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Asphalt Mix Rejuvenators Synthesis

NRRA Flexible Team

Asphalt Mix Rejuvenators

FINAL REPORT

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CHAPTER 1: BACKGROUND

1.1 INTRODUCTION

Asphalt binder is essentially composed of two main fractions, which are asphaltenes and maltenes. Rostler and White asserted that asphaltenes are the stable component giving asphalt binder its structure, while maltenes are more susceptible to oxidation but help the binder to maintain flexibility and strength. Due to the exposure to sun, water, and air, the ratio of the contents of maltene to asphaltene diminishes, which causes the asphalt pavement to be stiffer and brittle (cited in Bennert, Ericson, and Pezeshki, 2015).

In recent years, the asphalt industry has seen an increase in utilizing reclaimed asphalt pavements (RAP) and recycled asphalt shingles (RAS) in new asphalt concrete pavements. This raises concern as recycled mixes containing high-RAP or RAS, due to aging and oxidation, have a higher content of asphaltenes and exhibit an increase in binder stiffness (Willis and Tran, 2015). Mogawer and others have discovered that the high stiffness also contributes to difficulty in workability, which will cause the pavement to exhibit low density and fail prematurely due to improper compaction (cited in Haghshenas et al., 2016). Hence, rejuvenating additives are incorporated into asphalt mixes to neutralize the effects of using higher percentages of RAP and RAS in new asphalt concrete pavements.

The implementation of incorporating rejuvenating agents in high-RAP or RAS asphalt mixes have led to the evaluation of their capability to restore the properties of aged binder to a condition that is similar to virgin asphalt binders. Petroleum-based rejuvenators contain maltenes that reverse the aging effects by balancing the ratio of maltenes to asphaltenes. Bio-based rejuvenators have advertised benefits showing that bio-based products can be used with high RAP and RAS content mixes in an environmentally friendly manner (Willis and Tran, 2015).

Prior to selecting any type of rejuvenator, it is important to evaluate its effectiveness in the aspects of the level of diffusion or penetration, and the stability of a rejuvenator (Bennert, Ericson, and Pezeshki, 2015). This can be determined through different testing methods, which were covered in the literature review conducted.

This synthesis includes a summary of experiences from various agencies and industries on the use of asphalt mix rejuvenators. A literature review was performed and includes but is not limited to: the type of rejuvenators used, dosage rate, method of blending the rejuvenators with the RAP or/and RAS, percentage of RAP and/or RAS used, and type of testing conducted to evaluate the effectiveness of a rejuvenator.

1.2 IMPETUS FOR THIS NRRA FLEX TEAM RESEARCH

1.2.1 NRRA Members Involved

Eight state agencies that are currently involved in the mix rejuvenators synthesis, include the California Department of Transportation (Caltrans), Illinois Department of Transportation (DOT), Iowa DOT, Michigan DOT, Minnesota DOT, Missouri DOT, North Dakota DOT, and Wisconsin DOT.

1.2.2 Impetus

The purpose of this project is to compile a synthesis of current practices being used by the states and industries in the area of mix rejuvenators. This synthesis provides the state of practice in the NRRA member states and will be used as guidance for the NRRA's Asphalt Mix Rejuvenator Field Section research that was in the contracting stage as of March 2020.

CHAPTER 2: SURVEY RESULTS

An online survey was distributed across the agencies and industry to collect information on mix rejuvenators.

The survey questions distributed were as follows.

1. Have you worked on any constructed roadways or test sections that included mix rejuvenators?
2. If yes, what type of products are being used?
3. What is the maximum amount of recycled asphalt shingles (RAS) and reclaimed asphalt pavement (RAP) allowed without the use of rejuvenators?
4. What is the maximum amount of recycled asphalt shingles (RAS) and reclaimed asphalt pavement (RAP) allowed with the use of rejuvenators?
5. Does your agency have any special provisions or specifications on mix rejuvenators?
6. Have any performance measures been conducted on the constructed roadways or test sections?
7. If yes, what type of performance measures have been collected?

2.1 AGENCY RESPONSES

Below is a summary of the responses received from agencies on the survey questions listed above in 2019.

2.1.1 Asphalt Mix Rejuvenators Experience

Limited experience was found among NRRA agency members. Seven member states responded to the survey (**Table 2.1**) and only three states have experienced the use of rejuvenators in asphalt mixtures.

Table 2.1. Relevant experience on asphalt mix rejuvenators from different agencies.

Agency	Relevant Experience
Caltrans	No
Illinois DOT	No
Michigan DOT	No
Minnesota DOT	Yes
Missouri DOT	Yes
North Dakota DOT	No
Wisconsin DOT	Yes

2.1.2 Type of Products Used

Three agencies have incorporated different rejuvenating products as listed in **Table 2.2**, on a trial basis. Minnesota DOT has tested Delta S® and Anova® 1815; Missouri DOT has tested Evoflex® CA and Hydrogreen; Wisconsin DOT has tested Anova® 1815 on the National Cooperative Highway Research Program (NCHRP) 9-58 project (**Table 2.2**).

Table 2.2. Type of rejuvenating products incorporated into the HMA mixes.

Agency	Type of Product	Manufacturer
Minnesota DOT	Delta S®	Collaborative Aggregates LLC
	Anova® 1815	Cargill, Inc.
Missouri DOT	Evoflex® CA	Ingevity
	Hydrogreen	Asphalt & Wax Innovations, LLC (AWI) and Green Asphalt Technologies, LLC
Wisconsin DOT	Anova® 1815	Cargill, Inc.

Below is a summary description of the products directly obtained from the official webpages of the manufacturers and they are solely for reference. The NRRA is not affiliated with any of the manufacturers and does not endorse any of the products listed.

DELTA S®

https://collaborativeaggregates.com/about-delta-s/

"As a true rejuvenator, Delta S® returns the binder in recycled asphalt to its original functionality by reversing the natural oxidation process that causes pavement to become brittle. The binder softens the workability and then stiffens for durability and an undiminished lifespan. By restoring the binder in recycled asphalt to its original performance, Delta S® allows RAP to be used in significantly higher proportions. Test data concludes that 50% RAP rejuvenated with Delta S® has a comparable performance and lifespan to 100% virgin asphalt."

ANOVA® 1815

https://www.cargill.com/bioindustrial/anova/asphalt-rejuvenators

“In addition to shifting the PG grade of virgin bitumen, Anova® modifiers also rejuvenate RAP and RAS restoring properties of aged bitumen, allowing for more versatility in mix designs.” This product “does not negatively impact rutting resistance of rejuvenated RAP mixture” and it “enhances low temperature cracking resistance of asphalt mixture, even at high RAP content”. Anova® rejuvenators also have “low volatile organic compounds and low volatile mass loss (as measured by the Rolling Thin Film Oven).”

EVOFLEX® CA

https://www.ingevity.com/uploads/market-pdfs/EvoFlex-CA.pdf

Evoflex® CA is an “an engineered family of additives that allows greater use of reclaimed asphalt materials.” This product is “designed to improve the contribution yield of binder from recycled materials. Evoflex® CA additives also function as rejuvenators and offset the potential negative impact of increasing the use of highly oxidized materials. Greater amounts of reclaimed products can be added while Evoflex® CA maintains the flexibility and low-temperature crack resistance of the mix.”

HYDROGREEN

http://awi-gat.com/wp-content/uploads/2014/11/HYDROGREEN-BRIDGING-THE-GAP-BETWEEN-RAS-AND-HMA-NOV-2-2013.pdf

Hydrogreen is a “liquid product added to the asphalt binder to re-disperse asphaltenes and counter the stiffness of the RAP/RAS binders.” This product “successfully converts the high RAP/RAS asphaltene proportion back to virgin binder qualities.”

2.1.3 Maximum Recycled Asphalt Shingles (RAS) and Reclaimed Asphalt Pavement (RAP) Allowed

Table 2.3 summarized the maximum RAS and RAP allowed as specified by each agency without incorporating rejuvenators. These limits are defined in 2019 and may be revised and updated in the future.

Without the incorporation of rejuvenators, the maximum amount of RAS and RAP allowed differ from state to state. Some states do not allow the use of RAS in the asphalt mixtures while the Missouri DOT only enables RAS in mixtures requiring a PG 64-22 contract grade. Other states have varying RAS limits depending on asphalt grade or pavement lift.

As for the use of RAP, Michigan DOT allows a higher RAP percentage as long as blending charts have been employed and all the volumetric testing requirements have been fulfilled. Other states have varying ranges based on mixture type, asphalt grade, life type, or location of mixture placement (mainline or shoulder).

Minnesota DOT has different requirements based on the asphalt grade and lift type. A PG 58X-34 (where X represents the traffic level in accordance with the AASHTO M221, *MSCR* standard) requires a higher ratio of added new asphalt binder to total asphalt binder, since this grade is commonly specified to be used in new construction.

In addition to the limits summarized in **Table 2.3**, the Wisconsin DOT has different requirements for RAS, RAP, and fractionated RAP (FRAP) when used in combination, which the maximum allowable binder replacement is 35% for the lower layers and 25% for the upper layer. The RAS component cannot exceed 5% of the total weight of the aggregate blend. In a Stone Matrix Asphalt (SMA) mixture, the maximum allowable percent binder replacement from RAS, RAP, and FRAP in combination is 15%.

Table 2.3. Maximum content of RAS and RAP allowed without incorporating rejuvenators.

Agency	Maximum RAS Allowed without the Use of Rejuvenators	Maximum RAP Allowed without the Use of Rejuvenators
Caltrans	Currently not allowed but working to include RAS in the mix in the future	25% binder replacement
Illinois DOT	5%	Varies with mixture type (45% Asphalt Binder Replacement (ABR) on HMA binder, 40% on HMA surface without polymer, 15% with polymer)
Michigan DOT	17% by weight of the total binder content	Not specifically limited but blending charts required for higher amounts and still must pass all volumetric testing requirements
Minnesota DOT	20% to 30% of the total binder derived from RAS depending on the asphalt grade. Similar requirements apply to a combination of RAS and RAP	20% to 35% of the total binder derived from RAP depending on the asphalt grade and lift type (wear and non-wear)
Missouri DOT	Only allowed in mixtures requiring a PG 64-22 contract grade	Allows RAP up to 30% for high type mixtures before extraction and grading is required

Table 2.3 (continued). Maximum content of RAS and RAP allowed without incorporating rejuvenators.

Agency	Maximum RAS Allowed without the Use of Rejuvenators	Maximum RAP Allowed without the Use of Rejuvenators
North Dakota DOT	Not allowed	25% of the mix, by weight for mainline and 35% of the mix, by weight for shoulders
Wisconsin DOT	RAS if used alone, varies with pavement lift (25% Asphalt Binder Replacement (ABR) on lower layers, 20% ABR on upper layer)	RAP and fractionated RAP (FRAP) in any combination, vary with pavement lift (40% Asphalt Binder Replacement (ABR) on lower layers, 25% ABR on upper layer)

With the use of rejuvenators, the allowable contents of RAS and RAP do not differ for Caltrans, Michigan DOT, and Missouri DOT. Other agencies have not specified the limits for RAS and RAP usage with the use of rejuvenators.

2.2 INDUSTRY RESPONSES

A summary of the responses received from the manufacturers on their rejuvenating products in 2019 is provided (**Table 2.4**). The NRRA is not affiliated with any of the manufacturers and does not endorse any of the products listed. Additional information on the manufacturers can be found in the **Appendix A**.

2.2.1 Type of Products

Asphalt & Wax Innovations, LLC (AWI) and Green Asphalt Technologies, LLC have manufactured PAVSAV™, which "high performance liquid chromatography shows that PAVSAV™ mimics the maltenes phase of the asphalt binder and supplements the maltenes component to produce the performance effects of rejuvenation, asphaltenes dispersion, viscosity reduction as well as improvement in low temperature flexibility."

Cargill, Inc. has manufactured Anova® 1815 additive, which is a chemically modified vegetable oil-based product. MnROAD had test sections built in 2018 using this Anova® rejuvenator, with a combination of 25% and 45% RAP and PG 58S-28 virgin binder. The Anova® 1815 additive has also been used in a few other projects in Minnesota, Wisconsin, New Jersey, and at the National Center for Asphalt Technology (NCAT) in Alabama.

Collaborative Aggregates LLC has manufactured Delta S®, which returns the binder in recycled asphalt to its original functionality by reversing the natural oxidation process that causes pavement to become brittle. NCAT has performed work on performance-based mix designs containing high RAP (50%) content utilizing Delta S® rejuvenator chemistry.

Georgia-Pacific Chemicals LLC has manufactured TUFFTREK 4002, which uses renewable oil technology. This product has been used in the experimental sections that had 50% RAP aggregate (60% RAP binder replacement) for a 2019 Nebraska Department of Transportation trial. This product has also been used on other projects and trials in the US.

Ingevity has manufactured Evoflex® CA and this product has been used and approved by the City of Chicago and the Illinois Tollway. This product can "effectively solubilizing the asphalt in recycled materials, increasing the blending of the virgin and the oxidized binders. Mixes with high amounts of recycled content made with Evoflex® CA have improved coating and workability with wide variety of paving materials."

POET, LLC has manufactured JIVE™, an asphalt rejuvenator and modifier. The unique composition of JIVE as a result of POET's patented technology, helps to disperse asphaltenes to prevent brittleness as observed in higher RAP mixes and introduce components that improve asphalt durability. JIVE™ has been utilized in seventeen states across the US, in Canada, and overseas. NCAT published a study evaluating the performance of high RAP binder and mixes using JIVE™ as a rejuvenator. In addition, multiple universities have or are evaluating JIVE™, including the currently ongoing ICT R27-196 study for

Illinois DOT. Multiple industrial partners and DOTs are trialing or commercially using JIVE™ to allow balanced mix design in high RAP mixes.

Table 2.4. Type of products from various manufacturers.

Manufacturer	Type of Product	Description
Asphalt & Wax Innovations, LLC (AWI) and Green Asphalt Technologies, LLC	PAVSAV™	A renewable USA based technology that is 100% Green and produced from plant materials
Cargill, Inc.	Anova® 1815	A chemically modified vegetable oil-based product
Collaborative Aggregates LLC	Delta S®	A non-toxic asphalt additive that acts as a rejuvenator to recycled asphalt binder and as a warm mix additive to asphalt mixes
Georgia-Pacific Chemicals LLC	TUFFTREK 4002	Utilizes renewable oil technology and it is bio-based, renewable resource
Ingevity	Evoflex® CA	An environmentally friendly, nontoxic solution to increasing the amount of RAP and RAS incorporated into mixes
POET, LLC	JIVE™	Produced from 100% homegrown American corn, it rejuvenates RAP mixtures by restoring the aged bitumen’s properties, allowing for more flexibility in mix designs

2.2.2 Incorporation of Rejuvenators in Recycled Asphalt Shingles (RAS) and Reclaimed Asphalt Pavement (RAP)

All six rejuvenating products, which are PAVSAV^{TM}, Anova® 1815, Delta S®, TUFFTREK 4002, Evoflex® CA, and JIVE^{TM}, can be incorporated into RAS and RAP. The limits of percentage of RAS and RAP allowed incorporating rejuvenators are on a project-by-project basis, which depend on the age of RAS and RAP, binders used, sources of RAS and RAP, and other factors.

2.2.3 Performance Measurements

The performance testing provided by different manufacturers and suppliers was summarized as follows. Testing has been conducted with and without aging and different parameters have been evaluated.

- Asphalt Pavement Analyzer (APA)
- Bending Beam Rheometer (BBR)
- Disc-shaped Compact Tension (DCT) Test
- Dynamic Shear Rheometer (DSR)
- Dynamic Moduli Test
- Elastic Modulus Test
- Hamburg Wheel Tracking Test (HWTT)
- Indirect Tensile Asphalt Cracking Test (IDEAL-CT)
- Indirect Tensile (IDT) Test
- Illinois Flexibility Index Test (I-FIT)
- Overlay Tester (OT)
- Semi Circular Bend (SCB) Test

2.2.4 Aging Information Provided by Manufacturers

Manufacturers stated that aging resistance of rejuvenators themselves (outside) bitumen is becoming an area of focus globally as a potential flag for rejuvenators that do not perform well in long term aging. The 40-hour Pressure Aging Vessel (PAV) aging is not sufficient in determining aging resistance of most rejuvenators other than re-refined engine oil bottoms (REOB). Multiple PAV – 60 hours of aging – appears to be a key differentiator in identifying recycling aids that are susceptible to oxidation.

CHAPTER 3: LITERATURE REVIEW

This section is intended to provide a brief synopsis on some of the key areas of asphalt mix rejuvenators. It is provided as a starting point for future NRRA Flex Team projects and is not intended to replace more comprehensive reviews (Epps Martin et al., 2017).

3.1 REJUVENATOR DOSAGE SELECTION

The study conducted by the National Cooperative Highway Research Program (NCHRP) stated that the typical industry practice is to follow the producer's recommendation on the dosage and proportion of the rejuvenator with respect to the base binder (Epps Martin et al., 2017). The Nebraska DOT and New Jersey DOT in their studies had rejuvenators incorporated into the RAP mixtures based on the manufacturer's recommendation (Haghshenas et al., 2016; Bennert, Ericson, and Pezeshki, 2015). However, Bennert, Ericson, and Pezeshki queried the recommended manufacturer's dosage rate applied, which is calculated from the percentage of recycled RAP or RAS with respect to the total weight of the asphalt mixture (2015). In theory, the dosage rate should be determined from the virgin binder with respect to the recycled binder in the mixture.

Epps Martin et al. emphasized the importance of determining an optimum rejuvenator dosage that provides a good balance between cracking and rutting performance (2017). The recommended approach to select rejuvenator dosages in the NCHRP study is increasing rejuvenator dosage without sacrificing the high-temperature PG (rutting resistance). Blending charts can be used to determine the limits of recycled materials and the balance between the recycled and base binders at selected rejuvenator dosages.

Shen, Amirkhanian, and Miller in 2007 determined the dosage of rejuvenator needed to restore the RAP binder to a condition similar to a virgin binder using the blending charts determined through Dynamic Shear Rheometer (DSR) and Bending Beam Rheometer (BBR). This method of obtaining the optimum dosage of rejuvenator has been validated since there were good correlations between the performance and the rejuvenator dosage. As for the allowable percentage of RAP in the Superpave mixtures, it should be noted that the limits are influenced by the properties of both the RAP binder and RAP aggregate, and the ability to meet the requirements under the Superpave specifications.

Another study conducted by Lee, Mokhtari, and Williams in 2018 employed a similar method, in which the Bending Beam Rheometer (BBR) tests were performed to determine the optimum dosage of each rejuvenator such that the low-temperature PG of PAV-aged (long-term aging) binder improves to be equivalent to that of a virgin binder.

3.2 BLENDING METHOD

Blending of rejuvenator with the recycled mixtures is one of the important topics being discussed in this literature review as it may affect the performance of rejuvenated mixes, either positively or adversely. Haghshenas et al. suggested that depending on the type of blending procedures, the outcomes in determining the effectiveness of a rejuvenator may be different (2016). Bennert, Ericson, and Pezeshki (2015) added the rejuvenator directly to the heated binder promptly before the mixing and fabricating of specimens. Later in the study, the authors stated that this pre-blending method of rejuvenator may reduce the concentration of the rejuvenator and exhibit a diminished effectiveness since the rejuvenated binder needs to coat the RAP and virgin aggregate.

Blending of the rejuvenator with the binder is an important aspect during construction as well. Rejuvenator products have been added in several manners in previous projects including RAP stockpile marinating, in-line blending at the HMA plant during production or blending at an asphalt terminal. In-line blending of the rejuvenator adds the rejuvenator to the binder at the HMA plant and is similar to the addition of a liquid warm mix asphalt (WMA) additive. Terminal blending provides the most control in the mixing and dosage process but can introduce additional logistical challenges. Blending for field construction has not been widely discussed in this Literature Review as most of the literature was focused on laboratory testing.

3.3 EVALUATION OF REJUVENATED ASPHALT PERFORMANCE

3.3.1 Asphalt Laboratory Aging Protocol

Short-term aging on virgin asphalt binder is simulated using the Rolling Thin Film Oven (RTFO) test following AASHTO T240-94 (Lee, Mokhtari, and Williams, 2018; Epps Martin et al., 2017; Mohammadafzali et al., 2017). A 20-hour Pressure Aging Vessel (PAV) test following AASHTO R 28 is then performed on the aged asphalt, which prior, has been subjected to short-term aging condition, to simulate long-term aging (Lee, Mokhtari, and Williams, 2018). It was cited by Mohammadafzali et al. (2017) that a study carried out in Florida assessed a 20-hour PAV to be comparable to 8 years of field aging. In the study conducted by the NCHRP, an extended 40-hour PAV aging was conditioned on the binders (Epps Martin et al., 2017). In order to simulate approximately 24 years of service, three PAV cycles (a total of 60 hours) were performed by Mohammadafzali et al. on the samples in addition to the RTFO (short-term) aging.

As for mixture aging, Epps Martin et al. performed revisions to the aging protocols as stated in AASHTO R 30 (2017). The aging processes include conducting short-term oven aging (STOA) on loose mix for 2 hours (standard STOA specified in AASHTO R 30 is 4 hours) at 135˚C prior to compaction and an additional long-term oven aging (LTOA) on compacted specimens for 5 days at 85˚C. Bennert, Ericson, and Pezeshki (2015) in the University of Massachusetts – Rutgers University study performed similar LTOA protocols as Epps Martin et al., but with an extended STOA of 4 hours instead of 2 hours. The NHCRP study concluded that a more extensive LTOA protocol (loose mix to be subjected at 95˚C or 135 ˚C prior to compaction) is needed to simulate close to 7 to 10 years of field aging, which this window of time is considered as when the pavements are most susceptible to cracking (Epps Martin et al., 2017).

Mohammadafzali et al. investigated the aging of rejuvenated asphalt binders compared with virgin binders in 2017. Critical PAV time has been used to evaluate the recycling agent’s impact. Critical PAV time is defined as the PAV aging time to increase the high-temperature PG from the virgin binder (70˚C in this study) to 95˚C.

3.3.2 Asphalt Rheological Properties

Although the effectiveness of rejuvenation decreases with time, the rejuvenated binder blends showed improvements in performance as compared to the control blend without rejuvenator added (Epps Martin et al., 2017). Rheological parameters at intermediate temperatures in Black space and the evolution of Glover-Rowe (G-R) parameter denote the aging and rejuvenating process. However, another alternative parameter can be used to evaluate the balance between the recycled and base binders, rejuvenator, and the effectiveness of rejuvenator (initially and with aging) is the crossover temperature ($T_{\delta=45^{\circ}C}$) obtained from the Dynamic Shear Rheometer (DSR) master curves. Crossover temperature is defined as solid- to fluid-like transition temperature.

Performance grading of recovered asphalt binders can be evaluated to determine the effectiveness of the rejuvenators (Bennert, Ericson, and Pezeshki, 2015). Carbonyl index and sulfoxide index of binders obtained from Fourier Transform Infrared (FTIR) Spectroscopy can be used to determine the degree of oxidation, which a higher index dictates a higher degree of oxidation (Lee, Mokhtari, and Williams, 2018). FTIR results showed that all rejuvenator types effectively reduce the degree of oxidation of aged asphalt binder.

Chemical compositions of rejuvenated binders can be evaluated using the Saturates-Aromatics-Resins-Asphaltenes (SARA) analysis. Atomic Force Microscopy (AFM) has been used to determine the nanoscopic surface properties of rejuvenated binders and the results proved that all rejuvenators reduce the asphaltene contents in the binders.

3.3.3 Stiffness, Rutting, and Moisture Resistance

Dynamic Shear Rheometer (DSR) indicated that although all the rejuvenators helped to soften the aged binders at various degrees, they were not able to restore the properties of aged binders to those resembling the virgin binder (Lee, Mokhtari, and Williams, 2018).

An Asphalt Pavement Analyzer (APA) has been used to determine the rutting resistance of the asphalt mixtures, which concluded that the rut depth of all rejuvenated recycled mixtures was lower than the specified criteria (Shen, Amirkhanian, and Miller, 2007). Haghshenas et al. conducted dynamic creep test and presented that the permanent deformation of recycled mixtures improves with the incorporation of rejuvenators (2016).

Rutting performance has been evaluated using Hamburg Wheel Tracking Test (HWTT) by the University of Massachusetts – Rutgers University, in which the performance of rejuvenated mixtures falls between the performance of the control mixture and RAP mixture without incorporating rejuvenator (Bennert, Ericson, and Pezeshki, 2015). Overlay Tester and APA have also been performed on the rejuvenated mixtures to evaluate the long-term performance of a rejuvenator. Overlay Tester results indicated that the rejuvenators used may not exhibit stability when experiencing high temperature for a longer period of time. APA results showed similar trends as the Overlay Tester, in which the effectiveness of the rejuvenators diminishes with the increased hours of conditioning.

An Indirect Tensile Strength (ITS) test has been employed to evaluate the bearing strength and moisture susceptibility of the rejuvenated mixtures, which showed that rejuvenated mixtures with RAP perform equally as virgin mixtures (Shen, Amirkhanian, and Miller, 2007). The University of Massachusetts – Rutgers University evaluated the moisture resistance using HWTT. The results indicated the rejuvenated mixtures have performance between control mixture and RAP mixture without rejuvenator (Bennert, Ericson, and Pezeshki, 2015). Nonetheless, findings from Semi-Circular Bend (SCB) test showed that recycled mixtures with rejuvenators experience reduced moisture resistance (Haghshenas et al, 2016).

3.3.4 Reflective, Fatigue, and Low-Temperature Cracking Performance

Cryo-Scanning Electron Microscopy (Cryo-SEM) has been employed to quantify the fractured surfaces of both aged and rejuvenated binders formed at -165˚C, which results showed that the surface of rejuvenated binders has remarkably less amounts of cracking than that of aged binders (Lee, Mokhtari, and Williams, 2018).

A Flexural Beam Fatigue test performed by NJDOT showed that at higher strain levels, rejuvenated mixtures perform better than RAP mixtures without rejuvenators (Bennert, Ericson, and Pezeshki, 2015). Similar fatigue tests were conducted by the University of Massachusetts – Rutgers University using different types of rejuvenators and a majority of the rejuvenated mixtures portrayed an improvement in fatigue resistance.

The Overlay Tester conducted by NJDOT showed that RAP mixtures with rejuvenator generally performed better than RAP mixtures without rejuvenator (Bennert, Ericson, and Pezeshki, 2015). Rejuvenators proved to be capable of providing continuous fatigue resistance even after extended hours of aging (LTOA).

The University of Massachusetts – Rutgers University tested the mixtures using the Thermal Stress Restrained Specimen Test (TSRST) device, but with the specimens compacted using Superpave gyratory, to determine the cracking behavior of mixtures at low-temperature (Bennert, Ericson, and Pezeshki, 2015). The low-temperature cracking susceptibilities of the RAP mixtures with rejuvenators are enhanced when compared to both the control mixtures and the RAP mixtures without rejuvenators. The performances of RAP mixtures with rejuvenators were relatively similar for both STOA and LTOA, which indicate that further aging did not cause a notable effect on the low cracking temperature with the incorporation of rejuvenators.

Lee, Mokhtari, and Williams performed Disc-shaped Compact Tension (DCT) tests to evaluate the low-temperature cracking performance of the rejuvenated asphalt mixtures (2018). DCT results verified that rejuvenators when applied at optimum dosage rates to high RAP mixtures help to enhance their low-temperature cracking properties. Mohammadafzali et al., 2007 evaluated the low-temperature properties of the recycled binder blends through the Bending Beam Rheometer (BBR) test in terms of m-values. Results from the BBR test showed that the type and dosage of the rejuvenator are two important criteria that affect the low-temperature characteristic of recycled binders.

3.3.5 Field Study

Test sections constructed in Iowa (Lee, Mokhtari, and Williams, 2018) showed that rejuvenated asphalt mixtures with high RAP have better low-temperature cracking resistance. Yet the rejuvenators did not provide any improvements in the moisture susceptibility and rutting resistance, some samples even experienced stripping, according to the findings from Hamburg Wheel Tracking Test (HWTT).

Five test sections were built in Texas to verify the proposed mix design method, which involves choosing appropriate recycling agents based on the recycled binders (Zhou, 2018). Next, the dosage ranges of each recycling agent are evaluated through the binder tests. The last step in the proposed mix design method is to establish the optimum dosages of the recycling agents through mixture tests. The HWTT was conducted to measure the rutting resistance and the Texas Overlay test was performed to determine the cracking resistance of all the mixes. Performance of test sections was not disclosed in the paper. There has been limited information on field performance included in this Literature Review as most of the literature available was focused on laboratory testing.

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APPENDIX A

Contact Information of Manufacturers

CONTACT INFORMATION OF MANUFACTURERS

The NRRA is not affiliated with any of the manufacturers nor endorse any of the products listed in this synthesis. However, if interested in learning more on the products, the contacts of manufacturers that have provided information on their products to be included in this synthesis can be found below.

ASPHALT & WAX INNOVATIONS, LLC (AWI) AND GREEN ASPHALT TECHNOLOGIES, LLC

Product:	PAVSAV™
Name:	Terry Naidoo
Email:	terry_naidoo@awi-gat.com

CARGILL, INC.

Product:	Anova® 1815
Name:	Hassan Tabatabaee, Ph. D.
Email:	Hassan_Tabatabaee@cargill.com

COLLABORATIVE AGGREGATES LLC

Product:	Delta S®
Name:	Steven Wallace
Email:	SteveW@CollAgg.com

GEORGIA-PACIFIC CHEMICALS LLC

Product:	TUFFTREK 4002
Name:	Ryan Lynch
Email:	Ryan.Lynch@GAPAC.com

INGEVITY

Product:	Evoflex® CA
Name:	Jonathan MacIver
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POET, LLC

Product:	JIVE™
Name:	Alex McCurdy, Ph. D.
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