UPCYCLING END OF LIFE WIND TURBINE BLADES TO YIELD RECYCLING AGENTS TO SUCCESSFULLY INCREASE RECYCLED ASPHALT PAVEMENT (RAP) FOR CHEAPER AND GREENER PAVEMENTS IN WYOMING

Date submitted: Friday, October 11th, 2024

Proposal Submitted To:
Wyoming Department of Transportation (WYDOT) in response to the "Call for Proposals for the First Quarter Research Advisory Committee SPR-B Funds"

WYDOT Project Champion
Mr. Ethan Crockett
Asphalt and Chemistry Engineer
Wyoming Department of Transportation
ethan.crockett@wyo.gov
307-777-4726

Proposal Submitted By:
Western Research Institute
Laramie, WY

Principal Investigator
Dr. Yogesh Kumbargeri
Lead Research Engineer
Western Research Institute
3474 North 3rd Street, Laramie, WY 82072
ykumbarg@uwyo.edu
307-721-2203

Co-Principal Investigator
Dr. Jeramie Joseph Adams
Vice President
Western Research Institute
3474 North 3rd Street, Laramie, WY 82072
jeramie.adams@uwyo.edu
307-721-2324

TABLE OF CONTENTS

1.Introduction and Literature Review:

More than 93 percent of highways and roads in the United States are built using Hot Mix Asphalt (HMA) or Warm Mix Asphalt (WMA) mixtures (1). The use of Recycled Asphalt Pavement (RAP) reduces the need for virgin materials, by conserving valuable raw materials in the form of asphalt binder and aggregates, and it can reduce energy consumption and lower the CO_2 footprint for paving operations. Savings from utilizing RAP allows road owners to achieve more roadway maintenance and construction activities within their limited budgets. The use of RAP in HMA dates back to the early 1900s, however, research and implementation was not accelerated until the 1970s and 1980s due to a skyrocketing cost of oil during the Arab oil embargo, which impacted asphalt binder availability and cost (1-3).

The latest comprehensive nationwide data and statistics available for RAP usage are available in the National Asphalt Pavement Association (NAPA) survey report for the 2022 construction season (4). During that time, RAP usage in the US was estimated to have reduced the need for 4.9 million tons (26.9 million barrels) of asphalt binder and more than 93 million tons of aggregate resulting in a total estimated savings of more than $4.6 billion. In addition to cost savings, RAP is reported to have environmental benefits as well. The use of RAP in new asphalt mixtures reduced greenhouse gas (GHG) emissions by 2.7 million metric tons (MMT) of CO_2e, which is equivalent to the annual emissions of more than 600,000 passenger vehicles (4).

Of states responding to the NAPA survey, 10 states had RAP dosages below 20%, 17 states had RAP dosage from 20-29% and only 3 states used upwards of 30% RAP (4). In terms of the states close to Wyoming, and with similar climatic conditions, Colorado has been using about 19% RAP, whereas Utah reported 23% (4). The most recent available from Wyoming showed 12% RAP in 2017. Based on further discussions with Wyoming Department of Transportation (WYDOT) personnel, 15% has been confirmed as the highest dosage of RAP used in Wyoming as of 2023.

If RAP can be increased by 10% (i.e., from the existing 15% to 25%), WYDOT would have a cost savings about 10% on fresh binder and aggregates. Based on 2022 data from WYDOT, this would save WYDOT $7.5 million. Furthermore, if high RAP pavements with RAP contents of 30%, 40% or higher were to be built, it would lead to further dramatic cost savings for the state. Hence, increasing RAP content for road construction would be financially and environmentally beneficial to the state of Wyoming. In general, higher amounts of RAP (>20%) are not used without special treatments because the brittle nature of RAP can rapidly manifest in the new pavement resulting in premature cracking and failure. Recycling agents (also referred to as rejuvenators), or softer asphalt bases, are often used to soften RAP so that more of it can be used without sacrificing the quality of the new road. Recycling agents do cost more than asphalt (around $1,500-3,500/ton) but they are used at low dosages (2-10%, typically 3-7%).

The Western Research Institute (WRI) has been working to develop new solutions for asphalt recycling and circular economy of wastes. WRI is currently involved in a project with National Center for Asphalt Technology (NCAT) to characterize various recycling agents and to relate their chemistry to test track performance under NCHRP project 10-114 (5). WRI is also involved with an international study aimed at evaluating different recycling agents through the Asphalt

Industry Research Consortium (AIRC) project, Iteration 3. Beyond asphalt testing and analyzing, WRI is also studying Wyoming issues such as upcycling end-of-life wind turbine blades (WTB) to eliminate landfilling while producing value added products (upcycling) for the paving industry. WRI has developed a technology utilizing a thermochemical process to convert the epoxy resin in WTB into an effective recycling agent using vegetable oil-based solvents. Figure 1 shows the concept for upcycling WTB developed by WRI.

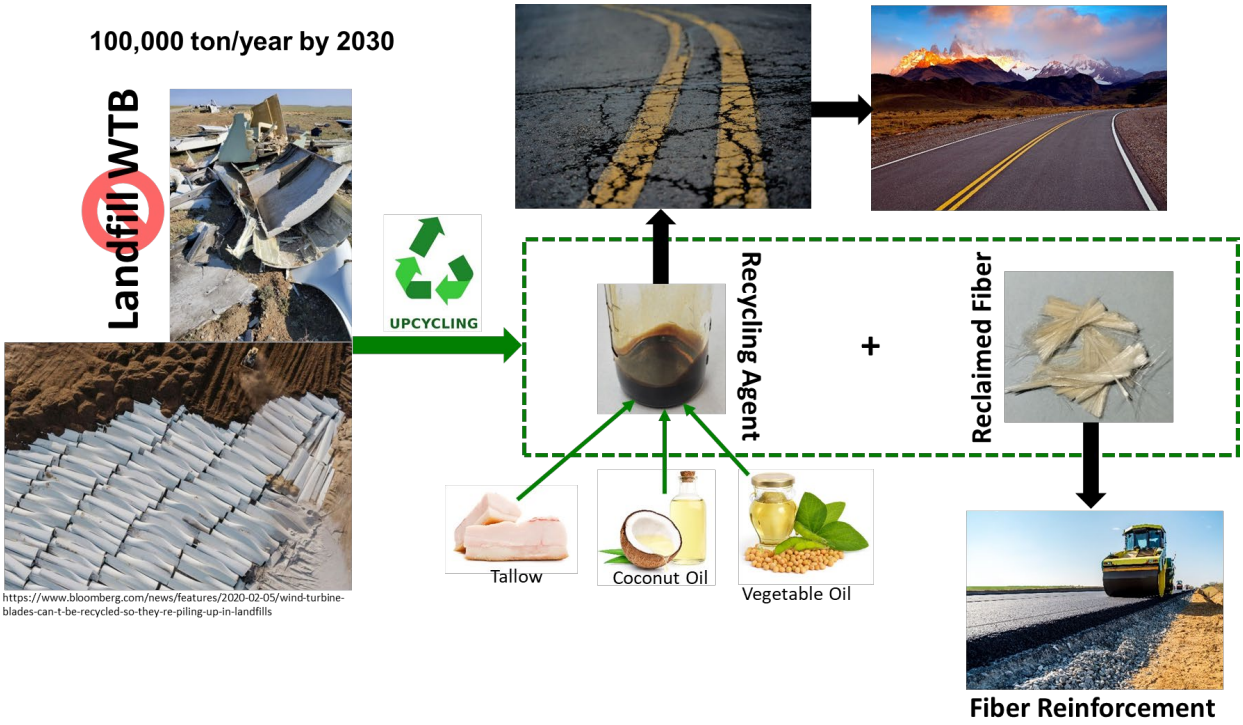

Figure 1. Figure showing the upcycling of WTB to produce recycling agents and reclaimed fibers for use in the asphalt industry. Reclaimed fibers can also be remelted and recycled into new WTB and may be used in a variety of other composite compounding products.

1.1 WTB waste issue affecting Wyoming

WTB waste is a global, national, and Wyoming issue, especially since WTB is one of the main renewable energy sources that has grown rapidly in the last two decades. WTB are typically replaced about every 20 years as preventative maintenance, or they are replaced by more advanced technologies that can produce more energy. Wyoming has one of the few regional landfills that will accept WTB. This landfill is located in Casper, and it has been featured on national news highlighting the negative environmental impact of WTB waste. Compounding this issue is the fact that Wyoming has also been significantly increasing development of its wind energy sector and replacing and upgrading WTB. Wyoming currently produces 2,508 MW of electricity from wind energy and another 3,503 MW of wind energy is currently under construction in Carbon County (6). Figure 2 shows a recent map of wind turbines in Wyoming and the surrounding area.

Controversial WTB waste produced from this important renewable energy resource has been recently debated in Wyoming legislation. For instance, a ban on landfilling WTB was proposed

in Wyoming House Bill 217 which also sought to mandate recycling (7). Alternatively, House Bill 129 proposed to use WTB for backfilling of coal mining sites as part of the reclamation process (8). Globally, there has been a partial shift from landfilling WTB to utilizing the epoxy resin and carbon fiber content in the blades as a fuel for cement kilns. Landfilling, mine reclamation, and burning do not provide environmentally friendly long-term strategies. Burying blades locks the highly engineered resins and fibers in the ground, while burning converts them into the greenhouse gas CO_2. WRI has developed a process to chemically convert the epoxy resin into asphalt recycling agents (RAs) using renewable vegetable oil-based solvents. Figure 3 shows a photograph of WTB, recycling agent from WTB developed by WRI (WTB-RA), and reclaimed fibers from WTBs collected from the Casper landfill and Arlington in 2021.

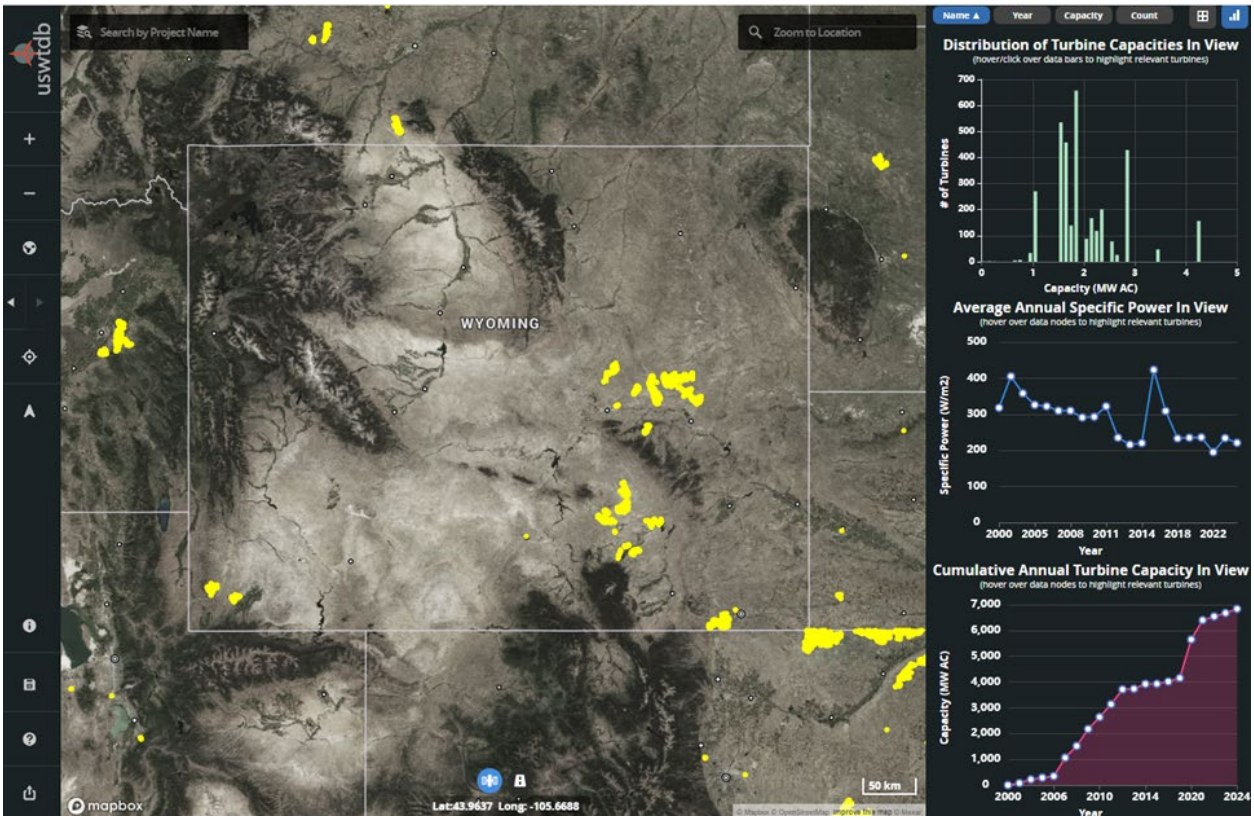

Figure 2. Image from US Wind Turbine Database (September 23, 2024) showing the WTB located within Wyoming and surrounding area.

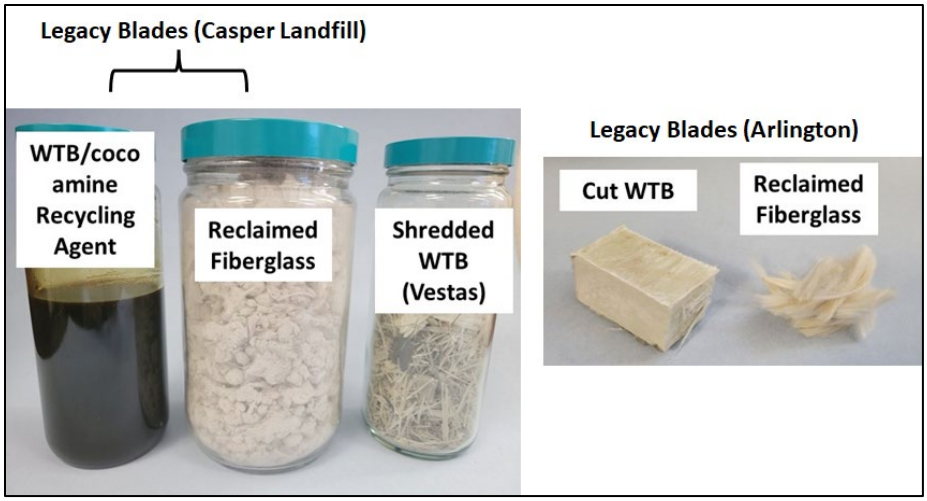

Figure 3. Photographs of WTB-RA, reclaimed fibers, and WTB (chunks and shredded).

1.2 Details about WTB-RA technology developed by WRI

WTB-RAs, produced using Wyoming WTB materials and coco amine, have been tested in several different aged asphalts such as a Wyoming asphalt BI0003 (Holly Asphalt Company, Holly Frontier, Cheyenne WY PG 58-28) that was part of FHWA's Asphalt Research Consortium. It has also been tested in multiple problematic binders from the Strategic Highway Research Program (SHRP) such as AAE-1 (air blown Lloydminster crude oil form Canada), AAF-1 (very poor oxidation properties from a California Costal crude oil), and AAM-1 (high molecular weight high wax content from West Texas Intermediate crude oil). In the case of BI0003 after aging the asphalt by RTFO/40hr PAV (to simulate field aging), the WTB-RA softened the asphalt similar to a commercial vegetable oil RA at various concentrations. This is shown in Figure 4.

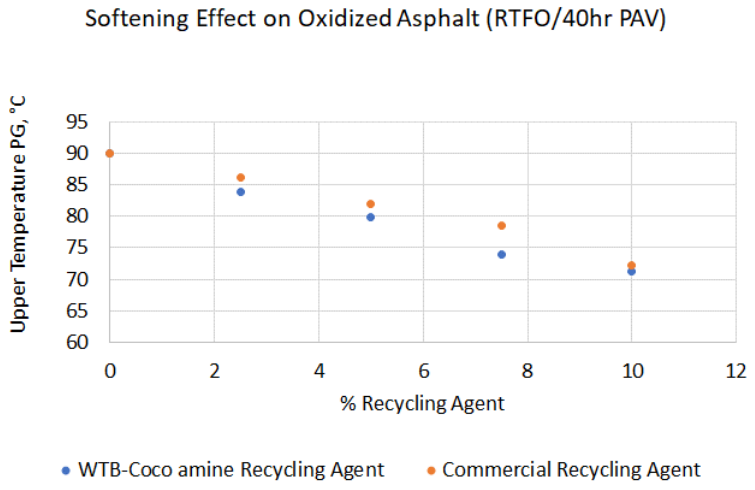

Figure 4. Graph showing upper PG for BI0003 RTFO/40hr PAV treated at different dosages (2.5, 5, 7.5, and 10%) of a commercial vegetable oil-based RA and the WTB-RA.

The softening at the upper PG is important, but more important is how the WTB-RA impacts the low temperature properties. To understand more about the impact on low temperature properties, multiple asphalts were selected that have very negative ΔTc values and exhibit unusually high embrittlement after aging. These binders were the aged (RTFO/40hr PAV) SHRP binders AAE-1, AAF-1 and AAM-1. All three binders softened at about the same rate for the upper temperature PG properties, as shown in Figure 5. However, the softening effect at the low temperature was highly source dependent. Of the low temperature properties, Tc(m) is the most important parameter since this relates to the material's ability to relax stress which makes it a predictable indicator of cracking. Figure 6 shows the Tc(m) for these binders using different concentration of the WTB-RA. The WTB-RA softened the upper and lower temperature properties of AAE-1 to about the same degree when judging by the slopes of correlations. The softening at the low temperature was slightly less effective for AAF-1, and for the special case of the high molecular wax high wax content AAM-1 the softening was even less effective (slope for upper PG was -2.132 but for Tc(m) it was -0.996). The less effective nature for AAF-1 and AAM-1 is likely due to the unusually high wax content and the behavior of the waxes in these two sources. AAM-1 is a binder which doesn't respond well to additives because its chemistry is very different from most asphalt binders. Despite the slight deviation in softening between the upper and lower temperatures, AAF-1 did show a favorable effect by increasing the ΔTc cracking parameter, as shown in Figure 7. This result shows that for some binders relaxation can be preferentially restored to improve cracking resistance.

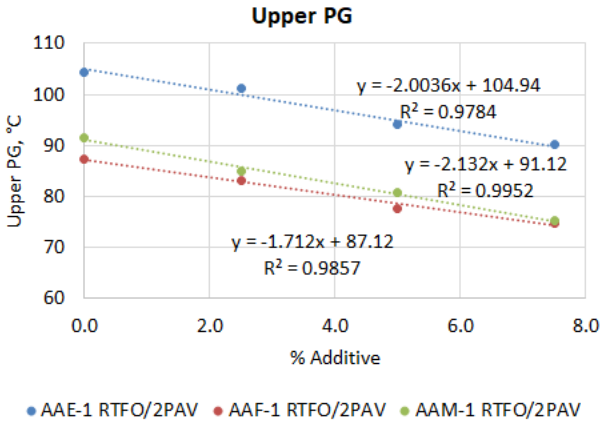

Figure 5. Graph showing change in upper PG for RTFO/40hr PAV aged problematic SHRP binders AAE-1, AAF-1 and AAM-1 with increasing concentration of WTB-RA.

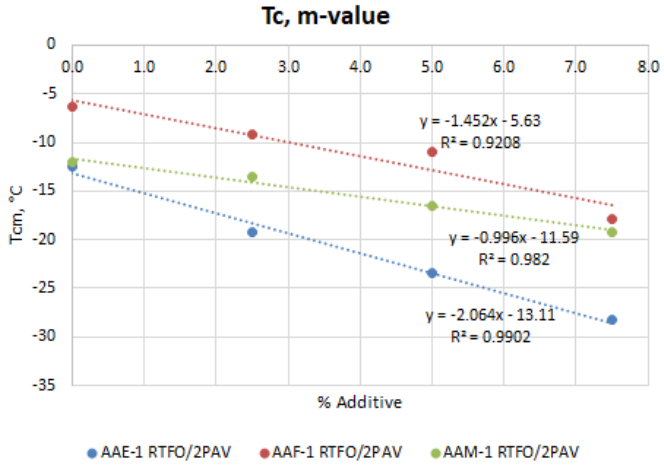

Figure 6. Graph showing change in the Tc(m) with increasing WTB-RA concentration for problematic SHRP binders AAE-1, AAF-1 and AAM-1 that were aged (RTFO/40hr PAV).

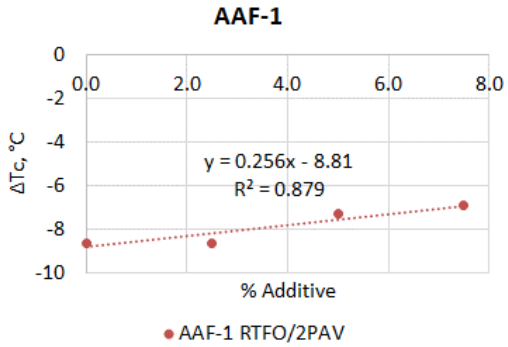

Figure 7. Graph showing ΔTc values for RTFO/40hr PAV AAF-1 binder with increasing concentration of WTB-RA.

The positive effect on the ΔTc value for AAF-1 treated with WTB-RA was confirmed with the linear amplitude sweep (LAS) test. As the concentration of the WTB-RA increased the number of cycles to failure also increased as shown in Figure 8.

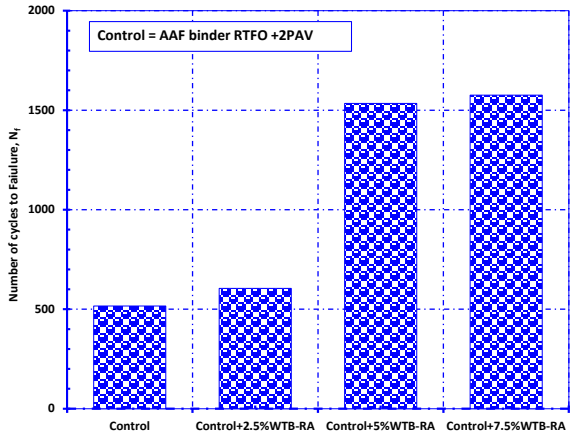

Figure 8. Graph showing LAS test results for RTFO/40hr PAV AAF-1 treated with increasing concentration of WTB-RA.

Of particular interest is the fact that WTB epoxy resin molecules are highly inert and stable towards oxidation. This characteristic was also present with the WTB-RA when studying its oxidation behavior. This was shown by taking the WTB-RA and the commercial RA and aging them by RTFO/20hr PAV and RTFO/40hr PAV and analyzing the materials by the Saturates, Aromatics, Resins-Asphaltene Determinator (SAR-AD). The data showed that the commercial RA composition had changed dramatically whereas the WTB-RA only showed a minor change with aging. The RTFO/PAV and RTFO/40hr PAV aged commercial rejuvenator still behaved as a viscous liquid after aging, but it had become significantly more polar reporting mostly to the asphaltene fraction. During aging, asphalt will also produce new asphaltenes. The rapid increase of asphaltenes from the commercial RA will compound the phase separation issues that occur as the binder ages and builds up its own asphaltenes. This combined effect is expected to accelerate cracking and premature failure in the field. However, for the WTB-RA it should remain effective at softening especially since it will not create additional asphaltenes and it will continue to stabilize the buildup of asphaltenes that are generated from the binder with aging. This is demonstrated in that after aging WTB-RA for RTFO/40hr PAV there is no significant build up of asphaltenes and only a slight increase in resins. The resins will continue to help dissolve/disperse and stabilize asphaltenes as they build up in the binder as it ages. Figure 9 shows a column plot for the SAR-AD data for the commercial RA and WTB-RA before and after aging by RTFO/20hr PAV and RTFO/40hr PAV.

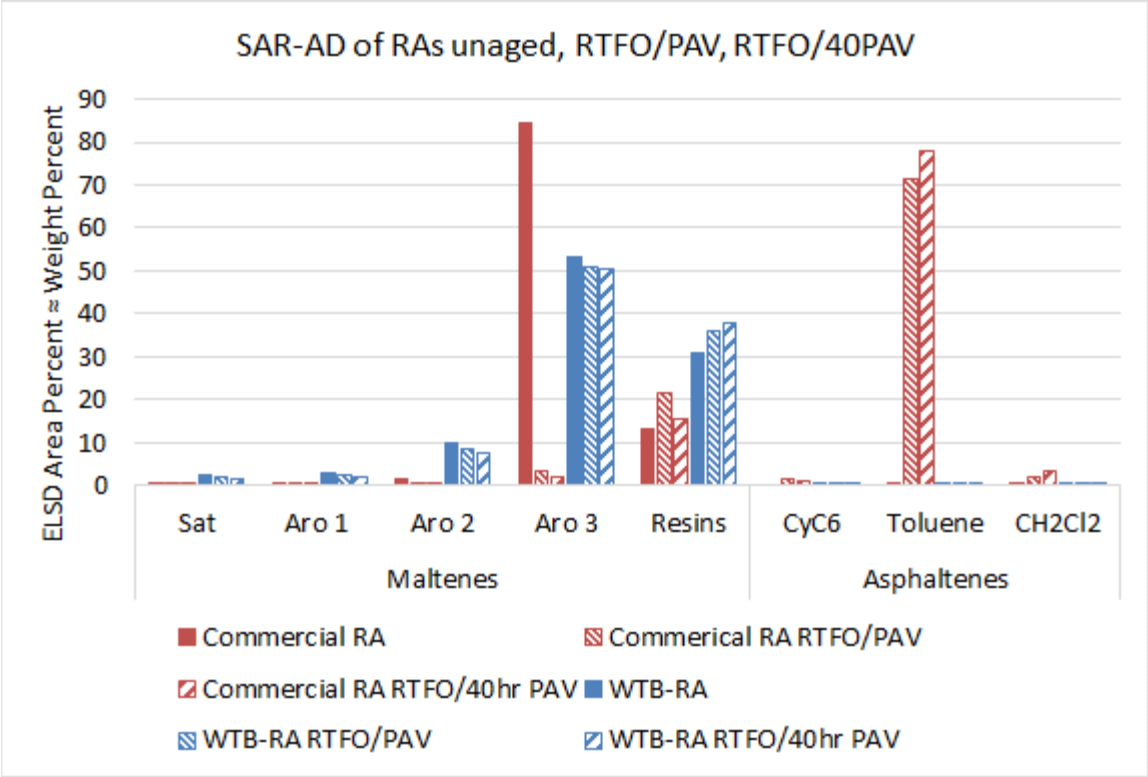

Figure 9. Graph presenting saturates, aromatics, resins and asphaltenes (using SAR-AD) data for the commercial RA and WTB-RA unaged, RTFO/PAV, and RTFO/40hr PAV.

The accelerated aging of the commercial RA compared to the WTB-RA also occurred in the asphalt blends. This was seen by blending the RAs with a laboratory RAP at 7.5 wt% and aging the blend by RTFO/20hr PAV and RTFO/40hr PAV. SAR-AD data shows that the asphaltenes build up more with aging for the commercial RA than with the WTB-RA, as shown in Figure 10.

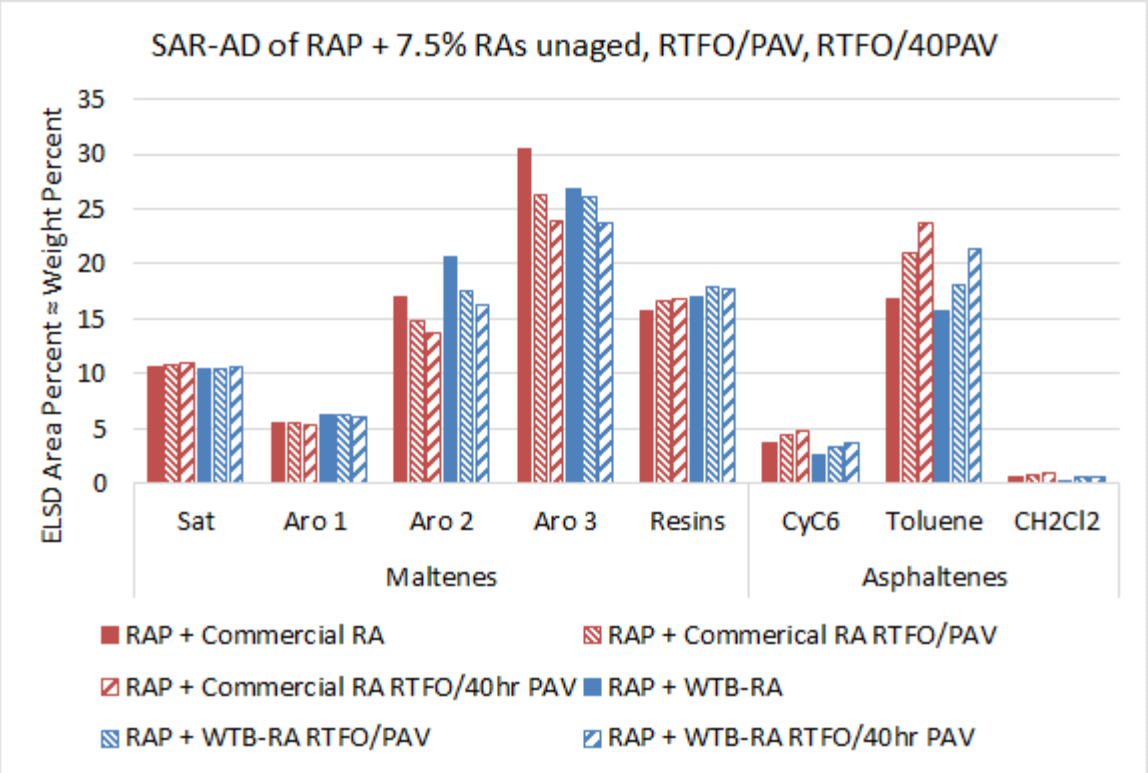

Figure 10. Graph presenting saturates, aromatics, resins and asphaltenes (using SAR-AD) data for laboratory RAP blended with 7.5% of the commercial RA and WTB-RA and the samples after RTFO/20hr PAV and RTFO/40hr PAV.

A particularly useful metric from SAR-AD data is the colloidal instability index (CII). This is a ratio which relates the asphalt's compositional fractions that destabilize asphalt to the fractions which stabilize asphalt. This is calculated by taking the sum of the saturates, aro 1, and asphaltenes (bad for the stability of the asphalt) and dividing it by the sum of the aro 2, aro 3, and resins (good for the stability of the asphalt). When the CII is plotted as a function of aging severity the slope for the WTB CII increases at a lower rate compared to the RAP, while the commercial CII slope increases at a slightly higher rate than the RAP. This shows how the WTB-RA can reduce the effects of aging whereas the commercial RA can make it slightly worse than the aging of RAP alone. Figure 11 shows the CII trends for unaged, RTFO/20hr PAV, and RTFO/40hr PAV for the RAP, RAP + 7.5% commercial RA, and RAP + 7.5% WTB-RA.

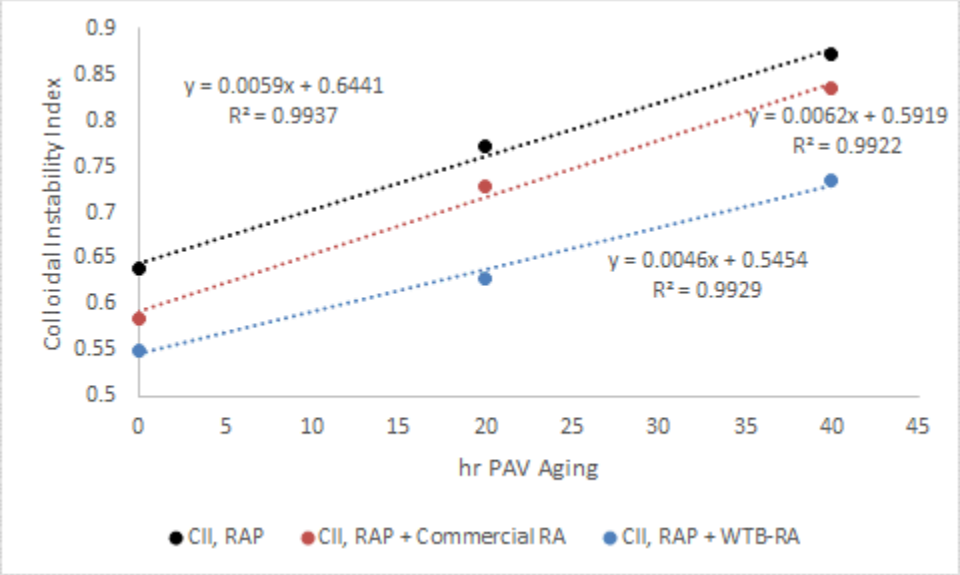

Figure 11. Plot showing Colloidal Instability Index (CII) trends for increased PAV aging (0, 20 and 40 hrs) for RAP, RAP + 7.5% commercial RA, and RAP + 7.5% WTB-RA.

These effects on the chemical composition of the RAP blends were, of course, also manifested in the rheological response of the blends. Overall, the commercial RA had a better softening effect at the low temperature properties (Tc(m)), but it began to lose this advantage after aging. The loss in softening effect was also seen at the upper PG. Figure 12 shows the upper and lower PG for the RAP, RAP + 7.5% commercial RA, and RAP + 7.5% WTB-RA at different levels of aging.

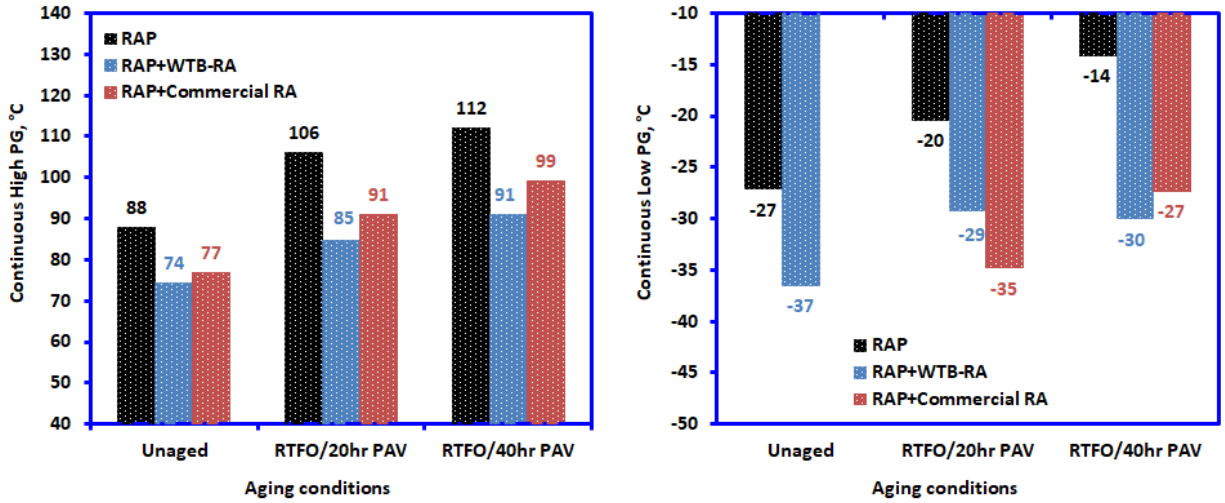

Figure 12. Plot showing the upper PG (left) and lower PG (right) for RAP, RAP + 7.5% commercial RA, and RAP + 7.5% WTB-RA unaged and after RTFO/20hr PAV and RTFO/40hr PAV.

Recent parameters calculated form the Dynamic Shear Rheometer (DSR) data frequency sweeps at different temperatures have been proposed as more accurate indicators of asphalts brittle and ductile behavior. These parameters are the Pavel-Kriz phase angle and the temperature at which

the phase angle at 27 °. For the Pavel-Kriz parameter the data showed that the RAP + 7.5% WTB performed better at all levels of aging, whereas the temperature at which the phase angle of 27 ° showed that the Commercial RA performed better initially but then after 40hr PAV the WTB performed better. The temperature at which the phase angle of 27 ° is likely more representative of the overall low temperature properties, whereas the Pavel-Kriz phase angle is more related to the intermediate temperature. Figure 13 shows the Pavel-Kris phase angle and the temperature at which the phase angle of 27 ° for the RAP and the RAP treated with RAs at 7.5% at increasing ageing severity.

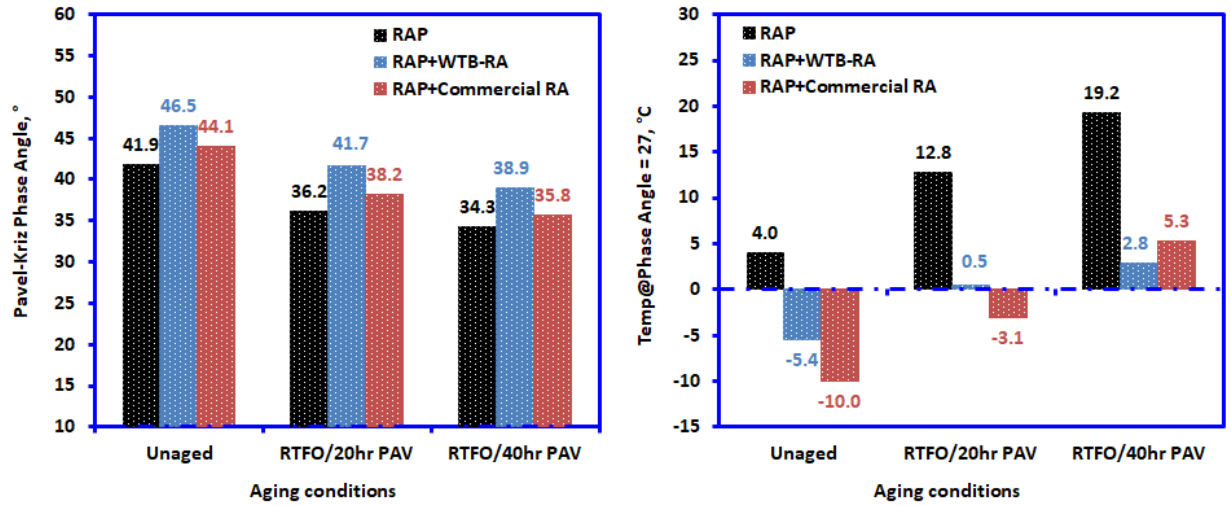

Figure 13. Plot showing the Pavel-Kriz phase angle (left) and temperature at 27° phase angle (right) for RAP, RAP + 7.5% commercial RA, and RAP + 7.5% WTB-RA unaged and after RTFO/20hr PAV and RTFO/40hr PAV.

Raw data in the Black Space diagrams also show less brittle and more ductile behavior of the WTB treated RAP after 20hr and 40hr PAV aging from the shift of the data down and to the right. This is shown in Figure 14.

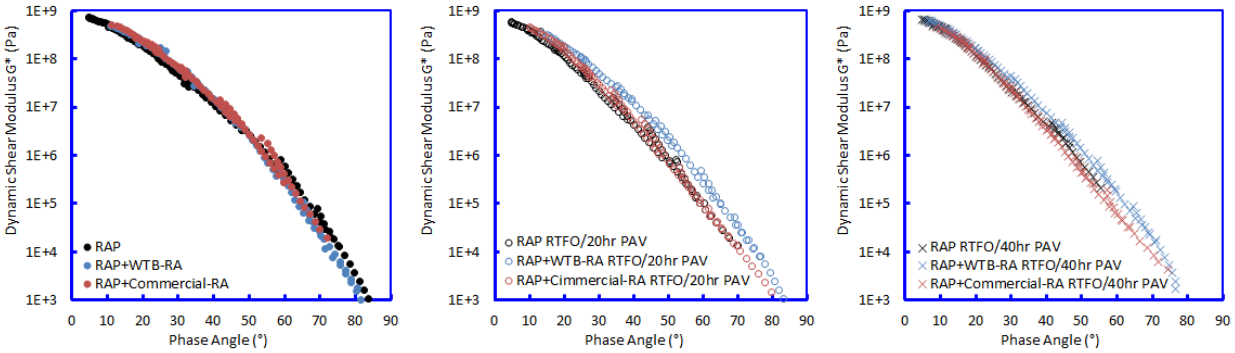

Figure 14. Black Space plots for RAP, RAP + 7.5% WTB-RA, and RAP + 7.5% commercial RA unaged, after RTFO/20hr PAV, and after RTFO/40hr PAV. Data collected using 4 mm DSR with frequency sweeps at isotherms at -30, -15, 0, 15, 30 and 45 °C.

Based on these studies it is shown that the WTB-RA is highly inert, and it continues to retard the embrittlement of asphalt with successive aging compared to a common vegetable oil-based commercial RA.

To date the WTB-RA has been produced from WTBs from the Casper landfill and from a total turbine replacement/upgrade (repower) by Arlington in 2021. Both sources of blades appear to produce a very similar WTB-RA although the Arlington WTB-RA has not been tested in asphalt. More work is needed to understand if the WTB-RA quality will be consistent over additional sources of WTB.

2.Problem Statement (including background statement):

In the US, RAP usage during the 2022 construction season is estimated to have reduced the need for 4.9 million tons (26.9 million barrels) of asphalt binder and more than 93 million tons of aggregate with a total estimated value of more than $4.6 billion (4). The use of RAP in new asphalt mixtures reduced greenhouse gas emissions in 2022 by 2.7 million metric tons of CO_2e, which is equivalent to the annual emissions of more than 600,000 passenger vehicles (4). In the last 5 years, multiple states have practiced greater than 20 percent RAP. The following states have used 25-35 percent RAP: Alabama, Florida, Georgia, Illinois, Maryland, Michigan, Missouri, North Carolina, Ohio, Oregon, South Carolina, Utah, and Virginia (4). Last data available from Wyoming shows 12 percent in 2017 and based on further discussions with WYDOT personnel, 15 percent has been confirmed as the highest dosage rate used in Wyoming. Each 10 percent of RAP incorporated in a new road saves $3/ton and 5.9 percent GHG emissions (10), with savings being larger for polymer modified asphalt. If RAP can be increased by 10%, WYDOT would have cost savings of about $7.5 million on raw material cost per year. Hence, increasing RAP usage would be beneficial to the state of Wyoming. Currently, in the US more RAP recycling is being performed using softer binder (18%) while recycling agents are being used at a lower rate of 7% (4). Having a larger domestic source of effective, long-lasting, and consistent recycling agent would help Wyoming and the US to recycle more RAP.

WTB waste is a major blemish on the renewable wind energy industry. To date there are no large-scale economical products being produced from WTB that eventually do not end up in landfills or as fuel. WRI has developed a process to keep WTB waste out of landfills and from being burned for fuel. This process produces an upcycled oil as a WTB-RA which is then used to recycle RAP. Not only is the WTB-RA eliminating the WTB waste, it helps the asphalt industry to become more circular while also storing CO_2 in the form of biogenic carbon. This biogenic carbon comes from the renewable vegetable oil-based solvent used in the process to remove and modify the epoxy resin molecules in the WTB turning them into the WTB-RA. The process developed by WRI has a dual role in helping Wyoming improve the carbon footprint of two very important industries for our state (wind energy and asphalt), but it also has huge national and global implications. If the technology is proven to be economical it could also lead to a new industry in Wyoming to upcycle blades and ship high-value finished product WTB-RA to other states. WRI is working with And3 Innovations (https://www.and3innovations.com/) who is interested in commercializing the process in Gillette to produce WTB-RA.

The WTB-RA technology has been proven using one source of WTB (Casper landfill) and needs

to be validated with other source of WTB. The process needs some optimization and a techno economic evaluation to ensure that the product can be produced economically. More information is needed from WYDOT to show that it can be competitive at the equivalent dosage rate that WYDOT has been using recycling agents. Additional bench marking is needed to show the effectiveness of the WTB-RA compared to other RAs, especially those used by WYDOT.

3.Objectives:

Overall, this proposal seeks to further demonstrate that the WRI process can produce an effective WTB-RA from different WTB sources, to show that the cost of the RA would be comparable to other commercial RA, and to demonstrate that the performance is as good or better than the WYDOT RA and other RA.

The proposed project has the following specific objectives:

- Evaluate at least three different WTB sources in the WRI process.
- Semi-optimization of the process to develop the techno economic analysis and cost for the WTB-RA. Compare the WTB-RA cost to other commercially available RA and the RA used by WYDOT.
- Verify that the WTB-RA has as good or better performance as the commercial RA used by WYDOT, not only at unaged and 20 hr PAV aging condition but also after extended aging conditions including 40 hr PAV and up to 60 hr PAV in a Wyoming binder.
- Benchmark WTB-RA effectiveness in at least two different Wyoming binders over extended aging conditions to other commercial RAs with at least 30% of RAP.

4.Benefits:

Outcomes from the proposed project will have the following benefits to WYDOT and the state of Wyoming:

- This project will help WYDOT increase the RAP usage in Wyoming up to 30% while using WTB-RA (made right here in Wyoming) and further help gain confidence to build high RAP pavements (upwards of 30% and 40% RAP) in the future. Based on 2022 data, increasing RAP utilization by 10% could save $7.5 million on raw material costs and hence further increasing RAP dosage (30% and higher) would result in significantly larger savings for WYDOT and the state of Wyoming.
- Generate the inputs necessary to convince Wyoming partners (And3 Innovations) to develop a plant in Wyoming to convert WTB into valuable WTB-RA. If successful, this would generate a whole new industry in Wyoming. This will develop a strong Wyoming WTB based industry in Wyoming, create local jobs and help in the economic development of the state. WRI is working with And3 Innovations in Gillette as they are interested in developing and commercializing the WTB-RA process. And3 Innovation has already been contacted by several power companies in Wyoming and the surrounding region to take blades from the various maintenance and repower operations over the next few years.
- A process to help Wyoming eliminate WTB waste in its landfills while producing products useful for WYDOT to increase RAP utilization while generating a new industry for WTB upcycling.
- Storage of CO_2 in Wyoming asphalt due to the biogenic carbon content in the WTB-RA.

- Lower CO_2 impact of paving operations due to higher RAP utilization (5.9% for every 10% RAP utilized).

5.Applicable Questions:

The following questions/aspects mentioned in the "call for papers" document have been answered below:

- Are there any potential barriers to implementation (e.g. material, technology, vendors, legal/regulatory, public perception)? For each potential barrier, identify strategies to mitigate these potential barriers.
    - The main barriers that exist for this project are: 1) is the process universal for various types of WTB; 2) how does the cost compare to other RA; 3) how does the WTB-RA compare after extended aging compared to the WYDOT recycling agent; 4) can the WTB-RA be successfully used to increase RAP utilization up to at least 30%.
    - The strategies to address these barriers are: 1) test the process with various types of WTB, additional blade material has already been obtained from the Casper landfill and from Vestas; 2) Semi optimization of the process to develop the techno economic analysis so that more accurate costs can be estimated; 3) test WTB-RA in Wyoming asphalt and compare to WYDOT RA after aging blends at the same additive concentrations for up to 60 hr PAV; 4) Test WTB-RA with Wyoming RAP at 30% in fresh Wyoming asphalt.
- What is the expected period for implementation?
    - If this study is successful in meeting all its objectives, WRI will work with And3 Innovations to develop a timeline to get a pilot facility built to produce the WTB-RA. This is estimated to take approximately one year after the completion of this study until material becomes available to use for test section. However, during this study it may be determined that additional studies are needed.
- Does the project involve action on Federal lands or other conditions that will require National Environmental Policy Act (NEPA) documentation (e.g. Categorical Exclusion or Environmental Assessment), and/or forest service or other permits?
    - No
- What are the major uncontrollable factors and/or unknowns in the project such as weather, wildlife, material properties, traffic, etc.? For each uncontrollable factor, address whether there could be additional costs or delays.
    - The major unknown is the cost of the WTB-RA. This has been estimated to be $1,500-2,500/ton. If the cost is significantly higher additional optimization of the process may need to be performed to bring the cost down. This could cause a delay with the project while additional optimization is occurring.
- Should the project be segmented into phases with go/no-go decision points based on known unknowns (e.g. technology, partnerships, regulatory)?
    - No
- If the project involves evolution of one or more technologies, is a technology road map provided showing how these technologies fit together?
    - Not applicable
- Will a Buy American Waiver be necessary?

    - No
- Will any data produced by this project be considered confidential or sensitive?
    - The details of the process and the techno economic analysis will be considered confidential. WRI already has a patent pending on the process WO2023287607A1 Asphalt Materials from Wind Turbine Blades and Other Composite Materials with a priority date of July 5, 2022.
- Will the data and/or report from the final project be copyrighted, patented, or trademarked?
    - The data and final report shall be copyrighted by WRI and WYDOT. It is not expected that data from this study will warrant patent protection since WRI already has a patent on the technology.

6.Statement of Work:

The work plan is divided into six tasks. The overall work plan has been presented in Figure 15 followed by detailed description of each task in the paragraph below.

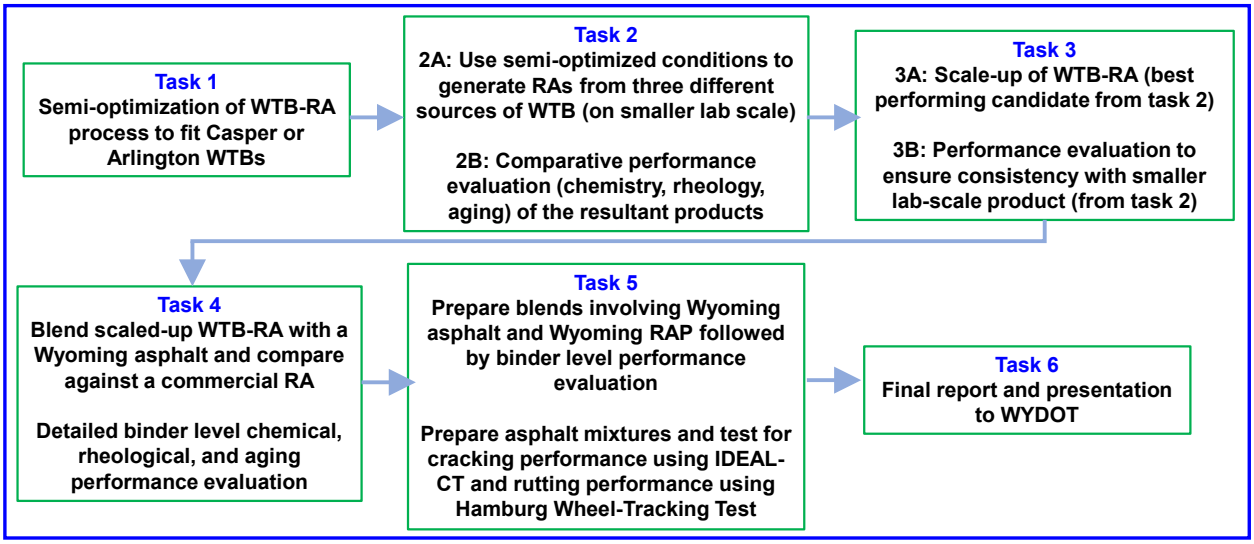

Figure 15. Proposed work plan. This figure provides information about the work plan of the proposed project with overall details of each task

Details of each task:

Task 1. Perform semi-optimization of the process on Casper or Arlington WTBs. This will be performed by varying the temperature, solvent ratio, and residence time of the reaction in a flow through reactor system. Vacuum distillation will be performed to generate the WTB-RA products. Products will be characterized by their viscosity and their glass transition using differential scanning calorimetry (DSC). The distillates will be characterized by gas chromatography mass spectrometry (GCMS) to determine solvent recyclability and any byproducts. The mass balance will be calculated, and solvent consumption (reaction + degradation) determined. Different solvents may be tested if they are believed to produce better or cheaper results.

Task 2. Use semi-optimized conditions to test at least three different sources of WTB to produce

WTB-RA. Mass balance will be calculated, and solvent recyclability and byproducts will be characterized by GCMS. Products from the different WTB sources will be characterized by thermogravimetric analysis (TGA), SAR-AD, size exclusion chromatography (SEC), CHNOS, Fourier transform infrared spectroscopy (FTIR), viscosity, aging stability (RTFO + 20, 40 and 60 hr PAV), and DSC.

Task 3. One source of WTB-RA will be scaled up to produce hundreds of grams of the product. The scaled-up WTB-RA product will be characterized by SAR-AD and DSC to confirm consistency with the smaller batch.

Task 4. The scaled-up WTB-RA product will be blended in one source of a common Wyoming asphalt binder at 7.5 wt% and the blend will be aged by RTFO followed by 20, 40 and 60 hr PAV. A similar blend will be produced using the WYDOT RA and the blend will be aged similarly. The unaged and aged blends will be analyzed by DSR for upper PG and lower PG. Additional rheological analysis will be performed by comparing the Black Space diagrams, calculating ΔTc, Glover-Rowe, cross over temperature, temperature where phase angle is 27, Pavel-Kriz, and other parameters as determined necessary. The unaged and aged blends will also be characterized for the chemical composition using FTIR to monitor carbonyl and sulfoxide groups during aging, and by SAR-AD. The samples before and after aging will also be characterized for the critical cracking temperature (Tcr) using the Asphalt Binder Cracking Device (ABCD). The Tcr and Tc(S) (if measurable) will be used to estimate the ΔTf parameter which is also related to field cracking. This data will be used to compare the long-term stability of the WTB-RA to the WYDOT RA.

Task 5. Blends will be prepared with 2 different sources of a common Wyoming asphalt binder + 7.5% WTB-RA + 30% binder extracted from a Wyoming RAP. A control will be prepared where the WTB-RA is omitted. The blends will be aged by RTFO/60hr PAV. Other similar blends with the 2 sources of asphalt binder will be produced using at least two different commercial RAs and the blends aged by RTFO/60hr PAV. DSR, DSC, and SAR-AD analyses will be performed on the unaged and aged blends and the unaged and aged control consisting of the base binders with 30% RAP. This task will also involve asphalt mixture preparation and cracking performance evaluation using IDEAL-CT and rutting performance using Hamburg Wheel-Tracking Test. Please note that the asphalt mixture preparation and testing will be performed through an experienced third-party asphalt mixture testing laboratory that WRI will internally subcontract to.

Task 6. Generation of final report and presentation of result to WYDOT.

The section below provides a more in-depth description of some of the test methods that will be used in this proposed project.

ΔTc Parameter

ΔTc is determined using the results of AASHTO T313 (bending beam rheometer) determined at multiple low temperatures. From this test, the creep stiffness (S) and creep rate (m) are

determined according to AASHTO M320/M332 limiting values (300 MPa and 0.300, respectively). "Critical temperatures" are thus determined by interpolating between passing and failing temperatures, at the S and m criteria, and are called Tc(S) and Tc(m). The delta Tc parameter (ΔTc) is defined as the difference between Tc(S) and Tc(m)), as shown in Equation 1.

$$\Delta Tc = Tc(S) - Tc(m) \quad \text{(Eq 1)}$$

A low ΔTc parameter, <-5 °C at RTFO/40hr PAV, is generally attributed to problematic and unbalanced colloidal systems in asphalt binders, multiphase modified binders (including PMAs), and sometimes incompatible blends as reported in the literature by several researchers including WRI (9, 10, 11*).*

In terms of testing to obtain Tc(s) and Tc(m), a Dynamic Shear Rheometer (DSR) with 4 mm diameter parallel plates will be used as opposed to a Bending Beam Rheometer (BBR). The 4 mm plate method was developed at Western Research Institute (WRI) as part of a Federal Highway Administration (FHWA) contract (12, 13).

Asphalt Binder Cracking Device (ABCD) test and ΔTf parameter

The Asphalt Binder Cracking Device (ABCD) test was developed as a binder counterpart to the thermal stress restrained specimen test (TSRST) test for mixtures, and the method is prescribed in AASHTO T387. TSRST has long been used to evaluate mixture cracking resistance and non-linear viscoelastic properties such as (E* and δ). Originally, ABCD was compared to BBR and proposed as an alternative approach to determine a binder's low-PG temperature. However, NCHRP 9-60 revisited this original purpose, and reconsidered ABCD as a binder cracking test (14). ABCD consists of binder sample poured in hollow silicon rings designed with a protrusion, and which the assembly is equipped with a strain gauge. During the testing, the binder sample is cooled down in a temperature chamber with a cooling rate of 20°C/h. As the temperature drops, the coefficient of thermal contraction (CTC) differential between asphalt and the confining ring creates increasing thermal stresses in the binder until failure occurs. Failure is defined by crack initiation through the sample cross-section which surrounds the protrusion. The protrusion causes localized stress concentrations which control the location of crack initiation in the binder specimen. The failure temperature is denoted as Tcr.

The NCHRP 09-60 findings consist of a new combined ABCD/BBR parameter called ΔTf (f for failure). ΔTf is defined as the difference between the temperature at which the binder stiffness is 300 MPa (Tc(S) from BBR) and Tcr from ABCD. The ΔTf parameter is defined as the difference between Tc(S) and Tcr, as shown in Equation 2.

$$\Delta Tf = Tc(S) - Tcr \quad \text{(Eq 2)}$$

In the current PG specification, two temperatures are assumed to be critical for binder cracking: Tc(S) (S=300 MPa) and Tc(m) (m=0.3). However, by comparing to field data, ΔTf appears to more accurately predict field cracking than Tc(S), Tc(m) or ΔTc for modified binders by comparing the Tc(S) to the actual cracking temperature at a given cooling rate. From this comparison a positive ΔTf means that the binder actually cracks under ABCD conditions at a temperature below the temperature corresponding to 300 MPa (Tc(S)), and vice-versa.

ΔTc and ΔTf represent two very different cracking properties and thus complement each other. ΔTc captures relaxation but fails to differentiate failure strength. ΔTf, ranks failure properties in line with effective polymer modification, but fails to pick up binders with problematic relaxation characteristics and generally low compatibility. Research outcomes from NCHRP 9-60 (14, 15) project has exhibited the efficacy of these parameters to assess cracking and embrittlement potential of asphalt binders in general, but PMAs in particular, which will be extremely significant for this proposed project given the extensive use of PMAs in the state of Wyoming.

Chemical Composition of Binders (SARA fractions) Using SAR-AD™

The saturates, aromatics, resins and asphaltene fractions (and relevant subfractions) are determined by SAR-AD. SAR-AD is a patented method developed by WRI which uses a high-performance liquid chromatography (HPLC) system to separate saturates, aromatics and resin fractions (SAR) coupled with the Asphaltene Determinator (AD) solubility separation (16-19). SAR-AD separates the asphalt binder into eight fractions (including subfractions): saturates, aromatics 1, aromatics 2, aromatics 3, resins, cyclohexane-soluble asphaltenes, toluene-soluble asphaltenes, and methylene chloride-soluble asphaltenes. Aromatics 1, aromatics 2, and aromatics 3 are subfractions of aromatics with respect to aromatic ring size, with aromatics 1 having one isolated aromatic ring (it is the least aromatic and polar of the aromatics fraction) and aromatics 3 having the largest fused aromatic ring structure of the aromatics with 5 or more rings (these molecules are the most aromatic and polar subfraction within the "aromatics" fraction). Aromatics 2 contains molecules with 2-4 fused rings. Resins are similar to the aromatics except that they contain polar functional groups of nitrogen, sulfur and oxygen. Cyclohexane-soluble asphaltenes, toluene-soluble asphaltenes, and methylene chloride-soluble asphaltenes represent asphaltenes of increasing polarity or aromaticity (or decreased solubility). These subfractions are extremely important to understand internal asphalt binder stability (how well dispersed/dissolved are the asphaltenes), potential for cracking with aging, crude oil origin, refining practices (which can impact the relaxation properties and aging), and it has been shown how effective these are to understand the performance of PMAs (14, 15, 20, 21), which will be of paramount importance to this proposed project.

Fourier Transform Infrared Spectroscopy (FTIR)

FTIR is used to determine various chemical functional groups. In particular it is useful to evaluate oxidation of asphalt binders. Carbonyl and Sulfoxide groups are quantified after long-term aging relative to the unaged binder, and the difference is calculated and reported as the 'FTIR aging index'. In the asphalt community, the magnitude of the aging index is known to have correlations with field cracking tendencies. FTIR is also used to characterize the presence, concentration, and sometimes type of polymer, particularly in the case of SBS.

Size Exclusion Chromatography (SEC)

SEC measures the hydrodynamic radius of molecules, which is related to the apparent molecular weight. The apparent molecular weight can represent molecules held together through self-association, as is often the case for asphaltenes. Previous work by WRI has shown the importance of SEC in characterizing PMAs with a unique capability to link the SEC outcomes to asphalt performance, especially for problematic PMAs.

Indirect Tensile Asphalt Cracking Test (IDEAL-CT)
The IDEAL-CT test is similar to the traditional indirect tensile strength test. The test applies a vertical monotonic load on a cylinder specimen at a constant rate of 50 mm/min. The test is stopped when the load is reduced to 0.1kN. During the test, the cross-head displacement is continuously monitored and recorded. Data analysis is conducted based on the load versus displacement curve. The test outcome/parameter CT Index is calculated as a function of total fracture energy and the slope of the post-peak curve at 25 percent reduction from the peak load. CT Index measures the propensity of the asphalt mixture to cracking and is a test method gaining importance in the upcoming balanced mix design (BMD) methodology.

Hamburg Wheel-Tracking Test (HWTT)
The Hamburg Wheel Tracking Test (HWTT) per AASHTO T 324 is widely used by asphalt researchers and pavement engineers to evaluate the rutting resistance and moisture susceptibility of asphalt mixtures. The test can be performed either on asphalt mixture cylinder or slab specimens. The specimens are loaded for a maximum of 20,000 wheel passes or until the specimens deforms by a pre-determined rut depth (typically 12.5mm). Typical result curves consist of post compaction phase, creep phase, and stripping phase. This is an extremely popular rutting characterization test used by road agencies throughout the US and especially by WYDOT.

Project timeline:
The team expects the project to be completed in 12 months. A proposed timeline for the tasks is presented in Table 1. The start of the project is assumed to be January 2025 and is reflected accordingly in the proposed timeline.

Table 1. Estimated timeline for the proposed tasks. The table shows 6 tasks and the proposed monthly timeline of start and end of each task.

Task	Task Description	Project Month											
		1	2	3	4	5	6	7	8	9	10	11	12
1	Semi-optimization of WTB-RA process												
2	Validation with other WTB sources												
3	WTB-RA scale up												
4	WTB-RA compared to WYDOT RA in WY asphalt under extended aging												
5	WTB-RA + 30% RAP comparison to commercial RA												
6	Final report												

7.Budget:

The proposed total budget for the entire project is **$294,284.80** with details presented in Table 2. The indirect cost rates for fringe benefits, overhead, and G&A that have been used in this proposal are per the approved rates from National Energy technology Laboratory (NETL), which is a cognizant agency. A letter to WRI from NETL (cognizant agency) approving these rates has

been provided as an attachment to this proposal document. Furthermore, a letter from the WRI Controller confirming the same has also been provided as an attachment.

Table 2. Estimated budget for the proposed 12-month project. The table presents the breakdown of all the costs including direct cost, technical transfer, indirect costs, etc.

Description	WRI Budgeted Amount
Direct Cost	
Total Personnel Costs	$ 98,554.55
Principal Investigator	$ 19,616.76
Other Personnel	$ 78,937.79
Fringe Benefits	$ 56,639.30 (WRI fringe benefits: 57.47%)
Research Travel	$ -
Report Generation	$ -
Supplies	$ 10,000.00
Other	$ -
Technical Transfer	
Conferences/ Report/presentation	$ 10,000.00 PI and Co-PI presenting at two regional and/or national conferences from the following list: 1. Transportation Research Board (TRB) Annual Meeting , 2. Rocky Mountain Asphalt User Producer Group (RMAUPG) meeting, 3. Association of Asphalt Paving Technologists (AAPT) Annual Meeting, 4. State Asphalt Pavement Conferences, 5. Association Of Modified Asphalt Producers (AMAP) Annual Meeting
Miscellaneous Travel	$ -
Indirect Costs	
Project Administration	$ -
Overhead	$ 91,764.14 (WRI overhead 93.11% on total personnel cost $98,554.55)
Indirect Costs	$ 27,326.82 (WRI G&A: 23.05%)
In-Kind Match	$ -
TOTAL	$ 294,284.80

8.Implementation:

- This project will help WYDOT increase the RAP usage in Wyoming from 15 percent to upwards of 30 percent while using alternative, upcycled WTB-RA made right here in Wyoming. Having said that, it should be noted that although this study will yield asphalt binder and mixture performance test results based on WYDOT materials, it will need field validation. Hence, it is recommended that an additional phase of field validation would be required to give WYDOT confidence in the implementation of this technology. Furthermore, to help in the implementation process, WRI will be performing seminars for

WYDOT engineers once the study is completed, and during any additional phases needed for field validation.

- Techno economic analysis data on process to produce WTB-RA, and the study on different WTB sources, will provide necessary information for commercial viability. If the process is commercially viable, WRI will work with their Wyoming partner And3 Innovation to begin pilot plant designs to prepare for scale up. Additional optimization of the process and further validation at the pilot plant level will require more development. If this development goes smoothly then it is expected that in 1-2 years after this study that WTB-RA can begin to be produced from Wyoming WTB and made available on the market. This will develop a strong Wyoming WTB based industry in Wyoming, create local jobs and help in the economic development of the state. And3 Innovation has already been contacted by several power companies in Wyoming and the surrounding region to take blades from the various maintenance and repower operations over the next few years.

9.Technology Transfer:

Dissemination and effective transfer of technology and research outcomes are important, not only to benefit all the stakeholders for effective implementation and deployment, but also for future development. It should be noted that the primary outcomes of this study are to benefit WYDOT. A secondary aspect of this study would be to achieve a broader national and international validation and dissemination to the scientific community.

As part of this project, the following avenues will be employed to disseminate the research outcomes:

- Seminar or workshop for WYDOT personnel (primary): The primary focus for technology transfer will be communication with WYDOT for implementation. The project team would like to put together a seminar/workshop/webinar so as to disseminate and present the project outcomes specifically for WYDOT personnel.
- Peer reviewed journals and/or conference proceedings (secondary): This will include publication(s) in reputed peer reviewed journals papers in the field of pavement engineering such as Transportation Research Record (TRR), American Society of Civil Engineers Journal of Materials in Civil Engineering (from ASCE), International Journal of Pavement Engineering, etc. and/or conference proceedings as applicable.
- Conference presentations (secondary): This will include presenting at important conferences (within the United States) such as Transportation Research Board (TRB), Association of Asphalt Paving Technologists (AAPT), Rocky Mountain Asphalt User Producer Group (RMAUPG), Petersen Asphalt Research Conference, etc.

10.Data Management Plan:

The PI and the project team will provide/transfer all the front-end, as well as background data generated as part of this project to WYDOT to ensure the highest level of transparency for implementation. The following questions/aspects mentioned in the “call for papers” document have been answered below:

- Which data and/or datasets shall be linked to the final report: The foreground data that corresponds to deliverables will be provided in the report as tables, figures and such other methods. The background data will be provided either as much as

possible within the appendix of the final report (based on the size of the data) while the remaining portion of it will be submitted in an electronic format (flash drive) for WYDOT to archive/store/refer/transfer.

- Where the data and/or datasets shall be archived: Data and/or datasets, both raw and finished, shall be archived on portable flash drive (i.e., thumb drive); total quantity estimated to be less than 1 gigabyte per the PI.
- The retention period for archived data and/or datasets: Retention period shall be three (3) years.
- What file format will be used to archive the data and/or datasets: The data will be provided in the formats readable by Microsoft office applications (MS word, MS Excel, MS PowerPoint, etc.) for smoother storage and distribution.
- How the data and/or datasets shall be labeled: PI and the project team will label the data set as it pertains to various sections of the report so that it can be referred with convenience. Having mentioned that, the PI will work with the WYDOT project manager to ensure that all the data labeling is per WYDOT rules and requirements.
- How the data and/or datasets will be cataloged: PI and the project team will catalogue the data set as it pertains to various sections of the report so that it can be referred with convenience. Special care will be taken especially if and when any existing WYDOT data (from earlier projects) will be utilized in the project and the cataloguing process shall be such that it will help synchronize the old and new data together.
- What metadata shall be attached to the data and/or datasets: This information is provided per the "Data Management Plan and Metadata Schema Template" and is being submitted as an attachment to this proposal
- What written consents, licenses, or other tools will need to be attached to the data and/or datasets to ensure privacy and intellectual property: The PI doesn't anticipate need of working with any proprietary data in this project, and hence doesn't foresee the need for written consents, licenses or any tools.
- The procedure for accessing the data and/or datasets at the end of the project: A letter will be provided by the PI, which can act as a key or a guide on how to smoothly access and navigate through the dataset. This letter will have all the related information and any special procedure (if need be, based on the type and format of the dataset)

11.References:

1. Epps-Martin, A. et.al., NCHRP Research Report 927. (2020) Evaluating the Effects of Recycling Agents on Asphalt Mixtures with High RAS and RAP Binder Ratios. Washington, DC: The National Academies Press. https://doi.org/10.17226/25749
2. Carvalho, R., Shirazi, H., Ayres, M., and Selezneva, O. (2011) Performance of Recycled Hot-Mix Asphalt Overlays in Rehabilitation of Flexible Pavements Transportation Research Record, no. 2155, pp. 55-62. DOI: 10.3141/2155-06
3. Reclaimed Asphalt Pavement in Asphalt Mixtures: State of the Practice, Federal Highway Administration (2011), Report No. FHWA-HRT-11-021
4. NAPA, (2024) Asphalt Pavement Industry Survey on Recycled Materials and Warm-Mix Asphalt Usage 2022, Information Series 138
5. https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=5146

6. https://windexchange.energy.gov/states/wy
7. https://wyoleg.gov/Legislation/2020/HB0217
8. https://wyoleg.gov/Legislation/2020/HB0129
9. Elwardany, M. D., Planche, J-P., and King, G., (2020) Universal and Practical Approach to Evaluate Asphalt Binder Resistance to Thermally-Induced Surface Damage. Construction and Building Materials, Vol. 255, 2020, p. 119331.
10. Robertson, R. E., J. F. Branthaver, P. M. Harnsberger, J. C. Petersen, S. M. Dorrence, J. F. McKay, T. F. Turner, A. T. Pauli, S.-C. Huang, J.-D. Huh, J. E. Tauer, K. P. Thomas, D. A. Netzel, F. P. Miknis, T. Williams, J. J. Duvall, F. A. Barbour, and C. Wright. (2001). Fundamental properties of asphalts and modified asphalts, volume I: Interpretive report. No. FHWA-RD-99-212
11. Christensen, D., D. Mensching, G. Rowe, R. M. Anderson, A. Hanz, G. Reinke, and D. Anderson. (2019). *Past, Present, and Future of Asphalt Binder Rheological Parameters*: Synopsis of 2017 Technical Session 307 at the 96th Annual Meeting of the Transportation Research Board. Transportation Research Circular, (E-C241), Transportation Research Board, Washington, D. C.
12. Farrar, M., Sui, C., Salmans, S., Qin, Q. (2015) Determining the Low Temperature Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR); Western Research Institute: Laramie, WY, Technical White Paper FP08.
13. FHWA Tech brief (2017). Four-mm Dynamic Shear Rheometry, FHWA, U.S. Department of Transportation: Washington, D.C., publication no. FHWA-HRT-15-053.
14. Kumbargeri, Y., Planche, J-P., Adams, J.A., Elwardany, M.D., and King, G., (2023) Effect of Binder Chemistry and Related Properties on the Low-Temperature Performance Parameters of Asphalt Binders. Transportation Research Record. DOI: 10.1177/03611981231155173
15. Elwardany, M. D., Planche, J-P., and King, G., (2020) Universal and Practical Approach to Evaluate Asphalt Binder Resistance to Thermally-Induced Surface Damage. Construction and Building Materials, Vol. 255, 2020, p. 119331.
16. Adams, J.A., Elwardany, M.D., Planche, J-P., Boysen R.B., and Rovani, J., (2019) Diagnostic Techniques for Various Asphalt Refining and Modification Methods, Energy &Fuels, 33, 2680−2698, DOI: 10.1021/acs.energyfuels.8b03738
17. Boysen, R. B., Schabron, J. F. (2013) The Automated Asphaltene Determinator Coupled with Saturates, Aromatics, Resins Separation for Petroleum Residua Characterization. Energy & Fuels, vol 27, pp. 4654−4661.
18. Adams, J. J., Schabron, J. F., Boysen R, (2015). Quantitative Vacuum Distillation of Crude Oils to Give Residues Amenable to the Asphaltene Determinator Coupled with Saturates, Aromatics, and Resins Separation Characterization. Energy & Fuels, vol 29, pp. 2774−2784.
19. FHWA Tech brief (2016). Automated High-Performance Liquid Chromatography Saturate, Aromatic, Resin, and Asphaltene Separation, FHWA, U.S. Department of Transportation: Washington, D.C., publication no. FHWA-HRT-15-055.
20. Kumbargeri, Y., Planche, J-P., Adams, J.A., Rovani, J., and Elwardany, M.D., (2024) Comprehensive Selection of Base Asphalt Binders for Effective Formulation of Polymer-Modified Asphalts. Transportation Research Record. DOI: 10.1177/03611981231217271
21. Adams, J.A., Elwardany, M.D., Planche, J-P., Boysen R.B., and Rovani, J., (2019) Diagnostic Techniques for Various Asphalt Refining and Modification Methods, Energy

&Fuels, 33, 2680−2698, DOI: 10.1021/acs.energyfuels.8b03738