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Project Title

Effectiveness of Sustainable Asphalt Recycling Agents

University

South Dakota State University

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Research Needs

Reclaimed Asphalt Pavement (RAP) is the most widely recycled material globally [1]. Nationwide, more than 100 million tons of Hot-Mix Asphalt (HMA) are milled annually in road resurfacing projects. About 80% of this amount is reused as RAP [2]. Recent studies have shown that, in addition to preserving the environment, significant savings in cost are realized with increased use of RAP due to reduced requirement of the virgin binder. Based on the Virginia Department of Transportation data, about $3.7 per ton of mix can be saved for each 10% increase in RAP amount [3]. Based on the data collected between 2009 and 2010, about 96% of contractors have been using RAP in asphalt production. In 2009, 56 million tons of RAP materials were used nationally. In 2010, the total use reached 62 million tons. Assuming an average of 5% asphalt binder in RAP, this represents over 3 million tons (19 million barrels) of asphalt binder conservation [4]. It is reported that using between 20% and 50% of RAP can result in between 14% and 34% in savings in construction costs [5]. Based on a national survey conducted by Jones [6], one of the major barriers to using RAP in HMA mixes is binder issues. Binder issues generally consist of blended binder grade and concerns related to early failure, specifically due to fatigue and thermal cracking. The aforementioned binder issues are mainly related to the brittleness (viscosity and modulus) of the asphalt binder in the RAP. The asphalt binder in RAP is aged and highly oxidized, making it substantially stiffer and of higher viscosity than the virgin binders. Despite higher stiffness and improved performance against rutting [7, 8], a stiffer binder generally increases the propensity to cracking and reduces fatigue life [9-12]. Also, the mix's susceptibility to fatigue failure and thermal cracking was found to increase due to incorporating RAP into HMA [11]. Adverse effects of RAP on the fatigue life of pavements generally begin to show when the RAP content is higher than 20%, as reported by McDaniel et al. [13]. Therefore, its use has been limited by several DOTs to avoid premature pavement failures. To mitigate the increased brittleness of asphalt binder as a result of incorporating RAP in the mix, the use of Asphalt Recycling Agents (ARAs) has gained momentum. An ARA is an organic material used to restore aged asphalt to desired specification [14]. ARAs are added to either highly oxidized asphalt mixes or those containing high amounts of RAP to balance their brittleness to avoid premature pavement failures due to fatigue and thermal cracking [15]. According to Epps et al. [14], the ARAs added to recycled mixes serve four overarching purposes: (i) decrease the stiffness of the binder to facilitate construction and improve mix performance; (ii) improve the durability of the mix by enhancing the resistance to cracking by increasing the phase angle (δ) of the blended binder; (iii) make more recycled binder available for coating aggregates; and (iv) provide sufficient binder to fulfill mix design requirements. Sources of the commercially available rejuvenators are as follows [14]: (i) Aliphatic, Naphthenic, and Paraffinic rubber processing oils; (ii) Maltenes and resins from solvent de-asphalting; (iii) Re-refined waste lube oils; and (iv) derivatives of lipid-based vegetable oils. A summary of the categories of commercially available ARAs is shown in Table 1. The effectiveness of an ARA depends on its ability to disperse and diffuse. Other important factors affecting the effectiveness of an ARA in balancing the brittleness of the asphalt mix and adjusting the rheological properties and PG grade of an aged binder include the type and amount of the ARA, PG grade of the virgin binder, PG grade and amount of RAP, and mixing time and temperature [14]. It should be noted that the use of ARA in asphalt recycling is not recommended or even banned by several state DOTs due to the lack of specifications and concerns regarding their effectiveness in increasing the ductility of the mix. Also, uncertainties associated with the rutting performance of the mixes containing ARAs have limited their use [15]. While using a number of ARAs has been found to make it possible to hit the target PG grades by adjusting their amounts in a recycled mix, their effectiveness when their type and materials' source change remains unknown [15-17]. Therefore, the proposed study will evaluate the effectiveness of different types of ARAs with sustainable sources. For this purpose, a comprehensive laboratory testing program on asphalt binders and mixes will be pursued. Specifically, changes in PG grade and MSCR grade of the asphalt binders due to using different types and amounts of RAP and ARAs will be determined. Asphalt mixes containing the virgin binder, different amounts of RAP, and ARAs will be designed and tested to determine the effectiveness of the ARAs in increasing and maintaining the resistance of the mixes containing RAP to fatigue, low-temperature cracking, rutting, and moisture-induced damage when compared to those without ARA and virgin mixes. The findings of this study are expected to pave the road for using higher amounts of RAP in asphalt mixes to utilize the economic and environmental benefits of asphalt recycling to a greater extent without compromising the performance and durability of asphalt mixes. Additionally, the database developed in this study can be used as a preliminary step toward balancing the ARA and RAP content to achieve durable mixes.

Table 1. Categories of Commercially-Available Rejuvenators (after Epps et al. (2016) and NCAT (2014))

Category	Types	Description
Paraffinic Oils	Waste Engine Oil (WEO)	Refined used lubricating oils
	Waste Engine Oil Bottoms (WEOB)	
	Valero VP 165®	
	Storbit®	
Aromatic Extracts	Hydrolene®	Refined crude oil products with polar aromatic oil components
	Reclamite®	
	Cyclogen L®	
	ValAro 130A®	
Napthenic Oils	SonneWarmix RJ™	Engineered hydrocarbons for asphalt modification
	Ergon HyPrene®	
Triglycerides and Fatty Acids	Waste Vegetable Oil	Derived from vegetable oils
	Waste Vegetable Grease	
	Brown Grease	
	Oleic Acid	
Tall Oils	Sylvaroad™ RP1000	Paper industry by-products Same chemical family as liquid antistrip agents and emulsifiers
	Hydrogreen®	

Research Objectives

Specific objectives of the proposed study are as follows.

1. Conduct a literature review on the use of different types of ARAs from sustainable sources and the state of practice regarding the use of ARA in asphalt mixes.
2. Characterize the effect of different amounts and types of three major groups of sustainable ARAs, namely Paraffinic Oils (PO) from refined used lubricating oils, Triglycerides/Fatty Acids (TFA) from vegetable oils, and Tall Oil (TO) from paper industry byproducts, on the Superpave Performance Grade (PG) of asphalt binder blends containing 35% RAP binder mixed with a virgin binder (PG 58-34).
3. Determine the optimum amount of ARAs of each category (PO, TFA, and TO) when used with 35% of RAP and virgin binder (PG 58-34) to achieve a blend with a PG grade similar to that of the virgin binder.
4. Determine the effectiveness of each ARA when used with the RAP and virgin binder blend in restoring the rheological properties of the virgin binder.
5. Evaluate the binder blends' stress sensitivity, creep characteristics, and elastic recovery containing different amounts and types of ARAs (PO, TFA, and TO) mixed with 35% RAP and the virgin binder (PG 58-34).
6. Characterize moisture-induced damage characteristics by evaluating the adhesion of asphalt binder blends containing 35% RAP, virgin binder (PG 58-34), and different types of ARAs (PO, TFA, and TO) with different aggregates, namely quartzite, granite, and limestone before and after moisture-conditioning.
7. Characterize the effect of using optimum amounts of ARAs (PO, TFA, and TO), determined in the binder study, in Superpave asphalt mixes on their resistance to rutting, cracking, and moisture-induced damage.

Research Methods

The proposed study will focus on evaluating three major groups of ARAs from sustainable sources, namely Paraffinic Oils (PO) from refined used lubricating oils, Triglycerides/Fatty Acids (TFA) from vegetable oils, and Tall Oil (TO) from paper industry byproducts. It is proposed to evaluate the aforementioned ARAs on two levels, namely asphalt binder and asphalt mix.

<u>Asphalt Binder Study</u>: In the asphalt binder study, the effect of ARAs, namely PO, TFA, and TO, each represented by one product, on asphalt binder blends' rheological properties and their adhesion characteristics with different aggregates will be studied. More specifically, 35% of the simulated RAP binder (prepared by long-term aging of virgin binder in RTFO and PAV devices) will be blended with a PG 58-34 virgin binder, widely used in South Dakota and other northern states.

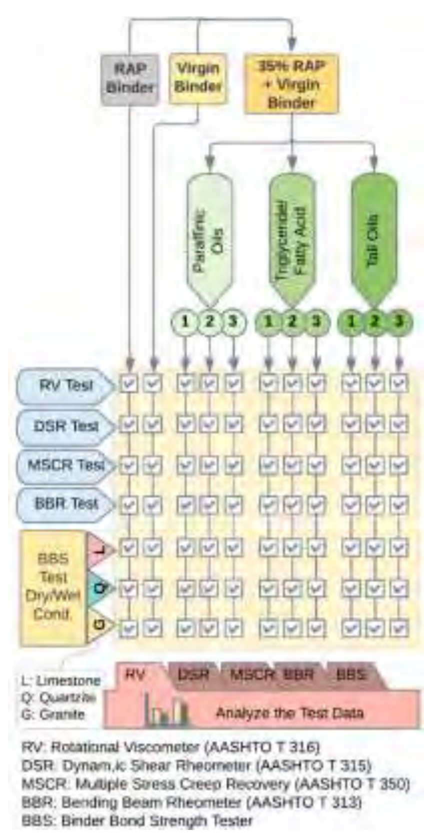

Figure 1. Workflow and Test Matrix for Binder Study

Then, RAP binder and virgin binder blends will be mixed with each ARA type at their manufacturer-recommended dosages and two other amounts representing a higher and lower limits. The high and low tolerance limits will be applied from results obtained from PG grading of RAP and virgin binder blended with ARA dosage to achieve virgin binder's PG grade. For this purpose, adjustments will be made in ARA amounts and tested until achieving a PG grade as close to that of the virgin binder as possible. All asphalt binder blends, including virgin binder only, those containing the virgin binder and RAP, and those containing the virgin binder, RAP, and ARA will be tested for dynamic viscosity, standard Superpave® PG grading, and MSCR grading. Also, the adhesion of asphalt binder blends with different aggregates, namely limestone, granite, and quartzite, will be determined in dry conditions and after moisture-conditioning. Figure 2 shows the workflow, materials, and test matrix proposed for the asphalt binder study. After completing the binder study, the results will be analyzed, summarized, and used to determine the required amounts of each type of ARA used in asphalt mixes.

Asphalt Mix Study: After evaluating the effects of the ARAs on the rheology and adhesion properties of the asphalt binders, this part of the study is proposed to focus on testing asphalt mixes mainly. This section will evaluate one product from each sustainable category of ARAs studied in the previous section (PO, TFA, and TO) when used in an asphalt mix. For this purpose, asphalt mixes will be designed using 0% RAP and 35% RAP containing the optimum dosage of the ARAs determined in the binder study. Then, asphalt mixes will be tested to determine their resistance to rutting, moisture-induced damage, and fatigue cracking. Figure 2 shows the workflow, materials, and test matrix proposed for the mix study. Rutting and moisture-induced damage potential of the asphalt mixes will be evaluated by conducting the Hamburg wheel tracking and tensile strength ratio tests on samples with 7.0% ± 0.5% air voids, according to AASHTO T 316 and AASHTO T 283, respectively. Additionally, the resistance of the mixes to cracking will be evaluated by conducting semicircular bend and 4-point bending beam tests following ASTM D8022 and AASHTO T 321 standard methods, respectively.

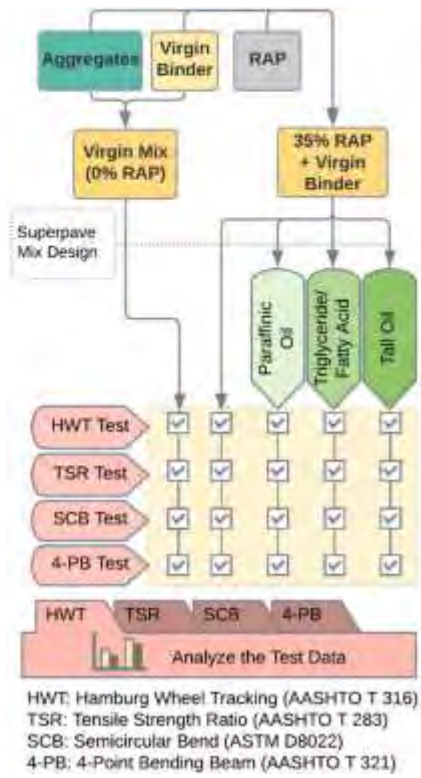

Figure 2. Workflow and Test Matrix for Mix Study

After completing the mix study, the results will be analyzed and summarized.

Expected Outcomes

The outcomes of this project and the database of asphalt binder and mix characteristics developed in this study are expected to help facilitate the development of specifications to be used in design and construction using HMA mixes containing sustainable asphalt recycling agents and high amounts of RAP. More specifically, the developed database is expected to help select the environmentally friendly ARA options and their dosages to utilize the maximum advantage of using RAP in HMA without compromising the durability and performance characteristics of the mix when compared with virgin mixes. In addition, adhesion test data is expected to single out any combinations of asphalt binder-aggregate-ARA, which may be incompatible at the component level. This is expected to significantly reduce the risk of moisture-induced damage due to using incompatible mix ingredients with the selected ARA type.

Relevance to Strategic Goals

The expected outcomes of this project are directly related to the following USDOT strategic goals: Environmental Sustainability and Economic Competitiveness. Outcomes of the proposed project will facilitate the incorporation of high amounts of RAP in new asphalt mixes by utilizing environmentally friendly recycling agents to promote the sustainability of transportation infrastructure. This not only will result in a reduced need for petroleum-based new asphalt binder, but it is also expected to reduce the landfills as an environmental concern and improve the economic advantage of asphalt mixes as a construction material.

Educational Benefits

This project will provide an excellent learning opportunity for graduate and undergraduate students. A graduate student will be working on this project as a GRA. The results of this study will be used to provide materials for their thesis. The outcomes of this study will be blended with students' learning experiences in the classroom. More specifically, it will be used for selected lectures in the CEE 765: Pavement Design, CEE 792: Pavement Sustainability, and CEE 411/511/L: Asphalt Materials and Mix Design and Lab.

Technology Transfer

In close collaboration with the South Dakota Local Transportation Assistance Program (SDLTAP), the findings of this project, after completion, will be presented during South Dakota Annual Asphalt Conference. This well-attended conference allows broader participation by pavement engineers, the asphalt industry, SDDOT personnel, NAPA members, and other stakeholders. Moreover, research papers will be published, and presentations will be delivered at conferences and other occasions to effectively disseminate this study's findings. Toward building a stronger transportation workforce, a significant component of MPC's mission and vision, it is envisioned to blend research ideas and innovations in the classroom.

Work Plan

The proposed work plan consists of twelve major tasks as follows:

Task 1 – Literature Review: The literature review for this study will focus on different types of sustainable ARA options and their characterization. Also, the available literature on the effect of incorporating different types of sustainable ARAs in asphalt binders and mixes on their mechanical characteristics will be summarized.

Task 2 – Material Collection: The required materials for this study will be collected in close collaboration with our industry partners. Asphalt binders will be collected from Jebro Co. in Sioux City, IA. Aggregates and asphalt mixes will be collected from Bowes Construction Co. in Brookings, SD, and Concrete Materials Co. in Sioux Falls, SD. The ARAs will also be collected from their suppliers. The research team has a successful experience in collaborating with industry partners.

Task 3 – Asphalt Binder Viscosity and PG Grading: As noted earlier, 0% and 35% of simulated RAP binder, prepared by long-term aging procedure using a Pressure Aging Vessel (PAV) per AASHTO R 28 [18], will be blended with a virgin binder (PG 58-34) and different dosages of three types of sustainable ARAs, namely PO, TFA, and TO. The blended binders will be tested for viscosity using a Rotational Viscometer (RV) according to the AASHTO T 316 [19] method to determine their mixing and compaction temperatures in production and construction. Also, the blends of RAP, ARA, and virgin binder will undergo the necessary short-term aging using a Rolling Thin Film Oven (RTFO) per AASHTO T 240 [20] and long-term aging using PAV per AASHTO R 28 [18] to prepare the specimens for conducting the tests for determining the PG grade of asphalt binder according to AASHTO M 320 standard specification [21]. The Superpave® PG grading tests will include testing binder blends in a Dynamic Shear Rheometer (DSR) following AASHTO T 315 [22] and Bending Beam Rheometer (BBR) as per AASHTO T 313 [23] standard methods. The optimum contents for each ARA type will be determined based on the PG grading results. The ARA at its optimum amount, when blended with 35% RAP and virgin binder (PG 58-28), is expected to reproduce the PG grade of the virgin binder.

Task 4 – Asphalt Binder MSCR Grading: Multiple Stress Creep Recovery (MSCR) tests on the binder blends will be conducted at the testing temperature determined based on PG grade and at two stress levels (0.015 psi and 0.464 psi) per AASHTO T 350 [24]. The MSCR results will include non-recoverable creep and % recovery. The MSCR test accounts for the effect of the different traffic loading on the asphalt binder's permanent and recoverable deformations. MSCR grading of tested binder blends will be determined by following AASHTO M 332 standard specification [25].

Task 5 – Asphalt Binder Adhesion Test: The Binder Bond Strength (BBS) test will be conducted to evaluate the effects of using different ARAs and RAP on the adhesion of the asphalt binder with different types of aggregates, namely limestone, quartzite, and granite, per the AASHTO T 361 [26] test method. According to the standard, samples will be tested in dry condition and after moisture-conditioning. The effects of using ARAs and RAP on the adhesion of asphalt binder and aggregates are essential for the resistance of asphalt mix to moisture-induced damage and raveling.

Task 6 – Superpave® Asphalt Mix Design: Asphalt mixes containing different amounts of RAP (0%, 35%), optimum amounts of the ARA (based n the findings of the binder study), a virgin binder (PG 58-34), and aggregates, will be designed and produced in the laboratory. The volumetric mix designs of the proposed mixes will be conducted in accordance with Superpave® requirements following AASHTO M 323 specification [27] and AASHTO R 35 standard practice [28]. The optimum amount of binder content will be determined and used for preparing the mixes in the laboratory.

Task 7 – Hamburg Wheel Tracking Test (HWT) (Resistance to Rutting and Moisture Damage): The HWT tests will be conducted on asphalt mixes per the AASHTO T 324 standard method [29]. The test specimens of 6 in. diameter and 2.4 in. height prepared using a Superpave® Gyratory Compactor (SGC) will be tested. The test will be conducted to evaluate the rutting resistance up to a maximum number of 20,000 wheel passes on specimens submerged in the water bath with a temperature of 122 ± 1.8°F. The moisture damage potential of the mixes will be evaluated from a striping inflection point (SIP). A new method introduced by Texas Transportation Institute for analyzing the HWT test data will also be applied as an alternative technique to isolate the rutting and moisture-induced damage and study them separately.

Task 8 – Indirect Tensile Strength Ratio (TSR) (Moisture-Induced Damage): Moisture-induced damage potential of the mixes will be determined based on their retained indirect tensile strength ratio following the AASHTO T 283 standard method [30]. In this method, the tensile strength decay due to accelerated moisture and temperature conditioning is measured to indicate the moisture-induced damage. The TSR value for each mix will be determined by dividing the average tensile strength of conditioned by that of unconditioned specimens. Also, the average toughness index [31] ratio of conditioned samples to that of unconditioned ones will be calculated as a new mechanistic approach based on fracture mechanics for determining the moisture-induced damage potential. The indirect tensile strength TSR tests will be conducted using an MTS loading frame available to researchers.

Task 9 – Semicircular Bend (SCB) Test (Cracking Resistance): The SCB test will be conducted on semicircular specimens 6-in. in diameter, 3-in. in height, and 2-in. in thickness with three notch depths, namely 1.0 in., 1.3 in., and 1.5 in per ASTM D8022 standard method [32]. The notches will be cut in the samples using a heavy-duty precision saw machine. Then, the samples will be tested using a fully automated test procedure in an IPC Asphalt Mix Performance Tester (AMPT) available in SDSU's Asphalt Laboratory (Figure 3). During the testing, the temperature will be maintained at 77°F (intermediate temperature) in accordance with the PG grade of the mix. This test will be conducted by applying a monotonically increasing load at a rate of 0.02 in/min until failure. The critical strain energy release rate, called the critical value of J-integral or *Jc,* will be calculated. The SCB test results will be used to characterize the cracking potential of the asphalt mixes based on the fracture mechanics concept.

Figure 3. SCB Test in Progress (SDSU's Asphalt Laboratory)

Task 10 – Four-Point Bending Beam (4-PB) Test (Fatigue Life): The 4-PB test will be conducted on rectangular prismatic specimens of 15 inches in length by 2 inches in height by 2.5 inches in width. The prismatic samples will be cut using a heavy-duty precision saw machine from a block sample compacted using a slab compactor. Then, the samples will be tested in a 4-PB jig installed in an AMPT available in SDSU's Asphalt Laboratory. During the testing, the temperature will be maintained at 77°F in accordance with the PG grade of the mix. The 4-PB tests will be conducted in accordance with AASHTO T 321 standard method [33]. It is important to note that the 4-PB test is considered the industry gold standard for reliable measurement of the fatigue life of the asphalt mixes. However, factors such as the need for specialized equipment, time required for sample preparation and testing, and trained, skillful operators have limited its use to research. As a result, surrogate tests, such as SCB are applied by the mix design labs.

Task 11 – Analyze Test Results, Summarize the Findings, and Report: After completing the testing program, the findings of this study will be compiled and analyzed. Important effects of using different types and amounts of the ARAs on asphalt binder and mix properties will be summarized and reported in the project's final reports.

Task 12 – Outreach and Technology Transfer Initiatives: It is proposed to present the findings of this project to a broad audience with the help of SDLTAP through South Dakota Annual Asphalt Conference. This well-attended conference allows broader participation by pavement engineers, the asphalt industry, the South Dakota Department of Transportation's personnel, NAPA members, and others. In addition, research papers will be published, and presentations will be made at conferences and other occasions to disseminate this study's findings effectively. Toward building a stronger transportation workforce, a major component of MPC's mission and vision, it is planned to blend research ideas and innovations in the classroom.

Project Cost

Total Project Costs:	$134,192
MPC Funds Requested:	$ 67,092
Matching Funds:	$ 67,100
Source of Matching Funds:	South Dakota State University

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