ANALYZING THE EFFECTS OF REJUVENATORS IN BALANCED MIX DESIGN WITH HIGH PERCENTAGES OF RECYCLED ASPHALT PAVEMENT

by

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ABSTRACT

Interest in sustainable practices have increased in several industries, including civil engineering pavement materials. The incorporation of Recycled Asphalt Pavement (RAP) into new pavement mix design is a popular method of application for sustainable practice and is accompanied by numerous economic and environmental benefits. There is significant interest in using large amounts of this RAP material in pavement design to maximize the benefits, but several problems arise when utilizing "high" amounts of this material (more than 25% RAP replacement) due to aged and oxidized binder that negatively impacts the properties. The use of rejuvenators (RAs) and Balanced Mix Design (BMD) are some solutions that are used to minimize negative impact on overall mix properties. RAs are added to high RAP-inclusive mixes to revitalize the RAP binder properties to allow for the best mix characteristics. BMD has quickly gained traction and popularity over the Superpave mix design method, as BMD considers the interaction effects of recycled materials and additives while also balancing performance testing results and designing pavement to a specific area condition. The application of sustainable practices such as high RAP mix design must result in a pavement that fulfills its purpose, and service life, and does not suffer from premature failure in the field for it to be worthwhile. Continuous research in this area of interest is crucial for the future of pavement materials.

This research project aims to provide a methodical approach to high RAP mix design that can be applied to pavement design for future works. It also works to evaluate the performance of two RAs in RAP mixes at 25%, 50%, and 70% RAP replacement. The performance tests assess the rutting and cracking resistance with the goal of balancing these two so both perform adequately well. Additionally, two different RA doses are compared for RA1 (bio-based). A simple cost savings analysis is reviewed for the mix options per ton. Finally, a brief exploration of the chemical analysis comparison for different binder blends provides some insight into the different performance test results. The results of this research indicate a successful process of high RAP mix design and promising savings for the use of RAP in HMA mix design. The bio-based RA (RA1) performed the best overall of the two RAs, and the dose selection contrast of results reinforces that the initial method of RA dose selection is promising.

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ANOVA	Analysis of Variance
ASTM	American Society for Testing and Materials
BBR	Bending Beam Rheometer
BMD	Balanced Mix Design
CA	Coarse Aggregate
DOT	Department of Transportation
DSR	Dynamic Shear Rheometer
FA	Fine Aggregate
FHWA	Federal Highway Administration
FTIR	Fourier Transform Infrared
High RAP	Mixes with ≥ 25% RAP replacement
HMA	Hot Mix Asphalt
HWTT	Hamburg Wheel Tracking Test
IAS	Idaho Asphalt Supply Inc.
IDEAL-CT	Indirect Tensile Asphalt Cracking Test
ITD	Idaho Transportation Department
NAPA	National Asphalt Pavement Association
NCHRP	National Cooperative Highway Research Program
OBC	Optimum Binder Content

PG	Performance Grade
RA	Rejuvenator / Recycling Agent
RAP	Recycled Asphalt Pavement
SuperPave	Superior Performing Asphalt Pavements

CHAPTER 1: INTRODUCTION

Sustainability has generated a lot of interest and has a lot of great benefits in pavement material design applications, specifically the use of Recycled Asphalt Pavement (RAP), which would otherwise be considered a waste product and discarded. Despite the challenges of high RAP mix design application, the research thus far has a strong base of promising future incorporation to work successfully in balancing performance, cost, and environmental considerations. The overall goal of this area of research is to work out the problems associated with replacing high levels of RAP with virgin material in the Hot Mix Asphalt (HMA) design, specifically, with performance testing and field application results. Previous method such as Superpave use only volumetric verification, but performance capabilities often fall short, especially when incorporating high levels of RAP material and other additives. Some problems associated with this process are an incomplete blending of RAP binder with overall mix binder, negatively impacting cracking resistance with mixes that are not optimally rejuvenated, and negative rutting resistance if the mix is over-rejuvenated. Thus, the concept of balancing the asphalt mix properties to result in optimal performance, blending properties, and chemical consistency is an important goal.

1.1 Background

There are many methods of mix design for hot mix asphalt (HMA) pavement that are constantly being improved upon. The consideration and application of the Balanced Mix Design (BMD) method have grown in popularity in recent years due to its increased effectiveness, optimal selection of mix design characteristics, and increased assurance that pavement performance will act as intended. Compared to previous methods, such as Superpave or Marshall mix design, BMD incorporates performance testing often in the form of rutting and cracking resistance. A full-scaled BMD process would entail first determining the optimum asphalt content (OAC) then increasing and decreasing by some amount (±0.5% for example) and conducting testing to determine the best selection of asphalt or rejuvenator dosage to maximize the enhancement of the mix performance. It has been shown that when performed correctly, BMD can result in higher performance, longer service life, and cost savings (Meroni et al., 2020). To analyze the rutting resistance many DOTs, including the Idaho Transportation Department, use the Hamburg Wheel Tracking Test (HWTT), as it is consistent, easy to use, and repeatable in comparison to the other rutting resistance procedures (Walubita et al., 2019). The Indirect Tensile Cracking Test (IDEAL-CT) has grown in popularity for quantifying cracking resistance due to its low cost, easy sample preparation, and relatively low variability. However, this equipment and procedure still have some uncertainty and problems associated with it but suitable to incorporate into specifications for performance testing (Zhou et al., 2017).

Recycled Asphalt Pavement (RAP) is the byproduct of removing and milling an existing surface pavement structure. Given that surface pavement is comprised of aggregate and asphalt binder, both components can be reused and take place of some percentage of virgin material in a new mix. This allows for numerous economic and environmental benefits due to the reduction of mining, manufacturing, and buying virgin material (Williams & J. Richard Willis, 2022). ‘High’ RAP specifically refers to incorporating more than 25% RAP replacement in an HMA mix, which often requires special design and the use of a blending chart (*Asphalt Pavement Recycling with Reclaimed*

Asphalt Pavement (RAP) - Recycling - Sustainability - Pavements - Federal Highway Administration, 2022). However, there are some challenges associated with the use of high RAP aggregate including variability associated with RAP sourcing, control of gradation, available RAP binder properties, and the degree of blending that occurs between the RAP binder and overall mix binder (Kaseer et al., 2019; Sharma et al., 2021; Zhang et al., 2021). As a result of a mix that has not been adequately designed to accommodate these considerations, the cracking resistance is likely to be negatively impacted due to the increased stiffness resulting from large amounts of RAP replacement (Sharma et al., 2021). It is also often assumed that 100% of the available RAP is utilized in the overall mix, however, research indicates that this degree of blending is really less than 100% (Kaseer et al., 2019).

The application of rejuvenators (RAs) has been shown to improve the mix properties and performance results by revitalizing and softening the RAP binder to allow for better mixing in the combined mix (Abdelaziz et al., 2021; Mohammadafzali et al., 2019; Yin et al., n.d.). RAs are developed from different waste or engineered products such as plant/bio-oils, waste oils (often from petroleum processes), and engineered products (Sharma et al., 2021).

The concept of BMD, high RAP implementation, and the use of rejuvenators to create a balanced mix result in a need for a consistent method of mix design to account for the uncertainty in each of these areas. It is clear why the industry is gravitating towards the application of BMD and high RAP mix design to accommodate new challenges as sustainability becomes an increasingly influential topic. The use of BMD and RAs to improve the performance of high RAP mixes has promising research results thus far and is a worthwhile topic to further develop.

1.2 Problem Statement

The research described in this thesis document intends to conduct experimental laboratory analysis to further investigate the successful incorporation of high levels of RAP material into new pavement mix designs with the assistance of rejuvenators. The successful implementation of this process along with a BMD approach will revolutionize the pavement industry. Reusing large amounts of recycled material in this way has various benefits including significant monetary savings and a reduction in carbon emissions from minimizing the virgin material procured; a process that is expensive, labor-intensive, and contributes to diminishing natural resources. The influence of sustainability in infrastructure is a crucial motivation for this area of research and this project.

The primary difficulty of this process is the current lack of standard mix design practice to account for the influences of variable RAP properties, interaction effects, and overall mix performance. This research seeks to further explore this area of pavement research and investigate the realistic application of high RAP replacement mixes. A key goal outcome is the development of a standard process and method of mix design that can be applied to various circumstances. During the initial process of investigating the existing research in this area of exploration it became very clear that despite substantial progress, there is still a substantial amount of work to be done for high RAP-inclusive mixes and RAs. The potential benefits are significant enough to continue further refining the current practice to allow these innovative methods to morph into standard practice. The Idaho Department of Transportation supported the development of this project. Thus, the design and outcome of this thesis work aimed to develop an applicable method for an Idaho specific pavement design.

1.3 Thesis Summary

This research project is comprised of summaries that outline the existing research and results, the comparison of two RAs with one RA at two different doses, and an analysis of RAP binder and RA effects on overall mix performance. The mix design specifications were conducted with Idaho pavement application in mind, so the current ITD specs for highway pavement construction were met. This research was highly experimental with lots of mixing, blending, compacting, and testing in a control laboratory setting, so it is expected that real field application of these mixes would produce varying results.

The primary objective of this research is to evaluate the effect of rejuvenators in improving the performance of asphalt mixtures with high RAP contents. The tasks that were achieved to meet this goal are as follows.

1. Quantify the success of the rejuvenator's performance while considering the RA type and dosage.
2. Evaluate the RA performance by analyzing the rheological properties of the binder blends, chemical analysis on the binder blends (via FTIR), and performance testing on the HMA mixes with RAP and RAs.
3. Apply the Balanced Mix Design (BMD) concept to develop a standard process of high RAP mix design to optimize mix performance.
4. Study the potential economic savings that result from using rejuvenators and high RAP.

5. Compare current practice for 25% RAP replacement to potential alternatives in terms of performance and cost.

The research described in this thesis aims to satisfy each of the research objectives and contribute findings to the pavement research and construction industry.

The thesis work is organized as follows. Chapter 2 describes manuscript 1 which is a paper that is intended to be submitted to the ASCE Journal of Performance Constructed Facilities. This paper lays out the groundwork of the research motivation and developed a consistent method of high RAP mix design that can be applied to different design specifications. This method lays out a strong base for moving forward with high RAP mix design as it minimizes the impact of influential variables such as gradation and asphalt content. Mitigating problematic areas of influence that can be controlled in the mix allows for optimal design on the binder contributions, which is a more challenging area to control. Chapter 2 focuses on the gaps in research that are currently a problem. The proposed method of high RAP mix design is described as a big idea, then is followed by this process being applied to an Idaho mix design method, but with no rejuvenators incorporated. The purpose of this is to outline the general trends and challenges that accompany high RAP inclusive mixes. This paper also lays out the general approach and initial considerations on how to manage RAP material to mitigate the influence on the overall mix performance.

Chapter 3 contains manuscript 2 which is a journal paper that will be submitted to the International Journal of Pavement Engineering. This paper continues with the next steps following the process described in manuscript 1. This manuscript 2 paper aims to show how the addition of RAs improves the performance of these RAP-inclusive mixes. Two RA types are compared and analyzed throughout this study; RA1 is bio-based and RA2 is a petroleum waste oil. The RA dosages were selected based on the original high-temperature rheological properties of the binder blends that match the target/virgin binder which resulted in RA1 being dosed at 8.3% and RA2 being dosed at 11.3% (by weight of RAP binder). Additionally, a second RA1 dose was selected by using the RA dose that met the minimum requirement of the original low-temperature m-value which results in a second RA1 dose at 6.6% (by weight of RAP binder). This manuscript went one step further to incorporate the chemical analysis to correlate to the performance testing results to attempt to identify trends between the rheological properties, chemical profile, and performance results of the different binder blend options. Finally, a brief cost-benefit analysis is considered to further elaborate on the benefits and challenges of implementing a high RAP mix option into practice.

Chapter 4 summarizes the outcomes of the research work conducted and includes potential options for future research to continue developing because of these efforts.

CHAPTER 2: dEVELOPMENT OF cONSISTENT gRADATION (CONSI-GRAD) FOR HIGH RAP MIX DESIGN STANDARD PRACTICE

The following manuscript was written by Amanda Mullins. The manuscript begins on the next page and will be submitted to the ASCE Journal of Performance Constructed Facilities.

2.1 Abstract

Sustainable solutions and alternatives have increased in popularity in all aspects of civil engineering, including asphalt pavement materials. The use of Recycled Asphalt Pavement (RAP) in new pavement mix design has gained significant traction in recent years due to environmental and economic benefits that have high potential when using recycled materials to replace virgin materials. However, problems arise in RAP replacement when more than 25% RAP replacement occurs ("high" RAP). The application of a Balanced Mix Design (BMD) approach can aid high RAP mix design to appropriately prepare this pavement design. The common application of BMD can often lead to a level of uncertainty due to variations of gradation, asphalt content, and resulting volumetrics. Current practice lacks a consistent method of incorporating high RAP in mix design to optimally perform well for state or federal standards. In this research, the Consi-Grad method of high RAP mix design is proposed and outlined. The Consi-Grad method considers a combination of Superpave and BMD to develop a mix design for high levels of RAP replacement that meet volumetric requirements and have adequate performance testing results. In this study, a virgin/control mix was designed with 0% RAP. The resulting gradation and asphalt content are kept consistent throughout the RAP-inclusive mixes to ensure no discrepancies occur due to these two variables. The outlined method includes a research project that utilizes this procedure to develop optimal mix design parameters for 0% (control/virgin), 25%, 50%, and 70% RAP replacement mixes. IDEAL-CT and HWTT are utilized to evaluate the cracking and rutting resistance respectively. The results indicate a promising starting point for this method.

2.2 Introduction

Reclaimed Asphalt Pavement (RAP) is the byproduct of crushed asphalt pavements from existing roadway surfaces. RAP is mainly aggregate and aged asphalt binder that has been oxidized over the span of the pavement service life. Both materials contribute to new pavement mix designs. The Federal Highway Administration (FHWA) encourages the use of recycled materials in modern pavement mix design given the design is cost-effective, environmentally conscious, and performs well (*Asphalt Pavement Recycling with Reclaimed Asphalt Pavement (RAP) - Recycling - Sustainability - Pavements - Federal Highway Administration*, 2022). Standard practice considers mixes with less than 15% RAP replacement do not require the use of a blending chart to blend back the stiff binder to the target PG grade. If the RAP replacement is between 15%-25%, it's suggested to use a virgin PG binder grade lower than the target grade. When the RAP replacement is more than 25% RAP, it is considered a "high" RAP mix which necessitates the use of a blending chart to correctly design the asphalt mix (Sharma et al., 2021).

There is a great deal of economic and environmental benefits that can result from incorporating RAP material into new pavement mix design (Williams & J. Richard Willis, 2022). Increasing the use of recycled materials allows for raw materials and resources to be preserved. The 2020 National Asphalt Pavement Association (NAPA) industry survey report estimated that 87 million tons of RAP material were used in new asphalt construction. This resulted in a reduction in the amount of virgin asphalt binder and aggregate by 4.4 million mix tons equating to an estimated 24 million barrels and 82 million tons, respectively. The incorporation of RAP material decreased greenhouse gas emissions by 2.3 million metric tons of CO2 and saved roughly 58.4 million cubic yards of landfill space (Williams & J. Richard Willis, 2022). In addition to the environmental savings, there are also many economic savings associated with RAP usage. By reducing the need for raw materials, overall mix design costs are lowered which allows for projects with limited budgets to achieve more maintenance and construction. In the same 2020 NAPA report, the reduced virgin binder and aggregate resulted in an estimated $2.9 billion saved from material costs. By saving the RAP material from being discharged into landfill space, approximately $5.1 billion in gate fees for disposal were saved (Williams & J. Richard Willis, 2022).

While there are numerous benefits to implementing a high RAP pavement mix design, this process is accompanied by several challenges. Developing a high RAP mix design is a more involved process that takes longer than a virgin mix design due to the uncertainty associated with RAP sourcing, consistency, and properties. RAP binder availability is assumed to be one of the following; 100% available, partially available, or 0% available (acts as “black rock” in the mix). Note that availability refers to the aged asphalt binder surrounding the aggregate in RAP that can contribute to the overall asphalt content in the mix (Kaseer et al., 2019; Mohammadafzali et al., 2019; Zhang et al., 2021). Many highway agencies in the past and to this day develop RAP-inclusive mix designs on the assumption that RAP binder availability is 100%. However, making this assumption can lead to overly “dry” mixes that have less asphalt content than the optimum target amount. Consequently, aged RAP asphalt mixes demonstrate worse performance, e.g., flow, adhesion, and cohesion, than virgin asphalt mixes. For example, if 100% availability is assumed, but realistically there is only 65% RAP binder being actively contributed to the overall asphalt content in the whole mix, then the actual asphalt content in the mix will be lower than the optimum design asphalt content (%). This can ultimately result in premature failure in the field (Kaseer et al., 2019).

Superpave is a widely used method of asphalt mix design that is primarily based on volumetric validation and proportioning. However, as the industry moves towards sustainable practices and increases the amount of recycled materials, Superpave often fails to account for interactions of recycled materials. Successful incorporation of recycled materials requires sufficient asphalt to meet volumetric design criteria and performance testing criteria. Owing to the variability of RAP in both asphalt content and lack of fractionation, the incorporation of RAP continues to be evaluated in high RAP mix performance. Since Superpave primarily uses volumetric properties verification as an indicator of a good performing mix, these specific interactions and performance evaluations are often overlooked. In recent years, the asphalt pavement industry has gravitated towards the concept of Balanced Mix Design (BMD), which is an improved method over the current Superpave process (Meroni et al., 2020; West & Taylor, 2019). The goal of utilizing a BMD approach is to design a mix that performs well by balancing rutting and cracking distresses in the mix. BMD accomplishes this through performance testing, specifically cracking and rutting resistance tests, to ensure the mix is successful and balanced. A secondary goal of BMD is to utilize testing criteria that are simple, affordable, and accurate enough to indicate good performance instead of relying on volumetric properties as indicators of good mix characteristics (West & Taylor, 2019).

Increasing the amount of RAP material often leads to mixes that are significantly more stiff, brittle, and vulnerable to cracking, raveling, and other distress. This is the result of the aged and oxidized RAP binder that is contributed to the mix (Mohammadafzali et al., 2019; Yin et al., n.d.). While there is significant research that has been conducted on methods of approaching RAP inclusive mix design, there is a need for a standard practice method. A standard approach that considers material variability, the influence of different mix components, high RAP mix performance thresholds, and the general uncertainty surrounding this area of sustainable asphalt solutions would be a methodical process that can be continuously refined and is repeatable; this is the purpose of this proposed procedure. The variability of RAP properties such as gradation, true grade, and available asphalt content have a significant impact on RAP replacement mix properties, and this impact is significantly harder to control as the RAP percentage increases to 'high RAP' amounts. The motivation for this research is to provide a simple method for mitigating the variability effect from these mix properties by eliminating variation from gradation and overall asphalt content in a high RAP mix design. This process combines the mix design methods of Superpave and BMD to bridge the gap between these two methodologies.

The goal of this paper is to outline a standard practice mix design that systematically combines the successful prospects of previously proposed research practices in this area of interest to provide the asphalt pavement community with a consistent method to reference for high-RAP mix design. The Experimental Procedure section will lay out the materials and methods used; including the project parameters and mix design characteristics for an Idaho pavement project design. The Results section will visually depict and compare the performance outcome for each mix and use ANOVA analysis to evaluate the statistical significance of the RAP mixes. Finally, the Conclusion section will summarize the findings and key highlights of the presented research.

2.3 Methods

Superpave (Superior Performing Asphalt Pavement) mix design has been the standard in many states for quite some time. This method was a result of several pavement organizations coming together to establish a new and improved method of HMA pavement mix design to increase pavement service life, performance, and efficiency. This method was developed and took the place of the Marshall mix design, its predecessor. The Superpave process incorporated the new PG binder grading system, a system of grading asphalt binder that considers traffic and environmental conditions, and a method of performance prediction and volumetric verification (*What Is Superpave?*, n.d.). However, with time many DOTs noticed pavement distresses developed such as cracking, rutting, raveling, and moisture damage associated with mix performance testing (West et al., 2018). This is a problem that is exacerbated by the incorporation of RAP in asphalt mixes.

The Balanced Mix Design (BMD) process evolved to address these mix performance problems. BMD mix design incorporates two or more performance testing methods to ensure successful mix characteristics by balancing rutting and cracking distresses during the design of an asphalt mixture. The concept of BMD is to develop an HMA mix design that considers the aging, traffic loading, and climate conditions of a specific area (Meroni et al., 2020; West et al., 2018; Ziari & Hajiloo, 2023). A complete BMD application includes first determining the Optimum Binder Content (OBC) in accordance to the procedure in AASHTO R35 to meet the volumetric requirements found in AASHTO M323 using the Superpave process. Then samples are fabricated from the same mixes with more and less asphalt (± 0.5% for example) and conducting performance testing to find the OBC that balances the rutting and cracking resistance (Ziari & Hajiloo, 2023). Furthermore, as the incorporation of recycled materials becomes more prominent in pavement design, the BMD approach will result in a higher confidence level for pavement mix performance in field applications (Meroni et al., 2020).

A study compared mixes at 30% and 45% RAP replacement; one set was prepared traditionally in accordance with Virginia DOT requirements and the other with a BMD approach (Meroni et al., 2020). The results of this study indicated certain BMD mixes had better performance and cost-effectiveness compared to Superpave mixes. However, when incorporating different gradations, AC content, and volumetric properties in a mix design, the results can have significant variation and an unknown source of what is influencing the mix performance. By using several different combinations with no method of control over these variables, thus likely creates a source of uncertainty. To implement accurate and efficient design, there is a urgent need to develop a method to handle this issue.

In this regard, the Consi-Grad method of mix design for high RAP replacement has been developed in this paper. It is considered as an intermediate step between Superpave and BMD mix design. Many DOTs, Idaho included, use volumetric verification for mix design and limit the amount of RAP replacement allowed to incorporate into a mix. The flowchart of this method is shown in Figure 2.1 below. This begins with a selection of local specifications for the state or federal requirements of mix design. Then, the materials are gathered and tested to determine resulting properties such as gradation of RAP and virgin aggregate, asphalt content contributed by the RAP and it’s true grad, and the virgin binder need to meet requirements. Then, the virgin mix design is developed to determine the optimal asphalt content and gradation of mix to meet the required specifications. Performance testing is conducted on this virgin mix to ensure good performance. Then, the

RAP replacement mix design begins, and the combined gradation (virgin + RAP aggregate) is designed to be consistent with the virgin mix design. The primary considerations for this method (Consi-Grad) is keeping the gradation and asphalt content consistent with the virgin mix design (0% RAP) to eliminate influential effects from these variables to focus on the rejuvenation and its effectiveness in improving rutting and cracking resistance.

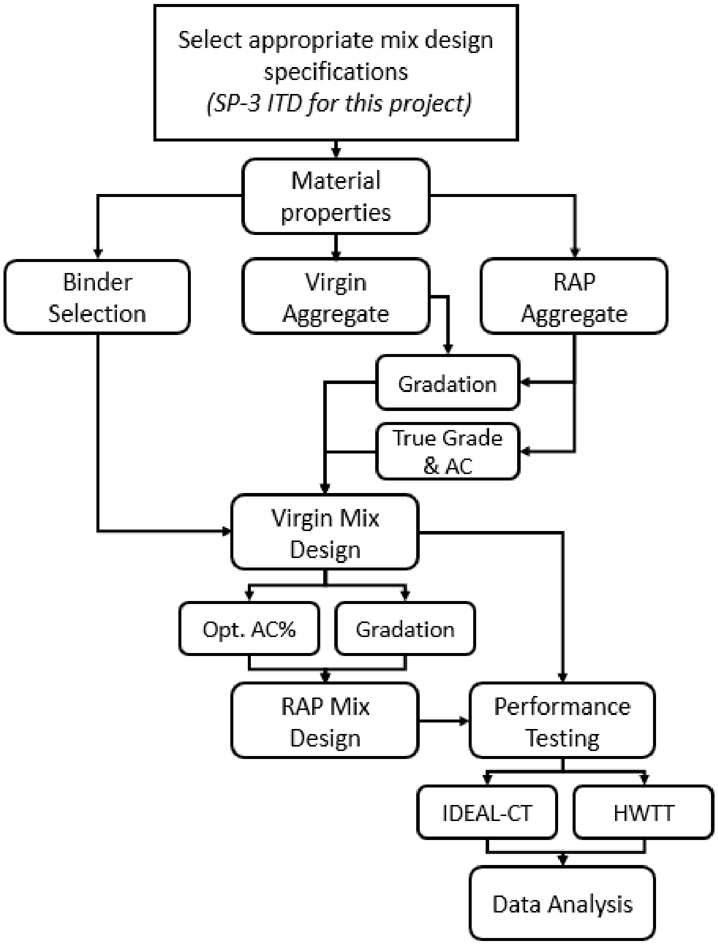

Figure 2.1 Consi-Grad Mix Design Flowchart

This section describes the detailed methods and project parameters for a research project implementing the Consi-Grad method previously outlined. This project was designed with Idaho pavement specifications in mind. The regional climate, expected traffic loading, and materials were based on Idaho data, and the pavement design criteria for Idaho highway design is used. When applying this methodology to a research or pavement construction project, the applicable specifications and climate for the area should be considered.

2.3.1 Materials and Mix Design

The mix design was conducted in accordance with Idaho Transportation Department (ITD) Standard Specifications for Highway Construction for SP-3 specifications, which is used for medium-heavy traffic conditions and is frequently used in Idaho pavement projects (*2018 Standard Specifications for Highway Construction*, 2018). The designated virgin binder was PG 70-28, as it is a common asphalt binder used in Idaho highway pavement projects. The virgin and RAP aggregate were provided locally by Knife River, Inc. The asphalt binder was developed and supplied by Idaho Asphalt, Inc. The virgin/control mix will be compared to the RAP replacement mixes to evaluate the resulting effect of incorporating RAP in the mix.

2.3.2 Testing Methods

The rutting resistance is evaluated using the Hamburg Wheel Tracking Test (HWTT) testing method. The HWTT procedure is common for many DOTs due to its superior functionality and ease of use in comparison to alternative rutting evaluation methods (Walubita et al., 2019). The HWTT was also selected due to its use for Idaho specification of HMA asphalt pavement design. This procedure applies repetitive wheel tracking loads from two separate wheel attachments (2 samples per wheel). The samples are submerged into a water bath that stays consistently at 50°C as the wheels run back and forth across the samples for 20,000 passes with a load of 705 ± 4.5 N. The rutting depth (mm) per pass is recorded and output to a graph while also accounting for stripping occurrence by calculating the inflection point in the graph based on the rutting data.

The IDEAL-CT was used to assess the cracking resistance of the mixes. The use of IDEAL-CT has quickly grown in popularity due to its low cost, practicality, and fast turnaround (Zhou et al., 2017). The IDEAL-CT procedure analyzes samples of various sizes and has a similar process as the original indirect tensile strength test. It is common to fabricate and test samples with the same dimensions as the HWTT for ease of laboratory sample preparation. The sample is loaded at a rate of 50 mm/min (displacement). There are several usable outputs including the fracture energy, peak load, CTindex, and graph depiction of the load vs. displacement.

All HWTT and IDEAL-CT samples were prepared in accordance with AASHTO T 324 section 6.2.4 and conditioned according to the procedure outlined in AASHTO R-30 section 7.3.2.1. Samples were compacted in accordance with AASHTO T312 section 8.1.7. All samples were compacted to a thickness of 62 mm, diameter of 150 mm, and air void content of 7% ± 0.5% with the determined air void content conducted according to AASHTO T269 and AASHTO T209.

2.4 Results

The results of the application of the Consi-Grad method are described here and follow the flow chart outline in Figure 2.1. The mix design results are seen first then followed by the met criteria specifications used for the mix design process. Then, the initial performance testing results are displayed and discussed.

2.4.1 Mix Design Results

The RAP, virgin aggregate, and virgin binder are selected and tested. The determination of the gradation and available asphalt binder from the RAP material was done in accordance with AASHTO T 308 by use of an ignition oven. The resulting gradation and available RAP binder was the resulting average of 8 random samples collected from the RAP material used. The true RAP grade asphalt was determined by analyzing the RAP binder that was recovered following the procedure outlined in AASHTO T164 (method A - centrifuge extraction). The final material properties and project parameters are outlined in Table 2.1.

Table 2.1 Material Properties and Parameters

Property/Parameter	In Project Use:
Design Specifications	ITD SP-3 (medium-heavy traffic flow)
RAP Percentages:	0 % (Control/Virgin mix) 25 % 50 % 70 %
True RAP Grade:	PG 82-16
Available Asphalt Content (RAP):	5.3%
Target Binder Grade (virgin) :	PG 70-28
Optimum Asphalt Content in Mix:	5.3%

The required volumetric and material specifications for this SP-3 selection of HMA pavement design can be seen in Table 2.2 below. When applying this method for research or industry purposes, the specific requirements local to the area of interest should be considered.

Table 2.2 Design Specifications for ITD SP-3

Mix Property	Job Mix Formula	Spec.
Percent Asphalt by Weight of Total Mix	**5.3**	-
Percent Asphalt by Weight of Aggregate	5.3	-
Percent Air Voids (Pa)	4.1	4.0
Voids in Mineral Aggregate (VMA)	14.7	14 min
Compacted Unit Weight Gmb, pcf	2.307	-
Theoretical Maximum Density Gmm, pcf	2.406	-
Percent Effective Asphalt Content (Pbe)	4.7	-
Percent Absorbed Asphalt (Pba)	0.54	-
Specific Gravity of Binder (Gb)	1.0331	-
Percent Gmm @ N Initial (7 gyrations)	86.7	≤ 89.0
Percent Gmm @ N Design (75 gyrations)	95.9	96.0
Percent Gmm @ N Maximum (115 gyrations)	96.8	≤ 98.0
Dust to Asphalt Ratio (DP)	1.1	0.8-1.2
Percent Passing #200 Sieve	5.0	3.0-6.0
Voids Filled with Asphalt (VFA)	72.1	-
Laboratory Mixing Temperature for Design (˚F)	336	327-337
Laboratory Compaction Temperature for Design (˚F)	314	306-316
Laboratory Sample Weight for Volumetric Testing (g)	4741	-
Ignition Oven (NCAT) Correction Factor @ 538 ˚F	0.37	-
Los Angeles Abrasion (LAR) (%)	29	40 max
Sand Equivalent	64	45 min
Fracture Face Count (%)	98	75 min (2 Face)
Fine Aggregate Angularity (%)	46.1	45.0 min
Flat and Elongated Particles in Coarse Aggregates (%)	0	20 max (3:1)
Coarse Clay Lumps and Friable Particles	0	0.3 max
Fine Clay Lumps and Friable Particles	0	0.3 max
Percent Natural Sand	0	15 max
Coarse Sodium Sulfate Soundness	1.1	12 max

A significant key consideration for this mix design procedure is maintaining a consistent gradation in line with the virgin/control mix. The original RAP gradation and the final overall mix gradation are shown in Figure 2.2. The final selection of mix gradation fell within the ITD upper and lower limits and outside of the restricted zone. It should be noted that in order to achieve consistent gradation between the 0%, 25%, 50%, and 70% RAP replacement mixes, only the virgin aggregate gradation was altered to create a combined gradation that is consistent with the virgin mix.

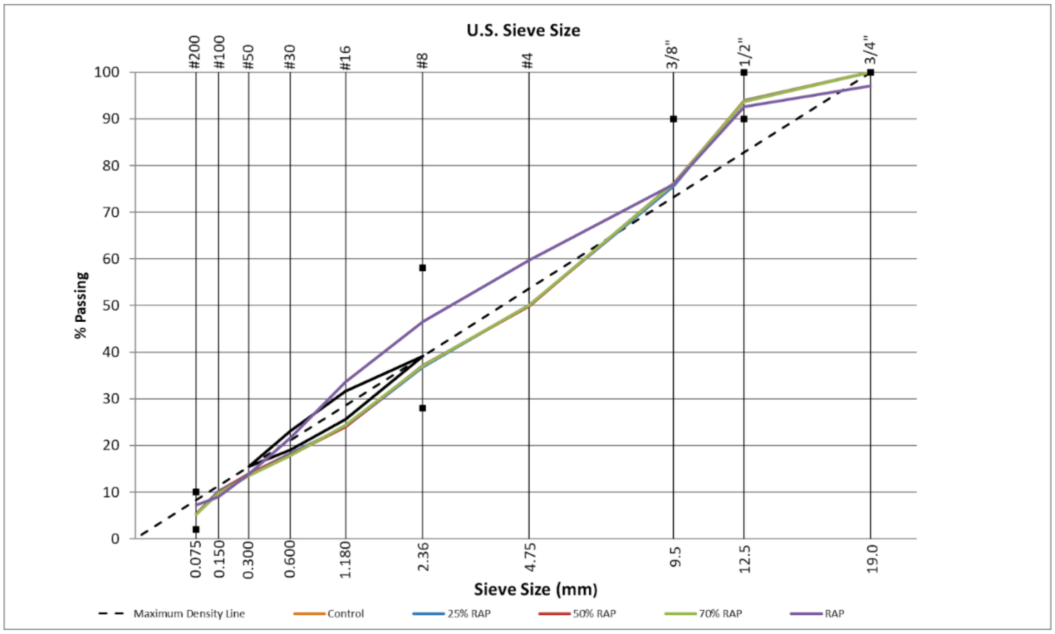

Figure 2.2 Gradation of RAP and HMA Mixes

The combined gradation and overall asphalt content of each mix is uniform across the board to match the control/virgin mix. The gradation and AC content are selected based on the correct combination to meet all the specifications in ITD Standard Specifications for Highway Construction for SP-3.

2.4.2 Performance Testing Results

The results for the rutting resistance via the HWTT rut depth are shown in Figure 2.3. As expected, the rut depth decreases as the RAP replacement increases; this is due to the increased stiffness of mixes due to the oxidized RAP and its contribution to an overall stiffer mix. Current practice for Idaho SP-3 pavement design requires less than 10 mm of rut depth at 15,000 passes (out of 20,000 total); if 10 mm or more occurs before this, the pavement design fails (*2021 Supplemental Specifications for 2018 Standard Specifications for Highway Construction*, 2021). No stripping occurred in any of the mixes in this study which is characteristic of a mix with an appropriate amount of asphalt in its design as dry mixes tend to strip and ravel. While the virgin/control (0% RAP) mix had the highest rut depth, it still performed very well with less than 4 mm rut depth; this indicates a good control mix.

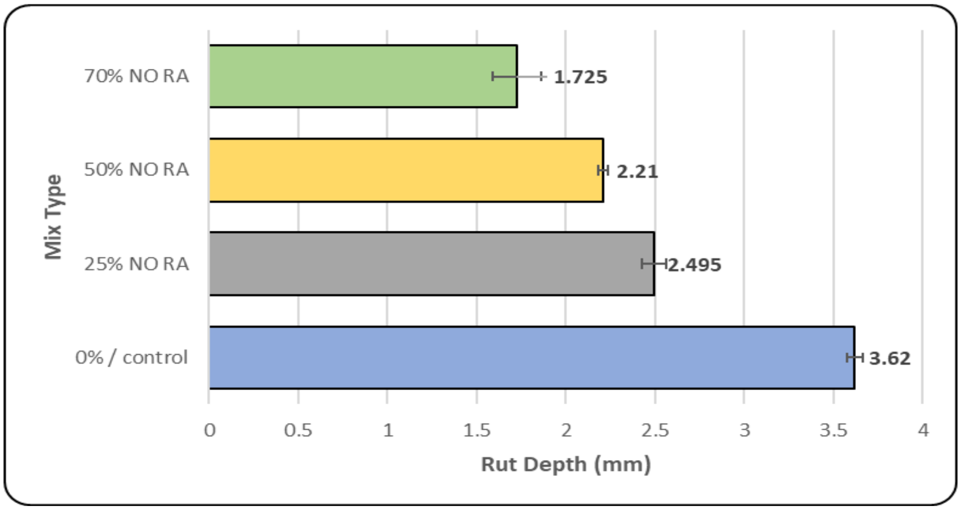

Figure 2.3 Rut Depth (mm)

A one-way ANOVA analysis was run on the HWTT and IDEAL-CT results to compare the performance of each RAP percentage and to determine if there is a noteworthy difference. As seen in the ANOVA table below, the p-value is below 0.05 (the selected alpha confidence level) for the percentage of RAP, meaning the HWTT is sensitive to this variable. When using multiple comparisons to further identify the significance between each one, the 0%, 25%, and 70% RAP replacement mixes are significantly different. However, 50% and 70% are not significantly different, nor is the difference between the 25% and 50% RAP replacement mixes.

Table 2.3 ANOVA Analysis for HWTT Rut Depth (mm)

Source	Degrees of Freedom	Sum of Squares	Mean Squared Err.	F-stat	p-value
% RAP	3	3.8770	1.29235	49.47	0.001
Residual	4	0.1045	0.02612	-	-
Total	7	3.9815	-	-	-

The CTindex indicates cracking resistance via the IDEAL-CT results are displayed in Figure 2.4. As expected, the CTindex decreased as the RAP replacement increased which is due to the oxidized and aged binder increasing the stiffness of the mix. The current threshold for Idaho HMA mixes is a CT index of 80 or higher (*2021 Supplemental Specifications for 2018 Standard Specifications for Highway Construction*, 2021). As seen in the results, the virgin mix met this criterion very well. However, it is also seen that the RAP-inclusive mixes do not meet this threshold.

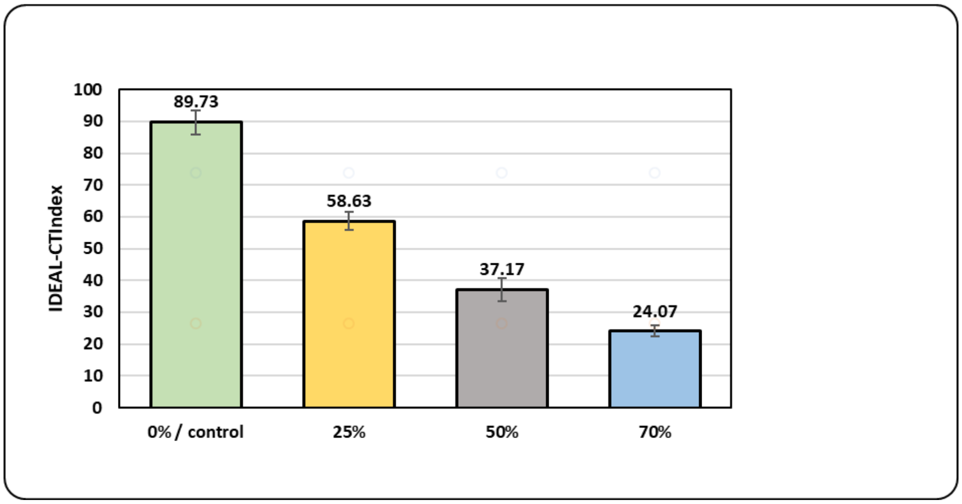

Figure 2.4 IDEAL-CT Results (CTindex)

For the IDEAL-CT CTindex results, the 0%, 25%, and 70% RAP replacement mixes are statistically significantly different while 50% and 70% are not significantly different using the same one-way ANOVA layout. The results from this initial application and testing of the proposed Consi-Grad method have promising outcomes, do not have a large amount of variation, and follow expected trends.

The one-way layout ANOVA analysis results for the CT index are described in the table below. It is seen that the p-value is <0.05 (the Tukey's selected alpha) which shows there is statistical significance between the different levels of RAP replacement. When conducting the multiple comparison, which determines the significance between each individual RAP replacement percentage, there is statistical significance between level of RAP, except 50% and 70% RAP which are not statistically different.

Table 2.4 ANOVA Analysis for CT index

Source	**Degrees of Freedom**	**Sum of Squares**	**Mean Squared Err.**	**F-stat**	**p-value**
% RAP	3	7402.3933	2467.4644	56.09042288	0.0001
Residual	8	351.926667	43.9908333	-	-
Total	11	7754.32	-	-	-

2.5 Conclusions

This research was proposed to provide the pavement industry with a method for incorporating high RAP in mix design. While there are procedures for BMD and recycled material, it often fails to consider the uncertainty associated with RAP and overall mix gradation, asphalt content, and volumetric properties. The use of performance testing to analyze and verify mix characteristics. The following Consi-Grad method is proposed in this work in order to eliminate variation from these mix variables that can be controlled. The proposed Consi-Grad can be condensed and summarized in the steps listed below.

1. Select the specific current mix design specifications for the project design.
2. Material property analysis
    1. Select and verify virgin asphalt binder.
    2. Virgin aggregate (gradation and aggregate properties)
    3. RAP aggregate (gradation, available asphalt content, and true grade)
3. Design virgin mix design (0% RAP) to meet specification requirements.
    1. Optimum asphalt content (%)
    2. Optimum gradation
4. Performance testing for virgin mix design - control mix (rutting and cracking)

5. Use optimum asphalt content and gradation to develop RAP-inclusive mixes.
    1. Only alter virgin mix gradation to meet overall mix gradation.
6. Performance testing for RAP inclusive mixes (rutting and cracking)

As previously mentioned, this proposed method is designed to act as a steppingstone to bridge the gap between Superpave and BMD for RAP inclusive mixes. The outcome is to eliminate known variance from the mix variables to allow for optimal design considerations for the binder mix component. This contributes a strong base for the pavement community to work from to implement a method of high RAP mix design. The next step in this process, is to incorporate the use of rejuvenators and recycling agents (RAs) to improve the performance of the RAP-inclusive mixes by developing a blending chart. The big picture of this contribution is setting up the groundwork of a process to follow to mitigate unwanted influence from certain mix contributions.

2.6 Acknowledgments

The author is grateful to the Boise State University Department of Civil Engineering for the continuous support of this area of research. The author is also grateful to Idaho Asphalt Supply Inc. for guidance, support, and materials for the entirety of this project. Finally, the author is appreciative of the Idaho Transportation Department for supporting and taking an interest in this field of research for Idaho.

2.7 Author Contributions

All authors reviewed the results and approved the final version of the manuscript.

CHAPTER 3: ANALYZING THE EFFECTS OF REJUVENATORS IN BALANCED MIX DESIGN WITH GHIGH PERCENTAGES OF RECYCLED ASPHALT PAVEMENT

The following manuscript was written by Amanda Mullins. The manuscript begins on the next page and will be submitted to the International Journal of Pavement Engineering.

3.1 Abstract

Recycled Asphalt Pavement (RAP) mixes are widely used due to the environmental and economic benefits that are associated with replacing virgin material with recycled material. However, when including a high amount of RAP replacement (more than 25%), the longevity of the mixture, specifically the cracking and rutting resistance, is negatively impacted. The incorporation of rejuvenators into these high RAP mixes is used to revitalize and restore pavement characteristics. This study evaluated the performance of two rejuvenating agents, namely a bio-based and petroleum-based rejuvenator to investigate the ability to restore mix properties for RAP mixes at 25%, 50%, and 70% replacement. The properties of the mixes were evaluated based on balanced mix design (BMD) concepts to balance rutting and cracking resistances via the Hamburg Wheel Tracking Test (HWTT) and Indirect Tensile Asphalt Cracking Test (IDEAL-CT). The mix design process maintains a consistent aggregate gradation and asphalt content to minimize confounding the effect of gradation and asphalt content with the performance of rejuvenators at multiple RAP percentages. The evaluation of these mixes will consist of three tiers of analysis: rheological characteristics of binder blends, performance testing, and chemical assessment. A Fourier transform infrared spectrometer (FTIR) was used to compare the chemical structures of the blended asphalts for different treatments. The properties from the virgin (0% RAP) mix were used as the baseline to evaluate the effects of different RAP contents and different rejuvenator effects. The outcome of this research resulted in an improved method of high RAP mix design, a comparison of two rejuvenator performances, and a three-tier method of testing to best evaluate the mix performance.

3.2 Introduction

The asphalt and pavement industry has gravitated towards sustainable solutions in Civil Engineering application over time. As a result, the incorporation of Recycled Asphalt Pavement (RAP) has increased in new pavement design. The goal in utilizing RAP material is to get maximum use from the materials and reduce the need for virgin material. It is estimated that 87 million tons of RAP were used in 2020, RAP incorporation in new pavement design has increased by 55.4% since 2009 according to the National Asphalt Pavement Association (NAPA) pavement industry survey (Williams & J. Richard Willis, 2022). As the industry increases RAP use in various civil engineering construction projects, it’s important to consider the benefits and problems associated with high RAP implementation in HMA.

In 2020, it was estimated that the incorporation of RAP in new asphalt mixes lowered the emissions of greenhouse gasses by 2.3 million metric tons of CO2 which is roughly equal to 510,000 annual common vehicle emissions. An estimated 58.4 million cubic yards of landfill space is also conserved by reclaiming 96 million tons of RAP (Williams & J. Richard Willis, 2022). In addition to carbon emissions, there are various economic benefits that accompany the integration of RAP in other project applications (Yin et al., n.d.). According to the same report, due to RAP utilization in 2020, construction estimated saving a total of 4.4 million tons of asphalt binder and over 82 million tons of aggregate, which saved construction costs an estimated $2.9 billion. By reclaiming nearly 96 million tons of RAP for alternate use in future projects, at least $5.1 billion was saved in gate fees for landfill disposal (Williams & J. Richard Willis, 2022).

While the use of high RAP HMA mix design is appealing for environmental and economic benefits, this is accompanied by several challenges. Generally, high RAP mix design takes more time and effort than a conventional virgin mix design. While the available aged RAP binder has significant potential to contribute to the overall asphalt content of the mix, these high RAP mixtures are often more stiff, brittle, and susceptible to cracking and other durability distress problems as a result of aged and oxidized asphalt binder (Mohammadafzali et al., 2019; Yin et al., n.d.). To restore the aged RAP binder and increase its' effectiveness, many researchers and DOT's have been studying the effects of Rejuvenating Agents (RAs). The purpose of rejuvenators in RAP inclusive mix is to revitalize the rheological properties of aged RAP binder to better contribute to the overall mix (Abdelaziz et al., 2021; Epps, et al., 2020; Zhang et al., 2021). However, there are some limitations of adding rejuvenators to RAP inclusive mixes in regard to overall effectiveness, specifically the degree of blending which outlines the RAP binder is one of the following; no blending occurs, partial blending, or complete blending (Kaseer et al., 2019; Mohammadafzali et al., 2019; Zhang et al., 2021).

Many groups (Meroni et al., 2020; West & Taylor, 2019) in the pavement industry have moved towards a Balanced Mix Design (BMD) process, which is an extension and improvement over the current Superpave method. Superpave is the widely used method in the pavement industry, which is primarily based on volumetric mix design and proportioning. As the pavement community gravitates towards incorporating more recycled material, Superpave fails to consider the interactions between new materials and recycling agents. However, the goal of a BMD is to design a mix that performs well to the specific conditions it's designed for. BMD uses specific distress testing to analyze pavement performance; resistance to rutting and cracking. The goal of BMD is to outline testing criteria that are simple, affordable, and accurate enough to indicate good performance, as opposed to volumetric properties that are used as good mix characteristics (West & Taylor, 2019).

The asphalt industry is gravitating towards incorporating sustainable solutions into practical application, which includes high RAP replacement in HMA mix design. Yet there is a need for a standard method of mix design development and performance verification during the mix design process. The primary goal of this project is to develop a consistent method of high RAP mix design to implement for future use and application known as ConsiGrad. This paper will ultimately outline this method and the key considerations of verification along the way.

Furthermore, there are several other significant research objectives that are explored throughout this research project; they are as follows.

1. Develop standard procedure of high RAP replacement mix design and rejuvenator dosage determination to implement in future industry or research practice.
2. Evaluate and compare the effect of two rejuvenators in improving the performance of asphalt mixes with high RAP replacement.
3. Compare and correlate results from performance testing, asphalt binder testing, and chemical analysis (FTIR) to assess the trends of RAP replacement and rejuvenators within this study.
4. Compare current practice of medium RAP replacement (17%-25%) to alternative use of RAs.

Two rejuvenators are compared in terms of overall performance and binder blend chemical composition analysis. The experimental research flow chart plan is outlined in Figure 3.1. A total of five asphalt mixtures were prepared and tested for the purposes of this experimental work; virgin/control mix (0% RAP), 25% RAP replacement, 50% RAP replacement, 70% RAP replacement, and 25% RAP with binder grade bump down. Current practice for the Idaho Department of Transportation (ITD) specifies that between 17% and 25% RAP replacement mixes require a PG binder grade bump down, which in this case is PG 64-34 for a target grade of PG70-28. This current state of practice will be compared to the method of utilizing rejuvenators to revitalize the available RAP binder. The RAP inclusive mixes (25%, 50%, and 70%) are each mixed with two rejuvenators. Two primary rejuvenators were utilized; one bio-based (RA1) and one petroleum based/aromatic (RA2). The virgin/control mix results will be compared to the RAP inclusive mixes to quantify the effectiveness of the rejuvenators in the overall mix characteristics and performance. In addition to performance testing, the blends of RAP binder and each rejuvenator were tested further using Attenuated Fourier Transform Infrared spectroscopy (FTIR-ATR) to supplement the blend characteristics by performing chemical composition analysis.

3.3 Experimental Activity and Methodology

The experimental method this research followed was built on a process successfully outlined by many other researchers in this area of interest with several methods altered. Other researchers concluded success in controlling variables such as gradation and asphalt content to eliminate variable influence within control and focus on binder interaction performance (Zhang et al., 2021).

In this work, we proposed a Consi-Grad Method to solve the inconsistent gradation issue in high RAP mix design. The flowchart overview of the mix design process that was followed could be applied in the future of industry or research is displayed in Figure 3.1. The primary concept of this mix design process is to first develop a virgin mix design to meet the specification requirements depending on the state or research bounds. The control/virgin mix design was developed according to AASHTO R 35 requirements. Using the gradation and optimal overall asphalt content determined in the virgin mix design, the RAP mix design is developed based on the RAP binder properties and required mix properties. Both binder property testing, and performance testing are used as methods of evaluation for all mixes.

The next component of this method is developing a blending chart to determine the rejuvenator dose appropriate for the mix. This is based on binder material properties, specifically the binder blend testing results, to ultimately have RAP + RA binder blends similar to the target PG binder grade.

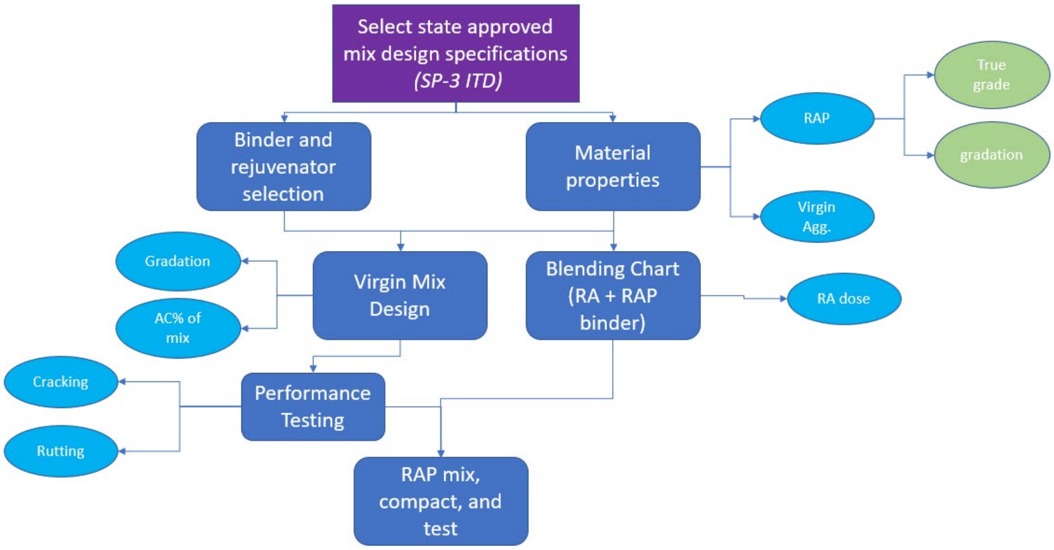

Figure 3.1 RAP Inclusive Mix Design Process

The key focus for the methodology of this project is to focus on the relationship between the available RAP binder, rejuvenators, and the virgin binder. To achieve this, the other variables in the HMA mix design are kept as consistent as possible to eliminate the confounding the effect of rejuvenation with the gradation and oil content in the mix. The controlled variables in this benchmark study are mix gradation, overall asphalt content, and target asphalt PG grade.

3.3.1 Project Parameters

The material properties and mix design parameters are shown in Table 3.1. This research project was supported and funded by ITD to further explore high RAP replacement mixes with the use of rejuvenators. The virgin/control mix design was developed to meet all the volumetric mix design requirements specified in the ITD 2021 Supplemental Specs. for Highway Construction - section 405 (*2021 Supplemental Specifications for 2018 Standard Specifications for Highway Construction*, 2021). The mix design selected was an SP-3 (medium-high traffic flow) mix that is commonly used for most Idaho pavement projects. The key consistent outcome of the virgin mix design is the overall asphalt content and gradation that resulted in a final mix to meet these requirements. The target asphalt binder grade selected was PG 70-28 due to its common use in Idaho pavement projects of this scope. The virgin and RAP aggregate were provided locally by Knife River Inc. The RAP gradation and available RAP asphalt content was determined by following the procedure in AASHTO T 308. A total of 8 random samples were tested and averaged for this result. The true RAP grade asphalt was determined by testing the recovered RAP binder that was recovered by a third-party lab following the procedure outlined in AASHTO T164 (method A - centrifuge extraction).

Table 3.1 Material Properties and Parameters

Property/Parameter	In Project Use:
RAP Percentages:	0 % (Control/Virgin mix) 25 % 50 % 70 %
True RAP Grade:	PG 82-16
Available Asphalt Content (RAP):	5.3%
Target Binder Grade:	PG 70-28
RA1 dose (bio-based):	8.3% (by weight of RAP binder)
RA1 dose (bio-based):	6.6% (by weight of RAP binder)
RA2 dose (aromatic):	11.3% (by weight of RAP binder)
Overall Asphalt Content:	5.3%

Incorporating high levels of RAP into HMA mix design with the assistance of rejuvenators can be a difficult and wildly variable process (Epps, et al., 2020). Having a standard process to follow in both research and industry practice is a key component to successfully incorporating high levels of RAP into the asphalt and pavement industry. A key consideration utilized in the methods of this research project is to eliminate variation potential from three factors: the overall mix gradation, asphalt content, and PG grade. This can be very difficult when considering a high RAP mix design.

The gradation for each mix type is shown in Table 3.2. To achieve constant gradation for each mix, only the virgin aggregate gradation was altered to obtain the same combined gradation for each mix, the RAP gradation was left unchanged; this is another factor in the proposed Consi-Grad method. In this regard, we propose a "Consi-Grad method" of high RAP mix design to enable a reliable comparison between each RAP dosage while keeping a consistent RAP gradation and overall gradation throughout the testing procedure. The RAP aggregate was not sieved, as the virgin aggregate was, due to the breakdown of RAP material that may occur which is likely to change the RAP properties. Instead, the RAP was hand sieved to split the material on the No. 4 sieve where material above the No. 4 screen is considered *Coarse RAP Aggregate,* and material passing the No. 4 sieve is considered *Fine RAP Aggregate*. The coarse and fine RAP are separately mixed with a riffle splitter to best eliminate bias, then the splitter is used to divide the large RAP sample into a smaller sample weight to further section out for individual batch samples which is accomplished by reducing the sample size following the procedure described in AASHTO T248 – method B: quartering by APEX. Achieving this method of consistent gradation may not always be possible due to variations in RAP sourcing, service life, and environmental conditions.

Table 3.2 Mix Gradations (% Passing)

Sieve Size	Virgin agg. 0% RAP	Virgin agg. 25% RAP	Virgin agg. 50% RAP	Virgin agg. 70% RAP	RAP agg. - all mixes	Combined Gradation
1”	100%	100%	100%	100%	100%	100%
½”	94%	94%	94%	94%	94%	94%
⅜”	83%	83%	83%	83%	83%	83%
No. 4	46%	42%	35%	22%	57%	46%
No. 8	32%	29%	22%	9%	42%	32%
No.16	23%	20%	13%	1%	33%	23%
No. 30	18%	16%	11%	1%	25%	18%
No. 50	12%	10%	8%	0%	17%	12%
No. 100	8%	7%	6%	0%	11%	8%
No. 200	5.0%	4.3%	2.9%	0%	7.2%	5.0%

3.3.2 Rejuvenator Dosage

The two rejuvenators utilized in this project are RA1 and RA2. RA1 is a bio-based rejuvenator oil and RA2 is an aromatic petroleum-based rejuvenator. It has been demonstrated in other research that petroleum-based oil rejuvenators often require a higher dosage to achieve the ideal viscous effects of the blend (Epps, et al., 2020). Both RA1 and

RA2 were developed by Idaho Asphalt Supply, Inc. and the primary goal of incorporating these is to revitalize the RAP binder properties. To determine each rejuvenator dosage (RA1 and RA2), the following process was conducted. First, a third-party commercial lab extracted ~600 grams of RAP binder material. Using the recovered RAP binder, two binder blends were mixed: one using RA1 and the other using RA2. Two doses for each RA were used to conduct binder testing and develop a resulting blending chart. RA1 was dosed at 5% and 8% of RAP binder weight, and RA2 was dosed at 8% and 12%. The binder testing results are shown in Table 3.3. The goal in incorporating rejuvenators into the RAP binder blend is to blend the RAP PG 82-16 grade down to the target grade of PG 70-28. As shown in Table 3.3, RA1 was able to reach this target grade but RA2 did not meet the low-temperature target. The original high-temperature grade of the target binder (PG 70-28) via the Dynamic Shear Rheometer (DSR) value for G*/sin(δ) at 70℃ (1.36 kPa) was used for the blending chart to develop the RA doses. As RAP incorporation increases, the mix stiffness is often seen to increase, however, the rutting resistance of the mix needs to be sustained (Kaseer et al., 2020). The logic here is to ensure that the rutting and stripping resistance is not compromised to assess the cracking resistance of the mixes. This method is meant to be a benchmark study in this area of rejuvenator dosage. In future research, it would be beneficial to further utilize aged asphalt blend samples for rejuvenator dosage.

Table 3.3 Binder Blend Critical Temperatures (˚C)

		RAP	**RA1: Bio-Based**		**RA2: Petroleum Based**	
			5%	8%	8%	12%
Org. High	(G*/sinδ) (1 kPa)	85.3	81.9	74.2	78.7	70.7
RTFO High	(G*/sinδ) (2.2 kPa)	89.0	84.1	81.2	81.2	75.6
PAV Int. Temp	(G*/sinδ) (5000 kPa)	28.5	-	-	-	-
PAV BBR	BBR, Stiff, (300 MPa)	-24.5	-31.2	-34.7	-36.2	-40.7
	BBR, m-value (0.3)	-16.2	-24.5	-31.7	-17.3	-20.0
True Grade		PG 85.3-16.2	PG 81.9-24.5	PG 74.2-31.7	PG 78.7-17.3	PG 70.7-20
PG Grade (M320)		PG 82-16	PG 76-22	PG 70-28	PG 76-16	PG 70-16

The resulting blending chart for the determination of each rejuvenator respectively is shown in figure 3.2. The PG 70-28 value for ORG G*/sin(δ) at 70℃ was 1.36 which acted as the target value for the two rejuvenated binder blends. Since only two doses were compared for each RA type, a linear relationship was assumed to develop the trendline for the resulting RA dose.

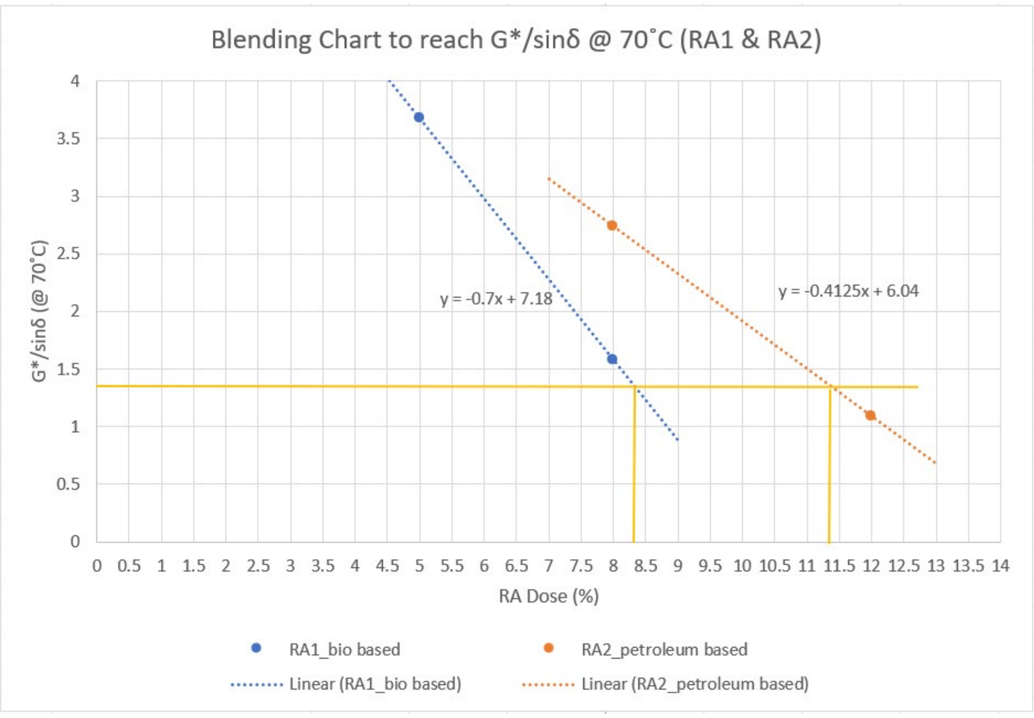

Figure 3.2 RA Dose Binder Blending Chart

The other calculated options for RA dose given different binder characteristics are summarized in Table 3.4. In this experimental process, RA1 was tested at two different doses given it performed the best of the two RAs in the first round of testing. As previously mentioned, the first dose at 8.3% was calculated by considering the ORG G*/sin(δ) at 1.36 kPa. The second dose at 6.6% was derived from the m-value #2. While the virgin binder resulted in an m-value of 0.320, the standard limit for binder testing is an m-value of 0.300, so this resulting RA1 dose was also considered. The blue highlighted dosages indicate the selection for the RA1 dose, and the green highlighted dose is the optimal RA2 dose.

Table 3.4 Calculated RA Doses (by weight of RAP binder)

DSR/BBR property	PG 70-28 value	RA type	RA dose (%)
Stiffness (BBR)	245	RA1	**3.6**
		RA2	**-1.3**
m-value (BBR)	0.320	RA1	**8.3**
		RA2	**31.6**
G*/sin(δ)	1.36	RA1	**8.3**
		RA2	**11.3**
Log [G*/sin(δ)]	0.13354	RA1	**8.5**
		RA2	**11.0**
m-value (#2)	0.300 (standard minimum)	RA1	**6.6**
		RA2	**23.6**

Further analysis and evaluation of different binder property characteristics should be examined in future research (Amy Epps, et al., 2020). For example, the RTFO or PAV results can be evaluated for use in developing a blending chart to determine optimum rejuvenating agent dosages based on their respective target properties.

3.3.3 Testing Matrix

Common practice for ITD pavement mix designs include primarily performance testing and volumetric verification. In addition, binder testing is performed to ensure that all the binders used meet the specifications requirements. Using this method, this research project went a step further to incorporate better practices for future research or industry practice. The methodology of this testing verification process can be summarized in three steps.

1. Performance Testing - HWTT (rutting resistance) and IDEAL-CT (cracking resistance)
2. Binder Blend Testing - RAP, PG 70-28, PG 64-34, Blend 1 (RA1), Blend 2 (RA2)
3. Infrared Spectrometry Analysis - Analyze chemical composition and characteristics.

The combination of these three methods of analysis for the mix and binder performance complement each other. The performance testing gives an indication of how a mix is effectively working in terms of rutting and cracking resistance. The binder blend testing results give further indication of the physical properties associated with the binder blends in comparison to the target PG-grade binder. Finally, the infrared spectrometer analysis goes beyond physical properties and into the chemical composition differences between the blends and components.

The testing matrix for performance, binder blend, and FTIR testing is summarized in Table 3.5. The primary distresses analyzed are rutting resistance using the HWTT and cracking resistance using the IDEAL-CT. The selection of these performance testing methods compared to other options is due to the use of these in current ITD specifications. In the ITD specifications (*2021 Supplemental Specifications for 2018 Standard Specifications for Highway Construction*, 2021), the current practice specifies that no more than 10 mm of rut depth should occur before 15,000 passes, as well as no stripping. All HWTT samples were prepared in accordance with AASHTO T 324 section 6.2.4, conditioned by the procedure in AASHTO R-30 section 7.3.2.1, and compacted according to AASHTO T312 section 8.1.7. The IDEAL-CT is the cracking identification parameter in this same standard. The current CT index set by ITD for HMA mixes is 80, however, evaluating this current limit is within the scope of this project. All IDEAL-CT samples were prepared in accordance with ASTM D8225-19.

The 0% RAP (virgin/control) mix was the first set of samples tested to be used as the comparison results to the RAP-inclusive mixes. Next, the RAP-inclusive mixes (25%, 50%, and 70%) are mixed, compacted, and tested using RA1 and RA2 to compare the effectiveness of these rejuvenator types. The current ITD practice specifies that when using RAP replacement between 17%-25%, the standard practice is to use a PG binder that is one grade below the design target grade, which is PG 64-34 in this case. An additional consideration in this research project is to compare the current standard ITD practice to the method of utilizing rejuvenators for 25% RAP replacement.

Table 3.5 Testing Matrix - Performance, Binder Blends, FTIR

	0% RAP (control)	25% RAP	50% RAP	70% RAP
NO RA (PG 70-28 only)	✓	✓	✓	✓
Blend 1 (RA1 @ 8.3%)	-	✓	✓	✓
Blend 2 (RA1 @ 6.6%)	-	✓	✓	✓
Blend 3 (RA2 @ 11.3%)	-	✓	✓	✓
PG 64-34 with RAP	-	✓	-	-

3.4 Results

3.4.1 HWTT Results

The HWTT results for each HMA mix variation can be seen in Figure 3.3. All HWTT samples met the requirements listed in AASHTO T 324, specifically a thickness of 62 mm and air void content of 7% ± 0.5%. All samples were tested in accordance with AASHTO T269 and AASHTO T209 to calculate the corresponding air voids of each sample. For this initial set of performance tests, only one set was evaluated for each mix, which includes a total of 4 samples (2 each "side").

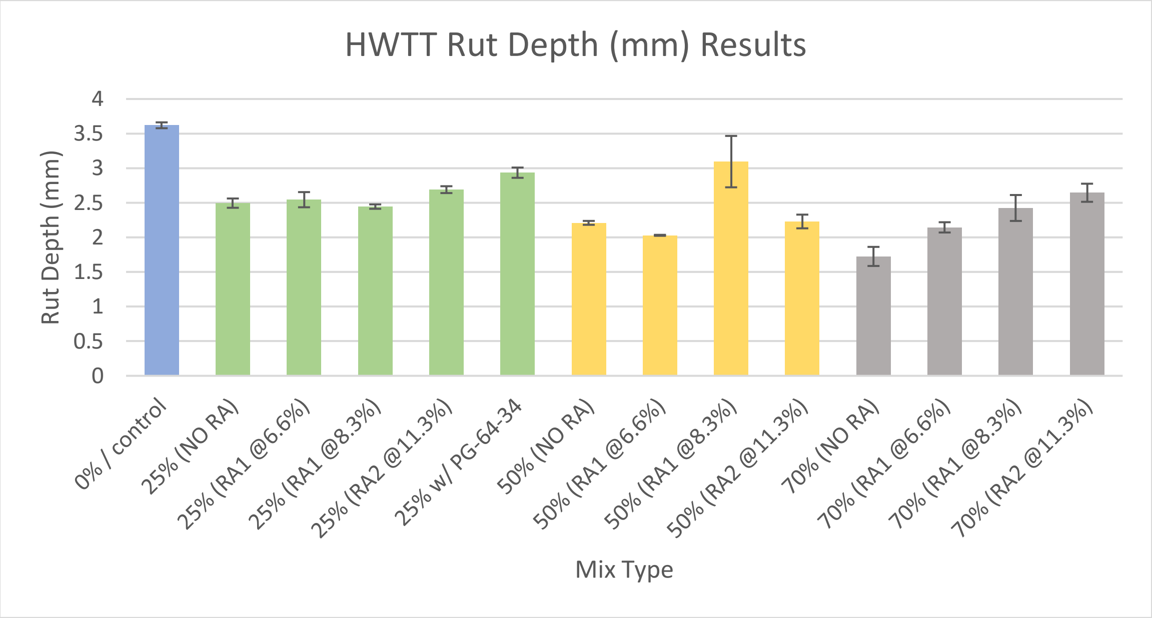

Figure 3.3 HWTT results (mm)

As summarized in Figure 3.3, the bar plot shows that all mixes performed well in terms of rutting and stripping resistance, as the results were well below the limit outlined in ITD's specification. This was expected given that the rejuvenator dosage was determined based on the $G^*/\sin(\delta)$ of PG 70-28 at 70°C, meaning that the mix was designed to meet the rutting and stripping resistance limits. It is also seen that the rut depth is lower in all the RAP inclusive mixes compared to the control (0% RAP) mix. This was expected as RAP replacement is commonly associated with higher mix stiffness and rutting resistance, but it was reassuring to see results that indicate the rutting resistance was kept intact (Kaseer et al., 2020)'. It is evident that replicate samples may need to be tested to see a clearer trend for rutting resistance compared between the two rejuvenators.

3.4.2 IDEAL-CT Results (CT index)

The results for the IDEAL-CT samples can be seen in the Figure 3.4 and it should be noted that all tested samples met the air void requirement of 7% ± 0.5%, as well as kept a consistent thickness of 62 mm. The standard practice method of testing was followed according to ASTM D8225 at 25°C. The two key results analyzed are the CT index and the Fracture Energy (J/m^2). While the CT index is commonly used as the deciding factor in HMA cracking resistance including the ITD spec, the fracture energy is another potential indicator of good material that will be considered as a point of comparison. Each result value is calculated from an average of three samples.

For each section of performance analysis described below, a one-way ANOVA analysis was performed for each comparison to determine the statistical significance of interactions among the RAP %, RA type, and RA dose. The overall trends of each RAP replacement percentage and treatment types are summarized in Figure 3.4.

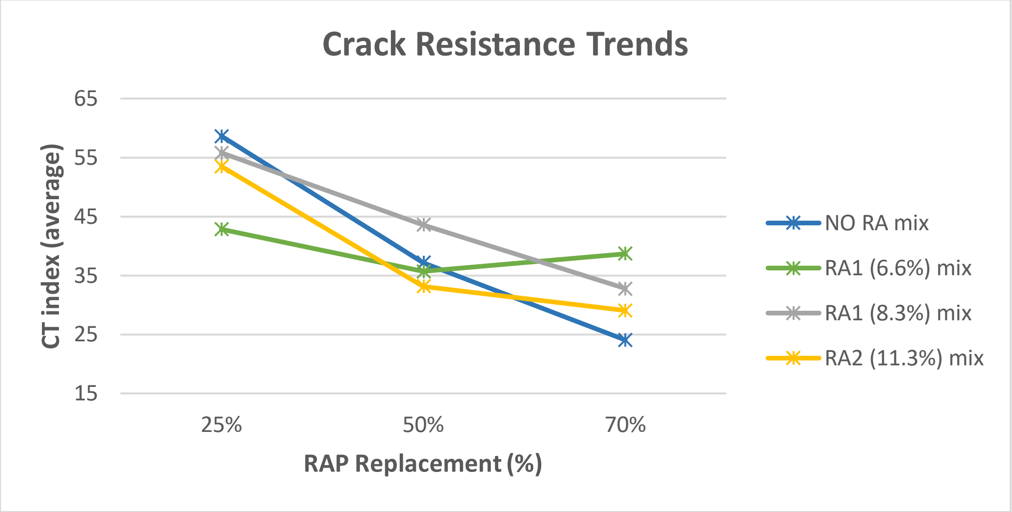

Figure 3.4: HWTT results (mm)

3.4.3 IDEAL-CT Results – RAP Replacement Percentage

The CT_{index} results comparing each of the cracking resistance results for the different levels of RAP replacement (%) are shown in Figure 3.5. It should be noted that none of these mixes contain any rejuvenators or recycling agents in them. The expected trend is seen; as the RAP replacement increases, the cracking resistance decreases. It is also noted that the control/virgin mix (0% RAP) performed very well, which indicates a successful mix design.

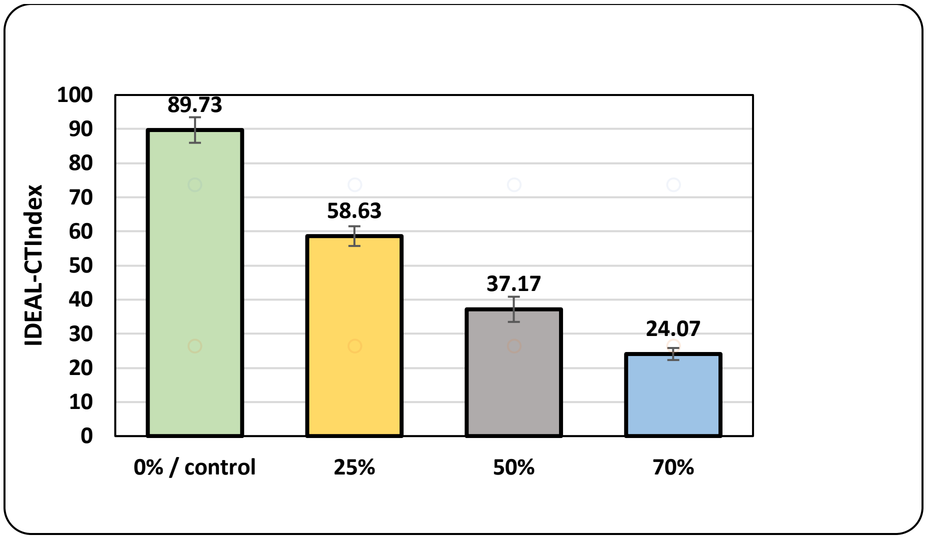

Figure 3.5 IDEAL-CT NO RA results (CT index)

The results of the ANOVA analysis for this RAP percentage comparison indicated there is a statistically significant difference between each RAP percentage, as expected. When conducting multiple comparisons between the different RAP percentages, it was found that there is no significant difference between 50% and 70% RAP ("high" RAP). However, there is significant difference between 0%, 25%, and "high" RAP.

Table 3.6 **ANOVA Analysis for CT index**

Source	Degrees of Freedom	Sum of Squares	Mean Squared Err.	F-stat	p-value
% RAP	3	7402.3933	2467.4644	56.09042288	0.0001
Residual	8	351.926667	43.9908333	-	-
Total	11	7754.32	-	-	-

3.4.4 IDEAL-CT Results – RA Treatment

The CT_{index} results comparing the two RA treatments for 25% RAP replacement are shown in Figure 3.6. Additionally, Figure 3.6 also includes the mix that uses no RAs but uses PG 64-34 as the virgin binder, which is current practice (use one binder grade bumped down). It is seen there is very little difference between the cracking resistance of these different treatments at 25% RAP replacement.

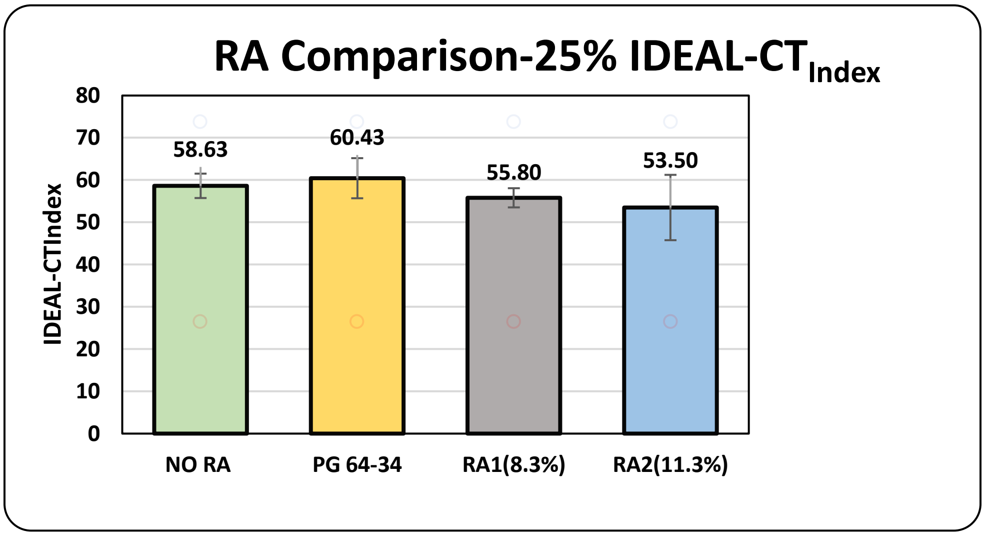

Figure 3.6 IDEAL-CT 25% RAP results (CT index)

There is also no statistically notable impact in the comparison of these treatments as seen in the ANOVA table below since the p-value is greater than 0.05.

Table 3.7 ANOVA Analysis for CT index (25% RAP)

Source	Degrees of Freedom	Sum of Squares	Mean Squared Err.	F-stat	p-value
% RAP	3	84.34	28.11	0.19	0.899
Residual	8	1171.49	146.44	-	-
Total	11	1255.83	-	-	-

The CT_{index} results comparing the two RA treatments for 50% RAP replacement are summarized in Figure 3.7. It is seen that RA1 does improve the performance compared to the mix with no RA, but RA2 does not seem to improve the mix performance.

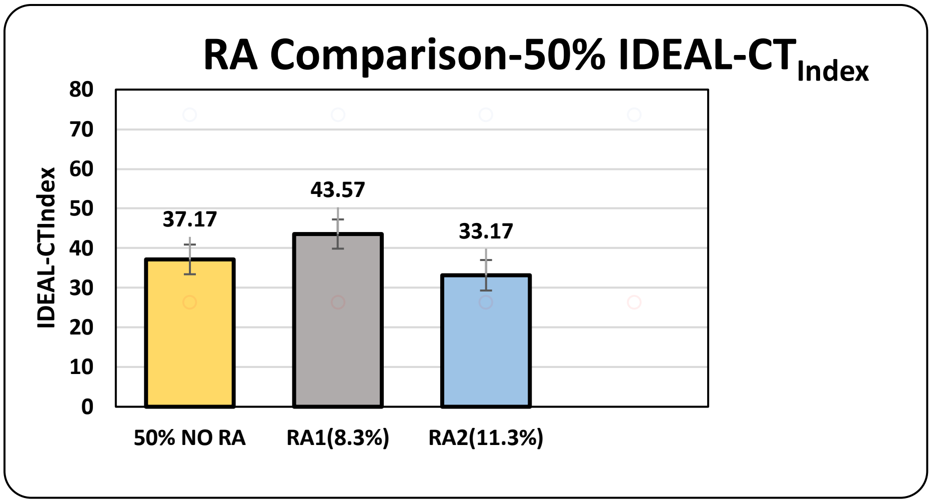

Figure 3.7 IDEAL-CT 50% RAP results (CT index)

However, there is no statistically significant difference in cracking resistance for these three mix types as indicated in the table below.

Table 3.8 ANOVA Analysis for CT index (50% RAP)

Source	Degrees of Freedom	Sum of Squares	Mean Squared Err.	F-stat	p-value
% RAP	2	165.1	82.56	1.59	0.280
Residual	6	311.9	51.98	-	-
Total	8	477	-	-	-

The CT_{index} results comparing the two RA treatments for 70% RAP replacement is shown in Figure 3.8. Both RA1 and RA2 improve the cracking performance of the 70% RAP replacement mix type when compared to the 70% RAP mix with no RA treatment.

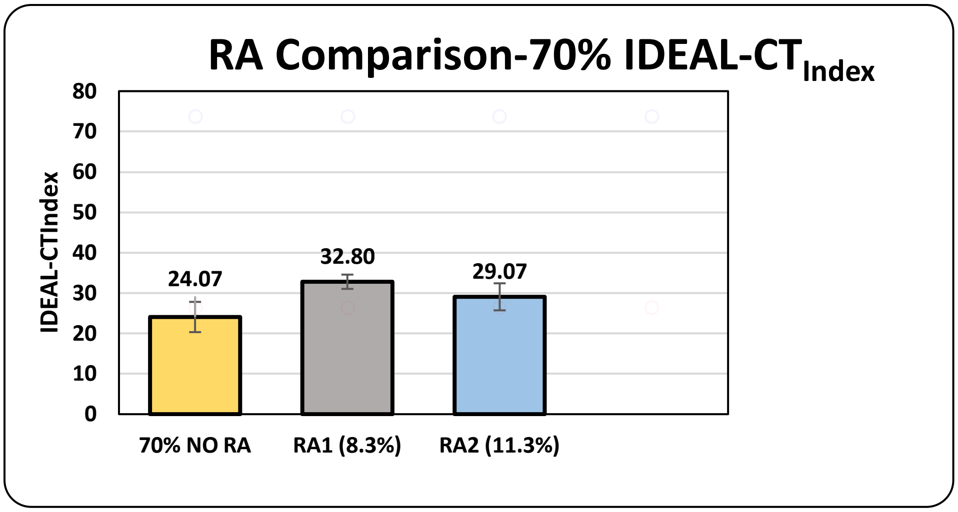

Figure 3.8 IDEAL-CT 70% RAP results (CT index)

It is in the resulting ANOVA table below that there is no statistical difference between the RA treatments for 70% RAP.

Table 3.9 ANOVA Analysis for CT index (70% RAP)

Source	Degrees of Freedom	Sum of Squares	Mean Squared Err.	F-stat	p-value
% RAP	2	115.2	57.6	2.12	0.202
Residual	6	163.4	27.23	-	-
Total	8	278.6	-	-	-

3.4.5 IDEAL-CT Results – RA1 Dose Comparison

The CT_{index} results comparing the two RA1 doses for 25% RAP replacement is shown in Figure 3.9. It is shown in the figure that RA1 dosed at 6.6% is noticeably lower than the other options. The lower dosage was not as effective in improving the cracking resistance when compared to the other mixes with No RA, PG64-34, or RA1 at 8.3%.

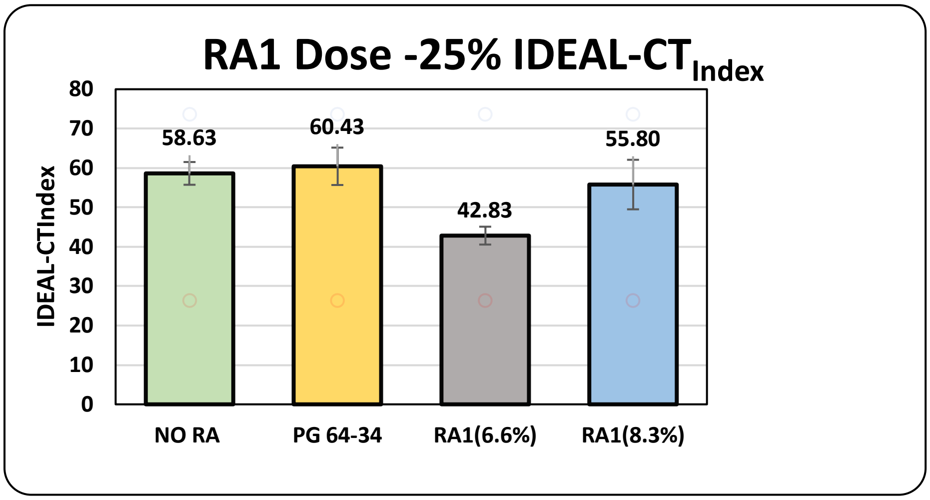

Figure 3.9 IDEAL-CT 25% RAP results (CT index) – RA1 Dose

As previously seen, the 25% RAP replacement mixes did not have a statistically notable difference in terms of cracking resistance even in terms of RA1 dose. This is further seen in the ANOVA table below

Table 3.10 ANOVA Analysis for CT index (25% RAP) – RA1 Dose

Source	Degrees of Freedom	Sum of Squares	Mean Squared Err.	F-stat	p-value
% RAP	3	570.2	190.07	2.24	0.161
Residual	8	679.8	84.98	-	-
Total	11	1250.0	-	-	-

The CT_{index} results comparing the two RA1 doses for 50% RAP replacement is are displayed on Figure 3.10. The ANOVA analysis indicated that there is no statistical difference between the different RA1 doses at this 50% RAP replacement. However, there is a slight improvement in cracking resistance over no RA treatment and RA1 at a dosage of 6.6%.

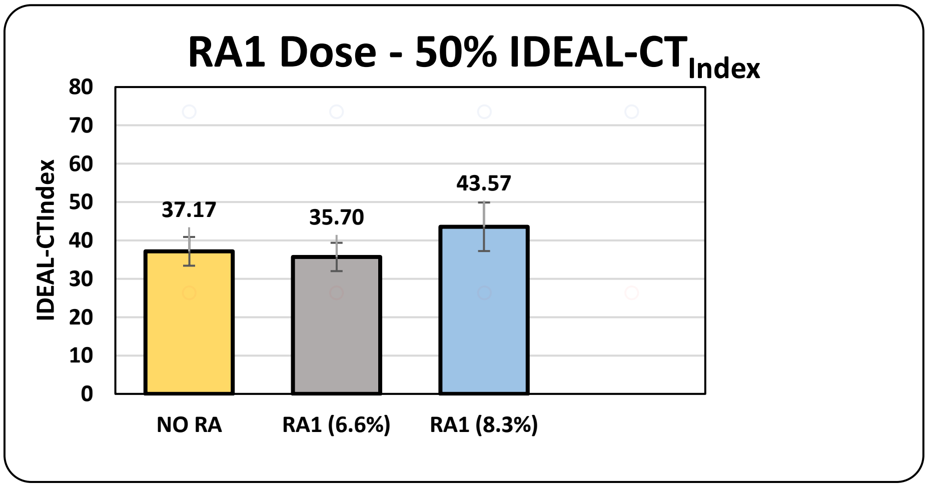

Figure 3.10 IDEAL-CT 50% RAP results (CT index) – RA1 Dose

The RA1 dose does not have any statistical impact on the 50% RAP replacement results; this is shown in the ANOVA table seen below.

Table 3.11 ANOVA Analysis for CT index (50% RAP) – RA1 Dose

Source	Degrees of Freedom	Sum of Squares	Mean Squared Err.	F-stat	p-value
% RAP	2	105	52.5	0.51	0.624
Residual	6	615.7	102.62	-	-
Total	8	720.7	-	-	-

The CT_{index} results comparing the two RA1 doses for 70% RAP replacement are summarized in Figure 3.11. The RA1 did improve the cracking resistance of the 70% RAP mix but is still substantially lower than the current ITD criteria (80).

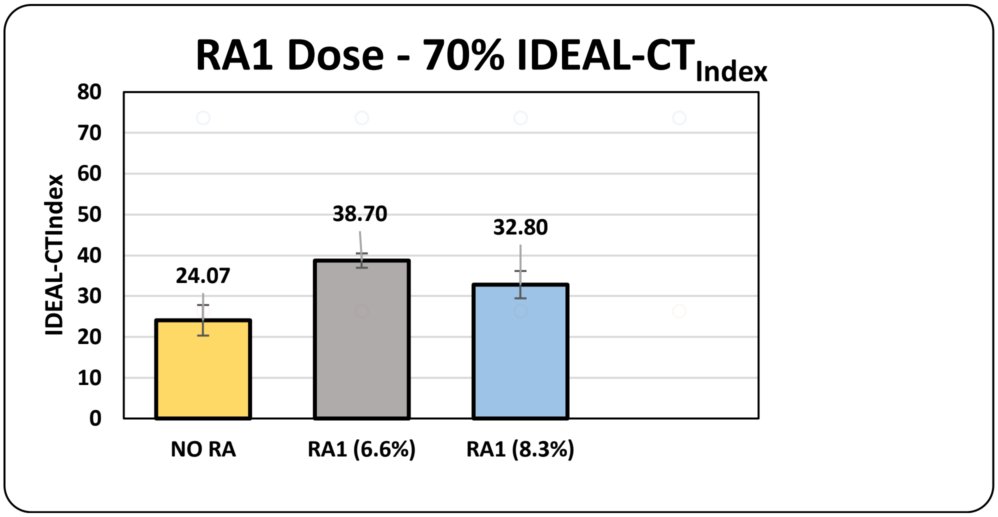

Figure 3.11 IDEAL-CT 70% RAP results (CT index) – RA1 Dose

As seen in the ANOVA analysis table below, there is a statistically significant difference between RA1 doses at 70% RAP. When conducting the multiple comparison, the results indicate that there is significant difference between NO RA and RA1 dosed at 6.6%.

Table 3.12 ANOVA Analysis for CT index (70% RAP) - RA1 Dose

Source	Degrees of Freedom	Sum of Squares	Mean Squared Err.	F-stat	p-value
% RAP	2	325.2	162.61	5.14	0.05
Residual	6	189.7	31.62	-	-
Total	8	514.9	-	-	-

3.4.6 ANOVA Analysis Results

In addition to the one-way ANOVA analysis performed on individual comparisons, a two-factor fixed ANOVA analysis is also conducted on the data to determine the statistical significance of interaction effects for HWTT and IDEAL-CT results. This research study considers two independent factors; the first factor is rejuvenator type (NO RA, RA2 @ 11.3%, RA1 @ 6.6% and 8.3%) and the second factor is the percentage of RAP replacement (25%, 50%, 70%). The dependent variable that is being analyzed and quantified in this study are the results (CT index, rut depth). This analysis was performed with a 95% confidence interval ($\alpha = 0.05$).

The F-stat, which is a calculated ratio between the different mean squared errors of the source and residual, determines the p-value. If the determined p-value is greater than $\alpha = 0.05$, the influence is statistically insignificant. A p-value resulting in less than $\alpha = 0.05$ indicates a statistically significant interaction. The ANOVA results for HWTT rut depth, CT index, and Fracture Energy are described in the tables below.

Table 3.13 HWTT - ANOVA Analysis

Source	Degrees of Freedom	Sum of Squares	Mean Squared Err.	F-stat	p-value
RA type	3	1.02543	0.3418111	4.1820283	0.030477
% RAP	2	0.381325	0.190663	2.33274	0.139378
RA x RAP %	6	1.355642	0.22594	2.76436	0.063205
Residual	12	0.9808	0.08173	-	-
Total	23	3.7432	-	-	-

The data displayed in Table 3.14 summarizes the results of the ANOVA analysis conducted on the HWTT rut depth data. From this analysis, it is apparent that the only significant influence that impacts rutting resistance is the type of rejuvenator. The analysis suggests that RA type in the context of bio-based rejuvenators and petroleum derived rejuvenating agents (RA1 and RA2, respectively) have disproportionate effects on the rutting resistance of a RAP asphalt mix. Furthermore, the data suggests that special considerations should be made when selecting rejuvenating agents as the data suggests that rejuvenating agent chemistry plays a role in rutting resistance performance due to the differing chemical compositions of the rejuvenating agents used in this study.

Table 3.14 CT index - ANOVA Analysis

Source	Degrees of Freedom	Sum of Squares	Mean Squared Err.	F-stat	p-value
RA type	3	167.65	55.88	0.68725	0.5686
% RAP	2	2945.91	1472.96	18.11395	0.000016
RA x RAP %	6	780.16	130.03	1.59902	0.190706
Residual	24	1951.59	81.32	-	-
Total	35	5845.31	-	-	-

Table 3.14 outlines the results of the ANOVA analysis conducted on the CT index results. This two-way layout indicates that the percentage of RAP replacement does have a statistically significant impact on the results of the CT index value. The analysis suggests that the IDEAL-CT test is more sensitive to percentage of RAP incorporated in a mix than the RA type. This suggests that limiting the percentage of RAP is more effective in mitigating cracking distress than the chemical composition of rejuvenating agents. A further point of future research would be to investigate whether higher percentages of rejuvenating agent have a statistically important effect in mitigating cracking distresses when measured in the IDEAL-CT test.

Table 3.15 Fracture Energy - ANOVA Analysis

Source	Degrees of Freedom	Sum of Squares	Mean Squared Err.	F-stat	p-value
RA type	3	10838414.1	3612804.69	1.6900802	0.6901
% RAP	2	18809660	9404829.99	4.3996059	0.02356
RA x RAP %	6	15523367.8	2587227.97	1.2103125	0.33516
Residual	24	51303668.1	2137652.84	-	-
Total	35	96475110	-	-	-

Similarly, Table 3.15 summarized the ANOVA analysis performed the fracture energy recorded from the IDEAL-CT. The results indicate that the RAP replacement is the primary significant factor in the cracking resistance between each of these mixes. This result is in line with the conclusion gained in the ANOVA analysis of CT Index summarized in Table 3.15.

3.4.7 Cost Benefit Analysis

A brief cost benefit analysis is seen in Figure 3.12 below. The costs used for the virgin aggregate and virgin binders were estimated by averaging some data for these costs over several months from ITD projects. The RA costs were provided by the manufacturer. In addition to cost breakdown, the CT index is also included above each bar to consider the cracking resistance and cost analysis together. As expected, in general the cost decreases as the RAP replacement increases. However, the CT index is also correlated with this and dcreases as the RAP replacement increases.

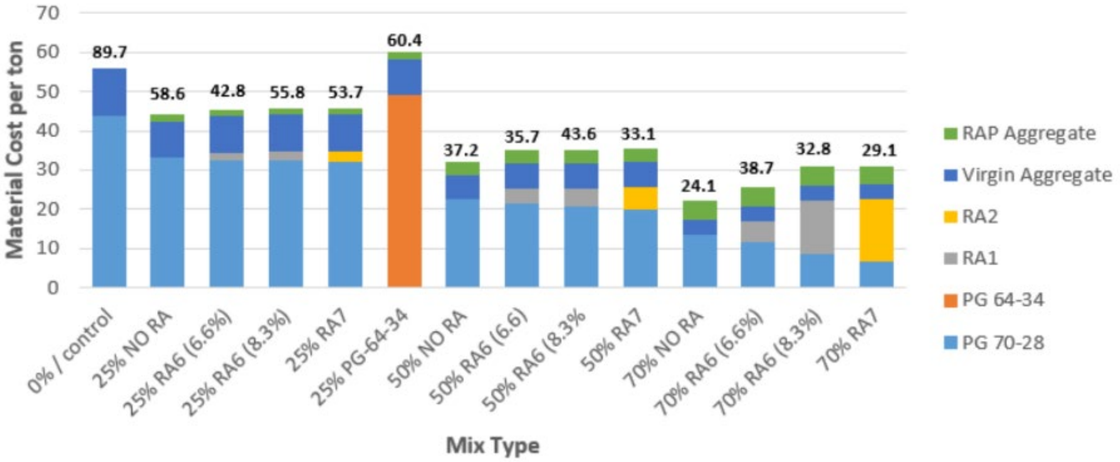

Figure 3.12 HWTT results (mm)

There are some interesting things seen in the cost analysis Figure 3.12 above. It is evident that the virgin asphalt binder is the costliest portion of any of the mixes. This adds to the motivation for finding a sustainable way to improve the availability of RAP binder in these mixes; to lower the need for large amounts of virgin binders which will ultimately reduce cost significantly. However, the distress resistance also needs to be met for it to be worth it. Another interesting trend is seen with the 25% RAP inclusive mixes. Here, we analyzed the cracking resistance and cost analysis of the current practice, which is to use one virgin binder grade lower than the target design PG binder (PG 64-34 in this case) and compared it to the application of rejuvenators and a no RA mix. While the cracking resistance results were not statistically significantly different, the use of RAs in these mixes decrease the overall mix cost by ~$15/ton in comparison to the current practice.

3.4.8 FTIR Analysis

The final step in our analysis of this study is characterizing the blended RAP and rejuvenating agent binder blends via infrared spectrometer (FTIR) to investigate the chemical composition and identify differences to understand the outcomes in mix performance and binder testing. Infrared spectrometry uses infrared radiation to pass through a sample, where some of this radiation is absorbed. Different chemical molecules produce a different ‘fingerprint’ section and level of absorbance, so the wavenumber and level of absorbance can be used to identify or compare the chemical composition of different samples. The following blends and mix components are chemically compared using the FTIR; RAP binder, PG 64-34, PG 70-28, PG 64-34 w/ RAP binder, RA1, RA2, blend1 (RA1 @ 8.3% w/ RAP), and blend2 (RA2 @ 11.3% w/ RAP). Where the dosages correspond to the optimum dosage needed to blend the RAP binder back to the target PG grade of PG70-28.

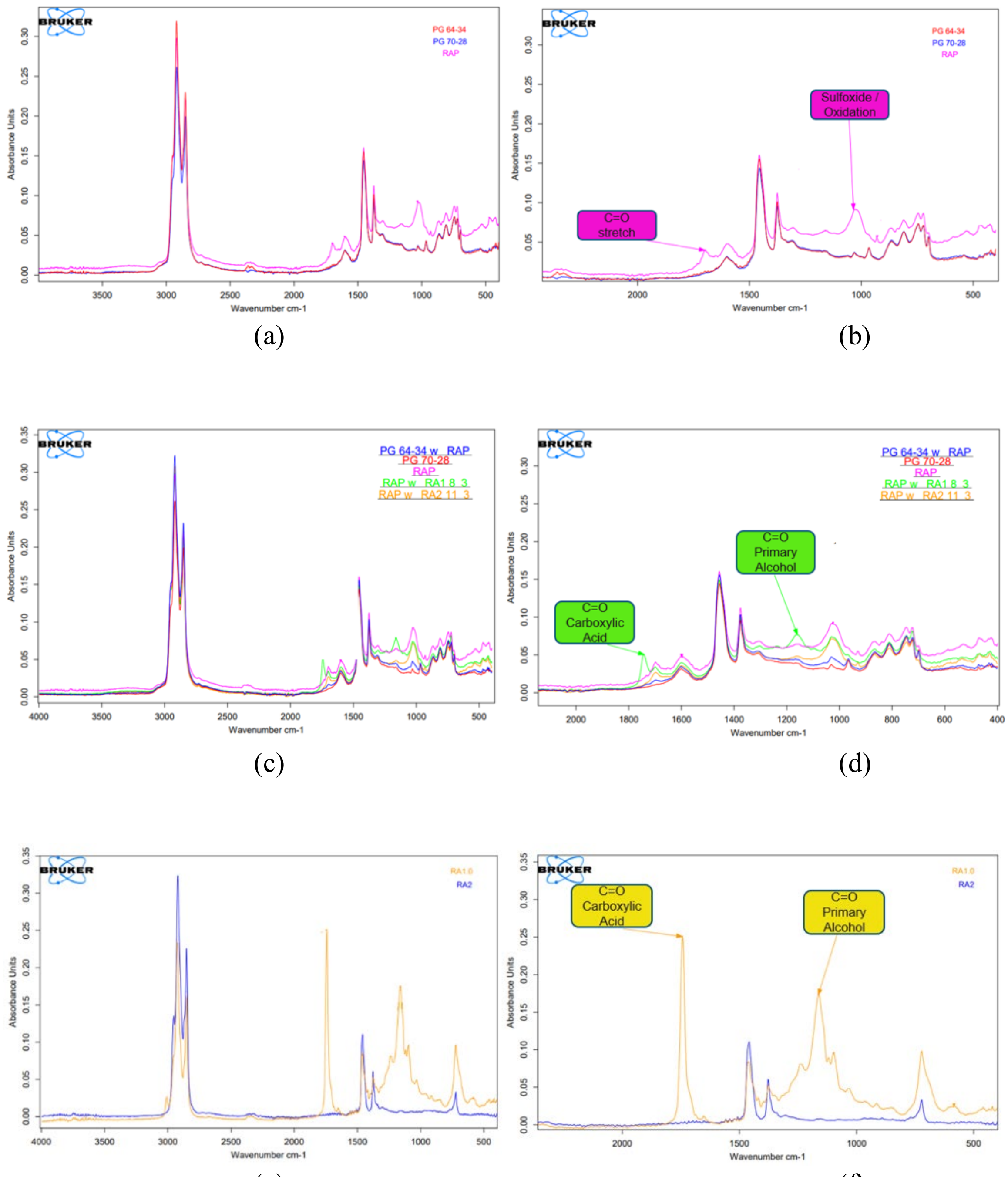

Figure 3.13 (a-f) FTIR Chemical Composition Analysis

(a) PG 70-28, PG 64-34, RAP; (b) PG 70-28, PG 64-34, RAP - fingerprint sec.
(c) PG 70-28, PG 64-34 w/ RAP, RAP, blend1, blend2;
(d) PG 70-28, PG 64-34 w/ RAP, RAP, blend1, blend2 - fingerprint sec.
(e) RA1, RA2; (f) RA1, RA2 - fingerprint sec.

The FTIR graph compares the absorbance spectra of molecular compounds versus their corresponding wave number measured incm^{-1}. The comparison of the different blends and components utilized in the RAP inclusive and virgin mixes are summarized in Figure 3.13 (a-f). For each set of FTIR results, the graph on the left corresponds to the complete chemical profile of the binder. The graph on the right corresponds to the fingerprint region of the chemical profile shown on the left with specific identifying characteristics of the binder.

Figure 3.13 (a) and (b) compare the chemical composition of the RAP, PG 64-34, and PG 70-28. This graphically depicts the differences between the RAP binder, which is aged and oxidized, in comparison to virgin binders PG64-34 and PG70-28. This reinforces the goal of once again, utilizing the RAs to blend the RAP binder down to the PG 70-28 chemical composition. The labeled C=O stretching, and sulfoxide/oxidation are seen at a higher absorbance in the RAP binder. This is consistent with oxidized asphalt binders that display higher concentrations of sulfoxides as compared to the virgin binders that do not have significant amounts of sulfoxides present in their chemical compositions. The chemical difference between the PG 70-28 and PG 64-34 is not significantly different chemically based on the graph output comparing these two.

Figure 3.13 (c) and (d) examines the differences between the following blends: PG 70-28, PG 64-34 w/ RAP, RAP, blend1, blend2. Seen in Figure 3.13 (d), there are two unique peaks identified in blend1 compared to the other blends. Specifically carboxylic acid and primary alcohol are the two distinctive differences here, which makes sense given that RA1 is bio-based and chemically includes fatty acids. This is further seen in Figure

3.13 (e) and (f), which compare the chemical structure of RA1 and RA2. The FTIR analysis can be used to identify potential reasoning for material behavior in mix design.

3.5 Conclusions

This research project and the results are intended to act as a benchmark to pave the way for future research and industry practice for high RAP mix design. This is a difficult problem in the asphalt industry due to negative influence from RAP, RAP variability, control of RAP properties, and cracking resistance compromise. The results of this research propose the framework use of the Consi-Grad method for the development of high RAP mix design. In addition, the use of the IDEAL-CT resulting CT index of cracking resistance verification has historically indicated high variability. This research has outlined the statistical sensitivity of the IDEAL-CT and resulting fracture energy that could provide supplemental performance verification to current practice of solely using the CT index as an indicator of cracking resistance. The results collected thus far provides solid groundwork that has built and added to successful methods developed previously_(Kaseer et al., 2019; Zhang et al., 2021).

1. Implementing the Consi-Grad method of high RAP mix design has been outlined in this paper; specifically focusing on consistent gradation, overall mix asphalt content, conducting binder blend testing to output a rejuvenator blending chart for dosage, and utilizing RAP material without any alterations. This method has indicated success in effectively comparing performance testing between varying RAP inclusive mixes.

2. The bio-based rejuvenator (RA1) performed better in terms of cracking resistance in comparison to the petroleum-based rejuvenator (RA2), which suggests this rejuvenator type might be the optimal choice for revitalizing RAP properties.
3. Statistically speaking, the IDEAL-CT is sensitive to the percentage of RAP replacement. The only notable statistical significance when comparing the rejuvenator type and dose, was observed at 70% RAP replacement.
4. The method of developing a blending chart for rejuvenator dosage was successful in providing a starting point for a consistent method of binder blend analysis to determine optimum RA dose for mix design.
5. The FTIR analysis complemented the binder blend testing and performance testing results by giving a chemical composition profile of the differences between the blends.

3.6 Acknowledgments

We thank the Idaho Transportation Department (ITD) for supporting and funding this project. We thank Emad Kassem (University of Idaho) for the support and knowledgeable discussions included in conducting this research project. We thank Idaho Asphalt Supply Inc. for providing the asphalt binder, rejuvenators, and support used throughout this project. We thank Knife River Inc. for providing the virgin aggregate and RAP aggregate incorporated for all the mixes developed in this project.

3.7 Author Contributions

All authors reviewed the results and approved the final version of the manuscript.

CHAPTER 4: CONCLUSIONS

Using Recycled Asphalt Pavement material in the design of new pavement mixes has many benefits in terms of cost savings and sustainable solutions. Specifically, the interest in “high” RAP mixes (more than 25% RAP replacement) has grown substantially with DOTs and contractors. There are many challenges in this field of work that still need more improved solutions before successfully developing high RAP mixes to perform comparably well to virgin mixes. There are many factors that contribute to the difficulties of creating a well-performing high RAP mix including but not limited to; the method of mix design, RAP properties, degree of blending between RAP binder and overall mix, and dosage and effectiveness of rejuvenators.

Currently, there is no standard practice of operation for a method of mix design with high levels of RAP replacement and as a result, there is a need for a consistent procedure that can be followed and applied to various projects in the pavement industry. RAP properties such as gradation, available RAP binder, and true grade are all factors that are extremely difficult to control in terms of interaction and overall mix characteristics. These properties are difficult to control in mix design but even harder to control in real-world applications due to RAP source variability and influence. The end goal outcome of this broad area of research is to have a standard practice of mix design that incorporates BMD processes that can be applied to a wide range of projects with various climates, loading conditions, RAP properties, and still able to meet the criteria specifications of state or federal agency requirements.

There is significant past research in this area, and it is currently a hot topic in the pavement research industry. Some research projects have indicated very promising results by applying a BMD procedure to mix design to high RAP mixes that also have project cost savings and extended service life in some cases (Meroni et al., 2020). When exploring the use of RAs, previous research has also determined the high temperature binder blend criteria should be used to select the optimal RA dose (Epps, et al., 2020).

This research project contributed to this area of influence by a method of proposing a method of high-RAP mix design that mitigates influence from gradation and asphalt content. This project conducted a controlled experimental mix design that followed the prosed process to evaluate the performance of two RAs, comparison of influence from RA dosage, and relationship between the rheological properties, chemical composition, and performance of these RAP inclusive mixes at varying levels.

4.1 Contribution of Work

A proposed method of mix design (Consi-grad) was developed in this research based on an in-depth review of previous research that indicates a need for a consistent method to follow when considering high RAP mix design. This initially proposed method and the motivation for this research are followed by a comprehensive experimental design project that considered two RAs, two RA1 doses, three levels of RAP replacement (25%, 50%, and 70%), and a three-tier system of analysis for each binder blend and mix type. These two topics are described separately in two manuscripts that are to be submitted to two different journal publications and the two manuscripts are reviewed in depth throughout the course of this thesis paperwork.

This research project aimed to build on and tie previous and current research together to result in a much more consistent method of mix design that eliminates influence from variables in the mix such as gradation and asphalt content (AC%). This was a result of a lack of current practice that bridges the gap between the current practice of Superpave and the continuously developed BMD in the pavement industry. The proposed method considers a virgin mix that meets the criteria for volumetric requirements, then takes the key consistencies (gradation and AC%) and applies that to a RAP-inclusive mix. This first research introduction also sets up the stage for why there is a need for rejuvenating and recycling agents as RAP percentage increases. The motivation and the proposed method are described in manuscript 1 which is to be submitted to the ASCE Journal of Performance Constructed Facilities

Previous research has provided a strong base to develop from with good indicators of how to optimize the RAP contribution in the overall mix, performance testing that is suitable for these RAP-inclusive mixes, and methods of selecting RA type and dose. Additionally, the proposed method was conducted in an experimental design process and the results were analyzed to determine the statistical significance of factors such as RA type and dosage, and percentage of RAP replacement. This was done due to the overall gradation and asphalt content of the mixes being consistent and controlled to allow for specific interaction analysis of the binder component of the overall mix. This work was summarized in manuscript 2 and will be submitted to the International Journal of Pavement Engineering.

4.2 Implementation

The results of this research project effort are applicable to both the research industry and the construction industry (local or federal). Many DOTs are gravitating towards an interest in increasing the allowable percentage of RAP replacement in new pavement design. However, to apply this is specifications, there must be a way to ensure the pavement service life and performance is continued to be met, otherwise it is not worthwhile in the cost savings. Because of this, many state and federal agencies are conducting or funding research in interest to get to a point where high RAP-inclusive pavement can be confidently designed. This research was funded by the Idaho Transportation Department with the goal of laying down a solid base to start developing a path toward high RAP mixes. Additionally, the FHWA is conducting increasingly more research in this area as well to increase sustainability, cost savings, and innovative solutions for global challenges that may come down the line. The findings from this research will contribute to this end goal of successful, sustainable practice in pavement design.

4.3 Recommendations for Future Work

Throughout the process of this research project, several areas of potential future topics in this area of research rose to the surface. These possible future topics include field application, comparison of more RAs, conducting a full-scale BMD experimental design, additional analysis with FTIR testing, and including more performance testing such as the Tensile Strength Ratio (TSR - analyzes moisture susceptibility). There is a significant difference between research done in a controlled laboratory setting compared to field application industry setting for a project. This gap comes from HMA manufacturing and difficulty exactly controlling mix characteristics, and from influence from operators, field conditions, etc. Exploring the application of how a high RAP mix would realistically perform is a worthwhile area of investigation down the line. The two RAs tested are a good initial comparison, but it would benefit this area of research to further investigate additional RA types or similar ones; for example, comparing two different bio-oils. As previously mentioned, while this research did incorporate BMD method concepts to the approach, a full-scale BMD experimental analysis would consider optimum asphalt content, RAs, and performance testing to determine the optimal mix overall. This process would be a big undertaking and require a full-scale factorial design which is costly and time consuming, but would yield very interesting results to this area. Some research has shown promising results from analyzing the area under the peaks of the outcome FTIR curve to characterize the binder blends (Oldham & Fini, 2020). This would be a worthwhile approach to further understand the chemical properties of the blends and how it affects the rheological and performance properties. Finally, moisture susceptibility is another significant pavement distress that should be considered and tested with these high RAP mixes. As described, there are many topics in this area of research that would help solve some level of uncertainty that remains regarding the application of high RAP mix design implementation.

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