using Rolling Thin Film Oven Test (RTFOT) following by Pressure Ageing Vessel (PAV). Rheological measurements were conducted with temperature by means of a dynamic rheometer. Fourier Transform Infrared (FTIR) Spectroscopy was used to analyze the chemical characteristics of the asphalt mixes and waxes. The wax additives displayed significant stiffening effect at medium and high temperatures and was demonstrated by Dynamic Mechanical Analysis (DMA) temperature sweeps, decrease in penetration (at +25 oC), increase in softening point and penetration index, as well as force ductility results (at +5 oC). FT paraffin wax (Sasobit) showed the greatest stiffening effect in relation to the empirical parameters (softening point, penetration at 25 oC and force ductility at +5 oC), but not in terms of rutting factors by DMA. The use of polyphosphoric acid and polyethylene wax was found to result in significant improvement in the rheological behavior of the modified asphalt at medium and high temperatures.

Polacco et al. (2005) started with a preliminary characterization of different PMAs obtained by modifying an asphalt from vacuum distillation with several PE and PE-based polymers such as low-density polyethylene (LDPE), linear low-density polyethylene (LLDPE), copolymers of polyethylene with acrylic acid (PE-AA), glycidylmethacrylate (PE-GMA) and RET copolymers were used. A set of PMAs was made and characterization was performed using Ring and Ball softening point, morphological analysis and storage stability test. These tests revealed that the polymer-modified asphalt had a heterogenous structure and was not stable in terms of storage. Although the modification of the olefinic chain with addition of functional groups improved the miscibility of the polymer in asphalt, it did not help in improving the stability of the mix. A linear low-density polyethylene helped in obtaining an asphalt binder with improved mechanical properties in comparison with other mixes. The small and large deformations were used to study the rheological properties of the base and modified asphalt with this modifier in various concentrations. Based on the rheological analyses, it was suggested that there may be crosslinking due to thermomechanical stresses at the time of mixing (Polacco et al., 2005).

Bulatovic et al (2013) investigated the effect of ethylene vinyl acetate (EVA) copolymer on the morphology, rheological, and physical characteristics of modified asphalt before and after aging. Five polymer modified apshalts were produced giving varying content (2, 3, 4, 5, and 7 wt%) of EVA. Results of the viscoelastic parameters and permanent deformation resistance indicated an improvement in the rheological characteristics of the asphalt due to EVA polymer modification.

PMA with low EVA content (4%) indicated the existence of dispersed polymer particles in a continuous asphalt phase, at EVA content of 5% two twisted phases and creation of network structure was observed whereas at EVA content of 7% a continuous polymer phase was observed.

Weizhen et al. (2001) examined the production of polymer-modified asphalt using styrene butadiene styrene (SBS) polymer as a modifier and high viscous waste crude oil which is rich in aromatics (resins and asphaltenes) and poor in wax as a stabilizer. The effect of incremental content of SBS on modified asphalt was examined considering properties such as viscoelastic scope, viscosity (at 60oC), penetration (at 0.1mm), softening point, penetration index, ductility (at 5oC). A range of SBS content between 5% and 6% was considered a suitable range considering the viscosity, ductility and viscoelastic scope results. This was because below 6% some of the properties experienced significant improvement with some minor whereas for a SBS content greater than 6%, comprehensive modified effect was inconspicuous. Modified asphalts were produced by adding SBS at 5.0%, 5.5% and 6.0% ratio to the base asphalt A and 6% ratio to base asphalt. Laboratory results indicated that the SBS modified asphalts exhibited good pavement performance properties such as temperature susceptibility performance, high-temperature stability, low temperature cracking resistance, aging resistance and cutting resistance.

Shirini et al. (2016) studied the performance of rubberized porous asphalt in comparison with SBS modified porous asphalt mixtures. It was found that a concentration of 10% crumb rubber improved rutting and skid resistance of porous asphalt and the performance is comparable with SBS modified porous asphalt. Tayfur et al. (2007) studied the mechanical properties of modified asphalt mixtures in comparison with conventional asphalt using five different modifiers such as cellulose fiber, SBS, bituminous cellulose fiber, amorphous polyalphaolefin and polyolefin. The direct tensile strength test results supported the premise that polymer modified asphalt with these materials showed improved tensile strengths and increased rutting resistance. The test results from wheel tracking tests also provided evidence that SBS modified asphalt showed improved rutting resistance when compared to other asphalt modifiers.

Jamshidi et al. (2013) evaluated the rheological characteristics of Sasobit-modified asphalt mixture at elevated temperatures and different ageing conditions using response surface methodology. Results indicated that the blending temperatures of Sasobit modifiers with the base asphalt binder had no effect on high-temperature properties of PMA including viscosity and viscosity–temperature susceptibility for each ageing condition.

3.2 TESTS AND EXPERIMENTS FOR CHARACTERIZATION OF PMAs

The tests and experiments related to the physical and rheological characterization of asphalts and polymer-modified (PMAs) can be mainly classified into two main types: standardized tests and non-standardized tests. Standardized tests include rheological tests, ageing tests, solubility tests, tests on flash point test and chemical composition analysis. Rheological tests include tests for penetration, softening point, ductility, flash point, Fraass breaking point, kinematic viscosity, dynamic viscosity, viscosity using cone and plate viscometer, viscosity using Brookfield viscometer, viscosity using cone and plate viscometer as well as tensile tests and float tests (Isacsson and Lu, 1995). The penetration test (ASTM D 5) is an experimental test conducted to establish asphalt consistency. Increasing penetration value relates to softening of the asphalt whereas decreasing values relate to hardness and consistency. Softening-point test is an experiment which evaluates asphalt susceptibility to temperature as well as the temperature of flow initiation. Ductility test (ASTM D 113) evaluates the ability of the material to deform under tensile stress. The ductility test establishes the length that a standard briquette can be pulled from the asphalt cement without breaking at given temperature and acceleration. The bonding capability of asphalt is dependent on its ductility. The Fraass breaking point test evaluates the performance of the asphalt binder at low temperature (Oruc and Yilmaz, 2016).

Standardized ageing tests include Rolling thin film oven test (RTFOT), thin film oven test (TFOT), pressurized ageing vessel (PAV) and rotating flask. RTFOT (ASDM D 2872) and TFOT (ASTM D 1754) tests simulate primary or short-term ageing which occurs during the production, transport and laying of asphalt. Long-term field ageing can be simulated using pressurized ageing vessel (ASTM D 6521) test (Isacsson and Lu, 1995; Jamshidi et al., 2013; Susteric et al., 2013). Tests on flash point include Cleveland open cup test (COC Test) and Pensky-Martens closed cup test (PMCC test).

Multiple stress creep recovery (MSCR) test (ASTM D-7405-08) is a combination of creep and recovery tests used to determine rheological characteristics of various PMA mixes (Khadivar and Kavussi, 2013). MSCR test evaluates the non-recoverable compliance, the percentage of recovery and the sensitivity of asphalt binder to variations in voltage level (Gama et al., 2016). MSCR test employed in binder evaluation also offers a qualitative evaluation (pass/fail criterion) for polymer modification. The MSCR test has been used to improve accuracy of evaluation of rutting performance and identify the presence of polymer modifiers in asphalt binder (Yan et al., 2016).

A dynamic shear rheometer (DSR) is a type of testing equipment which applies sinusoidal, oscillatory loading to a material sample. Dynamic shear rheometer test ASTM (P246) is used to investigate rheological properties and permanent deformation of the asphalt. The test is used to determine viscoelastic parameters such as complex modulus, the complex viscosity, and the phase angle which are related to permanent deformation (Bulatovic et al., 2013). Dynamic shear rheometer tests are also used to evaluate resistance against fatigue cracks and rutting of the asphalt (Oruc and Yilmaz, 2016).

Non-standardized tests include rheological tests, compatibility/storage tests, adhesion/cohesion tests, ageing tests and methods of chemical analysis. Non-standardized rheological tests include flow behavior tests, elastic property tests, tensile property tests, static mechanical tests and dynamic mechanical tests (Isacssson and Lu, 1995). Rotational viscometer (RV) tests (ASTM D 4402) are conducted to determine the asphalt binder's viscosity characteristics at high temperatures (Jamshidi et al., 2013; Oruc and Yilmaz, 2016). Examples of flow behavior tests are flow test, apparent viscosity, absolute dynamic viscosity using coaxial cylinder, double ball softening point and dropping ball tests. Elastic property tests on the other hand include torsional recovery test as well as elastic recovery tests using ductilometer, sliding plate rheometer, ARRB elastomer, controlled stress rheometer or Hoppler consistometer (Isacsson and Lu, 1995). Elastic recovery tests evaluate the proportion of return of the asphalt to original state after elongation (Gama et al, 2016).

Examples of tensile property tests are toughness and tenacity tests, extraction test, force ductility test and direct tensile test (Isacsson and Lu, 1995). Indirect tensile test (IDT) mixture tests are employed in the evaluation of low temperature creep properties of asphalt mixes (Moon et al., 2013). Adhesion/cohesion tests include Vialit test, Brittleness temperature and Dropping temperature tests, contraction tests, boiling water stripping tests and Cohesion test using the Vialit pendulum ram. Methods of chemical analysis include spectroscopic methods such as Infrared spectroscopy and Nuclear magnetic resonance spectroscopy and Chromatographic methods such as Gas chromatography, High pressure liquid chromatography, thin layer chromatography with flame ionization detector and gel permeation chromatography (Isacsson and Lu, 1995). Fourier Transform Infrared (FTIR) Spectroscopy is used in analysis of the chemical characteristics of the asphalt mixes and waxes (Edwards et al, 2007).

4. FINDINGS

4.1 IMPROVING RHEOLOGY PERFORMANCE OF HIGH RECYCLED ASPHALT PAVEMENT (RAP)

According to the American Society of Civil Engineering (ASCE) 2009 infrastructure assessment report, the United States of America infrastructure achieved a D+ condition rating. This poor rating, coupled with tight DOT budgets, climate change and emission of greenhouse gasses, and the need to continuously expand our nation's infrastructure results in the requirement for innovative and sustainable techniques for infrastructure rehabilitation and construction projects to meet the tightening economic and environmental goals. As a result, there has been several recent research projects investigating the application of using recycled asphalt aggregate and binder to create a mixture of virgin aggregate and binder, recycled aggregate and binder, and polymer modifiers to improve or rehabilitate existing roadways and build new roadways (Bowers, 2016).

The main shortcoming of using recycled asphalt binder and aggregate into new and rehabilitated roadways has been known to be the poor performance of the reclaimed asphalt pavement mixture in terms of decreased capacity, increased rutting depth, and decreased fatigue cracking susceptibility with respect to equal numbers of load repetitions. However, there is a need to recycle the in-place aggregate and binder and it has been shown that the addition of polymer modification and rejuvenators can improve the rheological and performance characteristics of recycled asphalt for use into improved, rehabilitated or new roadways (Mogawer, 2016). The mixture of recycled aggregate and binder into virgin aggregate and binder with the addition of the polymer modifiers and rejuvenators reduces the demand for virgin aggregate and binder in the amount of new materials required for roadway construction (Bowers, 2016). This reduction in demand for virgin binder and aggregate has the potential to contribute to the economic and environmental sustainability of roadway construction due to less greenhouse gas emissions, less materials dumped in landfills, and reduced up-front cost of materials for construction (Bowers, 2016). However, it has been noted that before implementation of a recycled asphalt pavement with rejuvenators and polymer modifications a complete life-cycle cost analysis should be performed to determine the actual cost savings of the recycled asphalt pavements which takes into account the material cost savings, increased costs from the addition of rejuvenator and polymer modifications, and projected maintenance and rehabilitation costs (Bowers, 2016). Gaining a complete understanding of the true costs will help identify the long-term benefits of polymer modified recycled asphalt pavements (Mogawer, 2016). The environmental sustainability of recycling the asphalt aggregate and binder can be described by the Technical Nutrients flow diagram as described by McDonough and Braungart in Cradle to Cradle, see Figure A.1.3 (Bowers, 2016). For pavement construction this “circle of life” is illustrated by a 6 step process (Bowers, 2016). The traditional approach is disconnected at the 6th step, and the sustainable approach connects step 6 to step 1, to complete the circle, refer to Table A.1.2 (Bowers, 2016). The 6-step cycle is described below for both traditional asphalt construction and recycled asphalt construction (Bowers, 2016).

For the recycled asphalt mixtures to be feasible and applicable to wide scale projects the recycled asphalt mixture must perform as well as conventional asphalt with virgin aggregate in terms of structural performance, capacity and longevity (Mogawer, 2016). Many state DOT’s allow for up to 30% recycled asphalt aggregate and binder in mix designs; however, most states use only between 10% and 20% in actual practice (Mogawer, 2016). A recent research project is described in this paper and was published in the 2016 Transportation Research Record which investigated the performance and rheological characteristics of the use of polymer and rejuvenators in a 50% highly-recycled asphalt mixture (Mogawer, 2016). The title is Using Polymer Modification and Rejuvenators to Improve the Performance of High Reclaimed Asphalt Pavement Mixtures and the methods performed in this project are from the American Association of State and Highway Officials (AASHTO) standards (Mogawer, 2016).

The objectives of Using Polymer Modification and Rejuvenators to Improve the Performance of High Reclaimed Asphalt Pavement Mixtures was to determine a sufficient 50% recycled asphalt pavement material combination for the equivalent 9.5 mm surface layer asphalt mixture with virgin materials (Mogawer, 2016). The performance effects of five different rejuvenators and polymer modifications on the 50% recycled asphalt pavement were compared with the virgin material 9.5 mm control traditional asphalt. The performance of the mixtures was placed in terms of the evaluation of the amount of rutting, fatigue cracking, and low-temperature cracking after an equivalent amount of load repetitions. As a result of the combinations of mixtures of rejuvenators and polymer modified mixtures with the control group, it was possible to determine if rejuvenator combined with the recycle asphalt was sufficient, or if polymer modifications need to be added with the rejuvenator and recycle asphalt to achieve the performance of the traditional virgin asphalt. The types of rejuvenators used include aromatic oil, paraffinic oil, and three different unspecified “organic blends”. The different polymer modified asphalt binders used with the rejuvenators include PG 58-28 plus 7.5% styrene-butadiene-styrene (SBS), PG 64-28E (heavy traffic greater than 30 million ESAL, AASHTO M 332), and PG 58-28 plus low temperature Rosphalt 50-LT (Mogawer, 2016).

To determine if the recycled asphalt mixtures are susceptible to failure in the aggregate structure, failure by moisture damage, or failure by inadequate stiffness of the binder the AASHTO Hamburg Wheel-Tracking Device test was conducte. To determine the flexural cracking fatigue life of the recycled asphalt mixtures the AASHTO T321 Four Point Bending Beam Test was performed. Finally, the thermal cracking fatigue resistance for low temperature was evaluated for each recycled asphalt mixture in accordance with AASHTO TP 10-93 Low-Temperature Cracking Thermal Stress Restrained Specimen Test was performed. For all recycled asphalt rejuvenator and polymer modified binder mixtures tested, a rejuvenator was needed to meet the required volumetric properties. This was a setback in all tests where the addition of the rejuvenator softened the asphalt mixture and resulted in increased rutting susceptibility and decreased fatigue cracking resistance compared to the control group. However, more important is to note that the rutting performance and fatigue cracking resistance was restored or improved in some cases compared with the virgin aggregate and binder control group by the addition of 7.5% styrene-butadiene-styrene (SBS), PG 64-28E (heavy traffic greater than 30 million ESAL, AASHTO M 332), and PG 58-28 plus low temperature Rosphalt 50-LT (PMA 1, PMA 2, PMA 3), refer to Table A.1.1 (Mogawer, 2016).

The AASHTO Hamburg Wheel-Tracking Device rutting tests showed that the use of asphalt rejuvenators and the softer PG 58-28 binder increased the amount of rutting for the recycled asphalt pavement mixtures when compared to the traditional all-virgin control PG 64-28 mixture. However, the important point to make is that the rutting performance was restored in some cases to the control or even improved compared with the control with the addition of polymer modification binders. As seen in the Table A.1.1, for the traditional asphalt virgin material control group with PG 64-28 binder at 10,000 passes the depth of rutting was 0.76 mm, and at 20,000 passes was 1.29 mm. The comparison of the traditional virgin asphalt material group is made with the addition of various rejuvenators and polymer modified binders as shown below. It is pointed out that consistently the addition of the rejuvenator with the "softer" PG 58-28 binder decreased the rutting performance compared to the traditional virgin control group; however, when polymers were added, the rutting performance returned to comparable results from the traditional virgin control group. It should be pointed out that consistently the addition of the PMA 1, PMA 2, and PMA 3 throughout the entire AASHTO Hamburg Wheel-Tracking Device rutting tests resulted in less rutting depth at both 10,000 and 20,000 passes (Mogawer, 2016).

For 50% recycled asphalt pavement and no rejuvenator with PG 58-28 the depth of rutting at 10,000 passes was 1.09 mm and at 20,000 passes was 1.80 mm. This increased rutting is not surprising since 50% of the aggregate and binder are recycled, with no rejuvenator or polymer added to improve the performance. However, when PMA 1, PMA 2, and PMA 3 was added to the no-rejuvenator mixture the rutting performance increased substantially to include a range of 0.52 mm to 0.96 mm at 10,000 passes, and 0.71 mm to 1.19 mm at 20,000 passes. Similarly, for aromatic oil rejuvenator with PG 58-28 binder the depth of rutting at 10,000 passes was 5.06 mm and at 20,000 passes was greater than 20 mm. However, when PMA 1, PMA 2, and PMA 3 was added to the aromatic-oil rejuvenator mixture the rutting performance increased substantially to include a range of 0.24 mm to 1.39 mm at 10,000 passes, and 0.32 mm to 1.81 mm at 20,000 passes. Similarly, for paraffinic oil rejuvenator with PG 58-28 binder the depth of rutting at 10,000 passes was 1.46 mm and at 20,000 passes was 12.76 mm. However, when PMA 1, PMA 2, and PMA 3 was added to the paraffinic-oil rejuvenator mixture the rutting performance increased substantially to include a range of 0.41 mm to 0.69 mm at 10,000 passes, and 0.52 mm to 1.19 mm at 20,000 passes. For "organic blend 1, 2 and 3" rejuvenator with PG 58-28 binder the depth of rutting at 10,000 passes was ranged from 1.92 mm to 4.14 mm, and at 20,000 passes ranged from 16.7 mm to greater than 20 mm. However, when PMA 1, PMA 2, and PMA 3 was added to the "organic blend 1, 2 and 3" rejuvenator mixture the rutting performance increased substantially to include a range of 0.35 mm to 1.91 mm at 10,000 passes, and 0.33 mm to 4.58 mm at 20,000 passes (Mogawer, 2016).

To determine the flexural cracking fatigue life of the recycled asphalt mixtures the AASHTO T321 Four Point Bending Beam Test was performed, refer to Figure A.1.1 for the results of the test. Also, the thermal cracking fatigue resistance for low temperature was evaluated for each recycled asphalt mixture in accordance with AASHTO TP 10-93 Low-Temperature Cracking Thermal Stress Restrained Specimen Test was performed, refer to Figure A.1.2 for the results of the test. AASHTO fatigue cracking tests showed that the use of rejuvenators in the recycled asphalt pavement mixtures improved the cracking resistance when compared to the virgin aggregate and binder asphalt control mixture. Most importantly, when the 7.5% styrene-butadiene-styrene (SBS), PG 64-28E (heavy traffic greater than 30 million ESAL, AASHTO M 332), and PG 58-28 plus low temperature Rosphalt 50-LT were added the fatigue cracking resistance significantly improved as well. It is also pointed out that the low temperature AASHTO fatigue cracking tests showed that rejuvenators are needed to correct shortcomings in the low-temperature cracking resistance of the 50% recycled asphalt mixture compared with virgin aggregate and binder control mixture. It is shown that the number of cycles to fatigue failure is 50% less for the recycled asphalt mixture with no rejuvenator and no polymer modification, when compared to the virgin aggregate and binder control group (refer to Figure A.1.1) (Mogawer, 2016). It was shown that the combination of the PMA 1, PMA 2, and PMA 3 with rejuvenators had varying but increasing fatigue cracking performance with the addition of the various polymer modified binders. For all mixtures tested, an asphalt rejuvenator was needed to meet the required volumetric properties, however, the addition of the rejuvenator softened the mixture and resulted in rutting susceptibility; however, this rutting performance was restored with the addition of PMA binders and also greatly enhanced the fatigue cracking performance (Mogawer, 2016).

4.2 IMPROVING ASPHALT BINDER RHEOLOGY WITH HIGHLY POLYMER MODIFIED ASPHALT

Traffic intensities and loading on pavement continues to increase with time, and when coupled with DOT's tight budgets there is a need for "value engineering" for maintaining highway infrastructure (Willis, 2016). "Value engineering", is influenced by the life-cycle cost and short-term budget constraints which have shown to be a limiting factor in the maintenance, rehabilitation, and construction of highway pavements (Willis, 2016). With those concepts in mind, it has become increasingly more important to consider improve materials and designs that effectively meet desired performance goals, and there is potential for highly polymer modified asphalt mixtures to meet the increasing demand for greater and more intense traffic loading on highways. According to NCHRP Report 646: Validating the Fatigue Endurance Limit for Hot Mix Asphalt, published in the 2010 edition of the Transportation Research Board, shows that normal polymer dosage of 2% to 3% Styrene-butadiene-styrene (SBS) improves the fatigue crack resistance and rutting resistance when properly designed; however, may not provide the additional performance required to truly alter the endurance limit of conventional asphalt pavements to meet the increased demand on highways (Willis, 2016).

Highly polymer modified asphalt binders contains 7% to 8% of polymer to create a highly integrated polymer chain network. In Performance of a Highly Polymer-Modified Asphalt Binder Test Section at the National Center for Asphalt Technology Pavement Test Track, highly polymer modified pavements improve the rutting and fatigue performance of asphalt. It has been known in the past that polymer modification of asphalt binders improves the rheology of the asphalt surface layer by improving the fatigue rutting performance and the fatigue cracking performance of the asphalt mixtures. A 5.75-inch test section was built at the National Center for Asphalt Technology Pavement Test Track (NCAT) with highly polymer modified asphalt binder and compared to a 7-inch-thick control section that was built with conventional paving materials, refer to Figure A.2.1 for the cross sections used. The NCAT test track is a 1.7 mile closed loop full-scale pavement test facility located in Alabama (Willis, 2016).

The primary goal of the research project was to assess the long-term performance of the highly polymer modified asphalt mixture and compare it with the control conventional test section in terms of the in-place modulus, structural capacity, weekly strain pressure responses, extent of rutting, roughness, ride quality degradation, and extent of fatigue cracking. The results of the research study show that after 20 million equivalent single axle loads of traffic and six years of environmental effects the highly polymer modified test section shows less rutting and less cracking when compared to the conventional asphalt section control group; furthermore, the highly polymer modified section did not diminish in ride quality over time when compared to the control.

A very interesting point to note is that the cross section of the highly polymer modified section was thinner than the conventional control section by 1.25 inches, and still performed as well or better than the conventional section. The conventional asphalt test sections experiences cracking in 10% of the lane area, 13% in the right wheel path, and 21% in the left wheel path. For the highly polymer modified test sections 6% of the lane had cracked, 15% of the left wheel path, and 8% in the left wheel path. More important is to note that forensic coring showed that the highly polymer modified section cracks were only superficial surface cracks, while the conventional sections experienced bottom-up fatigue cracking (Willis, 2016).

Thus, the findings in this research project indicate that the improved performance of the highly polymer modified asphalt pavements can lend itself useful when applicable for long-term performance with a thinner cross section roadway. The performance test results showed that the cycles until failure (flow number) for the wearing course of the highly polymer modified section 4,825 versus 164 for the conventional asphalt section, and 944 for the highly polymer modified base course versus 139 for the conventional asphalt section. The combined rutting for the wearing and base course for the highly polymer modified section was 1.48 mm and 1.91 mm for the conventional asphalt test section. The complete rutting performance timeline in Figure A.2.2 (refer to Appendix) shows the performance of the highly polymer modified test section compared with the conventional asphalt test section over the six-year study (Willis, 2016). The moisture sensitivity of the highly polymer modified test section was recorded as 0.89 TSR for the wearing course versus 0.94 TSR for the conventional asphalt section wearing course, and 0.88 TSR for the highly polymer modified sections versus 0.86 TSR for the conventional asphalt test section base course (Willis, 2016). The standards to which these measurements and assessments were taken are listed below.

- PC binder grade was classified according to the AASHTO M320 standard
- Depth of rutting was in recorded in accordance with AASHTO TP 63 standard
- Cycles until failure (flow number) was in accordance with AASHTO TP 79 standard
- Beam fatigue endurance limit (microstrain) in accordance with AASHTO T 321 standard
- Moisture sensitivity (TSR) was in accordance with the AASHTO T 283 standards

CONCLUSIONS

It has been shown that polymers are widely used to enhance the engineering characteristics of asphalt as a binder in asphaltic concrete. Polymer modified asphalt generally offer longer life and enhanced pavement performance of the asphalt. Polymers enhance temperature susceptibility of asphalt by improving its stiffness at high service temperatures and decreasing its stiffness at low service temperatures (Bulatovic et al., 2013). Asphalt rheology properties such as fatigue cracking, rutting, hardening of asphalt binder, and temperature cracking potential affect the pavement performance. Addition of polymers in asphalt improves resistance to fatigue, rutting, temperature cracking and stripping (Khattak and Baladi, 1998) and considerably enhance the mechanical characteristics of asphalt mixtures and relatively reduce the binder drain down (Mokhtari and Nejad, 2012). Fibers have been found to enhance a vast array of engineering properties of asphalt matrix. These properties include moisture susceptibility, viscoelasticity, creep compliance, rutting resistance, low-temperature anti-cracking properties, fatigue life, durability of asphalt concrete mixtures, material toughness, tensile strength, dynamic modulus, elasticity, wear resistance (of AC mixtures that are employed as pavement wearing course) and reflective anti-cracking properties of AC mixtures and pavements.

It has been shown that there is potential for highly polymer modified asphalt mixtures to meet the increasing demand for greater and more intense traffic loading on highways (Willis, 2016). As a result, there has been several recent research projects investigating the application of using recycled asphalt aggregate and binder to create a mixture of virgin aggregate and binder, recycled aggregate and binder, and polymer/rejuvenator modifiers to improve or rehabilitate existing roadways, and build new roadways (Bowers, 2016). For the recycled asphalt mixtures to be feasible and applicable to wide scale projects the recycled asphalt mixture must perform as well as conventional asphalt with virgin aggregate in terms of structural performance, capacity and longevity (Mogawer, 2016). The rutting performance and fatigue cracking resistance was restored or improved in some cases compared with the virgin aggregate and binder control group by the addition of 7.5% styrene-butadiene-styrene (SBS), PG 64-28E (heavy traffic greater than 30 million ESAL, AASHTO M 332), and PG 58-28 plus low temperature Rosphalt 50-LT (PMA 1, PMA 2, PMA 3), refer to Table A.1.1. AASHTO fatigue cracking tests showed that the use of rejuvenators in the recycled asphalt pavement mixtures improved the cracking resistance when compared to the virgin aggregate and binder asphalt control mixture. Most importantly, when the 7.5% styrene-butadiene-styrene (SBS), PG 64-28E (heavy traffic greater than 30 million ESAL, AASHTO M 332), and PG 58-28 plus low temperature Rosphalt 50-LT were added the fatigue cracking resistance significantly improved as well. It is shown that the number of cycles to fatigue failure is 50% less for the recycled asphalt mixture with no rejuvenator and no polymer modification, when compared to the virgin aggregate and binder control group (Mogawer, 2016).

The long-term performance of the highly polymer modified asphalt mixture compared with the control conventional test section was placed in terms of the in-place modulus, structural capacity, weekly strain pressure responses, extent of rutting, roughness, ride quality degradation, and extent of fatigue cracking (Willis, 2016). It has been shown that after 20 million equivalent single axle loads of traffic and six years of environmental effects the highly polymer modified test section shows less rutting and less cracking when compared to the conventional asphalt section control group. Also, the highly polymer modified section did not diminish in ride quality over time when compared to the control. A very interesting point to note is that the cross section of the highly polymer modified section was thinner than the conventional control section by 1.25 inches, and still performed as well or better than the conventional section. Thus, the findings in this research project indicate that the improved performance of the highly polymer modified asphalt pavements can lend itself useful when applicable for long-term performance with a thinner cross section roadway.

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APPENDIX

A.1: IMPROVED RHEOLOGY PERFORMANCE OF HIGH RECYCLED ASPHALT PAVEMENT (RAP)

Mixture	Binder	Stripping Inflection Point	Rut Depth At 10,000 Passes (mm)	Rut Depth At 20,000 Passes (mm)
PG 58-28 all-virgin (informational only)	PG 58-28	5,900	>20	>20
Control with PG 64-28 (basis of comparison)	PG 64-28	None	0.76	1.39
50% RAP + no rejuvenator	PG 58-28	None	1.09	1.80
	PG 58-28 + 7.5% SBS	None	0.96	1.19
	PG 64-28E	None	0.52	0.71
	PG 58-28 + Rosphalt 50-LT	None	0.74	0.89
50% RAP + aromatic oil	PG 58-28	9,800	5.06	>20
	PG 58-28 + 7.5% SBS	None	0.40	0.50
	PG 64-28E	None	1.39	1.81
	PG 58-28 + Rosphalt 50-LT	None	0.24	0.32
50% RAP + paraffinic oil	PG 58-28	14,500	1.46	12.76
	PG 58-28 + 7.5% SBS	None	0.41	0.52
	PG 64-28E	None	0.69	1.19
	PG 58-28 + Rosphalt 50-LT	None	0.60	0.74
50% RAP + Organic Blend 1	PG 58-28	11,800	2.73	18.48
	PG 58-28 + 7.5% SBS	None	0.5	0.66
	PG 64-28E	15,200	1.55	4.58
	PG 58-28 + Rosphalt 50-LT	None	0.23	0.33
50% RAP + Organic Blend 2	PG 58-28	10,600	4.14	>20
	PG 58-28 + 7.5% SBS	None	0.48	0.67
	PG 64-28E	None	1.91	3.12
	PG 58-28 + Rosphalt 50-LT	None	0.72	0.86
50% RAP + Organic Blend 3	PG 58-28	12,900	1.92	16.70
	PG 58-28 + 7.5% SBS	None	0.51	0.68
	PG 64-28E	None	0.84	1.86
	PG 58-28 + Rosphalt 50-LT	None	0.35	0.44

Figure A.1.1: Results of the AASHTO *Hamburg Wheel-Tracking Device* test where a comparison of the virgin aggregate and binder control mixture was made with 50% recycled aggregate and binder asphalt mixtures with and without rejuvenators, and additions of polymer modifiers. This test helps to determine if the recycled asphalt mixtures are susceptible to failure in the aggregate structure, failure by moisture damage, or failure by inadequate stiffness of the binder and to determine what combinations of rejuvenators and polymer modifications to the binder result in similar or better rheological fatigue characteristics compared with the virgin aggregate and binder control mixture (Mogawer, 2016).

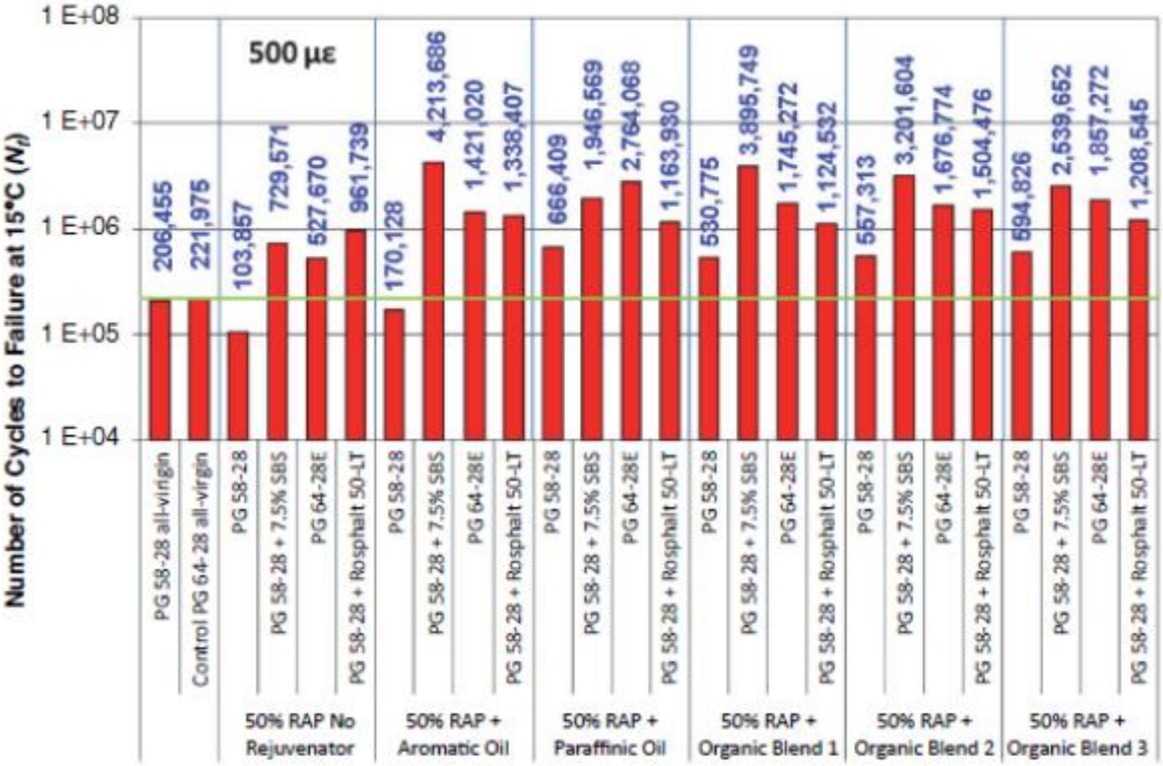

Figure A.1.2: Results of the AASHTO T321 *Four Point Bending Beam Test* to where a comparison of the virgin aggregate and binder control mixture was made with 50% recycled aggregate and binder asphalt mixtures with and without rejuvenators, and additions of polymer modifiers. This test helps to determine the flexural cracking fatigue life of the recycled asphalt mixtures in terms of the number of cycles to fatigue failure. This test also helps to determine what combinations of rejuvenators and polymer modifications to the binder result in similar or better rheological fatigue characteristics compared with the virgin aggregate and binder control mixture (Mogawer, 2016).

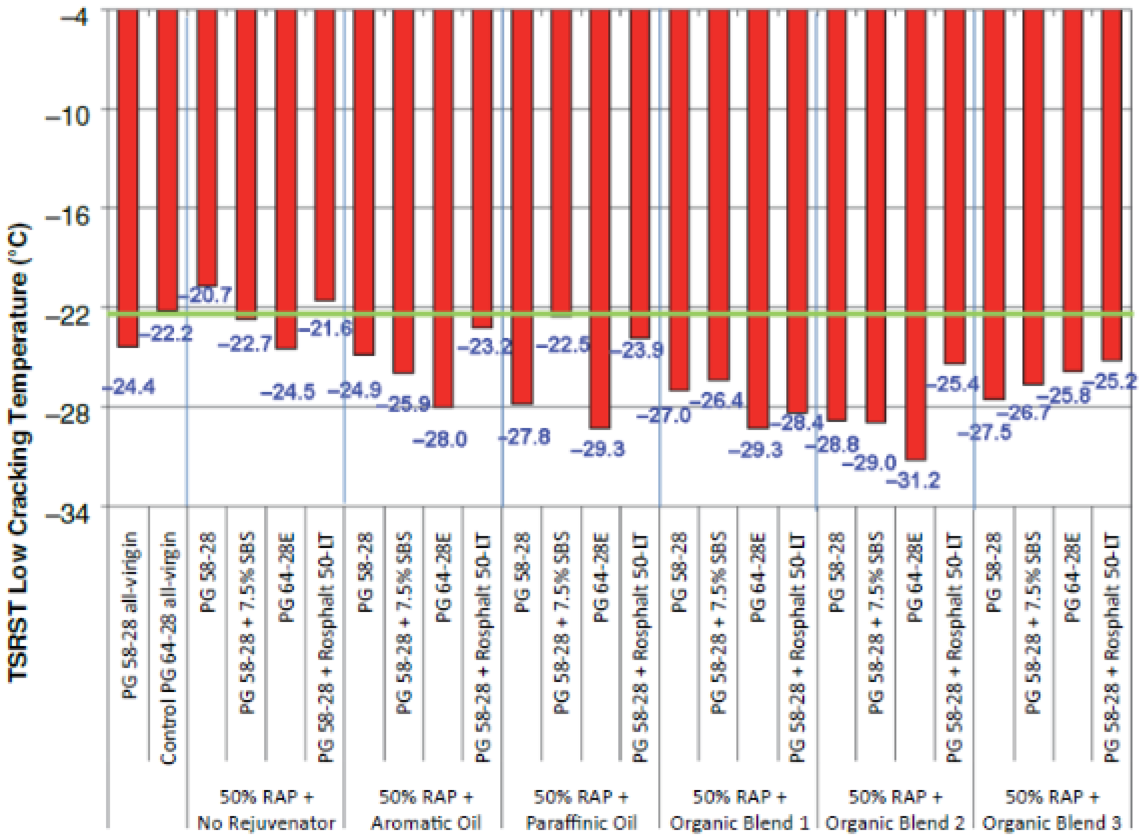

Figure A.1.3: Results of the AASHTO TP 10-93 *Low-Temperature Cracking Thermal Stress Restrained Specimen Test* where a comparison of the virgin aggregate and binder control mixture was made with 50% recycled aggregate and binder asphalt mixtures with and without rejuvenators, and additions of polymer modifiers. This test helps to determine the low-temperature thermal fatigue cracking temperature of the recycled asphalt mixtures. This test also helps to determine what combinations of rejuvenators and polymer modifications to the binder result in similar or better rheological fatigue characteristics compared with the virgin aggregate and binder control mixture (Mogawer, 2016).

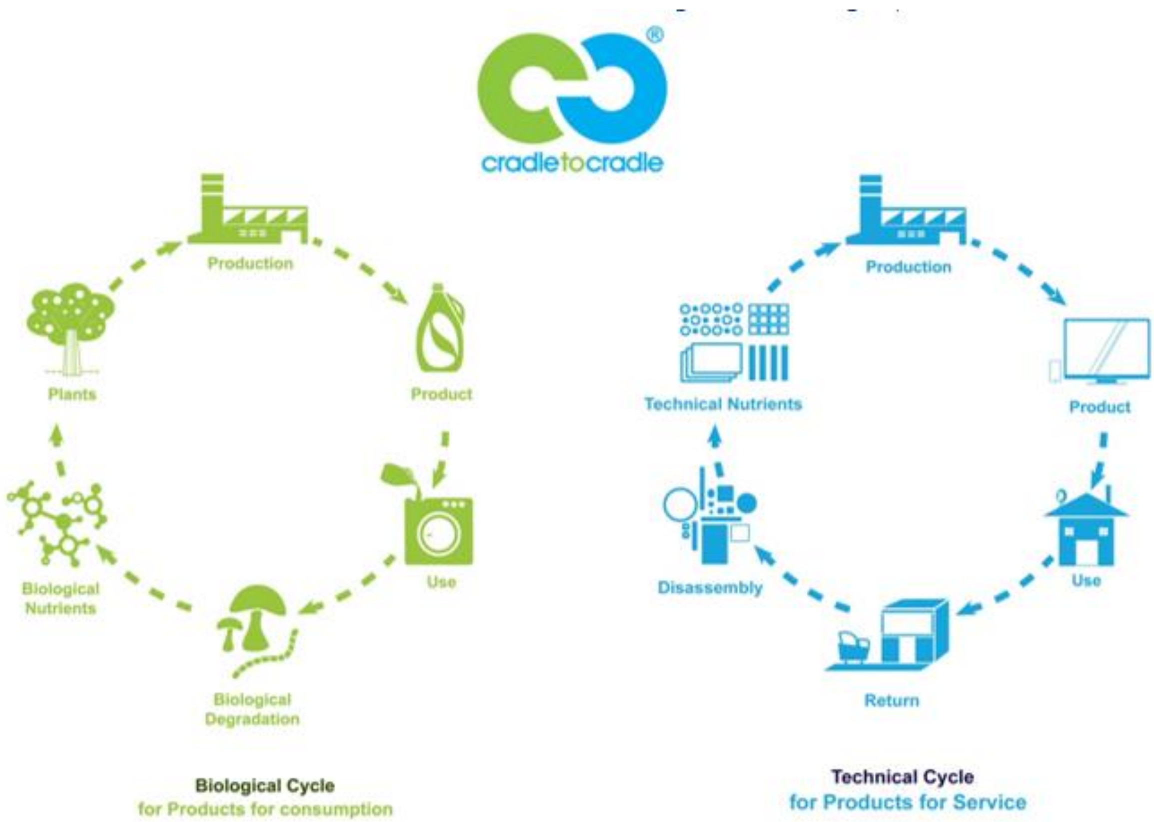

Figure A.1.4: Sustainability concept illustrating the concept of using recycled asphalt aggregate and polymer modified binders to reduce CO2 emission, decrease initial materials cost, and reduce dependence and size of landfills (Bowers, 2016).

Figure A.1.5: Recycled asphalt pavement showing the virgin binder, virgin aggregate, recycled aggregate and binder, and final recycled asphalt pavement. The rejuvenators and polymer modifiers are not shown in this image, which are essential to improve the rheological characteristics of the recycled asphalt pavement (Bowers, 2016).

Table A.1.1: Conventional asphalt life cycle compared with sustainable recycled asphalt with rejuvenator and polymer modifiers (Bowers, 2016).

Traditional Life Cycle of Asphalt Pavement	
Step	Description
1	Raw materials-virgin asphalt and virgin binder is gathered which increases greenhouse gas emissions through the production of oil (binder is from the bottom of oil barrels)
2	Raw materials are mixed at the plant
3	Paving takes place
4	The pavement serves society through service life
5	The pavement is removed
6	The used left-over pavement is stockpiled and sent to landfills for disposal
Sustainable Life Cycle of Recycled Asphalt Pavement	
Step	Description
1	Recycled and raw materials mixture- recycled and virgin aggregate and binder with polymer modifiers are gathered, reduced CO2 emissions by less required virgin binder from oil barrels
2	materials are mixed at the plant
3	Paving takes place
4	The pavement serves society through service life
5	The pavement is removed
6	The used left-over pavement is stockpiled and re-used in rehabilitation of existing roadways or new roadways to reduce dependence and size of landfills / stockpiles

A.2: IMPROVING ASPHALT BINDER RHEOLOGY WITH HIGHLY POLYMER MODIFIED ASPHALT

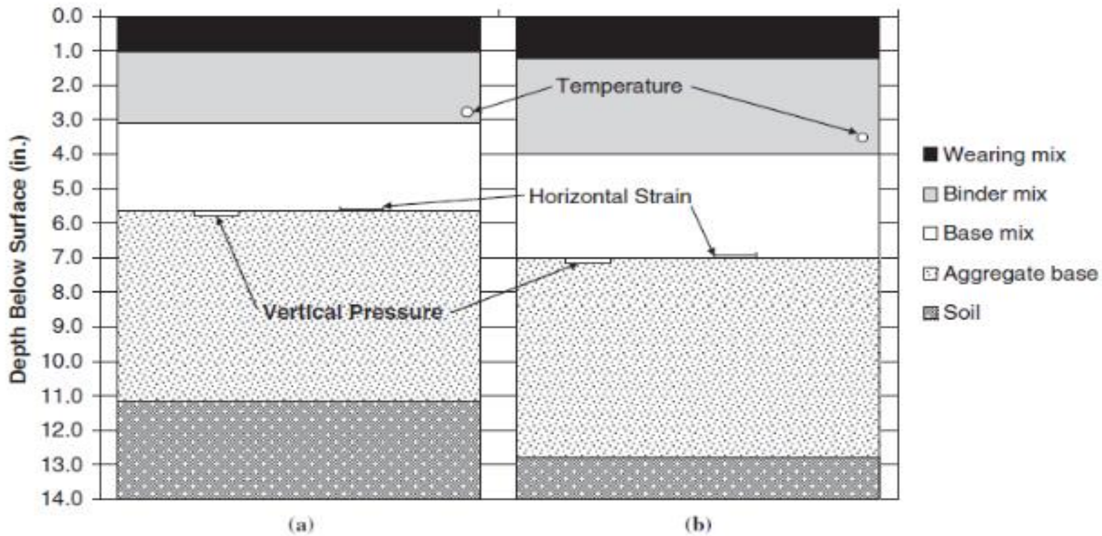

Figure A.2.1: Highly Polymer Modified cross section shown on left (a) and conventional asphalt pavement control section shown on right (b) (Willis, 2016)

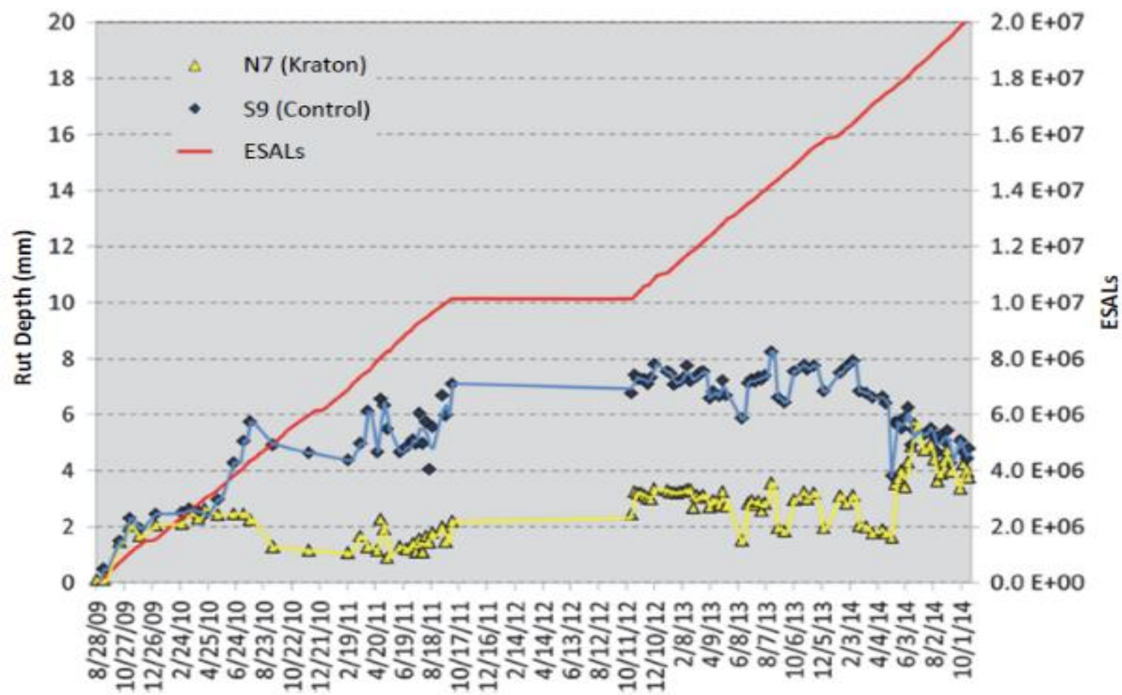

Figure A.2.2: Depth of rutting vs. traffic loading (ESAL's) vs. time (Willis, 2016)