

**INCREASING ASPHALT RECYCLING
TO REDUCE PAVING COSTS, IMPROVE
PAVEMENT LONGEVITY, AND REDUCE
ENVIRONMENTAL IMPACT**

Final Report

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Oregon Department of Transportation

INCREASING ASPHALT RECYCLING TO REDUCE PAVING COSTS, IMPROVE PAVEMENT LONGEVITY, AND REDUCE ENVIRONMENTAL IMPACT

SPR 862

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16. Abstract: Recycling highway construction materials and minimizing the use of virgin materials can reduce pavement life cycle costs, improve highway network conditions, conserve natural resources, and protect the environment. Although using recycled asphalt pavements (RAP) is beneficial in many aspects, aged binder in RAP gives rise to failure under repeated high axle loads and thermal effects. Thus, in Oregon, the use of RAP is currently limited to about 30% by weight of the mix. For asphalt mixtures with a higher percentage of RAP, various strategic measures have been developed, including increased binder content, binder grade bumping, rejuvenators, and warm-mix asphalt (WMA) additives. However, selecting the most effective rejuvenators and WMA technology for Oregon, developing methods and guidelines for choosing the proper amount of additives, and ensuring appropriate mixing to achieve high RAP mixes without compromising the performance of the asphalt pavements is crucial. In addition, practices for better managing the RAP stockpiles at the asphalt plants (including process controls) play an important role in the mix performance and need careful investigation. This research study addressed the above-mentioned concerns through comprehensive experimental and analytical work, including the evaluation of performance, cost, and environmental benefits of using high RAP, incorporating the strategic techniques. The effect of RAP source variability, as well as in-plant variability, has also been studied. Further, the results were confirmed through statistical analysis. Results of the analysis indicate that the performance of RAP mixtures depends on binder content, RAP content, and binder grade. Considering all aspects, the appropriate selection of a strategic technique could enable a 10% higher RAP than the current allowable limit in Oregon, ensuring adequate performance while lowering economic and environmental burdens.			
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SI* (Modern Metric) Conversion Factors

Approximate Conversions to SI Units

Physical Quantity	Symbol	When You Know	Multiply By	To Find	Symbol
Length	n	inches	25.4	millimeters	mm
Length	ft	feet	0.305	meters	m
Length	yd	yards	0.914	meters	m
Length	mi	miles	1.61	kilometers	km
Area	in ²	square inches	645.2	square millimeters	mm ²
Area	ft ²	square feet	0.093	square meters	m ²
Area	yd ²	square yard	0.836	square meters	m ²
Area	ac	acres	0.405	hectares	ha
Area	mi ²	square miles	2.59	square kilometers	km ²
Volume	fl oz	fluid ounces	29.57	milliliters	mL
Volume	gal	gallons	3.785	liters **	L
Volume	ft ³	cubic feet	0.028	cubic meters	m ³
Volume	yd ³	cubic yards	0.765	cubic meters	m ³
Mass	oz	ounces	28.35	grams	g
Mass	lb	pounds	0.454	kilograms	kg
Mass	T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
Temperature (exact degrees)	oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	oC
Illumination	fc	foot-candles	10.76	lux	lx
Illumination	fl	foot-Lamberts	3.426	candela/m ²	cd/m ²
Force and Pressure or Stress	lbf	poundforce	4.45	newtons	N
Force and Pressure or Stress	lbf/in ²	poundforce per square inch	6.89	kilopascals	kPa

*SI is the symbol for the International System of Measurement

** Volumes greater than 1000 L shall be shown in m³

SI* (Modern Metric) Conversion Factors
Approximate Conversions from SI Units

Physical Quantity	Symbol	When You Know	Multiply By	To Find	Symbol
Length	mm	millimeters	0.039	inches	in
Length	m	meters	3.28	feet	ft
Length	m	meters	1.09	yards	yd
Length	km	kilometers	0.621	miles	mi
Area	mm ²	square millimeters	0.0016	square inches	in ²
Area	m ²	square meters	10.764	square feet	ft ²
Area	m ²	square meters	1.195	square yards	yd ²
Area	ha	hectares	2.47	acres	ac
Area	km ²	square kilometers	0.386	square miles	mi ²
Volume	mL	milliliters	0.034	fluid ounces	fl oz
Volume	L	liters	0.264	gallons	gal
Volume	m ³	cubic meters	35.314	cubic feet	ft ³
Volume	m ³	cubic meters	1.307	cubic yards	yd ³
Mass	g	grams	0.035	ounces	oz
Mass	kg	kilograms	2.202	pounds	lb
Mass	Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
Temperature (exact degrees)	oC	Celsius	1.8C+32	Fahrenheit	oF
Illumination	lx	lux	0.0929	foot-candles	fc
Illumination	cd/m ²	candela/m ²	0.2919	foot-Lamberts	fl
Force and Pressure or Stress	N	newtons	0.225	poundforce	lbf
Force and Pressure or Stress	kPa	kilopascals	0.145	poundforce per square inch	lbf/in ²

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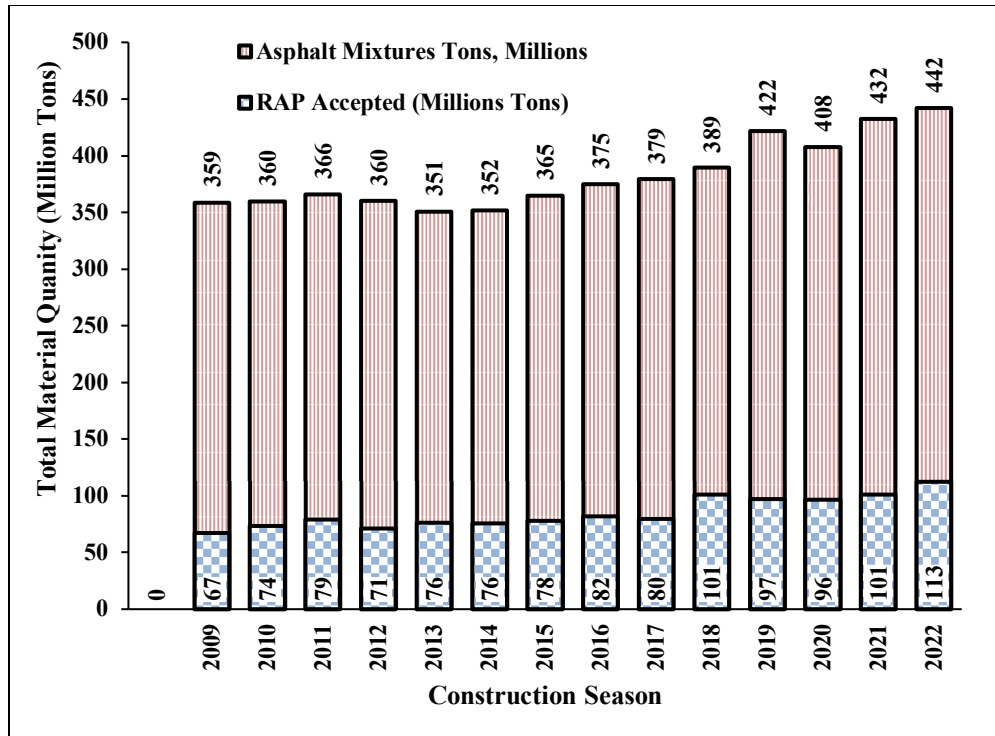
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1.0 INTRODUCTION

Recycling practices have become stringent, essentially to overcome scarcity and the higher cost of natural resources such as asphalt binder and mineral aggregates. The desire to conserve these natural resources and achieve sustainability in road construction has paved the way for the application of reclaimed asphalt pavement (RAP) material for paving purposes. In recent years, the Department of Transportation (DOT) in the United States has released a green signal on the application of RAP materials (in limited quantity) to produce the wearing/surface course of asphalt pavements (Williams et al. 2024). This is due to the scarcity and elevated cost of natural resources (asphalt binder and mineral aggregates) throughout the United States. In addition, the use of RAP is an approach to achieve carbon neutrality and move toward sustainable development (Costa et al. 2025; Mariyappan et al. 2023). In terms of carbon emissions, the National Asphalt Pavement Association (NAPA) (Williams et al. 2024) conducted a survey all around the United States and reported that the application of RAP in asphalt pavements leads to around 2.7 MMT CO₂e reduction in GHG emissions, which is equivalent to the annual emission caused by 596,000 passenger vehicles.

Considering the potential benefits of using RAP, DOTs are now moving ahead to pave asphalt pavements with higher amounts of RAP material. This impetus can be clearly observed in Figure 1.1, wherein the estimate shows the acceptance of RAP material increases with the construction season (2009-2022). The amount of RAP material increased from 67.2 million tons in 2009 to 112.6 million tons in 2022, resulting in a saving of around 4.9 million tons of asphalt binder and 93 million tons of natural mineral aggregates in 2022 (Williams et al. 2024). This estimate is higher than the numbers obtained in 2021, indicating an increase of around 2% in total asphalt mix production, with a 12% rise in RAP material acceptance. The accepted RAP material is used not only in the surface layer but also in unbound layers and other miscellaneous works. Figure 1.2 shows the estimated percentage of RAP material used in the United States in different layers and with different technologies. The majority of RAP was used in hot mix asphalt (HMA) and warm mix asphalt (WMA) production, and the lowest was reported for cold mix. This estimation came out in 2022, when the total production of asphalt mixture was approximately 441.9 million tons, including 112.6 million tons of RAP material accepted in asphalt plants throughout the United States. Out of 112.6 million tons of accepted RAP, 104.8 million tons of RAP were used for different purposes throughout the construction season, as shown in Figure 1.2. This indicated that more RAP was received than was utilized, resulting in an increment in the producer inventory of stockpiled material, which can be used for next year's construction season. It is a common practice to draw the RAP material from the inventory in cases when the RAP requirement is more than the available quantity in any particular construction season. As of 2022, the estimated amount of stockpiled RAP material is around 154.6 million tons across the United States (Williams et al. 2024).



Note: Bar represents the cumulative estimates per year.

Figure 1.1. Estimate of accepting RAP material for the construction season in the United States from 2009-2022 (Williams et al. 2024)

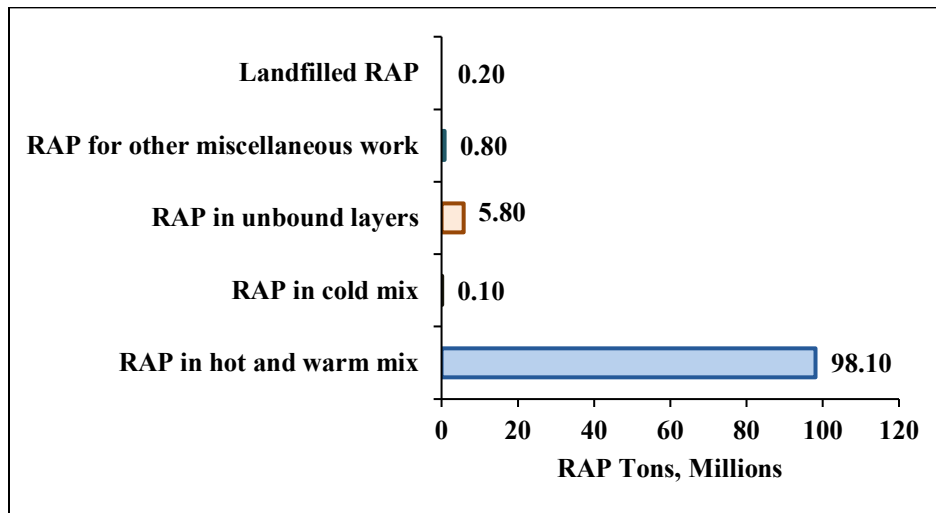


Figure 1.2. Estimate of the use of RAP for different construction sectors in 2022 within the United States (Williams et al. 2024)

Although using RAP is beneficial in many aspects, its application, quantity, and performance are usually governed by several factors, including RAP source, RAP binder content, age of milled pavement, neat binder grade, etc. (Bilema and Yuen 2025; Xia et al. 2025). On the other hand, incorporating high RAP raises several pavement-related concerns, including long-term

performance, material consistency, stiffness, blending challenges, compaction difficulties, and environmental impacts, which typically limit its use to about 10-25% (Alizadeh et al. 2025; Coleri et al. 2018a). *For this report, high RAP mixture is defined as the asphalt mixture containing 25% or more than 25% RAP.* In Oregon, for example, RAP content in asphalt mixtures is currently limited to 30% by weight of the total mix. Nonetheless, growing environmental pressures, combined with escalating costs of natural aggregates and virgin asphalt binders, urge the asphalt industries and agencies to utilize higher RAP contents.

RAP, in actuality, is not a single uniform material, but rather, it is a combination of used aggregates (coarse, fine, and fillers) and aged binder. Based on the aged binder condition, RAP can either be treated as a black rock (indicating inactive RAP binder) or RAP with an active binder, which may be partially or fully functional (Tebaldi et al. 2018). In the case of black rock, RAP material is taken as an aggregate, and the binder does not contribute to blending with the virgin binder (Lewis et al. 2024). In contrast, active RAP material can help lower the overall requirement of virgin binder by aiding in the blending process (Ali et al. 2021). The amount of inactive and active binder content in the RAP or the blending efficiency significantly affects the coating, workability, and durability of the asphalt mixtures, particularly when the RAP content is greater than 20%. In general, this scenario depends on the age of the demolished pavement from which the RAP is obtained.

In the past, Oregon Department of Transportation (ODOT) worked with the research team of Oregon State University (OSU)- Asphalt Materials and Pavement (AMaP) laboratory to understand the blending scenarios and quantify the amount of blending between RAP and virgin asphalt binder (Coleri et al. 2018a). The effect of different RAP sources, mixing temperature, and aggregate gradation on the blending mechanism was examined in the study. The recovered RAP binder was blended with the neat asphalt binder at different blending proportions (0%, 50%, and 100%) to replicate the degree of blending. It was found that only 45-60% of the RAP binder is blended/diffused within the actual asphalt mixture, indicating lower binder content than the design binder content because of the assumption of full blending. The research also revealed that higher production temperature does not solve the blending issues but provides similar results. Considering all the aspects, an average blending percentage of 56.5% was proposed for designing asphalt mixtures with high RAP content and desirable stiffness characteristics (Coleri et al. 2018a). Along with this research work, continuous collaboration between ODOT and OSU results in the development of balanced mix design (BMD) framework for Oregon (SPR 801), which categorized Oregon in a BMD pre-implementation phase (Coleri et al. 2020). As per the findings of the study, BMD is also an approach to increase the RAP material in asphalt pavements, ensuring adequate performance and durability. Further, the collaboration also introduces the concept of using RAP, a sustainable material, in the chip seals as a preventive measure on the Oregon road networks (SPR 858) (Baran et al. 2025a; b). In 2025, the OSU research team also recommended critical thresholds for cracking and rutting-resistant asphalt mixtures as a part of the BMD implementation plan (SPR852) to combat long-term performance goals for the Oregon road network (Chitnis et al. 2025). These critical thresholds were developed and validated through both laboratory and field projects.

With time, asphalt pavements are exposed to variable environmental conditions, traffic loading, and temperatures, which eventually affect the ability of the RAP binder to blend with the virgin binder. This is typically referred to as the aging process, during which the lighter oils and

maltenes present in the composition of asphalt binder evaporate and translate into high-viscosity asphaltenes (Bayoumi et al. 2024). As this transformation occurs, the binder becomes stiffer, resulting in reduced blending efficiency and thus contributing to pavement deterioration (Ferreira et al. 2021; Lewis et al. 2024). The aging process underscores the critical role that the age of RAP material plays in influencing the blending between RAP and virgin binder and the durability and performance of the RAP-inclusive asphalt mixture. Several other challenges occur with the use of RAP, including the inconsistency in the RAP material, which makes it difficult to achieve uniform performance throughout the pavement segment (Sukhija and Coleri 2025b). Apart from the performance, additional investment is required for the processing of RAP if used in large volumes, leading to high project costs (Zaumanis et al. 2014a). In addition, factors such as climatic exposure of RAP-inclusive asphalt pavements (highlighting the variation in RAP binder properties with climate), functional requirements (skid resistance and noise level), and user perception (ride quality and safety), all of which must be carefully managed. Owing to these challenges, RAP material extracted from the surface course was historically recycled into the base layer, where the strength and flexibility requirements are comparatively lower than those of the surface layers (Nahar et al. 2014; Zhao and Yang 2024).

Researchers found that various strategic techniques and RAP management schemes can be adapted to incorporate the RAP material in high proportions with desirable performance (Sukhija and Coleri 2025b; West 2015). These practices provide insight into how to manage the RAP material to achieve a higher level of uniformity in asphalt mixture production and construction with high RAP. In addition, it allows the use of high RAP as a major step towards constructing new asphalt pavements with adequate mechanical performance while promoting economic and environmental stewardship. Adequate performance at high RAP content tends to build the trust of engineers to use high RAP (preferably > 25%) in pavement recycling.

The strategic techniques include the use of rejuvenators, warm mix additives, increased binder content, binder grade bumping, and application of alternative materials for producing high RAP mixtures. In particular, Rejuvenators are the recycling agents that aid in restoring the chemical composition and the physical characteristics of the oxidized RAP binder (Naji and Taherkhani 2024; Prasad et al. 2023). In general, the addition of rejuvenators results in high aromatic content and a low asphaltene to maltene ratio (Jain et al. 2023, 2025). They increase the life of RAP material by imparting desired consistency and durability for achieving adequate engineering performance. They can vary in terms of size, shape, weight, or polarity (Yan et al. 2025).

Warm Mix Asphalt is a sustainable technology used to produce asphalt mixtures at lower temperatures (20-40°C) (Sukhija et al. 2023b, 2024). Since RAP is prone to cracking, such a reduction in temperatures helps mitigate further oxidative ageing of the RAP binder during production, which is especially important for the RAP mixture (Babazadeh and Taherkhani 2024). Despite lower production temperatures, WMA's ability to improve the coating, workability, and compatibility of the RAP-inclusive asphalt mixtures is a big advantage because it allows a higher RAP percentage without affecting the performance and improving the sustainability (De Pascale et al. 2025; Yousefi et al. 2025).

Increased binder content and Binder grade bumping are the adjustments in mix design attributes that can improve the RAP content by addressing the brittleness offered by the RAP binder (Coleri et al. 2018a). In increased binder content, an additional amount of binder is introduced to

increase the lubrication and binder film thickness over the aggregates, whereas binder grade bumping involves the replacement of binder with a low-grade binder (high-temperature grade lowered by one or two grades, depending on the specific requirement) to impart softness and flexibility in the mix. However, there are very limited studies in this direction, as other strategies, such as rejuvenators and warm mix additives, tend to deliver more benefits in terms of increasing RAP content while also lowering economic and environmental burdens.

Alternative materials, including the use of polymer-modified asphalt binder, crumb rubber, nanomaterial, fibers, waste plastic, etc., are valuable additions to the RAP mixtures for improving the quality, especially at higher RAP contents (Kocak and Asce 2024; Ziari et al. 2024). These materials can be integrated as a composite material with rejuvenators or WMA, or added separately (Arshadi et al. 2024; Lee and Minh Le 2025; Naji and Taherkhani 2024; Wang et al. 2025b).

Past experience (Lu et al. 2019, Xie et al. 2017, Zhou et al. 2016), also determined the synergistic effect of combining two different technologies, such as rejuvenators and WMA, to improve the RAP proportion with desirable performance, especially in addressing cracking concerns. It is expected that the addition of rejuvenators tends to restore the intrinsic properties of the stiff oxidized binder, while WMA helps lower the ageing of the asphalt mixture by reducing the production temperature. This implies that the performance is largely dependent on the type of materials and how they interact with RAP binder, rejuvenators, WMA, and the overall RAP content. By enhancing RAP mixture quality, these materials facilitate the use of higher RAP contents while maintaining robust quality control and assurance. Consequently, it is essential to investigate the integration of RAP management schemes, particularly those involving materials from different sources or samples collected from various locations within a stockpile, and their combined effects with widely adopted strategic techniques such as rejuvenators and WMA technologies. This also underscores the potential challenge of selecting the dosages as well as the most effective rejuvenators and WMA technologies. Furthermore, RAP is inherently a sustainable material, offering the potential to lower project costs, reduce carbon emissions, minimize landfill demand for reclaimed waste, conserve natural resources, and decrease fuel and energy consumption. Nonetheless, comprehensive life cycle assessment (LCA) and life cycle cost analysis (LCCA) are needed to substantiate its broader implementation in the field, particularly for high RAP proportions.

1.1 PROBLEM STATEMENT

The presence of aged asphalt binder on RAP aggregates significantly impacts the overall performance of asphalt mixtures, limiting RAP usage in Oregon to a maximum of 30%. While various strategic techniques have been proposed in the literature to enhance RAP utilization, selecting the most suitable methods and determining their optimal dosages remain critical challenges. Furthermore, improper RAP management and the direct use of unprocessed material in pavement construction lead to inconsistencies and non-uniformity in performance. To achieve high RAP content without compromising performance, effective RAP management practices must be developed and implemented. These practices should be evaluated in conjunction with strategic techniques to understand their interactions and general applicability across different material sources and influential variables. Incorporating these strategic techniques, along with improving plant RAP stockpile management, is expected to enable the use of higher RAP

percentages while enhancing long-term cracking resistance. Improved cracking performance and reduced asphalt mix costs will contribute to lower life cycle costs, reduced environmental impact, higher pavement condition ratings, and decreased roadway roughness across Oregon's transportation network.

1.2 OBJECTIVES AND SCOPE

The primary objectives of this research study are to:

1. **Assess performance impacts:** Investigate the influence of strategic techniques on the cracking and rutting performance of asphalt mixtures containing high RAP contents.
2. **Characterize binder behaviour:** Quantify the effects of rejuvenators and warm mix asphalt (WMA) technologies on the chemical composition and rheological properties of asphalt binders.
3. **Evaluate sustainability benefits:** Assess the changes in economic costs and environmental impacts associated with incorporating high RAP contents into asphalt mixtures.
4. **Analyze RAP management variables:** Determine the influence of binder grade, RAP source, and RAP sampling location on mixture performance as part of a comprehensive RAP management strategy.
5. **Develop implementation guidelines:** Formulate practical methods and recommendations for integrating rejuvenators, WMA additives, and RAP stockpile management practices into Oregon Department of Transportation (ODOT) processes to improve the quality and quantity of asphalt recycling in Oregon.

These aforementioned objectives are achieved through the following scope:

1. The potential of increasing RAP content in asphalt mixtures through higher binder content and binder grade bumping was evaluated using mechanical performance tests. Rutting susceptibility was assessed via the traditional Hamburg Wheel Tracking Test (HWTT), while fatigue cracking resistance was determined using the Indirect Tensile Cracking Tolerance Test (IDT-CT).
2. Other potential strategies, including the use of rejuvenators and warm mix asphalt (WMA) technologies, were also examined. The research plan first focused on determining and validating the optimal dosages of these additives, as well as identifying the appropriate production temperatures for WMA mixtures through a workability-based approach. Subsequently, asphalt binders were modified by incorporating the selected

dosages of rejuvenators and WMA additives using a high-shear mixer. These modified binders were then utilized to produce recycled asphalt mixtures containing varying proportions of RAP and evaluated in terms of mechanical performance (rutting and fatigue cracking).

3. The rejuvenator and WMA modified binders were experimentally evaluated in terms of chemical composition using Fourier Transform Infrared Spectroscopy (FTIR) and rheological characterization using a dynamic shear rheometer (DSR). Rheological tests include the evaluation of high-temperature performance grading and a robust binder fast characterization test (BTSV) to assess if the application of rejuvenator and WMA additives alters the behavior of virgin binders.
4. The economic and environmental impacts of the recycled asphalt mixtures prepared using different strategic techniques were determined through life cycle cost analysis and environmental life cycle assessment. This valuation revealed the advantage of using high RAP content in asphalt mixtures in terms of financial savings and sustainable infrastructure development.
5. The suitability of strategic techniques was also assessed by producing some of the asphalt mixture samples using a different source of RAP material obtained from a different asphalt plant. In addition, some of the RAP-inclusive asphalt mixtures were prepared using RAP materials acquired from a different location within the same RAP stockpile. These variations are included in this study to understand the change in performance of recycled asphalt mixtures with the change in RAP material sampling within and outside the asphalt plant. Also, it demonstrates the practicality of the RAP management scheme in improving asphalt recycling.
6. All the data and corresponding interpretations were compiled and consolidated into a report aimed at recommending updates to ODOT's current mix design guidelines.

1.3 REPORT ORGANIZATION

The organization of the report is as follows:

Chapter 1.0: This chapter introduces the problem statement, key objectives, and overall scope of the research work.

Chapter 2.0: This chapter synthesizes past work conducted in this domain, with emphasis on key interpretations, knowledge gaps, and associated challenges.

Chapter 3.0: This chapter details the materials and test methods adopted to accomplish the above-mentioned research objectives. The discussions on the characterization of asphalt binders and chosen additives are also presented in this chapter.

Chapter 4.0: This chapter presents the understanding of the adjustment in mix design attributes as a potential measure to enable higher RAP in the production of asphalt mixtures.

Chapter 5.0: This chapter explores the integration of additive-based strategic techniques, such as rejuvenators and WMA additives, with the view of increasing the RAP content in asphalt mix production. It also underscores the challenges associated with the selection of additive dosages and production temperatures of WMA.

Chapter 6.0: This chapter provides insights into the economic and environmental burdens of the RAP-inclusive asphalt pavements, highlighting how these impacts vary with different strategic techniques.

Chapter 7.0: This chapter examines the influence of the RAP management scheme, typically the impact of the RAP source and the RAP sampling location within a stockpile, on mixture performance. It further evaluates how these factors interact with rejuvenators and WMA additives within the mix design framework.

Chapter 8.0: This chapter illustrates a tentative conceptual plan for the field pilot section construction plan and performance monitoring.

Chapter 9.0: This chapter summarizes the key findings and highlights the major contribution of the study, while also providing potential directions for future research.

Chapter 10.0: This chapter lists all the references cited throughout the research work.

2.0 LITERATURE REVIEW

With the upsurge in urbanization, there is a drastic demand for extended road networks. Around 95% of the total road network comprises asphaltic pavements, and new pavement constructions are still underway worldwide. This resulted in an increased reduction of natural resources, and subsequently pointed out a need to find a suitable alternative that can be used fully or partially for the construction of asphalt pavement, provided that the alternative material should perform equivalent (or better) to the original material and should be cost-effective with a reasonable level of environmental impact (Hettiarachchi et al. 2019; Zaumanis and Mallick 2015).

Recycling asphalt pavements has become a prevalent technique for constructing asphalt pavements (Tarsi et al. 2020; Zhang et al. 2022). It acts as a sustainable pavement technology that ensures economic and environmental viability (Ben et al. 2022; Devulapalli et al. 2019). In addition, recycling addresses/counteracts the shortage of pavement materials such as asphalt binder and aggregates. However, the use of this technology is quite limited due to limited experience with this process and long-term performance concerns (Coleri et al. 2018a).

Reclaimed asphalt pavement (RAP) is the primary recycled product of asphaltic pavements (Copeland 2011; Hill et al. 2013). RAP has gained much popularity in the asphalt industry because it can mitigate the concerns associated with the disposal of waste material extracted after the service life of pavements (Alsalihi and Faheem 2020; Kusam et al. 2017). The process of using RAP in asphalt pavement is not new; rather, it started in the mid-1970s, and the advancement/development in RAP recycling is still in progress (Foroutan Mirhosseini et al. 2020; West et al. 2013). In the United States, the majority of state departments of transportation (DOTs) allowed the use of RAP, and approximately 28 of these DOTs attempted to design asphalt pavements with 20-30% RAP material, and about 4 DOTs are even using more than 30% RAP material (Williams et al. 2021). Figure 2.1 shows the maximum allowable percentage of RAP material in the surface course of asphalt pavements for different areas of the United States. This data was compiled based on the information highlighted in the standard specifications of state DOTs for road, bridge, and municipal construction. Most of the DOTs recommended adopting strategic measures if the RAP percentage exceeds 20% by weight of the total mix to ensure acceptable in-situ performance levels.

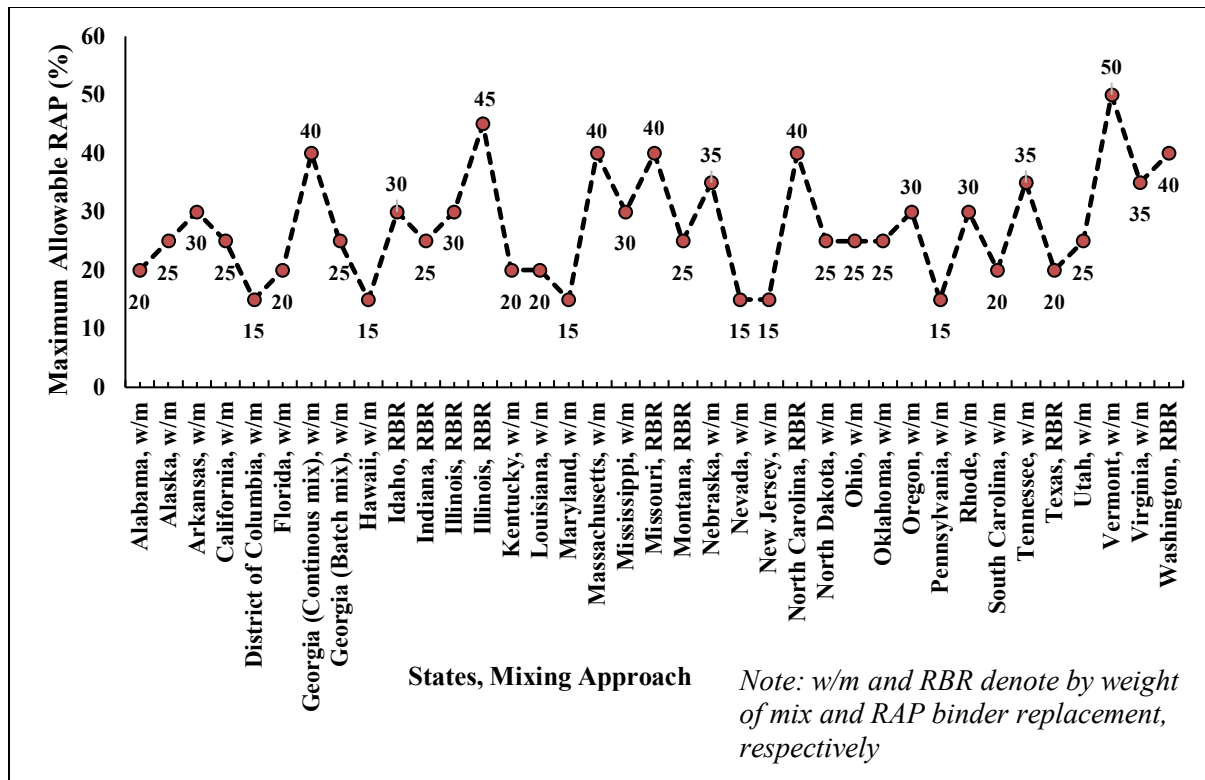


Figure 2.1. Allowable limit of RAP percentage for surface course

As per the survey conducted by Williams et al. (2021), more than 94.6 million tons of RAP material were milled and reused for the construction of asphalt pavements in the United States. Moreover, the use of RAP in construction work saved around 61.5 million cubic yards of landfill space for the disposal of extracted waste material (Williams et al. 2021). Such a high contribution indicates the potential of recyclability to minimize the use of natural resources, landfill space, and energy. It is well known that the use of RAP minimizes material cost and environmental impacts, eventually leading to higher cost savings and sustainable development (Calabi-Floody et al. 2020; Jahanbakhsh et al. 2020; Zaumanis et al. 2014a). However, various challenges arise with the use of RAP material during the design and construction stage, which limit the RAP proportions. Performance concerns are a major reason limiting the amount of RAP in the production of asphalt pavements (Antunes et al. 2019; Sharma et al. 2022). One other aspect affecting the RAP proportion is how the RAP is managed, starting from the milling operation till its use in the asphalt pavement (De Lira et al. 2015). Extracted RAP is usually non-homogeneous, which causes hindrance in the mix design, resulting in inappropriate asphalt binder content and aggregate gradation, higher variability in performance, and hence limits the RAP proportions (Tarsi et al. 2020). Non-homogeneity of RAP or the variability in resulting performance arises when the RAP from different sources is blended for a single project; RAP obtained from pavements with different in-service life, RAP extracted from pavements with distinct damage levels, multi-layer milling, etc. (Tarsi et al. 2020; West 2015). Thus, a proper RAP management scheme should be followed to reduce the variability in mix attributes and pavement performance.

In general, RAP comprises an oxidized binder film layer over the RAP aggregates that has aged over the service life of the extracted pavement. With the passage of time and experiencing differentiable traffic and temperature conditions, asphalt binder loses its volatile chemical components (conversion of maltenes into asphaltenes) and so its original viscoelastic characteristics, which consequently turns the RAP binder stiffer and brittle (Eltwati et al. 2022a; Kaseer et al. 2019b; Romera et al. 2006; Ziari et al. 2019a). Although the hardened binder layer can improve the rutting resistance susceptibility (Sun et al. 2019; Zaumanis et al. 2014b; Zhao et al. 2012), it adversely affects the performance against fatigue cracking, especially at higher RAP proportions (Daniel et al. 2010; Hill et al. 2013; Mogawer et al. 2013; Tam et al. 1992). The application of RAP, its quantity, and its performance are usually governed by several factors, including RAP source, amount of RAP binder, age of milled pavement, neat (a.k.a. virgin) asphalt binder grade, aggregate gradation, and production temperatures (Sharma et al. 2022; Tarsi et al. 2020; West et al. 2013). Furthermore, the blending between RAP binder and neat asphalt binder is essential to achieve adequate performance and longevity of RAP-inclusive asphalt pavements (Coleri et al. 2018a; Ma et al. 2022b). However, these issues are not very significant when RAP content is low ($\leq 20\%$) because there is not enough oxidized binder that can significantly change the properties of the final blended binder. Nevertheless, for high RAP contents ($\geq 25\%$), the presence of RAP binder can significantly change the blended binder properties and thereby affect the overall performance and expected service life (McDaniel et al. 2001; West et al. 2013). The definition of high RAP mixtures, i.e., mix with 25% or more than 25% RAP, was consistent with the previous studies conducted by the Federal Highway Administration (Copeland 2011) as well as in NCHRP report 752 (West et al. 2013).

In order to improve pavement longevity, along with reduced paving costs and environmental burdens, various strategic measures have been developed and proposed in the past literature (Behnood 2019; Guo et al. 2020a; Hettiarachchi et al. 2019; West et al. 2013). These strategic measures include the use of rejuvenators/recycling agents, warm mix asphalt additives, binder grade bumping, increasing neat asphalt binder content, and application of commonly used modifiers and fibers for the production of RAP-inclusive asphalt mixtures (Coleri et al. 2018a). These techniques also aid in increasing RAP contents above 20%, perhaps even up to 100%, without sacrificing long-term durability (Zaumanis et al. 2015, 2016). However, the selection of these techniques is not straightforward because it depends on various factors, including the quantity and stiffness of the oxidized RAP binder present over the RAP aggregates. The primary objective of using these techniques is the same, that is, to increase the RAP content or to provide improved performance at a fixed RAP content, but their working mechanism is quite different. The extent of improvement in performance or RAP content depends on the strategic measure and their accurate implementation in the mix design process. Since RAP could cause premature fatigue and low-temperature cracking due to stiff RAP binder, an appropriate technique could be one that provides enough resistance against fatigue cracking without degrading the rutting performance (West et al. 2013).

This literature review aims to conduct a comprehensive review of RAP management and the steps involved in processing, handling, and finding the variability in RAP. The suitable methods to characterize the RAP materials have been critically reviewed. The strategies to develop durable asphalt pavement with high RAP have also been reviewed and compiled for better understanding. The impact of RAP on the binder and mixture performance has also been focused on in this work. Overall, this literature review work intends to provide an updated overview of

high RAP in asphalt pavements. It is presumed that this individual report may provide a clear understanding of using RAP to a certain extent.

2.1 RAP MANAGEMENT TECHNIQUES

Most asphalt-surfaced pavements in the United States are constructed with RAP < 25%. The effective utilization of RAP is driven through a well-defined management scheme, which includes processing, handling, and characterization of RAP before the mix design process (West et al. 2013). However, there is a lack of proper guidelines on processing and handling RAP, which limits its use for pavement construction. The performance of RAP mixtures depends on how the RAP is managed throughout the production stage (Tarsi et al. 2020). Uncontrolled RAP processing and handling cause high variability, either in aggregate gradation or asphalt content. A few types of studies in the literature (McDaniel et al. 2001; West 2015) recommended using RAP from a single source to maintain homogeneity and consistent characteristics. For instance, the RAP obtained from a single source can be easily used in a small project; however, it is very challenging to use the RAP of a single source in a large project due to insufficient material or a large number of material requirements. RAP from multiple sources must be incorporated in this case to produce asphalt mixtures. Multiple sources comprise a huge difference in pavement structure and layer composition among the obtained RAP, resulting in an unpredictable performance (Austerman et al. 2020; Montañez et al. 2020). Thus, there is a need for a new mix design method that involves the performance testing of the mixes prepared with multiple RAP sources. Accordingly, the mix design practice should be adjusted to ensure pavement longevity. In addition, it may cause inhomogeneity, requiring further processing and management practices to offset the variability associated with multiple sources of RAP. An ideal approach is to limit the variability of stockpiled RAP to produce asphalt mixtures with high RAP content, considering the requirement of mix design and project cost (Copeland 2011). It must be noted that two basic indices, namely the cost-effectiveness and quality of RAP, should be prioritized throughout RAP management.

RAP management schemes differ from country to country or even state to state. Following a proper management scheme would aid in ensuring the performance characteristics of RAP mixes are better or similar to the asphalt mixtures with no RAP content in terms of long-term performance, environmental impact, and economic aspects (West 2015). In general, the management process starts with the milling operation, followed by the processing of RAP, which includes crushing and screening, stockpiling, meeting mix design requirements, and quality control during the preparation of recycled asphalt mixtures. These are discussed in the subsequent sections.

2.1.1 RAP Processing

2.1.1.1 Milling

It is well known that the properties of RAP depend not only on the pavement from where it is obtained, but also on the removal/scraping technique (Zaumanis et al. 2021). Old asphalt pavements are generally scrapped through the milling operations to produce RAP. Milling, an indispensable component of the recycling process, has now been considered under the RAP management scheme (West 2008, 2015). To date, the research evaluating

the effect of milling parameters and their significance is scant. The milling process requires a milling system (as shown in Figure 2.2) to remove the pavement surface. It can be carried out in a single pass or more, depending on the thickness of the pavement. A considerable amount of fine aggregates is generated during the milling operations. Thus, the final aggregate gradation of milled RAP is often finer and denser than the gradation of the natural aggregates (Antunes et al. 2019). These fine aggregates increase filler content (around 40%) in the overall design gradation and may negatively affect the mix volumetrics (Zaumanis et al. 2021). The generation of fines may be attributed to the degradation of aggregates during the milling operation. Also, there is a possibility of mixing RAP with the underneath base and subbase layer aggregates (Debbarma et al. 2020). It may indicate an inappropriate particle size distribution and affect the final aggregate gradation. In this situation, where the milled RAP is mixed with the aggregate material of underlying unbound layers, it is better to use the RAP in the base, subbase, and shoulders instead of asphalt mix production (Arshad and Ahmed 2017).



Figure 2.2. Milling of asphalt pavement

Since milling is a function of different parameters associated with the milling machine, there are chances of variations that can occur with the change in such parameters (Tarsi et al. 2020). These parameters include the type of milling equipment used to remove the material, drum size, speed of drum and milling machine, dimensions and angle of milling teeth, number of teeth, etc. Some of the parameters associated with the milling machine are shown in Figure 2.3.

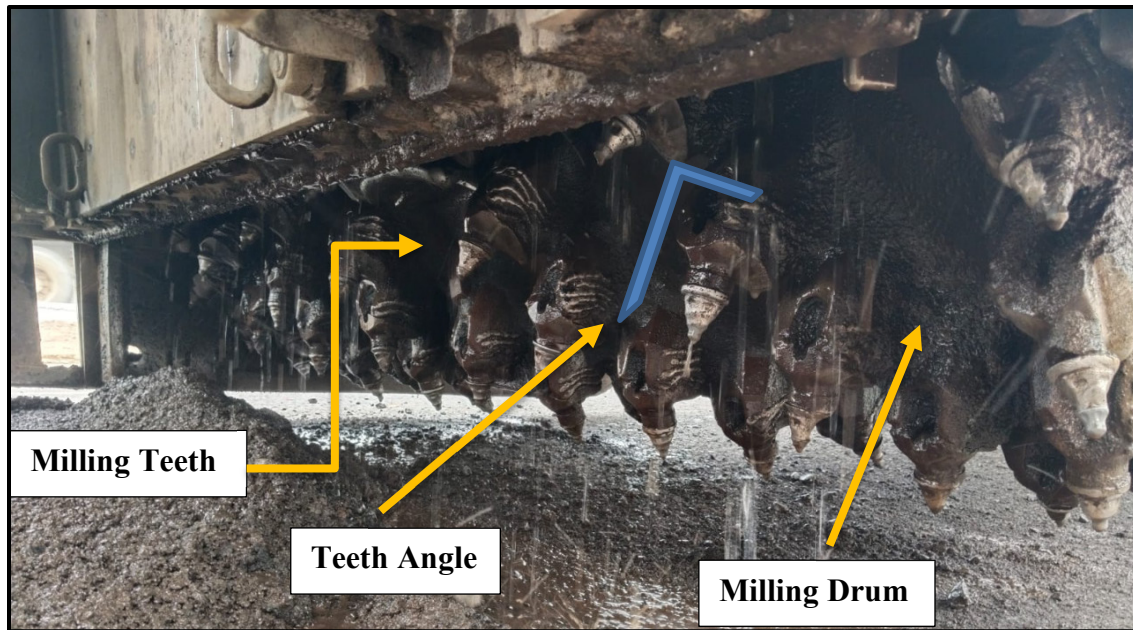


Figure 2.3. Milling machine parameters

Zaumanis et al. (2021) presented the significance of milling and hypothesized three different conditions in their research. These hypotheses are: a) ageing of asphalt binder during milling, b) variability in aggregate angularity, and c) change in aggregate chunk size, higher filler content, and ripping/breaking of aggregates while milling the old pavement. The authors also considered three sources of variation on these hypotheses. These variations are changes in the moving speed of the milling machine, drum rotation speed (slow, medium, and fast), and milling depth. Different combinations of moving speed and depth were chosen, and a comprehensive experimental program was designed. As per the findings of the study, none of the parameters except the moving speed of the milling machine influences the properties of the milled RAP. On the other hand, Diouri et al. (2020) indicated that milling depth also greatly influences the properties of RAP and aggregate gradation. The combined output of the investigations conducted by Zaumanis et al. (2021) and Diouri et al. (2020) inferred that higher depth and slow-moving speed lead to small agglomerations and, therefore, lower filler content. In addition, higher milling depth damages the underneath pavement layers (base/subbase), resulting in surface depressions (shallow or flat). Therefore, suitable caution should be taken in deciding the milling depth. It is recommended that the milling depth be chosen depending on the existing field condition, such as the depth of pavement layers, mix type, and drum speed. Considering the effect of milling teeth, irregular carbide or diamond cutters lead to small or large flake aggregates, which are not desirable.

Various research studies (Copeland 2011; West et al. 2013; West 2015) stated that RAP procured from milling operations does not necessitate further processing and thus can be directly used in pavement construction. This is due to the presence of a lump breaker, which resembles a small-scale crusher, between the cold bins and the conveyor belt. Their purpose is to crush the large lump into smaller RAP particles (size less than 2 inches). However, not in many projects, low/simple processing is required to further

break the small lumps/chunks of agglomerated RAP prior to stockpiling. Figure 2.4 presents the representation of unprocessed and processed RAP material. Overall, an appropriate milling tool and technique can generate RAP with high quality and less internal breakage. Consequently, it may increase the allowable RAP limit to a great extent (Antunes et al. 2019; Tarsi et al. 2020; Zaumanis et al. 2018).

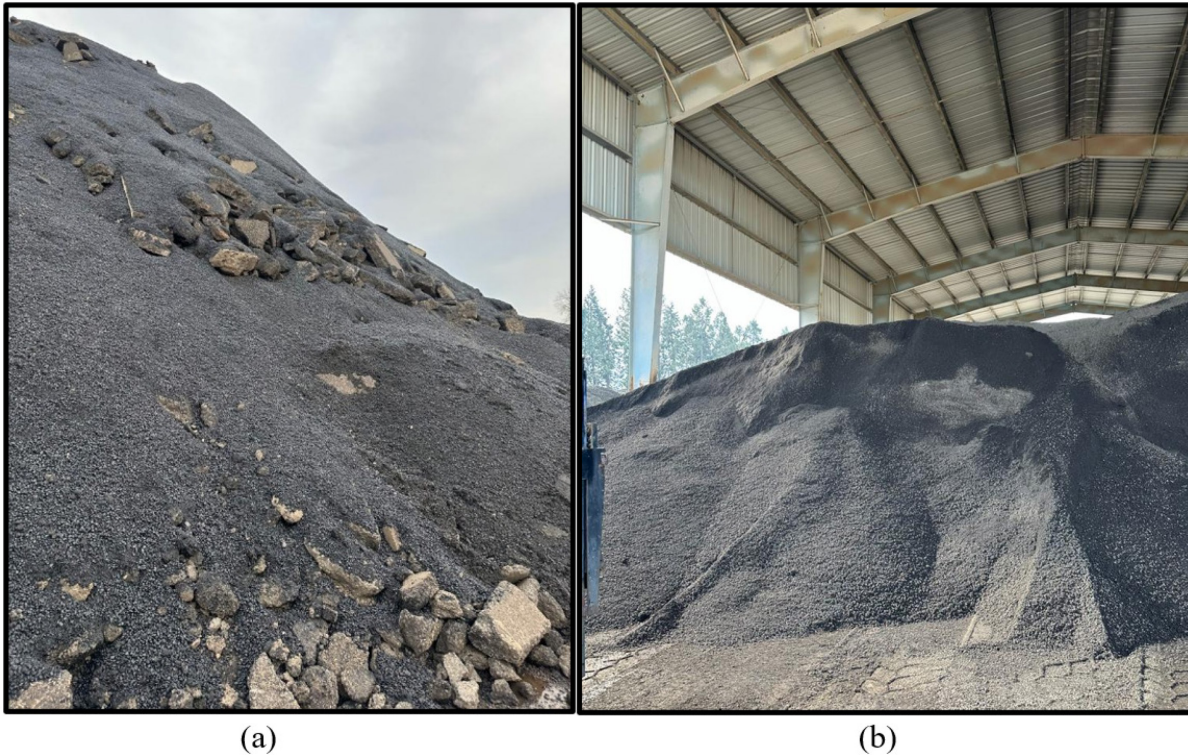


Figure 2.4. Milled RAP material (a) Unprocessed condition, (b) Processed condition

Pavement removal can also be done using heavy bulldozers. This technique of removing asphalt pavements is known as full-depth removal (Arshad and Ahmed 2017). It comprises ripping and breaking up to the full depth of the asphalt pavement structure. RAP produced using bulldozers is relatively more challenging as it is generated in large chunks. Since the RAP material obtained using this technique is in the form of large pavement rubbles or chunks, the amount of fines generated during the procurement is relatively less in a full-depth removal operation. Unlike milling, the material procured using this technique entails further processing before stockpiling. Also, it is a very slow process suitable for a small pavement area (West 2015). The relative advantage of this technique is the lower probability of reflection cracking. This is because the surface of the pavement layer after the milling operation is mostly leveled and free from irregularities such as ruts or bumps.

RAP properties may also vary depending on the source of milling operations (single project or multiple sources), irrespective of the milling technique. Milling carried on a single pavement often indicates consistent gradation and asphalt content (Copeland 2011; West et al. 2013; West 2015). In the case of a single project, screening is required only to

remove the oversized material. Nevertheless, if milling is subjected to different projects and the material is stockpiled at the same location, it may cause significant variation in the test results. Consequently, the stockpiled material entails further processing before producing the new asphalt mixtures. In general, milled RAP is managed following a series of technical operations such as crushing using small- and large-scale crushers (in-place and in-plant), screening using different screen decks, conveying/discharging material to specific locations, and stockpiling or stacking the procured RAP (Antunes et al. 2019; Gao et al. 2021; Tarsi et al. 2020).

2.1.1.2 Crushing and Screening

The purpose of the crushing operation is to convert the large chunks and agglomerations of RAP into smaller pieces (Zaumanis et al. 2022). Crushing can be done in place or at crushing plants, depending on the milling technique. The milling machine itself can reduce the size of RAP using in-place crushing wheels, whereas, in full-depth removal, the material is first loaded into the truck and hauled for crushing at the crushing plant. Due to the simple, time-effective, and more practical technique, the asphalt industries prefer the production of RAP material using the former case over the latter case (West et al. 2013).

Crushing at the plant can be carried out using different crusher types whose working principles differ, but the primary goal is similar. Most crushing plants use compression crushers and impact crushers (Arshad and Ahmed 2017). To produce a consistent RAP, the general practice is to initially blend the large lumps through the front-end loader/bulldozer, followed by crushing in the plant operation. This process eradicates the chance of getting materials that are oversized. Consistency in RAP can also be maintained by crushing the material in small quantities and stockpiling it with proper identification. Improper crushing may increase fines or generate fractured faces, which implies higher binder content and overall production cost (Newcomb et al. 2007; Zaumanis and Mallick 2015).

Various crushing machines are equipped with a recirculatory circuit (West 2015). The function of such a unit is to transfer the large size of material (which is retained on the attached sieve after the first pass of crushing) back to the crusher for re-crushing. The limitation of using the recirculatory circuit is the breakdown of aggregates, leading to excessive fine aggregates having irregular/nonuniform shapes.

A screening operation usually follows crushing. Screening of RAP separates the oversize material from the milled and crushed material (Zaumanis and Mallick 2015). In general, screens are installed just next to the crushers. However, West (2015) recommends setting up the screening deck before the crushing operation. The reason behind this suggested process is the production of a large amount of fine particles during the crushing operation. Placing screens before the crushers allows the finer particles to bypass the crushers, whereas the material retained on the screens will be subjected to the crushers for further processing. This will reduce the load of materials over the screens, thereby saving crushing time.

2.1.1.3 Fractionation

Maintaining consistency or reducing variability is the primary perspective of the RAP management scheme. Improper management limits the percentage of RAP in the asphalt mix by lowering the long-term performance of the pavement structure. A major factor contributing to RAP management is the aggregate gradation required for a mix design (Antunes et al. 2019; Tarsi et al. 2020). Control over the RAP gradation is challenging as the material tends to segregate during the stockpiling process, thereby limiting the RAP content to 20% or less (Sabahfer and Hossain 2015; West 2008). To overcome such shortcomings of using RAP, the fractionation process has recently gained much interest. Fractionation is the process of dividing the RAP (obtained after crushing and screening) into two (for example, coarse and fine) or more stockpiles (say, coarse, medium, and fine) (Han et al. 2019; Katla et al. 2022; Podolsky et al. 2019). Dividing the RAP into two or three fractions is generally referred to as a 2nd or 3rd level fractionation process. Figure 2.5 shows the fractionation of aggregate material into different sizes.

Separating/sieving the RAP into multiple fractions reduces segregation and allows full usage of RAP, depending on their desired size/gradation in asphalt mixture production. In addition, fractionation offers control over the asphalt binder content and RAP gradation, especially for high RAP-inclusive asphalt mixes, in the most economical manner (Colbert and You 2012). The fractionated material is conveyed directly from the stockpile through wheel loaders to the RAP feed bins of asphalt plants. Fractionation is usually required if the material retained on the 2.36 mm sieve is greater than 10-15% (Ministry of Transportation Ontario 2001). Except for this, the feasibility/effectiveness of fractionation depends on various factors, including RAP source, dosage, amount of fines/dust, asphalt binder content, ageing condition (in-service time of old pavement from which the RAP is procured), and the quality of asphalt binder and aggregates (Shannon et al. 2017; Shannon 2012; Shen et al. 2007).



Figure 2.5. Fractionation of aggregates based on their size

Based on the inferences of the previous literature, the impact of the fractionation technique was found to be contradictory. Shannon et al. (2017) developed a fractionation method based on sieve-by-sieve analysis with the presumption of incorporating high RAP

in asphalt mixtures. Nine different asphalt mix combinations were examined, considering three different RAP proportions and fractionation methods. The authors found that controlling the amount of fine RAP (a combination of fine aggregates and dust) during the fractionation allows up to 30% RAP to be used. This analysis considered the desired volumetrics and film thickness required to meet the mix design criteria for a standard hot mix asphalt (HMA). On the contrary, Sabahfer and Hossain (2015) assessed the effect of fractionation on the performance of RAP-inclusive asphalt mixtures. This study chose two RAP contents, i.e., 20% and 40%. The findings of this study indicated that fractionation is not a viable approach to improving the performance of asphalt mixtures.

The level of fractionation is also an important variable that needs to be considered while fractionating the RAP. A detailed study by Katla et al. (2022) found that shifting the fractionation level from the 2nd to the 3rd level increases the allowable limit of RAP by 10%. In addition, 3rd-level RAP fractionation significantly lowered the mix variability in terms of volumetrics and performance. Similar observations were reported by Shen et al. (2007), wherein the RAP dosage was increased (30% to 40%) by choosing a higher level of fractionation. It is inferred that a higher level of fractionation results in a higher allowable dosage of RAP to produce asphalt mixtures.

Although fractionations limit the variability in the overall mix design and offer a better performance of RAP asphalt mixtures, none of the specifications recommended incorporating RAP based on the fractionation method. In the same line of context, TxDOT (2014) reported higher RAP dosage with the fractionation technique. As per the Texas specifications, the allowable RAP dosage for the surface, intermediate, and base layer is 10%, 20%, and 30%, respectively. Conversely, the respective dosages were increased to 20%, 30%, and 40% after fractionating the material into coarser and finer RAP. From this viewpoint, some DOTs and other agencies recently adopted the fractionation process, particularly for high RAP mixes. The only reluctance to use this technique is attributed to the increase in project cost as extra space is required for stockpiling different RAP fractions, and extra bins are needed to feed different RAP fractions simultaneously (Barraj and Elkordi 2022; West et al. 2013). Thus, there is a need for comprehensive research to determine the optimum fraction method that can facilitate a higher percentage of RAP with cost-effectiveness.

2.1.2 Stockpiling Process

Milled RAP is generally stored in the form of stockpiles. RAP stockpiles are the large accumulation of milled material at asphalt production plants. All the RAP can be stored in single or multiple stockpiles, depending on the composition and characteristics of RAP, its source, availability of space at the site, RAP quantity, and project cost (Copeland 2011; West 2015). Few studies (Barraj and Elkordi 2022; Zhou et al. 2010) recommend adopting a separate RAP stockpile approach (either based on aggregate gradation or asphalt binder content) for attaining promising outcomes in terms of performance or allowable limits. Figure 2.6 shows the stockpiling of RAP material based on the maximum aggregate size. Separate stockpiling intends to facilitate a higher RAP percentage in the asphalt mixture, along with excellent quality assurance. However, the stockpile characteristics should be checked whenever a new RAP is mixed/added to the stored stockpiled material. Many times, a milling operation is implemented

on a single large project. In such cases, keeping the milled material in a separate stockpile is worthwhile to attain consistent and uniform characteristics throughout the new construction. On the other hand, material obtained from multiple sources can also provide consistent characteristics only when the contractor/engineer follows the special instructions specified in various guidelines and specifications. The best practice is to dig the RAP from different angles using an excavator for premixing the RAP prior to crushing and fractionation (Copeland 2011; West 2015). One other way to categorize the stockpiled RAP is its origin. These stockpiles are known as classified RAP (known origin, consistent characteristics) and unclassified RAP (unknown origin, highly unpredictable characteristics) (West 2015). In the latter case, the RAP sources from multiple sources are mixed in a single stockpile (Barraj and Elkordi 2022). Thus, prior precautions should be taken while dealing with unclassified RAP. Their allowable limit depends on different requisites, including the requirement of mix volumetrics, aggregate gradation, asphalt binder content, and consensus properties.

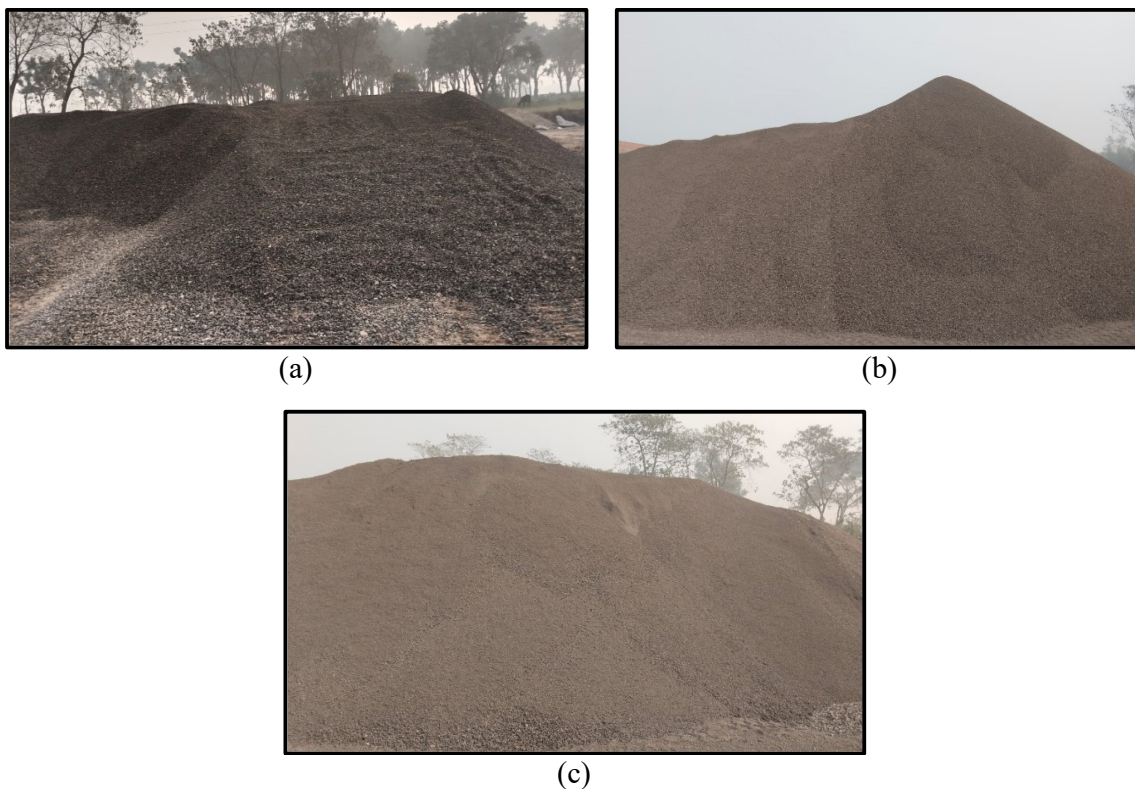


Figure 2.6. Stockpiling of RAP material based on the maximum aggregate size (a) 20 mm, (b) 10 mm, and (c) dust

One of the most important precautions for maintaining the mix design requirements is to keep the stockpiled RAP free from contaminants, such as dirt, field vegetation, and unwanted construction debris (Brantley and Townsend 1999; De Lira et al. 2015). The presence of these contaminants may indicate poor characteristics of RAP, eventually lowering the suggested RAP proportion. Thus, the quality control team should regularly inspect for contaminants (Copeland 2011). A common practice is excavating deleterious material from the yard, where the RAP is

stockpiled. On the other hand, while working with RAP on the field, contractors/engineers always experience an issue of segregation and moisture retention within the material (De Lira et al. 2015; Sabahfer and Hossain 2015; Tarsi et al. 2020; Zhou et al. 2010). This inevitably affects the performance, variability, and cost of the project. To overcome these concerns, various solutions have been endorsed in previous studies. These are briefly discussed in the subsequent sections.

2.1.2.1 Segregation Effect

Appropriate storage of RAP in stockpiles has always been a challenge for pavement industries. Improper stockpiling often results in material segregation, inaccurate volumetric characteristics, lower engineering performance, and durability issues (Sabahfer and Hossain 2015; Tarsi et al. 2020). Thus, prior measures must be taken to avoid the segregation of RAP during the stockpiling process. In general, coarse RAP particles exhibit more kinetic energy and weight, making them more likely to fall toward the bottom of the stockpile. This causes unevenness/inconsistency in aggregate gradation and asphalt binder content while sampling the RAP material. Extra fine aggregates from the stockpiles are generally preferred due to their higher binder content compared to the aggregates. Although fine RAP aggregates exhibit higher binder content, it is well known that the present binder is more aged, indirectly resulting in lower cracking resistance and, consequently, recommending a lower RAP content. The recommended way to reduce this inconsistency and improve uniformity throughout the stockpile is to use index-type conveyors, having the facility to raise the conveyor end till the height of the stockpile (height is generally limited to 9 meters) (Copeland 2011; West 2015). This practice avoids the accumulation of large size aggregate particles at the bottom of the stockpile, thereby limiting their segregation from the finer aggregate particles. Additionally, these studies suggested that storing the RAP material in layers using a small bulldozer could eradicate the effect of segregation to a great extent.

2.1.2.2 Moisture Retention

RAP tends to retain moisture, which indirectly limits the use of RAP in pavement construction. Wet RAP often sticks on the sides of screening decks and conveyor belts, which accumulates with time (Antunes et al. 2019). The presence of moisture in RAP may not affect the performance, but it will increase the project time and cost for processing RAP before construction. These concerns are likely if the stockpiling process is not managed precisely. Different techniques have been proposed to avoid these apprehensions. In the past two to three decades, RAP stockpiling was preferred on the low or horizontal surface with the perception that high and conical stockpiles may cause internal compaction due to their weight. Though with later research, this seems to be unrelated. Also, during the rainy season, these stockpiles may retain moisture over the crest due to their plain or low profile, which is again a critical point of concern. Besides, recent research (Copeland 2011; West 2015) recommends building a conical or high stockpile to offset water retention. Another possible approach is storing the RAP on a paved and sloped surface (Zaumanis and Mallick 2015). This would aid in facilitating drainage from RAP quickly and efficiently. Notably, the slope of the stockpile should be on the opposite side from where the RAP is subjected to cold asphalt binds. In line with

the same context, a common technique adopted by contractors and engineers to minimize the moisture content or protect the material during the rainy season is to cover the RAP with shelters or roofs prepared temporarily or permanently at the plant site, as shown in Figure 2.7. As per the studies in the literature (Tarsi et al. 2020; West et al. 2013), minimizing moisture retention by any means will be favorable in increasing the proportion of RAP in pavement construction.



Figure 2.7. Roofing of RAP material for minimizing moisture concerns

2.1.3 Plant and Source Variability

High variability in the material composition is a critical barrier that restricts the amount of RAP in producing new asphalt pavements. These variabilities may be associated with processing operations such as milling technique, crushing operation, screening size, and handling operations, including the stockpiling process (Gao et al. 2021; Zaumanis et al. 2018). In addition, pavement patching, crack seals, other maintenance materials, and treatments applied during the service life result in more variability in the recycled material (Cadaru et al. 2022). This often results in improper mix design, indicating deviation in asphalt content and aggregate gradation. These deviations are unpredictable and controlling them remains a critical challenge for the asphalt industry. Such possible concerns urge the engineers/contractors to work with either no RAP (virgin asphalt mixture) or low RAP content (<25%). Another probable reason is the limited research on RAP variability, management practice, and its impact on the behavior of the final asphalt mixture with recycled asphalt content (Ailing et al. 2019; Cadaru et al. 2022; Zaumanis et al. 2018).

The National Center for Asphalt Technology (NCAT) surveyed several contractors around the U.S. and determined the best RAP management practice that provides the highest homogeneity/consistency in RAP (West 2008, 2015). The report published by NCAT also includes the current practice for processing and handling RAP to maintain variability within limits. Few studies (Austerman et al. 2020; Montañez et al. 2020; Valdés et al. 2011; Zaumanis et al. 2018) examined the variability in the properties of asphalt binder and mixtures produced using RAP. While most researchers indicated the high variability in RAP properties (as shown in

Table 2.1), Estakhri et al. (1999) found that the variability in RAP mixtures is comparatively less than that of the asphalt mixture with no RAP content. The results were found to be consistent even at higher RAP proportions. The difference in the conclusions of past studies may be attributed to the difference in pavement condition from where the RAP was collected. In general, factors controlling the performance and variability of RAP materials are in-service life, traffic, production temperature, initial material properties, rehabilitation, and treatments (West 2015).

Zaumanis et al. (2018) conducted a comprehensive study wherein the variability in the results was assessed using the RAP obtained from 3 different roadways. The materials were collected before the milling in the form of cores, after the milling as a milled/crushed material, and after the re-mixing of stockpiles. After testing the collected RAP, Zaumanis et al. (2018) found that the variability is a function of the form of the collected samples (cores, milled material before and after processing), indicating higher variability for cores. The variability for milled RAP and the material obtained after re-mixing was the same. Thus, making the appropriate decision on the processing and handling of RAP material (including milling, crushing, screening, and stockpiling) before the start of the project could minimize the variability and indirectly maximize the percentage of RAP in asphalt mixtures.

These variability concerns are relatively lower when the material is procured from a single plant or source; nevertheless, it is very hard to control the variability when it is obtained from multiple plants or sources (West 2015; Zhou et al. 2010). It is recommended to mix the material milled from multiple sources and subject it to re-mixing before crushing and sieving to reduce the material's variability (Zhou et al. 2010).

Table 2.1. Inferences of past studies indicating higher RAP variability

References	Sample size	Considered parameters	Inferences
Solaimanian and Tahmoressi (1996)	Four different pavement structures (35, 35, 40, and 50% RAP)	Aggregate gradation, asphalt binder content, physical properties such as penetration and viscosity, volumetrics, and strength	• RAP mixture exhibits a higher mean standard deviation than the asphalt mixture without RAP. • The higher the percentage of RAP, the higher the deviations from the target value.
Montañez et al. (2020)	Six different sources of RAP	Sieve analysis, asphalt binder content, physical properties such as penetration value and softening point, and linear viscoelastic properties	• Variability in the RAP changes with the parameter selected. • A significant variation among the different sources of RAP was observed, irrespective of the test parameter. • The highest variation was observed in sieve analysis (around 85%) for the material passing the 0.075 mm sieve, while the variation in binder properties ranged from 7-35% depending on the test parameter (penetration, softening point, binder content, and complex modulus).
Valdés et al. (2011)	Two sources (20% and 60% RAP)	Asphalt binder content and aggregate gradation Note: Two-level fractionation technique was adopted (i.e., 0-8 mm and 8-25 mm)	• Coarser RAP fraction showed higher variation, regardless of the test parameter. • 60% RAP mixture exhibits higher variability in comparison to 20% RAP. • Recommended fractionation of RAP and the use of fine RAP fractions to reduce the variability. • Even 60% of RAP indicated promising results but necessitated proper RAP management to avoid heterogeneity among the collected material.
Austerman et al. (2020)	Six samples (15% RAP)	Asphalt binder content, aggregate gradation, volumetrics, and properties of recovered RAP binder	• A deviation greater than 10% was observed in aggregate gradation for all six samples. • Some RAP-inclusive asphalt mixtures failed to meet the volumetric requirements.

References	Sample size	Considered parameters	Inferences
			• RAP variability drastically affects the proportion of RAP to be used in pavement construction. • Significant variations were observed in air voids, theoretical maximum specific gravity, and RAP aggregate properties. • The properties of the recovered RAP binder were quite different and displayed higher deviations.
Gao et al. (2021)	RAP obtained from sixteen different construction sites (30% RAP)	Aggregate gradation, asphalt binder content, and physical properties	• The variability observed in aggregate gradation was not found to be very significant. • A noticeable difference was observed in asphalt binder content and physical properties. • Dividing the RAP sources into groups/clusters of similar characteristics minimizes the variability and consequently increases the allowable RAP limit.

2.1.3.1 Sampling Plan and Testing Frequency in a Stockpiled RAP

Sampling and testing frequency for RAP is necessary to ascertain the consistency within the RAP stockpiles. As per West et al. (2013), the material sampling process and test frequency may also incorporate variability in the results. Improper sampling and an insufficient number of test samples may lead to higher variability in test results (Copeland 2011). In general, the sampling size should be enough to perform a few variability checks, such as asphalt binder content, aggregate gradation, bulk density of RAP aggregate, RAP aggregate properties, and extracted and recovered binder properties (preferably for RAP >25%).

The minimum sampling plan and test frequency depend on the DOTs and construction agencies. The general practice is to conduct 1 set of tests per 1,000 tons of RAP within a particular stockpile to get a clear understanding of the consistency of the RAP material (West 2015). Regarding the number of test samples, a minimum of 10 tests per individual RAP stockpile sample is recommended to realistically quantify the variability between the samples of unique stockpile material (Copeland 2011). Projects that involve the utilization of multiple stockpiles of RAP necessitate the above-mentioned sampling and testing procedure for each stockpile before conducting the mix design.

Further, the question arises over the sampling time and location from which the material must be taken and tested. As per the previous reports (West et al. 2013; West 2015), the best timing for sampling is during the building of the RAP stockpile at the site from where the material will be transferred to the asphalt plants for production. This is because, with time, RAP forms a crust over the stockpiles, and taking the material from the top of the stockpile imitates incorrect results. Before sampling at the site, a mini stockpile should be prepared from the original stockpile in question. Front-end loaders or similar equipment should be used to construct a new sampling stockpile, which is further flattened using a back-dropping method for proper sampling (West et al. 2013; West 2015). Following the sampling process described above might aid in attaining a homogeneous RAP sample with consistent characteristics, irrespective of the stockpile location.

2.2 TEST METHODS FOR CHARACTERIZING RECLAIMED ASPHALT PAVEMENT (RAP) MATERIALS

RAP characterization is an essential task that needs to be performed before the mix design. The characterization tests include the determination of aggregate and asphalt binder properties in terms of aggregate gradation, the bulk specific gravity of aggregate, asphalt binder content, and asphalt binder grade (Hajj et al. 2012; Mikhailenko et al. 2020; West et al. 2013). These properties are of utmost importance for quality control (QC) and quality assurance (QA) of RAP-inclusive asphalt mixtures. Among these properties, aggregate gradation and asphalt binder content are the vital parameters required for the mix design purpose (Sharma et al. 2022; West et al. 2013).

2.2.1 Extraction and Recovery Process

The amount and properties of asphalt binder in RAP mixtures and the aggregate gradation can be identified after following a two-step protocol commonly referred to as the extraction and recovery process. The extraction process involves the separation of the asphalt binder layer from the surface of RAP aggregates with the use of chemical solvents or non-solvent methods, whereas the recovery process is carried out to recover the asphalt binder from the solvent (Coleri et al. 2018a). After the extraction and recovery, aggregate gradation can be determined, along with the quantification of asphalt binder content present in the RAP mix. However, the properties of asphalt binder before and after the extraction and recovery, particularly in RAP mixes, showed irregular trends. This is primarily attributed to the presence of a residual solvent or fine particulates within the recovered asphalt binder (Mikhailenko et al. 2020; Wakefield et al. 2018). Thus, proper care has to be taken to remove 100% fines and solvent from the recovered binder during the extraction and recovery process, and the reliability of recovering asphalt binder (without any traces of solvent/fines) depends on the test protocol. Various test methods have been developed for the extraction and recovery of asphalt binders. Each of the extraction processes, except the ignition method, utilizes solvents and additives for the extraction purpose (West et al. 2013; Ziyani et al. 2017). The primary difference in these methods is the effect of heat, the agitation effect, and the type of solvents. The details of these methods are briefly described in Table 2.2, and the overall procedure of the prescribed methods can be found in their respective standards.

Table 2.2. Description of extraction and recovery methods

Methods	Type	Standard Specifications	Description	Advantages	Disadvantages	Solvents
Centrifug e Extraction	Cold (Solvent- based extraction process)	ASTM D2172 (2011) AASHTO T164 (2014)	Asphalt mixture is allowed to submerge in the solvent for extracting the asphalt binder from the coated aggregates. The submerged material is subjected to centrifuge action where the mixture of solvent and asphalt binder is recovered in a glass beaker through the drainage pipe.	•Less ageing of asphalt binder •Effective for aggregate gradation	•Lower accuracy for determining asphalt binder content •Less feasibility for polymer-modified binders	•Trichloroethane •Trichloroethylene •Toluene •Benzene •Perchloroethylene •Normal propyl bromide •Methylene chloride •Xylene

Methods	Type	Standard Specifications	Description	Advantages	Disadvantages	Solvents
Soxhlet Extraction	Hot (Solvent-based extraction process)	Not Available	This method is preferred when the asphalt mixture has limited solubility in a solvent. In this method, the asphalt mixture is placed in a thimble that is positioned inside the Soxhlet chamber. The solvent loaded in a flask was continuously heated using a mantle to produce reflux action. The solvent vapors flow up in the distillation flask and drop into the thimble with the use of a condenser installed at the top of the extractor. When the Soxhlet chamber is full, the solvent siphons back into the refluxing flask containing the recovered binder and the heated solvent.	•Efficient in extracting solute from insoluble impurities •Simple and easy mechanism •Suitable for determining aggregate gradation	•Long extraction time •Consume large amount of solvent •Accelerates binder ageing •Not suitable for evaluating binder properties	•Dichloromethane •Trichloroethane •Trichloroethylene •Toluene •Benzene •Perchloroethylene •Xylene

Methods	Type	Standard Specifications	Description	Advantages	Disadvantages	Solvents
Reflux Extraction	Hot (Solvent-based extraction process)	ASTM D2172 (2011) – Method B AASHTO T164 (2014)	Reflux extraction works on the principle of reflux action, subjecting the solvent to heat and producing vapors. The solvent vapors are passed through the asphalt mixture kept in two wire mesh cones covered with filter paper. The solvent is refluxed over the asphalt mixture until the complete separation of the asphalt binder from the aggregate surface color of the solvent changes to light straw color.	• Suitable for quantifying asphalt binder content • Accurate for aggregate gradation • Suitable for modified asphalt binders	• Cause ageing effect • High risk as solvent is subjected to heat for a longer time period • Not feasible for assessing binder properties	• Trichloroethane • Trichloroethylene • Toluene • Benzene • Perchloroethylene • Normal propyl bromide • Methylene chloride • Xylene
		ASTM D2172 (2011) – Method C AASHTO T164 (2014)	In this process, the asphalt mixture is placed on a mesh which is equipped inside a container similar to a cooking pot. Thereafter, the solvent is poured over the aggregate mixture and subsequently the extraction lid is closed tightly. The cold water is passed at the top of the extraction setup to introduce the solvent condensation. The whole apparatus is subjected to heat for around 1.5 to 3			

Methods	Type	Standard Specifications	Description	Advantages	Disadvantages	Solvents
			hours for the complete extraction of asphalt binder.			
		ASTM D2172 (2011) – Method D AASHTO T164 (2014)	As per this method, the asphalt mixture is placed in a filter sack under a basket, which is attached to a suspension rod. The complete assembly is further kept inside an extraction kettle where the solvent is poured. Following the mixing of solvent and asphalt mixture, the condenser lid is closed and the cold water flowed through it. Unlike method C, the assembly is subjected to heat for 15-30 minutes in order to attain proper disintegration of asphalt			

Methods	Type	Standard Specifications	Description	Advantages	Disadvantages	Solvents
			binder from the aggregate based on the reflux action.			
Vacuum Extraction	Cold (Solvent-based extraction process)	ASTM D2172 (2011) – Method E AASHTO T164 (2014)	In this method, the asphalt mixture is kept in a metallic container and the solvent is poured over it. The liquid material is then subjected to a vacuum extractor pump, where a high suction is applied to pull the combined asphalt and solvent solution through a filtration medium. After one cycle, extra solvent is added and the process is repeated until the clear aggregate color is visible.	•Most accurate for estimation of asphalt content •Bets method for highly variable and absorptive aggregates	•Difficulty in cleaning process	•Ethyl Alcohol •Methylene Chloride

Methods	Type	Standard Specifications	Description	Advantages	Disadvantages	Solvents
Strategic High Research Program (SHRP) Method	Cold (Solvent-based extraction process)	AASHTO T319 (2022)	This method is coupled with the rotavapor recovery method, developed with the primary thought of avoiding the age hardening of the asphalt binder during the process of extraction and recovery. The SHRP method utilizes a horizontal metal cylinder to mix the solvent with the asphalt mixture. The cylinder is connected to a vacuum pump to pump effluent. The collected effluent is allowed to flow through a filter bed to remove the fines before the recovery process.	•Remove fine particles •Suitable for binder content calculation •High repeatability •Effective in removing 100% binder from aggregates •Suitable for aggregate gradation •Less ageing	•Very expensive •Require skilled labor	•Trichloroethylene •Toluene •Ethanol •Ensolv
Automatic Extraction System	Hot/Cold (Solvent-based extraction process)	Not Available	These methods are not part of any standard but comply with ASTM D2172 and work as a reflux or centrifuge-based extraction process. The aim of developing automatic systems is to reduce the amount of labor required for a particular extraction. In some of the automatic systems, automatic sieves are also attached to remove the fine particles from the	•Lower labor cost •Less exposure to harmful chemicals •Less variability in asphalt binder content •Very less use of hot materials	•Very costly setup •Require skills	•Trichloroethane •Trichloroethylene •Toluene •Benzene •Perchloroethylene •Normal propyl bromide •Methylene chloride •Xylene

Methods	Type	Standard Specifications	Description	Advantages	Disadvantages	Solvents
			solution of asphalt binder and solvent prior to the recovery process.			
Abson Recovery Method (Figure 2.8a)	Solvent-based recovery process	ASTM D1856 (2015) AASHTO R59 (2022)	As per this method, the extracted solvent and asphalt binder are subjected to distillation in a cylindrical tube. Heat is applied at the bottom of the beaker containing the extracted material using a heating flame, and immediately carbon dioxide is circulated to avoid the effect of heating/ageing on the asphalt binder.	•Less expensive •Easy to use	•More Variability •Presence of residual solvent in asphalt binder •Less effective in removing complete solvent	•Dichloromethane •Bromopropane •Trichloroethylene •Toluene
Rotary Evaporator (Figure 2.8b)	Solvent-based recovery process	ASTM D5404 (2011)	The extracted solution is kept in a rotating flask, which is half immersed in an oil bath heated at high temperatures (100-150°C). initially, a high vacuum is	•Less residual solvent •Suitable for high-viscosity binder	•Quite expensive	•Trichloroethane •Trichloroethylene •Toluene •Benzene •Bromopropane

Methods	Type	Standard Specifications	Description	Advantages	Disadvantages	Solvents
			applied to the solution through a vacuum pump along with the circulation of nitrogen gas. The purpose of nitrogen gas is to reduce the chemical change in the recovered binder (due to overheating/ageing).	•Less labour intensive •Less ageing of asphalt binder		•Perchloroethylene •Normal propyl bromide •Methylene chloride •Xylene
Ignition Method	High Heat	ASTM D6307 (2019) AASHTO T308 (2022)	Unlike solvent extraction processes, Ignition method does not involve the use of any solvent for the extraction of asphalt binder. The ratio of mass difference before the ignition and after the ignition to the mass before the ignition will give the estimation of asphalt binder content in the asphalt mixture. In the ignition method, the material is burned in a furnace (at very high temperatures) until the change does not go above 0.01% for 3 consecutive minutes. The obtained value is further adjusted using the correction factor/weight loss factor, which is defined because sometimes aggregates break down at	•Less time consuming •Inexpensive •Precisely estimation of asphalt binder content •Accurate aggregate gradation	•Not suitable for the evaluation of recovered binder properties •Not suitable for aggregate properties •Excessive high temperature	Not required

Methods	Type	Standard Specifications	Description	Advantages	Disadvantages	Solvents
			the high temperature of the furnace and provides a wrong estimation. It was identified that the results obtained using this method are highly dependent on the aggregate type. In the case of RAP mixes, the recommended temperature for the estimation of binder content is around 425-430°C, which is also a function of the RAP source.			



(a)



(b)

Figure 2.8. Commonly used solvent-based recovery methods (a) Abson recovery apparatus and (b) Rota evaporator (Sukhija and Coleri 2025c)

The properties of extracted asphalt binder and the aggregate gradation could vary significantly with changes in the extraction procedure. In this regard, Hajj et al. (2012) investigated the effect of different extraction and recovery methods on the asphalt binder content, aggregate gradation, specific gravity of RAP, and their impact on the volumetrics of asphalt mixtures. Three extraction methods (centrifuge, reflux, and ignition) and four different aggregate sources (two limestones (soft and hard), rhyolite, and granodiorite) were used to develop the experimental design. The authors found that centrifuge extraction yielded the lowest binder content compared to the reflux and ignition methods, irrespective of the aggregate type. After the extraction, the obtained aggregates were dried and subjected to sieve analysis. The findings of the study revealed that the centrifuge extraction and reflux method did not exhibit much difference in aggregate gradation as compared to the gradation of virgin aggregates, whereas a significant difference was observed when the extraction was performed using the ignition method. High temperatures in the ignition oven might break the aggregates, resulting in altered gradation curves. Also, these methods indicated lower or higher specific gravities than virgin aggregates, depending on the type of aggregates in question. Owing to the differences in the test methods and their corresponding results, there is a significant difference in the volumetric properties of the asphalt mixtures. This shows that the selection of the extraction method is also a critical research challenge that requires further investigation.

Overall, the selection of extraction methods should be based on the properties of the RAP material that need to be determined. Table 2.3 displays the recommended methods suitable for a particular RAP property (West et al. 2013). Because of aggregate degradation, a sand equivalent test should be conducted for RAP aggregates (McDaniel et al. 2001). Based on past studies (Mikhailenko et al. 2020; Wakefield et al. 2018; Ziyani et al. 2017), the most commonly used extraction and recovery methods are centrifuge extraction and rotavapor due to their simplicity, safe operation, the large volume of sample, and comparatively less ageing of asphalt binder.

Table 2.3. Recommended methods of extraction and recovery for different RAP properties
(West et al. 2013)

Property	Method recommended
Binder content	Ignition furnace
Gradation	Centrifuge extraction
Coarse aggregate fracture faces and fine aggregate sand equivalent	Solvent extraction or Ignition furnace
Los Angeles abrasion	Reflux extraction or Ignition furnace
Soundness	Centrifuge extraction
Bulk specific gravity	G_{mm} method if asphalt absorption can be assumed with confidence, or solvent extraction method
Binder properties	Centrifuge with Rotavap method or SHRP method

2.2.2 Bulk Specific Gravity of RAP Aggregates

The accurate determination of RAP aggregate bulk specific gravity ($G_{sb(RAP)}$) is a crucial task. Since the value of $G_{sb(RAP)}$ is required for the mix design, it is a valuable parameter that can drastically affect the volumetrics, particularly for high RAP mixes (Newcomb et al. 2007).

Different methods are available to evaluate the $G_{sb(RAP)}$. Commonly used methods are differentiated into three categories (Method A, B, and C). Method A involves the extraction of RAP binder from the RAP aggregates. Two simple methods include the extraction of RAP binder and recovery of RAP aggregates using ignition and solvent methods, followed by determining their specific gravity based on coarse and fine fractions (West et al. 2013). Method B, recommended by Kvasnak et al. (2010), involves the estimation of $G_{sb(RAP)}$ using the theoretical maximum specific gravity of RAP mixes ($G_{mm(RAP)}$). The following two equations (Equation 2.1 and Equation 2.2) were suggested for the evaluation of $G_{sb(RAP)}$. As can be seen, this method entails the percentage absorption of asphalt binder (P_{ba}), which is generally assumed based on the history of asphalt mixtures prepared with the same source of the material. Method C recommends using the effective specific gravity of the RAP aggregates ($G_{se(RAP)}$) instead of $G_{sb(RAP)}$ (Kvasnak et al. 2010). This entails the quantification of available RAP binder and $G_{mm(RAP)}$.

Hajj et al. (2012) characterizes different extraction methods (centrifuge, reflux, and ignition oven) using four different types of asphalt mixtures and performed a sensitivity analysis to determine the best method for the evaluation of $G_{sb(RAP)}$. The sensitivity of each method was judged based on its impact on the volumetric characteristics of the asphalt mixtures. The findings of the study indicated that ‘Method A’ resulted in a lower error, particularly when the RAP aggregates are extracted using a centrifuge or a reflux extraction process. For RAP content ranging 25%-50%, the error in voids in mineral aggregates (VMA) was under $\pm 0.4\%$. This is the primary reason former methods (ignition and solvent) are mostly used for correctly estimating $G_{sb(RAP)}$, as the percentage absorption value differs greatly from source to source and may create discrepancies in volumetric calculations. Notably, the higher the RAP content, the higher the variability/inconsistency, irrespective of the testing scheme.

$$G_{se(RAP)} = \frac{100 - P_{b(RAP)}}{\frac{100}{G_{mm}} - \frac{P_{b(RAP)}}{G_b}}$$

(Equation 2.1)

$$G_{sb(RAP)} = \frac{G_{se(RAP)}}{\frac{G_{se(RAP)} * P_{ba}}{100 * G_b} + 1}$$

(Equation 2.2)

2.3 MIX DESIGN OF RAP MIXTURES

As per the literature review (McDaniel et al. 2001; West et al. 2013), there is no difference between the mix design of virgin and RAP-inclusive asphalt mixtures. However, the mix design of the RAP asphalt mixture involves more complexities. A perfect RAP mix could perform equally (or even better than) with the HMA without RAP. Prior to the mix design, the RAP should be processed to reduce the variability in the final aggregate gradation and binder content (Copeland 2011). To evaluate the aggregate gradation, AASHTO M 323 (2022) recommends extracting the RAP aggregates using any extraction technique (solvent extraction or ignition). Thereafter, it is recommended to conduct a series of tests, such as aggregate gradation, fine and coarse aggregate angularity, flakiness, and elongation index, on the extracted aggregates.

Mix design for asphalt mixtures with RAP can be conducted using any mix design protocol, such as Marshall, Hveem, and Superpave (Copeland 2011). Nevertheless, the adoption of the technique is dependent on the country/state DOTs. For example, most of the DOTs in the United States exclusively followed the Superpave mix design procedure rather than the Marshall or Hveem. Irrespective of the mix design, it is necessary to control the design attributes in terms of RAP aggregate gradation and binder content. Along with this, several concerns need to be addressed while designing the RAP mixes (Copeland 2011; McDaniel et al. 2001; West et al. 2013; West 2015). These are: 1) appropriate blending of virgin and RAP binder- no accurate method available, 2) approach to determine the bulk specific gravity of RAP aggregates (especially VMA)- no direct approach, 3) handling of RAP- heating of RAP aggregates, and 4) production temperatures of RAP mixes (may be corresponding to a blended binder or neat binder).

In general, RAP mix design comprises four different mix components, i.e., RAP, natural aggregates, neat (virgin) asphalt binder, and additives (if any, including rejuvenators, antistripping agents, and warm mix asphalt). Figure 2.9 clearly shows how these components are used/mixed before the mix design (Newcomb et al. 2007). The properties of these materials are very important for the design process to achieve a promising mix design. It will aid in determining the type and amount of material to be added to meet the mix design requirements in terms of volumetrics and performance (Newcomb et al. 2007; Sharma et al. 2022). Figure 2.10 demonstrates the typical mix design procedure for designing RAP-inclusive asphalt mixtures.

Table 2.4 shows the classification of RAP mixtures based on a three-tier system (Copeland 2011; McDaniel et al. 2001). At low RAP proportions ($RAP < 15\%$), the relatively lower binder content over the aggregate surface results in minute negative effects on the performance of the final asphalt mixture, and thus, there is no requirement to change the asphalt binder grade. On the other hand, at high proportions, stiff/aged asphalt binder present on the aggregate surface influences the physical, chemical, rheological, and mechanical properties at the binder and mixture level. In such cases ($RAP > 25\%$), special treatment and consideration have to be given (Sharma et al. 2022). Notably, irrespective of the proportions, RAP should be subjected to lower temperatures (preferably, 110°C) in the laboratory for a time period of not more than 2 hours (McDaniel et al. 2001; Newcomb et al. 2007). The lower heating temperature of RAP is generally adopted to avoid the over-aging of the RAP binder and also simulate the RAP heating process during production. After the heating process of RAP, it is added to superheated natural aggregates and neat asphalt binder to produce RAP-inclusive asphalt mixtures. Thereafter, the prepared mixtures are subjected to conditioning as per the test requirements.

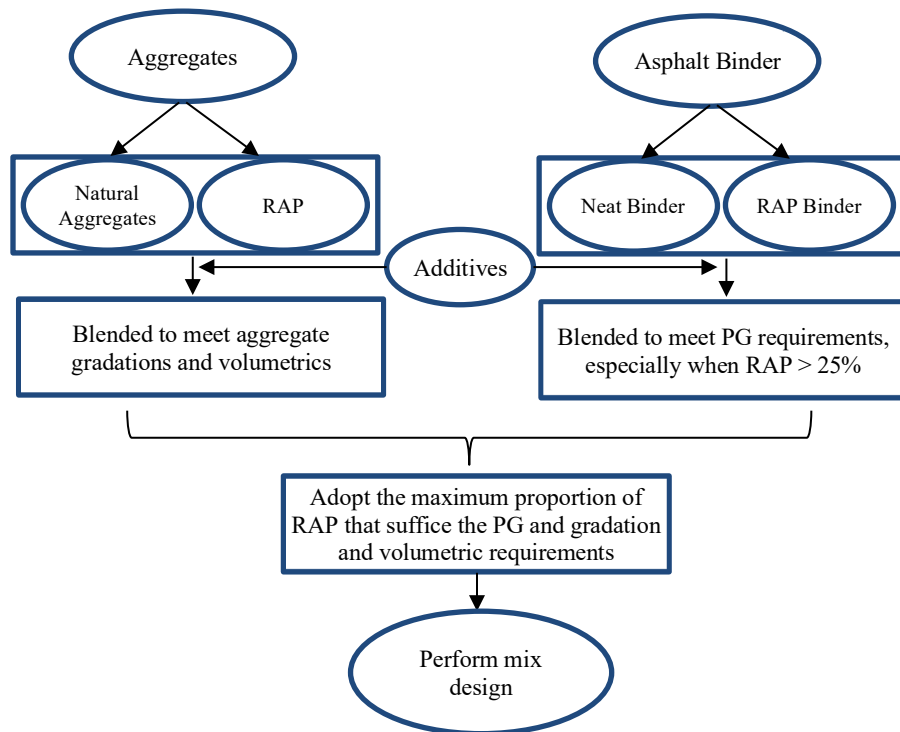


Figure 2.9. Material evaluation for RAP mix design

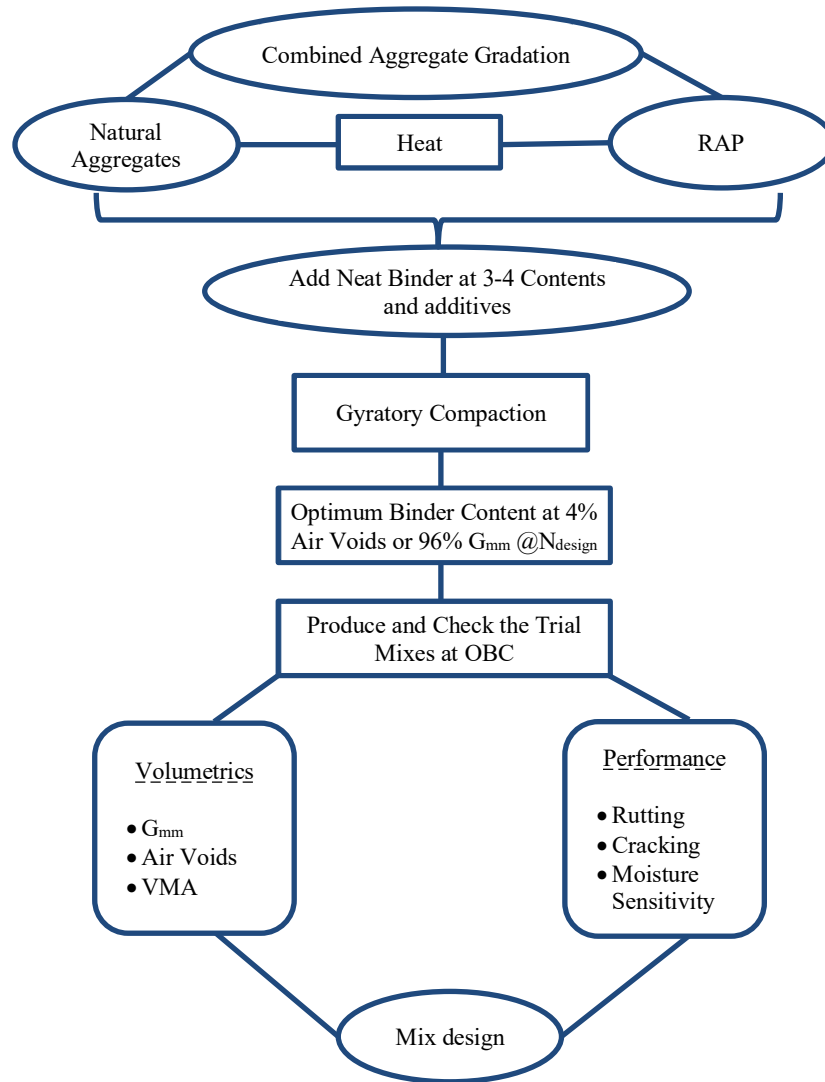


Figure 2.10. Mix design procedure for RAP-inclusive asphalt mixtures

Table 2.4. RAP proportions based on tier system

Tiers	RAP Proportions	Selection of Neat Asphalt Binder
1	$\leq 15\%$	No change in binder grade
2	16-25%	One grade lower virgin asphalt binder
3	$\geq 25\%$	Use of blending charts

2.4 STRATEGIES TO DEVELOP DURABLE PAVEMENTS WITH HIGH RAP

The scarcity and huge bump in the cost of natural aggregates and asphalt binders, coupled with the environmental regulations, motivated the asphalt industries to incorporate high proportions of RAP material in asphalt pavement construction. However, various concerns must be addressed before implementing high RAP content at the state level. RAP comprises a stiff and brittle asphalt binder, which, when used at higher content, drastically affects the pavement performance (Coleri et al. 2018a). Although higher RAP content results in improved rutting performance, it leads to higher cracking on the pavement's surface. To overcome these challenges, various DOTs recommended the strategies shown in Figure 2.11, to increase the RAP content in asphalt mixtures with adequate performance, as that of asphalt mixtures with no RAP. These strategies are generally mandatory when the RAP proportion is greater than 20% by weight of the total mix (McDaniel et al. 2001; West et al. 2013).

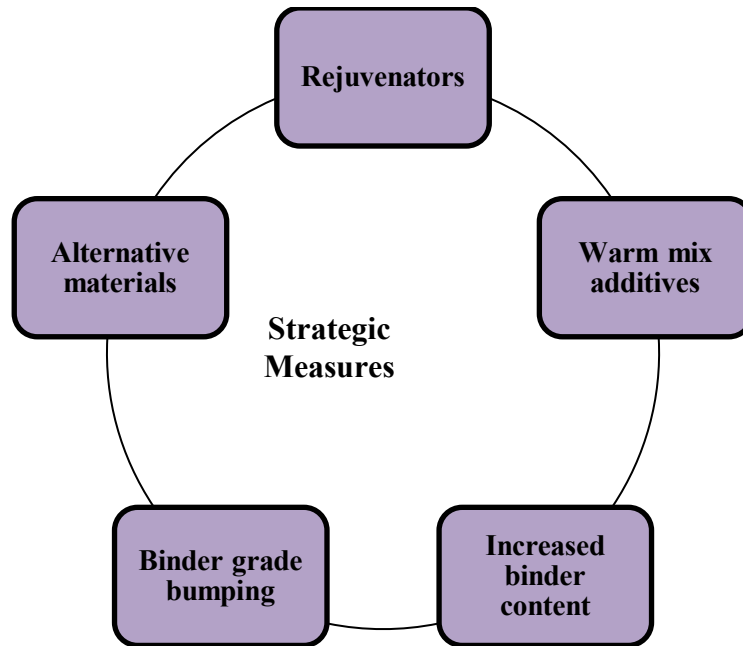


Figure 2.11. Strategic measures to improve RAP content

2.4.1 Use of Rejuvenators

The stiffness or the brittleness of oxidized RAP binder can be reduced or restored with the use of rejuvenators or recycling agents (Sukhija et al. 2022a). A rejuvenator is used to create a chemical reaction for rejuvenating the aged asphalt binder present over the RAP material (Coleri et al. 2018a). The function of a rejuvenator is to restore balance in the aged RAP binder by replenishing maltenes and softening the excessive asphaltene fraction, thereby bringing its properties closer to those of a neat asphalt binder (García et al. 2010). In addition, it improves the degree of blending to achieve an adequate mix of design that meets performance requirements. Rejuvenators can be added to the neat asphalt binder, RAP mixtures or RAP binder, depending on their chemical composition and blending process (Moghaddam and Baaj 2016). One of the

great challenges with the use of rejuvenators is the selection of rejuvenator type and its dosages. Many rejuvenator technologies have been developed over time due to the great attention to using high RAP in asphalt pavements. These are classified into different categories such as petroleum-based, organic-based, and commercial products (Behnood 2019; Kaseer et al. 2019b; Zaumanis et al. 2014a). Some of the commonly used rejuvenators are listed in Table 2.5. The dosage of rejuvenators also changes with the change in rejuvenator type because all rejuvenators exhibit different chemical compositions and may perform differently when added to the RAP mixture (Ma et al. 2015). Thus, a general practice is to adopt the manufacturer's recommendation for the optimum dosage, which is usually followed by various state DOTs in the United States.

Table 2.5. Some of the commonly used rejuvenators

Petroleum-based rejuvenators	Organic-based rejuvenators	Commercial rejuvenators
Aromatic extract, Paraffinic base oil, Naphthenic flux oil, Waste engine oil, Aromatic oil	Organic oil, Refined tallow, Distilled tall oil, Waste vegetable oil, Waste vegetable oil grease, Castor oil, Pongamia oil, Polanga oil, Soybean oil derivatives	Cecabase RWI, Cyclogen® L, Evoflex, Reclamite, Revive, Sasol orbital plus, ANOVA, Green-Tech , Agriculture-Tech, Nynas V115

Another challenge with the use of rejuvenators is their diffusion and distribution in RAP mixtures. Improper/non-uniform distribution of rejuvenators leads to inaccurate performance results with higher variability (Ma et al. 2015). In general, diffusion depends on the blending process and time. For the short blending process, it is hard for the rejuvenator to diffuse completely within the RAP binder. This is due to the highly oxidized RAP binder's short blending time and poor flowability. Therefore, after the addition of the rejuvenator in RAP, there should be sufficient time for the diffusion to take place to get a uniform distribution throughout the RAP mixture (Ma et al. 2015). As per the study conducted by Karlsson and Isacson (2003), around 48-144 hours was estimated as the average diffusion time for the complete diffusion of 10-50% rejuvenator (by weight of RAP binder), when it is poured directly over the RAP material. In addition, lower-viscosity rejuvenators diffuse faster and vice versa.

The influence of rejuvenators also varied with the blending process (mixing in the binder or the mix). Lu et al. (2019) investigated the effect of the rejuvenator and blending process for high RAP mixes (25%, 50%, and 70% RAP by weight of asphalt mixture). It was found that the impact of the blending process was not very significant for low RAP content. However, it substantially affects the performance when the RAP content is >50%. The overall results indicated that the direct addition of a rejuvenator to the RAP material is more beneficial than its blending with the neat asphalt binder. In the direct addition process, the rejuvenator was poured and allowed to stay on the RAP material for around 30 seconds, followed by the mixing of RAP with the natural aggregates in a mixer for 60 seconds. After the specified time, the neat binder was poured and blended for around 3 minutes to ensure uniform coating.

The effect of six different rejuvenators on the performance of asphalt binders and mixtures was examined by Zaumanis et al. (2015). The selected rejuvenators were waste vegetable oil (WVO), waste vegetable grease (WVG), aromatic extract, distilled tall oil, waste engine oil (WEO), and organic oil. 100% RAP was incorporated to ascertain the effect and importance of the

rejuvenators above. 9.5 mm Superpave-designed aggregate gradation was adopted for testing purposes, and the binder content of 5.94% was used to prepare all the asphalt mixtures. A PG64-22 neat asphalt binder was taken as a reference to compare the change in properties of the rejuvenated RAP binder. The dosage of rejuvenators was predefined and set to 12% by weight of the RAP binder. A series of tests were conducted at the binder level (i.e., penetration, softening point, linear amplitude sweep, and kinematic viscosity) and mixture level (such as Hamburg wheel tracking, fracture work density, creep compliance, tensile strength, and workability).

Results indicated that the effect of the rejuvenator depends on the test temperature. At intermediate temperatures, all the rejuvenators reduced the viscosity of RAP binder to the level of neat asphalt binder; on the other hand, although the rejuvenators lowered the viscosity at high temperatures, it was found to be higher than that of neat asphalt binder. Similar behaviour was observed for workability characteristics. Among different rejuvenators, the application of WVO improved the fatigue life (as per the LAS test) and was similar to the fatigue life obtained for neat asphalt binder. However, the trends were changed in the case of mixture fatigue life. At the mixture level, the mixture prepared with organic oil showed superior fatigue performance as compared to other rejuvenators. The difference in measured binders and mixture responses was attributed to the difference in loading modes between the selected test methods. Regarding rutting, none of the rejuvenated asphalt mixtures exhibit rutting concerns (rut depth < 12.5 mm at 10,000 passes). Based on all the testing aspects, organic oil and WVG outperformed and could be considered the best rejuvenation candidate for the RAP tested in the study. These results may change with the variation in RAP source and RAP binder content. The study by Zaumanis et al. (2015) showed that 100% RAP can be incorporated for the production of asphalt mixtures by adding an appropriate rejuvenator at the optimum dosage.

Rejuvenated asphalt binder with high RAP proportions (>25%) has often been characterized using micro and macro-level tests. In a study conducted by Hossain et al. (2020), the performance of 40% RAP mixture with some rejuvenation was determined using penetration, rotational viscosity, DSR, and atomic force microscopy (AFM) tests. Four different RAP sources were incorporated to understand the effect of rejuvenators more holistically. A commercial oil-based rejuvenator named Evoflex was used in this study, and the dosage was directly taken from the manufacturer (12.5% by weight of RAP binder). It was expected that the addition of Evoflex would improve the degree of blending between RAP and neat asphalt binder and eventually impart better coating and workability. As per the findings of the study, the addition of Evoflex reduced the stiffness of the RAP binder, and the effect of rejuvenation was clearly identified through morphological images. The authors reported that reduced stiffness would indirectly lower mixing and compaction temperatures, consequently aiding in conserving energy consumption and environmental stewardship. The high-temperature performance grade of all the RAP sources ranged from 76-82°C, but after the rejuvenation, the range shifted to 63-73°C. This is due to the change in the ratio of asphaltene/maltenes with the addition of an oil-based rejuvenator (Evoflex). Interestingly, AFM results revealed that the surface roughness of 40% RAP blends was nearly 50nm, but the same blend with Evoflex indicated high surface roughness i.e., 150nm. In general, the magnitude of surface roughness is an indicator of the adhesion properties (Lushinga et al. 2020), where a higher surface roughness indicates improved bonding between the asphalt mix components (such as aggregate, RAP, virgin asphalt binder, and additives) and vice versa.

Along with rejuvenators, different additives such as antistripping agents/anti-ageing additives were often added for preparing the RAP-inclusive asphalt mixtures. This is usually done to improve the performance of RAP mixtures under the adverse effects of moisture and ageing. Sukhija et al. (2022a) examined the combined effect of ageing and moisture on the asphalt mixtures prepared using 30% RAP material. One rejuvenator, two antistripping agents, and one antistripping rejuvenator were used for the experimental program. Seven different combinations of asphalt binders were prepared with the above-mentioned additives. The authors added the rejuvenator and antistripping agent directly to the neat asphalt binder before preparing the asphalt mixtures. The testing was conducted on loose asphalt mixtures (boiling water test and static immersion test), asphalt binder (high-temperature performance grading and zero shear viscosity), and also compacted asphalt mixtures (Marshall stability and retained Marshall stability). Results indicated that all the combinations exhibit higher moisture resistance, except the mixes prepared with neat asphalt binder and rejuvenator alone. The asphalt mix prepared with an antistripping rejuvenator additive showed superior active and passive adhesion, possibly due to the increase in cohesive bond with the addition of additives. Moreover, the use of an antistripping agent together with the rejuvenator improved the antistripping characteristics to a greater extent. Change in the physicochemical properties of the rejuvenator with the addition of an antistripping agent might be the probable reason for the improved performance. Based on the binder testing, it was found that the rejuvenator lowers the stiffening effect, whereas antistripping agents do not influence the rheological properties. Considering the ageing condition, any additive and rejuvenator had no remarkable effect. However, the asphalt mixtures produced with antistripping agents and rejuvenators in any combination were found to be more beneficial than the control mix (without any additive or rejuvenator). The authors also suggested allowing the interaction of rejuvenator and RAP material for a sufficient period of time to enhance the performance of RAP mixtures, especially those with high RAP contents.

2.4.2 Use of Warm Mix Additives

The application of RAP in asphalt pavements poses various challenges both in the design phase and during the construction (Tao and Mallick 2009; Zhang et al. 2022). These challenges arise due to the presence of an oxidized asphalt layer over the RAP aggregates, which often affects the mix workability and compaction ability (Coleri et al. 2018a; Farooq and Mir 2017; Mogawer et al. 2013; Vargas-Nordbeck and Timm 2012). In line with the context, high mixing and compaction temperatures of the RAP-inclusive asphalt mixtures are one of the major issues associated with the implementation of RAP recycling (Sukhija and Saboo 2020). A few studies in the literature (Guo et al. 2014, 2017; Tao and Mallick 2009) stated that the product temperature must be high enough to evaporate the moisture from aggregates yet low enough to avoid further ageing or burning of the RAP binder. However, lower production temperature for RAP mixtures corresponds to reduced mix efficiency due to insufficient adhesion between the asphalt binder and aggregates (Guo et al. 2020a). Therefore, warm mix asphalt (WMA) technologies are getting more attention from the perspective of RAP recycling because WMA can considerably reduce the mixing and compaction temperatures without affecting the performance of asphalt mixtures (Caputo et al. 2020; Shiva Kumar and Suresha 2019; Sukhija et al. 2021b; Wagh et al. 2022). Despite lower production temperatures, the use of WMA in RAP mixtures also leads to improved compaction and lower greenhouse gas emissions and energy consumption (Kumar et al. 2022). Moreover, WMA acts as a strategic technique to improve the quality and quantity of RAP in asphalt pavements (Coleri et al. 2018a).

The synergistic effect of RAP and WMA provides a way towards a sustainable infrastructure with similar performance as HMA prepared with natural aggregates and asphalt binders. The mix incorporating RAP and WMA exhibits superior rutting resistance due to the stiff RAP binder and improved workability due to the reduced viscosity with the addition of WMA.

Zhao et al. (2013) carried out a comparative study evaluating the performance of WMA-RAP mixtures designed for different structural layers (surface and base course). The foaming process and a chemical WMA agent (i.e., Evotherm) were used for the preparation of WMA mixtures. Depending on the structural layer, RAP content varied from 0% to 40%. A set of experiments was performed, including asphalt pavement analyzer, Hamburg wheel tracking, tensile strength ratio, resilient modulus, creep energy, 50% stiffness reduction test, and beam fatigue test. Overall results of this comprehensive study showed that the performance of the RAP-WMA combination depends on the type of WMA technology and RAP content. WMA mixtures with high RAP content (>30%) indicated lower rutting resistance than HMA mixtures with no RAP, irrespective of WMA technology. On the other hand, the same combination showed similar or even better fatigue resistance compared to HMA mixtures with low RAP content (15%). The authors concluded that the use of WMA with high RAP content (>30%) might exhibit rutting concerns but was found to be suitable for fatigue/cracking-prone areas. This might be attributed to the softening of the RAP binder with the addition of WMA, which improves the fatigue performance but lowers the load-carrying capacity and, thus, lowers the rutting resistance (Kumar et al. 2022).

Behbahani et al. (2017) evaluated the rutting characteristics of asphalt mixtures prepared with WMA and varying RAP percentages. Asphalt mixtures with four different RAP percentages (0%, 25%, 50%, and 75 % of total aggregates) were examined. Two WMA additives, i.e., Sasobit and Zycotherm, were used to prepare the WMA binders. Dynamic creep and wheel tracking tests were performed to assess the rutting performance, and their results were compared with the HMA mixtures containing the same percentages of RAP (without WMA additive). It was found that the increase in the percentage of RAP inevitably increased the rutting resistance in terms of flow number and rut depth. This is ascribed to the increase in stiffness of the asphalt binder, and so the asphalt mixture with the addition of higher RAP proportions. Although the asphalt mixtures with Sasobit were produced at a comparatively lower temperature than HMA mixtures, they showed higher rutting resistance, irrespective of the RAP proportions. The extent of improvement was more pronounced with 75% RAP content. However, the use of a chemical-based WMA additive (Zycotherm) indicated marginally lower rutting resistance than HMA mixtures at all the RAP contents. The authors clearly showed that the category of WMA technology (organic and chemical) significantly affects the performance of RAP-inclusive asphalt mixtures. The results obtained from the flow number were consistent with rut depths obtained using the wheel tracking test, where Sasobit outperformed, while the performance of Zycotherm and HMA was almost equivalent.

Figure 2.12 shows the allowable RAP proportions with WMA technologies based on the performance results obtained in past studies (Arshad et al. 2015; Ayazi et al. 2017; Barraji et al. 2022; Behbahani et al. 2017; Fakhri and Ahmadi 2017; Kim et al. 2017; Lu and Saleh 2016; Moghadas Nejad et al. 2014; Rondón et al. 2015; Sabouri et al. 2016; Sengoz and Oylumluoglu 2013; Singh et al. 2017; Song et al. 2018a; Valdes-Vidal et al. 2018; Xie et al. 2017; Zhao et al. 2012). As can be seen, the average RAP proportion depends on the performance criteria (here, rutting and fatigue). It was found that an average of 47-50% RAP (as shown with the red dashed

line in Figure 2.12) can be allowed with the use of WMA technology for adequate performance against rutting and fatigue distresses. These results depend on several factors, including RAP source, grade of neat asphalt binder, optimum binder content, WMA technology, WMA additive dosage, and production temperatures. Therefore, the implementation of combined RAP-WMA technology involves considering several factors that are crucial from a performance point of view. In this regard, Hettiarachchi et al. (2019) recommended selecting the appropriate WMA type and RAP proportion based on the application and climatic conditions of the pavement area.

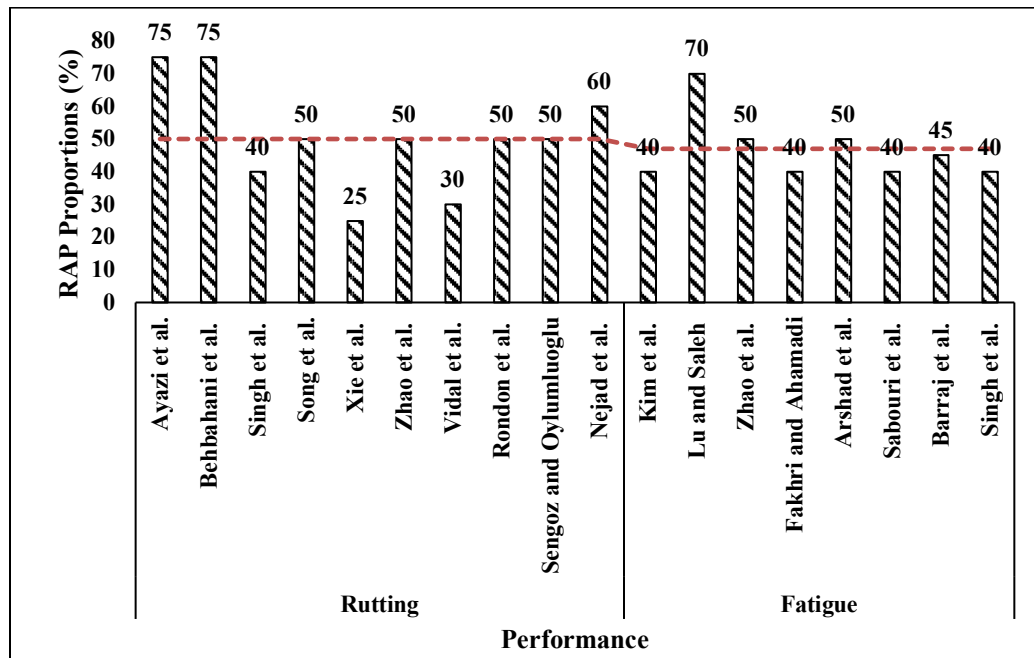


Figure 2.12. Allowable RAP percentages with WMA based on the results of past studies (Arshad et al. 2015; Ayazi et al. 2017; Barraj et al. 2022; Behbahani et al. 2017; Fakhri and Ahmadi 2017; Kim et al. 2017; Lu and Saleh 2016; Moghadas Nejad et al. 2014; Rondón et al. 2015; Sabouri et al. 2016; Sengoz and Oylumluoglu 2013; Singh et al. 2017; Song et al. 2018a; Valdes-Vidal et al. 2018; Xie et al. 2017; Zhao et al. 2012)

2.4.3 Increased Binder Content

In the case of high RAP mixtures, asphalt industries tend to give more attention to ensuring satisfactory field performance. If the performance of high RAP mixes is not comparable to asphalt mixtures with no RAP, the design attributes should be changed accordingly to improve the durability of high RAP mixtures, particularly when $RAP > 25\%$ (Willis et al. 2013). One suggested method for improving the performance is to increase the quantity of neat asphalt binder by some percentage. Although the use of increased binder content increases the cost of the overall asphalt mixture, the upfront cost can be offset with the use of high RAP proportions. A comparison of material cost with the use of 25% and 50% RAP at increased binder content versus the asphalt mixture prepared without RAP was demonstrated by the National Center for Asphalt Technology (Willis et al. 2012). As can be seen in Figure 2.13, the total material cost can be reduced by almost 14-32%, depending on the RAP proportion and increased binder content. Such potential savings and improved performance led the researchers (Coleri et al.

2018a; Haddadi et al. 2019; Sreedhar et al. 2021; Sreedhar and Coleri 2018) and engineers to adopt this strategic measure for increasing the proportions of RAP in asphalt pavements. A summary of a few of the past studies is shown in Table 2.6.

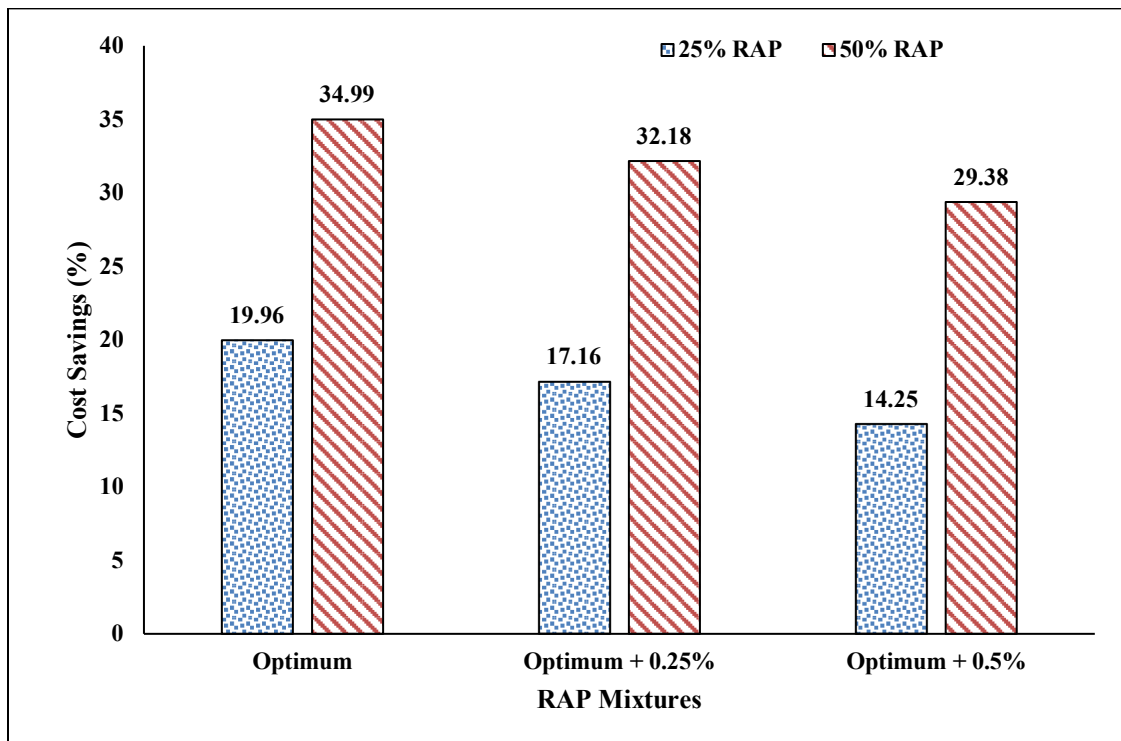


Figure 2.13. Potential cost savings with the use of increased binder content for high RAP proportions (Willis et al. 2012)

Table 2.6. Summary of past studies showing the effect of increased binder content on RAP mixtures

Reference	RAP (%)	Test Conducted	Mix Type and Neat Binder	Binder Content	Inferences	Remarks
Sreedhar and Coleri (2018)	20	• SCB • Dynamic modulus • Flow number	Mix 1 = PG70-22ER (OBC 6%) Mix 2 = PG70-22ER (OBC 5.3%) Mix 3 = PG70-22 (OBC 5.3%)	5.3% and 6%	• Increase in binder content from 5.3% to 6% lead to a higher flexibility index (almost 2-3 times higher). • 0.7% increase in binder content reduced the dynamic modulus, regardless of mix type. • As per flow number, all the asphalt mixtures are stiff enough against rutting distress.	• Increase in binder content does not contribute to rutting failure while significantly improving the pavement longevity in terms of higher cracking resistance.
Coleri et al. (2018b)	30 and 40%	MEPDG performance prediction	PG 58-34 PG 64-22 PG 76-22	6.0%, 6.4%, and 6.8%	• Binder content was found to be the most influenceable parameter affecting bottom-up-cracking. • Increase in binder content and a reduction in RAP content also lowers the cracking accumulation. • Even though increased binder content leads to higher material	• Oxidation of asphalt binder tends to increase its stiffness which indirectly inevitably improves the rutting resistance. • Considering performance and life cycle cost, an increase in binder content can be selected as a strategic

Reference	RAP (%)	Test Conducted	Mix Type and Neat Binder	Binder Content	Inferences	Remarks
					cost, it improves overall life cycle cost.	measure for improving the condition of the road network with higher cost savings.
Willis et al. (2013)	25% and 50%	• Asphalt pavement analyzer • Energy ratio test • Overlay tester	PG 67-22	Optimum, Optimum + 0.25%, and Optimum + 0.5%	• Use of higher binder content results in a higher number of cycles to failure for 25% RAP blends. • Increase in the fracture energy was observed with the addition of higher binder content. • The results obtained with a 0.25% addition of binder content were more pronounced than 0.5% higher binder content. • Both 25% RAP mix and 50% RAP mix with 0.25% extra binder content indicated better rutting performance than asphalt mixtures without RAP.	At higher RAP proportions (50%), the increased stiffness of the RAP binder most likely overshadowed the potential of the higher binder content.

2.4.4 Binder-Grade Bumping

An increase in RAP proportions is one of the primary objectives of the asphalt industry. However, they are reluctant to use high RAP because of the cracking concerns associated with stiff RAP binders. This problem can be strategically overcome by the use of soft binders, which can compensate for the stiffening effect of RAP binders. In general, the process of using soft binders is referred to as binder grade bumping, wherein the high-temperature performance grade (PG) of asphalt binder is lowered by one or two grades to reduce the overall viscosity of the final asphalt mixture with high RAP content (Coleri et al. 2018a).

Coleri et al. (2018a) conducted a comprehensive investigation to implement a high RAP proportion in asphalt pavements using soft binders. SCB, dynamic modulus, and flow number tests were carried out using different binder grades (PG58-34, PG64-22, and PG76-22) and two RAP proportions (30% and 40%). The results revealed the importance of using soft binders in terms of improved flexibility index. Based on the threshold limit of flexibility index ($FI > 9$) defined in another study conducted by the authors (Coleri et al. 2017), the asphalt mixture with 30% RAP and PG 58-34 binders imparted higher fatigue resistance, followed by 30% RAP with PG64-22, 40% RAP with PG 58-34, and 30% RAP with PG64-22. This comparison was made at a fixed binder content of 6.8%, however, the trend may change with the variation in asphalt binder content. As per the rutting characteristics, all the tested asphalt mixtures prepared with the softest binder PG58-34 passed the critical threshold specified in the study (flow number > 190). In addition, the increase in RAP content increases the flow number of the asphalt mixtures, which is attributed to the increase in the amount of stiff RAP binder. Irrespective of the RAP content, the mixtures with PG58-34 showed a lower dynamic modulus than the mixtures with a stiffer binder (PG76-22).

In a study conducted by Willis et al. (2013), the authors used a softer binder to improve the performance of RAP mixtures and eventually increase the RAP proportion. A comparison between the RAP mixtures prepared with PG67-22 and softer binder grade (PG58-28) was demonstrated for two different RAP proportions (25% and 50% RAP). Rutting (in terms of rut depth) and fatigue characteristics (in terms of fracture energy) were determined to assess the suitability of binder grade bumping in increasing the RAP content. The study showed that the RAP mixtures prepared with softer binder content are less resistant to rutting distress (higher rut depth) than the RAP mixtures prepared with PG67-22. This observation is independent of RAP contents, as shown in Figure 2.14. Though the mixture with 25% RAP and softer binder exceeded the critical threshold set for rut depth in the study (rut depth < 5.5 mm), the use of 50% RAP with the same binder was found to be suitable for the considered situation. The rut depth of the asphalt mixture prepared with 50% RAP and PG58-28 was found to be 3.90 mm, which is lower than 5.5 mm. Similarly, the fracture energy analysis showed that the application of the binder grade bumping technique improved the cracking resistance for both RAP mixtures. Figure 2.14 also shows that the fracture energy of the 25% RAP mixture was enhanced by approximately 34%, whereas the mixture with 50% RAP showed an increment in fracture energy by around 229% with the use of PG58-28 instead of PG67-22. The study clearly exposed the suitability of binder grade bumping for increasing the RAP content. However, further validation is required to implement this strategic measure as it sometimes causes rutting concerns based on the grade of the neat binder, RAP source, RAP percentage, and critical threshold limits (which depend on state specifications).

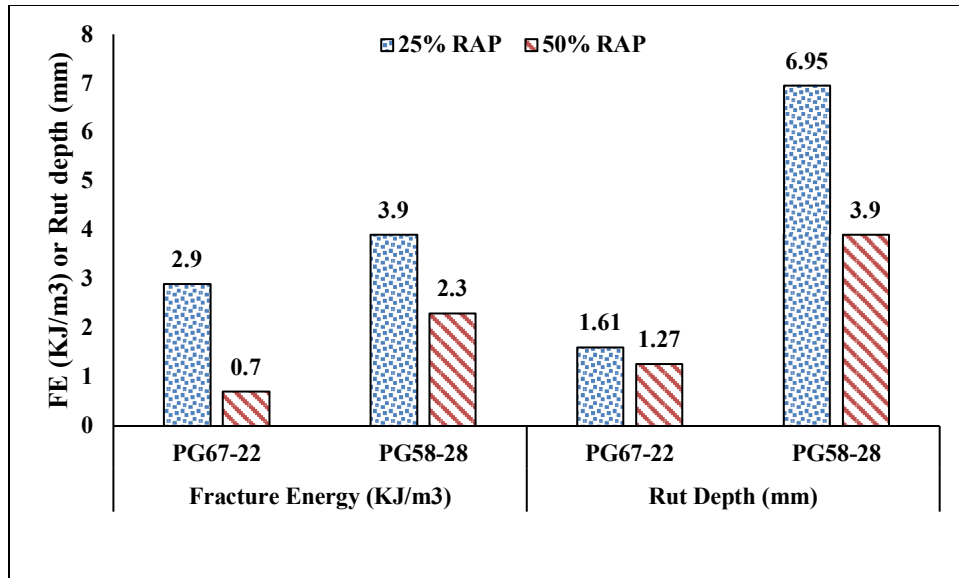


Figure 2.14. Variation in fracture energy (FE) and rut depth with the use of soft binder
(Willis et al. 2013)

The use of soft binder grade for the production of RAP-inclusive asphalt mixtures was also assessed by Pradhan and Sahoo (2022). The amount of RAP varied from 30% to 70%, and the PG70 binder was used as a neat asphalt binder for the preparation of asphalt mixtures. The amount of binder in RAP was determined through centrifuge extraction and reported as 3.64%. Indirect tensile strength, moisture sensitivity, resilient modulus, accelerated rutting test, and intermediate temperature cracking tests were carried out on RAP mixtures prepared with a softer binder and compared with asphalt mixtures prepared without RAP and PG70. The grade of the softer binder was evaluated using blending charts and was found to be varied based on the RAP content, target binder grade, and RAP binder grade. The grade of the RAP binder was found to be PG82, and the target binder grade was PG70. The optimum binder content of the asphalt mixture with no RAP was 5.5%. The grade of the softer binder was evaluated using the blending chart technique, in which the high-temperature RAP binder grade was taken as PG82-XX, and the target binder grade was fixed at PG70-XX. Figure 2.15 shows the high-temperature performance grade of a softer binder taking into account different RAP contents (Pradhan and Sahoo 2020). Since the compaction level for all the asphalt mixtures was the same, there was a variation in the volumetrics due to the soft binder's lower viscosity. The authors (Pradhan and Sahoo 2022) reported that the addition of soft binder results in higher tensile strength, which is even better than the asphalt mixture with no RAP. The increase in tensile strength with the use of soft binders ranged from 7% to 71% when the RAP content varied from 30% to 70%. The use of a softer binder also improved the moisture sensitivity and fatigue resistance of 30-40% RAP mixes to acceptable levels, but a further increase in RAP content resulted in unacceptable performance. The initial increase might be attributed to the increase in the amount of aged asphalt binder, but as the RAP content increases (>30%), there is a significant reduction in workability, which hinders the volumetrics, resulting in lower moisture resistance and higher cracking. The results showed that adding a softer binder does not affect the rutting resistance, which may be due to the stiffening effect of high RAP content. Despite a softer binder, all the RAP mixtures showed lower rut depth and higher resilient modulus than the asphalt mixture

prepared without RAP. A comparison of the cost was also carried out by Pradhan and Sahoo (2022). The cost analysis indicated that an increase in RAP content led to higher savings concerning material cost, even when the price of a softer binder grade was too high. More than 18% savings can be achieved using RAP with soft binder grade in comparison to an asphalt mixture with no RAP using PG70.

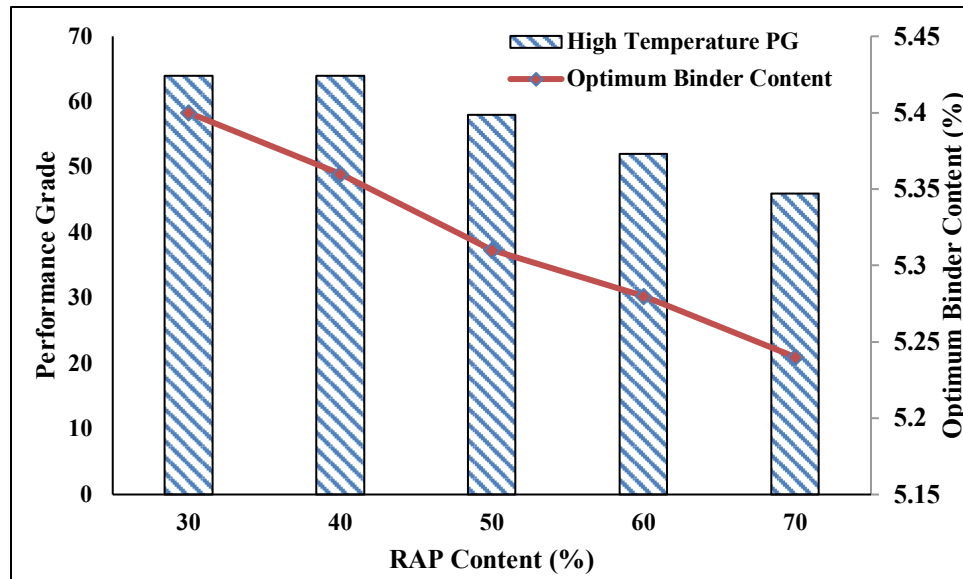


Figure 2.15. Required softer binder grade and optimum binder content corresponding to different RAP proportions adopted by (Pradhan and Sahoo 2020)

2.4.5 Use of Alternative Materials

RAP content < 25% is allowed for most asphalt pavements with the expectation of equivalent performance as asphalt mixtures with no RAP. As per past research studies (Ahmed and Hossain 2020; Behnood 2019; Kocak and Kutay 2017), the addition of RAP > 25% significantly affects the long-term durability of asphalt mixtures. Although there are several techniques, such as the use of warm mix asphalt, rejuvenator, increased binder content, or binder grade bumping to increase the RAP content or attain the equivalent performance as asphalt mixtures produced with natural aggregates and virgin asphalt binder, various studies in the literature (Baqersad and Ali 2021; Eltwati et al. 2022c; Jahanbakhsh et al. 2020; Mogawer et al. 2016; Torres et al. 2020) suggested the use of alternative materials for improving the performance of RAP mixtures, even at high RAP proportions. These alternative materials include the use of polymer-modified asphalt binder, crumb rubber, nanomaterial, fibers, waste plastic, etc., for producing high-quality RAP mixtures along with high RAP content. Much research work (Baqersad and Ali 2021; Eltwati et al. 2022c; Eskandarsefat et al. 2019; Fakhri and Amoosoltani 2017; Kim et al. 2009; Kocak and Kutay 2017; Torres et al. 2020) has been carried out in this direction to assess the impact of these alternative materials on the performance of the RAP binder/mixes or on increasing the RAP content. Table 2.7 shows the summary of some of the past research studies that have used the aforementioned materials in RAP recycling.

Table 2.7. Impact of alternative materials on the performance of RAP mixtures

References	Alternative Material	RAP Content (%)	Test Conducted	Inferences
Abreu et al. (2015)	High-density polyethylene (HDPE)	50%	• Moisture sensitivity • Wheel tracking test • Four-point beam bending • Stiffness modulus	• HDPE led to improved moisture resistance with an indirect tensile strength ratio of 82%, which is higher than the minimum specified limit for moisture-resistant asphalt mix (80%). • RAP mixture prepared with HDPE showed high performance at high temperatures, indicating improved rutting resistance. The addition of HDPE reduces the temperature susceptibility of the binder and increases the stability of the mixture. • The fatigue life of the HDPE-RAP mixture was found to be 5 times higher than that of the control asphalt mixture, but the reason for such improvement was not mentioned. • The stiffness modulus of the HDPE-RAP mix was not the highest, but it is still within the critical limits normally expected for asphalt pavements. • Overall, HDPE acts as a stabilizer that modifies the final binder grade and imparts enhanced performance.
Ziari et al. (2020a)	Glass fiber	0, 25, 50, 75, and 100%	• SCB fracture test	• Addition of glass fiber improved the cracking resistance. Fibers tend to reinforce the asphalt mixture and perform as a bridge on the crack, which avoids further propagation. Also, the incorporation of glass fibers imparts better coherence between the mastic and aggregates, resulting in lower stress concentration and excellent performance. • 100% RAP can be implemented with the use of 0.12% glass fibers without any significant cracking concern. • Glass fiber content and test temperature significantly affect the crack initiation and its propagation. • Excessive amount of glass fiber (0.18%) leads to agglomeration and eventually lowers the mix performance. • Authors stated that the adverse effect of RAP can be offset by the positive effect of glass fibers.

2.5 PERFORMANCE OF ASPHALT MIXTURES WITH HIGH RAP

An appropriate mix of design and RAP management scheme leads to improved performance, even at high RAP proportions. The stiff asphalt layer over the RAP aggregates creates uncertainty in the laboratory performance and limits their proportion for actual field implementation. For this reason, RAP material extracted from the surface course is often recycled into the base layer, where the flexibility requirement is comparatively lower than in the surface layers (Nahar et al. 2014). Although the presence of an oxidized RAP layer imparts improved moisture and rutting resistance, it typically hinders the performance of asphalt mixtures against fatigue cracking (Coleri et al. 2018a; b; Ghabchi et al. 2016).

As discussed, various strategic measures have evolved with time to improve the intrinsic characteristics of the RAP binder to those of a neat asphalt binder. However, adopting such measures sometimes imparts softness in the RAP binder and adversely affects the rutting performance (Behnood 2019; Pradhan and Sahoo 2022; Song et al. 2018a). Therefore, it is important to understand the actual performance of the RAP binder and the RAP-inclusive asphalt mixture in the laboratory prior to actual practice in the field.

It is well known that the rheological performance of asphalt binders has a direct relation to the mix performance (Singh and Kumar 2022; Walubita et al. 2022; Zhang et al. 2021). Different rheological characteristics and test parameters are developed to estimate the performance at the binder level using a dynamic shear rheometer (DSR). The rheological test methods and parameters generally include determining Superpave performance parameters, using accelerated rutting, and fatigue characterization tests such as multiple stress creep and recovery and linear amplitude sweep tests. These tests can run at a very wide range of test temperatures, frequencies, strains, and stresses, which can reliably simulate the mix response to field situations depending on the climatic conditions and ageing considerations. It has been found that the rheological performance of asphalt binders can be influenced depending on the aforementioned range of factors (Bi et al. 2020; Kleiziene et al. 2019; Sukhija et al. 2021a; Ziari et al. 2020b).

Similar to the testing at the binder level, the compacted asphalt mixture is also subjected to different performance tests. These tests are conducted to evaluate the performance of the asphalt mix against rutting, fatigue, and moisture distresses. Rutting behaviour is mostly adjudged using a Hamburg wheel rut tester, and an Asphalt pavement analyzer, whereas fatigue characterization is often carried out using a Four-point beam flexural test, an Indirect tensile cracking test, and a Semi-circular bending test. Moisture sensitivity of asphalt mixtures is mostly evaluated using the tensile strength ratio based on the indirect tensile strength test or employing the Hamburg wheel rut test (inflection point).

An attempt has been made to compile information on the performance of high-content RAP binders and mixtures (RAP >20%), along with their influential parameters. Since this section aims to understand the performance of asphalt binders containing high RAP content, it is desirable to adopt strategic measures as detailed in the preceding sections.

Table 2.8 shows the performance of RAP-inclusive asphalt binders and mixtures categorized based on strategic measures. Overall, RAP binders and mixtures indicated promising performance, particularly in terms of rutting and fatigue. Notably, most of the results displayed a

similar trend at both the binder and mixture levels. Apart from rutting and fatigue performance, a plethora of literature (Mogawer et al. 2012; Monu et al. 2019; Zhang and Bahia 2021) supports the use of RAP to improve moisture resistance, even after the adoption of strategic techniques. However, more research is required in this direction to determine the optimum dosage and selection of these strategic measures in order to improve the RAP proportion with balanced rutting and fatigue performance.

Table 2.8. Performance of RAP binders and mixtures based on strategic measures

Strategic Measure	Influential Parameters	Performance Effects	References
Rejuvenators	• RAP source • RAP content • Dosage of rejuvenator • Rejuvenator type • Neat asphalt binder • Characteristics of aged asphalt binder • Blending process • Blending time • Blending temperature • Aggregate source • RAP binder content • Neat asphalt binder content • Strain level	Binder level • Reduction in binder stiffness • Lower Superpave rutting parameter • Lower Superpave fatigue parameter • Reduced rutting resistance in terms of MSCR test parameters • Higher viscous nature • Higher fatigue life • Reduced oxidation effect Mix level • Increased fatigue resistance with the use of rejuvenator, especially at higher rejuvenator dosage • Rutting resistance may be higher or lower depending on the rejuvenator type and dosage • Reduced stiffness modulus • Improved recovery • Lower moisture-induced damage	(Ameri et al. 2018; Baqersad and Ali 2019; Chen et al. 2015; Eltwati et al. 2022b; Foroutan Mirhosseini et al. 2020; Mohi Ud Din et al. 2023; Mollamohammadi and Hesami 2023; Pradhan 2022; Pradhan and Sahoo 2020; Sukhija et al. 2022a; Taherkhani and Noorian 2019; Yu et al. 2020; Zhou et al. 2019)

Strategic Measure	Influential Parameters	Performance Effects	References
Binder grade bumping	• RAP source • RAP content • Neat asphalt binder grade • Age of milled pavement • Softer binder grade • Test strain levels • Aggregate source • RAP binder content • Neat asphalt binder content • Nominal maximum aggregate size	Binder level • Improved cracking resistance • Increased fatigue life • Comparable rutting performance • Lower Superpave fatigue parameter Mix level • Equivalent or lower rutting performance • Higher cracking resistance • Improved moisture resistance • Fracture energy depends on RAP content (may be positive or negative) • Improved flexibility index	(Ameri et al. 2018; Coleri et al. 2018b; Dony et al. 2013; Lee et al. 2023; Pradhan and Sahoo 2020; Willis et al. 2013; Yu et al. 2020)

Strategic Measure	Influential Parameters	Performance Effects	References
Warm Mix Asphalt	• RAP source • RAP content • Neat asphalt binder grade • Level of damage • WMA category • Test temperature • WMA additive dosage • Aggregate source • RAP binder content • Neat asphalt binder content • Aggregate gradation • Strain value	Binder level • Improved rutting resistance • Improved fatigue resistance • Lower production temperatures • Reduction in ageing susceptibility • Lower non-recoverable creep compliance • Higher recovery • Better elasticity • Enhanced Superpave performance parameters Mix level • Higher fatigue resistance • Rutting resistance is almost similar or even better to the control asphalt mixture • Improved thermal cracking • Higher moisture resistance	(Barraj et al. 2022; Gungat et al. 2016; Kim et al. 2017; Kumar et al. 2022; Li et al. 2021; Sun et al. 2019; Wang et al. 2017, 2022; Xu et al. 2023; Yu et al. 2020; Zaremotekhas et al. 2022)

Strategic Measure	Influential Parameters	Performance Effects	References
Increased binder content	• RAP proportions • Neat asphalt binder grade • Binder content • Strain levels • Aggregate source • RAP binder content • Neat asphalt binder content • Aggregate gradation	Binder level • Enhanced fatigue life based on LAS test Mix level • Rutting performance vary depending on the RAP content and increased binder content • Improved fracture energy • Higher cracking resistance • Improved flexibility index	(Coleri et al. 2018b; Sreedhar et al. 2021; Sreedhar and Coleri 2018; Willis et al. 2013)

Strategic Measure	Influential Parameters	Performance Effects	References
Alternative materials	• RAP source • RAP content • Modifier type • Characteristics of aged asphalt binder • Testing parameters • Modifier dosage • Aggregate source • RAP binder content • Neat asphalt binder content • Aggregate gradation	Binder level • Reduced ageing susceptibility • Decreased temperature sensitivity • Higher resistance against cracking • Improved rutting performance • Better elasticity • Increased complex modulus • Enhancement in high-temperature viscoelastic properties Mix level • Improved fracture energy • High critical energy release • High tensile strength ratio • Lower rut depth • Enhanced flow number • Improved flexibility index	(Eltwati et al. 2022b, a; c; Kamboozia et al. 2021; Li et al. 2021; Mohamed et al. 2022; Ramesh et al. 2022; Sreedhar et al. 2021; Sreedhar and Coleri 2018; Wang et al. 2023; Xu et al. 2022; Zhou et al. 2022; Ziari et al. 2019b)

The findings of the laboratory testing only provide an estimation of the possible behaviour of the asphalt mixtures in the field (Yang et al. 2022a). It is expected that if the RAP-inclusive asphalt binders and mixtures point out improved laboratory performance, they will also deliver adequate performance in the field. However, there are some exceptional cases where the RAP mixture failed in the field, but they imparted improved laboratory performance. These discrepancies may be attributed to the difference in the testing and simulation approach in the laboratory and field. One other suitable example is that in the laboratory, RAP is usually tested under controlled conditioning, whereas in the field, they are subjected to different other factors, not limited to temperature, variable traffic, environmental conditions, construction quality, pavement thickness, and structural capacity of the underlying pavement layers (Gong et al. 2018; Hatoum et al. 2022). Owing to the various factors affecting the RAP mixture performance, it is often very challenging to depict the exact reason for the premature failure of the pavement in the field. Nonetheless, in most of the case studies, the performance of RAP-inclusive asphalt mixture in the laboratory and field is quite comparable.

Although most of the pavements with high RAP content designed by following an appropriate mix design method performed well in the field, it is imperative to conduct a comprehensive assessment of field cores, which should be further tested in the laboratory to examine the short and long-term performance. In addition, a comparison of samples prepared with different approaches and locations, such as plant-mixed field compacted, plant-mixed lab compacted, and lab-mixed lab compacted samples, should be conducted to identify a correlation between these variables. These correlations would be beneficial in forecasting the long-term durability of RAP-inclusive complex asphalt mixtures through laboratory testing prior to their implementation in the field. Also, it will provide an idea of the appropriate strategic measures to be adopted for sustaining quality control and quality assurance, and improving pavement longevity with less economic and environmental burdens.

2.6 SUMMARY AND CONCLUSIONS

An attempt has been made to compile the inferences and observations of some recent past studies incorporating RAP (especially high RAP content) in asphalt pavement construction. Emphasis was placed on the adoption of a proper RAP management scheme and an appropriate mix design to facilitate the use of high RAP with little variability. Details of different RAP material characterization methods and mechanical performance have also been described. In addition, the research challenges and their remedial measures adopted in the existing laboratory studies have been reported. The key conclusions and research gaps derived from the review of past studies in the literature are as follows:

- A proper RAP management scheme contradicts the general belief of “high-performance variability in asphalt mixtures prepared using high RAP contents”. A higher percentage of RAP can be incorporated in the asphalt mixtures by following a proper RAP management scheme, even when the RAP is obtained from multiple sources or different locations from an individual stockpile.
- Blending different stockpiled materials obtained from multiple sources could substantially reduce the variability between and among the stockpiles. Also, stockpiles should be built in layers and on a paved surface with a definite slope to minimize the segregation and moisture

retention problems. Limiting these variabilities could help increase the percentage of RAP in producing recycled asphalt pavement without sacrificing performance.

- The amount and properties of asphalt binder in RAP mixtures and the aggregate gradation can be identified after following a two-step protocol commonly referred to as the extraction and recovery process. However, the properties of asphalt binder before and after the extraction and recovery, particularly in RAP mixes, showed irregular trends. This is primarily attributed to the presence of residual solvents or fine particulates within the recovered asphalt binder.
- The most commonly used extraction and recovery methods are centrifuge extraction and rotavapor due to their simplicity, safe operation, a large volume of sample, and comparatively less ageing of the asphalt binder. Considering the type of solvent, trichloroethylene and n-propyl bromide are the most frequently used solvents for the extraction and recovery process.
- An increase in RAP proportions is one of the primary objectives of asphalt industries; however, they are reluctant to use high RAP because of the cracking concerns associated with stiff RAP binder. This problem can be strategically overcome by adopting strategic techniques, such as the use of rejuvenators, soft asphalt binders, increased binder content, warm mix asphalt, and alternative materials. As per the review of previous studies in the literature, strategic techniques are mandatory when the RAP proportion is greater than 20% by weight of the total mix.
- Performance assessment supports the application of RAP material for paving purposes. The assessment was done with and without the use of strategic techniques. From this perspective, RAP binders and mixtures indicated promising performance, particularly regarding rutting and fatigue. Most of the results displayed a similar trend at both the binder and mixture levels.
- Production of asphalt pavements using RAP material can affect field performance or lead to premature failure if appropriate mix design protocols are not followed. Based on previous studies in the literature, most of the pavements with high RAP content were designed with appropriate mix design procedures that performed well in the field. Performance-based balanced mix design (BMD) methods are also important for achieving high RAP contents without sacrificing performance.

Understanding the complexities associated with using RAP material is the need of the hour, and thus, it is gaining a lot of attention worldwide. As reviewed in past literature, a proper mix design method with performance experiments and the adoption of an appropriate RAP management scheme can greatly improve the RAP content and pavement longevity. However, this has not been studied rigorously and can be a scope in future work related to RAP recycling. Also, the use of RAP can be promoted by investigating and correlating the performance of extracted RAP binders in terms of morphological, chemical, and rheological aspects. Correlations should be made between the performance at the binder and mixture levels to more clearly understand the mechanism of the RAP binder within the RAP mixture. The use of different sources of RAP material has to be focused on for further research in this direction. More comprehensive laboratory and field investigations are also required to accelerate the RAP recycling process.

Moreover, a cradle-to-grave life cycle assessment or life cycle cost estimation is needed to predict the long-term economic and environmental burdens of using RAP in asphalt pavements.

3.0 MATERIALS AND METHODOLOGY

The present study supports the goal to increase asphalt recycling in order to reduce economic and environmental burdens and improve pavement longevity by employing various strategic techniques. These strategic techniques involve the change in mix attributes, use of rejuvenators, warm mix asphalt (WMA) technologies, and better-reclaimed asphalt pavement (RAP) management practices. However, selecting the most effective technique for Oregon and ensuring appropriate RAP management schemes to achieve high RAP mixes without affecting the performance of the asphalt pavements is crucial. Thus, different combinations of asphalt binders, RAP content, rejuvenators, and WMA additives are included in the experimental design of this study. A series of testing procedures has been chosen to understand the benefits of implementing asphalt recycling on a larger scale. The final outcome of the present study is based on the mechanical performance and economic and environmental aspects.

This chapter provides a brief overview of the materials used throughout the research. The material characterization in terms of chemical composition and rheological properties of the asphalt binder has also been discussed. The binder-level characterization was conducted only on the virgin binders, both with and without the inclusion of WMA and rejuvenators, to assess the resulting changes in their behaviour. A couple of past studies in the literature recommend the evaluation of engineering and chemical properties of the virgin asphalt binders blended with WMA and rejuvenators (Elahi et al. 2021; Mehmood et al. 2024; Saboo et al. 2021; Sukhija et al. 2025; Wagh et al. 2025). Thus, in this research work, the team attempts to investigate how these additives affect performance at the binder level.

This chapter also includes the details on the test methodology; however, detailed descriptions of the experimental matrix are presented in subsequent chapters to avoid confusion, as each chapter involves a distinct test matrix and plan with varying material combinations. For example, in some chapters, only RAP from Source 1 was used, whereas in others, RAP from two different sources was incorporated to address specific research objectives. In addition, presenting this information here helps avoid redundancy in displaying the same aggregate gradation, basic asphalt binder properties, modified binder preparation, and mix design procedures throughout the report. While these conditions were kept constant, certain specific parameters were varied as required for each study.

3.1 MATERIALS USED

This section provides information on the materials utilized to prepare recycled asphalt mixtures. It also demonstrates the details on the aggregate gradation, preparation of modified binders, and mix design procedure. It has to be noted that the selection of construction materials (asphalt binder grade, RAP content, and compaction effort) and the corresponding mix design are usually based on the mix design level category. These mix design levels are primarily a function of the current and anticipated traffic volumes on the roadway and the roadway type (rural or urban). In general, the Oregon Department of Transportation (ODOT) specified four mix design levels for

the construction of asphalt concrete pavements in Oregon. Table 3.1 presents a general overview of these mix design levels. The present study focuses on recycled asphalt pavements with anticipated traffic greater than 1 million (i.e., Level 3 and Level 4 mix design levels).

Table 3.1. Mix design levels for asphalt concrete pavements in Oregon

Mix Design Level	Anticipated Traffic	Suggested Construction Areas
Level 1	Not available as it is not endorsed for most roads	Residential driveways, bike routes, hiking tracks, and recreational lots.
Level 2	< 1 million	Low-volume highways and roads.
Level 3	1 million – 10 million for rural roads and 1 million – 3 million for urban roads	State highways, major arterials, and heavy truck parking zones.
Level 4	> 10 million for rural roads > 3 million for urban roads	Interstates, roadways with very high traffic, and heavy trucks.

3.1.1 Aggregates and RAP

A single source of virgin aggregates with a nominal maximum aggregate size (NMAS) of ½ inch (12.5 mm) is used in the present research work. As per the ODOT, ½ inch (12.5 mm) NMAS asphalt mix is a dense graded mix type typically produced and placed in lift thicknesses ranging from 2 to 3 inches. The virgin aggregates were provided by the Knife River Corporation (KRC), Salem, Oregon.

This study involves the use of recycled asphalt pavement (RAP) materials for the preparation of asphalt concrete mixtures. Two sources of RAP materials (½ inch NMAS) were procured to assess the effect of RAP material source variation on the performance of asphalt mixtures. One source of RAP material (referred to as RAP1) was obtained from the KRC asphalt plant situated in Salem, Oregon, while another source of RAP material (denoted as RAP2) was provided by the KRC asphalt plant, located in Corvallis, Oregon. The asphalt binder content of the RAP materials was 4.97% for RAP1 and 5.52% for RAP2. In almost all the chapters, RAP1 was used for the experimental work, while in Chapter 7.0, RAP2 was also incorporated to understand the effect of the RAP source.

3.1.2 Asphalt Binder

This study incorporates two different grades of asphalt binder, i.e., PG 64-22 (unmodified) and PG70-22ER (polymer-modified). PG64-22 is generally used for Level 3 mixes, while PG70-22ER is typically utilized for Level 4 asphalt pavements in Oregon. Both the asphalt binders were supplied by McCall Oil & Chemical Co., located in Portland, Oregon. The basic properties of the asphalt binders are shown in Table 3.2. The mixing and compaction temperature ranges are calculated using the viscosity-temperature graph provided by the supplier. The temperature corresponding to the viscosity values of 0.17 ± 0.02 Pas and 0.28 ± 0.03 Pas is denoted as the mixing and compaction temperature, respectively. All the properties of both the asphalt binders

are identified to satisfy the standard limits specified in AASHTO M320, ASTM D6373, ASTM D2473, and AASHTO T301.

Table 3.2. Basic properties of the asphalt binders incorporated in this study

Binder Properties	PG64-22	PG70-22ER
Specific Gravity @ 15 °C (60 °F)	1.0381	1.0376
Flashpoint, °C	>230	>230
Dynamic Shear, G*/sinδ (at grade temperature), kPa	1.20	1.08
Rotational Viscosity, 135 °C, Pas	0.375	0.650
Rotational Viscosity, 165 °C, Pas	0.125	0.187
Mixing Temperature Range, °F	307-319	328-340
Compaction Temperature Range, °F	283-293	305-315
Loss on Heat (RTFO residue), %	0.205	0.223
Elastic Recovery (RTFO residue), %	-	58.75

3.1.3 Additional Additives

Since RAP material has an oxidized asphalt binder film over the RAP aggregates, this often affects the mix's workability and compaction ability. Additionally, RAP-inclusive asphalt mixtures entail high production temperatures that affect the performance of asphalt mixtures and increase the project cost. The oxidized RAP binder with limited maltene content may result in an asphalt mix with lower cracking resistance if the RAP content is high or if nothing is done to offset the stiffening effect of the brittle RAP binder. Thus, additional additives, such as rejuvenators and warm-mix asphalt (WMA) technologies, are often adopted as strategic measures to improve the quality and quantity of RAP in asphalt pavements. The synergistic effect of RAP and rejuvenator or RAP and WMA may help towards achieving a more sustainable process.

Rejuvenators tend to restore or reduce the stiffness of the oxidized RAP binder by creating a chemical reaction, which rejuvenates the properties of the RAP binder to get them close to the properties of the neat asphalt binder. On the other hand, WMA technologies are generally employed to reduce production temperatures without affecting the performance of asphalt mixtures, even at high RAP contents. Using WMA technologies also improves workability and lowers greenhouse gas emissions during the production of asphalt mixtures.

In the present study, two different rejuvenators (viz, REJ1 and REJ2) and two different WMA technologies (namely, WMA1, and WMA2) are included in an attempt to increase the RAP content without compromising the performance of the asphalt mix. Both WMA1 and WMA2 are chemical-based WMA technologies that allow the production of asphalt mixtures at lower mixing and compaction temperatures through enhanced coating and workability.

These rejuvenators and WMA additives are commercial products delivered by private companies within the United States. The details of the chosen rejuvenators and WMA additives, including their qualitative and quantitative characteristics, are given in Table 3.3. Notably, the dosages supplied by the manufacturers were based on the total binder (virgin + RAP binder) but added to the virgin binder for blending; hence, for RAP mixtures, these dosages were adjusted accordingly to accommodate the effect of the RAP binder using Equation 3.1. If the additive dosage is not adjusted, it may lead to underestimation because the RAP binder was not considered in the total binder calculation. A similar process was recommended by the manufacturer and also used in a previous study for producing additive-inclusive RAP mixtures (Kumar et al. 2022). In this study, the manufacturer-recommended dosages were not directly taken into the research work; they were initially validated before performance evaluation. These details can be found in Chapter 5.0 of the study.

Adjusted additive dosage (%)

$$= \frac{\text{Target additive dosage (\%)} \times \text{Total binder content (\%)}}{\text{Total binder content (\%)} - \text{Binder from RAP (\%)}}$$

(Equation 3.1)

Table 3.3. Characteristics of the chosen rejuvenators and WMA additives

Characteristics	Rejuvenator (REJ1)	Rejuvenator (REJ2)	WMA1	WMA2
Chemical composition	Tall oil fatty acid derivative	Corn oil, fatty acid residues, and methyl ester	Modified tall oil, fatty acid, and alkyl acid phosphate	Esters, phosphoric acid, and non-hazardous ingredients
Odor	Bland	Slight	Odorless	Mild
Physical state	Liquid	Liquid	Liquid	Liquid
Visual color	Amber (Dark)	Dark brown	Dark brown	Dark brown
Density at room temperature (g/cm³)	0.97	0.92	0.99	0.92-0.96
Viscosity, dynamic at room temperature (centipoise)	>118	> 150	487	< 250
Flash point (°C)	> 232	> 150	> 181	> 150
Solubility in water	NA	NA	Insoluble	Slightly soluble
pH value	8.3	5.3	2.3	2.5
Supplier-recommended dosage range by weight of total asphalt binder (Adjusted dosage as per Equation 3.1)	1.5% (2 % for RAP1 and 2.07% for RAP2)	1.5% (2 % for RAP1 and 2.07% for RAP2)	0.5% (0.67 for RAP1 and 0.69 for RAP2)	0.5% (0.67 for RAP1 and 0.69 for RAP2)

3.1.3.1 Preparation of Rejuvenators and WMA Blends

The rejuvenator and WMA additives were added to the virgin asphalt binder as per the manufacturer's recommendation. The virgin binder is first heated until it becomes fluid enough to be poured. A specified amount of preheated virgin binder is taken in a separate container and stirred using a shear mixer (Figure 3.1) for 5 minutes at a speed of 950-1050 rounds per minute (RPM) to eradicate air bubbles and ensure the binder's consistency. Following the stirring of the neat binder, the additives were added, and the blending process continued for an additional 10 minutes to produce WMA and rejuvenator-modified asphalt binders. The details of the base binder, additives, blending temperatures and time, and stirring speed are given in Table 3.4.

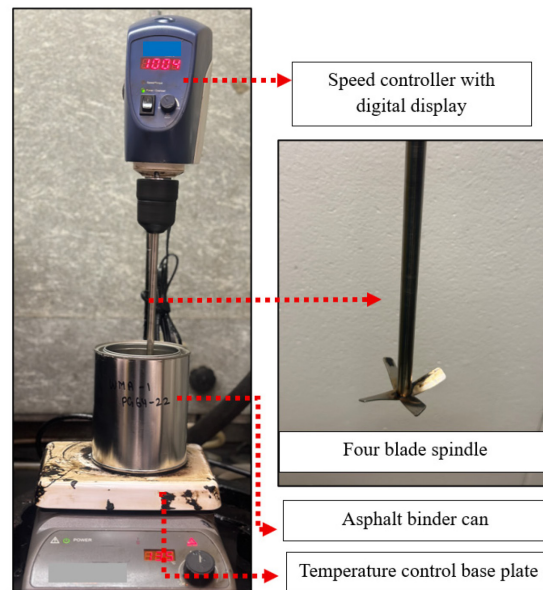


Figure 3.1. Shear mixer used for the preparation of modified asphalt binders

Table 3.4. Blending attributes for preparing rejuvenators and WMA modified binders

Base Binder	Additives	Blending Temperatures	Blending/Stirring Time	Stirring Speed
PG64-22	Rejuvenators: REJ1 and REJ2	130-140°C	5 minutes for the binder's consistency, followed by 10 minutes for blending the additives	950-1050 RPM
	WMA: WMA1 and WMA2			
PG70-22ER	Rejuvenators: REJ1 and REJ2	145-155°C	5 minutes for the binder's consistency, followed by 10 minutes for blending the additives	950-1050 RPM
	WMA: WMA1 and WMA2			

3.2 CHARACTERIZATION OF ASPHALT BINDERS AND ADDITIVES

The characterization of the asphalt binder was executed to understand how it performs in the presence of additives. The characterization was carried out by preparing the modified binders at the dosage recommended by the manufacturer (0.5% for WMA and 1.5% for rejuvenators by weight of total binder). The study on finding/validating the optimum dosages has been detailed in subsequent chapters. The binder level test described in this study includes the characterization of asphalt binder and additives using Fourier Transform Infrared (FTIR) Spectroscopy for chemical composition and rheological tests, such as high temperature performance grading and binder fast characterization test (BTSV), for binder properties. These are discussed next.

3.2.1 Fourier Transform Infrared Spectroscopy (FTIR)

FTIR is considered one of the most promising and widely used tools to identify/classify the chemical structure of the mixture components (Zhang et al. 2020). In this study, FTIR was executed using Nicolet iS50 FT-IR (Figure 3.2), following the Attenuated Total Reflectance (ATR) approach. FTIR test was carried out at Advanced Technology and Manufacturing Institute (ATAMI), an academic-industrial research center and business incubator run by Oregon State University (OSU). The spectrum was collected in the range of 600 cm^{-1} to 4000 cm^{-1} wavenumber with a resolution of 4 cm^{-1} , and the results are drafted in the form of absorbance.

The working principle of FTIR involves the absorption of infrared radiation at a defined frequency level to characterize any material's chemical structure. It uses a beam splitter (interferometer) to accumulate the interferogram data, which resembles a pattern of waves. These waves are generated based on the radiation received at different positions through fixed and movable mirrors. The same radiations (generally infrared radiations) are further interposed within the sample, which causes vibration in the molecular bond at distinct frequency levels, and signifies absorbance or transmittance of the radiations depending on their directions (Hou et al. 2018). The absorbance or transmittance values are digitized to visualize the actual spectrum data over a wide spectral range (wavenumber) (Kumar et al. 2019). Figure 3.3. demonstrates the schematic view of the working mechanism of FTIR.

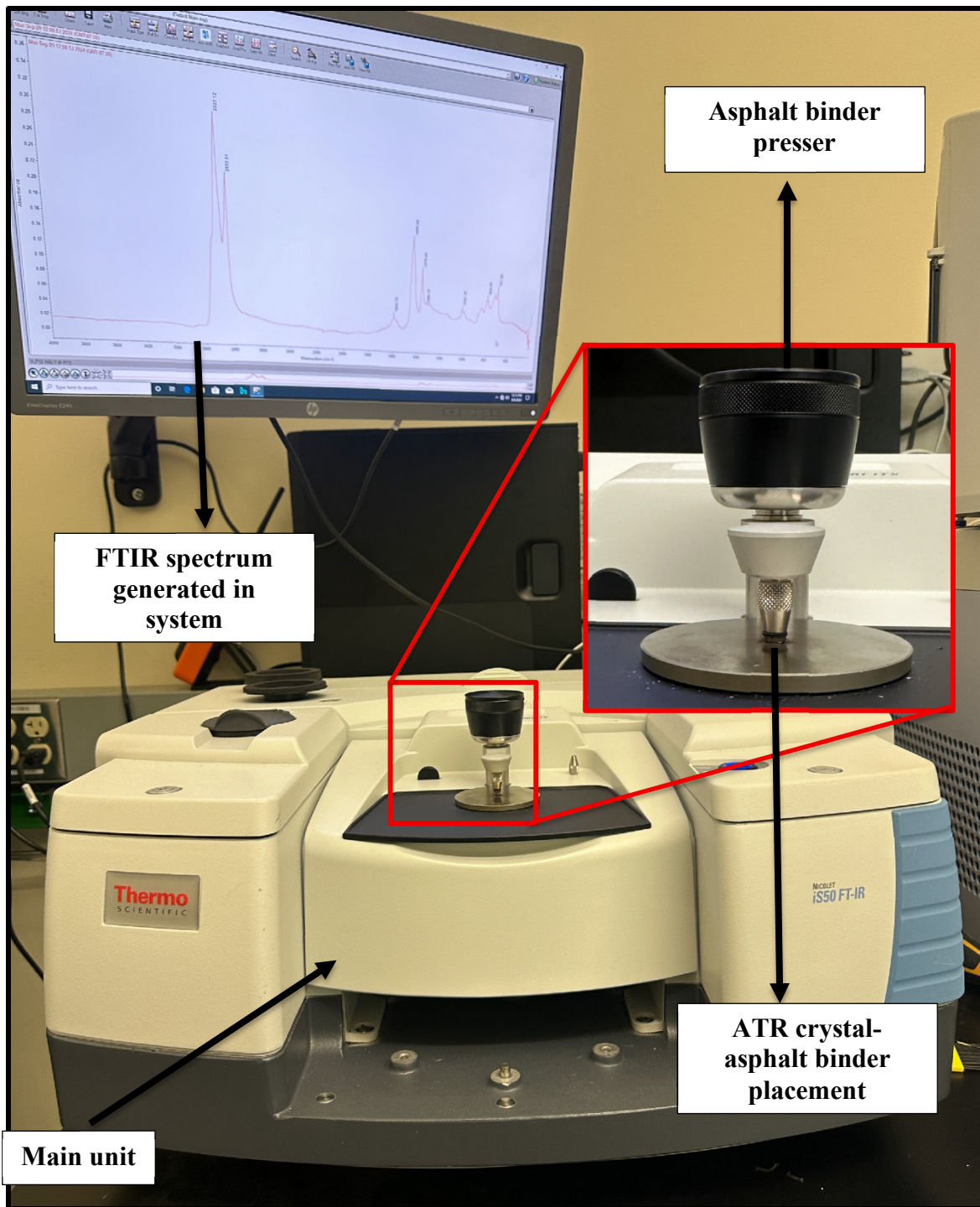


Figure 3.2. Fourier Transform Infrared Spectroscopy setup

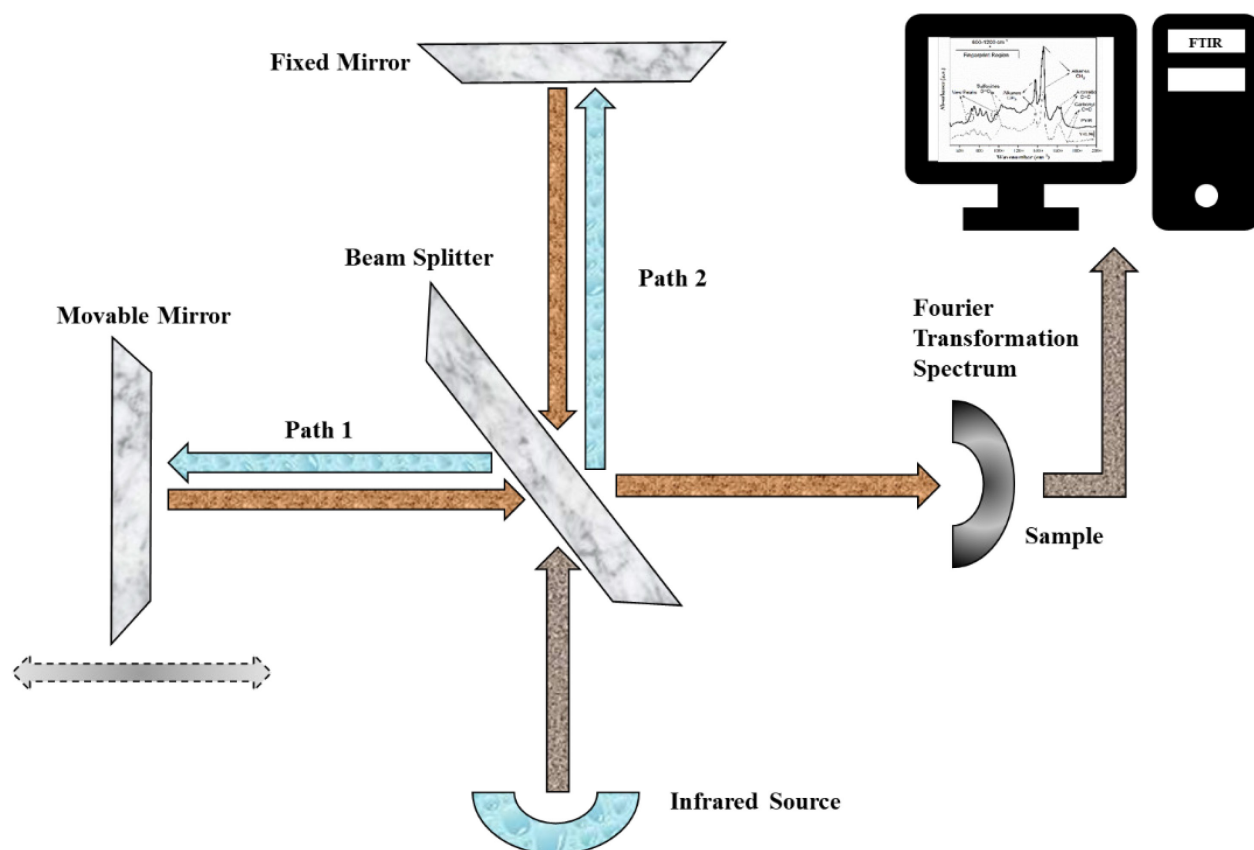


Figure 3.3. Schematic view of FTIR

3.2.1.1 FTIR of Neat Asphalt Binders

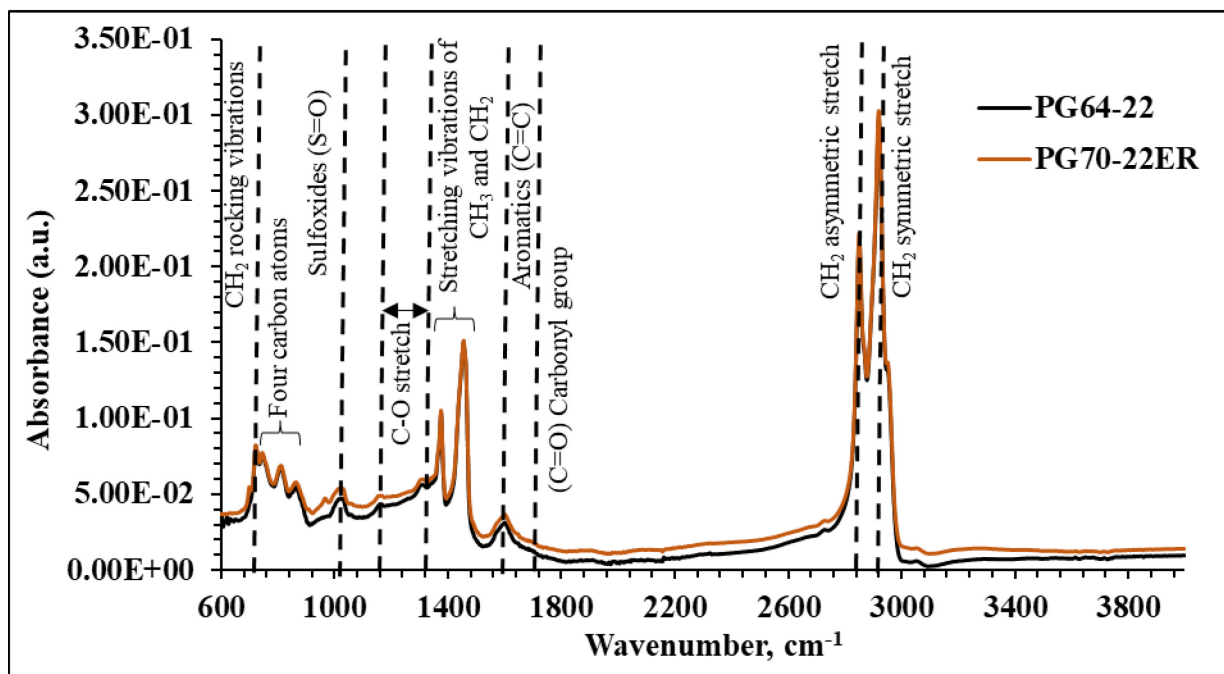
Since the two asphalt binders exhibit distinct chemical characteristics, primarily due to the presence of polymers in PG 70-22ER, they demonstrate different functional groups as identified through Fourier Transform Infrared Spectroscopy (FTIR). Figure 3.4a illustrates the FTIR spectra of both base binders.

A prominent peak at approximately 720 cm^{-1} corresponds to CH_2 rocking vibrations associated with long paraffinic chains. Several small peaks between $700\text{--}900\text{ cm}^{-1}$ indicate $=\text{C}\text{--}\text{H}$ in-plane bending vibrations in aromatic structures and olefins (Liu et al. 2019; Ma et al. 2022a). Moderate peaks observed around 1030 cm^{-1} confirm the presence of sulfoxides ($\text{S}=\text{O}$), which are significant indicators of oxidative ageing in asphalt binders (Nivitha et al. 2016). In addition, weaker stretching peaks near 1160 cm^{-1} and 1290 cm^{-1} suggest the presence of $\text{C}\text{--}\text{O}$ functional groups. Distinct asymmetric and symmetric stretching vibrations of CH_3 and CH_2 groups were noted between $1376\text{--}1452\text{ cm}^{-1}$, which are characteristic of asphalt binders as asphalt binder composition includes a long chain hydrocarbon with around 82-88% carbon and 8-11% hydrogen (Sukhija et al. 2025). A medium-intensity peak at approximately 1600 cm^{-1} reflects the presence of aromatic $\text{C}=\text{C}$ bonds (Ma et al. 2022a), while a weak peak near 1700 cm^{-1} indicates

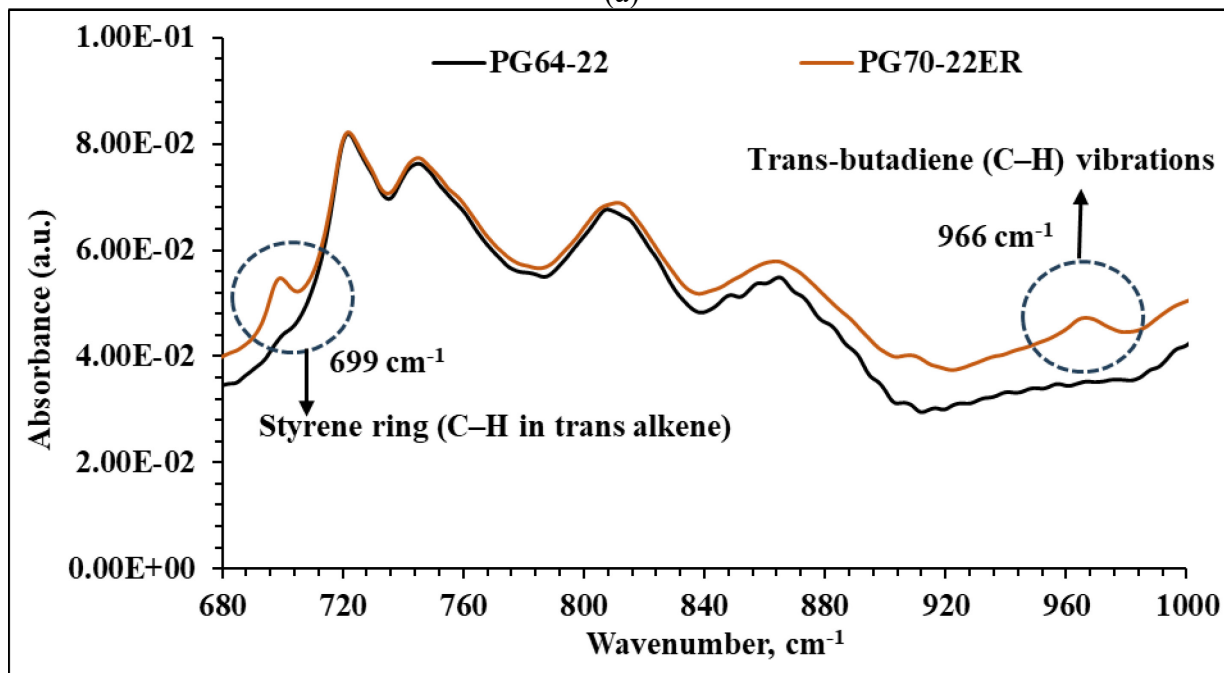
carbonyl compounds (C=O), another critical peak representing binder ageing (Yao et al. 2015). Other peaks include the region around 2850 cm^{-1} and 2925 cm^{-1} , indicating the CH_2 asymmetric and CH_2 symmetric stretch, respectively. These are primarily defined as the main hydrocarbon backbone with long-chain aliphatic (Albayati et al. 2025; Leodarta et al. 2025).

These characteristic peaks were consistent in both binders. However, additional peaks unique to the PG 70-22ER binder were identified. As shown in the zoomed-in FTIR spectrum (Figure 3.4b), distinct peaks at 699 cm^{-1} and 966 cm^{-1} correspond to the styrene ring (C–H in trans alkene, out-of-plane bending) and trans-butadiene (C–H) vibrations, respectively, confirming the presence of styrene–butadiene–styrene (SBS) polymer modification. These differences are consistent with the observations of previous studies in the literature involving the use of unmodified and polymer-modified asphalt binders (Lim et al. 2022; Sukhija et al. 2025).

Overall, the variations in peak positions and intensities between the two binders confirm the capability of FTIR to differentiate asphalt binders based on their chemical functional groups, thereby providing valuable insights for their characterization in pavement engineering.



(a)



(b)

Figure 3.4. FTIR spectrum of asphalt binders (a) Comparison of PG64-22 and PG70-22ER binder, and (b) Evolution of new peaks in PG70-22ER

3.2.1.2 FTIR Spectroscopy of Rejuvenators and Warm Mix Asphalt Additives

Similar to the base asphalt binders, Fourier Transform Infrared Spectroscopy (FTIR) was also performed on the additives to investigate their chemical characteristics and to identify functional groups distinct from those of asphalt binders. These are illustrated in Figure 3.5. In all the figures, the corresponding functional group of the additives has been marked. To understand the change in the functional group of these additives, zoomed-in images have also been added, as depicted in Figure 3.6. The dotted artwork within the zoomed-in figures indicates the peaks of interest. As shown in Figure 3.6a, a peak near 720 cm^{-1} was consistently observed across all additives. While this peak is typically associated with asphalt binder characteristics (Ma et al. 2023), its intensity varied noticeably in the additives. Such variations suggest that incorporating these additives may alter the engineering performance of asphalt binders. This effect is particularly significant for RAP mixtures, where adequate mobilization of the aged binder is critical to achieving desirable performance.

Both rejuvenators exhibited strong peaks between $1150\text{--}1250\text{ cm}^{-1}$ (C-O stretch), typically showing the presence of esters and free fatty acids (Leodarta et al. 2025; Wagh et al. 2025), referred to as the characteristic of rejuvenator chemistry. These compounds are primarily responsible for modifying the maltene content and thereby imparting the rejuvenation effect in RAP mixtures, as is also consistent with Chen et al. (2022). Although ester and free fatty acids were also present in the WMA additives, their intensity was notably weaker, indicating a limited role in rejuvenation.

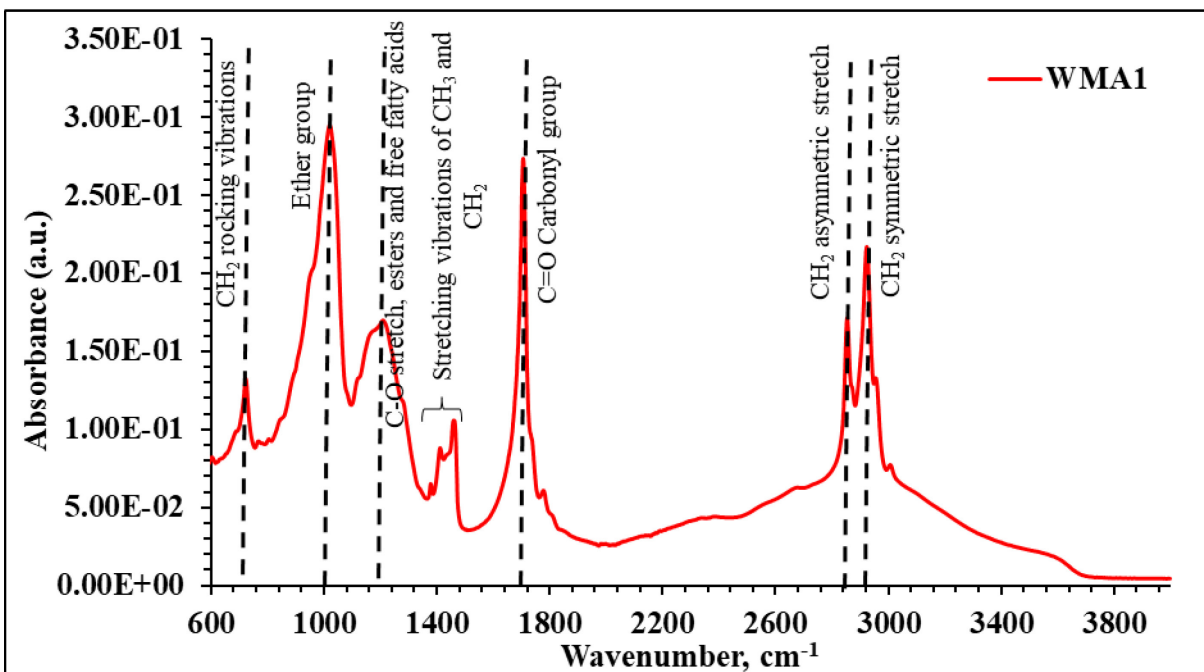
WMA additives, on the other hand, demonstrated surfactant-related peaks in the $1000\text{--}1100\text{ cm}^{-1}$ range, attributed to ether groups (Asemani and Rabbani 2020). These peaks are specific to WMA additives and are expected to influence binder characteristics primarily through enhanced adhesion and emulsification.

A distinct and strong peak near 1740 cm^{-1} was observed in both rejuvenators, overlapping with the carbonyl (C=O) group. This feature is linked to a higher susceptibility to oxidative ageing, consistent with past literature reporting accelerated ageing in rejuvenator-modified mixtures due to ester–carbonyl overlap (Jacobs et al. 2021; Uchoa et al. 2024). The presence of these ester compounds classifies the rejuvenators as bio-oils, fatty acid methyl esters, or tall-oil derivatives (Cavalli et al. 2018; Jacobs et al. 2021). Although WMA additives also showed weak shoulders near 1700 cm^{-1} (carbonyl group), their ageing effect is expected to be minimal and further mitigated by the lower production temperatures of WMA mixtures, which reduce thermal ageing.

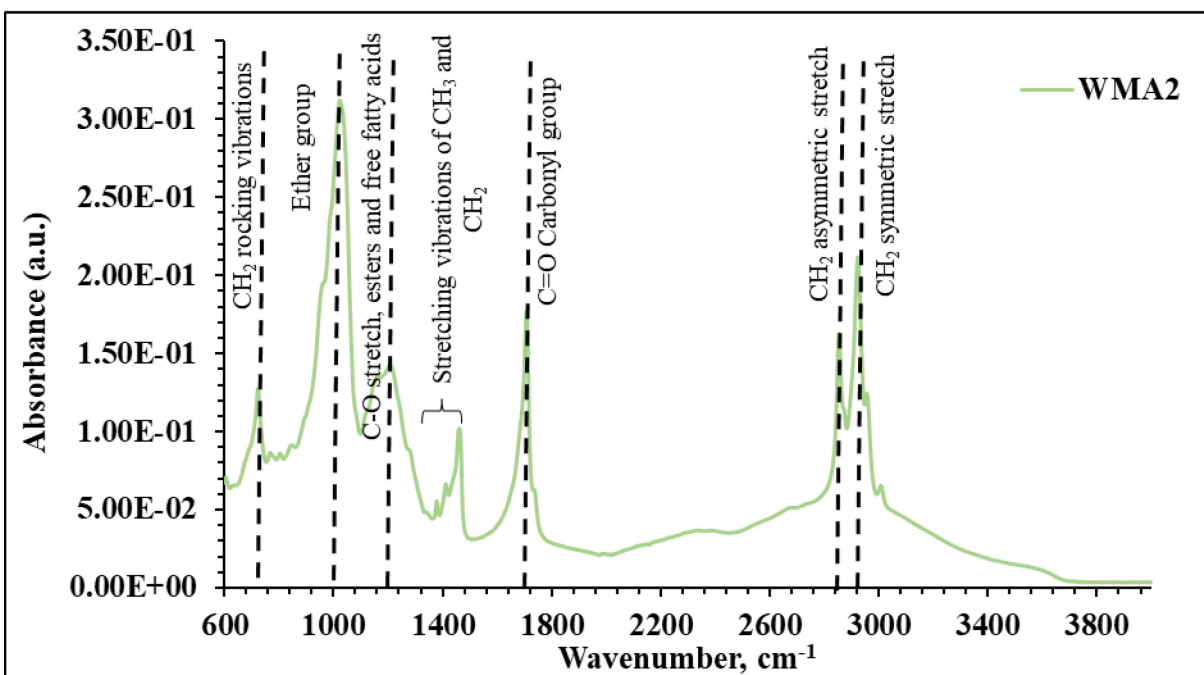
Additionally, peaks appearing beyond 2800 cm^{-1} (C–H stretching in CH_2 and CH_3) were identified in both rejuvenators and WMA additives. These peaks, associated with aliphatic and aromatic groups, align with the fundamental hydrocarbon backbone of asphalt binders and are expected to improve binder compatibility (Ma et al. 2023). Figure 3.6d highlights these comparative spectra for different additives.

Although both the rejuvenators and WMA additives appear chemically similar within their respective categories, the differences become evident in the intensity ratios and

baseline corrections of their FTIR spectra. The emergence of new peaks in these additives indicates that they likely influence the performance of both the binder and asphalt mixtures, particularly in the presence of oxidized RAP binder. In particular, esters were confirmed as the dominant functional groups in rejuvenators, playing a critical role in restoring the maltene content of RAP binder and thereby driving the rejuvenation effect. Conversely, the ether-related peaks unique to WMA additives highlight their surfactant-based behaviour, which is expected to enhance adhesion and emulsification between binder and aggregates, leading to improved moisture resistance of the mix (Sukhija 2022; Wagh et al. 2023).

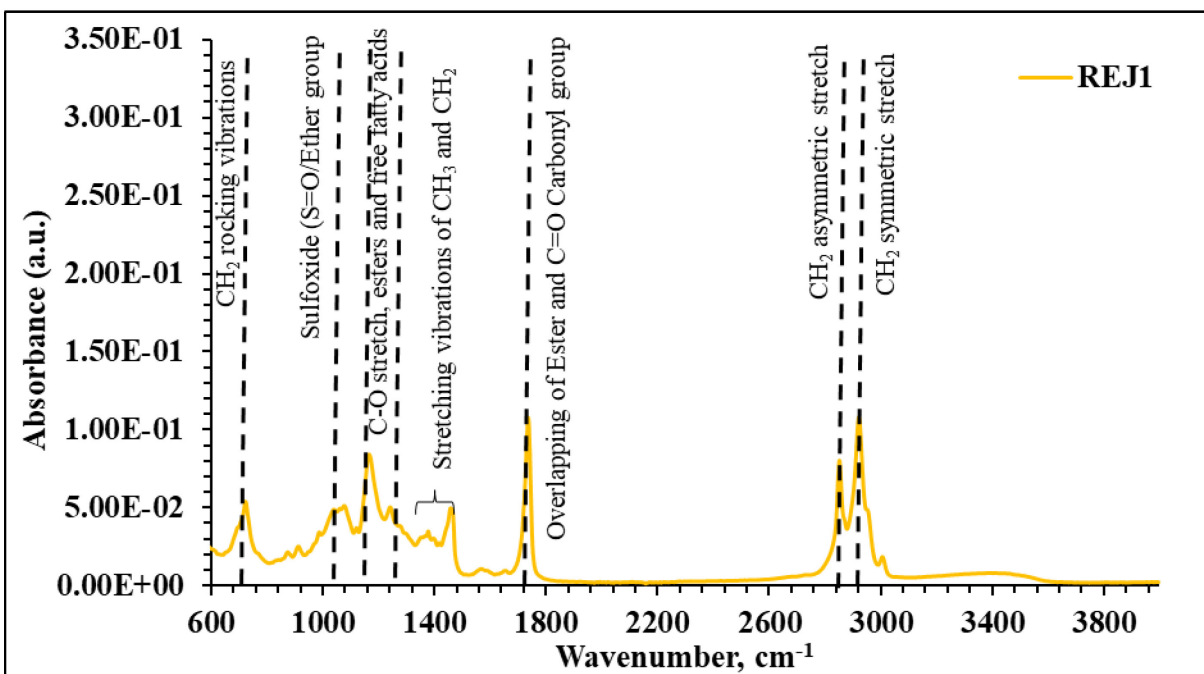


(a)

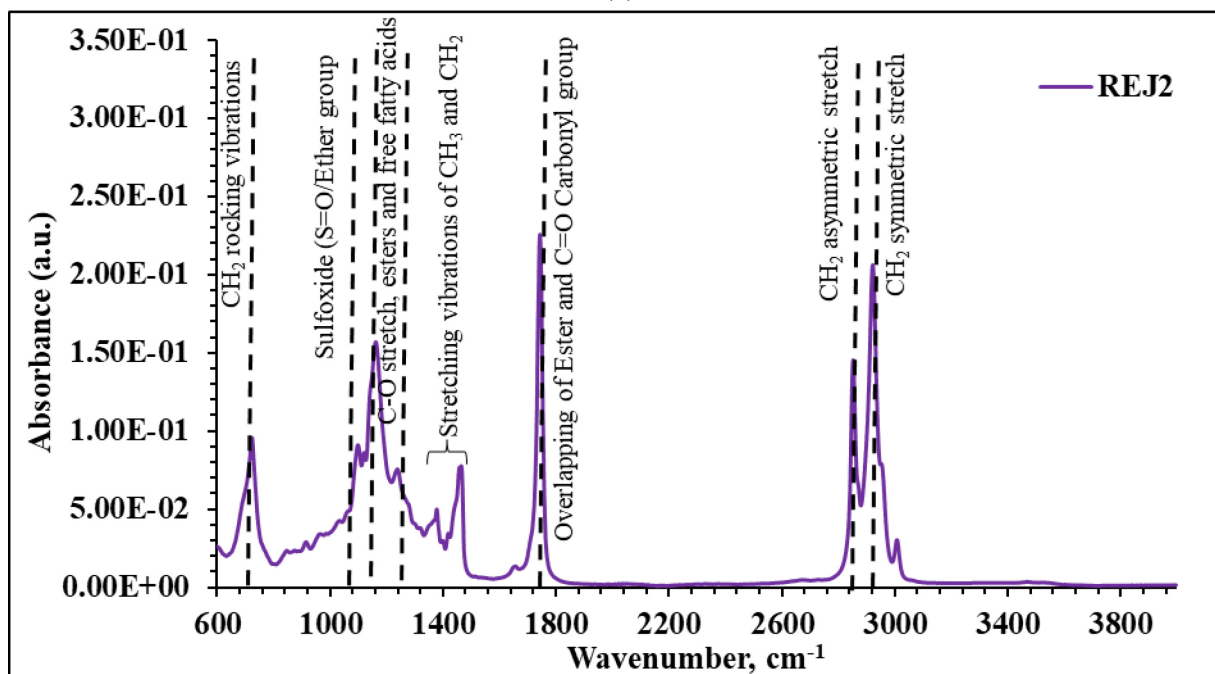


(b)

Figure 3.5. FTIR spectrum of WMA and rejuvenators (a) WMA1, (b) WMA2, (c) REJ1, and (d) REJ2



(c)



(d)

Figure 3.6 (continued). FTIR spectrum of WMA and rejuvenators (a) WMA1, (b) WMA2, (c) REJ1, and (d) REJ2

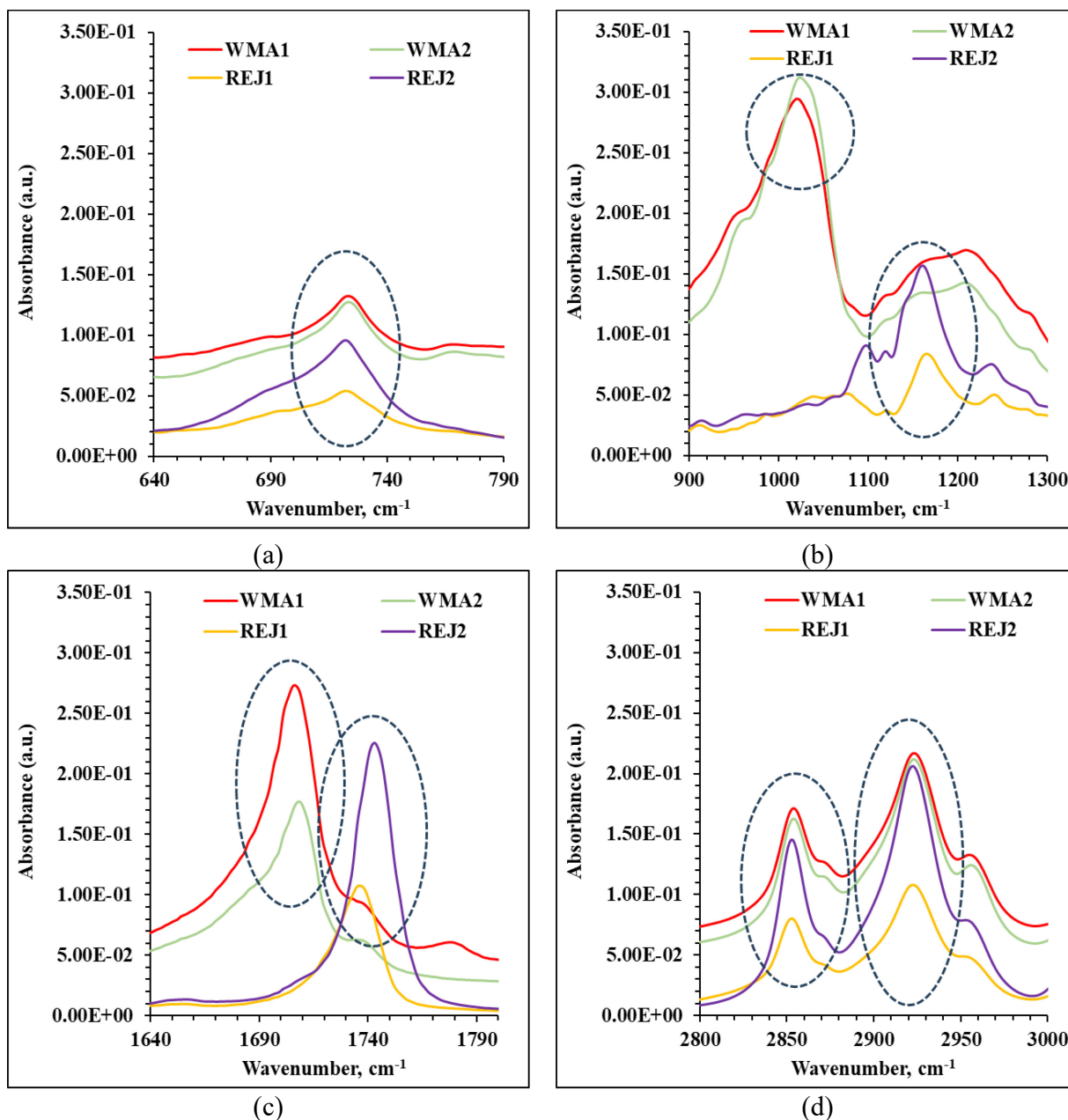


Figure 3.7. Zoomed in FTIR spectrum of WMA and rejuvenators (a) CH₂ rocking vibrations, (b) Ethers and esters, (c) Esters and carbonyl group, and (d) Aliphatic and aromatic hydrocarbons

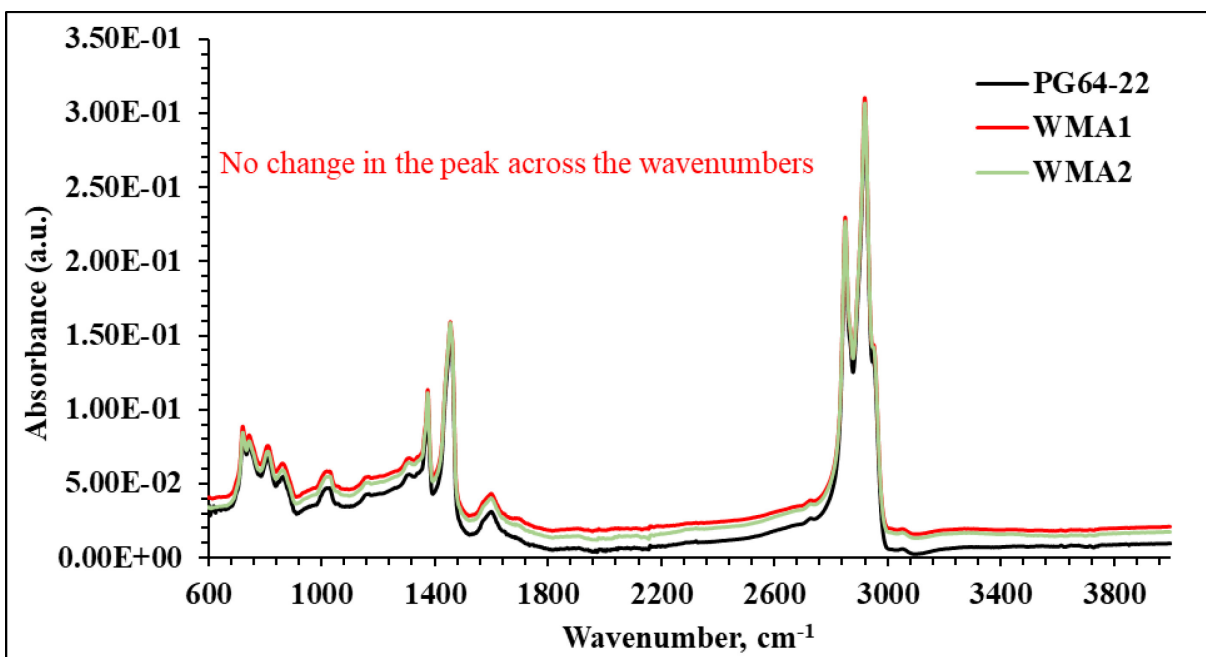
3.2.1.3 Interaction of Additives with Base Asphalt Binders

Figure 3.7 illustrates the effect of WMA additives and rejuvenators on the chemical characteristics of PG64-22 and PG70-22ER binders. The results indicate that rejuvenators chemically interact with asphalt binders, whereas WMA additives exhibit predominantly physical interactions. This observation is consistent with findings reported in previous

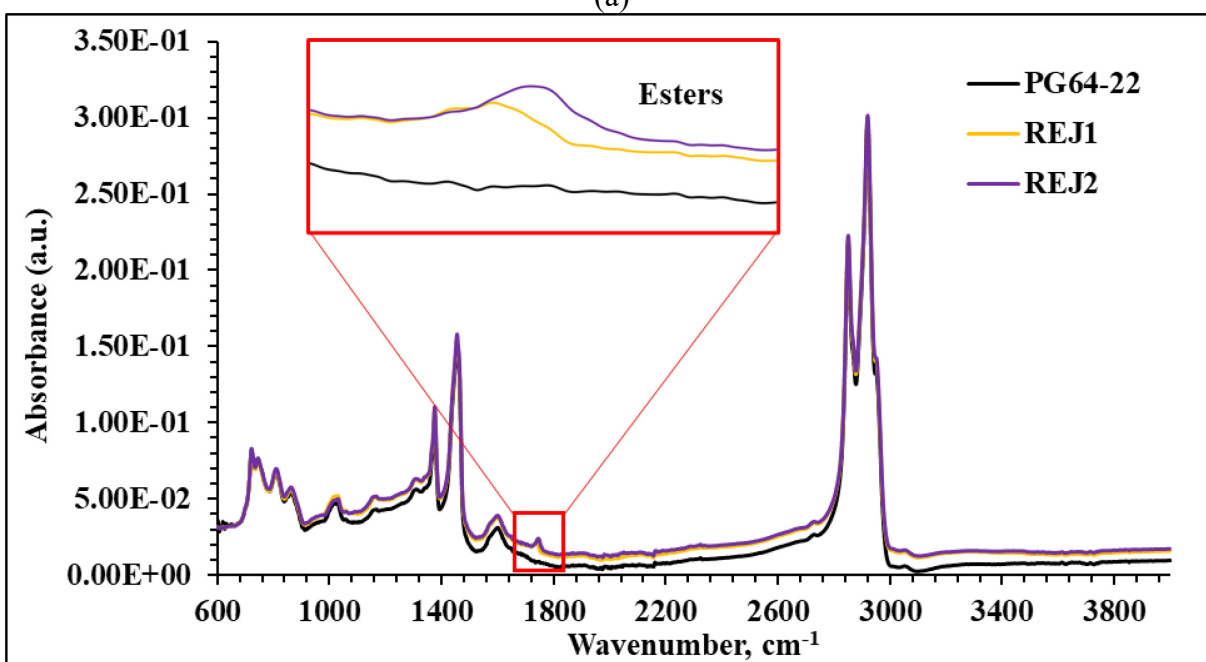
studies (Liu et al. 2018; Sukhija et al. 2025), where the appearance/disappearance of new peaks in FTIR spectra is a result of chemical reaction, whereas the absence of such changes indicates physical interactions (Sukhija et al. 2026).

The rejuvenator-modified binders show a distinct new peak around 1750 cm^{-1} , attributed to ester groups present in both rejuvenators. These esters alter the asphaltene-to-maltene ratio by increasing the oily maltene fraction, thereby softening the binder. Such chemical modification is particularly significant for RAP binders, where rejuvenators can restore aged binder properties more effectively.

Although trace amounts of esters were also detected in the WMA additives, their presence was minor and not evident in the spectra of WMA binders. Both WMA-modified binders largely retained the spectral features of the virgin binders. This suggests that chemical-based WMA additives do not alter the fundamental chemistry of asphalt binders; instead, their effect becomes evident at the binder–aggregate interface, where they enhance adhesion and coating at reduced production temperatures.

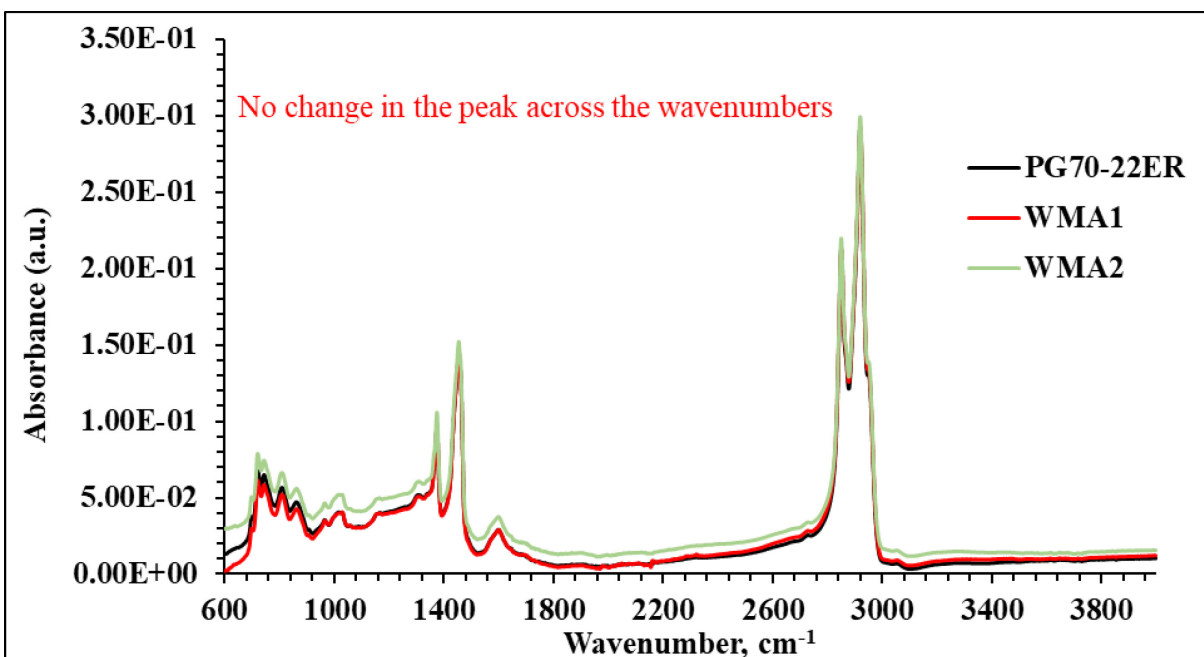


(a)

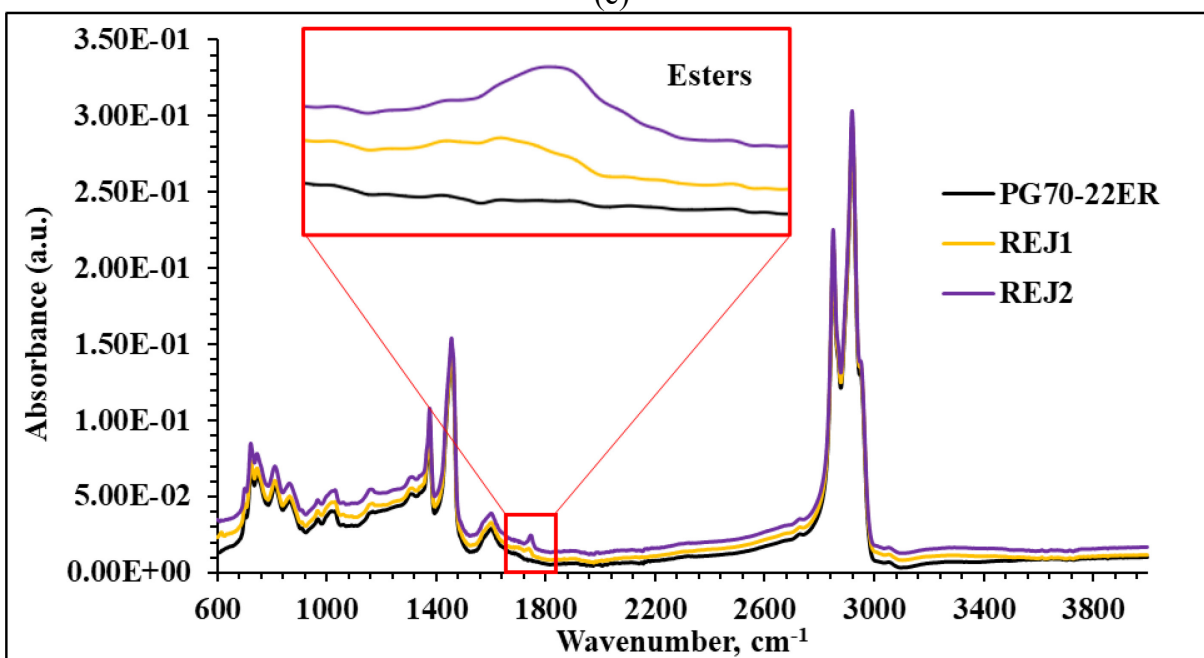


(b)

Figure 3.8. Variation in chemical composition of asphalt binders with the application of additives (a) WMA in PG64-22, (b) Rejuvenators in PG64-22, (c) WMA in PG70-22ER, and (d) Rejuvenators in PG70-22ER



(c)



(d)

Figure 3.9 (continued). Variation in chemical composition of asphalt binders with the application of additives (a) WMA in PG64-22, (b) Rejuvenators in PG64-22, (c) WMA in PG70-22ER, and (d) Rejuvenators in PG70-22ER

It is also worth noting that while the general peak positions remained consistent with those of the base binders (except for the additional ester peak in rejuvenator-modified binders), variations in peak intensity were observed. Such differences in intensity may influence performance in specific ways. Overall, these findings suggest that while

rejuvenators primarily promote chemical restoration, WMA additives contribute more through the improvements at the aggregate and asphalt binder interface, with both mechanisms ultimately affecting the performance of high-RAP asphalt mixtures. Notably, interface improvement benefit of WMA is not evaluated here due to the nature of the binder level experiments.

3.2.2 Rheological Performance of Modified Asphalt Binders

It is a belief that the addition of rejuvenators and WMA additives in virgin asphalt binder alters the performance at the binder level. However, literature suggests that such variation depends on the type of rejuvenators and WMA technology and their interaction with the base asphalt binders (Mohi Ud Din et al. 2023; Sukhija et al. 2025; Wagh et al. 2025; Xie et al. 2019). To assess these concerns, the research team evaluated the rheological performance of the asphalt binder. The study was executed using the dynamic shear rheometer (Figure 3.8) at the Asphalt Materials and Pavements (AMaP) laboratory, Oregon State University. The performed rheological characterization test methods and their results are described below:

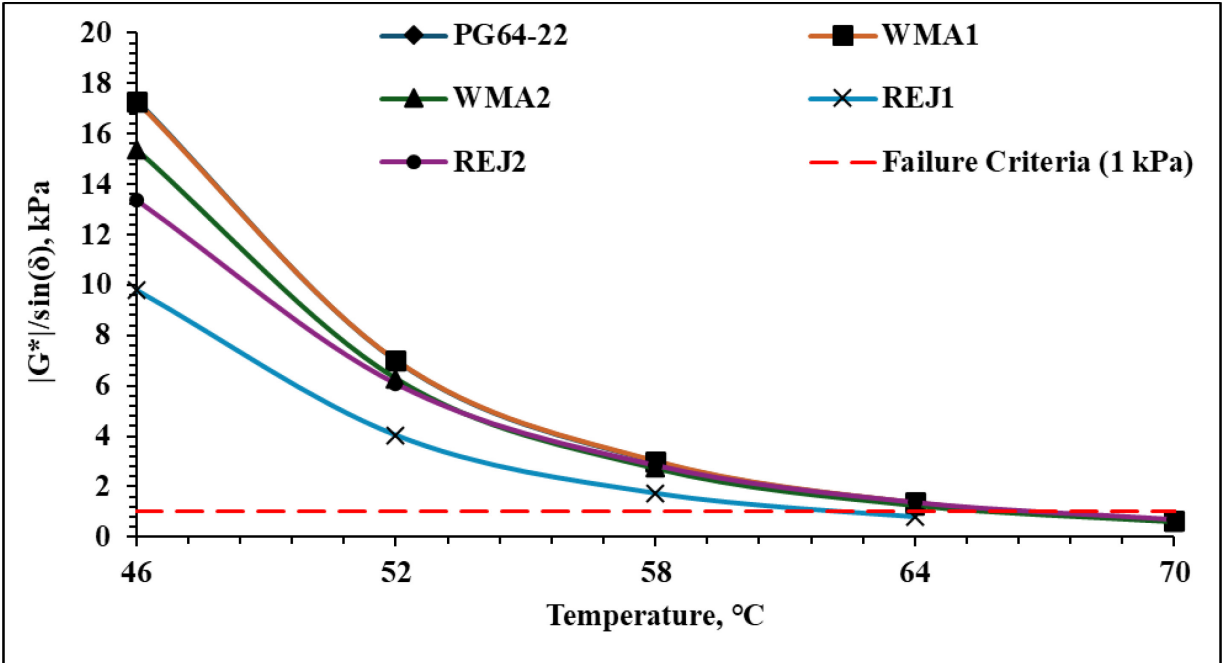


Figure 3.10. Dynamic Shear Rheometer used in this study

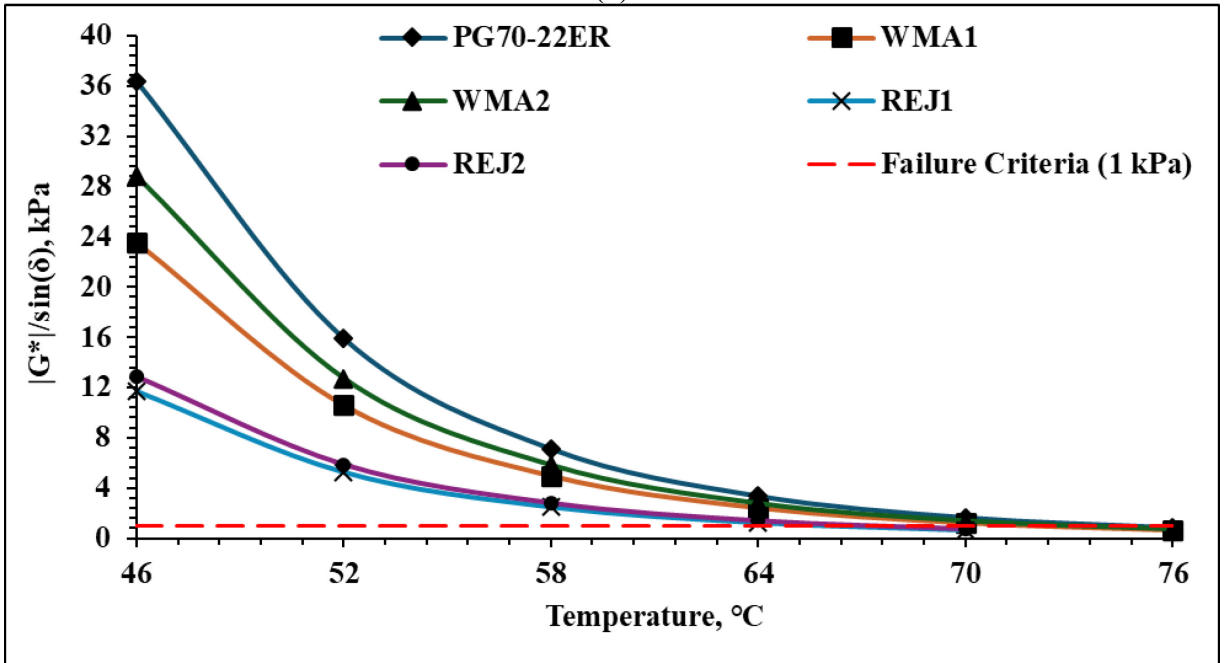
3.2.2.1 High Temperature Performance Grading (PG)

Performance grading of the asphalt binders was evaluated in accordance with AASHTO T315, (2020). According to the standard, the binder is subjected to a mean frequency of 10 rad/sec (1.59 Hz), simulating a vehicular speed of 55 mph. Since the testing was conducted on unaged samples in this study, the strain value was kept constant at 12%. In this test, the rheological properties, typically complex shear modulus (G^*) and phase angle (δ), are measured. G^* is defined as the total resistance to deformation, and δ denotes the time lag between the applied shear stress and resulting strain values under oscillating shear. The test was conducted at several temperatures starting from 46°C and increasing by 6°C increments till the failure of the sample. The failure temperature was identified as the temperature at which $|G^*|/\sin(\delta)$, generally defined as the Superpave rutting parameter, drops to 1 kPa. Based on this criterion, the high-temperature performance grading of the asphalt binders was determined.

As is obvious, with an increase in temperature, the $|G^*|/\sin(\delta)$ of asphalt binders reduces considerably, as shown in Figure 3.9. These trends are consistent for both the asphalt binders and for all the modified binders. This reduction is attributed to the softening or viscous nature of the asphalt binder at high temperatures. For rejuvenator-modified binders, the reduction in $|G^*|/\sin(\delta)$ appears to be more pronounced, primarily due to the softening effect imparted by the rejuvenators. This shows that their inclusion is expected to improve the RAP-inclusive asphalt mixtures by lowering the overall stiffness of the mix, as also revealed in previous studies (Basant et al. 2025; Pradhan and Sahoo 2022; Wang et al. 2025b). Unlike this behaviour, WMA2 performs slightly below its corresponding base asphalt binder, while WMA1 closely overlaps the behaviour of PG64-22 throughout the entire temperature range. Additionally, the WMA binders consistently exhibit higher $|G^*|/\sin(\delta)$ values than the rejuvenators across all test temperatures. The softening of asphalt binder with the incorporation of chemical-based WMA additives has also been reported in past studies (Sukhija et al. 2024, 2025; Wagh et al. 2025; Wang et al. 2020). Since the present study shows the binder testing in unaged condition, the benefits of WMA are generally observed after ageing due to their lower ageing temperatures. This testing plan is just to understand how the inclusion of WMA affects the properties of the asphalt binders. Overall, it was determined that both rejuvenators and WMA additives soften the asphalt binder, nevertheless, this behaviour is expected to positively influence the performance when stiff RAP is incorporated in the asphalt mixtures.



(a)



(b)

Figure 3.11. Variation in $|G^*|/\sin(\delta)$ with temperature (a) PG64-22 base binder and (b) PG70-22ER base binder

Using the $|G^*|/\sin(\delta)$ values and their critical thresholds of 1 kPa, the corresponding true failure temperature was determined for all the binders to differentiate in terms of their high PG. The research team at OSU carried out this analysis to understand if the addition of these additives changes the base binder grade. Considering true fail temperatures as shown in Figure 3.10, defined as the particular temperature at which $|G^*|/\sin(\delta)$ reaches 1

kPa, PG64-22 binder exhibits lower true fail temperature than PG70-22ER. This is primarily attributed to the increased stiffness of PG70-22ER due to the presence of a crosslinked polymer network within the asphalt matrix, as confirmed through the FTIR test in the previous section. Both WMA1 and WMA2 failed at around a similar temperature as those of their relative base asphalt binders. In PG64-22, the temperature shifts from 66.5°C to 66.6°C and 65.9°C for WMA1 and WMA2, respectively, indicating negligible differences. On the contrary, the failure temperature of WMA1 and WMA2 binders shifted to 71.9°C and 72.8°C, respectively, from 74.6°C (PG70-22ER), reflecting a reduction of around 2.4% for WMA1 and 3.6% for WMA2. Nevertheless, both the WMA technologies exhibit similar high-temperature performance grading and are in close proximity to their respective base binders. These findings revealed that the variation in the performance of WMA technologies depends on the binder grade, although the difference is less. This further supports the hypothesis that WMA additives enhance the overall binder–aggregate interaction instead of directly modifying the binder characteristics.

On the other hand, the addition of rejuvenators in base asphalt binders showed a different influence compared to WMA. In PG64-22, REJ1 failed at a lower temperature, consequently classified as PG58, while REJ2 performed the same as those of PG64-22. Interestingly, the difference becomes noticeable when the rejuvenators are blended with PG70-22ER, where the failure temperature lowered from 74.6°C to 65.6°C and 67°C for REJ1 and REJ2, reflecting approximately 12% and 10% reduction. Such a reduction highlights the softening effect imparted by the rejuvenators, which is primarily due to the addition of maltenes, as observed in FTIR analysis. Thus, previous studies recommend the application of rejuvenators in the RAP-inclusive asphalt mixtures in order to combat the stiff and oxidized RAP binder. Notably, this effect depends on the base asphalt binder, as rejuvenators perform well in PG64-22, while they result in increased softness in PG70-22ER, thereby leading to a reduction in high-temperature performance grade by one grade.

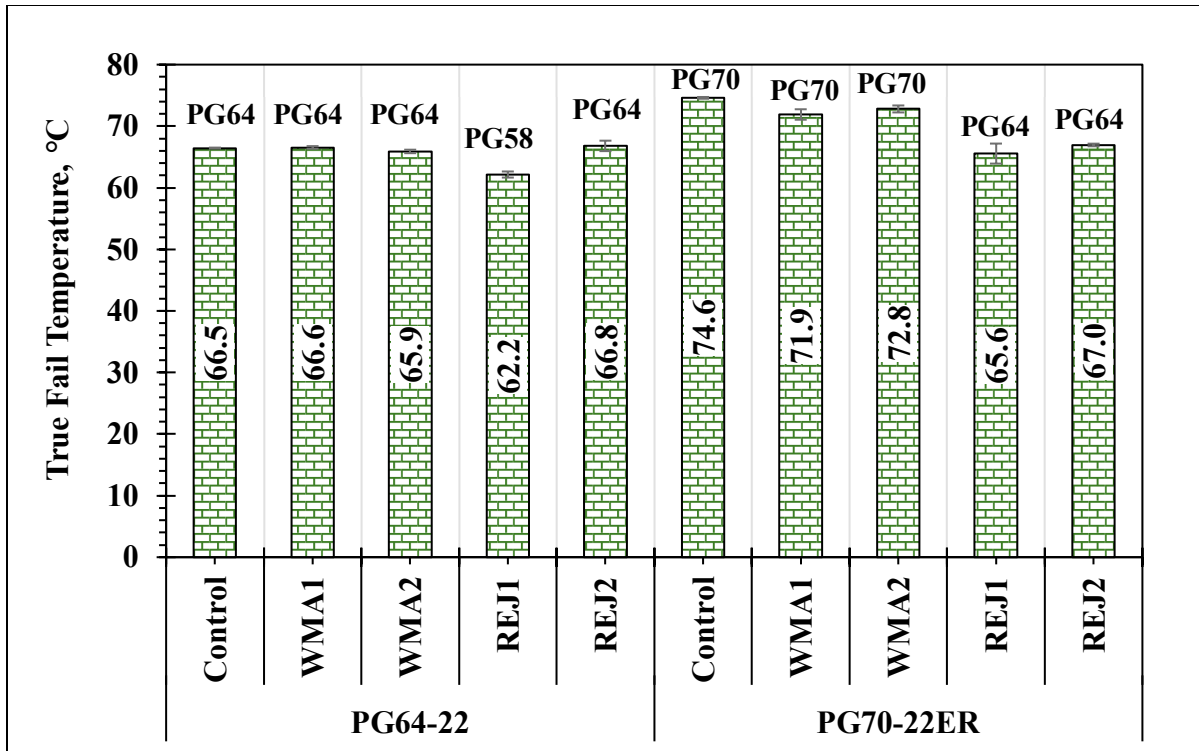


Figure 3.12. True-fail temperatures and high temperature PG of different asphalt binders

3.2.2.2 Binder Fast Characterization Test (BTSV)

As per the binder grading, it has been noted that the additives introduce softening in the base asphalt binders. Therefore, it is viable to understand the temperature at which the binder softens, similar to the traditional ring and ball test (AASHTO T53 2022; ASTM D 36 2014). BTSV (Bitumen-Typisierung-Schnell-Verfahren, in German) is a robust and feasible rheological test method applied especially for modified asphalt binders. This test determines the results in the form of temperature at which G^* reached 15 kPa and corresponding phase angle, referred to as T_{BTSV} and δ_{BTSV} , respectively. Here, a 15 kPa value of G^* is chosen as it correlates well with the traditional ring and ball test results (Liang et al. 2014; Zhu et al. 2021). The test generally starts at 20 °C and the temperature is further increased at a rate of 1.2 °C/min, measuring the change in the value of G^* and δ with change in temperature. Throughout the test, the binder is subjected to a constant shear stress of 500 Pa at a loading cycle of 10 rad/sec to maintain the linear viscoelastic regime. Due to the non-availability of a specific BTSV standard in the U.S., a European standard (EN17643 2022) was followed to perform the test in this study. Generally, a higher value of T_{BTSV} indicates the stiffness of the material, and a lower value of δ_{BTSV} denotes higher elasticity, thereby providing insights into the degree of modification (Alisov et al. 2020). A typical representation of BTSV test results is demonstrated in Figure 3.11.

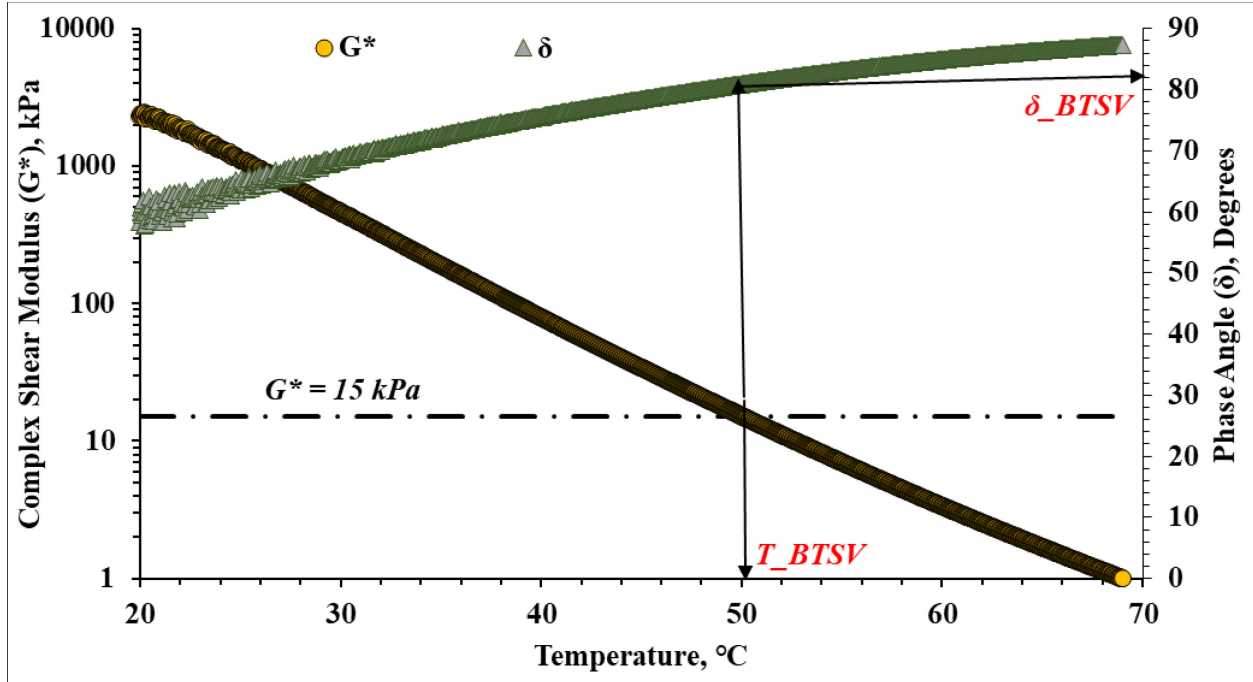


Figure 3.13. Schematic representation of BTSV results

Figure 3.12 indicates the BTSV results in terms of T_{BTSV} and δ_{BTSV} for comparing different asphalt binders on the same boundary level. The polymer-modified binders (PG70-22ER) exhibit a lower phase angle and a higher failure temperature compared to unmodified PG64-22 binders, clearly differentiating the binders and reflecting the modification effect. The combination of lower δ_{BTSV} and higher T_{BTSV} suggests the higher elasticity and stiffness of the PG70-22ER binders. Similar observations have been presented in a previous study where several unmodified and modified binders were characterized using the BTSV test (Alisov et al. 2020).

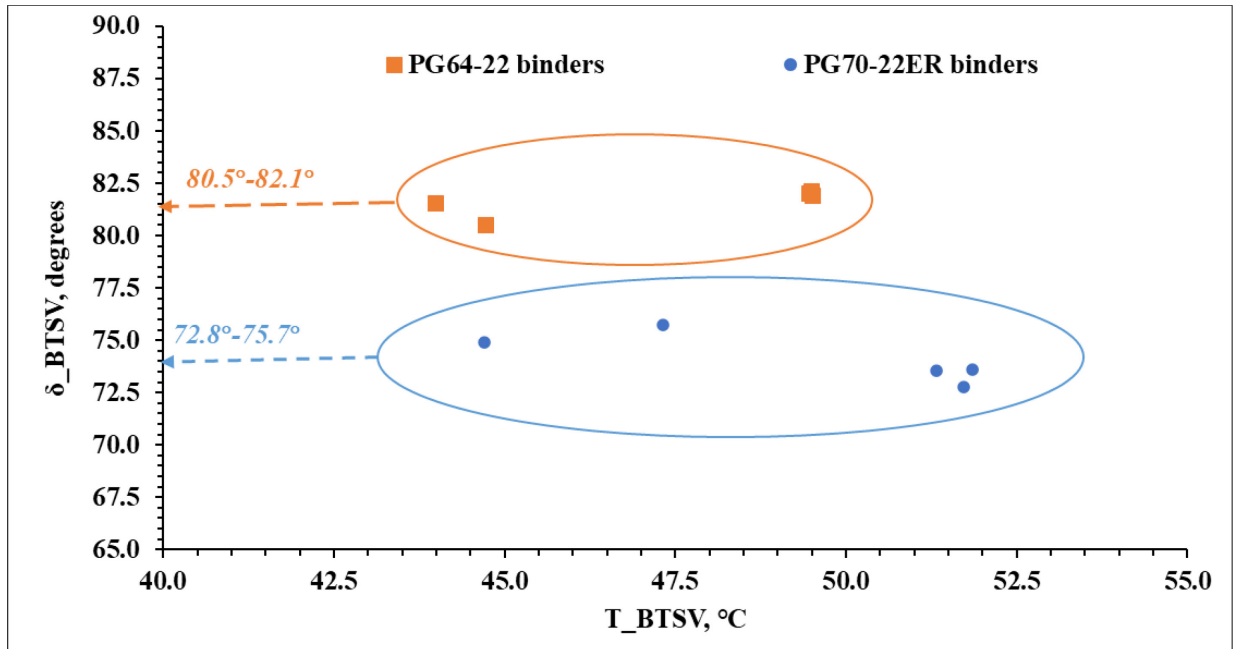
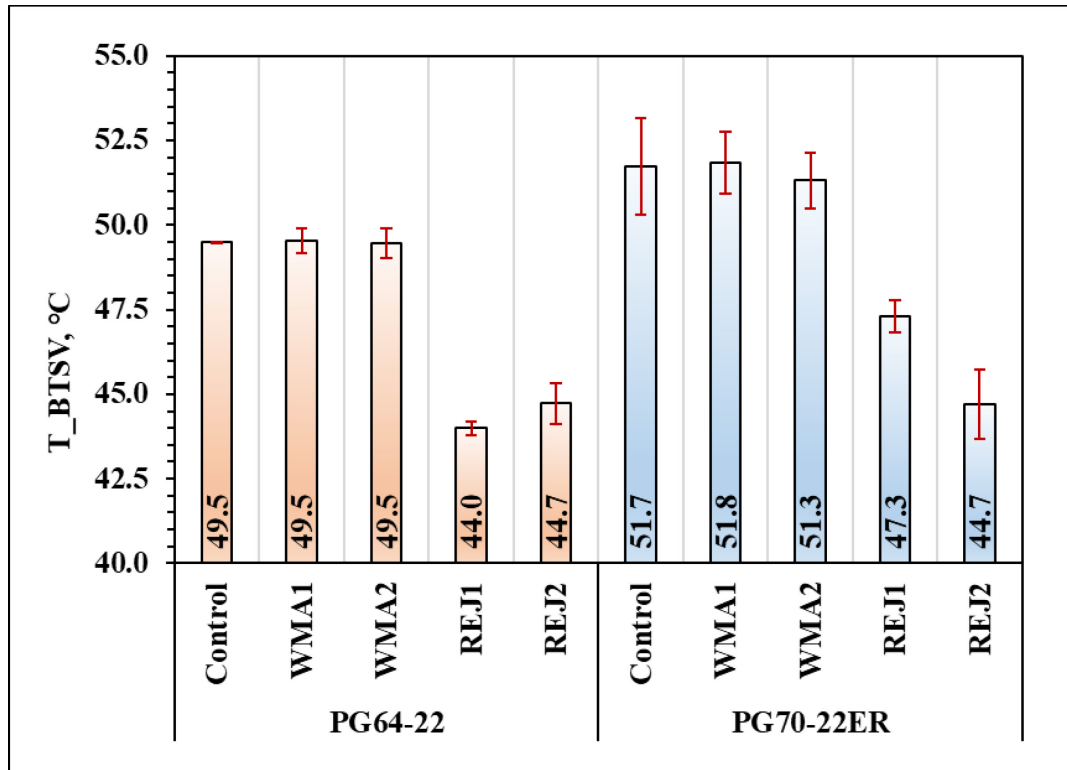


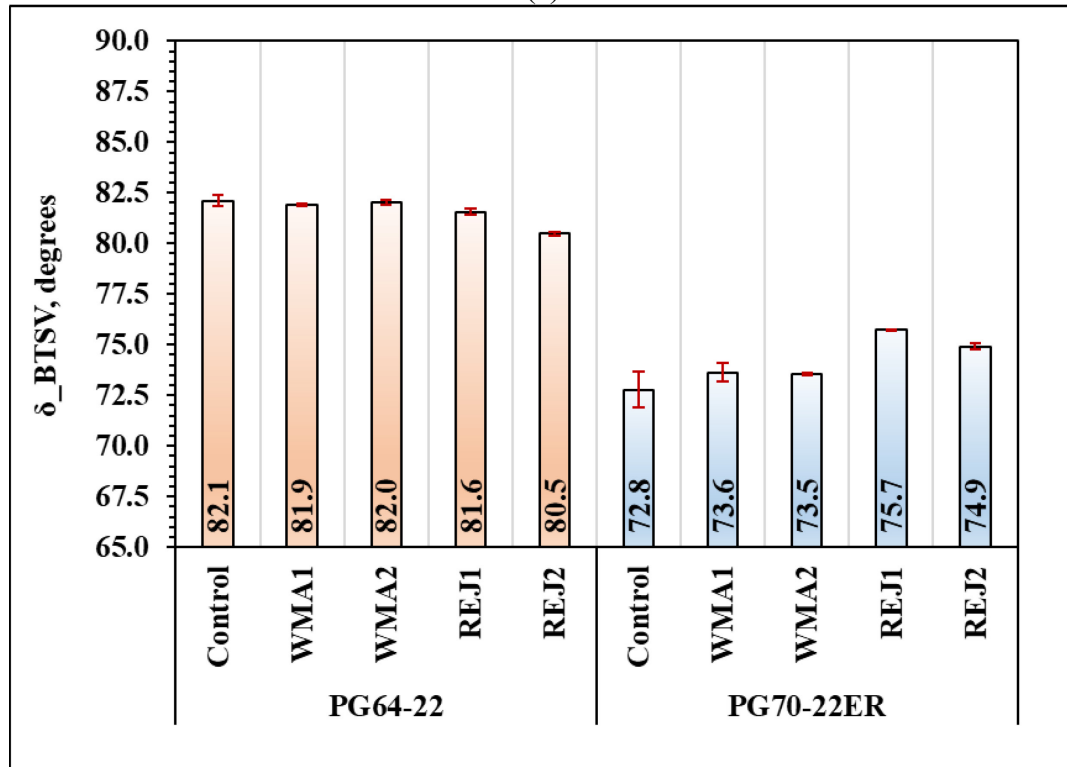
Figure 3.14. Differentiation of unmodified and polymer modified binders using BTSV test results

Although differences are evident in binder characterization, the application of either rejuvenators or WMA additives does not affect the elasticity of the binders; rather influences the hardness, particularly in the case of rejuvenators. This is illustrated in Figure 3.13, where comparisons with the base asphalt binders show that rejuvenators lead to a lower T_BTSV in both the binders, while the corresponding δ_BTSV remains consistent at a value around 75° and 81° in PG70-22ER and PG64-22, respectively. The corresponding reduction in the T_BTSV was calculated to be around 10-11% in PG64-22 binders and ranged from 9-14% in PG70-22ER binder, aligning with the previous attribution on the additive interaction with the base asphalt binders. The lower hardness resulting from the rejuvenator-modified binder is due to the presence of esters, as confirmed in the FTIR spectra, which impart softness in the virgin binder.

On the contrary, WMA binders perform almost similarly to their respective base asphalt binders, with T_BTSV and δ_BTSV values around 52 °C and 74 °C for PG70-22ER, and 49 °C and 82 °C for PG64-22, respectively. These findings are also consistent with the high-temperature PG results discussed in the previous section.



(a)



(b)

Figure 3.15. BTSV test results (a) Variation in T_{BTSV} and (b) Variation in δ_{BTSV}

Although both test results are crucial for assessing the behaviour of the additives, their significance can largely be understood after the preparation of asphalt mixtures with RAP material, since their impact is feasible for the rejuvenation and mobilization of RAP binder. However, the present binder-based study was only carried out on the virgin binders without incorporating the effect of RAP, just to assess the consequence of using these additives on the binder properties.

3.3 MIX DESIGN

RAP-inclusive asphalt mixtures were prepared to determine the effectiveness of high RAP mixtures on the mechanical performance. The asphalt mixtures were prepared to simulate Level 3 and Level 4 category asphalt pavements using different proportions of RAP material depending on the mix design levels. Figure 3.14 shows the combined aggregate gradations adopted in the present study. As is evident, the differences between the aggregate gradations for these two mix levels are minimal, and thus it is expected that the performance variations in the asphalt mixtures are primarily affected by the binder grade rather than the gradation differences. Therefore, the research team compared the results based on the binder grade (PG64-22 and PG70-22ER) instead of mix level (Level 3 and Level 4) during most of the tasks.

To prepare the asphalt mixtures, the asphalt binder is heated in a draft oven for two hours at its respective mixing temperature prior to mixing. Simultaneously, virgin aggregates are also placed in an oven at 10°C higher than the mixing temperature, whereas RAP aggregates are heated at a fixed temperature of 121°C. A portable bucket mixer was used to mix the preheated virgin aggregates, RAP aggregates, and asphalt binder in order to prepare a loose asphalt mixture. Since the performance testing has to be executed on these samples, the loose asphalt mixtures are exposed to short term ageing (STA) and long-term ageing (LTA) based on the standard test protocol for rutting and cracking. The rutting performance was evaluated on STA samples, while the cracking potential was measured on samples subjected to STA followed by LTA.

To simulate the STA, the loose asphalt mixture is subjected to an oven heating for 2 hours at 135°C (275°F) for HMA and 116°C (240°F) for WMA as per NCHRP 9-52 (Newcomb et al. 2015). Based on the standard protocol for Oregon (Coleri et al. 2020), the STA samples were further subjected to heating for 24 hours at 95°C in order to simulate LTA. Further, the aged mixture in a loose state is placed at its respective compaction temperature again for 2 hours before the compaction. Superpave gyratory compactor was used to compact the asphalt mixtures to 62 mm thickness with a diameter of 150 mm, ensuring $7 \pm 1\%$ air voids. These compacted samples are then conditioned based on the requirements of the performance testing. It should be noted that WMA mixtures were produced at lower temperatures than HMA (as described in subsequent chapters) to perceive the potential benefits of WMA technologies.

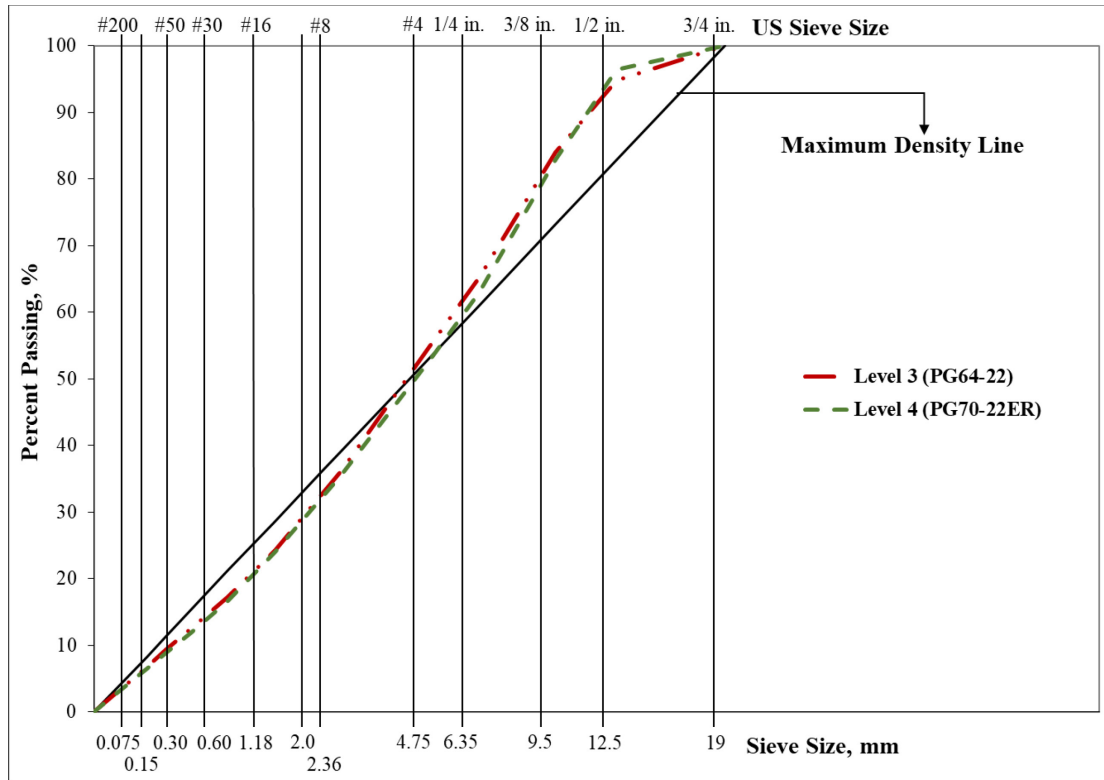


Figure 3.16. Designed aggregate gradation for Level 3 and Level 4 category asphalt mixtures

Since aged binder in RAP is less ductile than a virgin binder and gives rise to failure under repeated high axle loads and thermal effects, the proportion of RAP in asphalt pavements constructed in Oregon is currently limited to about 30% and 20% by weight of the mix in Level 3 and Level 4 categories, respectively. For asphalt mixtures with a higher percentage of RAP (higher than the current limit), different strategies, including the increased binder content, binder grade bumping, use of rejuvenators, and WMA technologies, are commonly adopted for improving the resistance to potential cracking failures. An attempt has been made to incorporate different RAP contents based on the mix design levels. Emphasis is given to evaluating the effectiveness of high RAP content for Level 3 and Level 4 mix category asphalt mixtures prepared with and without the strategic techniques.

3.4 TEST METHODOLOGIES

To achieve the study objectives, a series of experimental programs was presented across different chapters, aligned with the specific aims and summarized in Table 3.5. The primary test methods included the assessment of workability using the Superpave gyratory compactor, evaluation of cracking resistance through the Indirect Tensile Cracking Tolerance Test (IDT-CT), and investigation of rutting performance using the Hamburg Wheel Tracking Tester (HWT). These methods were chosen for their proven effectiveness in characterizing asphalt mixtures, as demonstrated in previous studies (Chitnis et al. 2025; Dessouky 2015; Dessouky et al. 2013; Kumar et al. 2024b; Rahman and Hossain 2014).

In addition to the experimental program, statistical analyses were performed using Analysis of Variance (ANOVA) and Tukey's pairwise post-hoc tests to validate the observed trends and attributions. The application and detailed outcomes of these statistical methods are presented within the respective chapters where they were employed.

Table 3.5. Test methods adopted in different chapters of the study

Characterization	Test Method	Concerned Chapters
Workability	Superpave Gyratory Compactor	Chapter 5.0
Cracking	Indirect Tensile Cracking Tolerance Test	Chapter 4.0, 5.0, and 7.0
Rutting	Hamburg Wheel Rut Tester	Chapter 4.0, 5.0, and 7.0

3.4.1 Workability Characteristics

Workability is generally defined as the ease with which the components of an asphalt mixture blend and respond to processes such as mixing, handling, placing, and compaction to achieve the desired lift thickness. Workability values offer insight into the ease of compaction, and in this study, they were evaluated based on the number of gyrations required to compact each asphalt mixture. Typically, mixtures with high RAP content or stiffer binders demand greater compactive effort to achieve the desired density in the field. This behaviour can be simulated in the laboratory using an advanced Superpave gyratory compactor (as shown in Figure 3.15), which measures the change in density and height of the asphalt mixture specimen corresponding to each gyration.

Based on these values, a height-based index was developed in previous literature to study the workability characteristics of the asphalt mixtures (Dessouky and Diaz 2015). This is typically known as Workability Energy Index (WEI) and is mathematically written as Equation 3.2. WEI represents the energy required to compact a loose asphalt mixture to approximately 92% of its theoretical maximum density (G_{mm}), corresponding to 8% air voids in the compacted specimen. The unit of WEI is N-m/gyration. A higher WEI value indicates greater workability, implying that less compaction energy (gyrations) is needed to achieve the target density.

$$WEI = \frac{\left(\frac{\pi d^2}{4}\right) P(h_{n=0} - h_{92})}{N_{92} - N_{n=0}}$$

(Equation 3.2)

In Equation 3.2, P represents the pressure used for compaction in kPa, d indicates the diameter in mm, and h_{n=0} and h_{n=92} are the height of the specimen at gyrations 0 (N_{n=0}) and 92% G_{mm} (N_{n=92}), respectively.



Figure 3.17. Superpave gyratory compactor used in the present study

3.4.2 Cracking Behavior

Cracking potential of the asphalt mixtures was assessed using the Indirect Tensile Cracking Tolerance Test (IDT-CT). The test was conducted at 25°C on LTA samples, and the compacted asphalt mixtures were conditioned in an environmental chamber for 2 hours at the test temperature prior to the testing. Following the test procedure mentioned in (ASTM D8225 2019), the cylindrical RAP mixtures compacted at 7 ± 1 air voids were subjected to an indirect tension along the diametrical plane with a compressive load consistently applied at a 50 mm/minute rate. The applied load and the corresponding vertical displacement were monitored to prepare a load-displacement curve, as shown in Figure 3.16. The obtained load-displacement curve was further analyzed to determine the cracking resistance in terms of a parameter typically known as the CT Index. Mathematically, the CT Index parameter can be written as (Equation 3.3):

$$CT\ Index = \frac{t}{62} \times \frac{l_{75}}{D} \times \frac{G_f}{|m_{75}|} \times 10^6$$

(Equation 3.3)

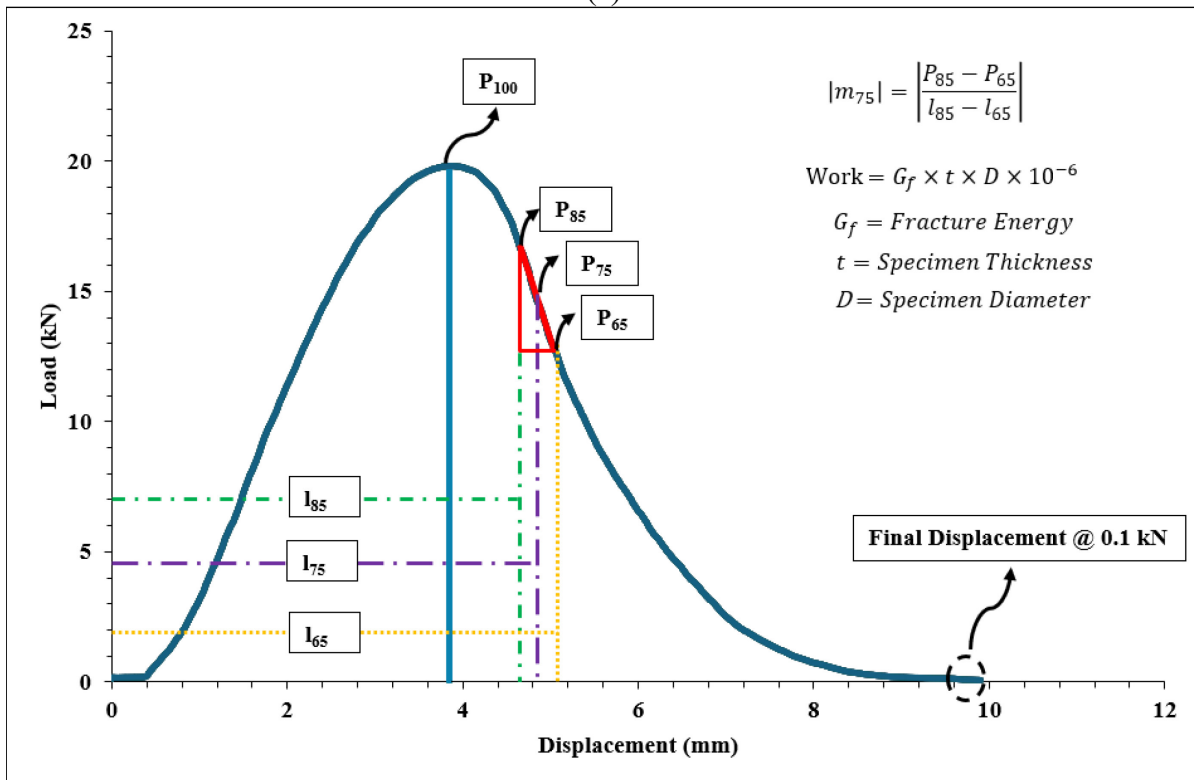
$$G_f = \frac{w_f}{t \times D} \times 10^6$$

(Equation 3.4)

Here, t is the thickness of the specimen (mm), $|m_{75}|$ and l_{75} indicate the slope (N/m) and displacement (mm) at the 75% peak load of the post-peak stage of the load-displacement curve, D is the diameter of the specimen (mm), G_f denotes the fracture energy (J/m²) evaluated using Equation 3.4.



(a)



(b)

Figure 3.18. Cracking behaviour test (a) IDT-CT setup and (b) Load-displacement curve from Ideal CT test

3.4.3 Hamburg Wheel-Tracking Test

HWTT is the most commonly employed performance test to determine the rutting susceptibility of compacted asphalt mixtures (slab or cylindrical specimens). As shown in Figure 3.17, a loaded steel wheel tracks on the compacted specimens submerged in a temperature-controlled water bath. The rutting resistance was measured in terms of rut depth or deformation with respect to the number of loading passes following (AASHTO T 324 2023). In the present study, the HWTT was carried out on STA samples at 50°C based on the previous recommendations made to assess the rutting behavior of asphalt pavements in Oregon (Coleri et al. 2020). The rutting performance of all the combinations of RAP mixtures compacted at 7 ± 1 air voids was measured using the rut depth values corresponding to 20,000 loading passes.

Although HWTT also provides valuable insights into creep slope, stripping inflection point, stripping slope, and moisture sensitivity (Yildirim et al. 2007), these factors were never observed in the Oregon mixes. As per the findings of a previous ODOT research project (SPR835), it was difficult to quantify whether the damage in the asphalt mixture is due to the rutting, moisture, or a combination of both (Coleri et al. 2023). This is likely due to the mixes being on the dry side (low binder content). The outcome of the research project also revealed that the test results in the HWTT are primarily controlled by the rutting resistance rather than the moisture effect. Thus, the study recommended that the stripping inflection point or the stripping slope should not be used to quantify the moisture sensitivity, especially for the Oregon mixes (Coleri et al. 2023).

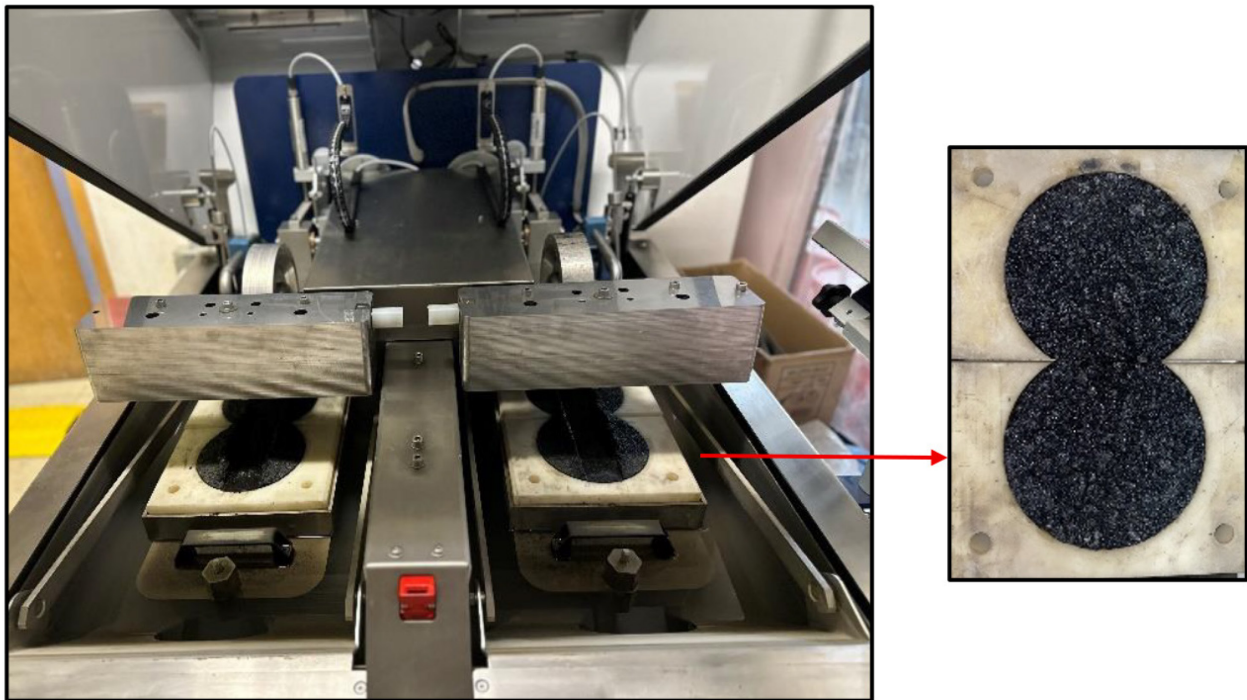


Figure 3.19. Hamburg wheel rutting test setup

3.5 SUMMARY

This chapter provides an overview of the materials utilized throughout this research study and their characterization. Details of the mix design process and the adopted methodologies are also presented. The testing temperatures were kept consistent throughout the entire study. In the subsequent chapters, the selected test methods are applied in alignment with the specific objectives addressed in each chapter.

Characterization test results revealed that rejuvenator-modified asphalt binders impart softness, resulting from the reduced high-temperature performance grading and lower T_{BTSV}, regardless of the base asphalt binders. Such variation is attributed to the presence of esters in the rejuvenators, as observed in the FTIR spectra, which chemically react with the base binder and thereby alter its performance. In contrast, WMA performs similarly to the base asphalt binder, as confirmed through high-temperature PG test and BTSV. Due to the surfactant nature, the benefits of WMA additives are primarily expected during their interaction with aggregates and creating better adhesion between the aggregates and the binder, particularly in terms of improved coating and adhesion at reduced production temperatures. This effect is expected to improve the moisture resistance.

4.0 ADJUSTMENT IN BINDER CONTENT AND BINDER GRADE FOR HIGH RECLAIMED ASPHALT PAVEMENTS IN OREGON

4.1 INTRODUCTION AND BACKGROUND

Over the past decades, the use of reclaimed asphalt pavement (RAP) materials has been gaining a lot of attention in the field of pavement engineering, and the overall trend indicates more divergence toward the application of high RAP (Lewis et al. 2024; Prasad et al. 2023). RAP material, in general, comprises an aged asphalt binder film over the aggregates, which imparts a stiffening effect to the asphalt mixtures and influences their overall performance, especially when the RAP content exceeds 20%. This stiffening effect may be beneficial for improving rutting resistance, but it may lead to cracking in the early stage of service life (Yu et al. 2024). Based on the experience in China (Yu et al. 2024) The addition of RAP affects the cracking potential, and thus, rutting tests may not be necessary for such mixtures unless a softening agent or binder grade bumping technique is used. In actual practice, high RAP content in a mix (>20-25%) may result in poor workability and improper densification, eventually leading to premature field failure (Daniel and Lachance 2005; Pradhan and Sahoo 2022). Despite such concerns, the scarcity and increase in the cost of natural aggregates and asphalt binders raise awareness in the asphalt industry to incorporate high RAP contents in asphalt pavements (Jahanbakhsh et al. 2020). In addition, applying high RAP content acts as a major step toward the 2050 mission of carbon neutrality and sustainable infrastructure development in terms of economic and environmental stewardship (AzariJafari et al. 2023).

In Oregon, RAP is employed for almost all pavement construction projects. However, the amount of RAP is limited to 20-30%, depending on the traffic conditions (ODOT 2019, 2021). Oregon Department of Transportation (ODOT) is actively looking for strategic techniques to improve the blending efficiency and increase the RAP content beyond the current limits with adequate performance. Common techniques include the adoption of proper RAP management, such as RAP processing and handling, and characterization of RAP before the mix design process (West 2015). Additionally, the RAP content can be increased with RAP fractionation techniques (Katla et al. 2022; Shannon 2012), the use of rejuvenators (Albayati et al. 2023; Behnood 2019; Prasad et al. 2023), warm mix asphalt (WMA) additives (Hettiarachchi et al. 2019; Yousefi et al. 2025), and various alternative materials (Eltwati et al. 2022c; Eskandarsefat et al. 2019; Wang et al. 2025a). The most potentially recommended strategy to increase the RAP content is to change the design attributes, especially when RAP is greater than 25% (Willis et al. 2012). To produce high RAP mixtures with acceptable performance, design attributes can be changed by increasing the binder or lowering the asphalt binder grade by one or two grades (referred to as binder grade bumping). The change in these attributes depends on the type and amount of RAP material in the asphalt mixture. The in-depth details on the selection of these management practices and strategic techniques can be found in **a systematic review conducted by Sukhija and Coleri (2025b).**

Generally, binder grade bumping or softer binders tend to reduce the overall viscosity and so the stiffness and brittleness in the mix, leading to improved performance at a lower cost. Not only in the United States, but also in other countries, the recommendation on the use of soft binders is consistent. A past European experience suggested the use of a softer binder to produce RAP mixtures with over 20% RAP in order to overcome the stiffening effect (Noferini et al. 2017). As per the Australian practice (AGPT04B 2014; VicRoads 2019), the use of lower-grade asphalt binder is to be adapted for mixes where RAP content is higher than 15%. Considering similar aggregate gradation and design film thickness, Tran and Hassan (2011) found that RAP content can be increased up to 20% with the use of a soft binder. On the other hand, despite a softer binder, the 30% RAP mix does not meet the specified requirements and thus necessitates further adjustment in the mix design attributes. Since the evaluation was done on a small data set with limited experiments, mostly focusing on the volumetric characteristics, it is essential to assess the effect of binder grade bumping on the performance of high RAP mixtures.

Binder grade bumping can be achieved by using a one-grade or double-grade lower binder, depending on the condition and amount of the RAP material. Here, single-grade bumping refers to reducing the high-temperature grade of the binder by one level, while double-grade bumping involves lowering both high-temperature and low-temperature grades by one level. For instance, if PG64-22 is the reference grade of the binder, then PG58-22 represents the single-grade bumped binder, and PG58-28 is the double-grade bumped binder. As per Aurangzeb et al. (2012), double-grade bumping does not exhibit a significant difference compared to single-grade bumping of the asphalt binder.

From the perspective of increased binder content, a study conducted by Sreedhar and Coleri (2018) found that an increase in binder content by 0.7% results in 2-3 times higher cracking resistance while maintaining the rutting characteristics (rut depth) below the critical design limits for Oregon asphalt mixtures. Another study by Willis et al. (2012) found that the RAP content can be increased to 25% with 0.25% higher binder content, warranting desirable rutting and fatigue performance. In line with the same context, Boriack et al. (2014) showed that the use of 0.5% additional binder content facilitates up to 20% RAP with improved fatigue and rutting performance of RAP mixtures. However, this additional binder content is not suitable to increase the RAP content to 40%, as evidenced by the inferior performance of the 40% RAP mixture. The authors also tried a 100% RAP mix and revealed that the dynamic modulus and rutting resistance were above the critical limits at all the tested binder levels (increased by 0.5%, 1%, and 1.5% from the design binder content). Nevertheless, fatigue resistance of the particular mix (100% RAP mix) was comparable to that of the 20% RAP mix with the addition of 1.5% extra binder content. This highlights that the quantity of additional binder is a function of RAP content and varies significantly when high RAP is used. Unlike binder grade bumping, although the use of higher binder content results in desirable performance, it increases the overall production cost due to extra binder. Perhaps the increment in the production cost can be offset with the use of high RAP content, thereby leading to lower life cycle costs (Coleri et al. 2018a).

It is quite challenging to determine which strategy (increased binder content or binder grade bumping) is more feasible for achieving satisfactory performance in the field. In addition, although accurately adjusting the asphalt binder content and grade improved the quantity of RAP material, selecting the amount of extra binder content and the softer binder grade is crucial and not a straightforward task. A comparative study revealed that selecting the best strategic

technique depends on the RAP content anticipated to be incorporated in the asphalt mixtures (Willis et al. 2012). The study recommended adopting an increased binder content strategy when the RAP content is lower than 30%, whereas a softer binder should be used if the RAP utilization is beyond 30% to design a high-performing and durable RAP-inclusive asphalt pavement.

Past experience highlights that the increase in the amount of RAP content with the adjustment in mix design attributes, such as asphalt binder content (increase in binder content) or binder grade (binder grade bumping), is often overlooked (Sukhija and Coleri 2025b). Instead of exploring these cost-effective techniques, the current focus on improving RAP utilization has been on the application of expensive alternatives, such as commercial rejuvenators, nanomaterials, polymers, and WMA additives. The findings of the present study are expected to encourage state agencies/DOTs to incorporate high RAP content in asphalt pavements, with the implementation of feasible strategic techniques.

4.2 OBJECTIVES

Considering all these aspects, the objectives of the present study are to:

1. Statistically analyze the intercorrelation between influential factors, such as binder content, binder grade, and RAP content, and subsequently identify the most influential parameter through univariate analysis.
2. Assess the influence of strategic measures on the rutting and cracking performance of high RAP asphalt mixtures.

The major contribution of the study includes the suitability of increased binder content and binder grade bumping to facilitate a 10% RAP increase beyond the current levels in Oregon (30% for Level 3 and 20% for Level 4 mix designs). As a whole, the present study aims to find whether the RAP content can be increased by adjusting mix design attributes in an optimal way.

4.3 MATERIALS AND MIX DESIGN

In this chapter, two asphalt binder grades were utilized: PG 64-22 (Level 3) and PG 70-22ER (Level 4). The physical properties of these binders are presented in Table 3.2 (Chapter 3.0). Virgin aggregates and RAP material sourced from Source 1, with a nominal maximum aggregate size (NMAS) of 12.5 mm (½ inch), were employed. The RAP binder content was determined to be 4.97%.

The asphalt mixtures were designed to represent Level 3 and Level 4 pavement categories with varying RAP proportions. The combined aggregate gradations adopted in this study are illustrated in Figure 3.14 (Chapter 3.0). The differences between Level 3 and Level 4 gradations were found to be minimal; therefore, performance comparisons were primarily made based on binder grade.

Mixture production followed the procedure outlined in Section 3.3 of Chapter 3.0, which also specifies the short-term and long-term ageing protocols. All asphalt mixtures were prepared to a

thickness of 62 mm and a diameter of 150 mm, compacted to achieve $7 \pm 1\%$ air voids, irrespective of RAP content, binder grade, binder content, mix design level, or ageing condition.

4.4 RESEARCH FRAMEWORK AND METHODOLOGY

Figure 4.1 shows the research framework followed to achieve the objectives of the present study. The overall study is subdivided into two different tasks. Section 4.5.1 Task I presents the relation between the influential factors and the performance parameters. In addition, their individual effect and contributions to the variation in the performance of RAP mixtures is highlighted. Statistical analysis was also performed to identify and validate the significance of these factors. Section 4.5.2 Task II focuses on understanding various strategies to increase the amount of RAP content in asphalt mixtures beyond their allowable limit.

Performance tests, including an indirect tensile cracking tolerance test (IDT-CT) and Hamburg wheel tracking test (HWTT), were carried out to understand RAP mixtures' cracking and rutting tolerance, respectively. The details of the adopted test methodology for HWTT and IDT-CT can be found in Section 3.4 of Chapter 3.0.

Table 4.1 presents the complete experimental test matrix. Four replicates were prepared for each combination, and the average value of performance test parameters, along with the standard deviation using the error bar, was shown throughout the study. Here, one error bar indicates one standard deviation. Considering all the factorials, a total of 144 samples were prepared and tested as per the experimental test matrix, shown in Table 4.1.

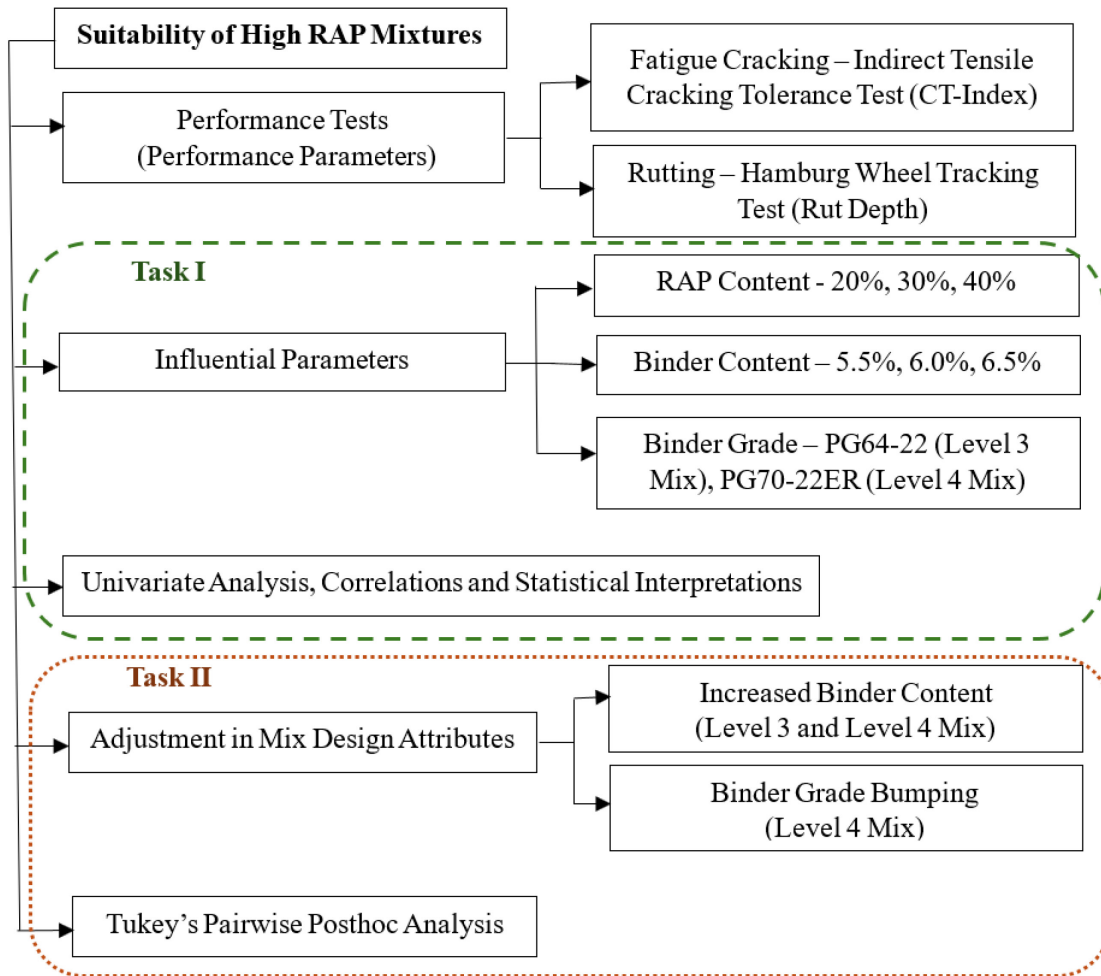


Figure 4.1. Research framework

Table 4.1. Experimental test matrix

Mix Design Level	Property	Test Method	RAP	Binder Content	Binder Grade	Test Temperature (Ageing Condition)	Strategic Measure
Level 3	Fatigue Cracking	IDT-CT	30% 40%	5.50% 6.00% 6.50%	PG64-22	25°C (LTA)	Increased binder content
Level 3	Rutting	HWTT	30% 40%	5.50% 6.00% 6.50%	PG64-22	50°C (STA)	Increased binder Content
Level 4	Fatigue Cracking	IDT-CT	20% 30%	5.50% 6.00% 6.50%	PG70-22ER	25°C (LTA)	Increased binder content Binder grade bumping (PG64-22 as a single grade bumped binder)
Level 4	Rutting	HWTT	20% 30%	5.50% 6.00% 6.50%	PG70-22ER	50°C (STA)	Increased binder content Binder grade bumping (PG64-22 as a single grade bumped binder)

Note 1: IDT-CT and HWTT indicate Indirect tensile cracking tolerance test and Hamburg wheel tracking test, respectively.

Note 2: Level 3 mixes are suitable for pavements with anticipated ESALs between 1 million - 3 million, while Level 4 mixes are recommended for pavement where estimated ESALs exceeds 3 million.

4.5 RESULTS AND DISCUSSION

This section presents the outcomes of the present study, focusing on the significance of various influential parameters, including binder content, RAP content, and binder grade, on the fatigue cracking and rutting behaviour of RAP mixtures, ultimately aiming to enhance RAP utilization in asphalt pavement production. As stated, the overall results of the study are discussed under two different tasks:

4.5.1 Task I- Preliminary Assessment on the Influence of Key Variables on Mix Performance

A commonly used Pearson correlation coefficient-based parametric analysis was carried out to measure the strength of linear correlation between any two parameters in question (or two sets of data). Basically, these correlations deliver an understanding of how and to what extent one

variable is related to the other variable. Generally, the Pearson coefficient ranges between ± 1 , where -1 indicates the strongest negative linear correlation, 0 suggests no correlation, and +1 denotes the strongest positive linear correlation.

Table 4.2 shows the correlation matrix developed using the outcomes of performance testing (IDT-CT and HWTT) conducted in the present study. The results revealed some correlation between the selected independent and performance parameters. Compared to the influence of binder grade and RAP content, the effect of binder content was calculated to be more pronounced, as indicated by the highest Pearson coefficient (+0.77 with CT Index and +0.88 with rut depth). This is in agreement with the findings of past studies conducted in areas with different geographical conditions (i.e., India, China, within the United States, etc.), indicating that the performance of asphalt mixtures is highly sensitive to binder content (Guo et al. 2020b; Harvey and Tsai 1996; Jiang et al. 2024; Saha Chowdhury et al. 2022). Variation in binder content specifically alters the flexibility of the asphalt mixture, leading to a deviation in the mechanical performance (Shaikh and Gupta 2024; Sreedhar and Coleri 2018). The existence of a strong intercorrelation between the binder grade and RAP content is ascribed to the incorporation of different RAP contents with different binder grades. For example, the mixes with 30% and 40% RAP were prepared using a PG64-22 binder (Level 3 mix category), while the PG70-22ER binder was used to produce 20% and 30% RAP mixtures (Level 4 mix category).

Based on the comprehensive experimental testing involving all the above-mentioned variables, descriptive statistics were prepared, and the results are shown in Table 4.2. From the results, the CT Index varies from 17.13 to 146.43, and the rut depth ranges from 1.91 mm to 5.87 mm depending on the amount of binder (5.5 to 6.5%), RAP content (20-40%), and binder grade (PG64-22 and PG70-22ER). Thus, the present study assessed the individual effect of these variables to identify the general pattern in the performance of RAP mixtures with the change in one characteristic or attribute while the other variables are kept constant. This type of analysis is typically called univariate analysis, wherein each variable in a group data set is explored individually. A similar analytical technique was recommended in a previous study to individually find the impact of each variable (Albayati and Sukhija 2024).

Table 4.2. Correlation matrix and description statistics

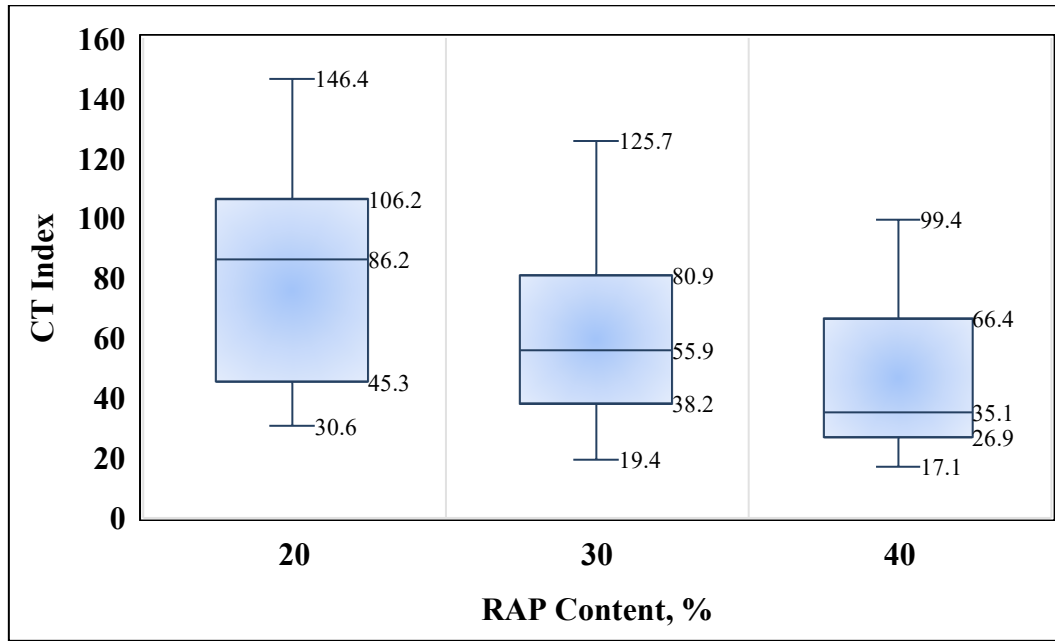
Correlation Matrix for CT Index	Variables	RAP Content	Binder Content	Binder Grade	CT Index
Correlation Matrix for CT Index	RAP Content	1	-	-	-
Correlation Matrix for CT Index	Binder Content	-0.027	1	-	-
Correlation Matrix for CT Index	Binder Grade	-0.701	0.037	1	-
Correlation Matrix for CT Index	CT Index	-0.388	0.771	0.152	1
Correlation Matrix for Rut Depth	Variables	RAP Content	Binder Content	Binder Grade	Rut Depth
Correlation Matrix for Rut Depth	RAP Content	1	-	-	-
Correlation Matrix for Rut Depth	Binder Content	0.003	1	-	-
Correlation Matrix for Rut Depth	Binder Grade	-0.720	-0.004	1	-
Correlation Matrix for Rut Depth	Rut Depth	-0.129	0.877	-0.098	1
Descriptive Statistics	Performance Parameter	Mean	Minimum	Maximum	Standard Deviation
Descriptive Statistics	CT Index	63.24	17.13	146.43	33.60
Descriptive Statistics	Rut Depth	3.36	1.91	5.87	0.94

4.5.1.1 Univariate Analysis of RAP Mixtures

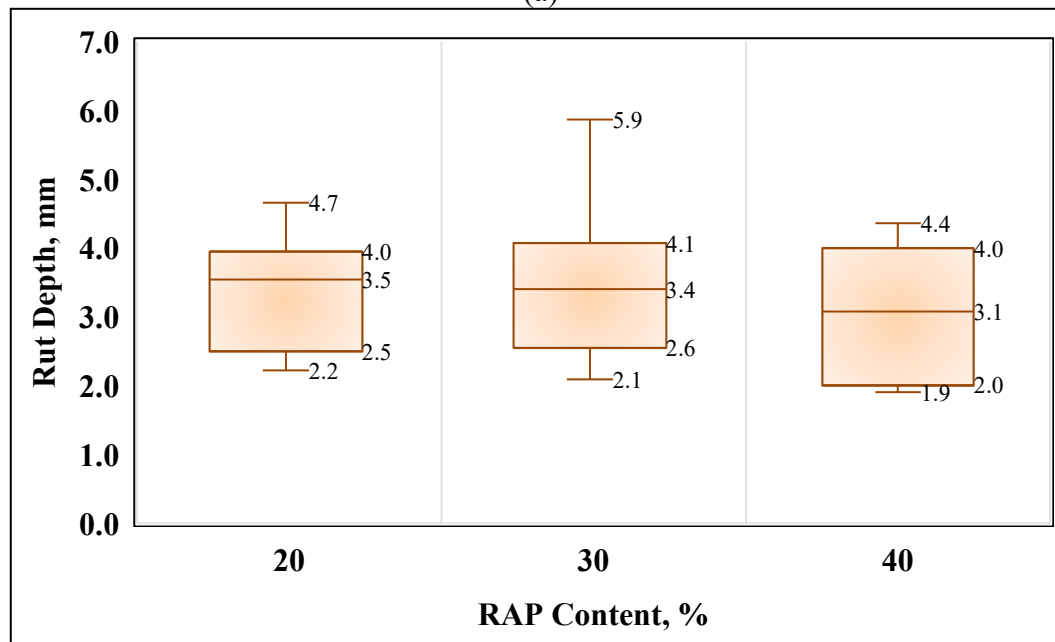
In univariate analysis, the complete set of results was first sorted by each influential parameter (one at a time) to understand the individual influence of these variables on the cracking and rutting performance. For instance, if the sorting is done concerning binder content, the average CT Index and rut depth values were determined at each binder content, irrespective of the other variables.

From the context of RAP content, a stiff oxidized asphalt binder film over the RAP aggregates results in improved rutting resistance while lowering the cracking resistance, as depicted in Figure 4.2. The shift in RAP content from 20% to 40% lowers the CT

Index and rut depth by around 45% and 10%, respectively. Increased rutting resistance (lower rut depth) is attributed to the increase in the stiffness of the asphalt binder, and thus, the asphalt mixture with the application of high RAP content; however, it inevitably elevates concerns about cracking, suggesting a need to control the limit of RAP content in the production of asphalt mixtures. It should be noted that past Oregon field trials that exceeded 7-8 mm rut depth in the laboratory resulted in premature rutting failures. Thus, the current aim is to target the maximum rut depth of around 4-6 mm while maintaining the cracking performance under the critical limits for RAP-inclusive asphalt mixtures.



(a)

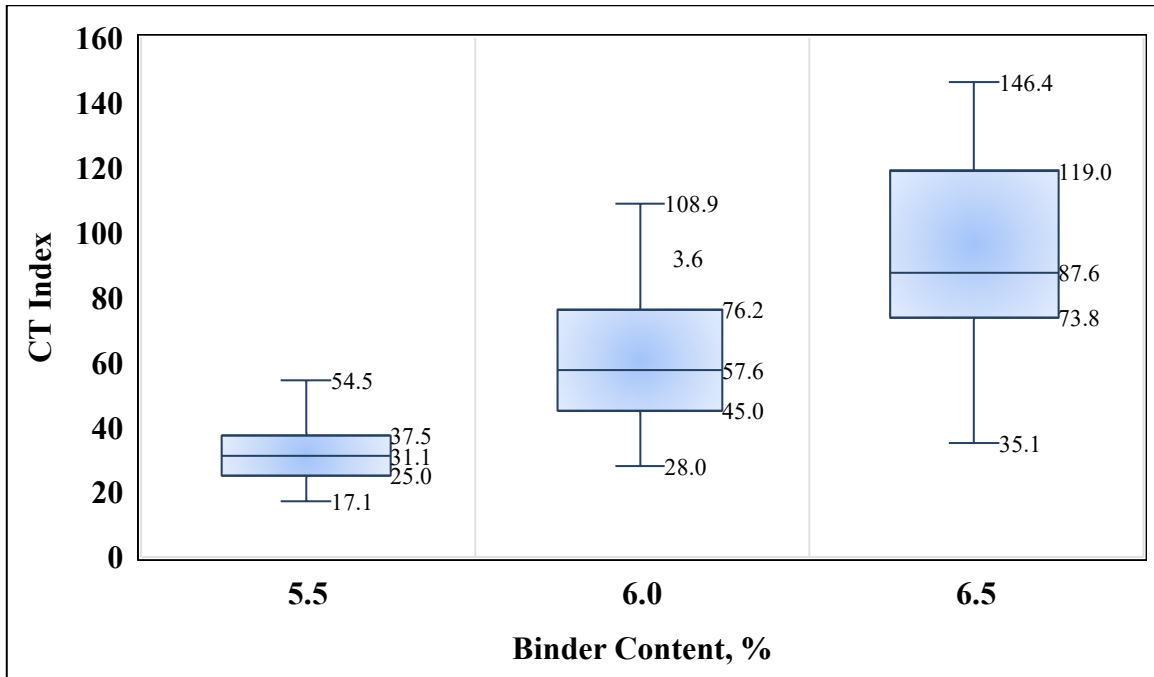


(b)

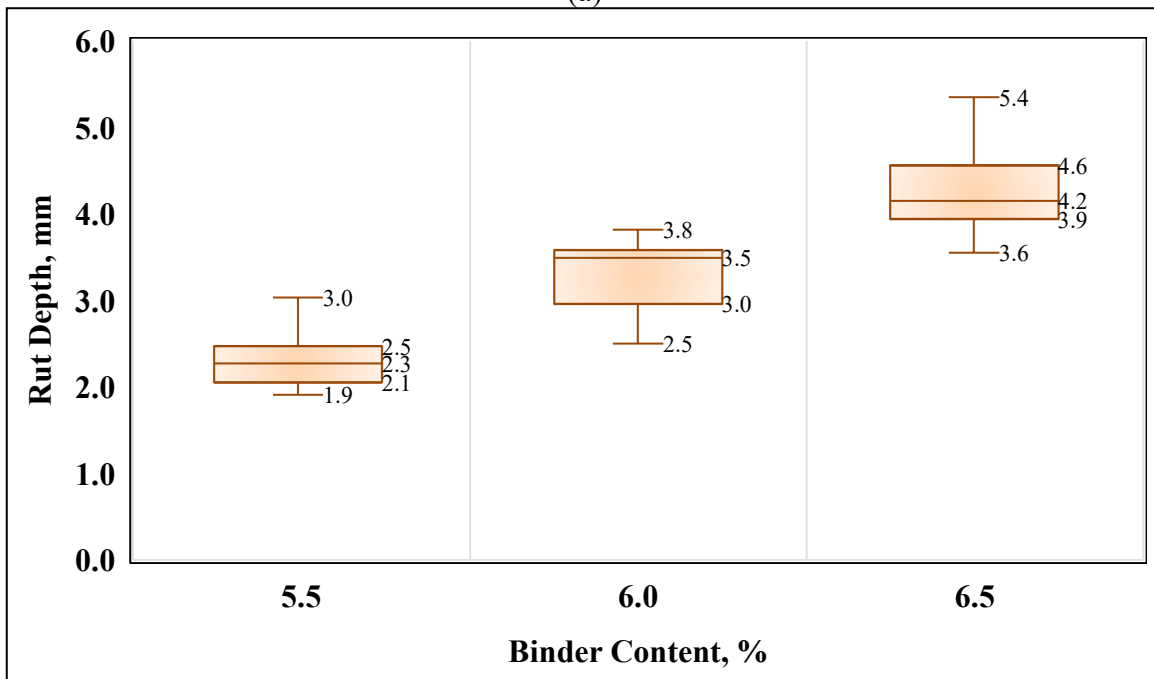
Figure 4.2. Influence of RAP content on the performance of RAP mixtures (a) CT Index and (b) Rut depth

Figure 4.3 presents the univariate analysis of RAP mixtures at different binder contents. As the binder content increases, there is a significant decrease in the rutting resistance, while it offers improved cracking resistance. The increase in binder content from 5.5% to 6.0% and 6.5% increases the CT Index by around 98% and 202%, respectively; concurrently, it also leads to an increase in rut depth by approximately 43% and 87%, respectively. The increase in CT Index and rut depth is attributed to the asphalt mixture's

enhanced flexibility and flow characteristics, which enable the mix to deform rather than fracture under continuous, repetitive loading.



(a)

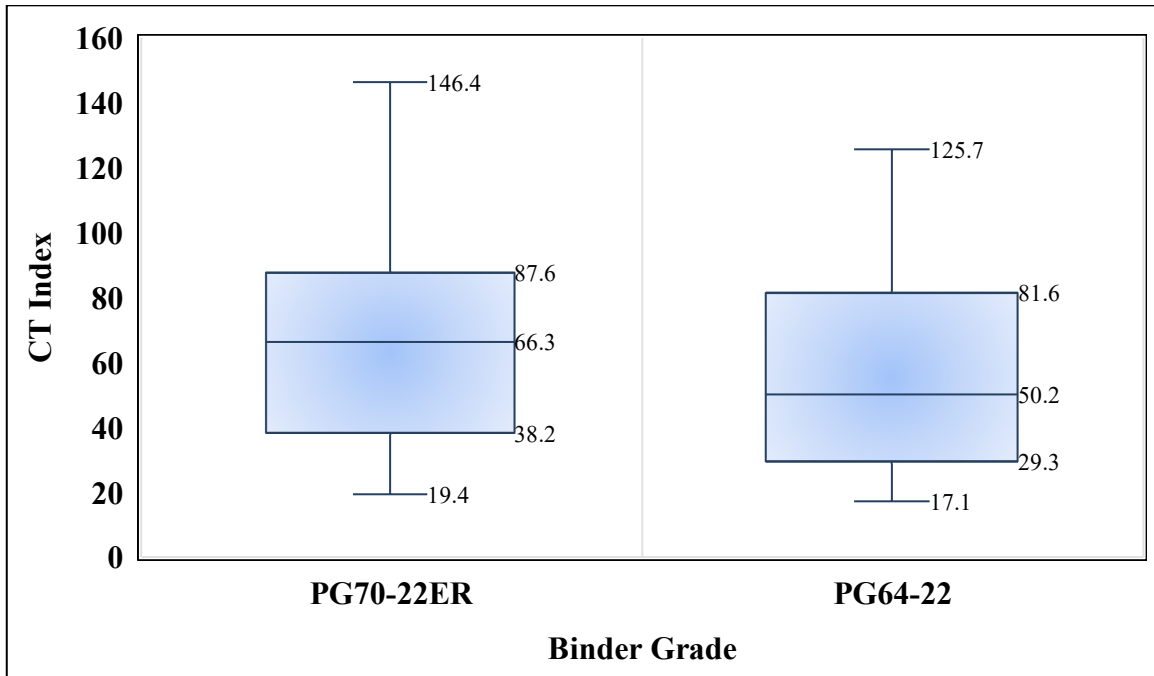


(b)

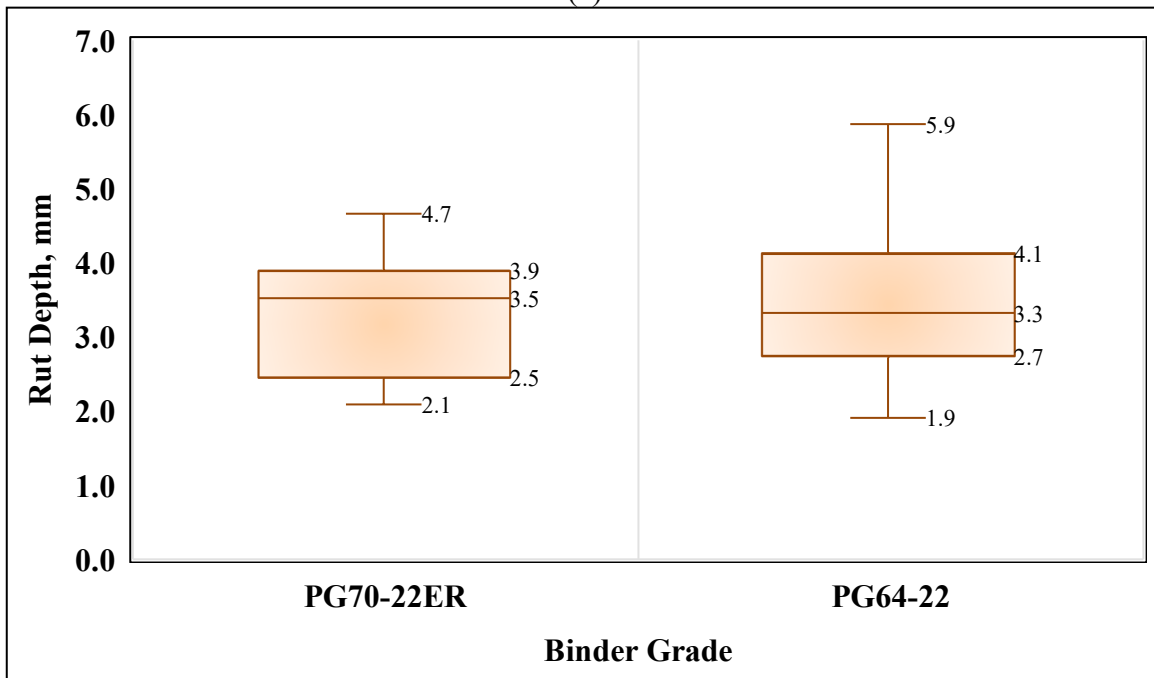
Figure 4.3. Influence of binder content on the performance of RAP mixtures (a) CT Index and (b) Rut depth

The other influential parameter for RAP mixtures is the asphalt binder grade. Figure 4.4 shows the variation in the performance of RAP mixtures prepared using two different grades of asphalt binder, i.e., PG64-22 and PG70-22ER. Notably, the PG64-22 binder is a relatively softer binder than the PG70-22ER binder; perhaps they are often chosen for constructing asphalt pavements based on the mix design levels. In general, the softer binder is recommended to improve the amount of RAP content in the asphalt mixture. This is because a softer binder tends to offset the effect of oxidized RAP binder, resulting in improved cracking resistance.

As shown in Figure 4.4a, the average CT Index of RAP mixtures prepared using PG64-22 binder results in an 18% lower CT Index than the RAP mixtures produced using PG70-22ER binder. The decrease in the CT Index with the use of a softer binder is attributed to the higher amount of RAP content (30% and 40%) in these mixes compared to the 20% and 30% RAP material in the mixes prepared using PG70-22ER. In addition, a stiffer binder (PG70-22ER) is used to prepare asphalt mixtures, which comprise polymers that resist cracking due to the elastic polymeric network. The results show that the RAP content is more dominant than the binder grade in influencing the cracking tolerance of the asphalt mixtures. On the contrary, the elastic network also improved the rutting tolerance of the asphalt mixture without cracking. The mixes prepared with PG64-22 possess higher rut depth and, consequently, lower rutting resistance than the PG70-22ER mixes, as depicted in Figure 4.4b. The average rut depth in the RAP mixtures prepared using PG70-22ER binder was 3.3 mm, which increases to 3.5 mm with the use of PG64-22, indicating a marginal decrease in rutting resistance. Similar to the effect of increased binder content, softer binder imparts (PG64-22) softness in the mix by reducing the overall viscosity of the RAP mixtures compared to stiffer and elastic binder (PG70-22ER) and eventually increases the rut depth (Coleri et al. 2018a). Additionally, the lower change in rutting values with soft binders is due to the higher amount of RAP content, which restricts the deformation of the final asphalt mix. Overall, it can be divulged that the synergistic effect of RAP and binder grade facilitates adequate rutting characteristics in RAP-inclusive asphalt mixtures.



(a)



(b)

Figure 4.4. Influence of asphalt binder grade on the performance of RAP mixtures (a) CT Index and (b) Rut depth

Note: PG64-22 mixtures box plot represents the performance of mixtures comprising 30% and 40% RAP, while PG70-22ER mixtures reflect the performance of the mixtures containing 20% and 30% RAP.

4.5.1.2 Statistical Inferences

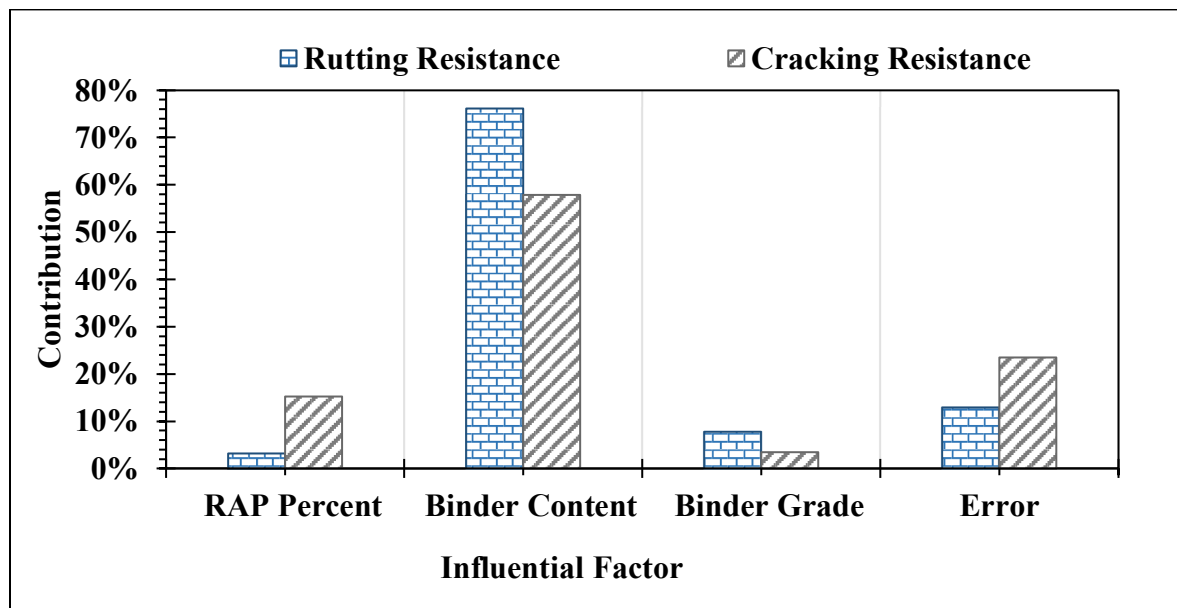
As per the results shown in the preceding sections, RAP content, binder content, and binder grade play a crucial role in governing the performance of RAP-inclusive asphalt mixtures. However, their significance and contribution towards the change in the performance of RAP mixtures are unknown. Thus, an Analysis of Variance (ANOVA) is performed to identify the parameter with the greatest contribution towards the variation in the performance. A confidence level of 95% was chosen throughout the statistical analysis, suggesting that the p-value should be less than 0.05 for any variable to significantly influence the performance parameters (CT Index and rut depth) of the RAP mixtures. The results of ANOVA are presented in Table 4.3.

A lower p-value ($p < 0.05$) corresponding to all the independent variables, including the amount of RAP, binder content, and binder grade, implies their significant influence on the fatigue and rutting performance of RAP-inclusive asphalt mixtures. Similar observations were reported in a previous study (Willis et al. 2013), indicating that the optimal use of RAP proportion with appropriate binder content and binder grade could result in enhanced performance and durability of RAP mixtures. A past European experience also revealed that RAP mixtures, even with high binder content, exhibit lower rut depth and cracking susceptibility than their respective conventional mixtures with no RAP (Celauro et al. 2010). This underscores the importance of adjustment in the mix design attributes for pavement longevity, especially with high RAP. In practical terms, an increase in RAP content or binder grade increases stiffness, which leads to reduced cracking resistance but improved rutting resistance (Willis et al. 2012). On the other hand, higher binder content increases flexibility, improving cracking resistance while decreasing rutting resistance (Coleri et al. 2018a; Sukhija and Coleri 2025b).

In order to determine the contribution of these variables to the performance of RAP mixtures, the ANOVA results were further examined, and the outcomes are presented in Figure 4.5. Attributable to the higher variability in the CT Index values, the amount of error in the model predicting the cracking resistance is considerably higher (i.e., 23.5%) than the error depicted in the model predicting rut depth values (13%) as per ANOVA results. The findings of the contribution values are in line with the performance testing results, wherein the influence of RAP content is more pronounced on the CT Index, while the combined effect of RAP content and binder grade describes the rutting behavior of RAP mixtures at a particular binder content. Among the considered variables, the major contributor producing the maximum variation in CT Index and rut depth was binder content (5.0, 5.5, and 6.0% here), with a contribution percentage of around 58% and 76%, respectively. This is in line with the previous studies in the literature (Guo et al. 2020b; Harvey and Tsai 1996; Jiang et al. 2024; Saha Chowdhury et al. 2022). Hence, the binder content should be chosen wisely to achieve adequate performance of RAP mixtures. Nevertheless, the effect of binder grade and RAP content should not be overlooked.

Table 4.3. Analysis of variance for CT Index and Rut depth

Source of Variation	Factorials	CT Index F-value	CT Index P-value	Rut Depth F-value	Rut Depth P-value
RAP Content	20%, 30%, 40%	18.97	0.000	15.63	0.000
Binder Content	5.5%, 6.0%, 6.5%	71.20	0.000	128.98	0.000
Binder Grade	PG64-22, PG70-22ER	8.45	0.005	26.37	0.000

**Figure 4.5. Contribution of influential variables on the performance of RAP mixtures**

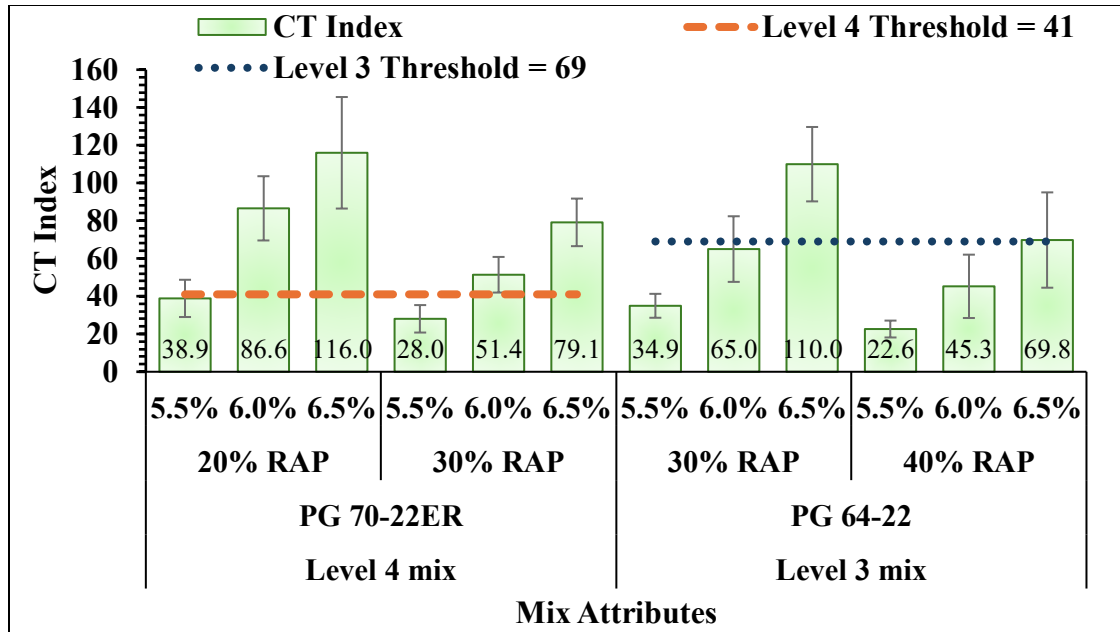
4.5.2 Task II- Strategies to Improve RAP Content

Since many sample combinations, defined based on the RAP content, binder content, and binder grade, were tested, a Tukey's pairwise post hoc analysis was carried out to determine whether there is a significant difference between the means of all the possible pairs of a given test data, considering the variability in the test results. The analysis was conducted with a 95% simultaneous confidence level, where the null hypothesis indicates the existence of similarity between the group means. Therefore, if the $p\text{-value} < 0.05$, it signifies there is a significant difference, and the null hypothesis is rejected, whereas $p\text{-value} > 0.05$ implies that the group means are statistically identical. From the perspective of the current study, the primary objective is to check if the means of performance parameters (CT Index and rut depth) for high RAP mixes are identical/different from the control samples, irrespective of the strategic technique. The findings of Tukey's pairwise comparison would aid in addressing the possibility of increasing the RAP content with the application of increased binder content or binder grade bumping.

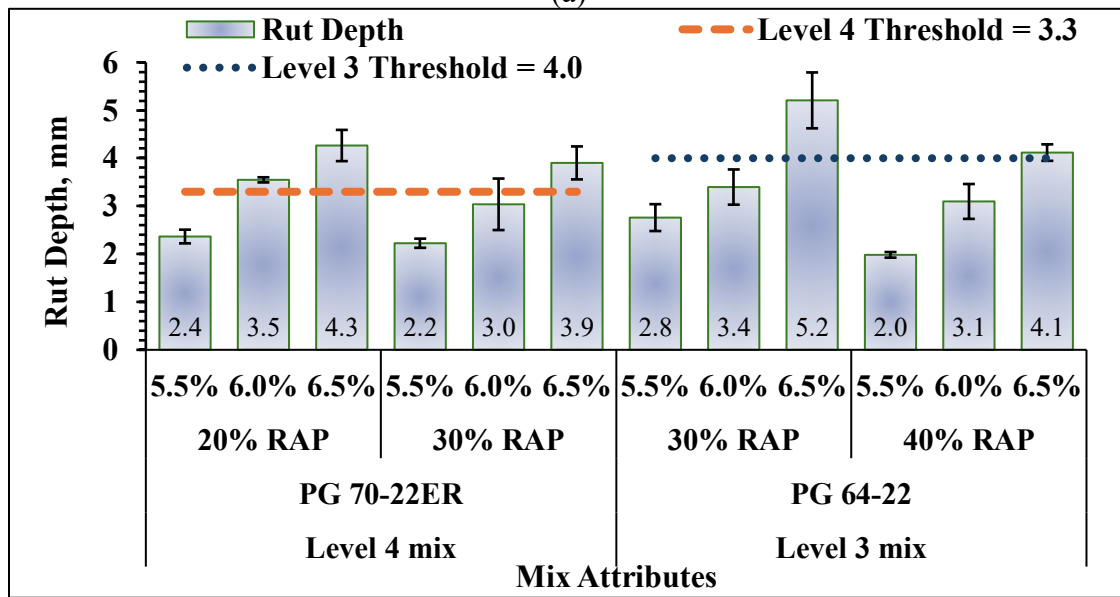
4.5.2.1 Adjustment in binder content

According to the results shown in Figure 4.6, an increase in binder content considerably affects the rutting and fatigue performance, leading to an increase in the CT Index and rut depth. The relatively higher film thickness over the aggregates at higher binder content might be a probable reason for such variation in the performance of asphalt mixtures. Although the value of performance parameters increases with binder content, applying a high amount of RAP material counteracts the obtained results, indicating a lower CT Index and rut depth at all the binder contents. This is attributed to the stiffening effect of asphalt mixtures at high RAP content, which contributes to lower cracking performance yet improved resistance to rutting. This trend was consistent for all the RAP mixtures, irrespective of the mix design levels (Levels 3 and 4). This implies a need to optimize/adjust the mix design attributes for a particular RAP mixture, especially the binder content, to achieve satisfactory long-term performance of RAP-inclusive asphalt pavements.

Considering the critical threshold values for the CT Index and rut depth developed for Oregon (Chitnis et al. 2025), a few combinations of RAP mixtures satisfactorily improved the performance. For example, a Level 4 mix having 30% RAP material with 6.0% binder content resulted in a higher CT Index (51.4) and lower rut depth (3.0 mm) than the critical balanced mix design (BMD) thresholds (CT Index = 41 and rut depth = 3.3mm) set by Chitnis et al. (2025), which is desirable for a durable asphalt pavement. Irrespective of the mix design level, all the RAP mixtures at 5.5% binder content attain the rut depth lower than the critical thresholds but failed to achieve the minimum CT Index values, and vice versa at 6.5% binder content. If the variability between the results of the CT Index and rut depth is considered, a few other combinations may pass the critical design thresholds as observed from the error bars, where one error bar indicates one standard deviation (passing above or below the threshold line) in Figure 4.6a and Figure 4.6b. However, merely based on these figures it is not easy to comment whether the increase in binder content improves the RAP content.



(a)



(b)

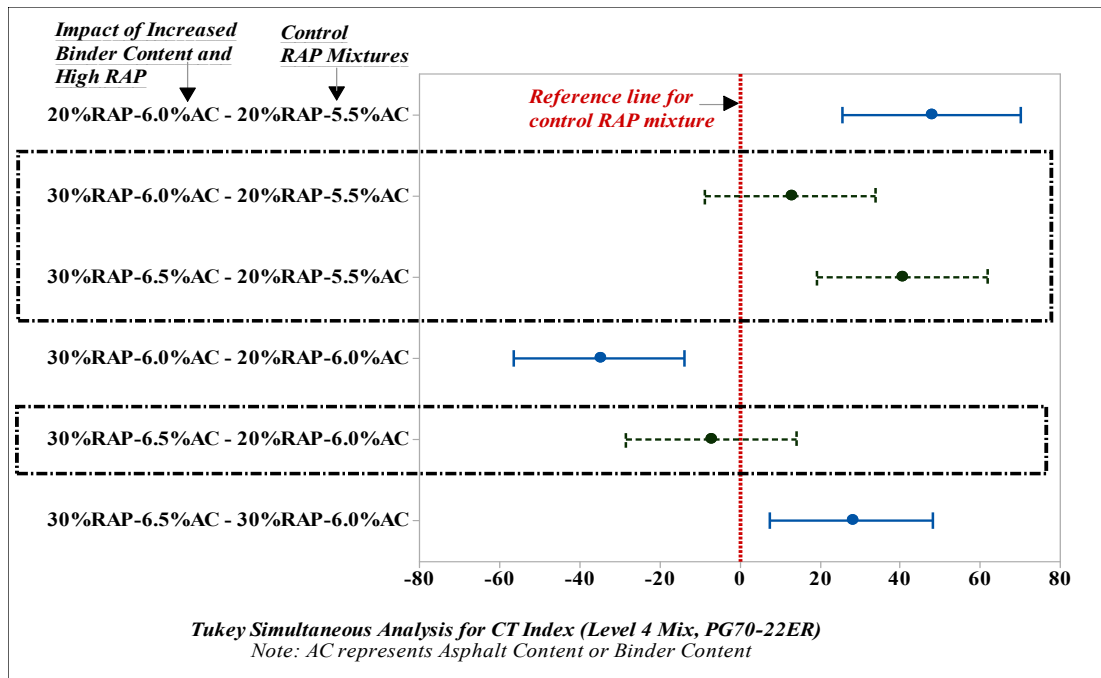
Figure 4.6. Impact of increased binder content on the performance of RAP mixtures (a) Cracking behaviour and (b) Rutting behaviour

The inferences of Tukey's pairwise post-hoc analysis can be an effective way to understand the similarity between different combinations of RAP mixtures based on their significance level. One such example of Tukey's pairwise analysis in the case of increased binder content strategy is the comparison between the Level 4 mix containing 20% RAP and 5.5% binder content and the mix having 30% RAP at 6% and 6.5% binder content to determine if the mean results are statistically identical or different. Similarly, several other pairs have been compared, and the complete set of parametric analyses with

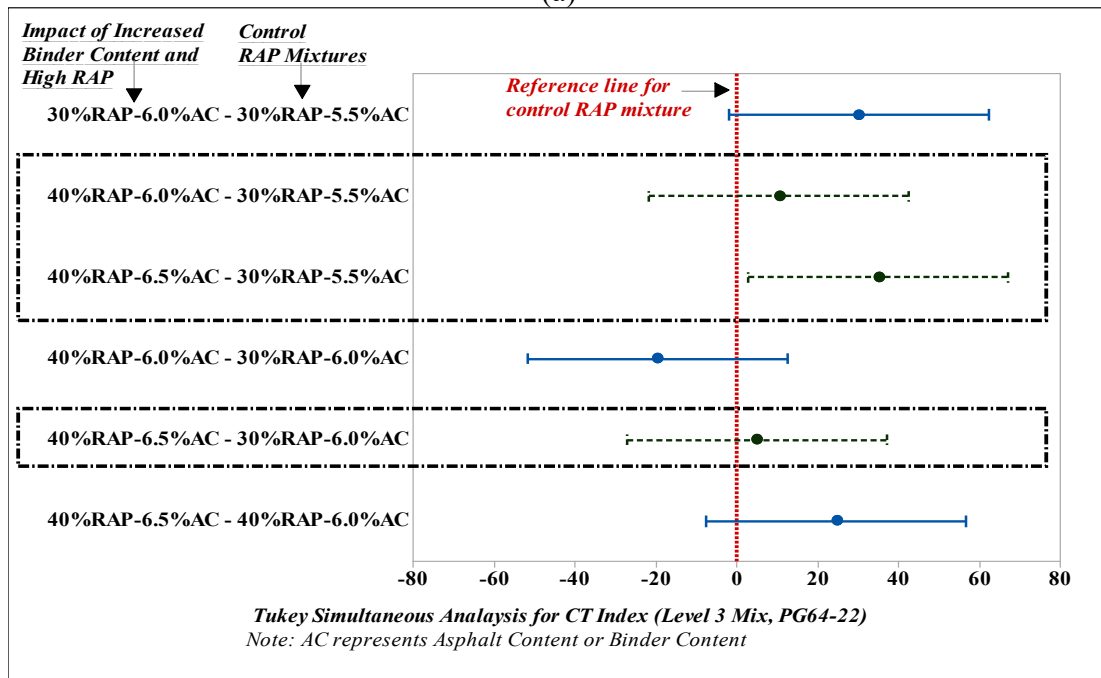
a 95% confidence level is shown in Figure 4.7 and Figure 4.8. The dotted lines at the zero (0) point in the figures are the reference lines used to determine the similarity and difference between the compared pairs. If an interval crosses the zero line, it implies that the corresponding means are significantly identical and vice versa (may be positive or negative). A positive value is desirable for a better CT Index, while a negative value for rut depth is more beneficial for pavement longevity.

The combinations indicating the effect of increased binder content on the CT Index and rut depth are highlighted within an annotated rectangular boundary in Figure 4.7 and Figure 4.8, respectively. As can be observed, the RAP mixtures for a Level 3 mix (prepared with PG64-22 binder), having 30% RAP at 5.5% binder content, can be appreciably replaced with 40% RAP if the binder content is increased by 0.5%, ensuring the rutting and fatigue performances are comparable to their respective control mix. Similarly, with an increase in binder content by 0.5% in 20% RAP mixtures of the Level 4 category, where the binder grade is PG70-22ER, the RAP content can be successfully increased by 10%. Although there are few mix combinations, such as 30% RAP at 6% binder content in the Level 3 category and 40% RAP mix at 6.5% binder in the Level 4 category, were found to be statistically different in terms of rut depths from their respective control mix prepared at 0.5% lower binder content (i.e., 20% RAP at 5.5% binder content and 30% RAP at 6% binder content for Level 3 and Level 4 mix category, respectively), their rut depths were still similar or lower than the critical thresholds designed for state of Oregon. Furthermore, a 1% increase in binder content results in improved cracking resistance but may increase the likelihood of rutting due to traffic movement during the early stages of pavement construction.

The experimental results and validation through Tukey's pairwise comparison demonstrate the effectiveness of an increased binder content strategy for increasing the amount of RAP by about 10% in asphalt mixtures with acceptable performance. However, the production of an asphalt mixture with this strategy may elevate the overall production cost, thereby necessitating cost clarification prior to its practical field implementation. The cost comparison analysis has been described in Section 6.4.2.3 of the report.

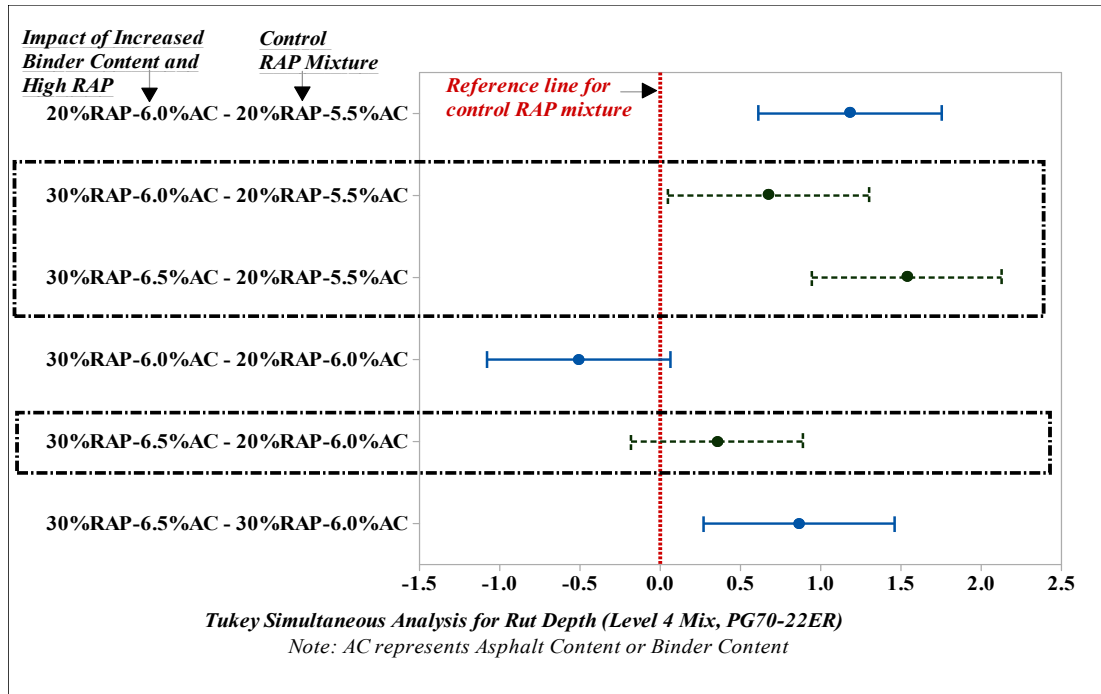


(a)

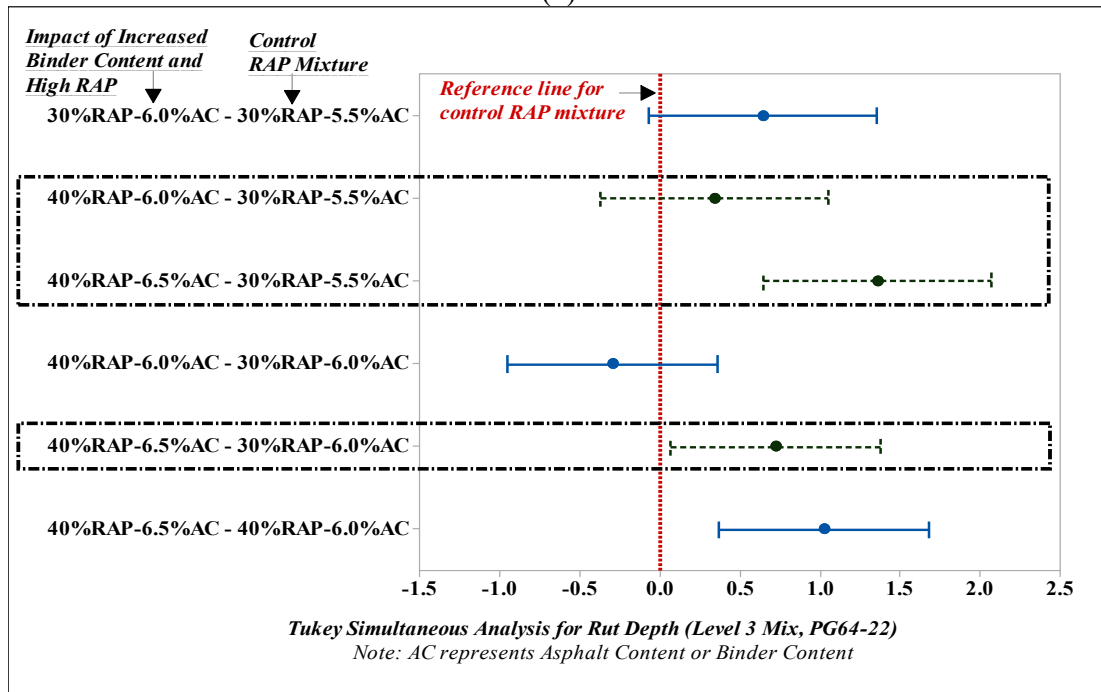


(b)

Figure 4.7. Tukey's analysis for the impact of increased binder content on CT Index (a) Level 4 mix (PG70-22ER binder) and (b) Level 3 mix (PG64-22 binder)



(a)



(b)

Figure 4.8. Tukey's analysis for the impact of increased binder content on Rut depth (a) Level 4 mix (PG70-22ER binder) and (b) Level 3 mix (PG64-22 binder)

4.5.2.2 Adjustment in Binder Grade

For assessing the influence of binder grade, the RAP-inclusive asphalt mixtures, having 20% and 30% RAP material, prepared using PG70-22ER binder, were compared with the high RAP mixtures (30% and 40% RAP material) produced using a lower grade binder, i.e., PG64-22. The grade was lowered by one degree with the aim of extending the RAP content by 10-20% compared to the control samples.

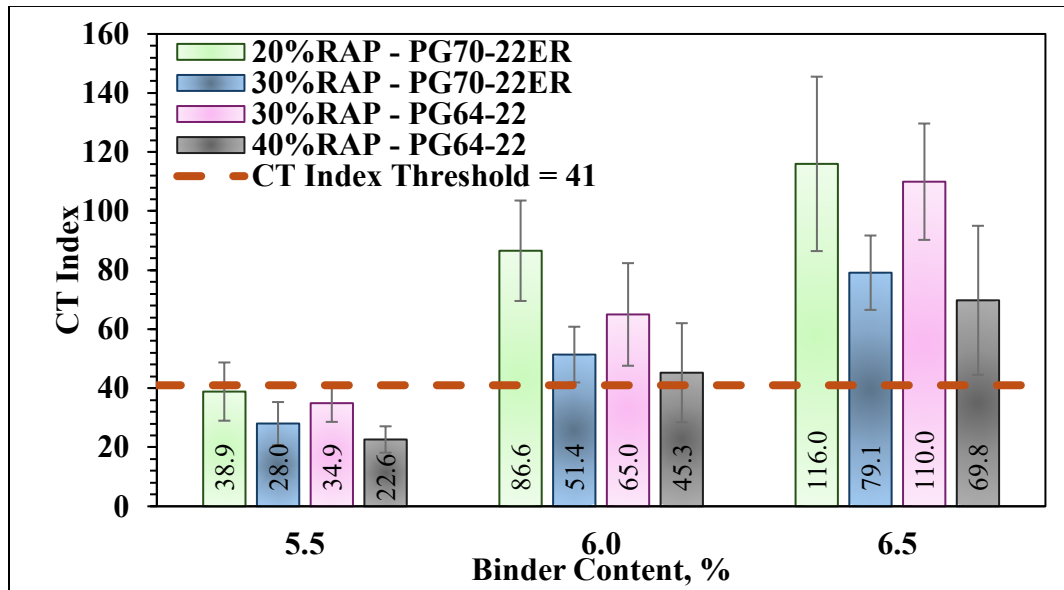
Figure 4.9 shows the effect of binder grade bumping on the cracking and rutting behavior of RAP mixtures. Owing to the increased stiffening effect and brittleness, the value of the CT Index and the rut depth reduced with the increase in RAP content. This is applicable to both the binder grades employed in this study. Notably, the extent of reduction in cracking tolerance and improvement in rutting resistance depends on the amount of binder in the asphalt mixture.

Although the increase in RAP material from 20% to 30% within the mix prepared with PG70-22ER reduces the CT Index value, using a softer binder or one-grade bumping neutralizes such influence. For instance, the CT Index for a RAP mix having 30% RAP material and PG70-22ER binder was found to be increased when the identical RAP mixture was prepared using a one-grade lower binder, i.e., PG64-22. The increase in CT Index value ranged from 24.5% to 39% depending on the binder content, implying the positive influence of grade bumping on the cracking resistance. Interestingly, the CT Index values of the RAP mixtures having 30% RAP and 40% RAP produced using PG64-22 (one grade bumped binder) were comparable to the RAP mixtures prepared with 20% RAP and 30% RAP material using PG70-22ER binder, respectively. Similarly, the difference in the CT Index of 40% RAP mix having PG64-22 binder and 30% RAP mix prepared with PG70-22ER binder was found to be marginal, but it is lower than the mix combination having 20% RAP and PG70-22ER binder.

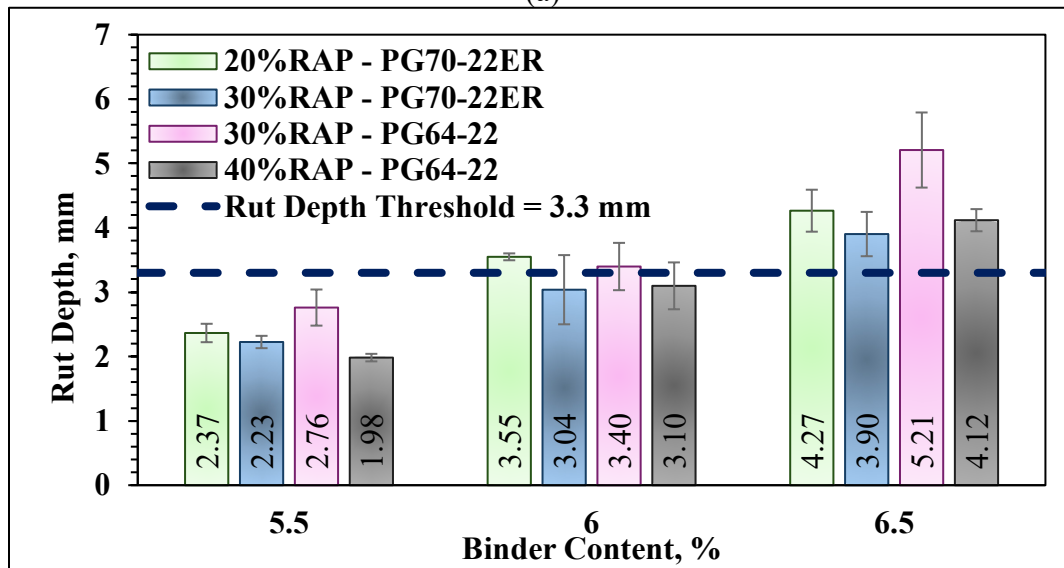
On the other hand, an increase in RAP material decreased the rut depth; however, using a softer binder grade further increases the rutting value and the rutting susceptibility. Considering a particular binder content, the difference in the rut depth of RAP mixtures prepared with different percentages of RAP material and binder grades is negligible. Among all the combinations of RAP mixtures, the maximum rut depth was 5.21 mm in the mix, which had 30% RAP, 6.5% binder content, and PG64-22 binder. The higher rut depth in this particular mix is attributed to the combined effect of high binder content and softer binder grade, reflecting the significance of decision-making on the selection of binder content and binder grade for the production of asphalt mixtures, as far as rutting is concerned.

As can be seen in Figure 4.9a, the CT Index of most of the evaluated RAP mixtures was above the critical CT Index thresholds (CT Index ≥ 41), except the two mix combinations at 5.5% binder content, namely: 30%RAP (PG70-22ER) and 40%RAP (PG64-22). The stiff binder in the former mix and high RAP in the latter mix, coupled with the effect of lower binder content (5.5%), would be the probable reason for inferior cracking resistance in these mixes. However, the same two mix combinations outperformed in terms of rutting resistance, as demonstrated in Figure 4.9b. Considering the critical

rutting thresholds (Rut depth ≤ 3.3 mm), although all the tested RAP mixtures prepared at 6.5% binder content achieve rut depth higher than 3.3 mm (around 4-5 mm, as shown in Figure 4.9b), this 3.3 mm threshold is still low and rutting failure is very unlikely. Thus, it is recommended to increase the critical threshold to at least 5.0 mm in the ODOT research project on BMD implementation (SPR852). Notably, the increase in rut depth is attributed to the pronounced influence of higher binder content over the RAP content and binder grade, which also aligns with the inferences of the statistical analysis described in the previous sections. *Additionally, these results indicate that RAP content can be increased by about 10% using a softer binder grade, without significantly affecting the cracking or rutting resistance of the asphalt mixtures.*



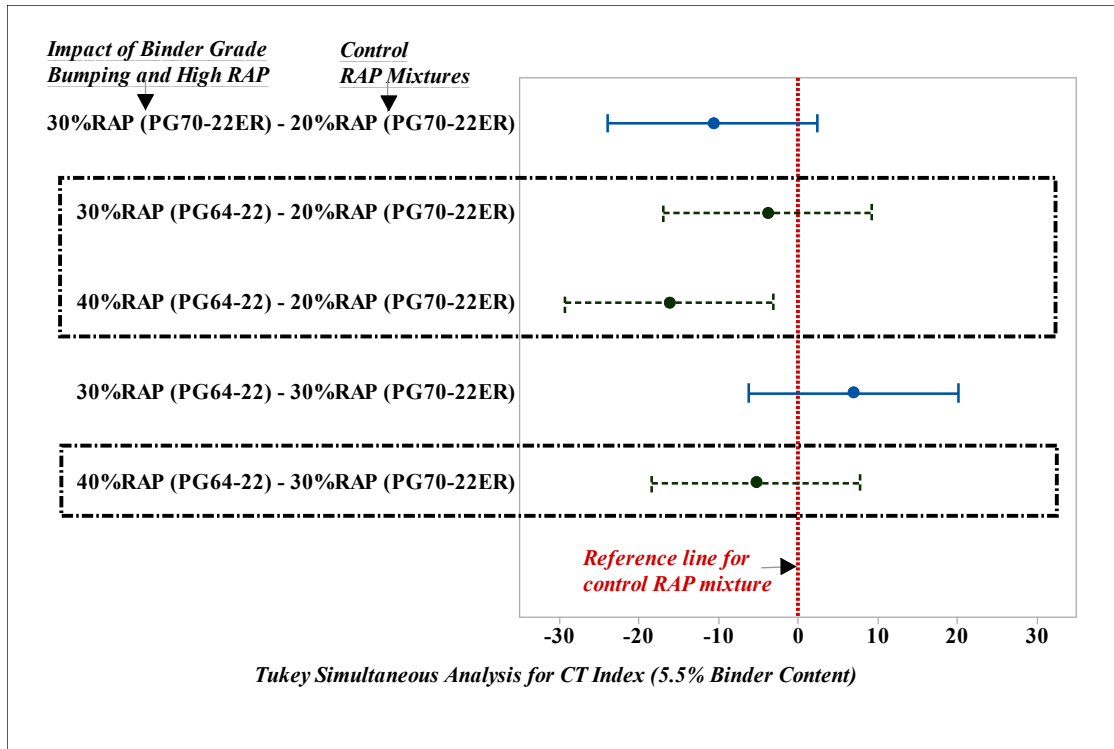
(a)



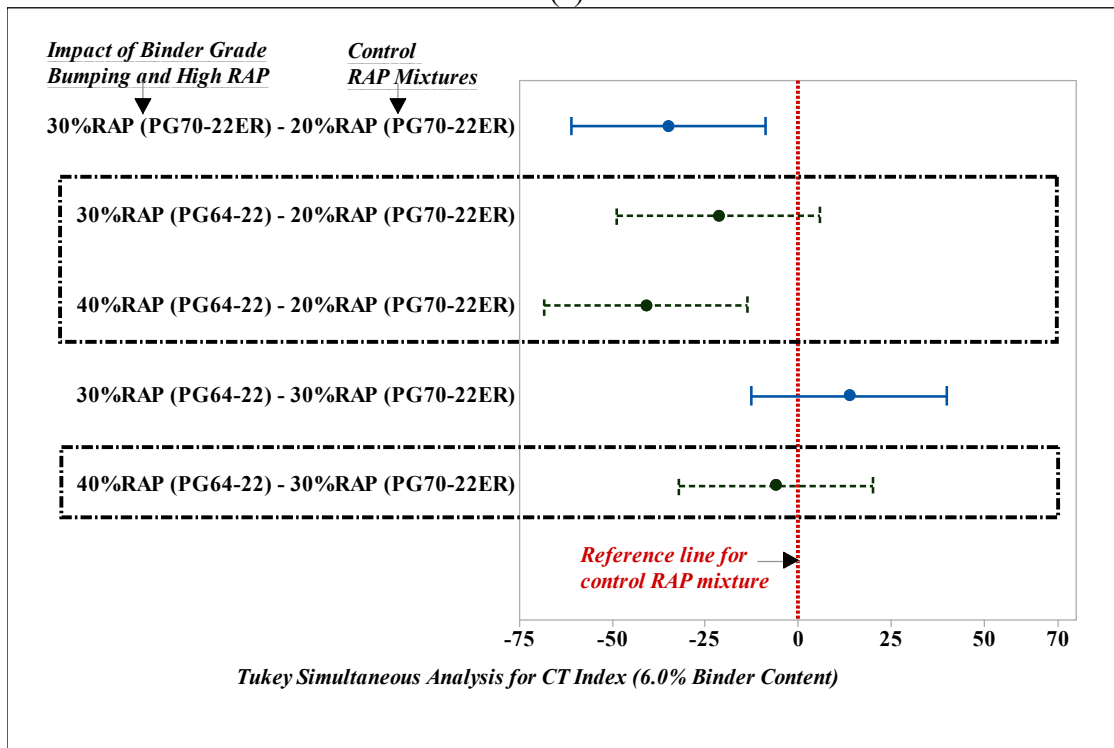
(b)

Figure 4.9. Impact of binder grade bumping on the performance of RAP mixtures (a) Cracking behavior and (b) Rutting behavior

According to Tukey's analysis shown in Figure 4.10 (a-c), bumping the grade of the binder from PG70-22ER to PG64-22 (one grade lower) permits 10% higher RAP in the mix relative to the control samples, indicating statistically identical results in terms of CT Index. However, some exceptional mix combinations exist for which the rut depth values are more than the rutting values of control samples. This results in statistically different rutting performance even if the RAP is increased by 10% after one grade bumping, as presented in Figure 4.11 (a-c) within the annotated rectangular boundary. These mix combinations are 30% RAP mix at 5.5% and 6.5% binder content prepared using PG64-22 binder (one grade bumped binder from PG70-22ER). Although the rut depth at 5.5% binder content for the mix containing 30% RAP and PG64-22 binder was not found to be statistically similar to the control samples, the resulting rut depth is far lower than the critical threshold (Figure 4.11a). Overall, Tukey's analysis confirms that the performance of high RAP mixtures is a function of the binder content. Thus, there is a need to optimize the design binder content for lower binder grade high RAP mixtures to achieve acceptable performance against rutting and fatigue cracking.

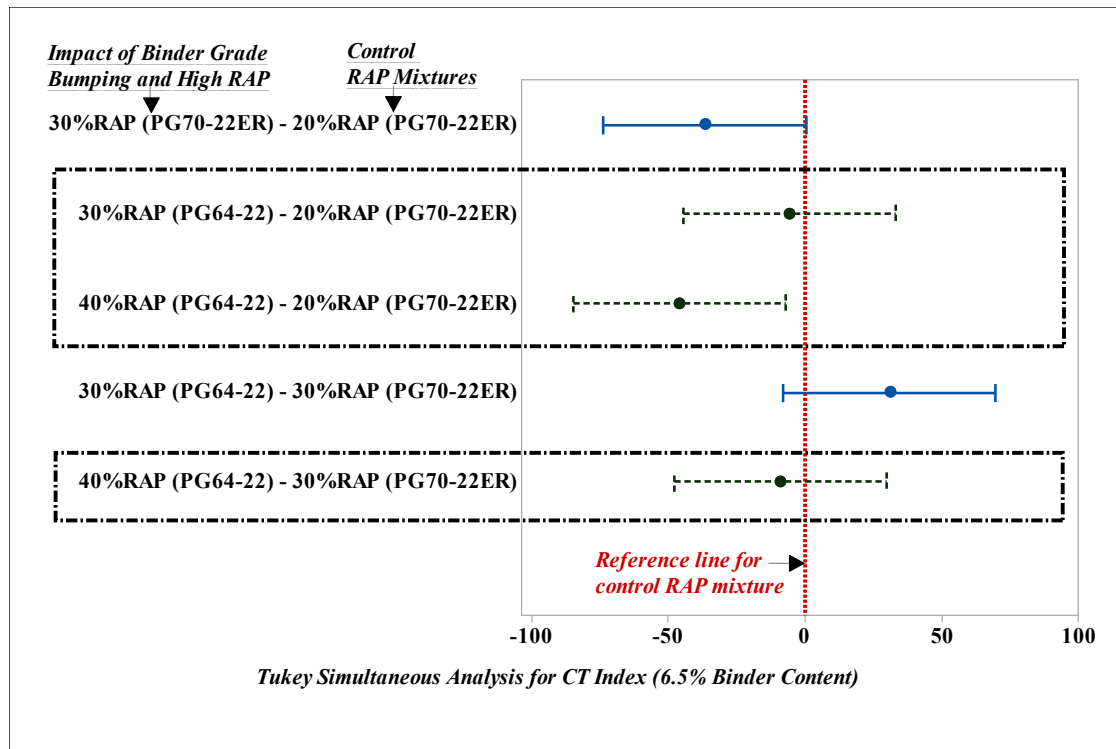


(a)



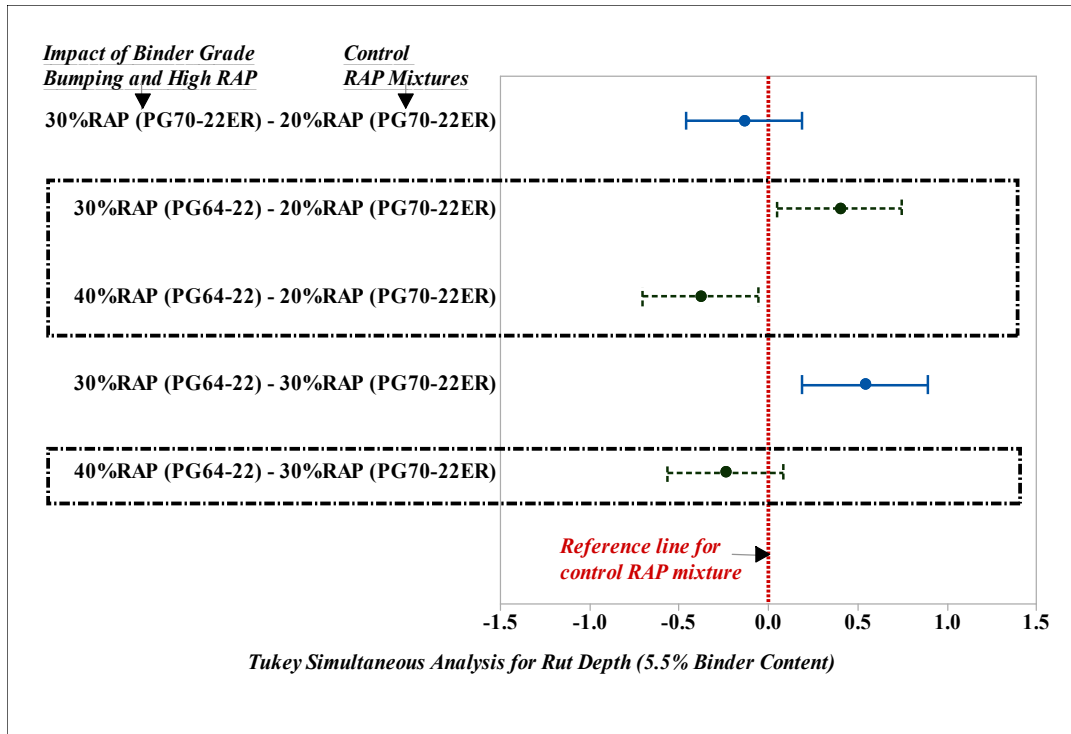
(b)

Figure 4.10. Tukey's analysis for the impact of binder grade bumping on CT Index at different binder content (a) 5.5%, (b) 6.0%, and (c) 6.5%

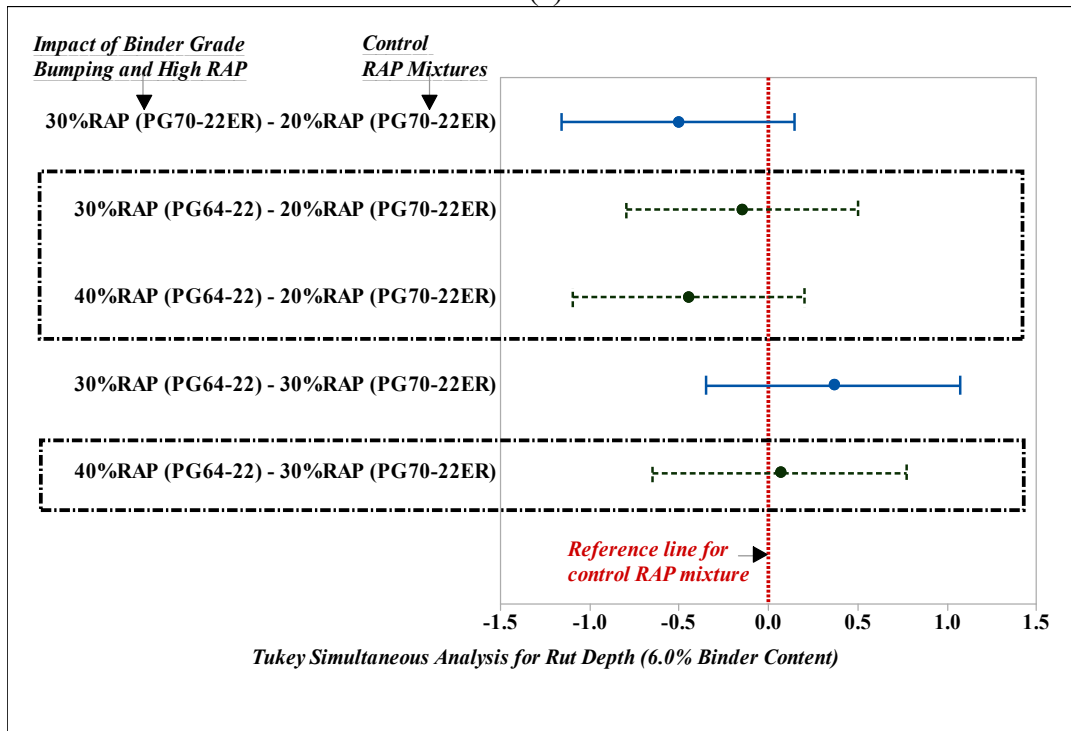


(c)

Figure 4.11 (continued). Tukey's analysis for the impact of binder grade bumping on CT Index at different binder content (a) 5.5%, (b) 6.0%, and (c) 6.5%

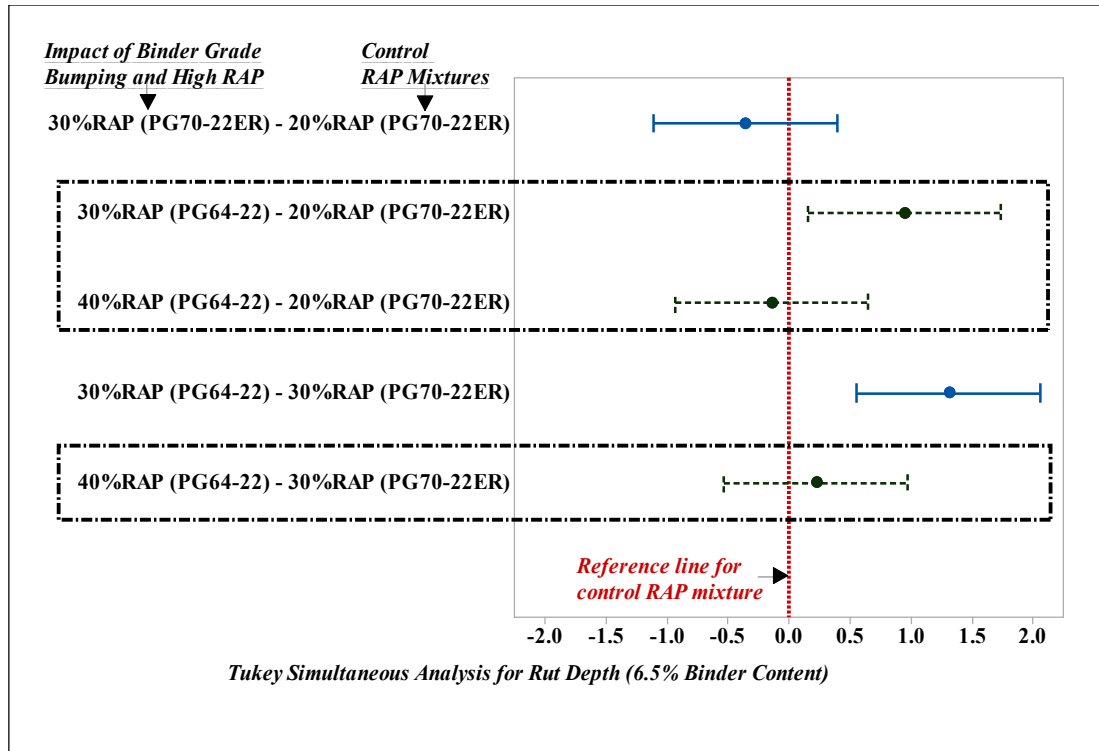


(a)



(b)

Figure 4.12. Tukey's analysis for the impact of binder grade bumping on Rut depth at different binder content (a) 5.5%, (b) 6.0%, and (c) 6.5%



(c)

Figure 4.13 (continued). Tukey's analysis for the impact of binder grade bumping on Rut depth at different binder content (a) 5.5%, (b) 6.0%, and (c) 6.5%

4.6 CONCLUSIONS

The key conclusions drawn from the experimental testing and statistical analysis are as follows:

- Binder content, RAP content, and binder grade significantly affect the fatigue and rutting behavior of RAP mixtures. Among such influential factors, binder content exhibits a higher contribution, representing 58% of the contribution in the case of the CT Index and 76% for varying the rutting characteristics.
- Experimental results indicated that adjusting the mix design attributes, i.e., increasing binder by 0.5% or bumping the binder by one grade, increases the CT Index (cracking resistance) and rut depth (rutting susceptibility). These strategies improve the current allowable limits of RAP content by 10% without affecting short-term (rutting) and long-term (fatigue cracking) performance.
- Few high RAP mix combinations were statistically different from their respective control mix despite using 0.5% higher binder content or one grade lower binder. However, their rut depths were similar to or lower than the critical thresholds designed for the state of Oregon (CT Index ≥ 69 and rut depth ≤ 4.0 for Level 3 mix and CT Index ≥ 41 and rut depth ≤ 3.3

for Level 4 mix). The rut depth thresholds specified in the BMD implementation project (SPR852) appear to be too low, even for mixtures with higher binder contents (e.g., 6.5%) evaluated in the present study. Therefore, it is recommended that the threshold be increased to approximately 5.0 mm.

5.0 STRATEGIC MEASURES FOR HIGH RAP ASPHALT MIXTURES: TEMPERATURE SENSITIVITY, ADDITIVE DOSAGE OPTIMIZATION, AND PERFORMANCE EVALUATION

5.1 INTRODUCTION

The production of high reclaimed asphalt pavement (RAP) mixtures presents several challenges, including concerns related to long-term performance, particularly cracking susceptibility, as well as ageing sensitivity, moisture-induced damage, and increased compaction effort (Kaseer et al. 2019a; Tarsi et al. 2020). These issues are primarily attributed to the presence of oxidized and stiff RAP binder. Extensive efforts have been undertaken to identify strategic measures aimed at improving the condition of the RAP binder, with the goal of increasing the allowable RAP content (Sukhija and Coleri 2025b). Such advancements contribute to the broader goals of sustainability and circular economy practices in pavement engineering.

Several strategies have been proposed to enhance the performance and constructability of high RAP mixtures. These include the use of alternative materials such as modified binders, waste materials, and fibers, incorporation of rejuvenators, application of warm mix asphalt (WMA) additives, increasing binder content, and adjusting binder grade (commonly referred to as binder grade bumping) (Arshadi et al. 2024; Coleri et al. 2018a; Tassiri et al. 2022; Xie et al. 2017; Ziari et al. 2020a). Among these, some studies have demonstrated that modifying mix design parameters, such as increasing binder content or using a softer binder grade, can facilitate higher RAP usage (Sukhija and Coleri 2025a; Willis et al. 2012). This has been described in the previous chapter as well (Chapter 4.0). However, the majority of existing literature emphasizes the effectiveness of rejuvenators and WMA technologies (Albayati et al. 2023; Behnood 2019; Hettiarachchi et al. 2019; Kaseer et al. 2019b; Prasad et al. 2023; Yousefi et al. 2025).

Rejuvenators function by restoring the properties of the aged, oxidized RAP binder and modifying its chemical characteristics, thereby enabling its effective reuse in asphalt mixtures. On the other hand, WMA technologies reduce the production temperatures of asphalt mixtures, thereby reducing the exposure of the already oxidized RAP binder to elevated temperatures and minimizing further stiffening. Both strategic measures (use of rejuvenators and WMA technologies) have been widely adopted in the production of asphalt mixtures containing high RAP content (Albayati et al. 2023; Behnood 2019; Hettiarachchi et al. 2019; Kaseer et al. 2019b; Prasad et al. 2023; Yousefi et al. 2025).

While these measures have demonstrated satisfactory performance in many cases, some studies have also reported inferior outcomes, especially in terms of rutting, highlighting the need for careful evaluation and optimization (Basant et al. 2025; Sabouri et al. 2016; Yousefi et al. 2021; Zhang and Bahia 2021). A key concern is associated with the evaluation of the appropriate additive dosage required to achieve satisfactory performance (Kaseer et al. n.d.; Prasad et al. 2025). According to a past set of studies (Darshan and Kataware 2025; Rodezno et al. 2021; Sukhija et al. 2025), using manufacturer-recommended dosages may serve as a starting point;

however, although this approach is convenient, it requires further validation and is often overlooked in practice. Improper dosage selection can adversely impact the long-term durability of asphalt mixtures (Limón-Covarrubias et al. 2023; Prasad et al. 2025). Along with the additive dosages, appropriate determination of WMA production temperature (both mixing and compaction) is crucial, as it directly influences the coating of asphalt binder over the aggregates and mix compaction (Saboo et al. 2023; Sukhija et al. 2021b).

Various approaches have been used to determine the correct dosage of these additives, including evaluations based on performance metrics (Jain and Chandrappa 2023; Kumar et al. 2024a; Sánchez et al. 2023), and volumetric properties (Kumar et al. 2024a; Sukhija et al. 2023a). These methods aim to ensure that modified mixtures offer performance comparable to or better than control mixtures or those produced with current RAP limits. Recent literature suggested the adoption of workability-based assessments as a practical and effective way of characterizing rejuvenator and WMA mixtures, as these additives influence the workability (Ali et al. 2014; Sukhija et al. 2021b; Tang et al. 2021, 2022; Yin et al. 2022). On the other hand, it is recommended to determine the mixing and compaction temperature following the conventional viscosity-based Equi-viscous approach using a Rotational Viscometer (ASTM 2016). In this method, the mixing and compaction temperatures are determined at binder viscosities of 0.17 Pa·s and 0.28 Pa·s, respectively, ensuring adequate coating and workability. However, this method may not be fully applicable to certain warm mix asphalt (WMA) additives, particularly chemical-based additives, which do not primarily function by reducing binder viscosity (Abed et al. 2019). Rather, their function is to reduce the surface tension of the asphalt binder in order to facilitate binder coating and compaction at reduced production temperatures. Similar to the evaluation of dosages, previous literature recommended identifying the appropriate production temperature of WMA mixtures based on workability characteristics (Abed et al. 2019; Wang et al. 2013). Although various devices and methods exist to assess workability, their primary purpose is to reflect the ease of mixing and compaction of asphalt mixtures. It has been reviewed that if the mixing and compaction are appropriate, the resulting mixture is likely to demonstrate satisfactory performance (Abed et al. 2019). As per a couple of previous studies, evaluation of WMA production temperature through the workability approach ensures appropriate binder coating, desirable compaction, and overall performance similar to that of conventional hot mix asphalt (HMA) (Wagh et al. 2025; Wang et al. 2013). Accordingly, the present study adopts this methodology to evaluate temperature sensitivity and to optimize the dosage of rejuvenators and WMA additives for the production of high RAP asphalt mixtures.

In Oregon, for the roadway network managed by ODOT, the current allowable RAP content is 30% for Level 3 and 20% for Level 4 pavements (Sukhija and Coleri 2025a). There is significant interest in advancing research efforts to enable the use of 10% higher RAP content beyond these limits. To support this goal, various strategic measures were implemented in this study, and the associated challenges were addressed through a detailed evaluation of workability characteristics followed by the performance evaluation. Statistical analysis was also performed wherever necessary to support the attributions. A comprehensive overview of the research scope is presented in Table 5.1 and the primary objectives are described in the next section.

Table 5.1. Details of the current allowable RAP limit, expectations, strategic measures, challenges and evaluation method

Mix Design Level	Asphalt Binder Grade	Allowable RAP Content	Research Attempts	Strategic Measures	Challenges	Evaluation Approach
Level 3	PG64-22	30% RAP	40% RAP	Use of Rejuvenators and Warm Mix Additives	Additive Dosages and WMA Production Temperatures	Workability Characteristics and Performance (Cracking and Rutting)
Level 4	PG70-22ER	20% RAP	30% RAP	Use of Rejuvenators and Warm Mix Additives	Additive Dosages and WMA Production Temperatures	Workability Characteristics and Performance (Cracking and Rutting)

Note: Effect of WMA production temperatures was determined for 30% RAP mixtures using PG64-22 binder, but the same has been validated for mixtures comprising PG70-22ER.

5.2 OBJECTIVES AND SCOPE

The primary objectives of this part of the research study are to:

1. Predict the optimal production temperature for warm mix asphalt (WMA) and evaluate the effect of reduced production temperature on the workability and performance of asphalt mixtures.
2. Optimize the dosage of rejuvenators and WMA additives (at reduced production temperatures) for producing high RAP mixtures in both Level 3 and Level 4 asphalt mixtures.
3. Evaluate the performance metrics in terms of cracking and rutting resistance of the high RAP mixtures prepared using rejuvenators and WMA technologies at their optimum dosage and appropriate production temperatures.
4. Assess the comparative effectiveness of different strategic measures (WMA additives vs rejuvenators) in enabling a 10% increase in RAP content for Level 3 and Level 4 asphalt mixtures.

The initial outcome of this study is expected to serve as a foundational step toward evaluating the performance of asphalt mixtures incorporating high RAP content by identifying the optimum additive dosages and appropriate WMA production temperatures, both of which are critical from a performance perspective. Furthermore, the high RAP mixtures (40% for Level 3 mixtures and 30% for Level 4 mixtures) were prepared at the optimum additive dosages and reduced

production temperatures for WMA, and their potential was evaluated in terms of rutting and fatigue cracking resistance. Using the performance test results for the current 30% RAP mixes (current limit in Oregon for Level 3) and 20% RAP mixes (current limit in Oregon for Level 4) as the reference (control samples), the possibility of achieving an acceptable level of long-term performance with high RAP asphalt mixtures by using rejuvenators and WMA was determined. Statistical analysis was carried out throughout the study to identify and confirm whether the results are statistically significant.

5.3 MATERIALS USED

Two performance graded asphalt binders, PG64-22 and PG70-22ER, were incorporated in this research work, depending on the mix design levels in Oregon, i.e., Level 3 and Level 4, respectively (ODOT 2019, 2021). A ½ inch (12.5 mm) nominal maximum aggregate size (NMAS) was used to produce Level 3 and Level 4 asphalt mixtures. The binder properties and adopted aggregate gradation are given in Chapter 3.0 (Section 3.1 and 3.3). In this work, RAP material was also incorporated to reduce the utilization of virgin asphalt binder and virgin aggregates to support sustainability. The RAP binder content was determined to be 4.97%, with a true high-temperature failure point of 93.7 °C. This is the actual temperature at which the binder fails to meet a specific performance criterion i.e., $G^*/\sin\delta$ drops below 1 kPa. The detailed information on the significance of this temperature is described in Section 3.2.2.

5.3.1 Introduction of Strategic Techniques

Due to the potential benefits highlighted in previous research studies (Foroutan et al. 2019; Limón-Covarrubias et al. 2023; Song et al. 2018b; Yang et al. 2022b), strategic measures, including the use of rejuvenators and WMA additives, were incorporated with the aim of using a 10 % higher RAP content beyond the current allowable limit in Oregon (30% RAP for Level 3 and 20% RAP for Level 4). Although the objective is to increase the allowable limit to 40% in Level 3 and 30

% in Level 4 category pavements, identifying the optimum dosage of rejuvenators and WMA additives remains challenging. Although the additive manufacturers suggested the dosage rates, the applicability of the suggested rate for the asphalt mixtures from different states is questionable due to the differences in the intrinsic properties of aggregate and asphalt binder. Overall, the goal of the research work is to enhance RAP usage without compromising workability and performance characteristics.

Two different rejuvenators (REJ1 and REJ2) and two WMA additives (WMA1 and WMA2) were incorporated with the aim of producing workable and durable high RAP mixtures. The details on these rejuvenators and WMA technologies, along with the discussion on the preparation of modified binders, can be found in Section 3.1.3 of Chapter 3.0. These details are not stated here to avoid redundancy in all the chapters.

Notably, the manufacturer-recommended dosages for increasing RAP content were 0.5% by weight of total binder for WMA additives and 1.5% for rejuvenators. However, the research team attempts to cross-verify if the recommended dosages are optimal to produce high RAP mixtures or whether lower dosages could suffice the needs. The evaluated dosages of both the rejuvenators and WMA technologies are listed in Table 5.2.

Table 5.2. Chemical composition and evaluated dosages of the selected rejuvenators and WMA additives

Characteristics	REJ1	REJ2	WMA1	WMA2
Chemical composition	Tall oil fatty acid derivative	Corn oil, fatty acid residues, and methyl ester	Modified tall oil, fatty acid, and alkyl acid phosphate	Esters, phosphoric acid, and non-hazardous ingredients
Additive dosage by weight of total asphalt binder	1% and 1.5%	1% and 1.5%	0.25% and 0.5%	0.25% and 0.5%

Note: Dosages should be adjusted depending on the RAP content and total binder content as per Equation 3.1 (Chapter 3.0).

5.4 WORKABILITY CHARACTERISTICS

5.4.1 Production of Asphalt Mixtures

In order to prepare asphalt mixtures for dosage optimization and production temperature evaluation, the preheated virgin materials (asphalt binder and aggregate), and RAP material were mixed at their required quantities using a portable bucket mixture. The pre-heating was executed for two hours at the temperatures shown in Table 5.3. In all the mixtures, RAP was heated to 121°C for two hours before mixing. After the mixing process, the loose asphalt mixtures were exposed to further conditioning for two hours at their respective compaction temperature (shown in Table 5.3) followed by their compaction using the Superpave gyratory compactor. Notably, the manufacturer recommends a 25 °C reduction in production temperature for WMA mixtures. This study attempts to validate that recommendation by evaluating the workability characteristics of WMA at various production temperatures, as presented in Table 5.3. For workability evaluation, all asphalt mixtures were prepared using a total binder content of 6.0% and compacted to produce specimens 62 mm thick and 150 mm in diameter, with a target air void content of $7 \pm 1\%$ to minimize bias.

Table 5.3. Pre-heating and compaction temperatures for different asphalt mixtures

Test Samples	Temperature Condition	Mix Material	Level 3 Pre-heating Temperatures	Level 3 Compaction Temperatures	Level 4 Pre-heating Temperatures	Level 4 Compaction Temperatures
Control Reference Samples	HMA	Asphalt Binder	153-160°C	140-145°C	165-171°C	152-157°C
Control Reference Samples	HMA	Aggregates	163-170°C	140-145°C	175-181°C	152-157°C
Rejuvenator Samples	HMA	Asphalt Binder	153-160°C	140-145°C	165-171°C	152-157°C
Rejuvenator Samples	HMA	Aggregates	163-170°C	140-145°C	175-181°C	152-157°C
WMA Samples	HMA	Asphalt Binder	153-160°C	140-145°C	165-171°C	152-157°C
WMA Samples	HMA	Aggregates	163-170°C	140-145°C	175-181°C	152-157°C
WMA Samples	HMA-25°C	Asphalt Binder	128-135°C	115-120°C	140-146°C	127-132°C
WMA Samples	HMA-25°C	Aggregates	138-145°C	115-120°C	150-156°C	127-132°C
WMA Samples	HMA-40°C	Asphalt Binder	113-120°C	100-105°C	125-131°C	112-117°C
WMA Samples	HMA-40°C	Aggregates	123-130°C	100-105°C	135-141°C	112-117°C

Note: Pre-heating temperature represents the mixing temperature of the mix. All asphalt mixtures were prepared using a total binder content of 6.0% for workability evaluation.

5.4.2 Experimental Work

The scope of this section is to evaluate the workability characteristics of asphalt mixtures produced using various strategic techniques, incorporating factors such as different dosages of additives (both WMA additives and rejuvenators) and variations in production temperatures specific to WMA technologies.

Workability values offer insight into the ease of compaction, and in this study, they were evaluated based on the number of gyrations required to compact each asphalt mixture. This behaviour can be simulated in the laboratory using an advanced Superpave gyratory compactor, which measures the change in density and height of the asphalt mixture specimen corresponding to each gyration. A schematic representation of this variation is illustrated in Figure 5.1, indicating the increase in density and decrease in height with the number of gyrations. In this study, the workability was evaluated in terms of Workability Energy Index (WEI), which is mathematically written as Equation 5.1. A higher WEI value indicates greater workability,

implying that less compaction energy (gyrations) is needed to achieve the target density. The detailed methodology of the workability test can be found in Section 3.4.1 of Chapter 3.0.

$$WEI = \frac{\left(\frac{\pi d^2}{4}\right) P (h_{n=0} - h_{92})}{N_{92} - N_{n=0}}$$

(Equation 5.1)

In Equation 5.1, P represents the pressure used for compaction in kPa, d indicates the diameter in mm, and $h_{n=0}$ and $h_{n=92}$ are the height of the specimen at gyrations 0 ($N_{n=0}$) and 92% G_{mm} ($N_{n=92}$), respectively.

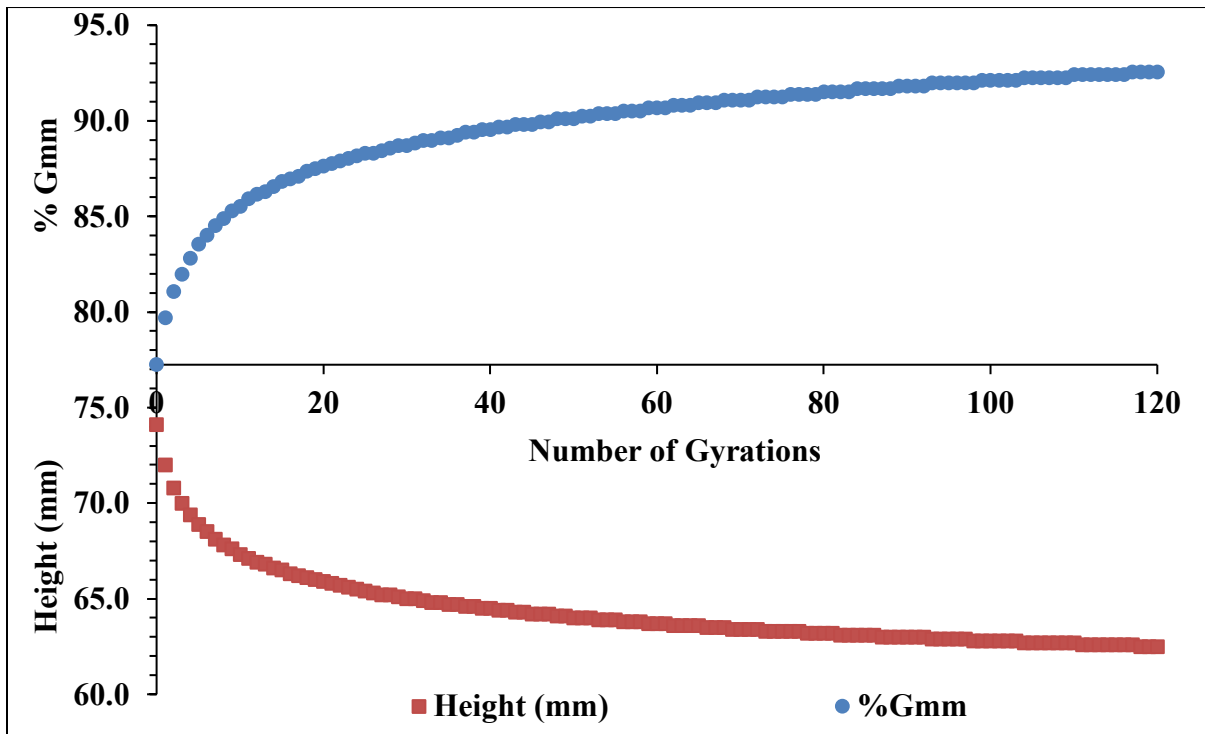


Figure 5.1. Variation in sample height and density with compactive effort (gyrations)

5.5 RESULTS AND DISCUSSION ON THE WORKABILITY CHARACTERISTICS

5.5.1 Selection of Optimum WMA Production Temperature

Figure 5.2 illustrates the influence of reduced production temperatures (mixing and compaction), WMA additive type, and dosage on the workability characteristics of Level 3 asphalt mixtures (30% RAP using PG64-22 binder) in terms of WEI. As observed, the trends are not consistent and largely depend on the interaction among these variables. Each additive at a given dosage level exhibits varying workability performance, and this variability does not follow a uniform pattern across different reduced temperature scenarios. For example, the WMA2-modified

mixture exhibited relatively higher workability at a 0.25% additive dosage compared to 0.5% when produced at conventional HMA temperatures. However, under a 25°C reduction in production temperature, the trend reversed, and the mixture with 0.5% WMA2 dosage demonstrated improved workability compared to the 0.25% dosage. Similar variations were observed for other mix combinations and thus not described here for brevity.

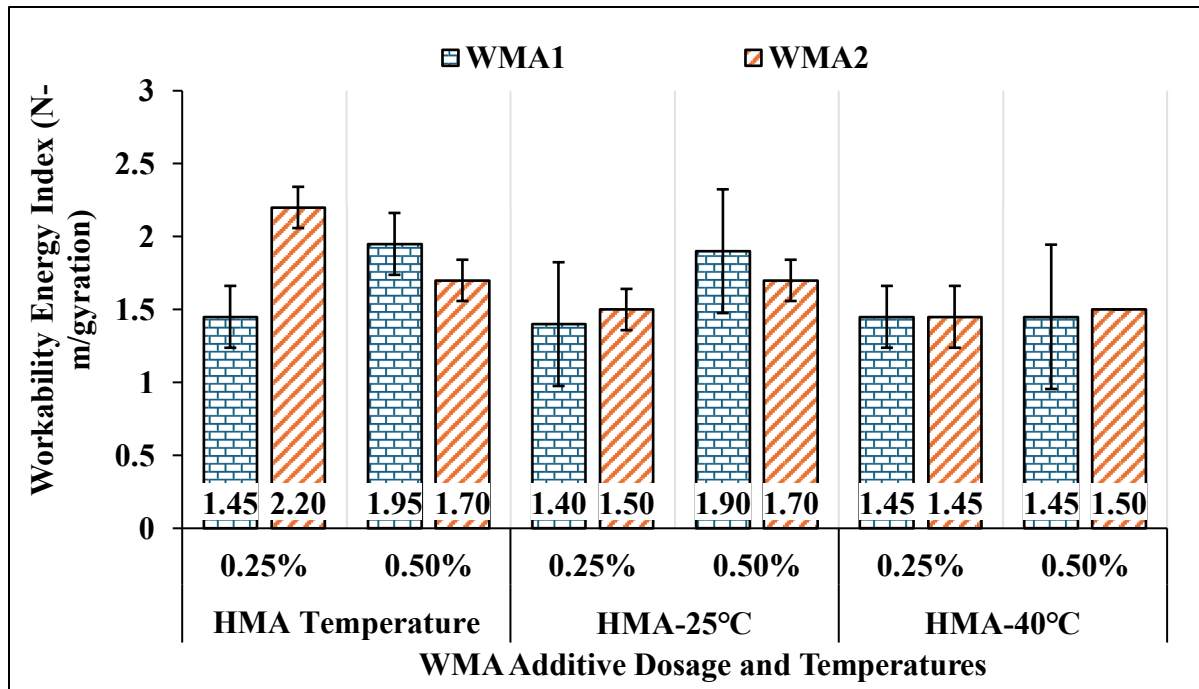


Figure 5.2. WEI of asphalt mixtures prepared with 30% RAP and PG64-22 binder (6% binder content) at different WMA additive dosages and production temperatures

Given the frequent overlap of error bars, particularly among mixtures with similar temperature reductions or additive dosages, statistical analysis was deemed necessary to determine whether the observed variations in WEI values are statistically significant. Based on the two-way analysis of variance (ANOVA) conducted at a 95% confidence level, no statistically significant effect of either WMA dosage or temperature reduction on WEI values was found. This outcome holds true for both WMA additives, as presented in Table 5.4.

Table 5.4. Statistical analysis (two-way ANOVA) to check the effect of WMA additives and production temperature on the basis of WEI values

Source of Variation	Selected Criteria	WMA1 F-Value	WMA1 P-Value	WMA2 F-Value	WMA2 P-Value
WMA Production Temperature	HMA, HMA-25°C, HMA-40°C	0.84	0.54	1.79	0.36
Additive Dosage	0.25%, 0.5% by weight of total binder	4.00	0.18	0.15	0.73

Note: P-value > 0.05 indicates no statistically significant difference in the mean values.

In light of these findings, and since no significant dosage-related differences were observed at specific temperature levels for a particular RAP content (30% RAP here), the research team

conducted a univariate analysis focused solely on the effect of temperature reduction, irrespective of the WMA additive dosage, for each additive. This was executed due to the dependency of the mix performance and durability on the production temperature of the asphalt mixture, particularly the coating of the asphalt binder and compatibility of the mix.

Figure 5.3 illustrates the WEI values of WMA mixtures across different reduced temperature scenarios for WMA1 and WMA2, respectively. Traditionally, WMA additives have been used in various U.S. states primarily as compaction aids, allowing mixtures to be produced at conventional hot mix asphalt (HMA) temperatures with WMA additives to enhance the compaction process and density. However, advancements in WMA technology have demonstrated that these additives can also facilitate mixture production at significantly reduced temperatures without compromising workability, mechanical performance, or long-term durability. In this study, three different temperature scenarios, i.e., HMA temperature (no reduction), 25°C reduction from the HMA, and 40°C reduction from the HMA, were evaluated to determine the optimal production condition for maintaining adequate workability. ***The current industry practice of producing WMA mixtures at HMA temperatures for compaction enhancement was used as the reference condition for comparison with the reduced-temperature scenarios.***

In Figure 5.3, the average WEI values for WMA1 mixtures decreased from 1.70 N-m/gyration at HMA temperature to 1.65 N-m/gyration and 1.45 N-m/gyration when produced at 25°C and 40°C lower temperatures, respectively. This corresponds to a reduction of approximately 3% and 15% compared to the control condition (HMA temperature). A similar trend was observed for WMA2 mixtures, where the highest WEI value was recorded at HMA temperature (1.95 N-m/gyration), followed by mixtures produced at HMA-25°C (1.60 N-m/gyration, ~18% reduction) and HMA-40°C (1.47 N-m/gyration, ~25% reduction). These results indicate a consistent decrease in workability with greater reductions in production temperature for both WMA additives.

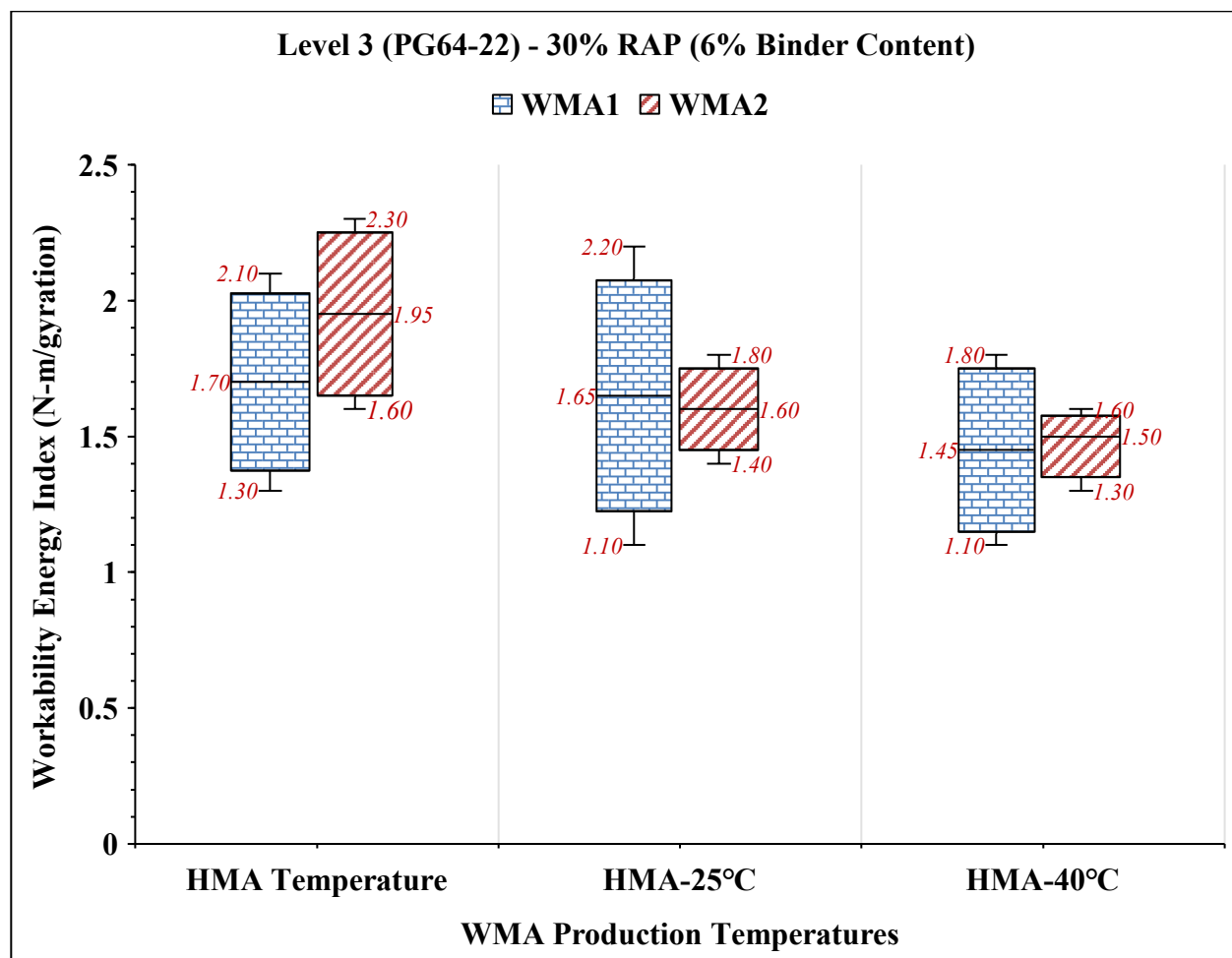


Figure 5.3. Average WEI values of Level 3 asphalt mixture (PG64-22) with 30% RAP and 6% binder content at different WMA production temperatures

To determine the optimal production temperature for WMA mixtures, Tukey's pairwise statistical analysis was conducted at a 95% confidence level. As presented in Table 5.5, reducing the production temperature of WMA1 mixtures by either 25°C or 40°C did not result in statistically significant differences in WEI values compared to the current practice of producing WMA at conventional HMA temperatures. This indicates that WMA1 mixtures can maintain adequate workability even when the production temperature is lowered by up to 40°C. However, although WMA1 exhibits adequate WEI at a 40°C reduced production temperature, visual observations revealed insufficient coating of the asphalt binder over the aggregates, which was not observed at the 25°C reduction level. While the application of WMA1 typically reduces the surface tension and improves the coating at moderately reduced temperatures, a 40°C reduction appears to compromise binder distribution, suggesting that this temperature is not appropriate for effective mix production using WMA1. This observation aligns with the previous studies (Sukhija et al. 2021b; Sukhija and Saboo 2020; Yu et al. 2022), which indicate that production temperature plays a crucial role in achieving proper binder coating, compaction, and long-term performance. In the WMA1 mix, it is expected that such a significant temperature reduction (-40°C) may lead to premature failures, including adhesive failure, and inferior mechanical

performance due to inadequate binder coating. Based on these findings, a 25°C temperature reduction was selected as the optimal condition for further production of WMA1 mixture.

Interestingly, WMA2 mixtures showed a statistically significant reduction in WEI when the temperature was reduced by 40°C relative to the HMA temperature condition (as shown in bold and italic in Table 5.5, p-value < 0.05). However, this difference was not statistically significant when compared to the mix produced at HMA-25°C, as indicated by a p-value > 0.05. In addition, the WEI value corresponding to the WMA2 mix produced at HMA-25°C was statistically similar to the HMA temperature condition, as p-value > 0.05, thereby supporting the acceptance of the null hypothesis. Overall, for both additives, irrespective of the dosage, the production temperature can be lowered by 25°C without affecting the workability characteristics. A 25°C temperature reduction also aligns with the manufacturer's recommendations to achieve the dual benefits of WMA technology, i.e., lowering the production temperature while preserving construction workability.

Table 5.5. Pairwise comparison between different production temperatures of WMA mixtures based on WEI values

Difference of Levels	WMA1 95% Confidence Interval	WMA1 P-Value	WMA2 95% Confidence Interval	WMA2 P-Value
HMA Temperature - HMA-25°C	(-0.783, 0.683)	0.980	(-0.775, 0.075)	0.107
HMA Temperature - HMA-40°C	(-0.983, 0.483)	0.623	(-0.900, -0.050)	<i>0.030</i>
HMA-40°C - HMA-25°C	(-0.933, 0.533)	0.734	(-0.550, 0.300)	0.700

5.5.2 Selection of Optimum WMA Additives Dosage

Once the production temperature is established, it is recommended to select a WMA additive dosage that facilitates the incorporation of higher RAP content in asphalt mixtures. Literature highlights WMA technology as an effective strategy to enhance RAP utilization (Alizadeh et al. 2025; Sukhija and Saboo 2020). The reason behind the RAP increment is attributed to the lower production temperatures of WMA, which reduces the extent of secondary ageing of the RAP binder compared to the conventional mixing process (HMA) process (Wang et al. 2022). As a result, the performance of the mixture remains within acceptable limits despite the higher RAP content. In addition, the use of WMA improves the aggregate to binder adhesion, resulting in improved bond between the RAP, virgin binder, and aggregates.

According to the current Oregon standard specifications, 30% RAP is allowed for Level 3 mixes, where the binder grade is PG64-22, while 20% RAP is typically used for Level 4 mix design levels with PG70-22ER. The research team investigated the potential to increase RAP usage by incorporating WMA additives at varying dosages, targeting 40% for Level 3 and 30% for Level 4. This indicates 10% higher RAP content than the current approach, without affecting the workability characteristics of the mixtures. The primary aim was to determine the optimum dosage at which the WEI values of higher RAP mixtures are either comparable or better than the

mixtures prepared with current allowable RAP limits (30% RAP for Level 3 and 20% for Level 4). Figure 5.4 presents the WEI values for both Level 3 and Level 4 mixtures, along with the reference WEI values corresponding to the current allowable RAP content. Even though the RAP content is lower in Level 4 mixtures, the presence of a relatively stiffer binder (PG70-22ER) results in lower WEI values and greater compactive effort required to achieve effective compaction. This observation is consistent with a previous study (Ali et al. 2014), which suggested that stiffer binders contribute to reduced workability due to the increased stiffness of the overall mixture.

As can be seen in Figure 5.4, the WEI value increases with the dosage of WMA additives, although the rate of increase varies depending on the type of additive and binder grade. In the Level 3 mix, the WEI value with 0.5% WMA1 is about 2.5 times higher than that observed with 0.25% WMA1, reaching a value of 2.20 N-m/gyration, comparable to the WEI of the reference mixture with 30% RAP (2.26 N-m/gyration). A similar trend is observed for WMA2, where 0.5% dosage yields a WEI comparable to the control, but the increase relative to the 0.25% dosage is approximately 1.8 times. On the other hand, Level 4 mixtures exhibited smaller differences in WEI across additive dosages, highlighting the interaction effect between the stiffer binder (PG70-22ER) and the WMA additives. The WEI values with the use of 0.5% WMA1 (1.23 N-m/gyration) and 0.5% WMA2 (1.25 N-m/gyration) were found to be comparable to the reference 20% RAP mix (WEI = 1.30 N-m/gyration). These WEI values are also 1.1-2 times higher than the corresponding 0.25% dosage mixes, depending on the additive type.

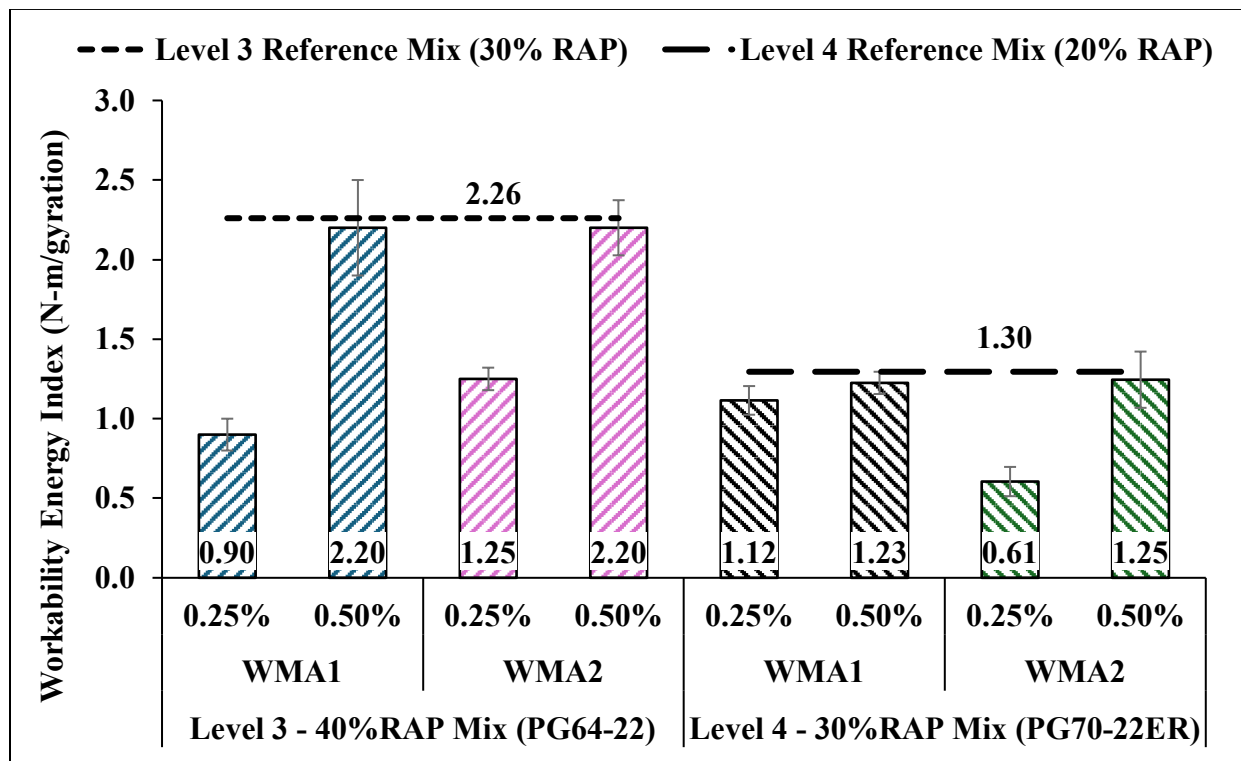


Figure 5.4. WEI values of high RAP mixtures at different WMA additive dosages for both Level 3 and Level 4 mix

Such comparable WEI values observed between WMA-modified high-RAP mixtures and conventional RAP mixtures suggest that WMA technology enables the use of increased RAP content without compromising workability. In conventional RAP mixtures, oxidized RAP binder is further subjected to high heating temperatures, leading to additional stiffening due to secondary ageing. Eventually, the use of WMA lowers the production temperature (by around 25°C in the present study), thereby limiting further oxidative hardening of the RAP binder. This reduction in secondary ageing helps maintain the mixture's workability even with higher RAP contents. Additionally, their use improves the aggregate to binder adhesion, resulting in improved interfacial bond within the asphalt mixture (Cui et al. 2024; Wagh et al. 2023). Nevertheless, performance verification is essential to confirm the potential of WMA for improving RAP utilization.

5.5.3 Validation of Optimum WMA Temperature and Additives Dosage

Since the effect of production temperature was initially evaluated for the mix produced using PG64-22 binder, the same dosage was subsequently used for PG70-22ER asphalt mixtures without further optimization. Therefore, it is viable to validate if the same dosage remains workable under different temperature conditions, particularly when the production temperature is reduced by 40°C or maintained at conventional HMA levels.

Figure 5.5 shows the validation of dosage and temperature reduction for Level 4 mix, where the binder grade is PG70-22ER, with the reference mix containing 20% RAP and no additive. The results indicate that a 0.5% dosage of either WMA1 or WMA2 is effective in producing mixtures with 30% RAP at a 25°C reduced production temperature. The corresponding WEI values are comparable to those of the reference 20% RAP mix at the same reduced temperature, and notably higher than those observed for the 20% RAP mix at conventional HMA temperatures. This suggests that these additives not only facilitate higher RAP incorporation but can also serve as compaction aids when needed. On the other hand, reducing the temperature by 40°C relative to HMA temperature leads to a reduction in WEI values, accounting for around 19% and 45% with the use of WMA1 and WMA2, respectively, indicating inadequate workability under such conditions. Besides, a 0.5% dosage of WMA additives combined with a 25°C temperature reduction is the optimal solution for producing workable high RAP mixtures, i.e., a 10% increase in RAP relative to the current practice in Oregon.

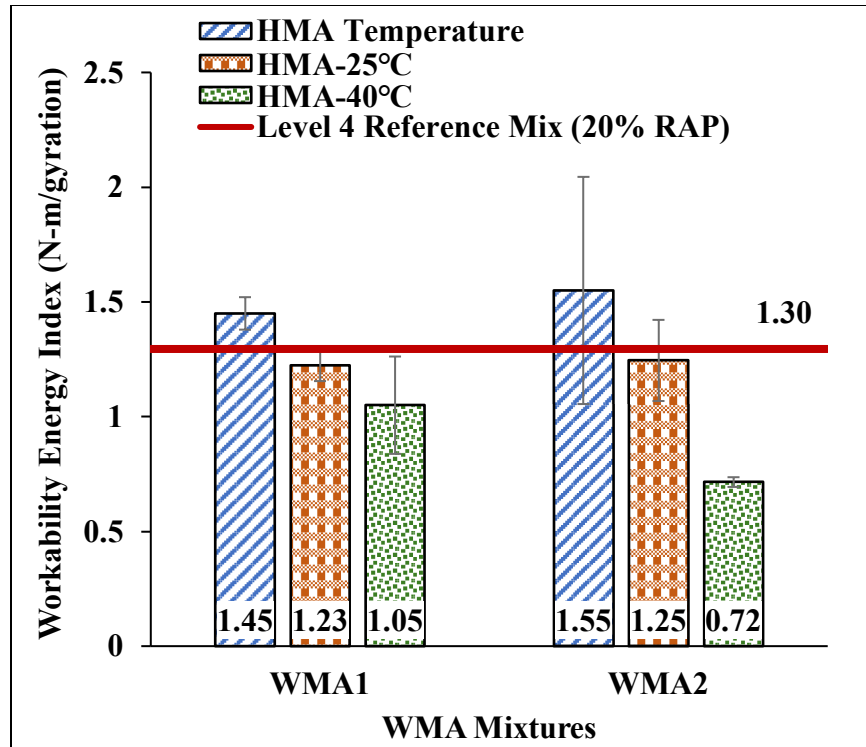


Figure 5.5. Validation of optimum WMA dosages and production temperatures for Level 4 asphalt mixtures (PG70-22ER binder)

5.5.4 Selection of Optimum Rejuvenators Dosage

The use of rejuvenators is another widely adopted strategic technique to increase the allowable RAP content in asphalt mixtures. Rejuvenators intend to rejuvenate the stiff and oxidized RAP binder by altering its chemical characteristics, thereby enabling it to behave more like a virgin binder. In this research work, the purpose of adding a rejuvenator is to identify how its addition affects the workability characteristics of the mix containing 10% higher RAP content relative to the current approach of incorporating 30% RAP in Level 3 and 20% RAP in Level 4 mixes. Following a similar methodology as in previous sections, a couple of rejuvenator dosages (i.e., 1% and 1.5% by weight of binder) were chosen to check if the same workability as that of the reference mix could be achieved with the use of rejuvenators, even with high RAP content.

Figure 5.6 presents the WEI values of Level 3 and Level 4 high RAP mixtures incorporating both the rejuvenators (REJ1 and REJ2) at both 1% and 1.5% dosages. The figures also show the reference WEI values corresponding to the mix produced with 30% RAP (Level 3) and 20% RAP (Level 4) for comparison. Irrespective of the rejuvenator dosage, the impact of increased RAP content on workability in Level 3 mixtures with 40% RAP appears minimal, as evidenced by the relatively lower WEI values observed in Level 4 mixtures containing 30% RAP. This is likely due to the use of a relatively softer binder grade (PG64-22) in the Level 3 mix, indicating that the binder grade plays a more dominant role in governing workability characteristics in these mixtures.

Apart from this, the application of rejuvenators at a 1.5% dosage level increases the WEI values, even more than average WEI values obtained for reference RAP mixtures in their respective mix design levels. Specifically, around 20% to 33% and 42% to 50% higher WEI values were observed in Level 3 and Level 4 mix, respectively. Nevertheless, the mixtures produced with a lower dosage of 1% (for both REJ1 and REJ2) did not yield desirable workability, primarily due to the inappropriate dosage to effectively accommodate 10% higher RAP content than the current allowable limits for both mix levels. These results show the critical importance of selecting an appropriate rejuvenator dosage to enhance the workability characteristics of high-RAP mixtures.

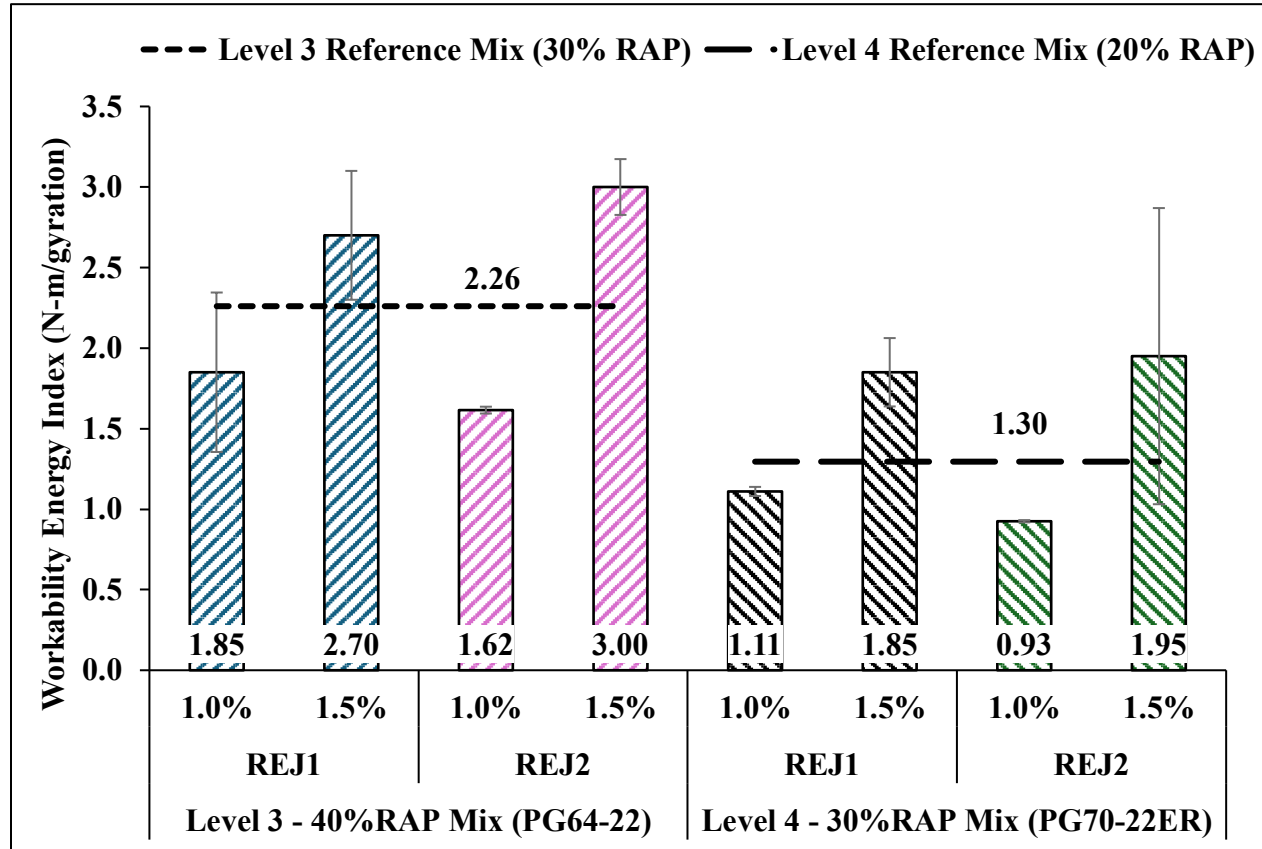


Figure 5.6. WEI values at different rejuvenator dosages for both Level 3 and Level 4 mix

Such improvement with rejuvenators is primarily due to alteration in the properties of RAP binder, an aspect that is beyond the scope of the present research work. In actual practice, oil-based rejuvenators, such as those used in this study, soften the aged RAP binder and lead to a reduction in the overall viscosity of the total binder, facilitating easier compaction. These findings are in line with previous studies (Foroutan et al. 2019; Limón-Covarrubias et al. 2023), highlighting the benefits of using rejuvenators for increasing the RAP content without compromising, and in some cases enhancing, mixture performance. However, since this section deals with the workability properties of the RAP mixtures, it is advisable to investigate the performance metrics to further reinforce these conclusions. The comprehensive performance testing plan and its inferences are discussed in Section 5.6.

5.5.5 Comparison between Optimum WMA Additives and Rejuvenators Dosages

Previous sections described the process for determining the appropriate WMA production temperature and optimizing the dosage of WMA additive and rejuvenator to increase the allowable RAP content limit based on the workability characteristics. Although both the strategic measures were found to enhance the use of 10% higher RAP in the asphalt mixture than the current allowable limit in Oregon, it is critical to understand which strategic technique is more effective and feasible from a workability standpoint. Notably, 25°C temperature reduction for WMA mixtures and the identified optimum dosages for WMA additives (0.5% by weight of the total binder) and rejuvenators (1.5% by weight of the total binder) were not against the manufacturer's recommendations to produce high RAP mixtures.

Figure 5.7 shows the complete dataset, including both the WMA additives and rejuvenators at their optimum dosages. Across the combinations, using WMA as a potential measure can aid in achieving the workability of the same as the reference mixtures (30% RAP in Level 3 and 20% RAP in Level 4), whereas the application of rejuvenators not only meets but exceeds the workability of the reference mixtures, as indicated by higher WEI values. These findings indicate that rejuvenators are consistently more effective than WMA additives in improving the workability of high RAP mixtures (40% RAP in Level 3 and 30% RAP in Level 4). This trend is further shown through the box plot in Figure 5.8, demonstrating WEI values corresponding to all the additives at their optimum dosages, regardless of the mix design levels. The variation in the results is due to the distinct working mechanisms of these strategic techniques, where WMA lowers the production temperatures and rejuvenators work on chemically restoring the aged RAP binder at conventional mixing and compaction temperatures.

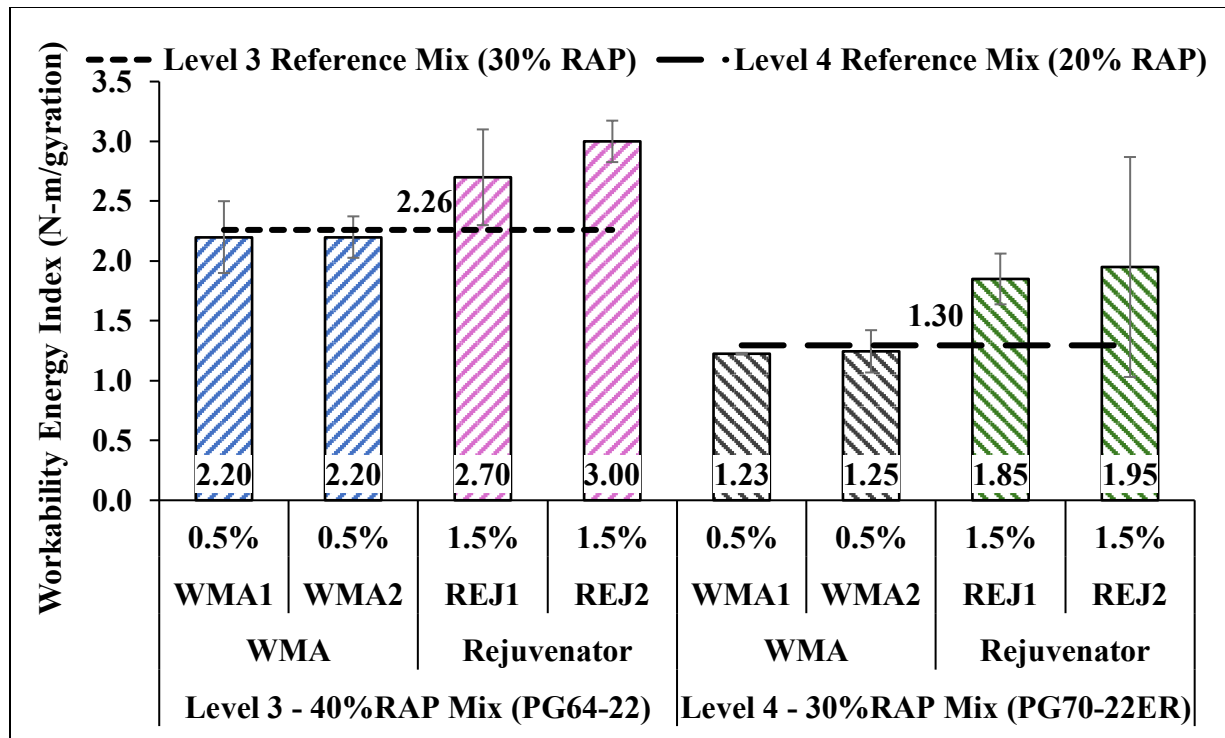


Figure 5.7. WEI values of WMA and rejuvenators mixtures at optimum dosages

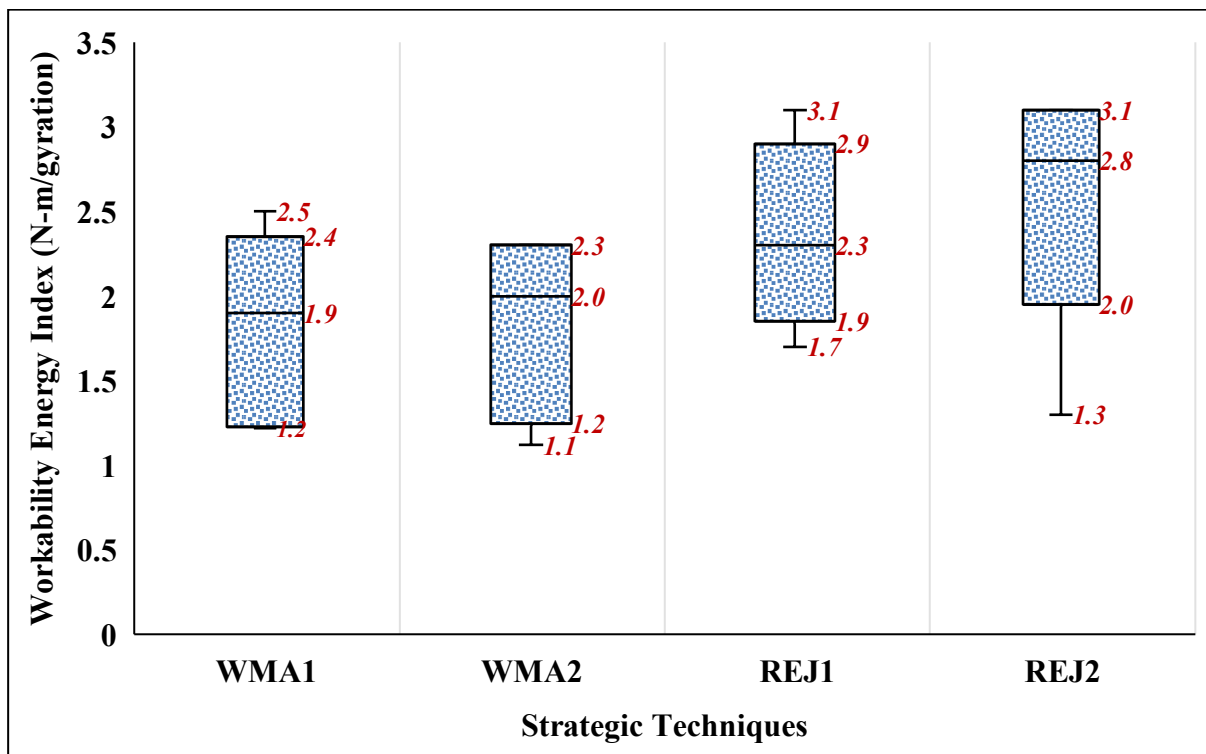


Figure 5.8. Box plot for WEI values of WMA and rejuvenators, irrespective of the mix design levels

Based on the statistical analysis presented in Table 5.6 (Tukey’s pairwise analysis), all the additives, irrespective of mix design level, perform statistically similarly in terms of WEI, with a couple of exceptions in the Level 3 mix. In particular, REJ2 was found to exhibit statistically different WEI values (remarkably higher) compared to both the WMA additives (WMA1 and WMA2). These statistical outcomes are consistent with the theoretical interpretations discussed earlier, highlighting the enhanced effect of rejuvenators. Nevertheless, all additive-modified mixtures were found to be statistically similar to their respective reference mixtures (p-value > 0.05).

Table 5.6. Pairwise comparison between different additives based on WEI values

Mean Comparison	Level 3 95% Confidence Interval	Level 3 P-value	Level 4 95% Confidence Interval	Level 4 P-value
WMA2 - WMA1	(-0.728, 0.728)	1	(-1.935, 1.975)	1
REJ1 - WMA1	(-0.228, 1.228)	0.203	(-1.330, 2.580)	0.607
REJ2 - WMA1	(0.072, 1.528)	0.032	(-1.230, 2.680)	0.508
REJ1 - WMA2	(-0.228, 1.228)	0.203	(-1.350, 2.560)	0.628
REJ2 - WMA2	(0.072, 1.528)	0.032	(-1.250, 2.660)	0.527
REJ2 - REJ1	(-0.428, 1.028)	0.577	(-1.855, 2.055)	0.996

Although the influence of WMA and rejuvenators was found to be beneficial for enabling 10% higher RAP content, the optimum dosages identified in this study were based solely on workability evaluations. Therefore, further validation through comprehensive performance testing is essential to ensure the durability and mechanical integrity of these modified mixtures at their optimum dosages. The subsequent section shows the influence of rejuvenators and WMA on the performance of high RAP mixtures prepared at the optimum additive dosages.

5.6 PERFORMANCE EVALUATION

As discussed in the previous chapter (Chapter 4.0), increasing the binder content and employing binder grade bumping enhances the cracking resistance but also results in higher rut depths. Nevertheless, both strategies allow for about 10% higher RAP utilization beyond the current allowable limits in Oregon while maintaining a balance between rutting and cracking performance. However, there are alternative approaches that are increasingly gaining attention in the construction industry, which are explored in this chapter. Previous chapters also emphasized that variations in binder content, RAP percentage, and binder grade significantly affect the cracking and rutting behavior of RAP-inclusive mixtures. In this context, the incorporation of additives such as rejuvenators and warm mix asphalt (WMA) technologies is expected to introduce even more complex interactions. Addressing these combined effects is essential to enable higher RAP proportions in the production of durable asphalt mixtures for Oregon’s roadway infrastructure.

Considering these aspects, the Asphalt Materials and Pavements (AMaP) research group at Oregon State University investigated the performance changes of RAP-inclusive asphalt mixtures produced with the incorporation of either rejuvenators or WMA technologies. The adopted experimental plan is shown in Table 5.8. The samples were prepared and tested for determining resistance against rutting and fatigue cracking using HWTT and IDT-CT, respectively. The details of the adopted test methodology are discussed in Section 3.4 (Chapter 3.0). The study was conducted at varying binder contents to determine whether the effectiveness of these additives is influenced by binder content. This assessment also aimed to determine the suitability of these strategic techniques for enhancing RAP utilization (40% for Level 3 and 30% for Level 4), as their performance was compared against control RAP mixtures containing 30% RAP in Level 3 and 20% RAP in Level 4 without any additives.

Based on the above research findings, Table 5.7 presents the complete details on the preparation of asphalt mixtures for the performance evaluation.

Table 5.7. Optimized additive dosages and production temperatures of the asphalt mixtures for performance evaluation

Test Samples	Additive Dosages	Temperature Condition	Mix Material	Level 3 MT	Level 3 CT	Level 4 MT	Level 4 CT
Control Reference Samples	No Additive	HMA	Asphalt Binder	153-160°C	140-145°C	165-171°C	152-157°C
Control Reference Samples	No Additive	HMA	Aggregate	163-170°C	140-145°C	175-181°C	152-157°C
Rejuvenator Samples	1.5% by weight of the total binder	HMA	Asphalt Binder	153-160°C	140-145°C	165-171°C	152-157°C
Rejuvenator Samples	1.5% by weight of the total binder	HMA	Aggregate	163-170°C	140-145°C	175-181°C	152-157°C
WMA Samples	0.5% by weight of the total binder	WMA (HMA-25°C)	Asphalt Binder	128-135°C	115-120°C	140-146°C	127-132°C
WMA Samples	0.5% by weight of the total binder	WMA (HMA-25°C)	Aggregate	138-145°C	115-120°C	150-156°C	127-132°C

Note: In all the mixtures, RAP was heated to 121°C for two hours before mixing. MT and CT represent mixing and compaction temperatures, respectively. Dosages should be adjusted depending on the RAP content and total binder content, as per Equation 3.1 (Chapter 3.0).

The production process for the performance evaluation of the asphalt mixtures is detailed in Section 3.3 of Chapter 3.0. The only difference in the production process of the WMA mixture is the reduced production temperatures and the corresponding short-term ageing (STA)

temperatures. For the STA of WMA mixtures, the ageing temperature was reduced to 116°C, while the STA temperature for HMA mixtures was taken as 135°C as per NCHRP 9-52 (Newcomb et al. 2015). Nevertheless, the long-term ageing (LTA) was carried out in the same way as that of HMA, by subjecting the loose asphalt mixtures to 95°C for 24 hours before the compaction process (Coleri et al. 2020). All the asphalt mixtures were prepared using a Superpave gyratory compactor, ensuring 7 ± 1 air voids in a sample of 62 mm thickness and 150 mm diameter. The samples were prepared at three different binder contents, as shown in Table 5.8.

The complete experimental design aids in quantifying the impact of using rejuvenators and WMA additives in asphalt mixtures. Following the experimental test results, statistical analysis and ranking were carried out to identify the most effective rejuvenators and WMA additives.

Table 5.8. Experimental plan for performance evaluation

Mix Design Level (Binder Grade)	Property	Test Method	RAP	Binder Content	Test Temperature (Ageing Condition)	Strategic Technique
Level 3 (PG64-22)	Fatigue Cracking	IDT-CT	30% (Control) 40%	5.50% 6.00% 6.50%	25°C (LTA)	WMA1 WMA2 REJ1 REJ2
Level 3 (PG64-22)	Rutting	HWTT	30% (Control) 40%	5.50% 6.00% 6.50%	50°C (STA)	WMA1 WMA2 REJ1 REJ2
Level 4 (PG70-22ER)	Fatigue Cracking	IDT-CT	20% (Control) 30%	5.50% 6.00% 6.50%	25°C (LTA)	WMA1 WMA2 REJ1 REJ2
Level 4 (PG70-22ER)	Rutting	HWTT	20% (Control) 30%	5.50% 6.00% 6.50%	50°C (STA)	WMA1 WMA2 REJ1 REJ2

Note: IDT-CT and HWTT in test methods refer to Indirect tensile cracking tolerance and Hamburg wheel tracking tests, respectively. LTA and STA indicate long-term ageing and short-term ageing conditions, respectively. RAP1 (RAP source 1) is used throughout this experimental work.

5.7 RESULTS AND DISCUSSION ON THE PERFORMANCE CHARACTERISTICS

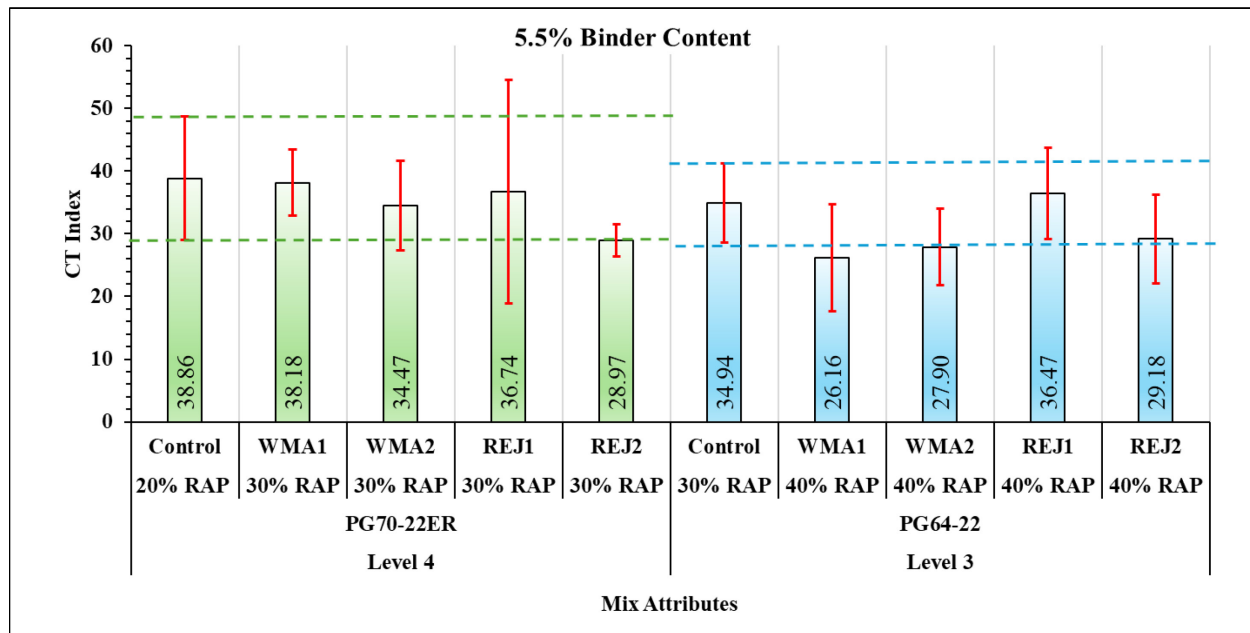
5.7.1 Effect of Additives on Cracking Resistance

Figure 5.9 illustrates the variation in cracking behaviour (CT Index) for high RAP mixtures in both Level 3 and Level 4 categories with the incorporation of strategic techniques. The results show that the application of these techniques enables the use of 10% higher RAP content than the current allowable limits in Oregon, as the cracking resistance remains comparable to or better than the control mixtures. For instance, at a binder content of 6.5%, the CT Index values of the modified mixtures varied between -4% to 21% for Level 4 and -12% to 17% for Level 3 relative to the control samples. Specifically, in the Level 4 category, the addition of WMA1, WMA2, REJ1, and REJ2 altered the CT Index by -4%, -3%, 21%, and -1%, respectively, while in the Level 3 category the corresponding variations were 8%, -12%, 17%, and -9%. Similar trends were observed at other binder contents, as shown in Figure 5.9a, Figure 5.9b.

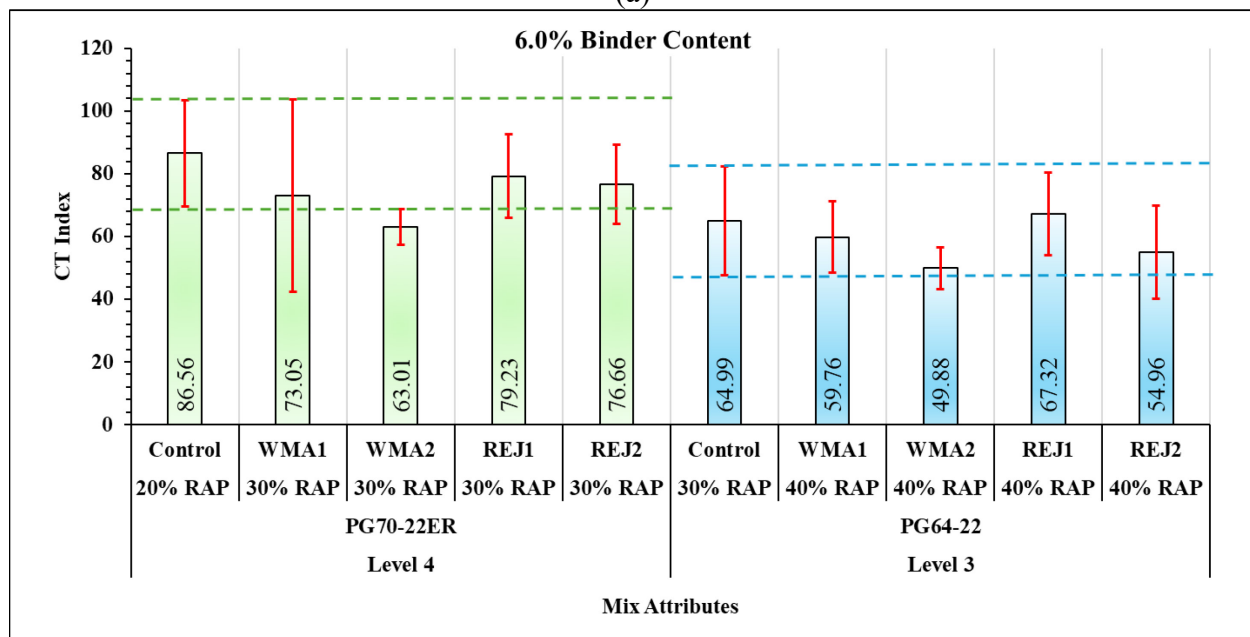
Along with this, the results revealed that the suitability of any additive can differ with the change in mix design level (particularly the binder grade), underscoring the importance of interaction effects. Previous studies (Aeron et al. 2024; Hu et al. 2025; Motevalizadeh et al. 2022; Yousefi et al. 2023) have also emphasized that the interactions of rejuvenators/WMA with other mix attributes play a critical role in the performance determination, especially at higher RAP contents, where a larger proportion of aged binder participates in the mixture. For example, at a 6% binder content, the use of REJ1 in Level 4 mixtures (containing PG70-22ER binder) showed a 5% reduction in CT Index, while its addition in Level 3 mixtures (with PG64-22 binder) resulted in a 4% improvement. Similar variations were observed across other binder-additive-RAP combinations, highlighting the complexity of these interactions and the need for further investigation. Overall, the benefits of rejuvenators and WMA additives in terms of cracking resistance were observed at higher binder contents used in the present study compared to the asphalt mixtures prepared using a low binder content.

Based on the results, all modified asphalt mixtures demonstrated satisfactory cracking resistance, even with 10% higher RAP content compared to the current control mixtures. Even though the RAP content is higher, which typically increases the amount of oxidized RAP binder and overall mixture stiffness, the integration of rejuvenators and WMA offsets these negative impacts. Specifically, the rejuvenators adopted in this research work comprised oily components (tall oil in REJ1 and corn oil in REJ2), which increase the oily fraction (maltenes), thereby reducing the asphaltene-to-maltene ratio (García et al. 2010). The presence of oily composition in the rejuvenators was also confirmed in the FTIR test results, as demonstrated in Chapter 3.0. This shift lowered binder viscosity, decreased mixture stiffness, and enhanced cracking resistance, as reflected by higher CT Index values. These findings are consistent with previous studies that reported improved flexibility and greater strain tolerance in rejuvenator-modified mixtures (Daryaei et al. 2025; Nguyen et al. 2024; Yousefi et al. 2023). Similarly, the application of WMA technologies facilitated higher RAP incorporation by lowering production temperatures by approximately 25 °C compared to HMA. This reduction minimized secondary ageing of the RAP binder (Wang et al. 2022; Yousefi et al. 2023), allowing the modified mixtures to achieve

cracking resistance comparable to that of the control mixtures within both Level 3 and Level 4 categories.

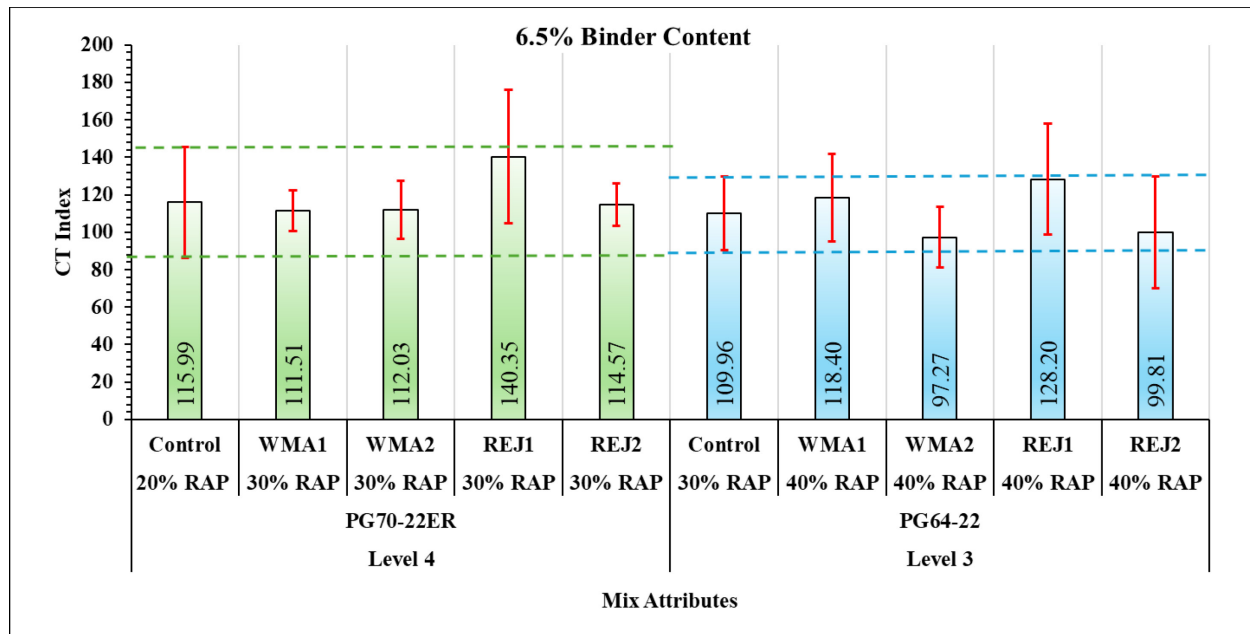


(a)



(b)

Figure 5.9. Variation in the CT Index with the addition of rejuvenators and WMA additives at different binder contents (a) 5.5% (b) 6.0%, and (c) 6.5%



(c)

Figure 5.10 (continued). Variation in the CT Index with the addition of rejuvenators and WMA additives at different binder contents (a) 5.5% (b) 6.0%, and (c) 6.5%

Note: Dotted lines indicate the upper and lower bound limits of the control samples.

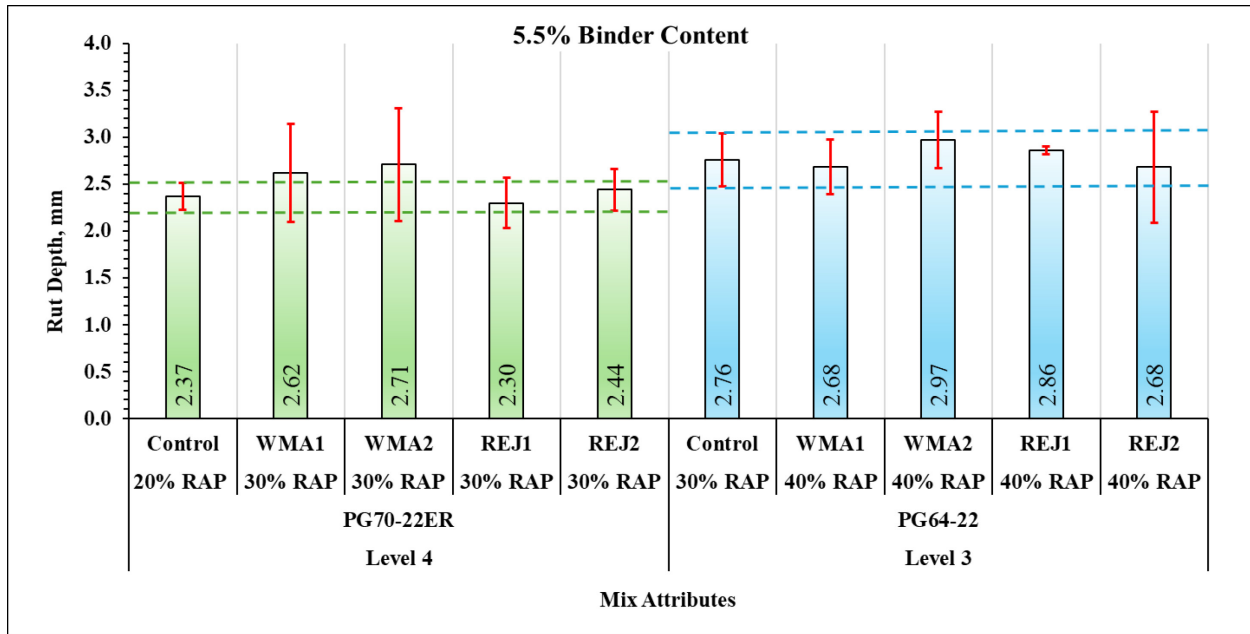
5.7.2 Effect of Additives on Rutting Resistance

According to previous studies (Obaid et al. 2024; Yousefi et al. 2023), the use of rejuvenators and WMA generally softens the asphalt binder, which can adversely affect rutting resistance. However, in certain cases, their influence is more pronounced on cracking resistance, while the increased RAP content and the associated stiffness of the aged RAP binder help counterbalance rutting potential (Obaid et al. 2024; Wang et al. 2022; Zaremotekhasas et al. 2022). The effects of these strategic techniques on rutting performance (in terms of rut depth) at binder contents of 5.5%, 6.0%, and 6.5% are presented in Figure 5.10.

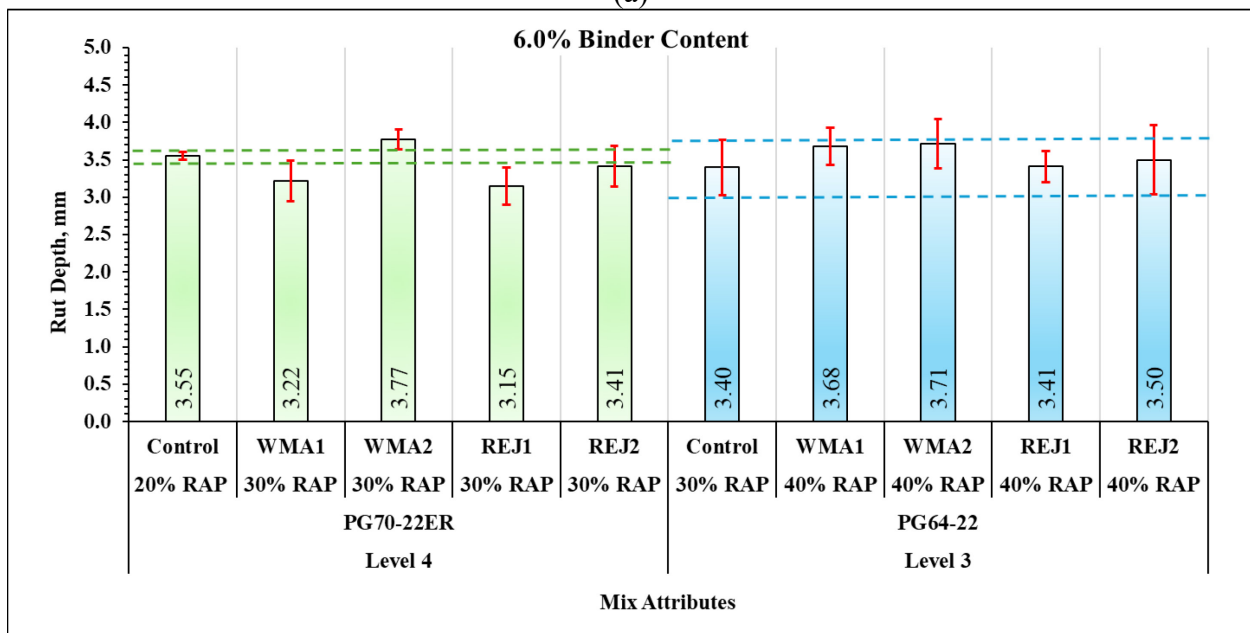
Considering all the aspects, the rut depth measured across the high RAP mixtures was found to be far lower than the 12.5 mm rut depth threshold adopted by various state DOTs and thus all the mixtures are classified as highly rut-resistant (Chitnis et al. 2025). This finding suggests that the influence of increased RAP content is more critical for cracking performance, whereas rutting is less of a concern within the evaluated conditions. Moreover, the effectiveness of rejuvenators and WMA additives should therefore be assessed primarily in relation to their impact on cracking potential. This is particularly important for Oregon mixtures as demonstrated in this study, where the highest observed rut depth of 5.21 mm in the Level 4 mixture with PG64-22 binder at 6.5% binder content, remained significantly lower than the nationally accepted 12.5 mm threshold. These results indicate that there is considerable scope to increase virgin binder content or additives in order to further enhance cracking resistance without compromising rutting performance.

Although the overall rut depths of the high RAP mixtures were well below the 12.5 mm threshold, it remains important to examine how the adoption of strategic techniques affects rutting performance relative to the corresponding control mixtures. As illustrated in Figure 5.10, rut depth increased with increasing binder contents, a trend consistent with the observations reported in the previous chapter (Chapter 4.0). The rate of increase, however, varied with the type of additive, binder content, and mix design level. For instance, at 6.5% binder content, the rut depths for 30% RAP mixtures with WMA1, WMA2, REJ1, and REJ2 were 4.68 mm, 4.35 mm, 3.99 mm, and 4.13 mm, respectively. Compared to the Level 4 control mixture (20% RAP with no additive), these values correspond to 1.10, 1.02, 0.93, and 0.97 times the control rut depth, indicating that WMA1 increased rutting by about 10%, WMA2 by 2%, while REJ1 and REJ2 reduced rutting by approximately 7% and 3%, respectively. When the high RAP mixtures (40% RAP) were compared with the control mixtures in Level 3 category (30% RAP without additive), the corresponding ratios shifted to 0.90 (WMA1), 0.98 (WMA2), 0.83 (REJ1), and 0.94 (REJ2), demonstrating reductions in rut depth of around 10%, 2%, 17%, and 6%, respectively.

Similar trends were observed at other binder contents, suggesting that a 10% higher RAP offset the impact of softness/reduced ageing imparted by the application of rejuvenators/WMA technologies. In addition, it was reviewed that the incorporation of rejuvenators improves the blending efficiency of the RAP binder, thereby improving the bond strength at the interface of the asphalt and aggregate matrix (Sukhija and Coleri 2025b; c), and contributing to greater load-carrying capacity. However, this aspect was beyond the scope of the present study and warrants further investigation. Similar to the CT Index findings, the interaction between the mix attributes defines the trends in the rutting behavior. Additionally, the adoption of rejuvenators and WMA technologies preserves the rut depth within acceptable limits while ensuring satisfactory cracking resistance, even with high RAP content.

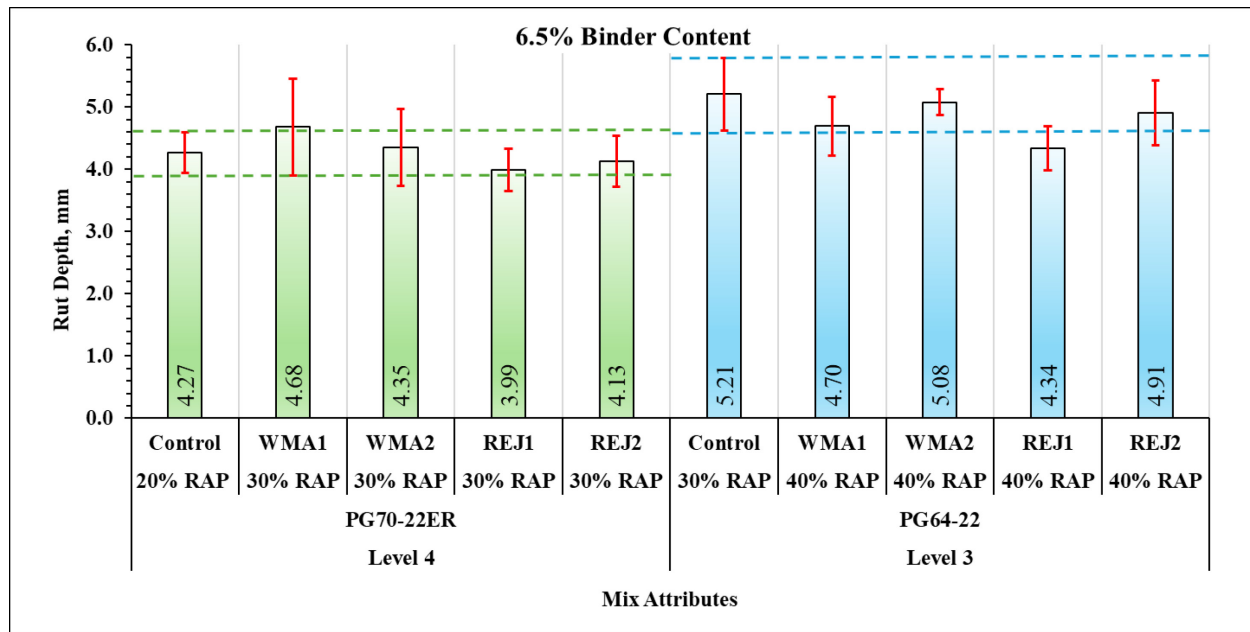


(a)



(b)

Figure 5.11. Variation in the rut depth with the addition of rejuvenators and WMA additives at different binder contents (a) 5.5% (b) 6.0%, and (c) 6.5%



(c)

Figure 5.12 (continued). Variation in the rut depth with the addition of rejuvenators and WMA additives at different binder contents (a) 5.5% (b) 6.0%, and (c) 6.5%

Note: Dotted lines indicate the upper and lower bound limits of the control samples.

5.7.3 Statistical Inferences on the Effect of Strategic Techniques on Mix Performance

The above discussion highlights the critical role of interactions among the asphalt binder, RAP material, and additives. Despite the higher RAP contents, the CT Index and rut depth of the modified mixtures remained statistically comparable to those of the control mixtures when the variations in results (as indicated by standard deviations) were considered. Most of the performance values fell within the upper and lower bound limits shown in the figures (Figure 5.9 and Figure 5.10). This observation was further validated through an Analysis of Variance (ANOVA) conducted at a 95% confidence level. The comparisons between all high RAP mixtures and their respective control mixtures, across both mix design levels, are summarized in Table 5.9.

In the Level 4 mixtures, the comparison between the control mixture with 20% RAP and the high RAP mixtures with 30% RAP (produced with WMA2, WMA1, and REJ1) indicated a statistically significant effect on rut depth (P -value < 0.05). Specifically, the use of WMA1 ($P = 0.017$) and REJ1 ($P = 0.004$) to increase RAP from 20% to 30% showed positive results, as both mixtures exhibited lower average rut depths than the control. Similarly, in the Level 3 mixtures, REJ1 demonstrated a significant effect ($P = 0.043$) when incorporated to increase RAP content from 30% to 40%, also resulting in lower rut depth. For cracking resistance (CT Index), all high RAP mixtures, 40% RAP in Level 3 and 30% RAP in Level 4, produced with rejuvenators or WMA additives were found to be statistically similar to their respective control mixtures (30%

RAP in Level 3 and 20% RAP in Level 4), with P-values > 0.05 at the 95% confidence level, except for the 30% RAP mixture with WMA2 in Level 4 (P = 0.019).

Overall, the statistical analysis confirmed that RAP contents can be increased by approximately 10% beyond the current allowable limits through the application of rejuvenators or WMA technologies. The underlying mechanisms include changes in the asphaltene-to-maltene ratio and increased flexibility with rejuvenators, or reduced production temperatures and lower ageing effects with WMA. However, the rate and extent of these improvements depend on factors such as mix design level, binder content, and binder grade.

Table 5.9. Pairwise comparison between different asphalt mixtures based on the cracking and rutting performance

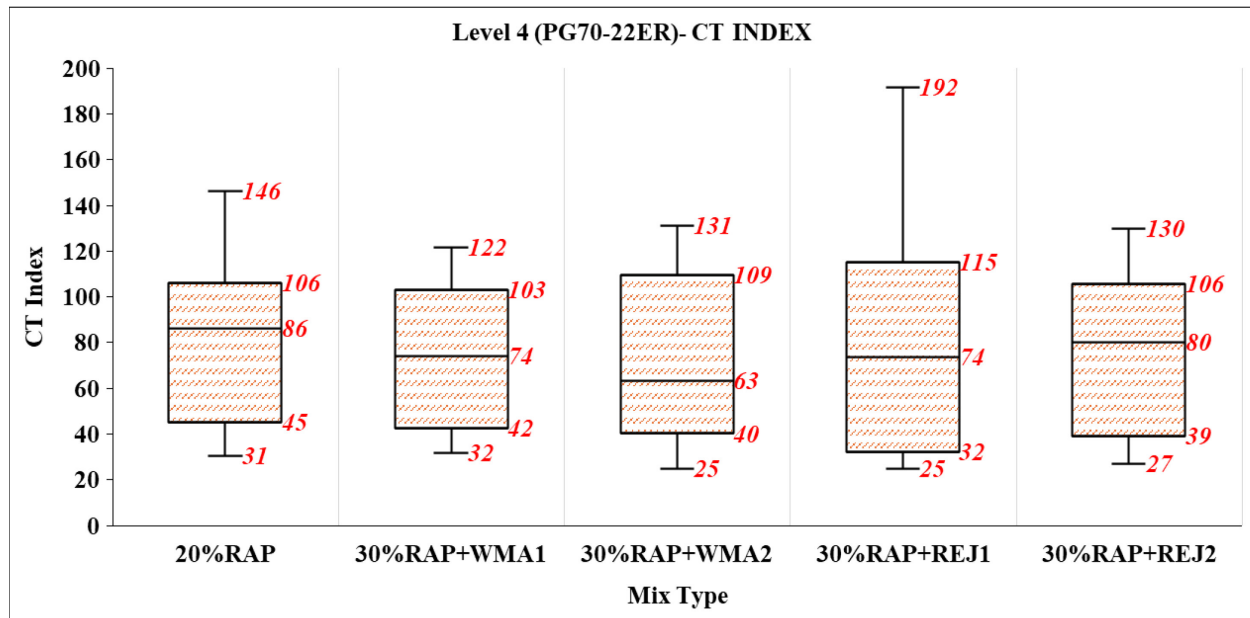
Mix Design Level (Binder Grade)	Source of Variation	CT Index 5.5%	CT Index 6.0%	CT Index 6.5%	Rut Depth 5.5%	Rut Depth 6.0%	Rut Depth 6.5%
Level 4 (PG70-22ER)	20% RAP (Control)-30% RAP (WMA1)	0.905	0.426	0.782	0.425	0.017	0.378
Level 4 (PG70-22ER)	20% RAP (Control)-30% RAP (WMA2)	0.481	0.019	0.793	0.113	0.002	0.817
Level 4 (PG70-22ER)	20% RAP (Control)-30% RAP (REJ1)	0.822	0.470	0.554	0.674	0.004	0.264
Level 4 (PG70-22ER)	20% RAP (Control)-30% RAP (REJ2)	0.095	0.274	0.922	0.573	0.247	0.612
Level 3 (PG64-22)	30% RAP (Control)-40% RAP (WMA1)	0.103	0.622	0.575	0.758	0.306	0.221
Level 3 (PG64-22)	30% RAP (Control)-40% RAP (WMA2)	0.111	0.108	0.336	0.367	0.293	0.701
Level 3 (PG64-22)	30% RAP (Control)-40% RAP (REJ1)	0.745	0.832	0.285	0.520	0.960	0.043
Level 3 (PG64-22)	30% RAP (Control)-40% RAP (REJ2)	0.211	0.108	0.544	0.835	0.738	0.471

5.7.4 Ranking of the Strategic Techniques based on Mix Performance

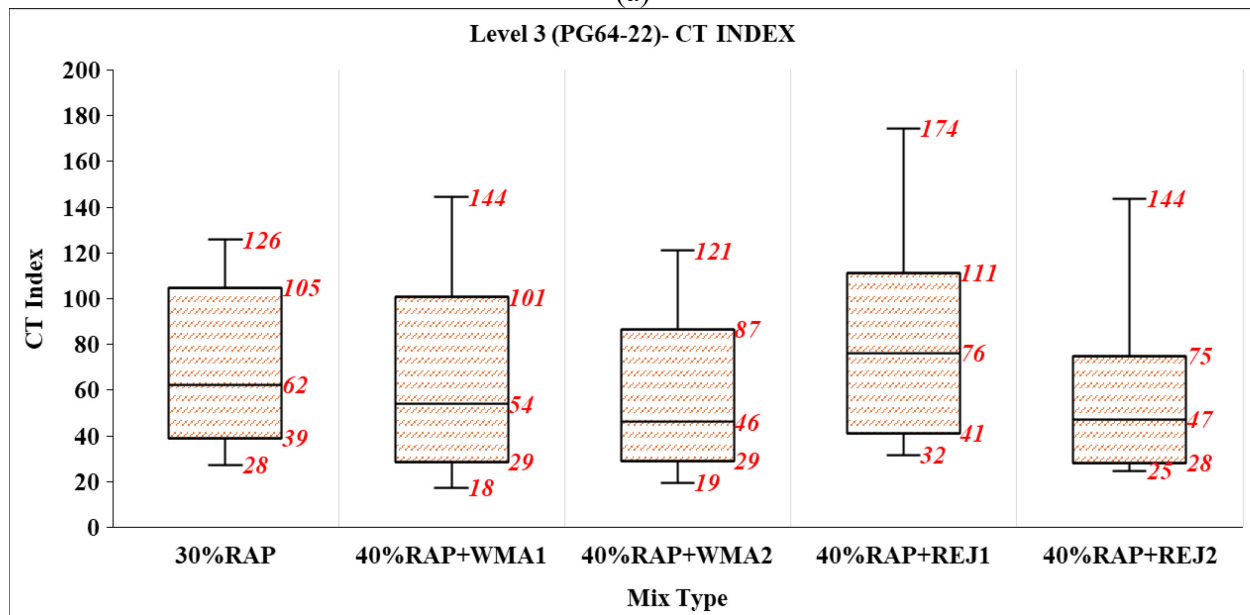
To understand which additive is best suited for maintaining the rutting and cracking resistance of the high RAP mixtures, main effect plots were drawn using the complete data set for each mix design level (Figure 5.11). These plots provide a straightforward way to compare different alternatives by illustrating the minimum and maximum performance ranges, along with parametric values at various quartiles. Notably, separate analyses were conducted for Level 3 and Level 4 mixtures, as the binder grades differ in their chemical and physical characteristics, which may impact the suitability of rejuvenators and WMA technologies.

The figures indicate that the high RAP mixtures exhibited performance trends consistent with their respective control samples across both cracking and rutting metrics. In both mix design

levels, even after accounting for the effect of binder content, all the asphalt mixtures were found to perform statistically similarly to their respective control mixtures, as indicated by the overlapping of their bars, which showed minimum and maximum performance values. Given this statistical similarity, ranking the additives based on their average performance values becomes essential for identifying the most effective strategic technique, whether rejuvenators or WMA technologies, for enabling 10% higher RAP utilization beyond the current allowable limits.

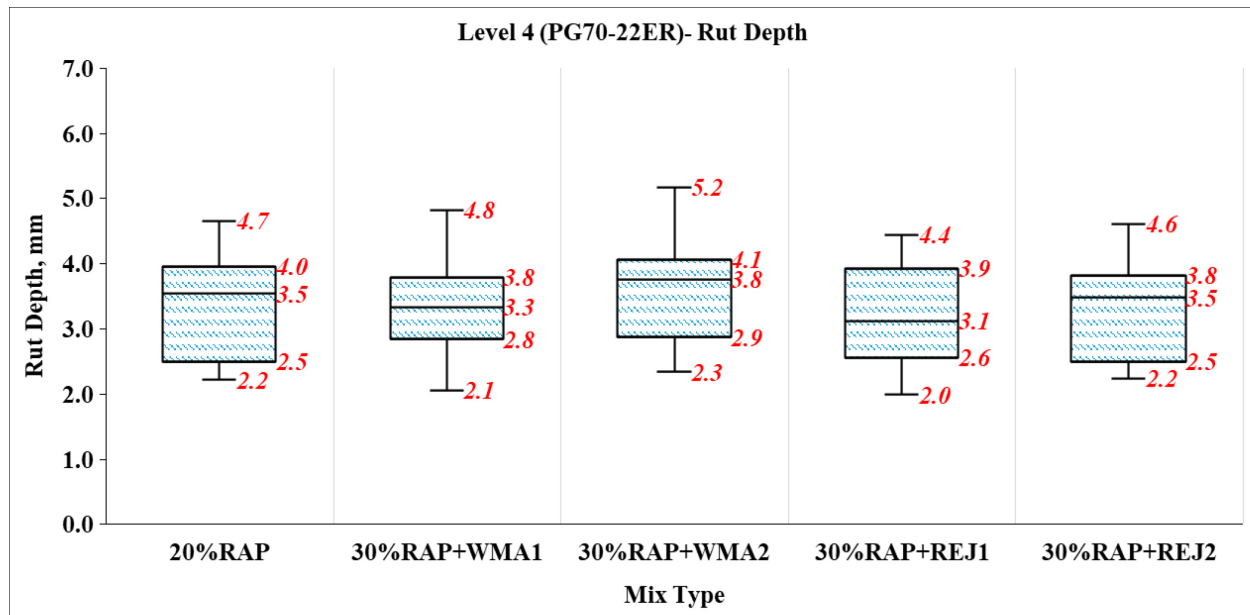


(a)

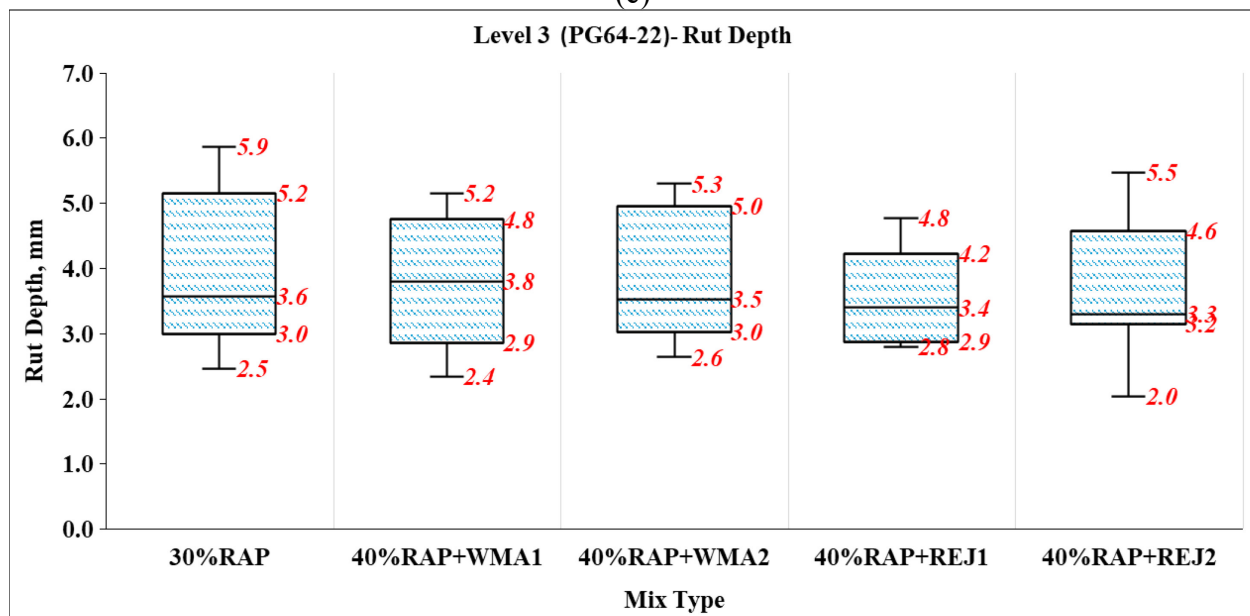


(b)

Figure 5.13. Variation in the performance with the addition of rejuvenators and WMA additives, irrespective of binder contents (a) CT Index (Level 4 mix) (b) CT Index (Level 3 mix), (c) Rut depth (Level 4 mix), and (d) Rut depth (Level 3 mix)



(c)



(d)

Figure 5.14 (continued). Variation in the performance with the addition of rejuvenators and WMA additives, irrespective of binder contents (a) CT Index (Level 4 mix) (b) CT Index (Level 3 mix), (c) Rut depth (Level 4 mix), and (d) Rut depth (Level 3 mix)

Table 5.10 shows the ranking of each of these strategic techniques with respect to the average CT Index and rut depth in each of the mix design levels. Although the performance is statistically similar to the control asphalt mixtures in each mix design level, REJ1 consistently outperformed other additives in terms of better cracking resistance and adequate rut depth for high RAP mixtures and was assigned as rank 1. This is consistent for both mix design levels, as

shown in Table 5.10. Across most combinations, the ranking follows a similar trend, where REJ1 is ranked 1, followed by REJ2 (rank 2), WMA1 (rank 3), and WMA2 (rank 4).

An exception was observed in the CT Index ranking for the Level 3 mixtures, where WMA1 (average CT Index = 64.9) slightly outperformed REJ2 (average CT Index = 61.3), resulting in an interchange of their positions. Thus, the ranking in this case was REJ1 > WMA1 > REJ2 > WMA2. This shift underscores how interactions among mix attributes, binder grade, binder content, and additive type can influence relative performance, even when overall statistical similarity is maintained.

On average, application of rejuvenators proved to be more effective than WMA technologies, as they consistently ranked superior in terms of CT Index and rut depth, thereby supporting the incorporation of 10% more RAP than the current allowable limits in Oregon. As far as each category is concerned, such as rejuvenators and WMA technologies, REJ1 emerged as the best-performing rejuvenator, while WMA1 outperformed the other WMA additives in balancing cracking and rutting performance. Notably, these rankings are assigned based on the current dataset; they may vary with different mix attributes or testing methodologies.

Table 5.10. Average ranking of the strategic techniques for high RAP mixtures

Strategic Techniques	Level 4 CT Index	Level 4 Rut Depth	Level 3 CT Index	Level 3 Rut Depth	Average Rank
WMA1	3	3	2	3	3
WMA2	4	4	4	4	4
REJ1	1	1	1	1	1
REJ2	2	2	3	2	2

5.8 CONCLUSIONS

Below are the conclusions resulting from this research work:

Temperature Sensitivity and Dosage Optimization

1. Although experimental work and statistical analysis revealed no significant effect of reduced production temperature for WMA1 (P-value > 0.05), a critical issue related to inadequate binder coating was observed when the mixture was produced at 40°C below the conventional HMA production temperature.
2. Despite a 25 °C reduction in production temperatures, both the WMA mixtures (WMA1 and WMA2) prepared with 30% RAP showed satisfactory workability, similar to that of the reference WMA mixtures produced at HMA temperatures.

3. WEI values were found to decrease by approximately 3-18% and 15-25% for WMA mixtures when the production temperature was reduced by 25°C and 40°C, respectively, in comparison to the WMA mixtures produced at actual HMA temperature conditions. These reductions varied based on the type of WMA additive used in Level 3 mixtures, and similar trends were consistently observed in Level 4 mixtures as well.
4. The incorporation of WMA additives at a dosage of 0.5% enabled an increase of 10% in RAP content (i.e., 40% RAP in Level 3 and 30% RAP in Level 4) while maintaining comparable WEI values to the reference mixtures produced with 30% RAP in Level 3 and 20% RAP in Level 4, even at 25°C reduced production temperatures.
5. Similar to WMA, the addition of rejuvenators (REJ1 and REJ2) at a dosage of 1.5% by weight of total binder effectively restores the stiff RAP binder, resulting in improved workability characteristics for the mix containing 10% higher RAP content than the current allowable limits. Depending on the type of rejuvenators, the WEI values were found to be 20%-33% and 42%-50% higher in Level 3 and Level 4 mix, respectively, compared to their respective references.
6. The evaluated optimum dosages, i.e., 0.5% for WMA (at 25°C reduced production temperatures) and 1.5% for rejuvenators, were consistent with the manufacturer's recommendations. While both additives improved workability, rejuvenator-modified mixtures consistently exhibited higher WEI values than WMA-modified ones at equivalent RAP contents. However, all modified mixtures remained statistically similar (P -value > 0.05) to their respective reference mixtures, which were produced within the current allowable limits.

Performance Evaluation

7. At their optimum dosages, the incorporation of rejuvenators and WMA additives enabled a 10% increase in RAP content while maintaining adequate cracking and rutting performance. The rate of performance change was influenced by the type of additive, binder content, and binder grade, reflecting the interaction effects among these factors.
8. Statistical analysis confirmed that nearly all high RAP mixtures exhibited performance either comparable to or better than the control samples, with the exception of a single case, WMA2 at 6% binder content, which showed a slight reduction in performance. These results validate that RAP contents can be increased by approximately 10% beyond current allowable limits through the use of rejuvenators or WMA technologies.
9. Among the evaluated strategies, rejuvenators outperformed WMA additives, with the overall ranking following the trend: REJ1 > REJ2 > WMA1 > WMA2. Specifically, REJ1 showed

the most favorable balance of cracking resistance and rutting performance in high RAP mixtures, followed by REJ2 in the rejuvenator category and WMA1 outperforming WMA2 among the WMA technologies.

After successful validation, these strategic measures should be applied for constructing trial sections and monitored periodically to understand the long-term behaviour of the modified asphalt mixtures with high RAP content, in particular, 10% higher RAP content than the current allowable limits in each category (30% RAP in Level 3 and 20% RAP in Level 4). A tentative conceptual field trial plan has been presented in Chapter 8.0 of this report. Apart from this, it is recommended to investigate the applicability and effectiveness of WMA additives and rejuvenators for RAP contents beyond the 10% increment, particularly in the range of 40–50%, to determine their potential for broader implementation in sustainable pavement practices.

6.0 PAVEMENT LIFE CYCLE ASSESSMENT AND COST ANALYSIS

6.1 INTRODUCTION

The transportation sector consumes a tremendous amount of energy and thus emits greenhouse gas (GHG) emissions. Around 60% of the oil produced in the world is directly used for the transportation sector (International Energy Agency 2021). The construction of asphalt pavements, a crucial component of infrastructure development, requires a substantial amount of energy to produce raw materials such as asphalt binders and aggregates. One commonly used technique to produce energy is fuel combustion, which in turn releases harmful emissions that can affect the environment and human health (Araújo et al. 2014; Shacat et al. 2022). Nevertheless, the Intergovernmental Panel on Climate Change (2014) aimed to reduce CO₂ emissions by 85-95% by the end of 2050. This highlights the importance of utilizing alternative materials in pavement construction to achieve carbon neutrality and promote sustainable development.

As stated in the previous chapters, RAP acts as a sustainable pavement material that paves the way toward a circular economy, aiming to lower economic burdens and environmental impacts without compromising the durability of the asphalt mix (Si et al. 2024). Using RAP can be an alternative to reduce carbon emissions in terms of harmful pollutants emitted during the production and use of conventional resources, such as natural aggregates and neat asphalt binder (McDaniel et al. 2001; West et al. 2013; Zhao and Yang 2024). Nevertheless, beyond performance evaluation, it is essential to provide clear justification and guidance to support policymakers and environmental stakeholders in promoting the use of high RAP contents in pavement construction. A comprehensive Life Cycle Assessment (LCA) is needed to determine the impact of high RAP on the environment.

In general, LCA is the analysis of any material/product from its production to its end-of-life. The analysis can be in terms of cost, environmental burdens, or both aspects. It can be done theoretically (based on regression equations) or using sophisticated computerized tools/software. The tools/equations remain the same for different materials/products, but the data inventory will change depending on the characteristics of the material/product in question and the location. Many studies (Abdalla et al. 2022; Chiu et al. 2008; Giani et al. 2015; Sukhija et al. 2022b; Yang et al. 2015; Yao et al. 2022) are available that cover a detailed explanation of different evaluation techniques for assessing the life cycle cost and environmental impact.

6.1.1 Previous Studies on Pavement Life Cycle Assessment

To promote the use of RAP based on life cycle performance and life cycle cost analysis, Coleri et al. (2018b) carried out comprehensive research work for the Oregon DOT. Various performance predictors, including rutting, roughness, and cracking, were considered for the analysis. The costs associated with material production, equipment, labor, traffic management, and lane closure were incorporated for a life cycle cost analysis. The study's findings revealed that the

higher the RAP proportions, the higher the cost savings. According to the authors, life cycle performance (mostly the fatigue cracking resistance) plays a crucial role in forecasting the life cycle cost of RAP-inclusive asphalt pavement, as it directly accounts for functionality, ride quality, repair and maintenance costs, and fuel efficiency. In a previous study, it was shown that carbon emissions can be reduced by 35% along with a reduction in cost as high as 50% for a 100% RAP mix relative to the virgin asphalt mixture (Zaumanis et al. 2014a).

Figure 6.1 illustrates the outcomes of several previous studies, showing the percentage reduction in economic and environmental burdens across various mix design scenarios. The percentage reduction varies based on several factors, such as the choice of LCA tools, material composition, pavement layers, data inventory, RAP source, RAP content, the grade of neat asphalt binder, and the degree of blending. Additionally, different studies consider various variables, such as raw material transportation distance, heating systems, production temperatures, fuel types, RAP heating and storage conditions (temperature/time), and whether the mix is from laboratory or production processes, leading to inconsistencies in reported benefits. However, these data points were determined and analyzed relative to the conventional mix used in each respective study. The analysis of compiled data indicated an average reduction of 27% in environmental burdens and 25% in economic savings for the asphalt mixtures prepared with an average RAP content of 45% compared to the asphalt mixture with no RAP.

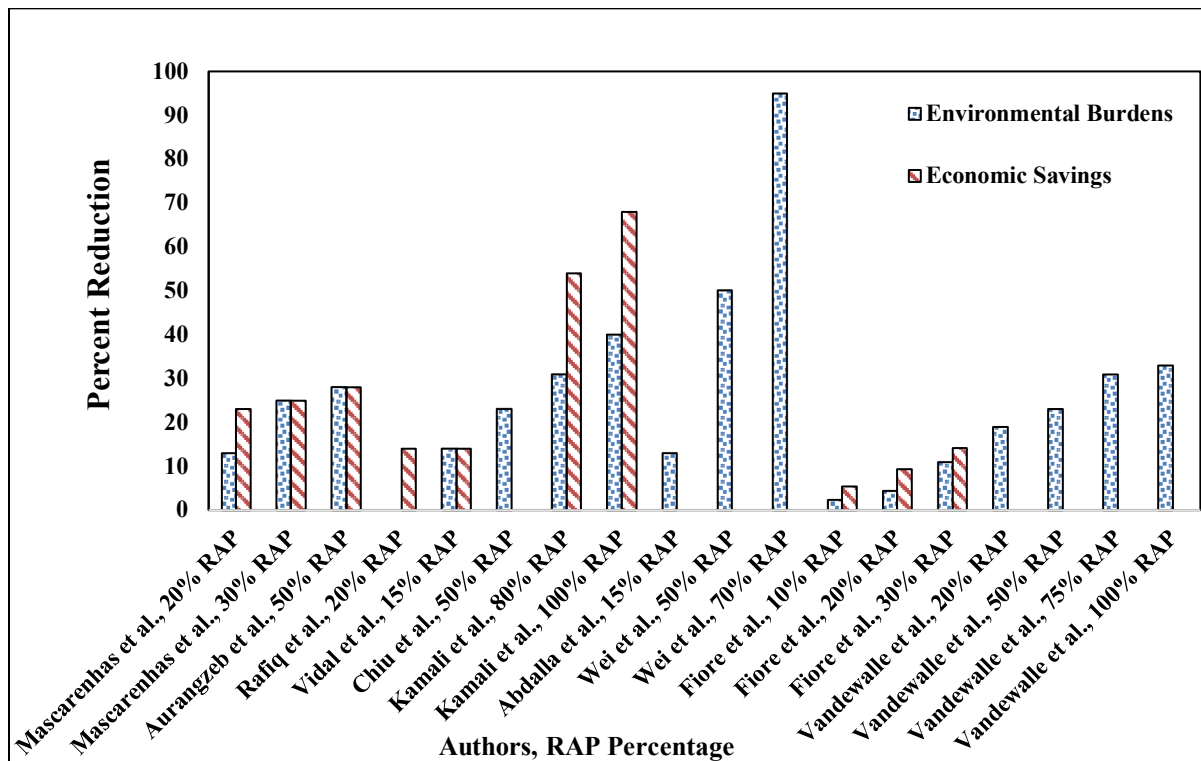


Figure 6.1. Reduction in economic and environmental burdens based on past studies using different percentages of RAP material (Abdalla et al. 2022; Aurangzeb et al. 2014; Chiu et al. 2008; Fiore et al. 2023; Kamali et al. 2022; Mascarenhas et al. 2023; Rafiq et al. 2021; Vandewalle et al. 2020; Vidal et al. 2013; Wei et al. 2021)

As per the data inventory (as shown in Figure 6.1), the maximum reduction in emissions and economic burdens can be accounted for 95% and 68%, respectively, depending on the factors described in the preceding sections. These benefits may further improve with the adoption/use of other strategies such as bio-based rejuvenators, warm mix additives, alternative waste materials, etc. (Bressi et al. 2021; Kamali et al. 2022; Santos et al. 2018; Zahoor et al. 2021).

Considering the variation in RAP content, Aurangzeb et al. (2014) demonstrate how energy consumption and GHG emissions vary with the increase in RAP content, assuming a 100% performance level. The results are presented in Figure 6.2, indicating a nonlinear relationship between the increase in RAP content and energy consumption, as well as GHG emissions. With the increase in RAP content from 0% RAP (control) to 30%, 40%, and 50% RAP, there is a reduction of approximately 7%, 10%, and 12% in energy consumption/GHG emissions, respectively. As per the findings, the highest energy consumption and corresponding GHG emissions were obtained for the material production phase, whereas the construction phase exhibits the lowest (6-8%). Taking into account the impacts and sources involved in the production of RAP-inclusive asphalt pavement (Table 6.1), the production of asphalt binder marks the highest contribution in terms of energy use and emissions (Yang et al. 2014). The listed amount is significantly higher than the other impacts, including HMA plant operations and aggregate production, with the lower amount attributed to the production of RAP and RAS, highlighting the improvement in sustainability through the recycling process.

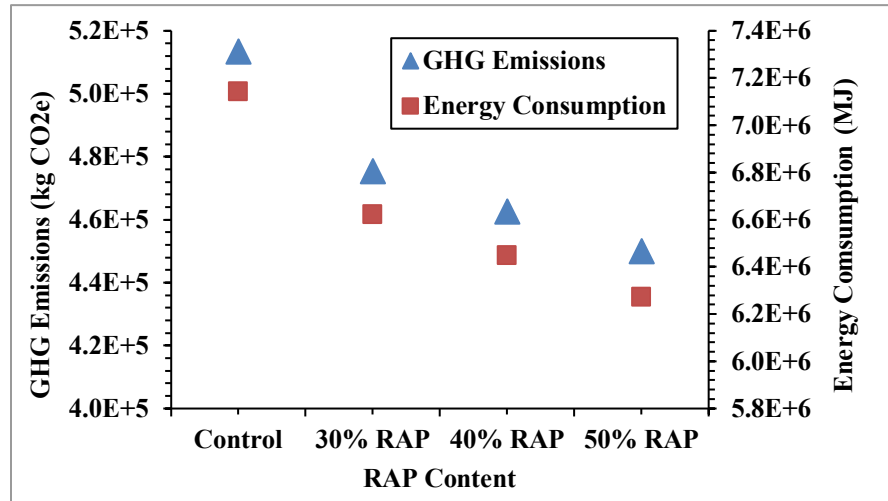


Figure 6.2. Variation of energy consumption and GHG emissions with RAP content
(Aurangzeb et al. 2014)

Table 6.1. Energy and emissions associated with asphalt pavement production (Yang et al. 2014)

Task/Process	Energy Usage (MJ/short ton)	Greenhouse Gas emissions (kg CO₂e/short ton)
Asphalt Binder Production	4,633	294
RAP/ RAS Production	17.4	1.3
Coarse Aggregate Production	29.8	2.1
Natural Aggregate Production	51	3.2
Asphalt Plant Operation	400.4	23.8

6.2 PROBLEM STATEMENT

It is important to note that the above-mentioned estimate may change with the adoption of other economic and environmental burden indicators, such as life cycle inventory, geographic location, life cycle span, material source, RAP content, additive used, etc. Overall, the application of RAP material in asphalt pavements can provide significant benefits in terms of both cost and environmental impact. The addition of rejuvenators and warm mix additives also supports the use of a high percentage of RAP, as observed in previous chapters. Nevertheless, every scenario depends on the RAP source, RAP percentage, neat asphalt binder content and grade, and additive (if any). In addition, the use of RAP in large volumes necessitates the addition of additives, such as rejuvenators or WMA, leading to the highest initial investment (Zaumanis et al. 2014a). Thus, a more comprehensive LCA (in terms of economic and environmental burdens) of RAP mixtures is required to cover the economic and environmental benefits, at least considering different RAP percentages, binder contents, binder types, and strategic techniques. This can provide an estimation of average potential savings with the use of higher RAP percentages before their implementation in Oregon. The analysis may also help identify the most influential parameters and the most effective strategic technique for enhancing sustainability.

6.3 RESEARCH METHODOLOGY

6.3.1 Life Cycle Assessment

According to the International Organization for Standardization (ISO) (ISO 2006), the LCA was determined following a common approach of defining the goal and scope, selecting life cycle inventory, assessing the life cycle impact, and interpreting the final outcomes to understand the effect of different influential factors on the environmental burdens. These approaches are detailed below:

- a) Goal and Scope:** This section comprises the objectives and establishment of system boundaries. The goal and scope of the present study are to understand how the environmental impacts vary with different influential factors, including binder type, RAP content, and binder content. In addition, the research team investigates how the impact of these techniques varies with the adoption of different strategic approaches, such as increasing binder content,

adjusting binder grade, using rejuvenators, and employing warm mix asphalt technologies, to improve the RAP content in asphalt mixture production.

The pavement LCA demonstrated in this study was determined based on 1 short ton declared unit of an asphalt mixture. This LCA covers cradle-to-gate analysis representing the impact across the raw material supply, its transportation, and production. These are often categorized as Material phase (A1), Transport (A2), Production (A3), and the combination of all these phases represents the total cradle-to-gate pavement LCA, as illustrated in Figure 6.3. The impact during the construction, use, rehabilitation, and end of in-service life is not considered in the present analysis.

In particular, the material phase of the present study includes the extraction of raw material and its processing. For example: aggregate quarry operation, binder refining, etc. The *transport phase* represents the transportation of these raw materials to the asphalt plant, more specifically, in terms of transportation distance, vehicle type, and fuel. On the other hand, the *production phase* involves the plant operation for the production of asphalt mixtures. These include the use of electricity, temperature, etc, whose details are mostly plant-specific. Among these phases, the material production is the most crucial phase, contributing to the environmental burdens (Praticò et al. 2020). In the current scenario, state transportation agencies are increasingly prioritizing the use of high RAP contents in asphalt mixtures to minimize raw material extraction and refining, thereby reducing carbon emissions and enhancing overall sustainability.

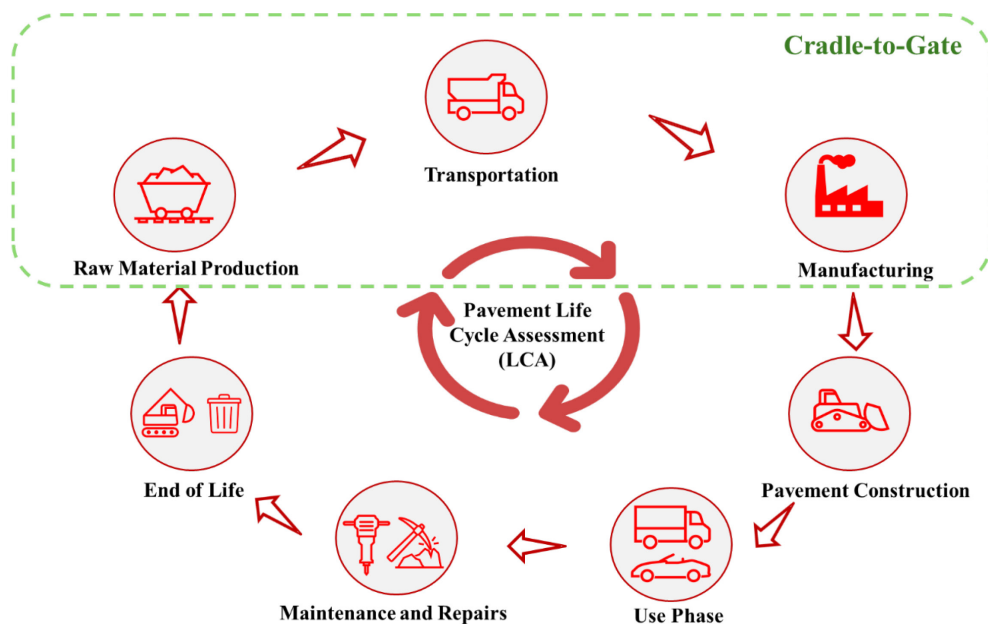


Figure 6.3. Different phases of pavement life cycle assessment

b) Life Cycle Inventory: This section presents the details of the input and output data, where inputs include factors such as the type of fossil fuel, energy consumption, vehicles used, and water requirements, while outputs primarily consist of the type and quantity of emissions generated during the operation. For the present analysis, Table 6.2 illustrates the asphalt plant input data used for the LCA. Since the present study involves the use of WMA technologies in selected asphalt mixtures, where the production temperatures were reduced by 25°C, the corresponding energy consumption and fuel use were adjusted accordingly. Based on the previous studies in this direction (NASEM 2014; Williams et al. 2024), reducing production temperatures by this amount decreases fuel consumption by approximately 20% compared to conventional hot mix asphalt (HMA). This was calculated by considering a reduction factor i.e., 1,000-1,100 British thermal unit (Btu)/°F/ton. Such adjustments are applied to the burner fuel section, which accounts for fuel used in both primary and secondary burners as well as ancillary combustion equipment. Additionally, adjustments are required for the oil heater used to fire the asphalt tank heaters; if a plant does not separately meter the oil heater fuel, it is acceptable to include this value under the burner fuel field. The adjusted values for WMA mixtures are also provided in Table 6.2.

Along with the plant data, the mix-related input data are also required: the percentage of virgin aggregates, RAP, and asphalt binder by total mass, with their corresponding values detailed in the subsequent sections.

Table 6.2. Data inventory for annual asphalt production

Declared data	Total annual amount for HMA	Total annual amount for WMA
Asphalt mix production	100,000 U.S. Short Tons	100,000 U.S. Short Tons
Total water requirement	1,500,000 Gallons	1,500,000 Gallons
Electricity (Grid power)	332,000 KWh	332,000 KWh
Burner Fuel (Natural gas)	25,000 mcf/yr	20,000 mcf/yr
Oil heater (Natural gas)	3,465 mcf/yr	2,772 mcf/yr
Equipment oil (Diesel)	8,730 gallons/yr	8,730 gallons/yr

The output data will be compiled in terms of environmental impacts categorized as Global warming potential (GWP), Ozone depletion potential (OD), Eutrophication potential (EP), Acidification potential (AP), and Photochemical ozone depletion potential (POCP).

c) Life Cycle Impact Assessment: The impact assessment was carried out using the Emerald Eco-Label tool following the TRACI v2.1 impact assessment methodology (Miller et al.

2024). All of these impact categories have different levels of significance for the environment due to their distinct key pollutants, as summarized in Table 6.3.

Table 6.3. Details on the impact category, their units, domain and associated key pollutants

Impact Category	Unit	Impact Domain	Key Pollutants
Global Warming Potential (GWP)	kg CO ₂ -equivalents	Climate change	CO ₂ , CH ₄ , N ₂ O
Ozone Depletion Potential (ODP)	kg CFC-11-equivalents	Stratospheric ozone	CFCs, halogens
Eutrophication Potential (EP)	kg N-equivalents	Waterbody	N, P compounds, NH ₃
Acidification Potential (AP)	kg SO ₂ -equivalents	Acid rain, soil pH	SO ₂ , NO _x , NH ₃
Photochemical Ozone Creation Potential (POCP)	kg O ₃ -equivalents	Smog formation	VOCs + NO _x

d) Interpretation: This section includes the interpretation of the results and formation of conclusions, along with recommendations. Parametric analysis and graphical representation were two of the simplest methods for interpreting the results. In this section, the complete data set is compiled and compared with each alternative to identify the most significant influential parameters and to determine the best suitable solution for increasing the RAP utilization in asphalt pavements.

6.3.2 Pavement Cost Analysis

RAP can be considered a sustainable material if, in addition to reducing emissions, it also contributes to lowering material costs. In this study, a cost analysis was performed using a tool developed by Coleri et al. (2018a), which enables comparison of different mix alternatives based on cost savings. This tool has been applied in several previous studies to quantify the cost of asphalt mixtures with varying binder grades, binder contents, and RAP contents (Coleri et al. 2017; Kumar et al. 2021, 2022). The tool estimates total cost by incorporating a hypothesized pavement geometry (length, lane width, number of lanes, and compacted layer thickness), material costs, and mix design properties such as compacted density, target binder content, RAP content, and RAP binder content. The outputs include section volume, tonnage, and corresponding mix cost.

Since the present study involves the use of WMA technologies, the tool was modified to account for the cost of additives and the reduction in burner fuel consumption, with WMA assumed to reduce fuel use by 20% for every 25°C decrease in temperature. The modified tool, therefore,

provides the total material cost, including burner fuel. This adjustment reflects current mix design practices, where different additives are routinely incorporated to enable high RAP utilization. The enhanced version of the tool can be used to compare multiple projects based on both material costs and total costs (including fuel savings). Results are summarized in terms of maximum and minimum costs, as well as cost differences between alternatives, as shown in the screenshot of the modified tool and summary page, as an example in Figure 6.4.

In the current analysis, the costs of materials (aggregates, RAP, and asphalt binders) were obtained from the Oregon Department of Transportation, while the costs of additives were provided by the manufacturers. These are illustrated in Table 6.4 and the same has been used throughout the analysis to avoid any bias. The segment properties were hypothesized for the analysis, where the geometry was considered to be straight with a single lane length of 1.0 miles, a lane width of 12 feet, and a compacted layer thickness of 2.0 inches. The compacted density of the mix was assumed to be 145 lb/ft³.

	A	B	C	D	E
1	RAP & RAS Cost Calculator				
2	Mix Design				
3	Inputs:				
4	Product	Cost	Unit	Source	Type
5	Binder Type	\$ 500.00	ton	ODOT	PG 64-22
6	RAP	\$ 17.50	ton	ODOT	
7	RAS	\$ -	ton	ODOT	
8	Aggregate	\$ 17.50	ton	ODOT	
9	Additive	\$ 2,205.00	ton	Manufacturer	
10					
11	Segment Property	Measure	Unit	Source	
12	Geometry	Straight	-	Assumption	
13	Length	1.0	mi	Assumption	
14	Lane Width	12.0	ft	Assumption	
15	Number of Lanes	1.0	each	Assumption	
16	Compacted Layer Thickness	2.0	in	Assumption	
17					
18	Mix Property	Measure	Unit	Source	
19	Compacted Density	145.0	lb/ft ³	NAPA website	
20	Target Binder Content	6.12%	by weight	Estimate	
21	RAP Content	40.0%	by weight	Estimate	
22	RAS Content	0.0%	by weight	Estimate	
23	Aggregate Content	53.88%	by weight	Calculation	
24	Binder Content (RAP material)	4.97%	by weight	Estimate	
25	Binder Content (RAS material)	0.0%	by weight	Estimate	
26	Virgin Binder Added	4.13%	by weight	Calculation	
27	Virgin AC less Additive %	4.04%	by weight	Calculation	
28	Total Additive	2.22%	by weight of Virgin AC	Estimate	
29	Total Additive Quantity	0.09%	by weight of mix	Calculation	
30					
31	Outputs:	Measure	Unit		
32	Section Volume	10560	ft ³ (all lanes)	Calculation	
33	Section Tonnage	765.6	tons (all lanes)	Calculation	
34	Mix Cost	\$ 29,592.74	segment	Calculation	
35					
36	Burner Fuel + Oil Heater	0.3	Natural Gas mcf/ton	Estimate	
37	Price	\$ 5.50	mcf	Estimate	
38	Fuel Cost	\$ 1,263.24	segment	Calculation	
39					
40	Total Cost	\$ 30,855.98	segment	Calculation	

Figure 6.4a. Asphalt mix cost calculator interface (a) Example calculation page and (b) Example summary page

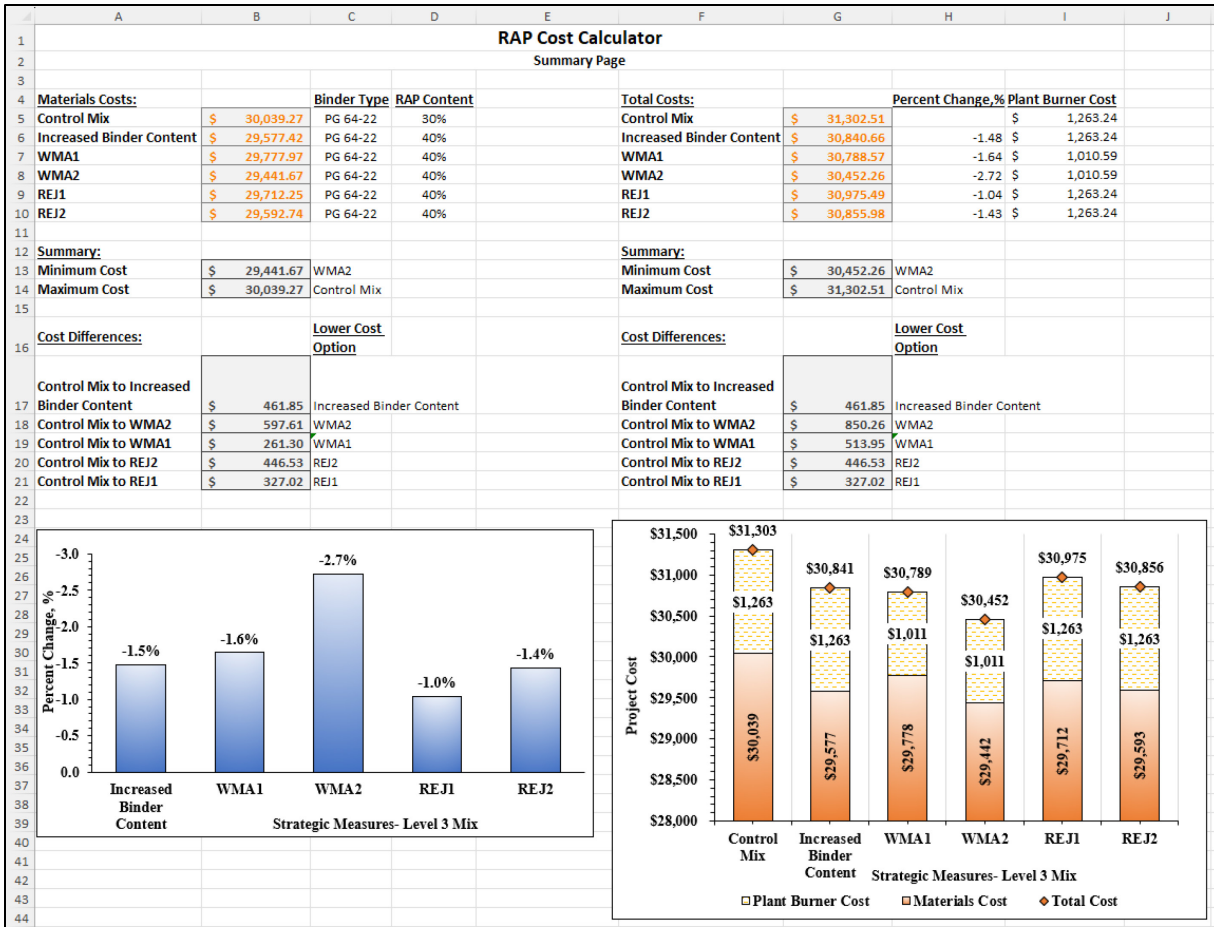


Figure 6.5b. Asphalt mix cost calculator interface (a) Example calculation page and (b) Example summary page

Table 6.4. Unit price of the material used for the cost analysis

Material Used	Price	Unit
Asphalt Binder (PG64-22)	\$ 500.00	per ton
Asphalt Binder (PG70-22ER)	\$ 590.00	per ton
Natural Aggregates	\$ 17.50	per ton
RAP	\$ 30.00	per ton
WMA1	\$ 2.75	per lb
WMA2	\$ 3.00	per lb
REJ1	\$ 1.00	per lb
REJ2	\$ 1.00	per lb
Burner Fuel (Natural Gas)	\$ 5.50	per mcf

6.4 RESULTS AND DISCUSSION

6.4.1 Preliminary Analysis for Environmental Burdens

In this study, a pavement LCA was conducted by considering two different binder grades, three RAP contents, and three binder contents to evaluate how changes in these mix attributes influence environmental burdens. Table 6.5 lists these chosen variables for the preliminary analysis. The purpose of this analysis was to identify the most influential factor in altering pavement LCA outcomes, so that greater emphasis can be placed on managing or reducing its associated impacts. The subsequent section reflects the observation based on the total impact (A1+A2+A3), considering materials production (A1), transportation (A2), and production (A3) stages.

Table 6.5. Selected factors for the preliminary analysis of pavement LCA

Factor	Values
RAP Content	20%, 30%, 40%
Binder Content	5.5%, 6.0%, 6.5%
Binder Type	PG64-22, PG70-22ER

GWP is primarily driven by the accumulation of greenhouse gases in the atmosphere, which directly contributes to climate change. The key pollutants responsible for GWP are carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O). Figure 6.5 illustrates the effect of these variables on GWP, which ranged from 59.23 kg CO₂-equivalent to 74.53 kg CO₂-equivalent, with a mean of 66.59 kg CO₂-equivalent, depending on the selected mix attributes. A general trend was observed in which higher binder content (varied from 5.5% to 6.5% in 0.5% increments) or polymer modification of the asphalt binder (PG70-22ER) led to increased GWP, while higher RAP content reduced it. For better comparison, the variation in GWP, due to the influential factors such as binder content, RAP content, and binder grade, is presented in Figure 6.6. This trend is further supported by the Pearson correlation coefficients (represented by 'r'), which show a stronger influence of binder content ($r = 0.787$), followed by binder grade ($r = 0.584$), while RAP content exhibits a negative correlation ($r = -0.192$), indicating its potential to reduce the overall GWP impact. The increase in GWP with binder content is attributed to the larger proportion of carbon-intensive asphalt binder, whose production requires high energy and pressure, resulting in higher GHG emissions.

Similarly, polymer modification raises GWP due to the additional energy required for chemical synthesis and processing of polymers compared to the PG64-22 binder. Conversely, incorporating RAP (varied from 20% to 40% in 10% increments) reduced the demand for virgin aggregates and asphalt binder, thereby lowering GWP. However, the relative difference in GWP remained less significant when the effects of the binder content and binder grade were considered, which can be attributed to the limited change in the proportions of virgin asphalt binder and aggregate relative to each other (20%, 30%, and 40% RAP).

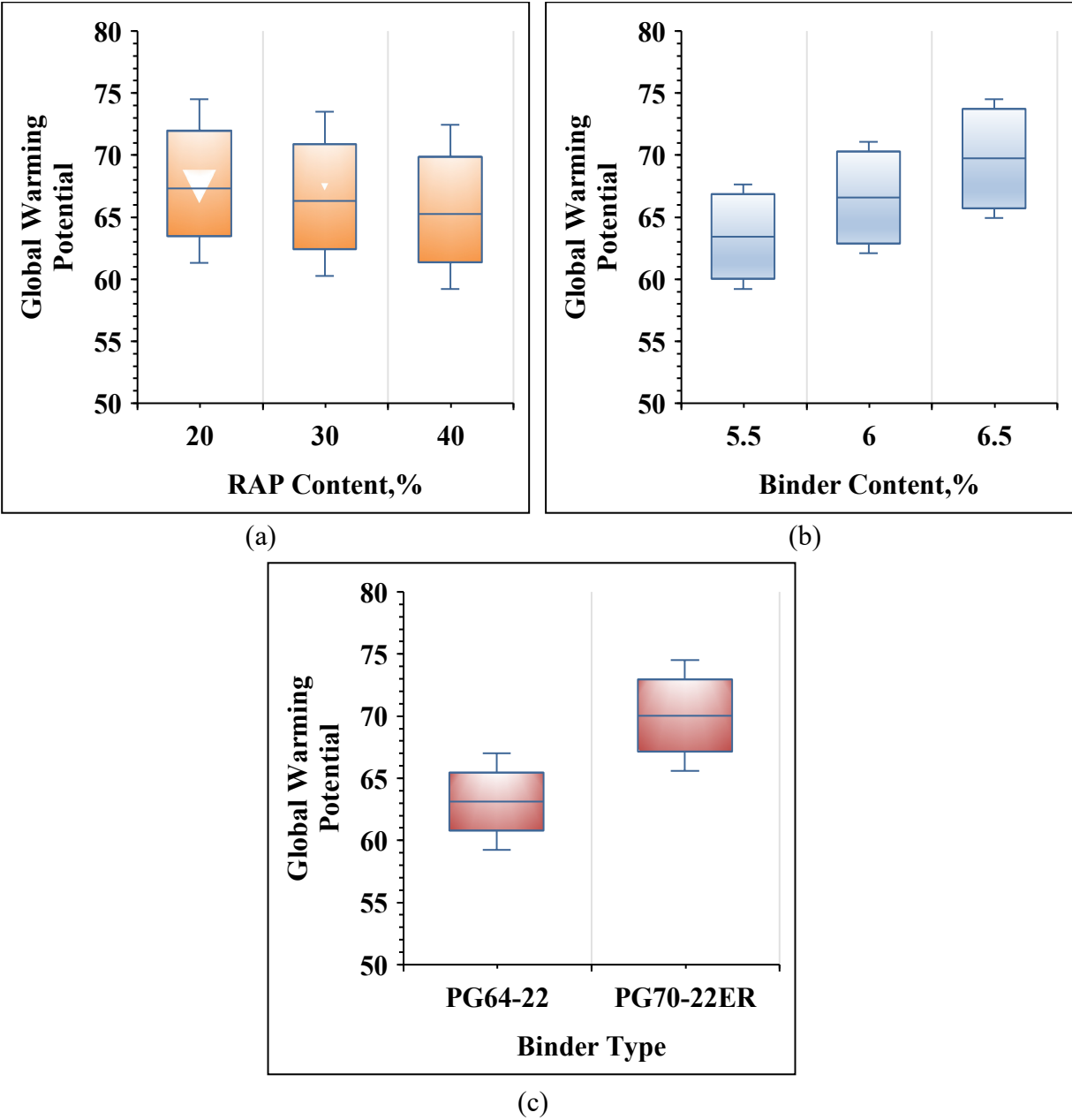


Figure 6.6. Influence of mix attributes on GWP (in kg CO₂-equivalents)

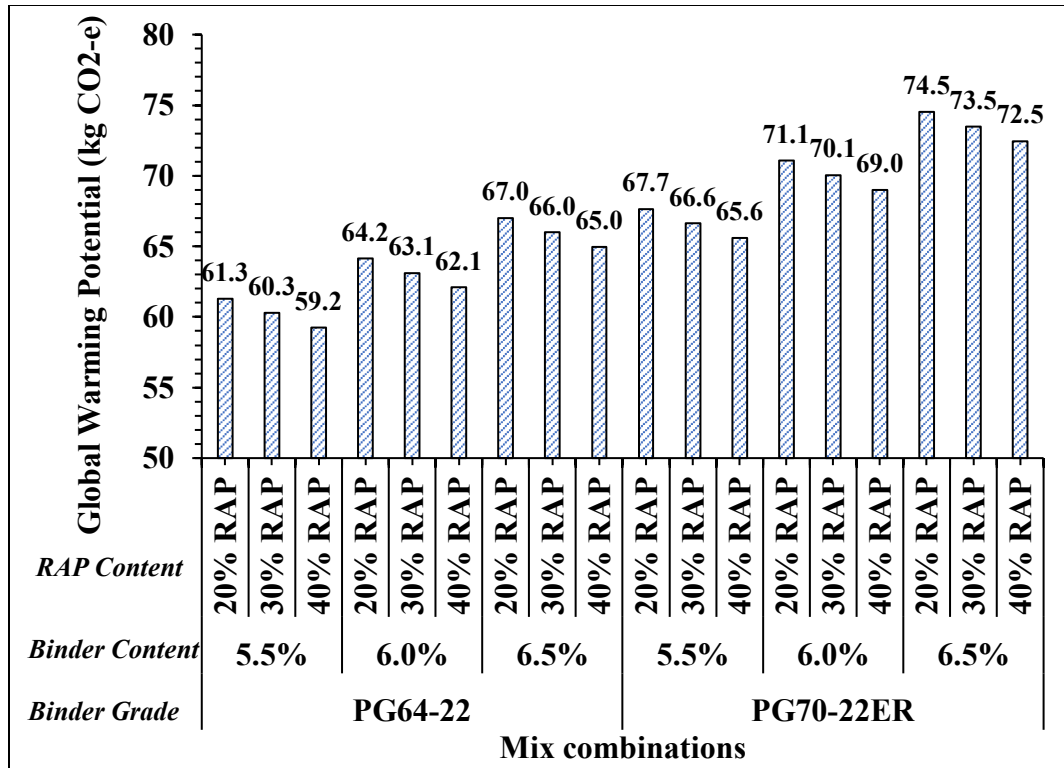


Figure 6.7. Complete dataset representing the variation in GWP

ODP quantifies the contribution of materials toward the depletion of the stratospheric ozone layer. The primary contributors are chlorofluorocarbons (CFCs) and other halogenated compounds containing chlorine and bromine, which are not typically associated with asphalt binder or aggregate production. Considering variations across all mix variables, the mean ODP was calculated to be $6.41\text{E-}08$ kg CFC-11-equivalent, ranging from $5.72\text{E-}08$ kg CFC-11-equivalent to $7.10\text{E-}08$ kg CFC-11-equivalent. As shown in Figure 6.7, the effects of increased binder content and change in binder grade were negligible ($r = 0.007$ for binder content and $r = 0.024$ for binder type), which can be attributed to the absence of ozone-depleting substances (e.g., CFCs) in their production processes. By contrast, an increase in RAP content resulted in a noticeable reduction in ODP, representing a very strong negative correlation with a Pearson coefficient of -1.00 . Although RAP itself does not contain halogenated compounds, this reduction is primarily attributed to the decreased transportation demand for virgin materials (binder and aggregates) from plants or quarries, which involves fuel use and auxiliary processes linked to ODP emissions. Since RAP is typically processed and reused on-site, higher RAP contents reduce the reliance on virgin materials, lowering both the number of transport trips and truckloads required. Consequently, ODP decreases with increasing RAP content.

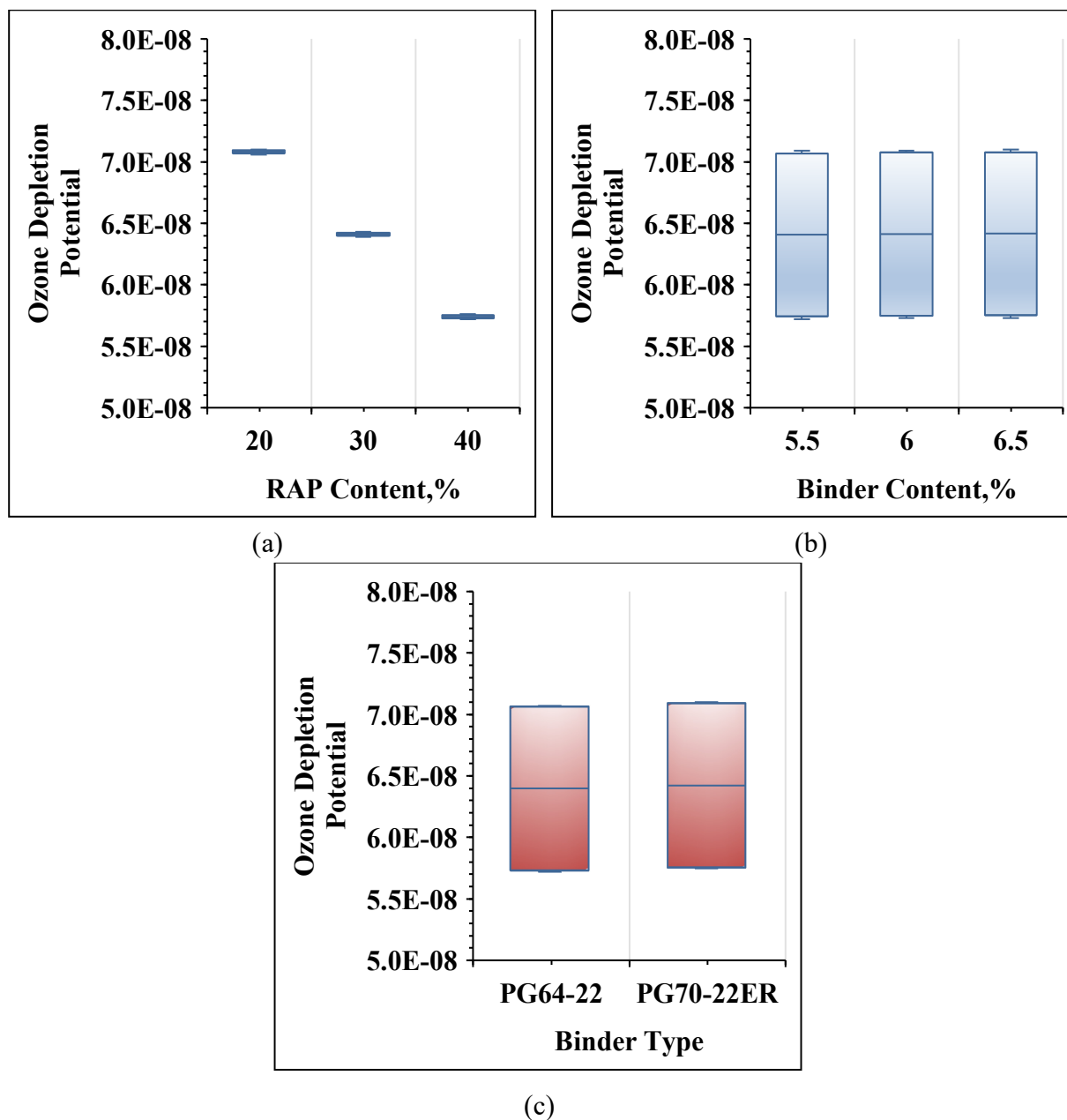


Figure 6.8. Influence of mix attributes on ODP (in kg CFC-11-equivalents)

EP represents the tendency of emissions to cause nutrient enrichment in water bodies and soils, primarily driven by nitrogen oxides (NO_x) and phosphates (PO₄³⁻). In this study, the calculated EP values ranged from 0.013 to 0.020 kg N-equivalent, depending on the mix attributes, as shown in Figure 6.8. The variation was mainly associated with binder grade ($r = 0.940$), where mixtures prepared with PG64-22 exhibited lower EP compared to those with polymer-modified PG70-22ER, due to the higher energy requirements and chemical processing of polymers, which can involve nitrogen-based compounds. An increase in binder content (from 5.5% to 6.5% in

0.5% increments) also led to slightly higher EP values, primarily due to greater energy consumption during binder production and associated NO_x emissions; however, the effect remained modest, with a Pearson coefficient of 0.324. In contrast, incorporating RAP (20-40% in 10% increments) generally reduced EP by decreasing the demand for virgin binder and aggregates, and lowering fuel consumption from long-distance material transport. However, the relative reduction was not very significant ($r = -0.082$), since the incremental change in RAP content was limited. Despite the overall low absolute EP values, these impacts are environmentally critical because of their potential to deteriorate water quality.

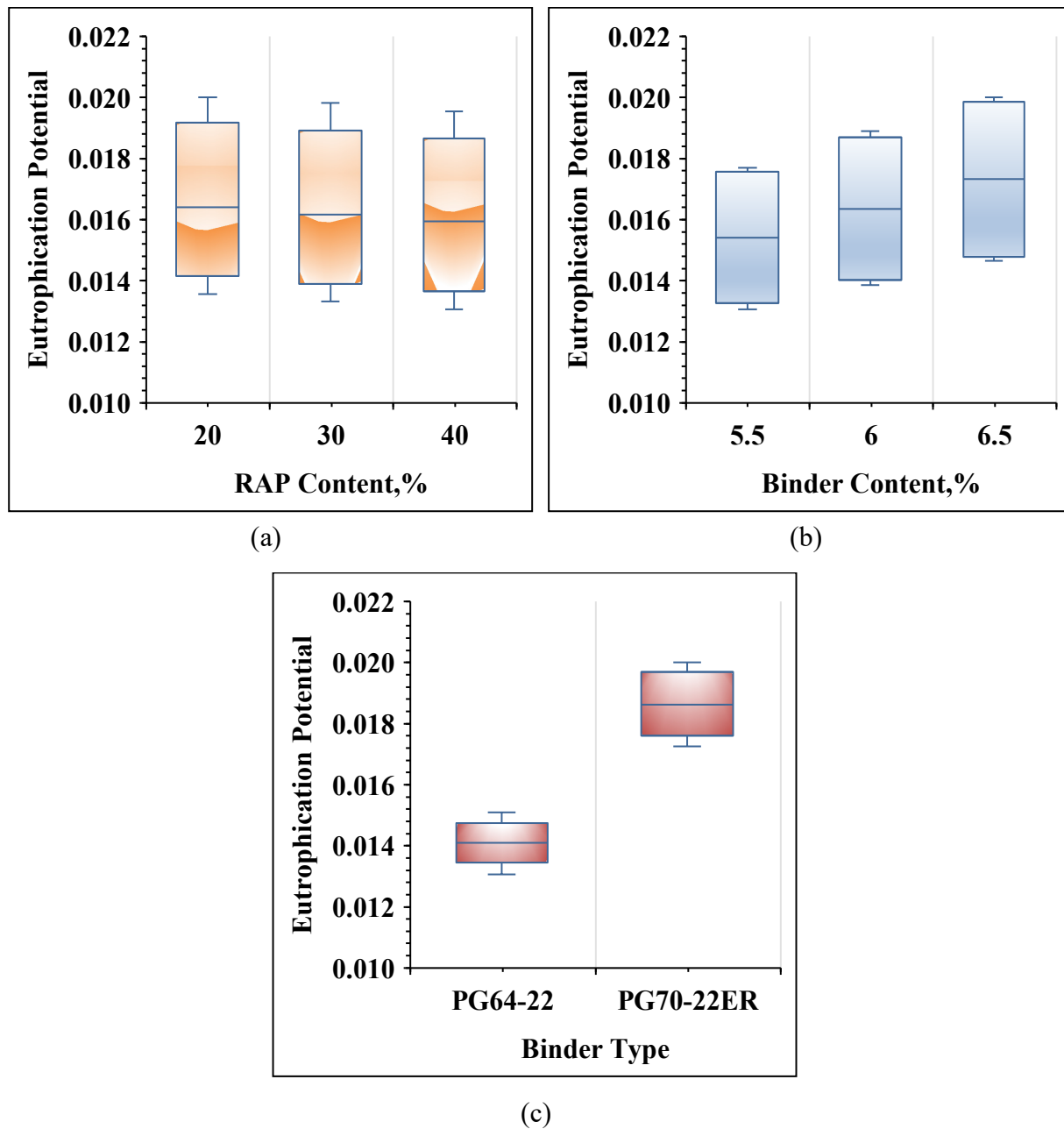


Figure 6.9. Influence of mix attributes on EP (in kg N-equivalents)

AP indicates the potential for emissions to contribute to acid rain as a result of chemical releases into the atmosphere, which can affect ecosystems and infrastructure. Sulfur oxides (SO_2), Nitrogen oxides (NO_x), and Ammonia (NH_3) are the major sources of AP. In the analysis presented in Figure 6.9, changing the binder grade, binder content and RAP content resulted in AP value ranging from 0.166 kg SO_2 -equivalents to 0.211 kg SO_2 -equivalents, with an average value of 0.187 kg SO_2 -equivalents. Similar to the trends observed for EP, a higher amount of binder content and polymer modification leads to the emission of sulphur-based compounds along with nitrogen (as observed in EP impact), thereby increasing AP and consequently affecting ecosystem and pavement infrastructure. As per the Pearson correlation coefficient, the effect of binder type is more prominent ($r = 0.752$) compared to binder content ($r = 0.582$). On the other hand, the use of higher RAP offered a benefit by lowering the AP value, mainly due to the lower sulphur-related emissions across the cradle-to-gate process. The corresponding Pearson correlation reveals a moderate negative correlation with an r value of -0.305.

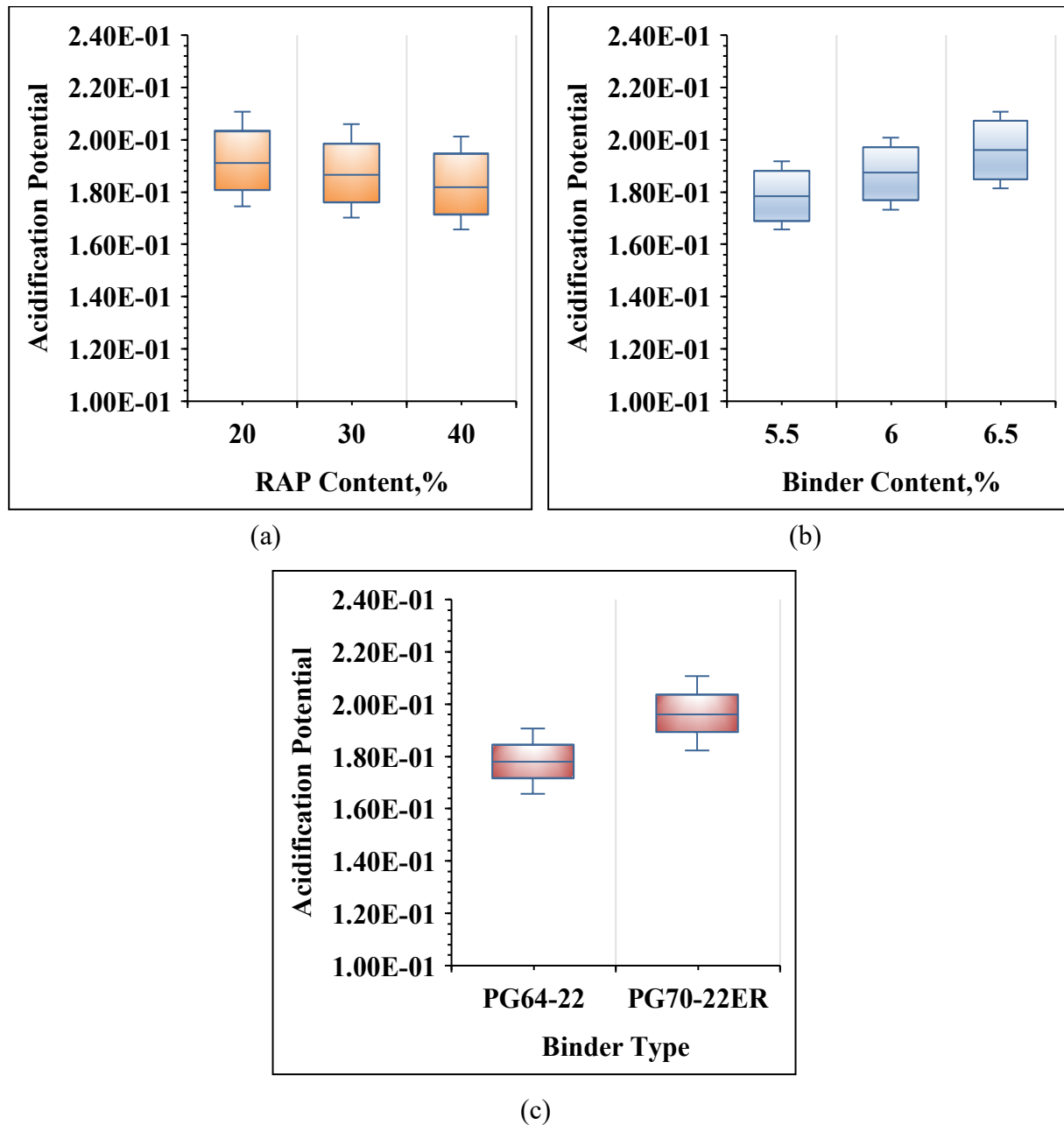


Figure 6.10. Influence of mix attributes on AP (in kg SO₂-equivalents)

POCP is a potential that provides insights into the formation of ozone through the emitted substances due to the photochemical reaction in the presence of sunlight. These emitted substances generally include volatile organic compounds (VOC) and nitrogen oxides (NO_x), both of which are harmful to human health, the ecosystem, and the climate. In general, a significant amount of VOC and NO_x are released during the production of asphalt mixtures, making the assessment of POCP a critical aspect of pavement LCA. Since these emissions are closely linked to mix production, higher binder contents and the use of polymer-modified asphalt

mixtures generally result in higher POCP values, as additional energy input and processing lead to increased VOC and NO_x emissions. This increases the amount of emissions released from the burners, leading to higher smog. However, their impact can be lowered with the use of higher RAP content in the production of asphalt mixtures, as it reduces the quantity of raw material production and its use. Unlike other impact categories, the correlation analysis (Figure 6.10) shows that POCP is influenced by multiple factors rather than dominated by a single one. The calculated Pearson correlation coefficients of 0.704 (binder type), 0.559 (binder content), and – 0.434 (RAP content) confirm that binder characteristics and content tend to increase POCP, while higher RAP levels exhibit a moderate negative correlation, indicating a mitigating effect on smog-related impacts.

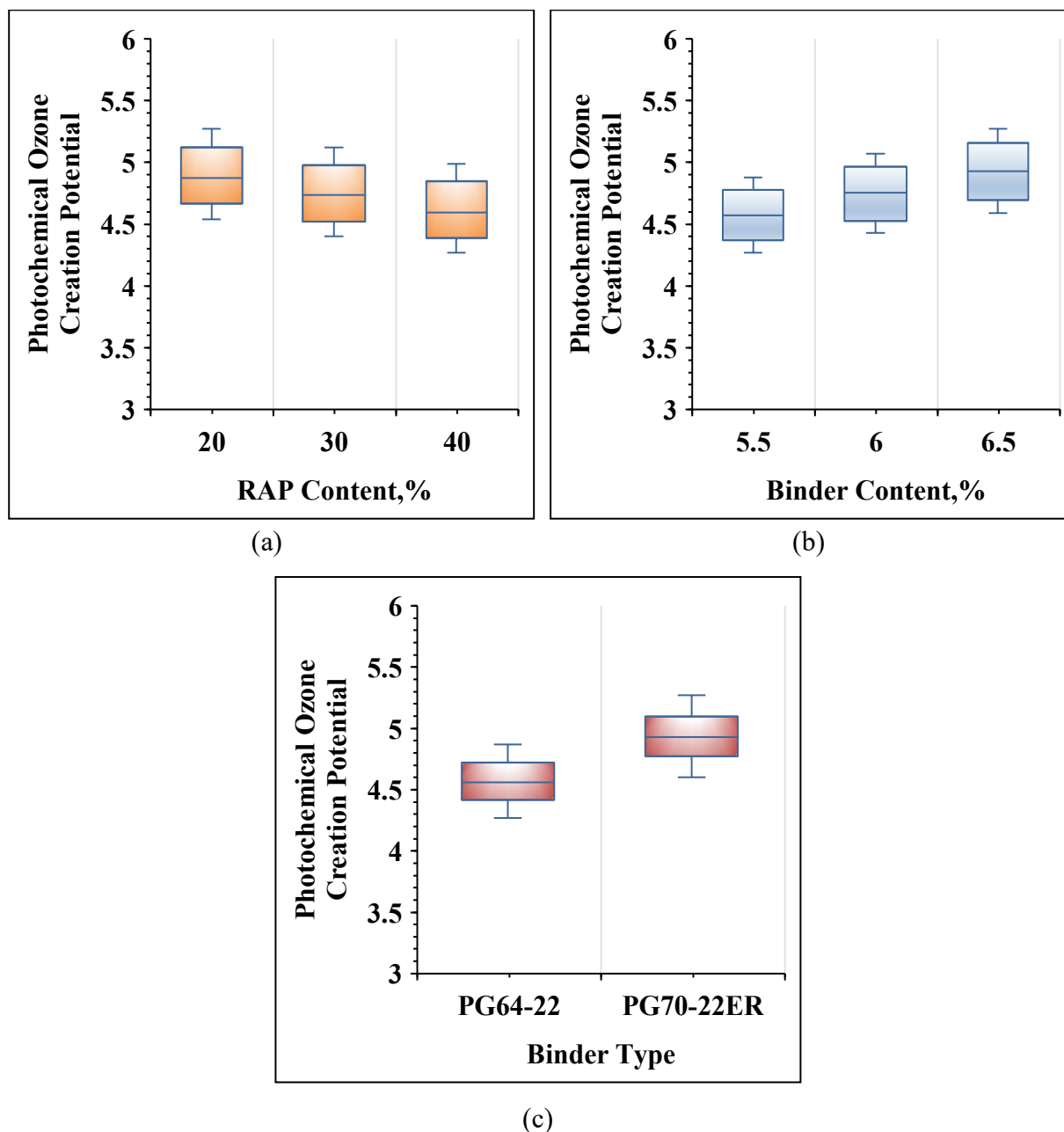


Figure 6.11. Influence of mix attributes on POCP (in kg O₃-equivalents)

Based on the analysis, all the investigated mix parameters influence the overall GHG emissions, although the magnitude of their impact varies depending on the specific environmental potential. The above analysis was based on the total emissions, and it is evident that all factors have a significant influence on each phase of the cradle-to-gate system, namely the raw material production (A1), transportation (A2), and manufacturing (A3) stages. Across most categories, the raw material production phase (A1) contributed the largest share of emissions (49-72%), followed by the manufacturing phase (16-32%) and transportation (10-22%) within the cradle-to-gate system boundary, as demonstrated in Figure 6.11. However, this trend was not consistent for

ODP, where the majority of emissions (61%) originated from the transportation of materials. This deviation is attributed to the fact that pavement materials such as asphalt binder and aggregates do not inherently contain halogenated compounds, whereas the fuel consumed during material transport contributes to ODP-related emissions. Excluding ODP, the dominance of the material production phase highlights the critical role of material selection in reducing GHG emissions, underscoring the need for careful evaluation of binder type, binder content, and RAP incorporation in sustainable pavement mix design.

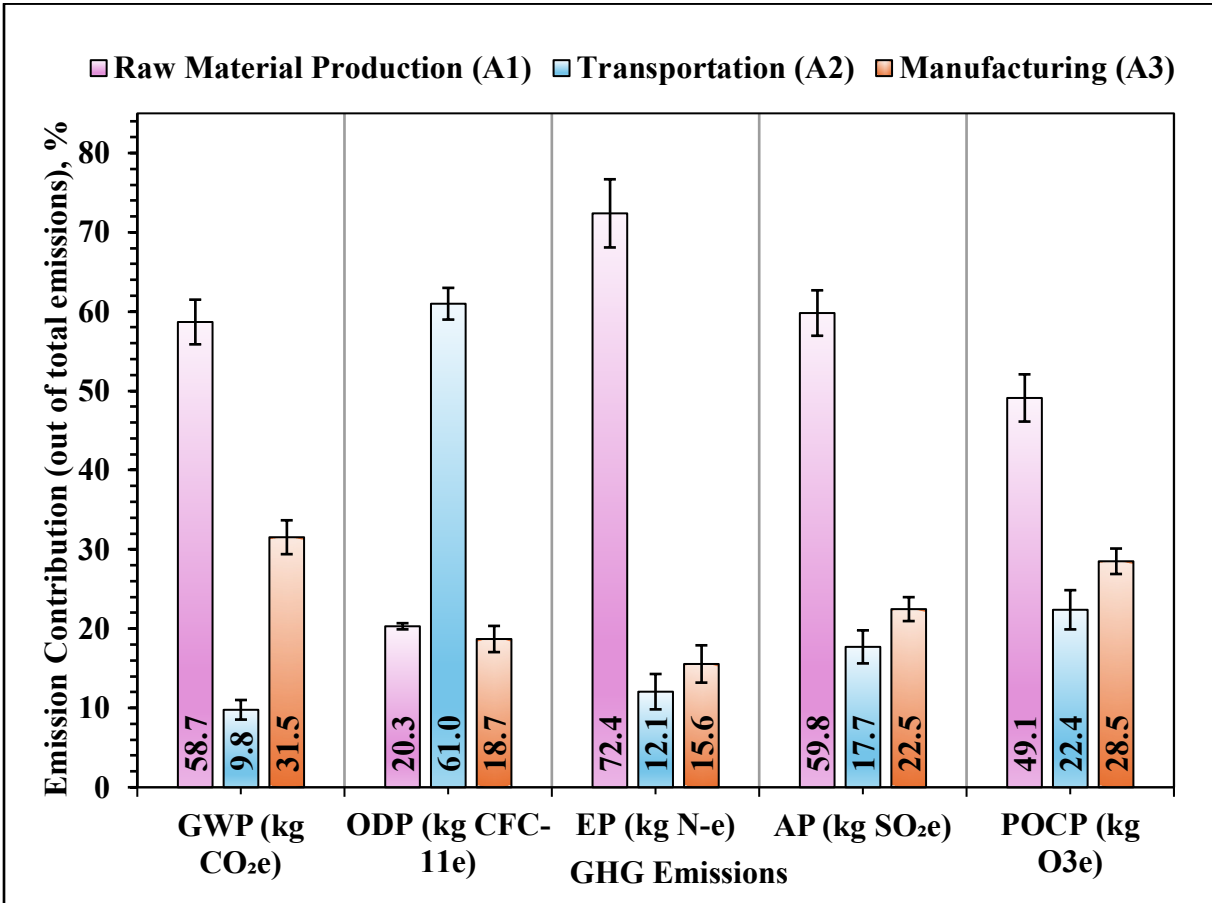


Figure 6.12. Contribution of different cradle-to-gate phases on the total GHG emissions

Among the different environmental potentials discussed above, the higher absolute values of emissions were obtained for GWP, which is dominated by the large amount of CO₂, CH₄, and N₂O during the cradle-to-gate process of pavement LCA. These greenhouse gases are released at a massive and unavoidable scale compared to other harmful emissions (Moretti et al. 2017). While the absolute value of GWP is far higher than the other environmental potentials, their impact and understanding are environmentally important as they directly influence the water bodies, ecosystem, infrastructure durability, soil condition, human health, urban smog, climate change, and overall atmosphere. Considering that GWP exhibits the most significant impact during asphalt pavement construction, the comparative evaluation of RAP-incorporated mixtures in the subsequent section was therefore carried out primarily on the basis of GWP values. This

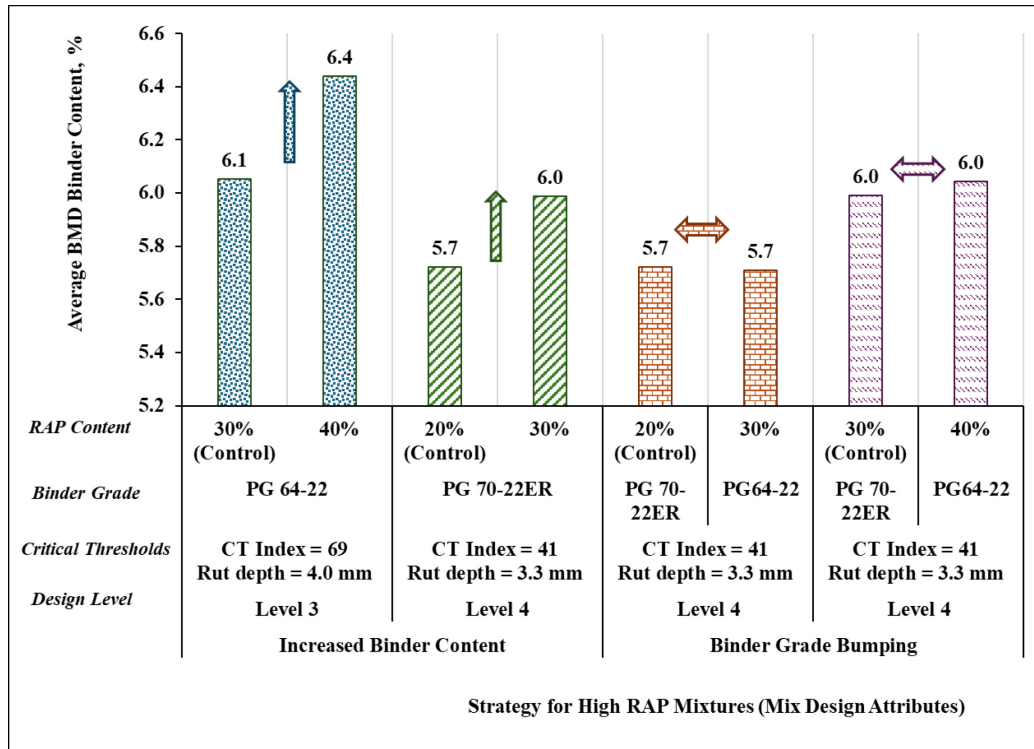
focus is justified as GWP reflects the effect of mix design factors on global warming, with key pollutants (CO₂, CH₄, N₂O) contributing to the overall environmental burden.

6.4.2 Impact of Different Strategic Techniques on Pavement LCA

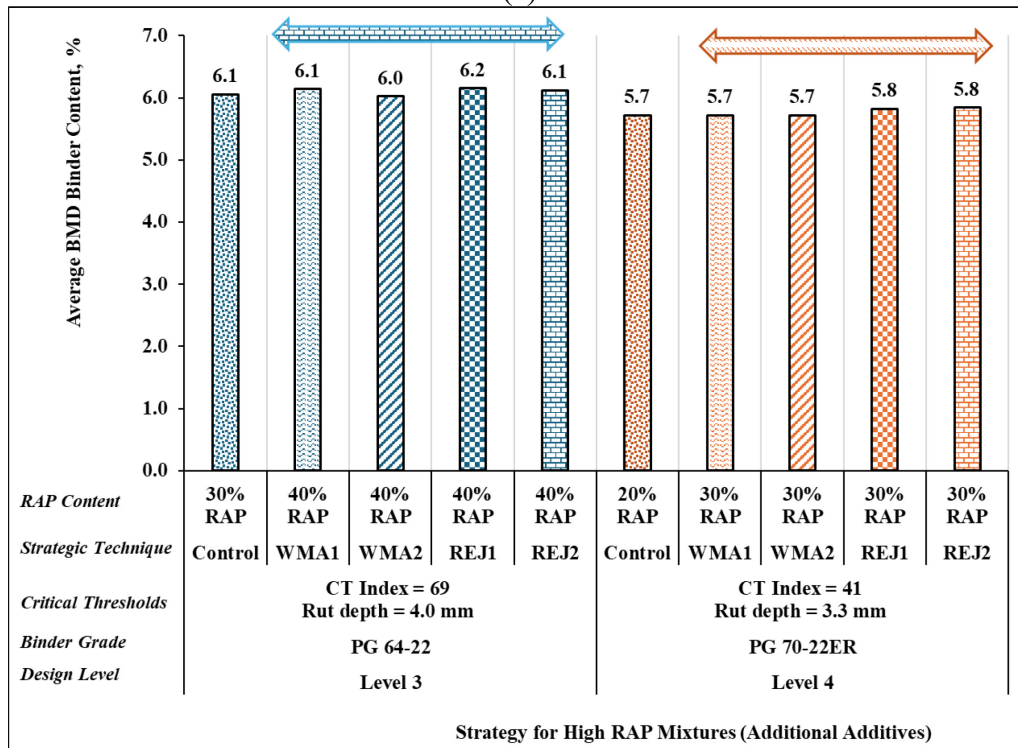
Given that there is a noticeable effect of RAP content, binder content, and binder type on the cradle-to-gate-pavement LCA, it is crucial to determine how these impacts are further affected by the adoption of different strategic techniques aimed at enhancing RAP utilization. These strategic techniques include changes in mix design attributes (binder content and binder grade bumping), use of rejuvenators (REJ1 and REJ2), and the application of warm mix asphalt technologies (WMA1 and WMA2). The qualitative and quantitative characteristics of the selected rejuvenators and WMA technologies can be found in Chapter 3.0. To assess their effects, mixtures with high RAP contents (40% in Level 3 and 30% in Level 4) were analyzed and compared with reference mixtures in each design level (30% RAP with PG64-22 in Level 3 and 20% RAP with PG70-22ER in Level 4). Notably, the effect of binder grade bumping was only examined for Level 4 mixtures, where the binder grade was bumped by one grade from PG70-22ER to PG64-22 to assess the effect of using a softer grade.

6.4.2.1 Integration of Balanced Mix Design

To ensure comparability across all mixtures at the same boundary level, the LCA was conducted using the balanced mix design (BMD) binder contents determined for each asphalt mixture as part of another project sponsored by the Federal Highway Administration (FHWA) through the Accelerated Implementation and Deployment of Pavement Technologies (AID-PT) program. It should be noted that the BMD binder content was determined using the critical thresholds of CT Index and rut depths developed for Oregon (Chitnis et al. 2025). These thresholds were estimated based on statistical analysis of the data set obtained from testing various plant-produced asphalt mixtures (Chitnis et al. 2025). Different thresholds were established depending on the mix design levels. These thresholds were also validated in the laboratory by testing several laboratory-mixed and laboratory-compacted (LMLC) specimens, as well as constructing field pilot sections. Figure 6.12 illustrates the value of optimum binder contents and the adopted critical thresholds for all combinations of RAP-inclusive asphalt mixtures.



(a)



(b)

Figure 6.13. Balanced mix design binder content for different asphalt mixtures (a) prepared by changing mix design attributes and (b) produced using additional additives

At the same boundary level (expecting identical performance), the results showed that increasing the binder content just by 0.39% in the Level 3 control mix (30% RAP mix) and 0.26% in Level 4 control mixes (20% RAP mix) leads to an improvement in the allowance limit of RAP content by 10%. Unlike the increased binder content strategy, the difference in binder content for one grade lower asphalt mixtures was calculated to be minimal, with a maximum difference of 0.06% between mix combinations having 40% RAP with PG64-22 binder and 30% RAP with PG70-22ER binder. This suggests that high RAP mixtures (10% higher than the current limits) can be prepared by simply increasing the asphalt binder grade without altering the amount of design binder content, potentially leading to a further reduction in cost compared to the increased binder content strategy.

Similarly, the use of additional additives, such as rejuvenators and WMA, also enables 10% higher RAP incorporation with only a minimal difference in their optimal binder content determined through BMD, as perceived in Figure 6.12. This outcome is attributed to the fact that several high-RAP mixtures demonstrated improved performance, and when evaluated against the critical thresholds, the BMD binder contents for high-RAP mixtures were found to be comparable to those of the reference mixtures within each mix design level. It is expected that the additional additives will improve the blending of RAP binder with the virgin binder, thereby compensating for the total binder demand and enhancing performance. As a result, even with increased RAP incorporation, the required binder content remained unchanged when assessed based on the BMD performance criteria.

6.4.2.2 Discussion on the variation in GHG Emissions for different strategic techniques

As stated previously, WMA mixtures were produced at 25°C lower temperatures than HMA, resulting in reduced energy consumption and fuel usage. According to previous studies (NASEM 2014; Williams et al. 2024), the use of WMA technologies is expected to achieve energy savings of approximately 1000–1100 Btu/°F/ton. In the present data inventory, natural gas was identified as the primary fuel for asphalt mixture production in Oregon. Accordingly, when the production temperature was reduced by 25 °C, the consumption of natural gas in both the burner and oil heater was assumed to decrease by 20%. The adjusted energy and fuel consumption values for WMA mixtures are provided in Table 6.2.

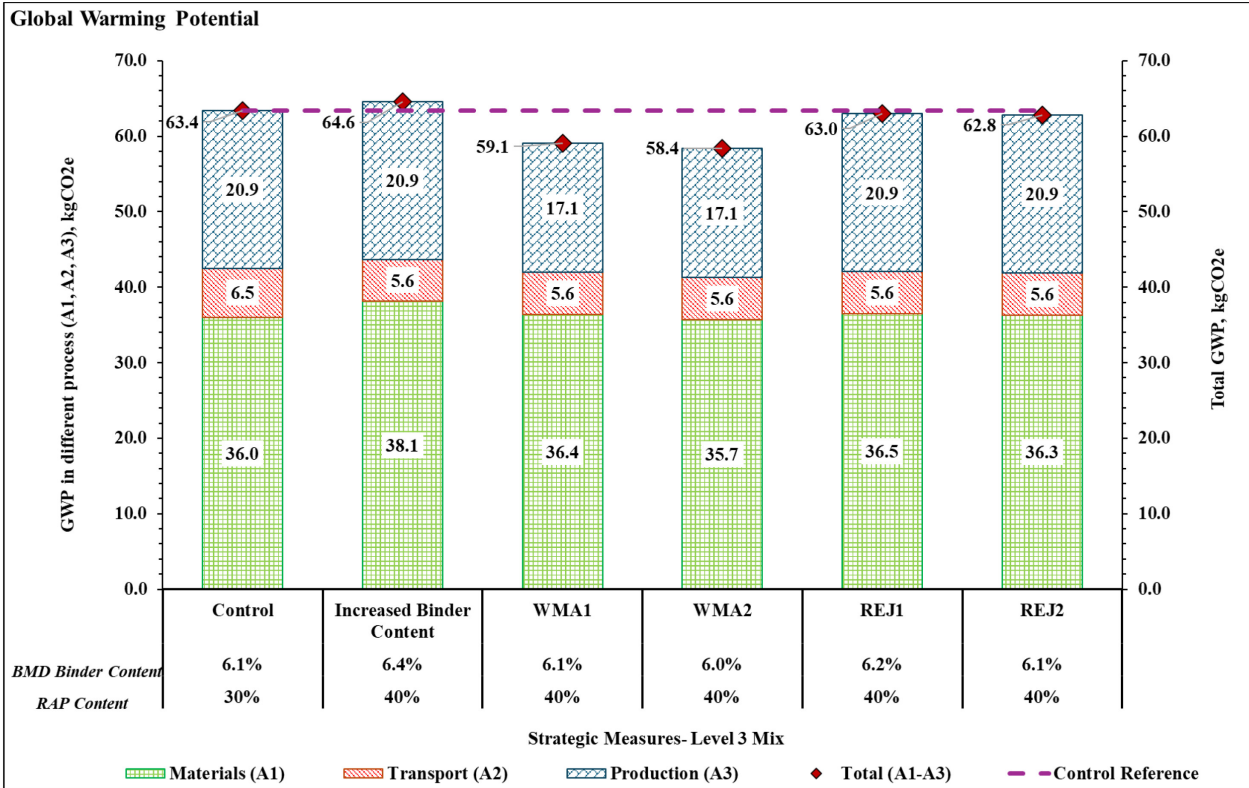
For the evaluation of GHG emissions, a few assumptions were made and kept constant throughout the analysis in order to avoid any bias. These assumptions include that RAP is processed and stored onsite, and the materials (aggregates and asphalt binder) are transferred using a truck from a distance of 50 miles (one-way). The quantities of RAP and asphalt binder, shown in Figure 6.12, were used, and the amounts of natural aggregates were adjusted accordingly for the present LCA.

Figure 6.13 represents the influence of strategic techniques on the GWP. It was found that these strategic techniques either lower the GWP values or at least maintain them at levels comparable to those of reference mixtures, especially due to the increased RAP content. Consistent with the Figure 6.11, the majority of emissions originated from the

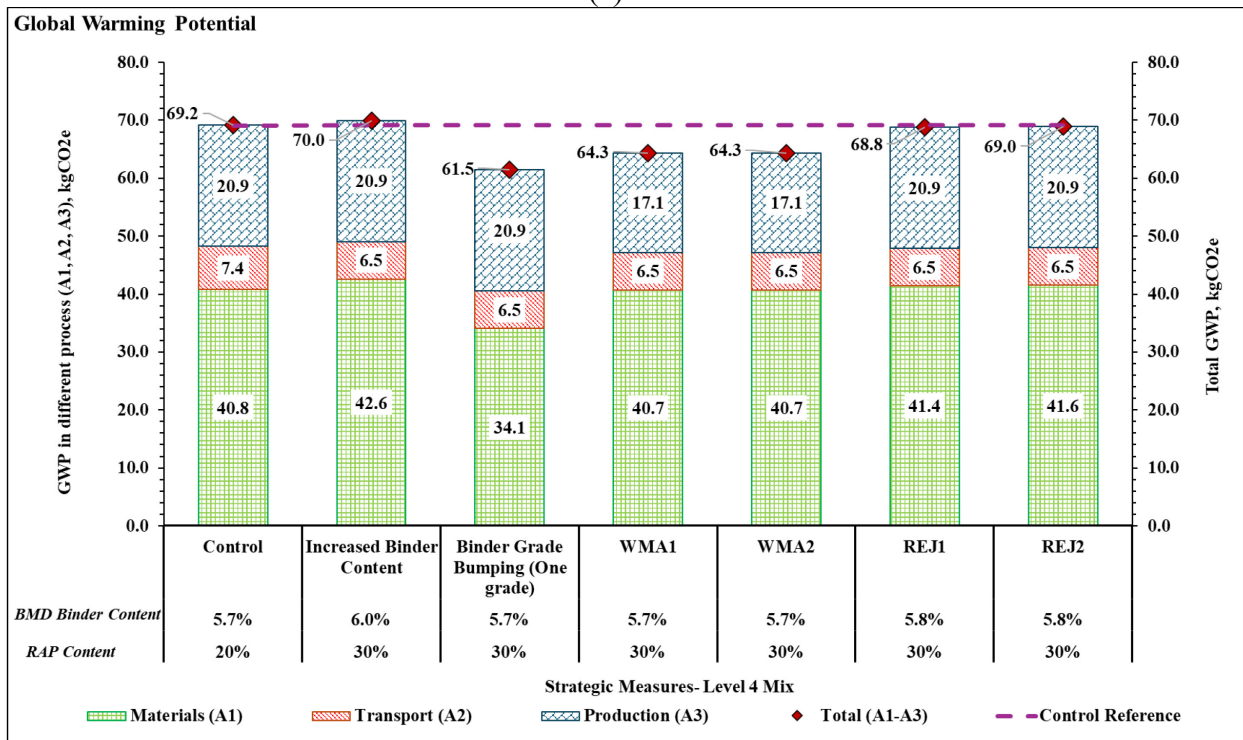
material production phase, followed by the manufacturing and transportation phases. These trends were found to be consistent in both the mix design levels with all the strategic techniques. In particular, a lower value of GWP in the manufacturing phase of WMA mixtures is attributed to the lower production temperature (25°C less than HMA), which decreases the consumption of burner fuel and oil heating, thereby significantly reducing GHG emissions. Except for WMA, all the asphalt mixtures exhibit a similar range of GHG emissions during the manufacturing phase, as the same production temperatures and fuel consumption were required for both control and rejuvenator-based mixtures.

Comparison of the transportation phase (50 miles one way using truck) reveals that the highest emissions were associated with the movement of virgin materials (aggregates and asphalt binder), with a value ranging from 6.5 kgCO₂e for the Level 3 mix (30% RAP mix with 6.1% binder content) and 7.4 kgCO₂e for the Level 4 mix (20% RAP mix with 5.7% binder content). All the other mixtures within their respective design levels exhibited similar transportation emissions, as RAP contents were held constant across those groups. The higher values in the reference mixtures are explained by the greater demand for virgin binder and aggregates, which required longer transportation distances, whereas RAP was processed within the plant itself. Considering the most dominant influence of the material phase, which provides the clearest insights into the suitability of these strategic techniques, the observed differences can be attributed to variations in BMD binder content and RAP incorporation across mixtures relative to their reference counterparts.

This finding aligns with the preliminary analysis conducted in this study, which identified binder content as the most influential parameter, compared to RAP content and binder type. Even small variations in BMD binder content can substantially affect GWP and, consequently, total GHG emissions. This highlights the necessity of exploring alternative binders, using additives to increase RAP content, and reducing reliance on carbon-intensive virgin binders in asphalt mixture production. This is clearly observed in the case of increased binder content, where, despite having a higher RAP content than the control mixtures, the strategic technique resulted in higher GWP due to the increased binder content (by as little as 0.39% in Level 3 and 0.26% in Level 4). This outcome underscores the rationale for conducting the preliminary analysis, which provides a foundation for understanding the relative significance of each influential parameter and how they alter GHG emission trends.



(a)



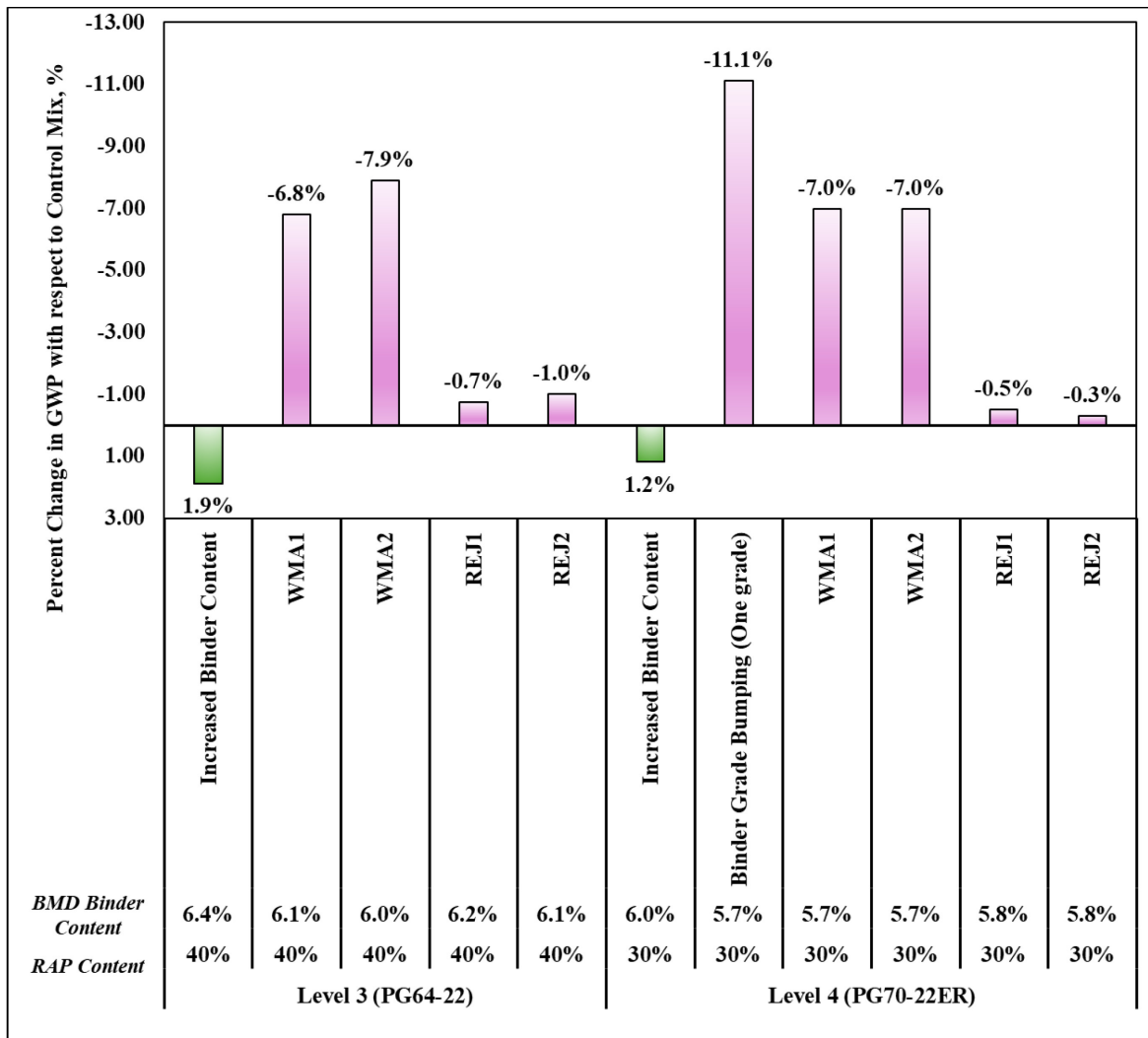
(b)

Figure 6.14. Variation in GWP with the use of different strategic techniques (a) Level 3 mix design and (b) Level 4 mix design

Figure 6.14 presents the percent change in the GWP values associated with the use of strategic techniques for increasing the allowable RAP content. In Level 3 mixtures, greater savings were observed in WMA mixtures since they reflect the dual benefits by both reducing the production temperatures and allowing for increased RAP incorporation compared to the reference mix. Depending on the WMA technology, the reduction in GWP ranged from 7–8%. This was followed by the use of rejuvenators, where the benefits are less than 1%. The limited improvement in this case is explained by the slight increase (up to 0.1% from the control samples) in BMD binder content for rejuvenator-modified mixtures, where the additional binder contributed GHG emissions equivalent to the reductions gained from higher RAP utilization.

On the other hand, in Level 4 mixtures, binder grade bumping proved to be the most effective technique, reducing GWP by around 12% compared to the reference mix. This is attributed to the effect of the polymer-modified binder in Level 4 mix, which involves additional energy for chemical synthesis and processing of polymers compared to the PG64-22 binder. The next most effective strategy was the use of WMA, which reduced GWP by about 7%, followed by rejuvenators, which offered only marginal benefits (<0.5%). Notably, the present analysis does not account for the GWP of the additives themselves; however, their production does result in some emissions. This suggests that binder grade bumping is comparatively more efficient than these commercial technologies.

In both the mix design levels, an increase in binder content facilitated the incorporation of higher RAP; however, the environmental burden associated with asphalt binder offset this benefit, resulting in a slight increase in carbon emissions (1-2%). This outcome stems from the fact that higher binder contents necessitate additional quantities of carbon-intensive asphalt binder, resulting in increased energy consumption during refining and production, which indirectly enhances the environmental impact. Overall, these observations align with the preliminary analysis, reaffirming that the careful selection of binder type, binder content, and RAP content is critical for producing sustainable asphalt mixtures. Although there is limited improvement in GHG emissions, it is advisable to quantify the material costs to select the most effective strategic techniques at both mix design levels, considering both economic and environmental aspects.



Note: Negative value indicates a reduction in emissions, and a positive value denotes an increase in emissions.

Figure 6.15. Percentage change in the total GWP with the use of different strategic techniques

Although the above discussion revealed the change in GWP with the adoption of strategic techniques, improvements were also observed in other impact categories, including ODP, AP, EP, and POCP. Their corresponding percentage change relative to the control mixtures (30% RAP in Level 3 and 20% RAP in Level 4) is summarized in Table 6.6. Consistent with the trends observed in GWP, the use of strategic techniques facilitated 10% higher RAP incorporation while generally reducing environmental burdens. However, the magnitude of reduction is a function of both the strategic techniques and the specific impact category. Interestingly, even though the increased binder content technique showed higher emissions in terms of GWP, it achieved approximately 10% savings in ODP across both mix design levels. This improvement is primarily linked to the reduced transportation demand for virgin materials, as high-RAP mixtures with increased binder content required about 10% less virgin material, thereby lowering ODP-related emissions. The overall analysis indicated that each strategic technique exerts a

different influence across environmental categories, and thus, their selection should be made carefully.

Table 6.6. Percentage change in emission relative to reference mixtures in each design level

Mix Design Level	RAP Content	BMD Binder Content	Strategic Technique	ODP	EP	AP	POCP
Level 3	40%	6.4%	Increased Binder Content	-10.5%	2.7%	<i>0.7%</i>	-0.2%
Level 3	40%	6.1%	WMA1	-10.8%	-2.9%	-4.5%	-5.9%
Level 3	40%	6.0%	WMA2	-10.8%	-4.2%	-5.6%	-6.8%
Level 3	40%	6.2%	REJ1	-10.5%	-0.6%	-1.5%	-2.2%
Level 3	40%	6.1%	REJ2	-10.5%	-0.9%	-2.1%	-2.4%
Level 4	30%	6.0%	Increased Binder Content	-9.4%	2.3%	<i>0.2%</i>	-0.6%
Level 4	30%	5.7%	Binder Grade Bumping (One grade)	-9.9%	-25.1%	-11.3%	-9.9%
Level 4	30%	5.7%	WMA1	-9.7%	-2.7%	-5.1%	-6.3%
Level 4	30%	5.7%	WMA2	-9.7%	-2.7%	-5.1%	-6.3%
Level 4	30%	5.8%	REJ1	-9.4%	<i>0.1%</i>	-1.4%	-2.0%
Level 4	30%	5.8%	REJ2	-9.4%	<i>0.1%</i>	-1.4%	-1.8%

Note: Negative value indicates a reduction in emissions, and a positive value (in Italics) denotes an increase in emissions.

6.4.2.3 Discussion on the variation in material cost with different strategic techniques

The cost of RAP mixtures is generally lower than that of asphalt mixtures prepared exclusively with virgin materials such as natural aggregates and asphalt binder, largely due to the higher cost of these virgin resources (Sukhija and Coleri 2025c). Recognizing this, ODOT began exploring strategies to reduce material costs by incorporating sustainable alternatives and refining mix design practices. Previous efforts of ODOT, in collaboration with the Oregon State University (OSU), demonstrated that costs can be reduced through the use of sustainable materials or by adopting balanced mix design (BMD) approaches, which allow higher RAP proportions in asphalt mixtures while maintaining adequate performance and improving sustainability (Coleri et al. 2018a, 2020; Kumar et al. 2021). More recently, research conducted by the OSU-AMaP research group highlighted that reducing pavement roughness levels can further lower user costs and enhance sustainability, with additional benefits expected when sustainable materials are integrated into the mix design (Coleri et al. 2025). In line with this perspective, ODOT initiated studies to identify strategic techniques for increasing allowable RAP

content without compromising performance. These strategies include increasing binder content, binder grade bumping, the use of rejuvenators, and WMA technologies (Sukhija and Coleri 2025c).

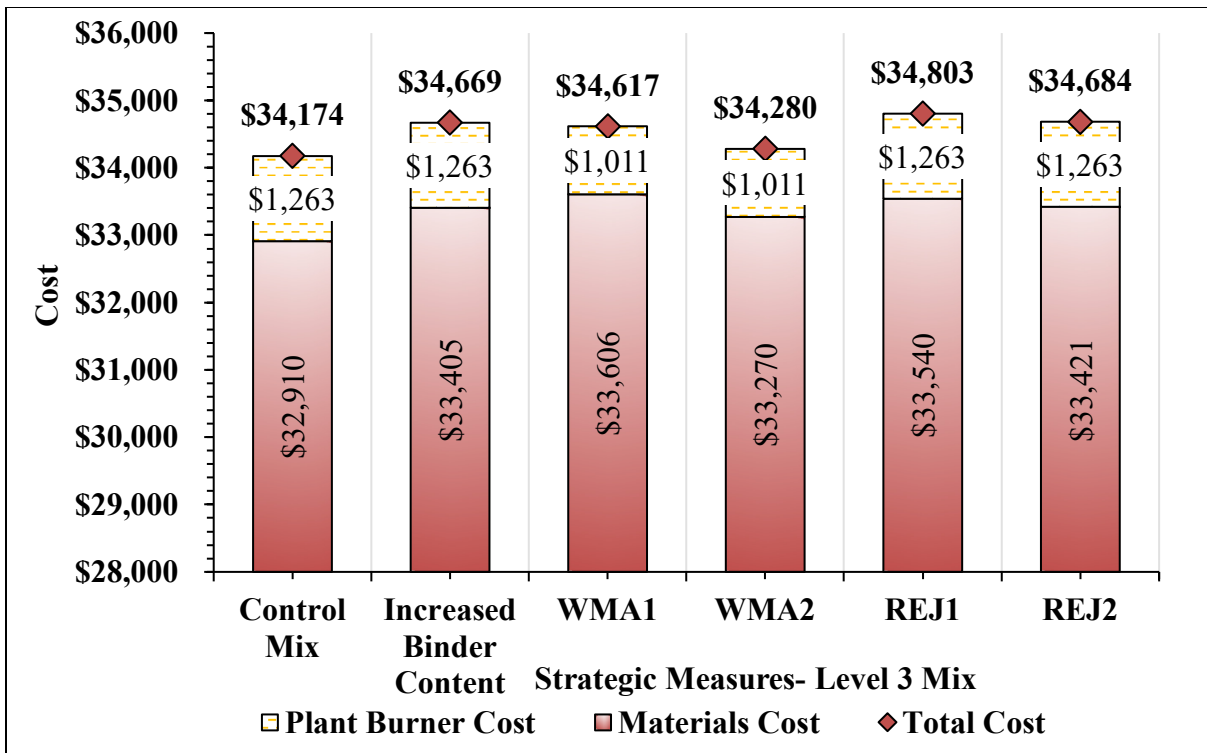
In this study, a comprehensive evaluation was carried out by incorporating these strategies to enable 10% higher RAP content in Level 3 and Level 4 mixtures relative to their current allowable limits (30% RAP in Level 3 and 20% RAP in Level 4). Performance evaluations presented in earlier chapters demonstrated that all the strategic techniques supported higher RAP incorporation while maintaining performance comparable to, or in some cases, better than that of the respective reference mixtures at both mix design levels. Furthermore, the preceding section established that these strategies are environmentally sustainable but warrant further investigation from an economic perspective. Cost analysis is particularly important to assess whether the expense of additives can be offset by the cost savings achieved through increased RAP utilization. Since the difference between the reference RAP contents and high-RAP mixtures is only 10%, the expected savings are not as substantial as when comparing against mixtures containing no RAP. Additionally, this study incorporated the effect of burner fuel savings associated with WMA technologies, which lower energy consumption by reducing production temperatures.

For cost comparison between different alternatives, the assumption on the section geometry is kept constant. The section length, lane width, number of lanes, and compacted layer thickness were assumed as 1 mile, 12 feet, single lane, and 2 inches, respectively. Based on this geometry, section tonnage was calculated to be 765.6 tons.

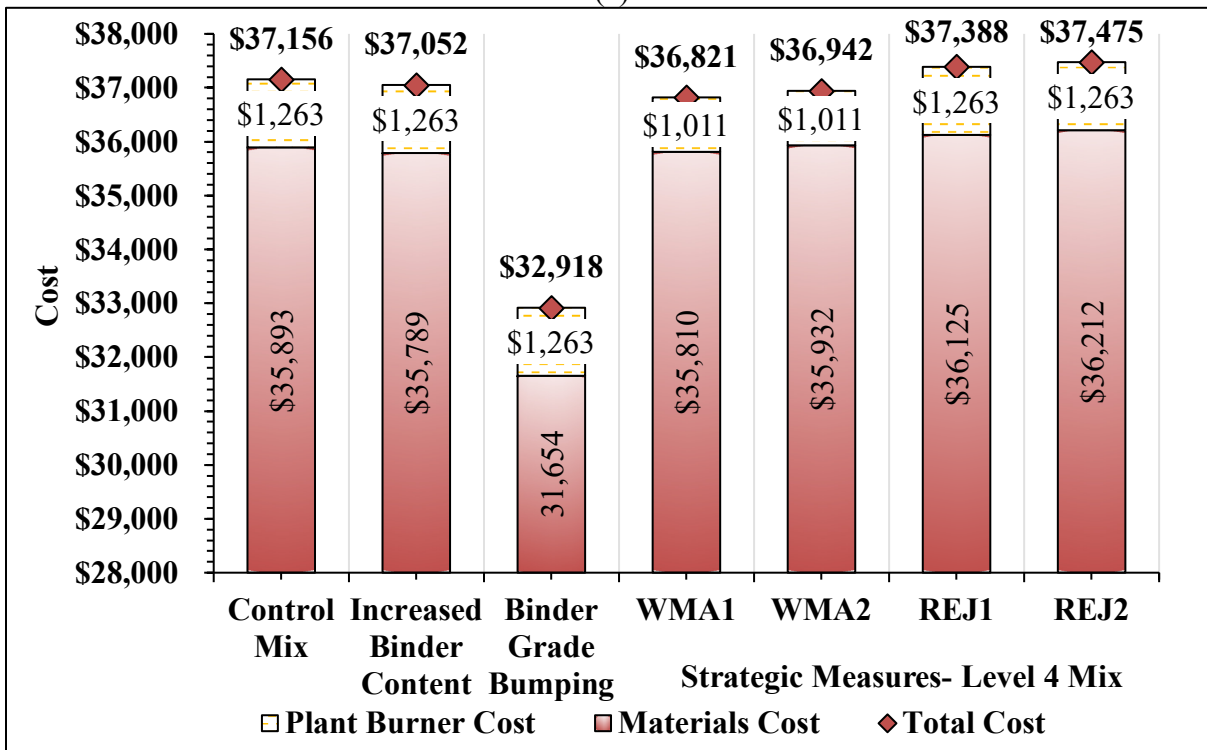
Figure 6.15 presents the cost calculation for various asphalt mixtures along with their corresponding percentage change in the Level 3 and Level 4 categories. In the Level 3 category, none of the strategic techniques provided cost savings; however, the application of WMA2 for high-RAP mixtures resulted in costs comparable to those of the control mixture. The adoption of other strategies resulted in a slight increase in cost, ranging from 1.3% to 1.8%, as demonstrated in Figure 6.16. Among the strategies, WMA technologies were the most effective, followed by the increased binder content strategy and the use of rejuvenators in the Level 3 category. The increased costs are primarily attributed to the higher price of additives, which cannot be fully offset by increasing the RAP content from 30% to 40%.

In the Level 4 category, the lowest cost was observed for mixtures prepared using a softer binder grade (binder grade bumping strategy). In this case, the total cost was reduced from \$37,156 to \$32,918, representing a significant reduction of approximately 11.4%. Although the burner fuel costs were the same as those in the control mixtures (Figure 6.15), the cost savings are linked to the use of PG64-22 binder (\$500/ton) in place of the more expensive PG70-22ER binder (\$590/ton). This outcome highlights that binder grade is a major contributor to total cost. In addition, the application of other strategic techniques resulted in costs that were approximately similar to those of the control mixtures, with less than 1% variation. Although RAP content was increased by 10% through the use of rejuvenators, this strategy was the least effective compared to binder grade bumping, WMA technologies, and increased binder content, largely due to slightly

higher BMD binder contents in rejuvenator mixes combined with the relatively high cost of rejuvenators. Additionally, the plant burner cost in the rejuvenator mixtures is comparable to that of the control samples due to similar production temperatures and fuel consumption. This explains the minimal difference in total cost and highlights how production temperature and fuel use influence overall cost- one of the key advantages of WMA mixtures. In fact, the adoption of WMA technologies provided dual benefits: a 7-8% reduction in GHG emissions and the conservation of natural resources with almost the same cost as control mixtures. From a cost perspective, the primary difference observed with WMA mixtures, regardless of the specific technology, stemmed from the lower plant burner fuel requirements associated with their reduced production temperatures.

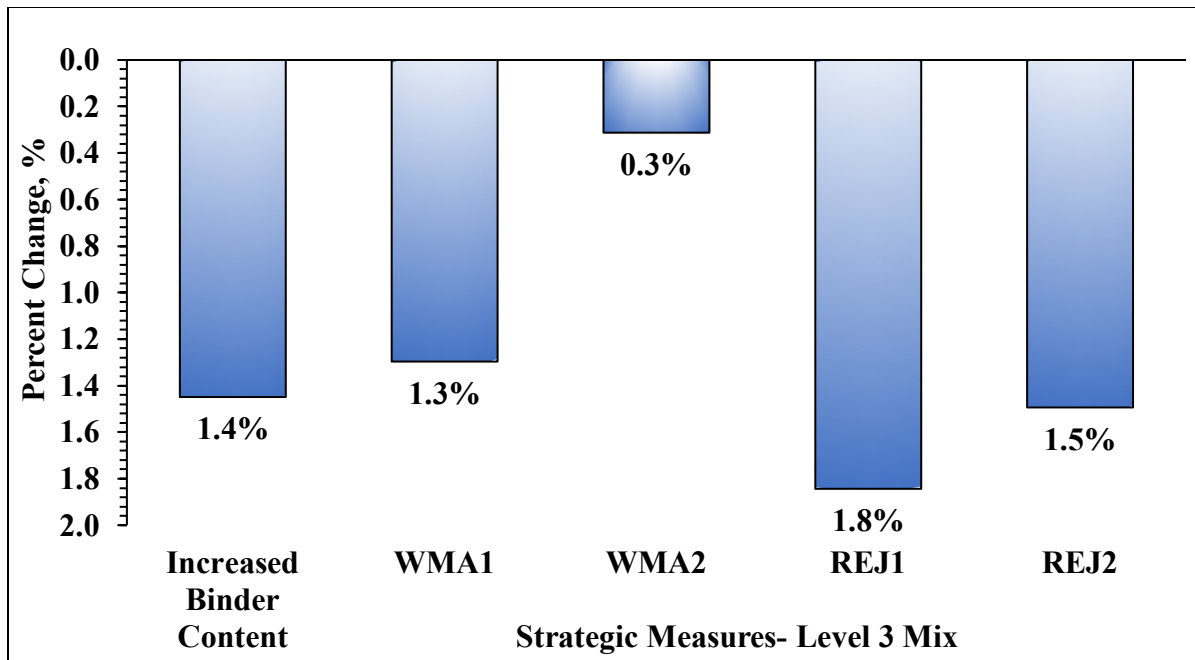


(a)

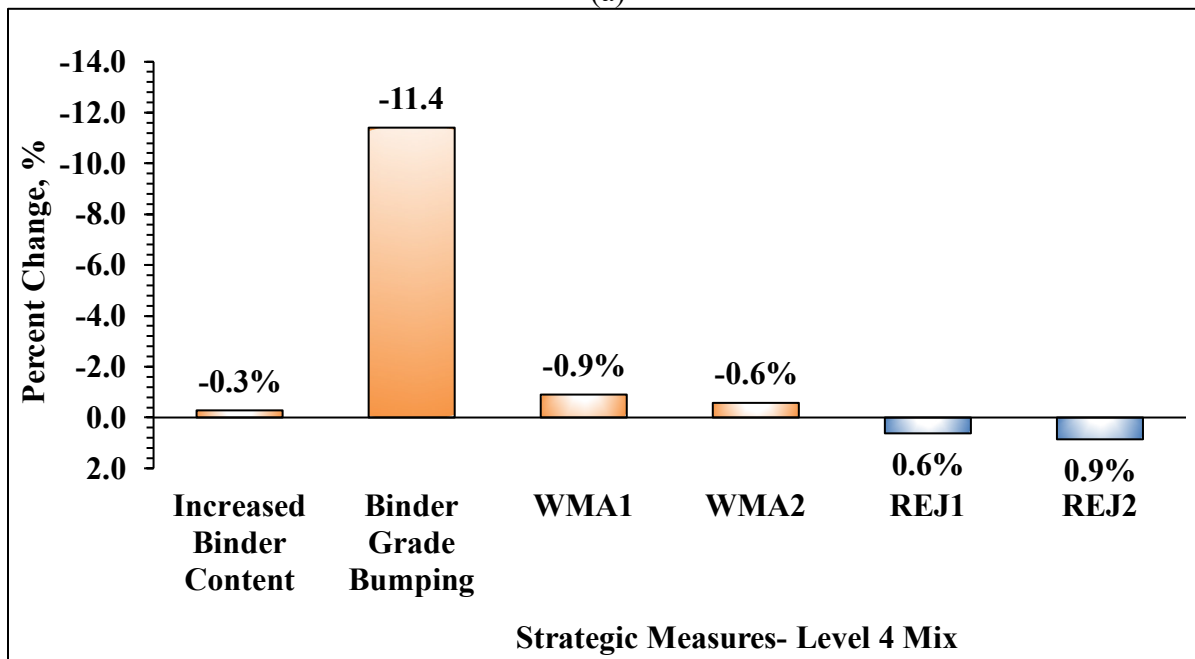


(b)

Figure 6.16. Cost calculation for RAP mixtures with different strategic techniques (a) Level 3 and (b) Level 4 (Note: RAP cost is \$30 per ton)



(a)



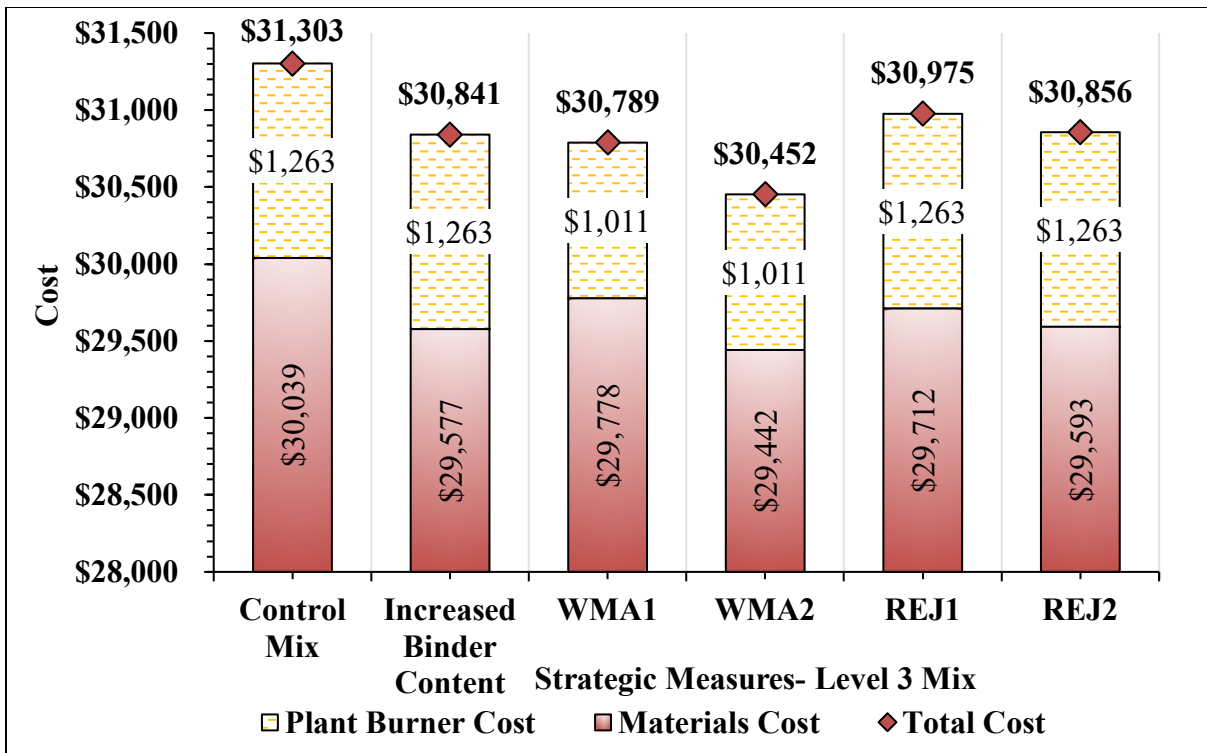
(b)

Figure 6.17. Percent change in the total cost relative to control mixtures (a) Level 3 and (b) Level 4 (Note: RAP cost is \$30 per ton)

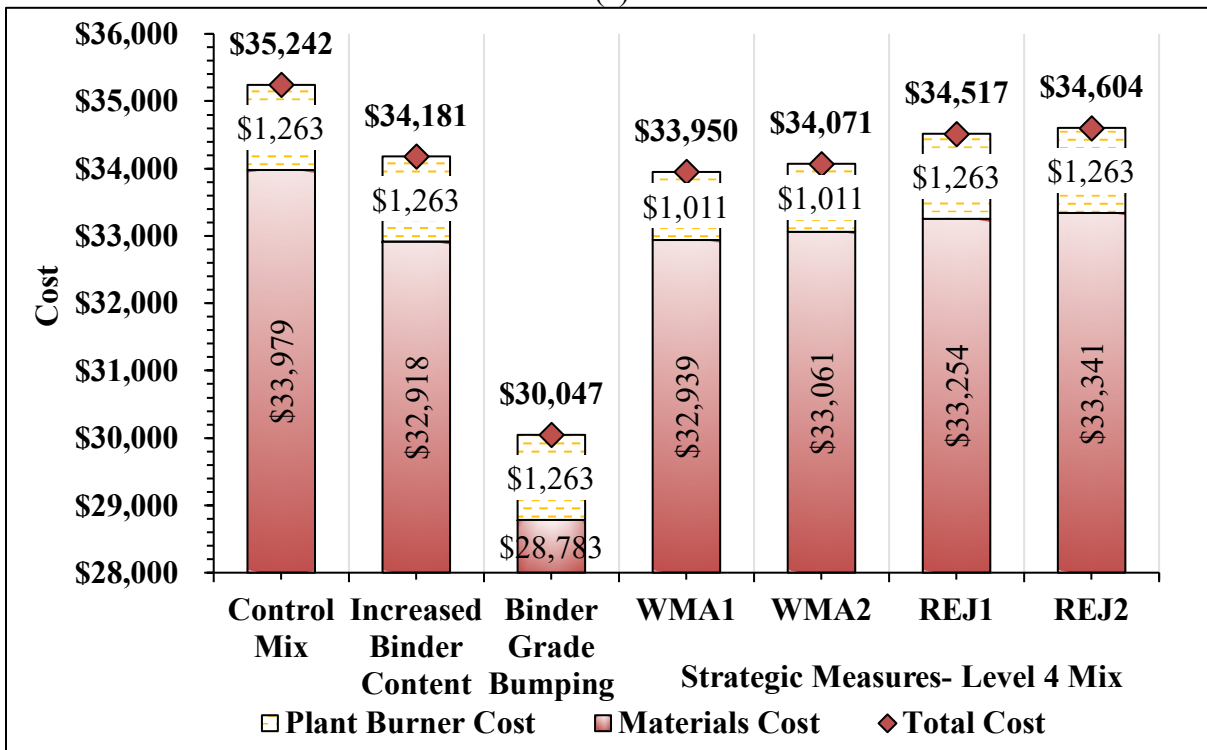
In addition to the cost of binder and additives, the cost of RAP selected for this analysis was relatively high (\$30 per ton) compared to natural aggregates (\$17.5 per ton), which may partly explain the limited cost-effectiveness of high-RAP mixtures. Although RAP content was increased by 10%, the elevated unit price of RAP may not have been sufficient to offset the additional costs associated with the strategic techniques. Since the

RAP cost is dependent on several factors, including processing requirements, material condition, and hauling distance between the plant and milling site, an additional assessment was carried out to evaluate total cost variations for high-RAP mixtures under the assumption that RAP is priced equivalently to natural aggregates (\$17.5 per ton). This analysis provides further insight into the extent to which RAP cost influences overall project cost when strategic techniques are employed for high-RAP mixtures. If the results are favorable, particular emphasis should be placed on reducing RAP processing costs in conjunction with other material costs to improve the economic feasibility of sustainable asphalt mixtures.

Figure 6.17 presents the cost calculation under the assumption that RAP is priced the same as natural aggregates (\$17.5 per ton). Under this scenario, unlike the earlier discussion, the application of any strategic technique was found to be cost-effective, yielding savings for high-RAP mixtures. In the Level 3 category, the use of WMA technologies was most cost-effective ($WMA2 > WMA1$), whereas in the Level 4 category, binder grade bumping proved most profitable, resulting in a reduction of approximately 14.7% in total costs. Across both design levels, the total cost of Level 4 mixtures remained higher than that of Level 3 mixtures, largely due to the relatively higher cost of asphalt binder and the lower RAP content in Level 4 mixtures. The comparison between rejuvenators and WMA technologies revealed consistent trends: WMA mixtures were more cost-effective than rejuvenator-based mixtures, primarily due to their lower production temperatures and reduced burner fuel requirements. As shown in Figure 6.18, the corresponding reductions achieved with WMA1, WMA2, REJ1, and REJ2 ranged from 1.6-3.7%, 2.7-3.3%, 1.0-2.1%, and 1.4-1.8%, respectively, depending on the mix design level. Similarly, increasing asphalt binder content by 0.39% in Level 3 and 0.26% in Level 4 to accommodate 10% higher RAP resulted in cost reductions of 1.5% and 3.0%, respectively.

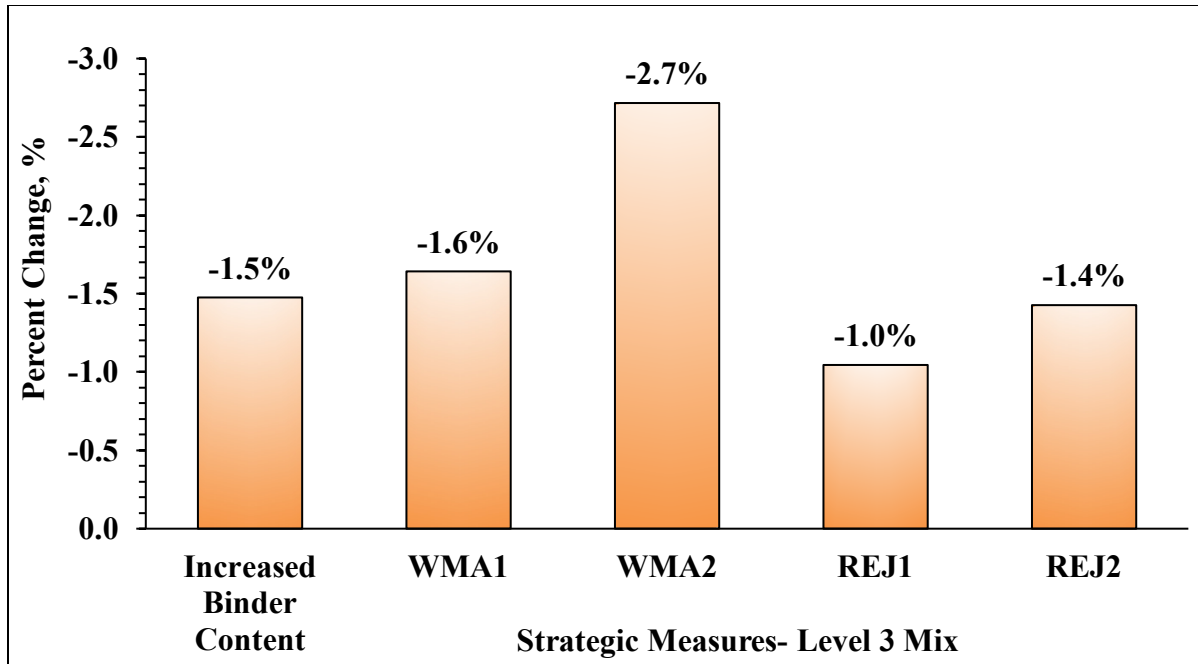


(a)

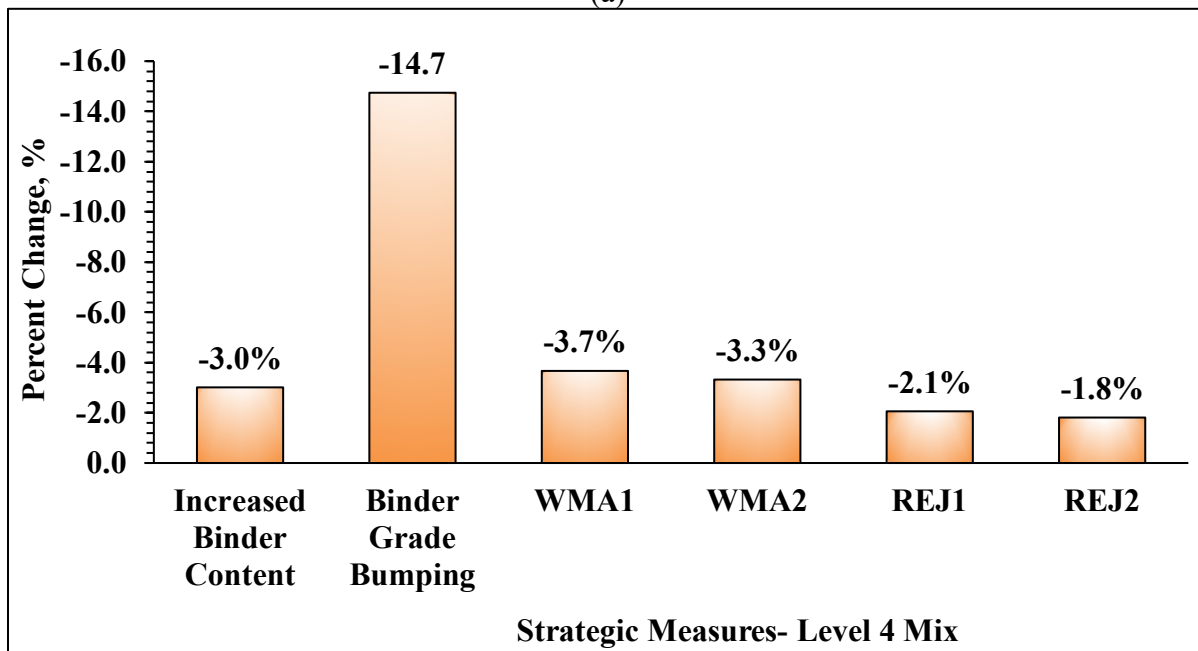


(b)

Figure 6.18. Cost calculation for RAP mixtures with different strategic techniques (a) Level 3 and (b) Level 4 (Note: RAP cost is \$17.5 per ton)



(a)



(b)

Figure 6.19. Percent change in the total cost relative to control mixtures (a) Level 3 and (b) Level 4 (Note: RAP cost is \$17.5 per ton)

This analysis underscores the critical role of RAP pricing in influencing project cost and highlights the need for decision-makers to consider RAP valuation when advancing circular economic practices and sustainability in road infrastructure. It should be noted that the present analysis was conducted just to compare different strategic techniques using unit prices provided by ODOT and additive manufacturers.

Nevertheless, actual project costs may vary depending on the mix attributes, additive type and dosage, unit prices, and section dimensions.

6.5 SUMMARY AND CONCLUSIONS

Increasing urbanization is driving higher demand for road infrastructure, which in turn places greater pressure on natural resources. A critical concern associated with this demand is the depletion of these resources, which must be minimized to ensure long-term sustainability. Moreover, the extraction of aggregates and refining of asphalt binder not only consumes significant resources but also increases both economic and environmental burdens. To address this, a preliminary analysis was conducted to examine the influence of mix design attributes, namely binder type, binder content, and RAP content, on GHG emissions. At the same time, state agencies are actively seeking alternatives to reduce these burdens by incorporating greater proportions of RAP. However, higher RAP usage can increase the risk of cracking, which has led to the development of various strategic techniques to improve RAP utilization while maintaining adequate performance. These include increasing binder content, binder grade bumping, the use of rejuvenators, and warm mix asphalt (WMA) technologies. While these strategies enable higher RAP incorporation with acceptable performance, they may also alter economic and environmental impacts, which must be carefully assessed. The present study, therefore, carried out a comprehensive cradle-to-gate LCA and cost analysis to evaluate the variations in GHG emissions and costs of high-RAP mixtures. All comparisons were made against the corresponding control asphalt mixtures within each mix design level.

1. The preliminary analysis revealed that all mix design attributes, binder type, binder content, and RAP content, influence GHG emissions, although the extent of their impact depends on the emission category. For instance, in the case of GWP, binder content was identified as the most influential factor, whereas RAP content had the greatest effect on ODP. This was confirmed through Pearson correlation coefficient comparisons.
2. Among different phases of LCA, the material stage contributes around 49-72% of emissions, which is followed by the production phase (16-32%) and transportation (10-22%). However, this trend was not consistent for ODP, where 61% of emissions originated from transportation, with the remainder attributed to material and production phases.
3. In Level 3 mixtures, WMA technologies reduced total GWP by 7-8% compared to the control mixtures. The primary benefit of WMA was observed in the production phase, where lower production temperatures resulted in reduced consumption of burner fuel and oil for heating.
4. In Level 4 mixtures, the most environmentally favorable strategy was binder grade bumping, which reduced GWP by approximately 12% compared to the reference mix. This improvement is linked to the replacement of polymer-modified PG70-22ER with unmodified PG64-22, as polymer modification involves more carbon-intensive

processing and therefore higher emissions. This was followed by using WMA, rejuvenators, and an increased binder content strategy.

5. RAP pricing was found to control the overall project cost and the cost-effectiveness of different strategies. When RAP was priced at \$30/ton, only binder grade bumping and WMA technologies were cost-effective in the Level 4 category, while none of the strategies were cost-effective in Level 3. However, when the RAP price was reduced to \$17.5/ton, cost savings ranged from 1% to 14.7%, depending on the mix design level and the strategic technique applied, highlighting the need for careful evaluation of the RAP material cost during the decision-making process.

7.0 COMBINED INFLUENCE OF RAP VARIABILITY, BINDER GRADE, AND STRATEGIC TECHNIQUES ON THE PERFORMANCE METRICS OF RAP MIXTURES

7.1 INTRODUCTION

Recycling has now become a common practice throughout the globe to combat the challenges associated with increased material cost and corresponding carbon emissions (Lewis et al. 2024; Xu et al. 2025a). Use of Reclaimed asphalt pavement (RAP) for recycling of asphalt pavements is currently a topic of significant interest, necessitating further development to improve the RAP proportion without affecting the performance (Tsakoumaki and Plati 2024). The application of RAP reduces the amount of virgin binder and natural aggregates, eventually lowering the overall materials cost and conserving natural vegetation. Although RAP material positively supports the economic and environmental concerns, previous studies in the literature (Li et al. 2025; Si et al. 2024; Yu et al. 2024; Zaumanis et al. 2014a) highlighted the concerns regarding its impact on the long-term performance and durability of the asphalt pavements. These issues stem from the oxidized and stiff RAP binder adhering to the RAP aggregates (Austerman et al. 2020; Elnaml et al. 2024). Apart from the RAP binder, the variability in the RAP material properties also contributes to such performance challenges (Austerman et al. 2020; Xu et al. 2025a; b), which are often overlooked during the mix design and decision-making process.

RAP is a non-homogeneous material, with its properties varying significantly across different sources or production plants (Tarsi et al. 2020). These variabilities arise from the differences in the exposure of old asphalt pavement in terms of traffic, climate, age of pavement, old pavement binder content, and grade, etc. (Sukhija and Coleri 2025b). Previous studies (Austerman et al. 2020; Khosla and Ramoju 2017) showed inconsistency in the properties of RAP material obtained within a state or even at different locations within a given stockpile over time. Such inconsistencies raise further quality assurance (QA) and quality control (QC) concerns, particularly with balanced mix design (BMD) approach, where mix design depends primarily on the performance (Duarte et al. 2025). In another study (Montañez et al. 2020), concerns over RAP variability led to the recommendation that special attention be given to material consistency when producing asphalt mixtures using RAP from different sources. This variability effect becomes more prominent when the RAP material from different sources is used in a single project (Gao et al. 2021; West 2015; Zhou et al. 2010), since the other sources of RAP may differ in in-service life, pavement damage levels, milling and crushing operations, etc (Wang et al. 2024). To minimize such variability, it is suggested to blend the RAP obtained from distinct sources and allow sufficient re-mixing prior to crushing and sieving to maintain the consistency and lower the variability (Zhou et al. 2010).

Even after stockpiling, exposure of RAP to high temperatures or storing it for a longer time period may cause variability in material properties, leading to non-uniform workability of asphalt mixtures, further limiting the use of RAP material (INVIAS 2022; Sukhija and Coleri 2025b; Zaumanis and Mallick 2015). In general, asphalt mixes with high RAP content tend to exhibit

large variability relative to low RAP mixtures (Valdés et al. 2011). From this perspective, an appropriate RAP management scheme should be followed to minimize the variability and ensure consistent performance, even with high RAP proportions (Sukhija and Coleri 2025b; Zhou et al. 2010).

Although the properties of asphalt mixtures varied with the change in RAP characteristics, the complexity increases when additives such as rejuvenators or warm mix asphalt (WMA) technologies are introduced (Behnood 2019; Guo et al. 2020a). These additives are typically included for the production of RAP mixtures to either increase the allowable RAP proportion or enhance mixture performance and durability (Albayati et al. 2023; Jain and Chandrappa 2025; Wang et al. 2025a; Zaumanis et al. 2015). Given that cracking is a critical concern in RAP-inclusive asphalt pavements, these additives either rejuvenate the oxidized RAP binder (using rejuvenators) or reduce the secondary ageing of RAP due to lower production temperature (with WMA), resulting in a lower likelihood of cracking with adequate rutting resistance (Sukhija and Coleri 2025c; West et al. 2013). However, in the presence of these additives, it is inevitably important to understand how these interact and perform with different binder grades and RAP sources. Despite their widespread use, there is very limited research in this direction, representing a potential research gap that needs to be addressed to support large-scale implementation of RAP-inclusive asphalt pavements. As most high RAP projects employ such strategic additives, this gap forms motivation for the present research.

This study addresses the concerns outlined above by investigating whether the performance of asphalt mixtures varies based on the source of RAP, while maintaining constant total binder content, aggregate gradation, and binder grade. Additionally, the effect of RAP sampling location within the stockpile was also determined to identify if it is one of the causes of performance variability in RAP mixtures. Considering the use of rejuvenators and WMA as a global initiative to improve sustainability, the performance interaction of modified asphalt mixtures with different mix combination (binder grade and RAP source) was also explored.

7.2 RESEARCH OBJECTIVES AND SCOPE

This part of the research work is conducted in two phases with distinct objectives as follows:

Phase I- Incorporate and evaluate the effect of different binder grades along with plant (between plant RAP material source variability) and stockpile (within the asphalt plant variability) variability as a part of the RAP management scheme in the production of RAP mixtures.

Phase II- Assess the influence of different strategic measures, including rejuvenators and warm mix additives (WMA), along with RAP material variability in terms of rutting and cracking performance.

The scope of the present work is to evaluate the performance of asphalt mixtures incorporating RAP materials sourced from different asphalt plants (between-plant variability) as well as from varying locations within the same RAP stockpile (within-plant variability). These variations are included in this study to understand the change in performance of recycled asphalt mixtures with the change in RAP material sampling. Also, it demonstrates the practicality of the RAP management scheme in improving asphalt recycling. Along with the RAP source, two different

performance-graded asphalt binders were incorporated to understand the cause of variability in RAP mixtures. Furthermore, additives such as WMA technologies and rejuvenators were incorporated to investigate whether performance trends observed with different RAP sources persist in the presence of these modifiers. The complete study involved statistical assessment of the experimental dataset through analysis of variance (ANOVA), Pearson correlation matrix, and Tukey's pairwise post-hoc analysis. This research approach not only identifies the underlying causes of performance variation in RAP-containing mixtures but also highlights the mix attributes contributing most to variability. The findings can support engineers in managing this variability more effectively, ultimately contributing to improved pavement durability and service life.

7.3 MATERIAL SECTION

A single aggregate source of ½ inch nominal maximum aggregate size (NMAS) was employed to produce asphalt mixtures, designed based on the aggregate gradation specified for Level 3 and Level 4 mixes in Oregon (ODOT 2019, 2021). Level 3 mixes are designed for the locations where the anticipated equivalent single axle load (ESAL) is 1 million-3 million, whereas for ESAL greater than 3 million, Level 4 mixes are recommended (ODOT 2019). Figure 7.1 presents the aggregate gradation of Level 3 and Level 4 mixes used for executing both phases of the study.

Two base asphalt binders, namely PG64-22 and PG70-22ER, were used in the experimental work. As per the Oregon Department of Transportation (ODOT) (ODOT 2019, 2021), PG64-22 is used for Level 3 mixes, while PG70-22ER is used for Level 4 mixes, and the same standard practice has been adopted in the present study. However, as is evident from Figure 7.1, the differences between the aggregate gradations for these two mix levels are minimal, and thus, it is expected that the performance variations in the asphalt mixtures are primarily affected by the binder grade rather than the gradation differences. Therefore, the research team compared the results based on the binder grade (PG64-22 and PG70-22ER) instead of the mix level (Level 3 and Level 4). A similar approach has been followed in a previously published research work by OSU-AMaP (Sukhija and Coleri 2025a).

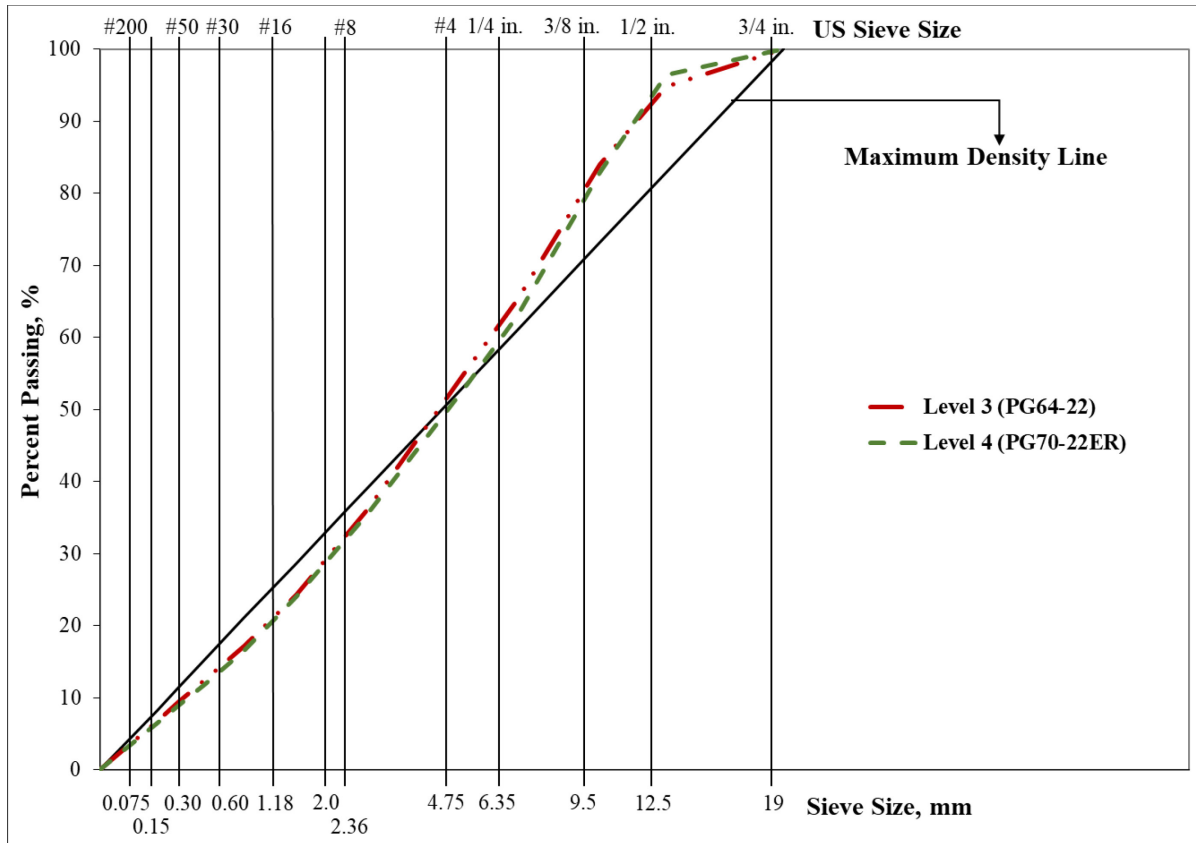


Figure 7.1. Aggregate gradations for Phase I and Phase II

RAP material from distinct sources (RAP1 and RAP2), defined based on the RAP binder content and true failure temperature, was also incorporated. Additionally, the RAP material was sampled from two different locations (L1 and L2) within the same stockpile to understand the cause of variability in the performance of RAP-inclusive asphalt mixtures. Figure 7.2 shows the representation of these RAP materials, categorized based on the RAP sources and RAP sampling location. For example, RAP1L1 refers to RAP source 1 sampled from location 1, and likewise, the other combinations were defined. Here, RAP2 appears to be more blackish while RAP1 is more brownish, confirming that RAP2 consists of slightly more binder content. This observation was validated by determining the binder content using a centrifuge extractor. RAP1 consists of 4.97% of RAP binder, having a true failure temperature of 93.7°C (following the high PG grading process), while RAP2 exhibits 5.52% RAP binder content and a true failure temperature of 90.8°C.

All asphalt mixtures were prepared with 30% RAP content and a total binder content of 6% to maintain consistency and remove variability associated with changes in RAP or binder content, which falls outside the scope of this component of the study.

**Variability in
RAP Material**

RAP Sources

RAP1

RAP2

RAP Sampling Location within Stockpile

***Location
1 (L1)***



RAP1L1



RAP2L1

***Location
2 (L2)***



RAP1L2



RAP2L2

Figure 7.2. Representation of the RAP material used in the present study

7.4 MIX DESIGN AND METHODOLOGY

To produce asphalt mixtures, the asphalt binder is preheated in the draft oven at the mixing temperature for 2 hours. At the same time, the aggregates are also heated at 10°C higher temperature than the mixing temperature, while the RAP material is subjected to heating at 121°C (Sukhija and Coleri 2025a). Following the heating process, the preheated materials are mixed thoroughly using a portable bucket mixer to produce a loose asphalt mixture. Since the performance testing has to be executed on these samples, the loose asphalt mixtures are exposed

to short term ageing (STA) and long-term ageing (LTA) based on the standard test protocol for rutting and cracking. The rutting performance was evaluated on STA samples while the cracking potential was measured on LTA samples.

STA of hot mix asphalt (HMA) samples was carried out by placing the loose mixtures in an oven for 2 hours at 135°C, following NCHRP 9-52 (Newcomb et al. 2015). Based on the standard protocol for Oregon (Coleri et al. 2020), the STA samples were further subjected to heating for 24 hours at 95°C in order to simulate LTA. Further, the aged mixture in a loose state is placed at its respective compaction temperature again for 2 hours before the compaction. A Superpave gyratory compactor was used to compact the asphalt mixtures to a thickness of 62 mm, with a diameter of 150 mm, ensuring 7 ± 1 air voids. These compacted samples are then conditioned based on the requirements of the performance testing.

The Indirect Tensile Cracking tolerance test (IDT-CT) was conducted to assess the cracking potential, while the Hamburg wheel rut test (HWTT) was employed to study the rutting characteristics of the asphalt mixtures. The complete experimental matrix of the present study is illustrated in Table 7.1, whereas the methodology adopted for performance testing is described in Section 3.4.2 and Section 3.4.3. Notably, four replicates were tested for each mix combination, and the error bars (one error bar indicates one standard deviation) have been marked in the figures to reflect the variability within the mix.

Table 7.1. Experimental Matrix

Study Phase	Test Method	RAP	Total Binder Content	RAP Sources	RAP Sampling Location	Binder Grade	Additives	Total Tests
Phase I	Fatigue Cracking - IDT-CT, and Rutting-HWTT	30%	6%	RAP1 and RAP2	L1 and L2	PG64-22 and PG70-22ER	No Additive	64
Phase II	Fatigue Cracking - IDT-CT, and Rutting-HWTT	30%	6%	RAP1 and RAP2	L1	PG64-22 and PG70-22ER	Rejuvenators : 2 Warm Mix Asphalt: 2	128

Note 1: 4 replicates were made for each test method.

Note 2: IDT-CT and HWTT in test methods refer to the Indirect tensile cracking tolerance test and the Hamburg wheel tracking test, respectively. The performance results of control samples (without an additive) from Phase I are used for comparison in Phase II.

7.5 RESULTS AND DISCUSSIONS

PHASE I

7.5.1 Individual Effect of Influential Variables on the Mix Performance

This section provides insight into the effects of binder grade, RAP source, and RAP sampling location on the cracking and rutting resistance of asphalt mixtures, as represented by the CT Index and rut depth, respectively. The dataset used for the interpretation was visualized as bar charts for each binder grade, as shown in Figure 7.3 and Figure 7.4. The average values are shown with error bars representing one standard deviation. The results were interpreted and compared across different combinations. For example, when evaluating the effect of binder grade, the dataset was separated by binder grade, and interpretations were made accordingly. This approach was consistently applied throughout the discussion, except for the RAP sampling location, where the dataset was divided based on RAP sources, resulting in four distinct combinations. The combinations for comparison in RAP1 are RAP1L1 and RAP1L2, while for RAP2, the combinations are RAP2L1 and RAP2L2. These combinations and their comparative results will be elaborated in the next sections.

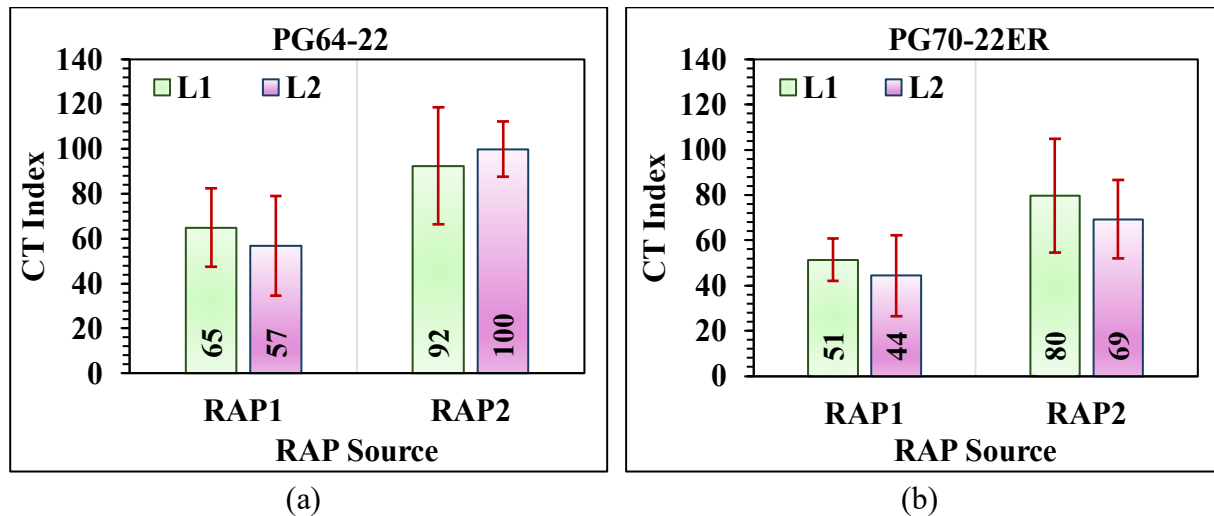


Figure 7.3. Variation in cracking resistance of asphalt mixtures (a) Mix with PG64-22 binder and (b) Mix with PG70-22ER binder

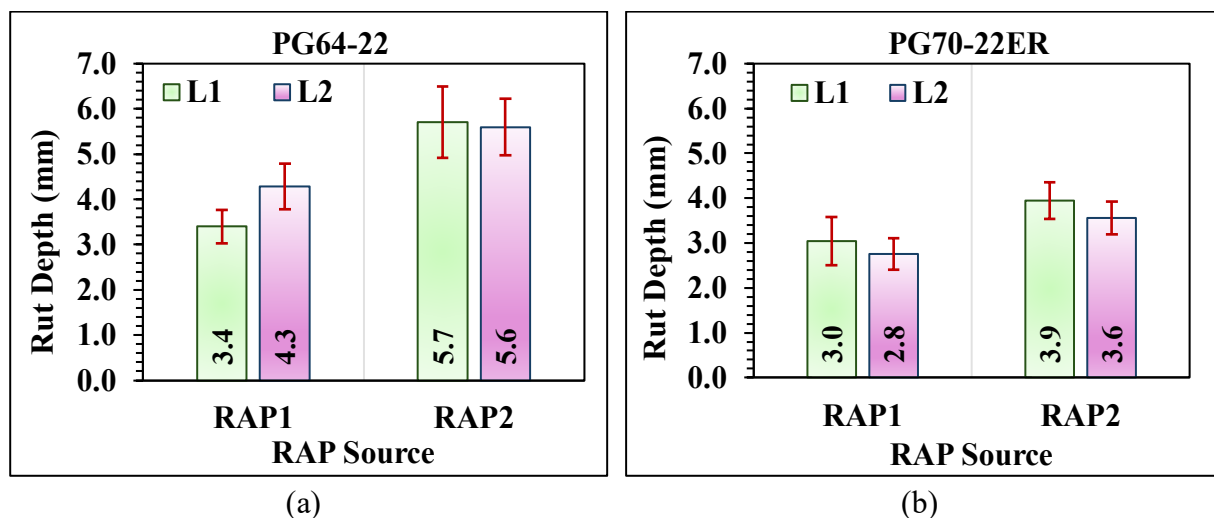


Figure 7.4. Variation in rutting resistance of asphalt mixtures (a) Mix with PG64-22 binder and (b) Mix with PG70-22ER binder

Along with the discussion on performance variations, a one-way ANOVA followed by Tukey's pairwise post-hoc analysis was carried out to identify the individual differences between the selected influential parameters. For example, the one-way ANOVA provides whether the performance differs significantly between the two binder grades without adjusting for other variables. A similar analysis was conducted for RAP sources and their sampling locations. Unlike the three-way ANOVA, which accounts for the influence of other factors, one-way ANOVA assesses the effect of each parameter in isolation. Statistical analysis was conducted at a 95% confidence level, with the null hypothesis stating that all group means are equal. Subsequently, Tukey's post-hoc analysis was used to group the parameters using alphabetical

symbols. Groups sharing the same letter are statistically similar, whereas groups assigned different letters indicate statistically significant differences in performance.

7.5.1.1 Effect of Binder Grade

The binder grade plays a critical role in the performance of RAP mixtures due to the complex interaction and blending required between the virgin and RAP binders. As illustrated in Figure 7.3 and Figure 7.4, asphalt mixtures prepared with PG64-22 binder exhibit superior cracking resistance compared to those prepared with PG70-22ER. Specifically, the reduction in CT Index for PG70-22ER mixtures ranged from 13% to 31%, with RAP2L1 showing the least reduction and RAP2L2 showing the highest. For RAP1, the use of the stiffer binder resulted in approximately 22% lower CT Index.

Conversely, the trend reversed in terms of rutting performance. Mixtures containing PG70-22ER demonstrated significantly improved rutting resistance. For instance, PG70-22ER binder improved rutting resistance by 12%-36% on average, depending on the RAP combinations (i.e., 12%, 35%, 32%, and 36% for RAP1L1, RAP1L2, RAP2L1, and RAP2L2, respectively). Even though the variation seems to be more between the binder grades, the resulting rut depths are far lower than the commonly accepted threshold of 12.5 mm rut depth recommended by various DOTs.

The overall behavior of the asphalt mixtures is clearly represented in the box plots in Figure 7.5, which summarizes the influence of binder grade on CT Index and rut depth. The average CT Index drops from 74 for PG64-22 mixes to 58 for PG70-22ER mixes; on the other hand, the rut depth changed from 4.7 mm to 3.3 mm, respectively. Further confirmation is provided by the one-way ANOVA and Tukey's pairwise grouping presented in Table 7.2. The analysis was conducted without adjusting for any additional variables, such as RAP source or RAP sampling location, using a 95% confidence level. The corresponding confidence intervals (CI) are also presented in Table 7.2. A p-value lower than 0.05 corresponding to both performance parameters suggests that both binders result in statistically different performance and are therefore categorized into distinct groups. Here, mixtures with PG70-22ER binder received a 'B' ranking due to reduced cracking resistance. However, in terms of rutting, the ranking shifted to 'A' due to their lower rutting values, which is desirable for a rut-resistant asphalt mix. This effect is attributed to the stiffer nature of the PG70-22ER binder, which contains a polymeric network that enhances the matrix stiffness, thereby improving rutting resistance. Similar trends reported in a previous study emphasize the critical role of selecting an appropriate virgin binder grade to achieve a durable and high-performing asphalt mixture (Chitnis et al. 2025; Sukhija and Coleri 2025a).

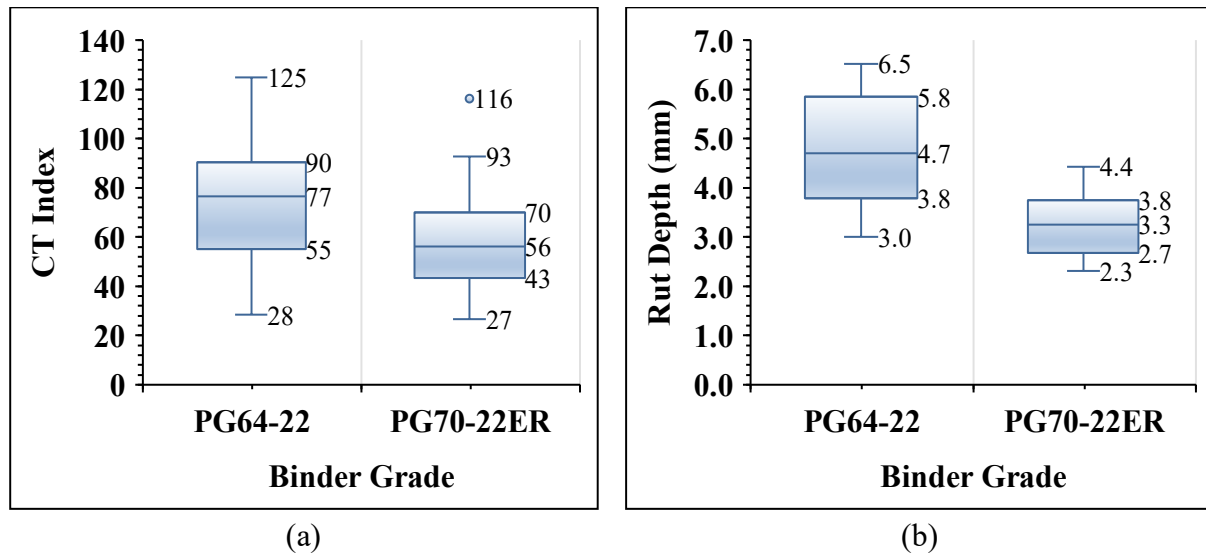


Figure 7.5. Effect of binder grade (a) CT Index and (b) Rut depth

Table 7.2. One-way ANOVA and Tukey's pairwise comparison for the effect of binder grades on the performance

Binder Grade	CT Index Mean	CT Index 95% CI	CT Index Group	CT Index P-value	Rut Depth (mm) Mean	Rut Depth (mm) 95% CI	Rut Depth Group	Rut Depth P-value
PG64-22	73.81	(63.25, 84.37)	<i>A</i>	0.041	4.74	(4.28, 5.20)	<i>B</i>	0.00
PG70-22ER	58.36	(48.05, 68.68)	<i>B</i>	0.041	3.29	(2.85, 3.73)	<i>A</i>	0.00

Note: In terms of alphabetical ranking and performance, *A* is superior to *B*.

7.5.1.2 Effect of RAP Source

As evident from Figure 7.3 and Figure 7.4, the mixtures comprising RAP2 delivered superior cracking resistance and a comparatively higher likelihood of rutting, resulting from higher CT Index and rut depth. This behavior is consistent for the RAP obtained from different locations within the stockpile. For instance, the CT Index of RAP2 mixes was found to be 1.42-1.75 times better than RAP1 mixes, where the virgin binder is PG64-22. The improvement range changed for the mixes produced using PG70-22ER binder, indicating 1.35-1.82 times enhancement in CT Index with RAP2. On the other hand, the rut depth in the mixes consisting of RAP2 ranged from 1.3-1.7 times and 1.2-1.4 times higher than RAP1 mixes prepared with PG64-22 and PG70-22ER binders, respectively.

The variation in the range implies the coupling behavior of virgin binder grade and RAP source, suggesting that RAP source, which is defined based on the available RAP binder

and RAP binder grade, plays a crucial role in affecting the performance of asphalt mixtures. Here, the measured binder content for RAP1 is 4.97% and RAP2 is 5.52%, while the true failure temperature of RAP1 is 93.7°C, which is comparatively stiffer than the RAP2 binder (90.8°C). Assuming 100% blending and given that the total binder content in both RAP mixes remains constant with adjustments made to account for the available RAP binder, the observed variation in the mix behavior may be attributed to the higher stiffness of the RAP binder. This implies that a softer RAP binder improves the lubrication (here, RAP2 binder), leading to improved resistance to cracking. The same behavior was observed in a previous ODOT-funded research study (Obaid et al. 2019) where different RAP sources were used, and the mix with RAP containing softer RAP binder improved the flexibility in the mixes, leading to higher cracking resistance.

The impact of softness in the RAP binder is clearly evident through the box plots in Figure 7.6, where the average CT Index of the asphalt mixtures containing RAP2 is higher than that of RAP1, and an opposite trend was observed for rut resistance (rut depth in RAP1 mix < rut depth in RAP2 mix). Similar to the effect of binder grades, statistically different performance was noted for both the RAP sources, as indicated by the P-value (0.00) in Table 7.3. Regardless of any other variable, the average CT Index shifted from 54 (for RAP1 mixes) to 84, whereas the rut depth increased from 3.3 mm (for RAP1 mixes) to 4.7 mm when the asphalt mixtures were produced with RAP2, highlighting the influence of RAP source on the performance of asphalt mixtures. Based on their average performance values, RAP2 was grouped as ‘A’ for superior cracking resistance, while RAP1 outperformed in terms of rutting resistance and was grouped ‘A’ under rut depth. Since the rut depth was significantly lower than 12.5 mm for both cases, there is more room for improvement in the cracking resistance by increasing the virgin binder content. In addition, with such minimal variation in rut depth for different RAP sources, it can be stated that the RAP source is a key factor influencing cracking resistance, aligning with previous studies (Saq et al. 2022; Singh and Girimath 2016).

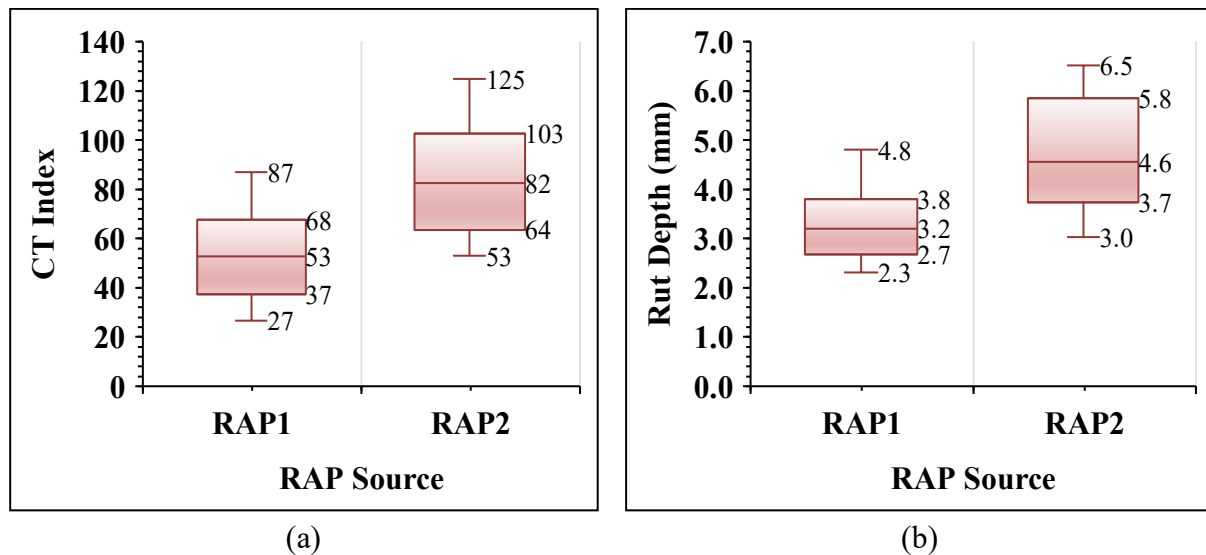


Figure 7.6. Effect of RAP source (a) CT Index and (b) Rut depth

Table 7.3. One-way ANOVA and Tukey’s pairwise comparison for the effect of RAP sources on the performance

RAP Source	CT Index Mean	CT Index 95% CI	CT Index Group	CT Index P-value	Rut Depth (mm) Mean	Rut Depth (mm) 95% CI	Rut Depth Group	Rut Depth P-value
RAP1	53.81	(45.87, 61.75)	<i>B</i>	0.00	3.33	(2.87, 3.79)	<i>A</i>	0.00
RAP2	84.41	(74.60, 94.23)	<i>A</i>	0.00	4.70	(4.23, 5.17)	<i>B</i>	0.00

Note: In terms of alphabetical ranking and performance, A is superior to B.

7.5.1.3 Effect of RAP Sampling Location in a Stockpile – Within-Plant Variability

High variability in the RAP material inevitably affects the pavement durability. As per the review of the literature (Tarsi et al. 2020; West 2015), along with the RAP source, the location from where the sampling is done also governs the final performance of the asphalt mixtures containing RAP. From this perspective, the test results were analyzed to see the effect of RAP sampling location. As can be seen in Figure 7.3 and Figure 7.4, the RAP sampling location does not follow a consistent trend; rather, the behaviour depends on the RAP source and its interaction with the virgin asphalt binder. Since two different virgin binders are considered, the unmodified binder (PG64-22) and the polymer-modified binder (PG70-22ER), variations in blending mechanisms are expected, resulting in differing interactions and contributing to the observed inconsistencies.

Box plots with variation in the CT Index and rut depth for different RAP sources and binder grades are presented in Figure 7.7. With the change in sampling location, the difference in CT Index ranged from 7 to 11, while it was less than 1 mm in the case of rut depth. Given the marginal differences in performance parameters across RAP mixes from different locations within the same stockpile, the influence of RAP sampling location appears to be less significant compared to the effects of binder grade and RAP source. This attribution is confirmed through the ANOVA results, which indicate a statistically insignificant impact of RAP sampling location ($P\text{-value} > 0.05$) for both RAP sources. As shown in Table 7.4, the P-values for CT Index are 0.397 for RAP1 and 0.761 for RAP2, while in the case of rut depth, the P-values are 0.588 and 0.669 for RAP1 and RAP2, respectively. These values suggest the acceptance of the null hypothesis, highlighting that the performance of the asphalt mixture does not vary significantly with RAP sampling location within the same RAP stockpile. Consequently, both L1 and L2 are grouped as ‘A’ across all the test scenarios, as demonstrated in Table 7.4. This result proves that proper RAP management and periodic blending of the RAP materials at the plant using excavators can significantly reduce within-plant RAP variability. A previous study also reported consistent properties of RAP material within the stockpiles; however, they identified noticeable differences in the properties of RAP material obtained from different sources within a state (Duarte et al. 2025).

Notably, the effect of RAP source and binder grade remains consistent, irrespective of the sampling location. For example, PG64-22 binder grade and RAP2 mix result in higher CT Index and rut depth. However, care should be taken when sampling the RAP, which is free from undesirable materials and pollutants, including underneath soil, excessive moisture, and deleterious materials. Additionally, RAP should be stockpiled under shelters to avoid exposure to direct sunlight and protect the RAP material from heavy rainfall. These RAP management practices and potential recommendations are critically reviewed and detailed in a recent review article by OSU-AMaP (Sukhija and Coleri 2025b).

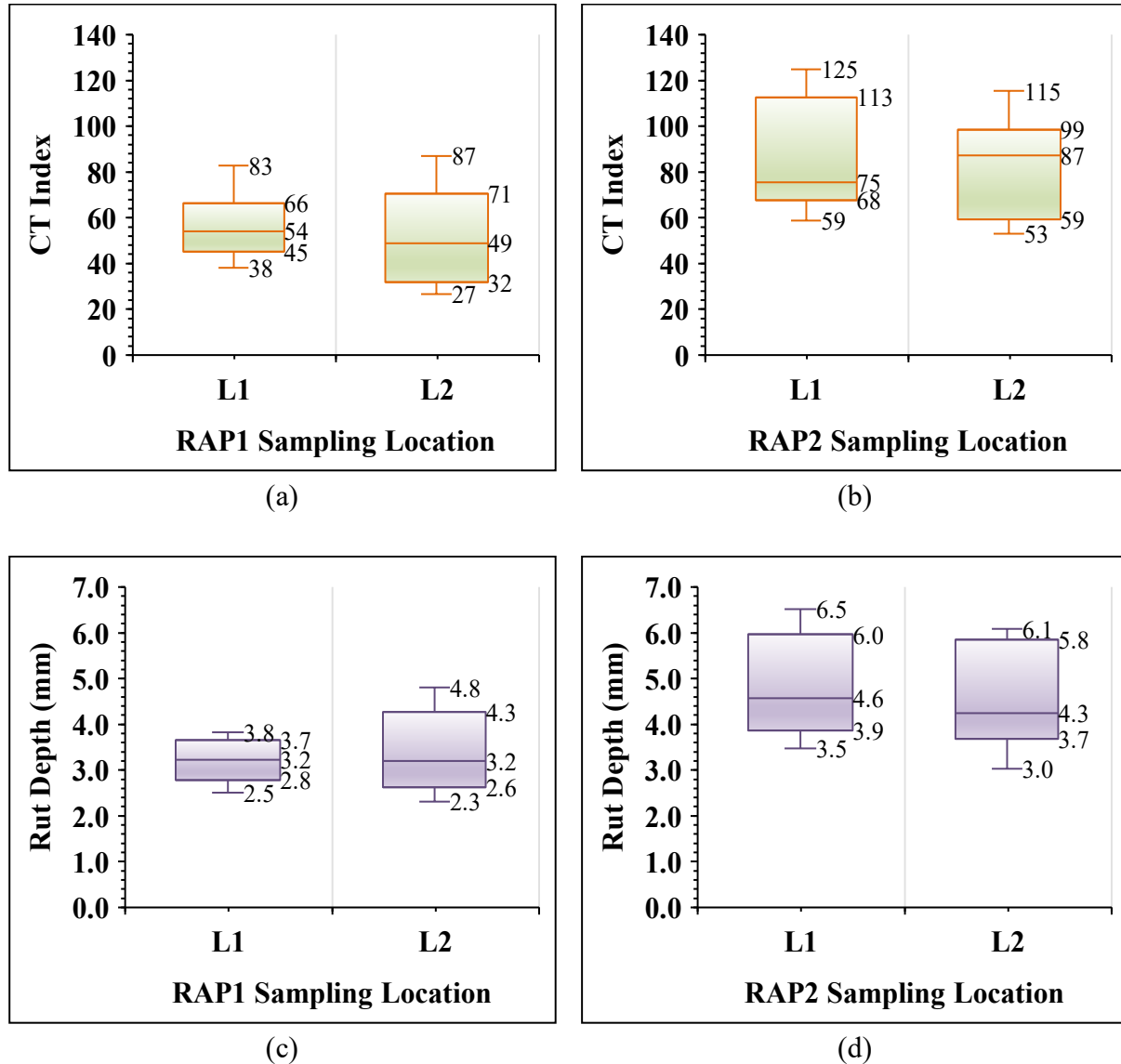


Figure 7.7. Effect of RAP sampling location (a) CT Index for RAP1 and (b) CT Index for RAP2, (c) Rut depth for RAP1, and (d) Rut depth for RAP2

Table 7.4. One-way ANOVA and Tukey's pairwise comparison for the effect of RAP sampling location on the performance

RAP Sampling Location	CT Index Mean	CT Index 95% CI	CT Index Group	CT Index P-value	Rut Depth (mm) Mean	Rut Depth (mm) 95% CI	Rut Depth Group	Rut Depth P-value
RAP1 L1	57.45	(45.97, 68.94)	<i>A</i>	0.397	3.23	(2.67, 3.77)	<i>A</i>	0.588
RAP1 L2	51.13	(41.29, 60.97)	<i>A</i>	0.397	3.42	(2.91, 3.94)	<i>A</i>	0.588
RAP2 L1	86.25	(68.87, 103.63)	<i>A</i>	0.761	4.83	(3.96, 5.69)	<i>A</i>	0.669
RAP2 L2	82.78	(66.39, 99.17)	<i>A</i>	0.761	4.57	(3.71, 5.44)	<i>A</i>	0.669

Note: Means that share the same alphabet are significantly similar.

7.5.2 Statistical and Correlation Analysis

Statistical analysis, using a three-way analysis of variance (ANOVA), was carried out to evaluate the statistical significance of the selected variables, i.e., binder grade, RAP source, and RAP sampling location, on the performance of asphalt mixtures. Initially, the performance tests were conducted, and a dataset was prepared corresponding to each combination of mixture variables. Thereafter, ANOVA was performed at a 95% confidence level to test the null hypothesis that all group means are equal. A P-value below 0.05 indicates that the null hypothesis is rejected, suggesting a statistically significant effect of the tested variable on performance. Conversely, a P-value above 0.05 suggests insufficient evidence to reject the null hypothesis, indicating no statistically significant difference among the group means.

According to Table 7.5, the ANOVA results indicate that both binder grade and RAP source have a statistically significant impact, as evidenced by P-values less than 0.05. Given that all mixtures had the same total binder content, these findings highlight the importance of binder stiffness (from both virgin and RAP sources) and their blending behavior. In contrast, variations in RAP sampling location within the same stockpile did not produce a significant effect, with P-values of 0.451 and 0.928 for CT Index and rut depth, respectively. This suggests that RAP can be sampled from any location within a well-maintained stockpile without substantially affecting performance. However, these attributions are based on a limited set of mix combinations and should be validated further using a larger and more diverse dataset.

Along with the ANOVA results in Table 7.5, the Pearson correlation coefficients were also determined and presented to understand how variations in performance parameters relate to changes in the identified influential factors (binder grade, RAP source, and RAP sampling location). A moderate negative correlation was observed between binder grade and CT Index, with a Pearson correlation of -0.313, implying that cracking resistance

tends to decrease as binder grade or binder stiffness increases. Nevertheless, a moderate to strong negative correlation was observed between binder grade and rut depth (Pearson correlation = -0.642), suggesting that higher binder grades, typically stiffer or polymer-modified, contribute to improved rutting resistance. On the other hand, the RAP source shows a positive correlation with both the CT Index (0.61) and rut depth (0.61). While the increase in the CT Index suggests improved cracking resistance, the corresponding increase in rut depth is undesirable for rut-resistant asphalt mixtures, highlighting a trade-off in performance. These changes associated with the RAP source are mostly due to differences in RAP binder stiffness and its interaction with virgin asphalt binder. According to the current dataset, the RAP sampling location has a minor impact on both rutting and cracking behavior, which is consistent with the ANOVA results.

Findings from both the ANOVA and Pearson correlation matrix also highlighted that the CT Index is primarily affected by changes in RAP source, followed by binder grade, which emerges as the most influential factor affecting variations in rut depth. These conclusions are derived based on the higher F-statistics as well as strong Pearson correlation factors among their counterparts. Apart from the correlation between the performance parameters and selected influential parameters, there exists very little interdependency between the selected influential variables, with correlation coefficients ranging from -0.046 to 0.029. This underscores the importance of isolating their individual effect in the present study.

Table 7.5. Statistical analysis for the complete dataset, including different binder grades, RAP source, and RAP sampling location

Source of variation	CT Index F-Value	CT Index P-Value	CT Index Pearson Correlation	Rut Depth F-Value	Rut Depth P-Value	Rut Depth Pearson Correlation
Binder Grade	8.47	0.006	-0.313	64.44	0.000	-0.642
RAP Source	26.75	0.000	0.608	56.75	0.000	0.605
RAP Sampling Location	0.58	0.451	-0.132	0.01	0.928	-0.027

Phase II

Since the first phase of the study highlights the significance of binder grade and RAP source on the asphalt mixture performance, it is viable to further understand how different additives interact with changes in binder grade and RAP source. The effect of RAP sampling location was excluded from this phase, as its influence on performance was found to be minimal. This phase of the study focuses on evaluating two warm mix additives (WMA1 and WMA2) and two rejuvenators (REJ1 and REJ2). The details on the chemical characteristics of these additives, and corresponding dosages, are presented in Table 7.6. Although dosages were adapted from the manufacturers, these were verified initially, and the results are shown in Chapter 5.0 of the present study. The dosages supplied by the manufacturer were based on the total binder (virgin + RAP binder), but added to the virgin binder for blending; hence, for RAP mixtures, these dosages were

adjusted accordingly to accommodate the effect of the RAP binder using Equation 7.1. If the additive dosage is not adjusted, it may lead to underestimation because the RAP binder was not considered in the total binder calculation. A similar process was recommended by the manufacturer and also used in a previous study for producing additive-inclusive RAP mixtures (Kumar et al. 2022).

Initially, the asphalt binder was placed in an oven at a specified temperature range (130-140°C for PG64-22 and 145-155°C for PG70-22ER) for 30 minutes to liquefy it. Thereafter, the preheated binders (without any additive) were stirred using a countertop mixer at a speed of 950-1050 RPM for 5 minutes to remove entrapped air and ensure uniform consistency. Following the stirring of the neat binder, the additives were added, and the blending process continued for an additional 10 minutes to produce WMA and rejuvenator-modified asphalt binders.

Adjusted additive dosage (%)

$$= \frac{\text{Target additive dosage (\%)} \times \text{Total binder content (\%)}}{\text{Total binder content (\%)} - \text{Binder from RAP (\%)}}$$

(Equation 7.1)

Both the WMA are chemical-based WMA technologies that allow the production of asphalt mixtures at lower mixing and compaction temperatures through enhanced coating and workability. In the present study, WMA mixtures were produced at temperatures 25°C lower than their respective conventional HMA mixtures, while the control and rejuvenator-inclusive asphalt mixtures were produced at HMA production temperatures, following the mix design process discussed in an earlier section. The mix design attributes, including the aggregate gradation, RAP sources, RAP content, binder content, base binder sources, used for Phase I, were kept consistent for Phase II to avoid any extraneous variability. As per NCHRP 9-52 (Newcomb et al. 2015), the STA temperature for WMA mixtures was reduced to 116 °C instead of 135 °C (recommended for HMA mixtures) to incorporate the effect of reduced ageing; however, the LTA was carried out in the same way as that of HMA.

Table 7.6. Qualitative and Quantitative characteristics of selected rejuvenators (REJ1 and REJ2) and WMA additives (WMA1 and WMA2)

Characteristics	REJ1	REJ2	WMA1	WMA2
Chemical composition	Tall oil fatty acid derivative	Corn oil, fatty acid residues, and methyl ester	Modified tall oil, fatty acid, and alkyl acid phosphate	Esters, phosphoric acid, and non-hazardous ingredients
Odor	Bland	Slight	Odorless	Mild
Physical state	Liquid	Liquid	Liquid	Liquid
Visual color	Amber (Dark)	Dark brown	Dark brown	Dark brown
Density at room temperature (g/cm³)	0.97	0.92	0.99	0.92-0.96
Viscosity, dynamic at room temperature (centipoise)	>118	> 150	487	< 250
Flash point (°C)	> 232	> 150	> 181	> 150
Solubility in water	NA	NA	Insoluble	Slightly soluble
pH value	8.3	5.3	2.3	2.5
Additive dosage by weight of total asphalt binder (Adjusted dosage as per Equation 7.1)	1.5% (2 % for RAP1 and 2.07% for RAP2)	1.5% (2 % for RAP1 and 2.07% for RAP2)	0.5% (0.67 for RAP1 and 0.69 for RAP2)	0.5% (0.67 for RAP1 and 0.69 for RAP2)

7.5.3 Interaction of Additives, Binder, and RAP Source on Cracking Behavior

Figure 7.8 presents the CT index values of asphalt mixtures prepared using different types of additives and RAP sources with PG64-22 and PG70-22ER binder, respectively. The incorporation of WMA additives and rejuvenators resulted in varying CT Index values, with the magnitude of variation influenced by the type of base asphalt binder and RAP source. However, the difference within the group is marginal, suggesting a significant interaction effect between the additives, base binder, and RAP source. For instance, in a mixture containing PG64-22 binder and RAP1, the CT Index values for WMA1, WMA2, REJ1, and REJ2 were found to be 0.81, 0.91, 1.16, and 1.02 times that of the control mixture (without additives). On the other hand, for the mix with the same binder but different RAP source (RAP2), the corresponding ratios increased to 1.03, 1.13, 1.36, and 1.55, respectively. A similar trend was observed for PG70-22ER binder. For the PG70-22ER (RAP1) case, the control mixture exhibited CT Index values of 0.70, 0.82, 0.65, and 0.67 times those of WMA1, WMA2, REJ1, and REJ2,

respectively. With PG70-22ER (RAP2), the ratios were 1.03, 0.89, 1.35, and 1.09, respectively, again highlighting the influence of RAP source and additive interactions. On average, the addition of WMA yields similar cracking performance to the control mixture, despite a lower production temperature, while rejuvenator-based RAP mixtures exhibit improved cracking resistance with a higher CT Index.

The above-mentioned findings warrant further statistical analysis to identify whether these differences are statistically significant at a 95% confidence level and to classify the groups accordingly using Tukey's pairwise post-hoc analysis. The analysis revealed that the CT Index was influenced by the interaction between the RAP source and base asphalt binder. Within mix combinations (PG64-22 (RAP1), PG64-22 (RAP2), PG70-22ER (RAP1), PG70-22ER (RAP2)), the P-value was found to be different, indicating either statistically significant or insignificant differences in the CT Index values. For instance, P-values of 0.204 for PG64-22 (RAP1) and 0.628 for PG70-22ER (RAP2) exceed the 0.05 threshold, supporting the null hypothesis and suggesting no significant difference in average CT Index with the incorporation of WMA additives and rejuvenators. Tukey's pairwise comparison further confirmed this, as shown in Figure 7.8, grouping all samples under the same category 'A'.

On the other hand, with 30% RAP in all the asphalt mixtures as mentioned in the experimental plan (Table 7.1), the difference in the cracking performance with different additives was statistically significant for the mix combinations PG64-22 (RAP2) (P-value = 0.027) and PG70-22ER (RAP1) (P-value = 0.030), as their P-values are less than 0.05. The individual statistical pairwise comparisons and 95% confidence intervals for CT Index values within mix combinations are illustrated in Table 7.7. Specifically, in PG64-22 (RAP2), a significant difference was observed between REJ2 and the control mix (no additive), with a P-value of 0.043. Similarly, in PG70-22ER (RAP1), comparisons of REJ1 and REJ2 with the control mix yielded P-values of 0.044 and 0.048, respectively. Although these rejuvenator-modified mixes showed statistically significant differences from the control, they yielded higher CT Index values, demonstrating improved cracking resistance. Consequently, Tukey's pairwise comparison grouped these rejuvenator mixes under the superior category 'A'.

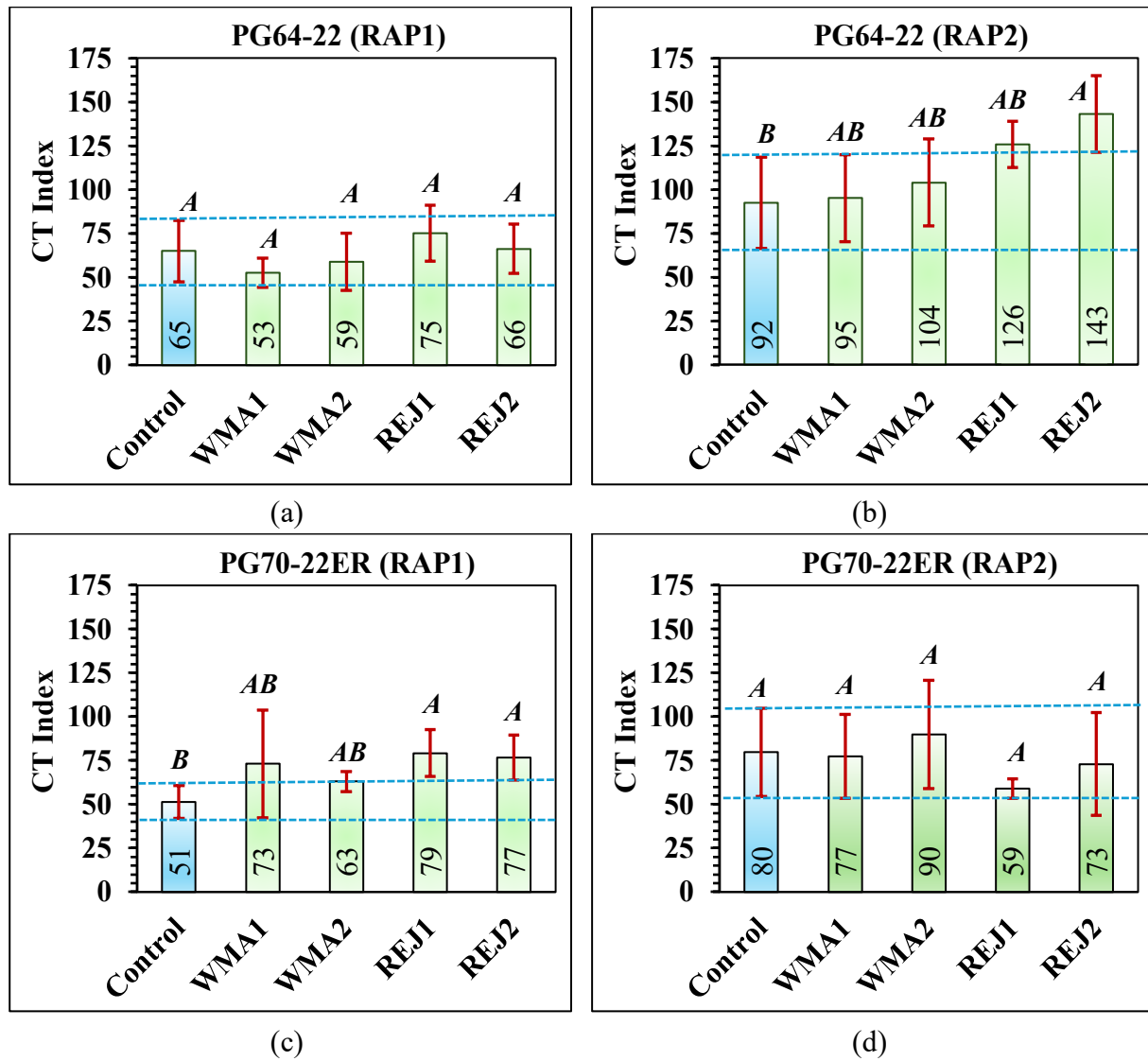


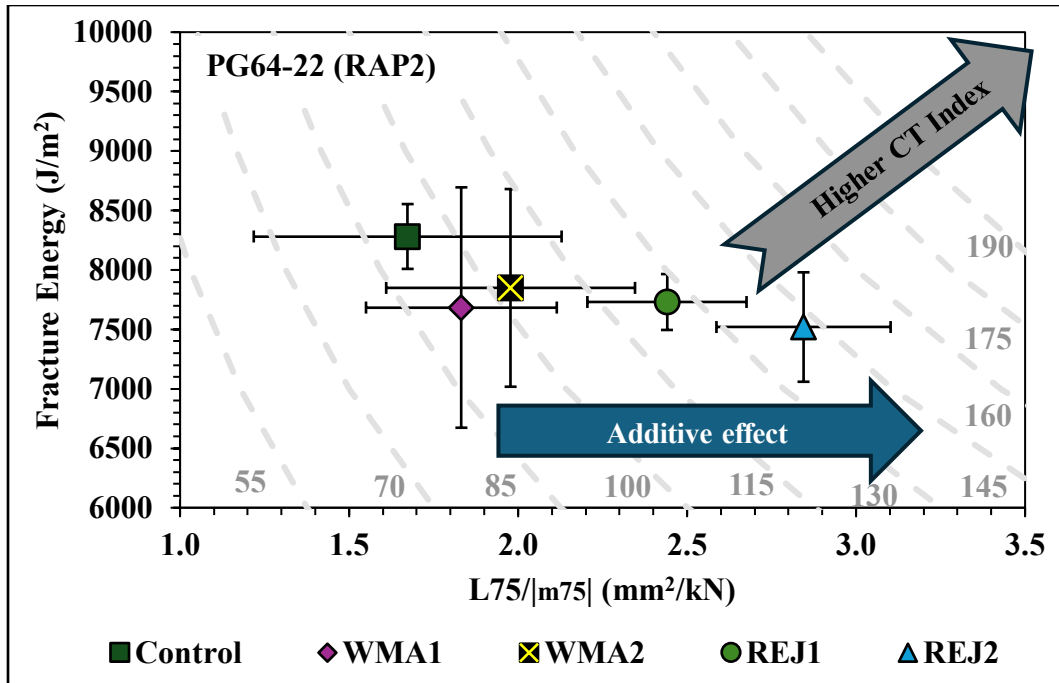
Figure 7.8. Cracking behavior of different asphalt mix combinations (a) PG64-22
Note: The dotted line represents the upper and lower bounds of the control samples.

Table 7.7. Tukey's pairwise post-hoc analysis for cracking behavior (CT Index) of WMA and rejuvenator mixtures for both the RAP sources

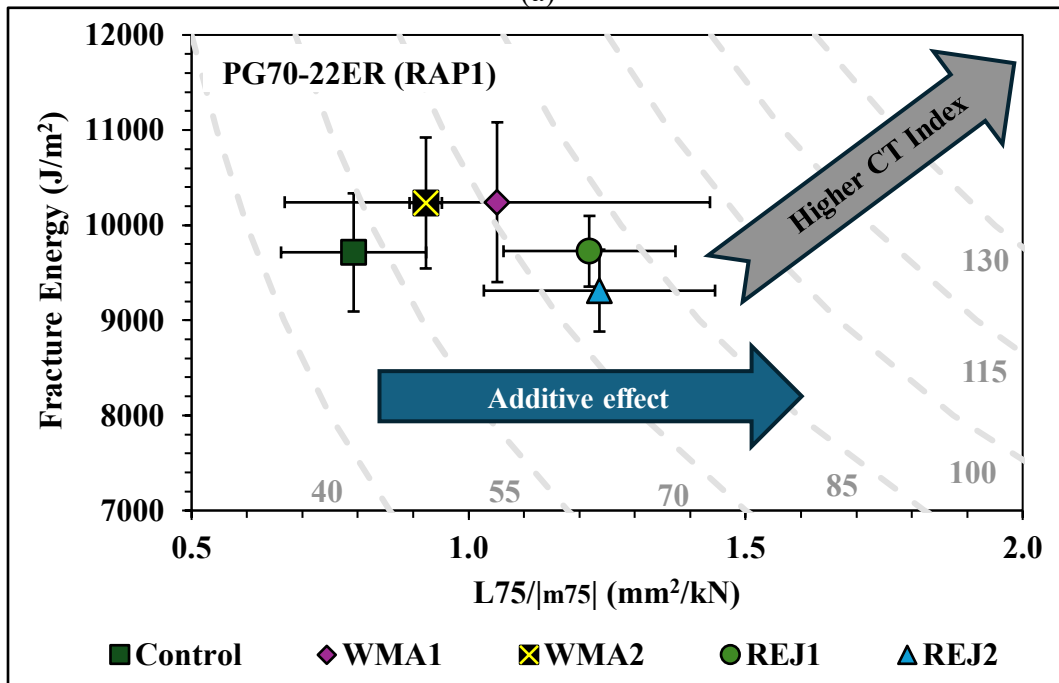
Difference of levels	PG64-22 (RAP1)95% CI	PG64-22 (RAP1) P-Value	PG64-22 (RAP2) 95% CI	PG64-22 (RAP2) P-Value	PG70-22ER (RAP1)95% CI	PG70-22ER (RAP1) P-Value	PG70-22ER (RAP2) 95% CI	PG70-22ER (RAP2) P-Value
WMA1 - Control	(-40.38, 15.54)	0.678	(-46.7, 52.0)	1.000	(-7.47, 50.79)	0.213	(-58.7, 53.9)	1.000
WMA2 - Control	(-34.08, 21.84)	0.964	(-35.2, 58.4)	0.938	(-15.70, 38.95)	0.715	(-46.2, 66.3)	0.979
REJ1 - Control	(-17.81, 38.11)	0.812	(-16.0, 82.7)	0.280	(0.52, 55.17)	0.044	(-81.6, 40.0)	0.820
REJ2 - Control	(-26.72, 29.20)	1.000	(1.3, 100.0)	0.043	(0.17, 50.37)	0.048	(-63.1, 49.5)	0.995
WMA2 - WMA1	(-21.66, 34.26)	0.960	(-37.8, 55.8)	0.975	(-40.3, 20.2)	0.859	(-43.8, 68.7)	0.955
REJ1 - WMA1	(-5.39, 50.52)	0.152	(-18.7, 80.0)	0.355	(-24.1, 36.5)	0.973	(-79.2, 42.4)	0.875
REJ2 - WMA1	(-14.30, 41.62)	0.598	(-1.4, 97.3)	0.059	(-24.67, 31.89)	0.995	(-60.7, 51.8)	0.999
REJ1 - WMA2	(-11.69, 44.23)	0.433	(-25.1, 68.5)	0.625	(-12.32, 44.76)	0.461	(-91.6, 29.9)	0.531
REJ2 - WMA2	(-20.60, 35.32)	0.931	(-7.8, 85.8)	0.128	(-12.77, 40.07)	0.552	(-73.1, 39.4)	0.879
REJ2 - REJ1	(-36.87, 19.05)	0.872	(-32.0, 66.7)	0.817	(-29.00, 23.85)	0.998	(-46.8, 74.8)	0.949

To further investigate the improved statistical variation in CT Index values with the addition of rejuvenators, interaction plots between fracture energy and post-peak behavior (expressed as the $L75/m75$ ratio) were developed for PG64-22 (RAP2) and PG70-22ER (RAP1). Here, $m75$ and $L75$ indicate the slope (N/m) and displacement (mm) at the 75% peak load of the post-peak stage of the load-displacement curve obtained from the IDT-CT test. The results are illustrated in Figure 7.9, where each color and shape indicates a different mix. According to the figures, since the CT Index is a function of fracture energy and post-peak behavior, the rejuvenated mixes, despite exhibiting fracture energy comparable to that of the control mixtures, demonstrated a higher CT Index. This improvement is attributed to the enhanced ductility, as reflected in the higher $L75/m75$ ratio of the rejuvenated mixes compared to the control samples. The $L75/m75$ ratio, commonly referred to as the Asphalt Flexibility Ratio (AFR), characterizes the ability of a mixture to sustain deformation beyond crack initiation. Higher AFR values observed in the rejuvenated mixes indicate a lower post-peak stiffness (gentler slope), enabling the material to resist crack propagation under repeated loading. This trend is consistent across both mix combinations (Figure 7.9), suggesting that rejuvenators restore the aged binder's flexibility and enhance the mixture's resilience to cracking. Notably, the increase in AFR with little to no change in fracture energy implies that after crack initiation, rejuvenated mixes can accommodate more deformation prior to complete failure, thereby improving overall cracking resistance.

Conversely, the asphalt mixtures with two alphabetic groupings (i.e., 'AB') indicate that the mix is categorized into two groups based on their average CT Index at a 95% confidence level. For example: mixes such as, REJ1, WMA1, and WMA2 in PG64-22 (RAP2) and WMA1 and WMA2 in PG70-22ER (RAP1) fall under group 'AB', suggesting that these mixes perform statistically similar to both the control mix (group 'B') and the rejuvenator-based mixes (group 'A'), with no significant differences between them. In WMA mixtures, the combined influence of fracture energy and AFR appeared to balance each other out, resulting in cracking performance comparable to that of the control asphalt mixtures.



(a)



(b)

Figure 7.9. Interaction diagram for asphalt mixtures having statistically significant differences in the CT Index (a) PG64-22 (RAP2) and (b) PG70-22ER (RAP1)

In general, WMA additives tend to reduce the secondary oxidation of RAP binder at high temperatures by lowering the mix production temperatures, thereby maintaining the cracking resistance of asphalt mixtures even at lower production temperatures. Conversely, the addition of rejuvenators helps improve the blending efficiency between the RAP binder and virgin asphalt binder and improves the interfacial bonding within the mix composite (Sukhija and Coleri 2025b; c). In addition, rejuvenators enhance the chemical balance of RAP binders by adjusting the asphaltene-to-maltene ratio and increasing aromatic content (García et al. 2010). This rejuvenation process softens the aged RAP binder, reducing the overall viscosity of the total binder, particularly due to the presence of oily composition in the rejuvenators. Consequently, while rejuvenators improve cracking resistance, the increased binder softness and lower binder viscosity could impact the rutting characteristics of the asphalt mixtures, which are discussed next.

7.5.4 Interaction of Additives, Binder, and RAP Source on Rutting Behaviour

Like the variation in CT Index, the rut depth of the mixes also varied considerably with the inclusion of WMA and rejuvenators. The effect of different additives on the rutting behaviour of asphalt mixtures with different binder-RAP combinations is shown in Figure 7.10. Across all mixtures, rut depths ranged between 3.40-4.51 mm for PG64-22 (RAP1), 5.61-6.97 mm for PG64-22 (RAP2), 3.04-3.77 mm for PG70-22ER (RAP1), and 3.95-6.00 mm for PG70-22ER (RAP2). These results align with earlier findings, which showed that the mix with RAP2 and PG64-22 binder exhibited a higher rut depth compared to its counterparts. In addition, the mix produced with PG70-22ER binder resulted in higher rutting resistance than the mix with PG64-22 binder, even in the presence of WMA additives or rejuvenators. Notably, the inclusion of WMA or rejuvenators did not alter the overall trends between RAP sources, reaffirming that RAP1 mixtures consistently outperformed RAP2 in rutting resistance.

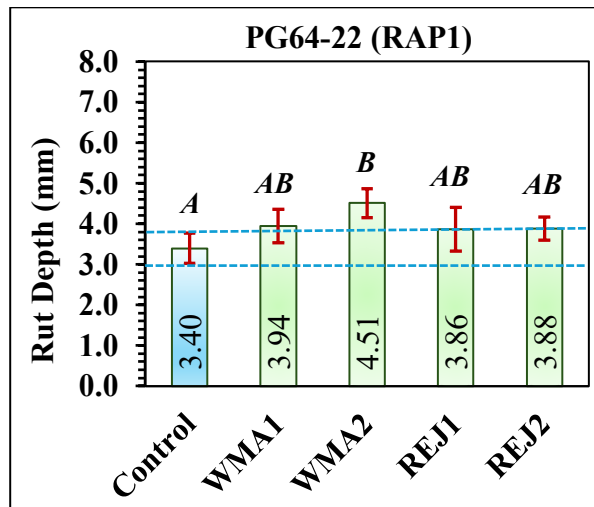
In most cases, the higher rut depth was observed for the WMA mixtures, followed by the rejuvenators and control mixtures. The lower rutting resistance in WMA mixtures can be attributed to reduced binder ageing from lower production temperatures (25°C lower than HMA or control sample), which results in lower stiffness and load-bearing capacity. Similar observations were reported in a previous study by Barra et al. (2022), which found that a chemical-based WMA agent either exhibited similar rutting resistance or slightly increased rut depth, depending on the type of asphalt binder, aggregate, and RAP material. With improved blending efficiency due to the addition of rejuvenators, the difference in the rutting resistance of rejuvenator-based and control mixtures remains marginal. This observation is consistent with prior studies (Arafat et al. 2023; Guduru et al. 2021), which demonstrated that rejuvenators (depending on their type) enhance cracking resistance without significantly compromising rutting characteristics. However, throughout the test results, the value of rut depth is considerably lower than the 12.5 mm critical rutting threshold adopted by various state DOTs, and thus, all the mixtures are classified as rut-resistant mixtures (Chitnis et al. 2025). This highlights the importance of these additives from the cracking perspective.

Similar to the cracking behaviour, statistically significant variations were observed in several mix combinations, indicating that the addition of WMA additives and rejuvenators has a significant influence on rutting resistance. Depending on the type of additive used, the rut depths were found to be lower, similar, or higher than those of the control mixtures within each mix

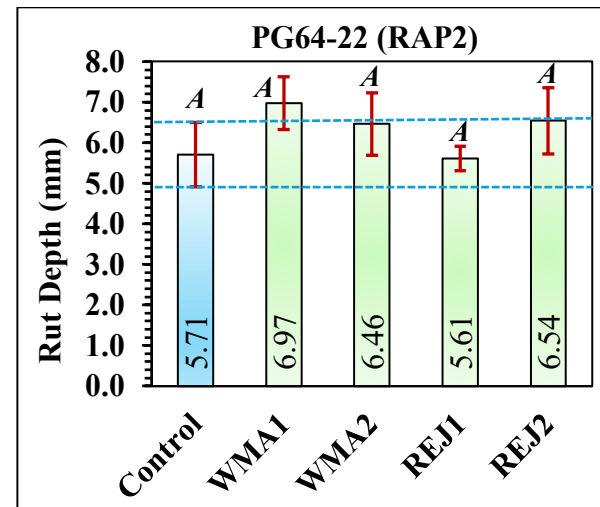
combination set (PG64-22 (RAP1), PG64-22 (RAP2), PG70-22ER (RAP1), and PG70-22ER (RAP2)). Notably, for PG64-22 (RAP2), the influence of additives on rutting resistance was statistically insignificant (P-value = 0.131), and all the asphalt mixtures were grouped under a single category i.e., 'A', as presented in Figure 7.10.

In contrast, for the remaining mix combinations, P-values were < 0.05 , confirming a statistically significant effect of WMA additives and rejuvenators on rutting performance. The P-values were 0.023, 0.017, and 0.009 corresponding to the mix combination PG64-22 (RAP1), PG70-22ER (RAP1), and PG70-22ER (RAP2), respectively. Based on Tukey's pairwise comparison, as shown in Table 7.8, WMA2 in PG64-22 (RAP1) and PG70-22ER (RAP1), as well as WMA1 in PG70-22ER (RAP2), exhibited significant differences in rut depth compared to the control mixture. This is the reason for the distinct group classifications for these mixes ('B'), as shown in Figure 7.10.

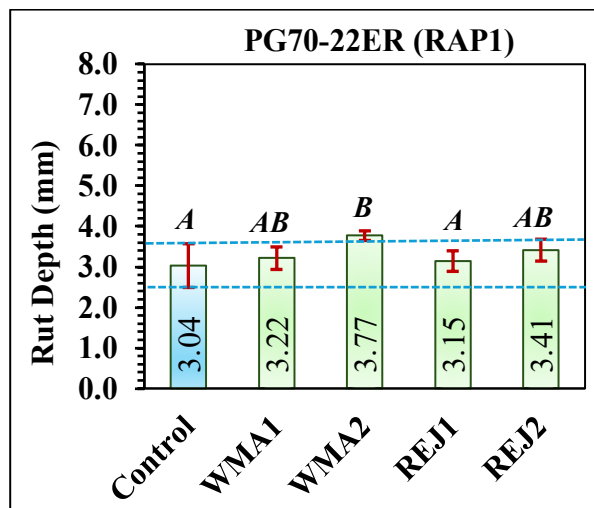
In particular, WMA allows the production of asphalt mixtures at lower temperatures, resulting in lower relative stiffness of the mixtures compared to conventional HMA, and can slightly reduce the rutting resistance. Nevertheless, as already observed, rut depths across all the asphalt mixtures remained well below the standard threshold of 12.5 mm, confirming their overall high rutting resistance. Rejuvenator-based asphalt mixtures (REJ1 and REJ2) exhibited statistically similar rut depths as the control asphalt mixtures across most mix combinations, supporting the earlier findings that the addition of rejuvenator enhances cracking resistance with a marginal influence on rutting. In the PG70-22ER (RAP1) combination, REJ1 was found to be significantly different from WMA2 (P-value = 0.04), placing it in a separate group (Figure 7.10c), however, it exhibited performance comparable to the control mixture.



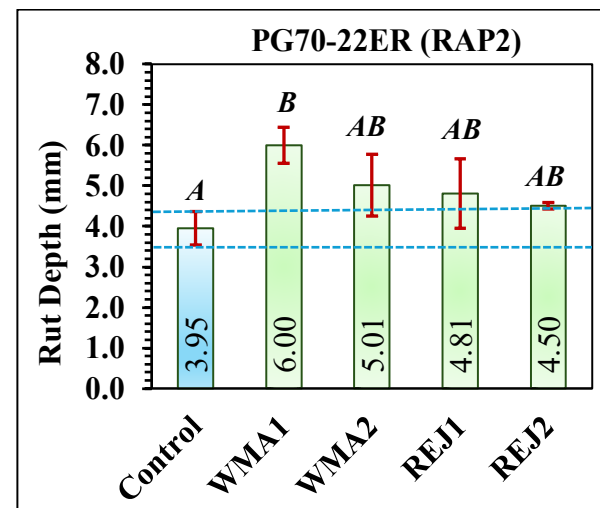
(a)



(b)



(c)



(d)

Figure 7.10. Rutting behavior of different asphalt mix combinations (a) PG64-22 (RAP1), (b) PG64-22 (RAP2), (c) PG70-22ER (RAP1), and (d) PG70-22ER (RAP2)

Note: The dotted line represents the upper and lower bounds of the control samples.

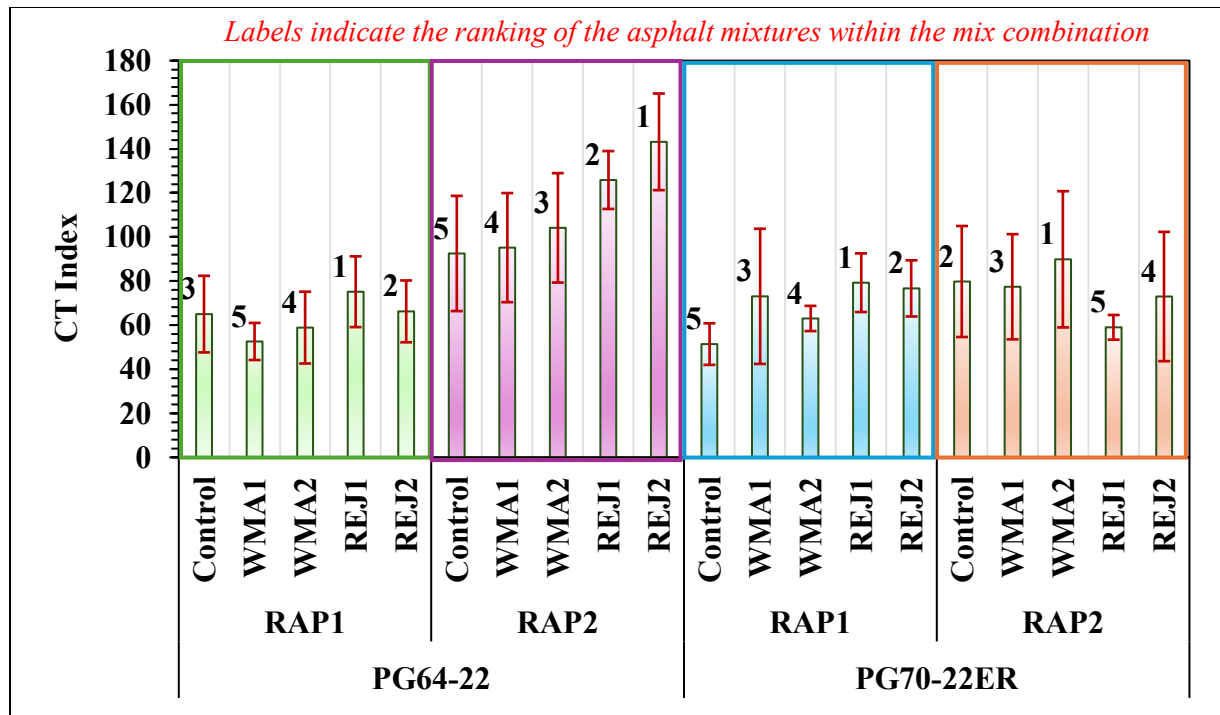
Table 7.8. Tukey's pairwise post-hoc analysis for rutting behaviour (Rut Depth) of WMA and rejuvenator mixtures for both the RAP sources

Difference of levels	PG64-22 (RAP1) 95% CI	PG64-22 (RAP1) P-Value	PG64-22 (RAP2) 95% CI	PG64-22 (RAP2) P-Value	PG70-22ER (RAP1) 95% CI	PG70-22ER (RAP1) P-Value	PG70-22ER (RAP2) 95% CI	PG70-22ER (RAP2) P-Value
WMA1 - Control	(-0.335, 1.420)	0.353	(-0.457, 2.983)	0.197	(-0.487, 0.842)	0.923	(0.647, 3.451)	0.005
WMA2 - Control	(0.238, 1.992)	0.010	(-0.840, 2.345)	0.577	(0.102, 1.363)	0.019	(-0.336, 2.468)	0.171
REJ1 - Control	(-0.412, 1.342)	0.497	(-1.817, 1.623)	1.000	(-0.518, 0.743)	0.981	(-0.540, 2.265)	0.332
REJ2 - Control	(-0.392, 1.362)	0.458	(-0.890, 2.550)	0.559	(-0.292, 1.037)	0.457	(-0.846, 1.958)	0.707
WMA2 - WMA1	(-0.305, 1.450)	0.305	(-2.231, 1.209)	0.873	(-0.075, 1.185)	0.100	(-2.482, 0.516)	0.278
REJ1 - WMA1	(-0.955, 0.800)	0.999	(-3.199, 0.479)	0.193	(-0.695, 0.565)	0.998	(-2.686, 0.312)	0.147
REJ2 - WMA1	(-0.935, 0.820)	1.000	(-2.272, 1.406)	0.940	(-0.470, 0.860)	0.896	(-2.992, 0.006)	0.051
REJ1 - WMA2	(-1.527, 0.227)	0.202	(-2.569, 0.871)	0.539	(-1.214, -0.026)	0.039	(-1.702, 1.296)	0.991
REJ2 - WMA2	(-1.507, 0.247)	0.225	(-1.643, 1.798)	1.000	(-0.990, 0.270)	0.440	(-2.009, 0.989)	0.803
REJ2 - REJ1	(-0.857, 0.897)	1.000	(-0.912, 2.766)	0.520	(-0.370, 0.890)	0.721	(-1.806, 1.192)	0.961

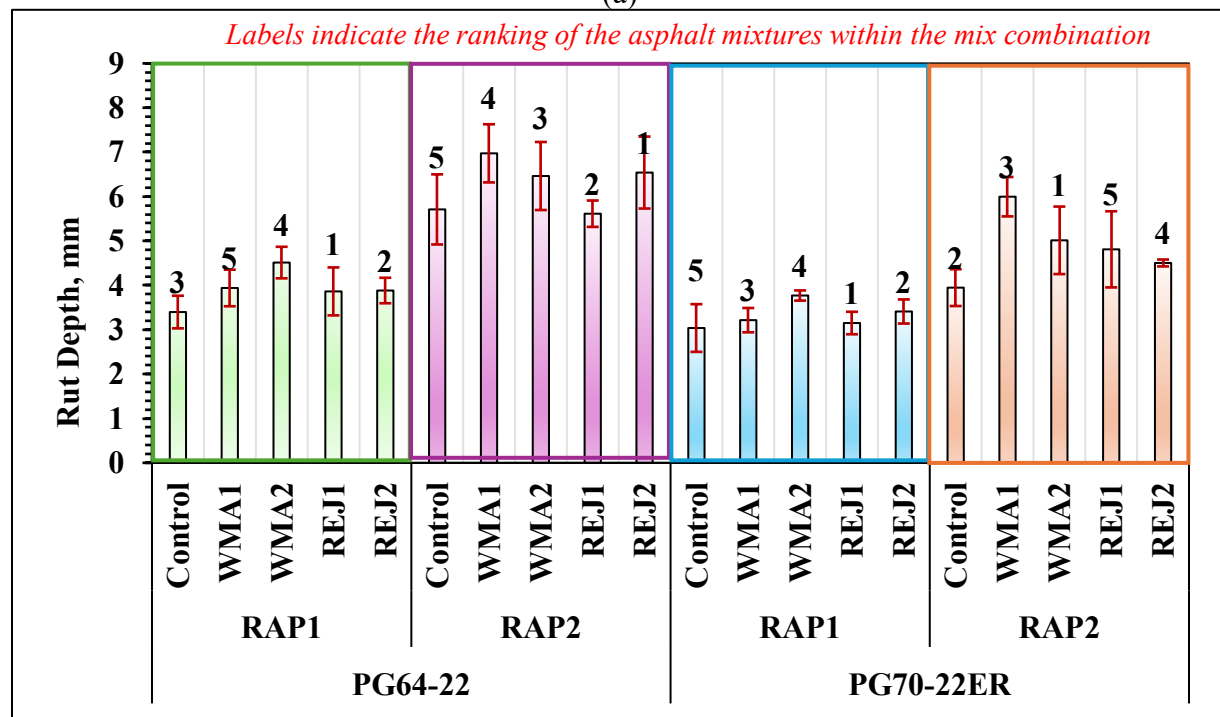
7.5.5 Discussion on Phase I and Phase II

The results of both phases of the study underscore the importance of mix variables, including the binder grade, RAP source, and RAP sampling location, on the cracking and rutting behavior of asphalt mixtures. It also highlights the variability introduced by WMA additives and rejuvenators, showing how their performance depends on interactions with these mix variables. In the above sections, the experimental results and the comparison of cracking and rutting potential were based on the average values obtained in the present study. Considering the variability within the results (as shown by the error bars) for each mix combination, it can be stated that the addition of WMA and rejuvenators either performed similarly or resulted in improved performance compared to control asphalt mixtures. For almost all combinations, the CT Index and rut depths fall within the upper and lower bounds of the control mixtures (Figure 7.8 and Figure 7.10).

Although there is a significant impact of binder grade and RAP sources, the present study indicated that these variations remain consistent with the inclusion of additives such as WMA and rejuvenators. Figure 7.11 shows the complete performance results derived in the present study. For instance, irrespective of the additive, the mix with RAP2 and PG64-22 binder offered improved cracking resistance, but the lowest rutting resistance compared to its counterparts. This is due to the softer binder grade of RAP binder (compared to RAP1) as well as virgin binder (compared to PG70-22ER).



(a)



(b)

Figure 7.11. Complete performance dataset and the corresponding ranking between different asphalt mixtures based on the performance parameters (a) CT Index and (b) Rut Depth

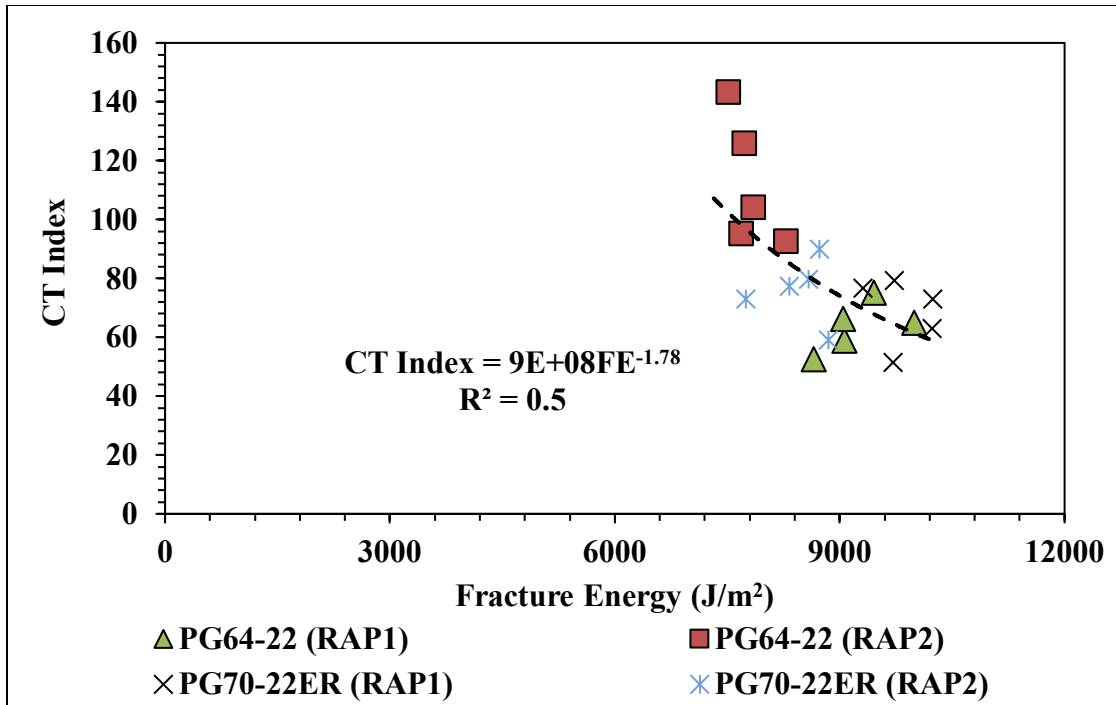
Note: Numbers on the bars indicate the ranking of the asphalt mixtures within their group.

Apart from the suitability of additives and their interaction with mix variables, it was found that the improvement in cracking resistance was primarily due to the increase in the AFR. Table 7.9 shows an example from the current dataset, wherein both the mixes exhibit almost similar fracture energy but differ in CT Index values, and consequently, the cracking resistance, particularly due to the variations in AFR value. In other words, the CT Index showed greater sensitivity to AFR values compared to fracture energy. Similar variations were observed in other mix combinations, but they are not presented here for brevity.

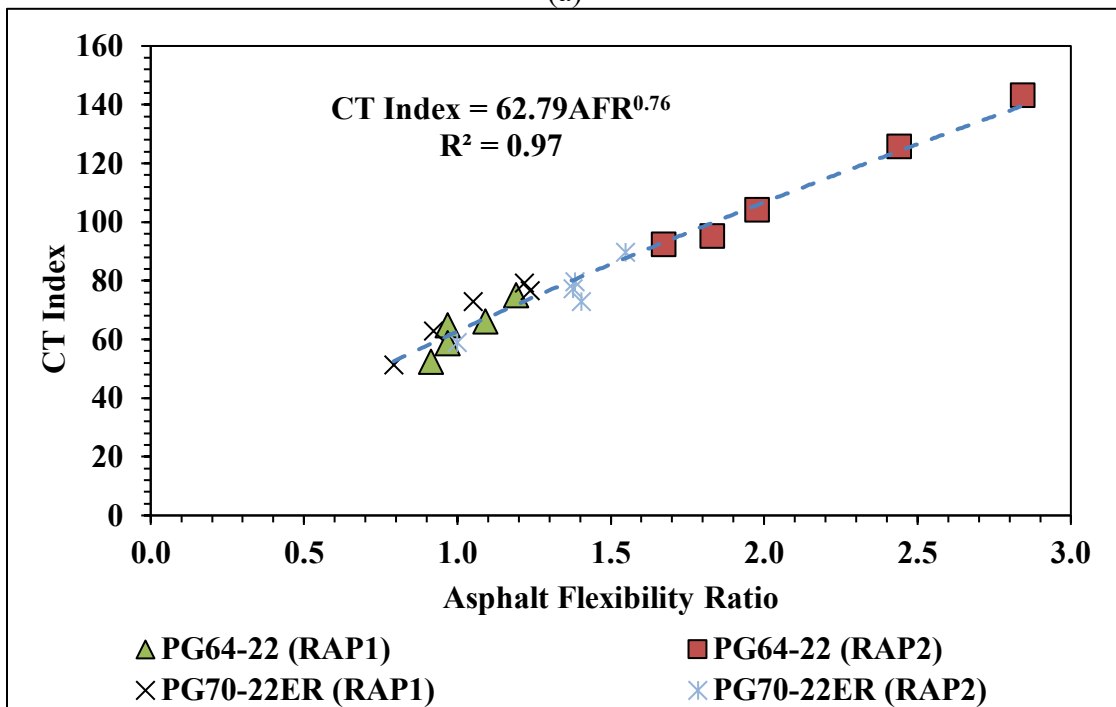
Table 7.9. Sensitivity of CT Index to fracture energy and AFR

Mix Combination	CT Index	Fracture Energy (J/m²)	AFR
PG70-22ER (RAP1)- Control	51.39	9713.63	0.79
PG70-22ER (RAP1)- REJ1	79.23	9725.86	1.22

To support this attribution, Figure 7.12 presents the relationship between these test parameters. As perceived, different mix combinations exhibit varying AFR and CT Index values, while fracture energy remains relatively consistent across all asphalt mixtures. The correlation analysis revealed an R^2 value of 0.5 and a negative Pearson coefficient (-0.66) between CT Index and fracture energy, indicating an unexpected trend where higher fracture energy corresponds to lower CT Index. These findings align with a couple of previous studies (Kaseer et al. 2018; Li et al. 2024; Sukhija et al. 2024), wherein fracture energy showed poor correlations with other cracking test parameters, suggesting that fracture energy alone is not suitable for reflecting the cracking performance of asphalt mixtures. On the other hand, the correlation between CT Index and AFR yielded an R^2 of 0.97 and a Pearson coefficient of 0.98, offering a strong positive relationship. This suggests that CT Index values and cracking resistance are relatively more dependent on the AFR, with higher AFR values leading to improved cracking performance. These findings align with previous studies (Leavitt et al. 2024; Yadav and Saboo 2025), supporting AFR as a reliable indicator for quantifying the cracking resistance of asphalt mixtures.



(a)



(b)

Figure 7.12. Correlation between cracking test parameters (a) Fracture energy and CT Index, and (b) Asphalt flexibility ratio and CT Index

7.6 CONCLUSIONS

The key findings of the study are as follows:

1. Statistical analysis indicated significant variation in the performance of asphalt mixtures with the change in binder grade (P-value = 0.006 for CT Index and 0.00 for rut depth) and RAP source (P-value = 0.00 for both CT Index and rut depth), while RAP sampling location (within-plant variability) had no statistically significant effect (P-value exceeds 0.05).
2. Mixes prepared with PG64-22 and RAP2 consistently demonstrate superior cracking resistance but lower rutting resistance, regardless of the RAP sampling location. In contrast, PG70-22ER reduced CT Index by approximately 13–31% and enhanced rutting resistance by 12–36%, depending on the RAP source and sample location.
3. Attributable to the softer RAP binder in RAP2, CT Index values were 1.35–1.85 times higher, while rut depths were 1.2–1.7 times greater compared to RAP1 mixtures. These differences led to the statistical grouping of RAP1 and RAP2 into distinct categories, as confirmed by Tukey's pairwise post-hoc analysis.
4. Although CT Index and rut depths varied with the addition of WMA additives and Rejuvenators, the overall trends between RAP sources remained unaltered, reaffirming that RAP1 (the source with the stiffer RAP binder) mixtures demonstrated better rutting resistance but lower cracking resistance than RAP2 mixtures. This result emphasized the importance of RAP binder stiffness on the overall performance of the mixture.
5. Rejuvenator-modified mixtures exhibited statistically significant improvements in CT Index compared to the control, reflecting enhanced cracking resistance (P-value < 0.05). However, their impact on rutting was marginal, as evidenced by small differences in rut depth and confirmed by statistical analysis (P-value > 0.05).
6. Due to reduced oxidative ageing at lower production temperatures, WMA mixtures exhibited similar or higher rut depths than the control, depending on the interaction with the base binder and RAP source. Despite this variation, their CT Index values belonged to the same statistical group as the control mixtures, indicating no significant difference in cracking resistance.
7. The variability in CT Index values with the inclusion of WMA additives or rejuvenators is strongly governed by changes in the AFR (L75/m75) parameter. This underscores the critical role of post-peak behavior in the IDT-CT load-displacement curve. A strong correlation ($R^2 = 0.97$; Pearson coefficient = 0.98) confirms that the CT Index is more sensitive to AFR than to fracture energy.

8.0 TENTATIVE PLAN FOR FIELD TEST SECTIONS

As per the findings from the laboratory portion of this study (Chapter 5.0), all the additives either improved or maintained the performance of high RAP mixtures (40% RAP in Level 3 and 30% RAP in Level 4) when compared to conventional RAP mixtures prepared with current allowable limits (30% RAP in Level 3 and 20% RAP in Level 4). In addition to performance improvements, the benefits were observed in economic and environmental aspects, depending on the mix combination defined based on the binder grade and additive type (Chapter 6.0). To strengthen the reliability of these results, field validation through pilot projects is recommended. Accordingly, the research team at OSU proposed the construction of pilot sections across various regions of Oregon, as outlined in Table 8.1. The proposed locations are also mapped to Oregon's diverse climatic zones, as illustrated in Figure 8.1.



Figure 8.1. Potential field test section locations representing Oregon's climate conditions (ODOT 2026)

Table 8.1. Details of potential (tentative) field test section locations with high RAP content in Oregon

Highways	Region	Mix Design Level	Base Binder	RAP Content
US-97	North Oregon	Level 3	PG64-22	40%
OR-140	South Oregon	Level 3	PG64-22	40%
I-84	East Oregon	Level 4	PG70-22ER	30%
I-5	West Oregon	Level 4	PG70-22ER	30%

Note 1: The production temperatures of WMA should be reduced by 25°C than the conventional HMA mixtures.

Note 2: Strategic techniques include Control, WMA1, WMA2, REJ1, REJ2.

In order to compare the field performance of high RAP mixtures prepared using different strategic technologies, a tentative section plan is proposed, as shown in Figure 8.2. For better comparison, a block section of each technology, such as WMA1, WMA2, REJ1, REJ2, should be constructed as a block section of approximately 2,500 ft in length, along with a control section produced without any additive or modification to serve as a reference. The qualitative and quantitative details of these strategic techniques are illustrated in Table 8.2.

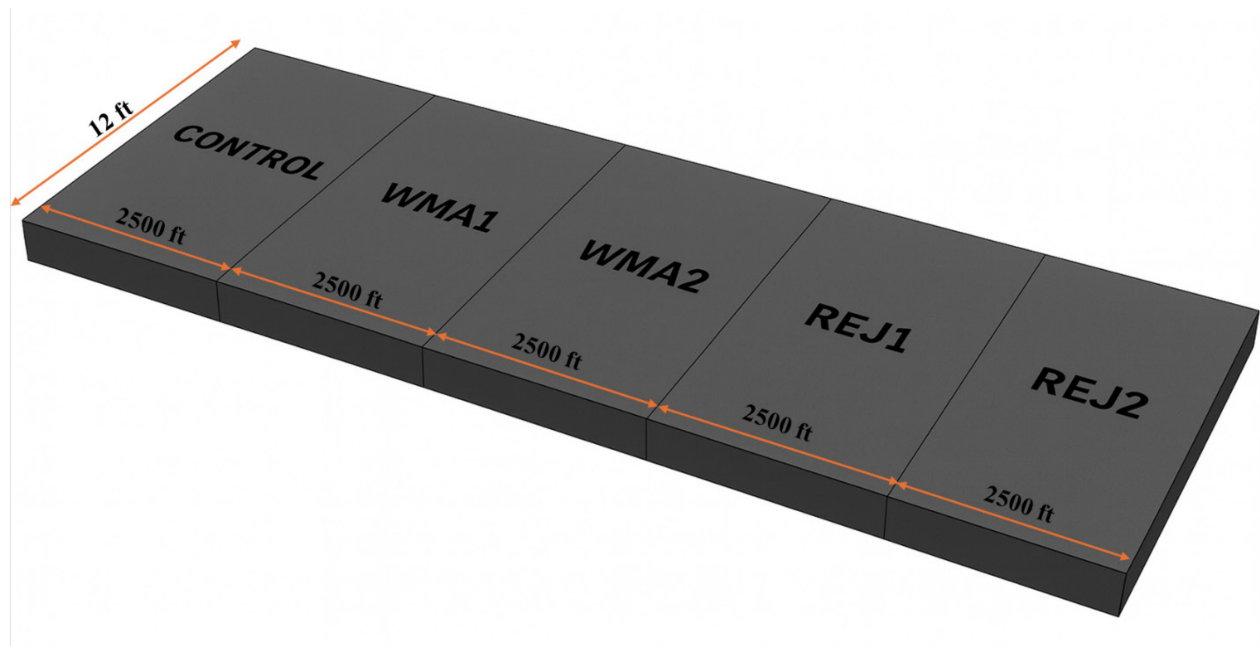


Figure 8.2. Tentative plan for constructing field test sections to compare different strategic technologies for high RAP mixtures

Table 8.2. Qualitative and Quantitative characteristics of selected rejuvenators (REJ1 and REJ2) and WMA additives (WMA1 and WMA2)

Characteristics	REJ1	REJ2	WMA1	WMA2
Chemical composition	Tall oil fatty acid derivative	Corn oil, fatty acid residues, and methyl ester	Modified tall oil, fatty acid, and alkyl acid phosphate	Esters, phosphoric acid, and non-hazardous ingredients
Odor	Bland	Slight	Odorless	Mild
Physical state	Liquid	Liquid	Liquid	Liquid
Visual color	Amber (Dark)	Dark brown	Dark brown	Dark brown
Density at room temperature (g/cm³)	0.97	0.92	0.99	0.92-0.96
Viscosity, dynamic at room temperature (centipoise)	>118	> 150	487	< 250
Flash point (°C)	> 232	> 150	> 181	> 150
Solubility in water	NA	NA	Insoluble	Slightly soluble
pH value	8.3	5.3	2.3	2.5
Supplier-recommended dosage by weight of total asphalt binder	1.5%	1.5%	0.5%	0.5%

Note: Additive dosages should be adjusted based on the RAP binder availability and total binder content

8.1 PREPARATION OF THE SAMPLES

For the preparation of asphalt mixtures, the mix design should be evaluated based on the balanced mix design (BMD) approach, as recommended in SPR852. As per our research findings, there is very minimal difference in the BMD binder content after the application of strategic techniques; however, verification prior to field implementation is advisable to ensure consistency and reliability. Since different additives have been recommended, including the use of rejuvenators and WMA, their dosages need to be carefully adjusted depending on the available RAP binder and total asphalt binder requirement in the mix, in accordance with Equation 8.1.

Adjusted additive dosage (%)

$$= \frac{\text{Target additive dosage (\%)} \times \text{Total binder content (\%)}}{\text{Total binder content (\%)} - \text{Binder from RAP (\%)}}$$

(Equation 8.1)

8.2 PROPOSED TEST PLAN

1. **Material Sampling and Mix Design:** Collect materials from the selected projects and determine the Optimum Binder Content (OBC) using the Balanced Mix Design (BMD) approach, as recommended in SPR852. The final Job Mix Formula (JMF) will be provided for production.
2. **Construction of Field Sections:** Construct test sections with high RAP mixtures (according to the designated mix design level), both with and without the application of strategic techniques such as warm mix asphalt technologies (WMA1 and WMA2) and rejuvenators (REJ1 and REJ2).
3. **Production Mix Sampling and Comparison:** Sample production mix to prepare Plant-Mix Laboratory Compacted (PMLC) specimens and compare them with Laboratory-Mix Laboratory Compacted (LMLC) specimens and the JMF targets to assess workability and performance.
4. **Field Coring and Laboratory Testing:** Perform coring of field-constructed sections and subject the samples to laboratory testing to evaluate in-field performance.
5. **Performance Monitoring:** Conduct periodic monitoring of the constructed sections to track performance over time, with emphasis on rutting, cracking, roughness, and other surface distresses.
6. **Accelerated Pavement Testing:** Implement accelerated pavement testing on a smaller test section constructed with the recommended strategic techniques, following a methodology similar to that used by the research team in SPR852 to compare volumetric and BMD-based projects.

The complete results will support the implementation of high RAP mixtures beyond the current allowable limit for the state of Oregon, resulting in improved durability, cost effectiveness, and sustainability of asphalt pavements. Furthermore, the findings will provide valuable insights into the suitability and applicability of various strategic techniques, such as warm mix asphalt technologies and rejuvenators, for enabling higher RAP contents. This implementation will also help evaluate the performance of these technologies under different climatic regions, thereby guiding their broader adoption in practice.

9.0 SUMMARY, CONCLUSIONS, AND FUTURE DIRECTIONS

During the past decade, concerns about potential premature pavement failures, including issues related to long-term performance, material consistency, binder stiffening, blending efficiency, compatibility, and environmental impacts from higher production temperatures, have slowed the adoption of higher RAP contents in asphalt mixtures across the U.S. Since then, the lower amount of RAP content, ranging from 10-30% has been adapted for recycling purposes in most of the states. However, the pressure from the environmental aspects, coupled with the increased price of natural aggregates and asphalt binders, urges the asphalt industries and agencies to utilize higher RAP contents. Thus, researchers found various strategic techniques and RAP management schemes that can be adapted to incorporate the RAP material in high proportions with desirable performance. The comprehensive review of the research studies in the literature, which showed the benefits of these measures, has been compiled and summarized in Chapter 2.0 of the present study. The adequate performance at high RAP content tends to instill confidence in engineers to use high RAP (preferably > 25%) in pavement material production. This recent momentum for increased RAP recycling could be a major step toward achieving carbon neutrality for the paving industry and its agencies, thereby enhancing sustainability in terms of pavement longevity, as well as environmental and economic benefits.

Given the growing emphasis on recycling and sustainability in Oregon, several objectives of this study were outlined in Chapter 1.0. These include evaluating mixture performance in terms of rutting and cracking, as well as assessing the associated economic and environmental impacts. This study also considers the effects of material variability, including RAP source differences and in-plant variability arising from stockpile location within a single RAP stockpile. In addition, this research study investigated how strategic techniques, such as rejuvenators and warm mix asphalt (WMA) additives, interact with these factors. Collectively, these evaluations provide valuable insights into effective RAP management strategies for producing high-RAP mixtures.

The present study aims to implement strategic measures to enhance RAP utilization, focusing on both mix design modifications, such as increased binder content and binder grade bumping, and the use of additives, including rejuvenators and WMA technologies. The objective is to increase the allowable RAP content in Oregon from the current limits of 30% in Level 3 and 20% in Level 4 to 40% in Level 3 and 30% in Level 4, while ensuring satisfactory performance. Key challenges, including the selection of appropriate additives and their dosages, determining reliable production temperatures, and other associated factors, were carefully considered.

Two asphalt binders were utilized throughout the study: PG64-22 for Level 3 mixtures and PG70-22ER for Level 4 mixtures. In addition, two rejuvenators (REJ1 and REJ2) and two WMA additives (WMA1 and WMA2) from two different producers were incorporated as strategic techniques to facilitate higher RAP utilization. A series of experiments was conducted, including the Indirect Tensile Cracking Tolerance Test (IDT-CT) to evaluate cracking resistance, the Hamburg Wheel Tracking Test (HWTT) to assess rutting performance, and Superpave Gyratory Compactor (SGC) testing to evaluate mixture workability, while statistical analyses were performed to understand the significance of the influencing variables. The in-depth details on the

materials used and the test methodology are presented in Chapter 3.0. This chapter also includes a discussion on the characterization of asphalt binders with and without WMA and rejuvenators.

This study highlights the impact of key factors, including binder content, RAP content, and binder grade, on the performance of RAP mixtures. As demonstrated in Chapter 4.0, adjustments in binder content and binder grade were shown to be effective in producing durable high-RAP mixtures with RAP levels beyond the current allowable limits in Oregon (20–30%).

Based on these findings, Chapter 5.0 examines additional strategic measures, including the use of rejuvenators and WMA additives. Several concerns related to their application, such as the selection of optimal dosages and the identification of reliable production temperatures for WMA mixtures, were addressed through workability assessments using the SGC. Once these variables were established, the feasibility of incorporating rejuvenators and WMA additives was evaluated through performance testing, with the goal of enabling a 10% increase in RAP content in ODOT mixtures.

Following the performance evaluation, Chapter 6.0 presents a cradle-to-gate life cycle assessment (LCA) and cost-effectiveness analysis to quantify the economic and environmental implications of higher RAP utilization and the adoption of strategic measures.

Finally, Chapter 7.0 explores the impact of RAP variability (within-plant and between-plants) on mixture performance. Two binder grades, two RAP sources, and two RAP sampling locations within the same stockpile were considered to broaden the applicability of the findings. Strategic techniques, including rejuvenators and WMA technologies, were also evaluated to determine how their effectiveness varied with RAP source and binder grade. A tentative plan for the field pilot section construction and performance assessment is also provided in Chapter 8.0.

9.1 KEY CONCLUSIONS

The conclusions derived from this comprehensive research study are as follows:

9.1.1 Material Characterization

- Fourier Transform Infrared Spectroscopy (FTIR) of the additives confirmed the presence of esters in rejuvenators, which aids in restoring the maltene content of RAP binder and thereby enhancing the rejuvenation effect. On the other hand, WMA comprises ether-related peaks in FTIR, underscoring their benefits on the interfacial bond between aggregate and asphalt binder.
- The warm-mix asphalt binders mainly showed physical mixing with the additives, while the rejuvenator binders showed signs of chemical reactions. One binder with added polymer (PG70-22ER) showed clear structural changes from the polymer's effect.
- Rheological characterization revealed that the WMA behaves similarly to the base asphalt binders, while the application of rejuvenators imparts softness in both the binders, leading to a lower value of softening temperature in the Binder Fast Characterization Test (BTSV). The high-temperature performance grade, indicating the deformation resistance, of the base

asphalt binders was also found to be affected by the addition of the rejuvenators. These characteristics are expected to improve the condition of highly oxidized RAP binder for its utilization in the production of asphalt pavements.

9.1.2 Adjustment in mix design attributes

- Preliminary analysis indicates that the performance of RAP mixtures depends on binder content, RAP content, and binder grade, and among all the factors, binder content is the most influential contributor, representing 58% of the contribution in the case of the CT Index and 76% for varying the rutting characteristics.
- The increase in binder content from 5.5% to 6.0% and 6.5% increases the CT Index by around 98% and 202%, respectively; concurrently, it also leads to an increase in rut depth by approximately 43% and 87%, respectively. However, it is worth noting that none of the mixes evaluated in this study exhibited a tendency to fail due to rutting, even at high additive or binder content levels. Thus, the benefits created in terms of improved cracking resistance should be considered more critical.
- Performance test results reflect that correct adjustment in the mix design attributes, including the binder content and grade, can be used as strategic techniques to improve RAP utilization by 10%. Based on the findings, increasing the binder content by 0.5% or bumping the binder by one grade increases the CT Index (cracking resistance) and rut depth (rutting susceptibility). Tukey's analysis shows that a further increase in RAP content (say, 20% from the current allowable limits) does not enhance cracking resistance, though it does improve the rutting resistance. This necessitates further adjustment in the binder content or the binder grade accordingly.

9.1.3 Temperature Sensitivity, Dosage Optimization, and Performance Evaluation

- Even when the production temperature was lowered by 25 °C, the WMA mixtures with 30% recycled material still worked well, similar to those made at normal hot-mix temperatures without any additives. Lowering the temperature further reduced workability slightly, but the effect depended on the type of additive used and the level of reduction in the temperature.
- Adding a small amount of WMA additives (0.5% by weight of total binder) made it possible to include about 10% more recycled material without losing workability, even at lower production temperatures. Similarly, using rejuvenators (1.5 % by weight of total binder) helped soften the aged binder in the recycled material, improving mix workability even with higher RAP content than normally allowed.
- The optimum dosages determined in this study, 0.5% for WMA (at 25 °C reduced temperatures) and 1.5% for rejuvenators, aligned with manufacturer recommendations. Both additives enhanced workability, though rejuvenator-modified mixtures consistently showed

higher WEI values than WMA-modified ones at equivalent RAP levels. Nevertheless, all modified mixtures were statistically comparable ($P > 0.05$) to their respective reference mixtures at current RAP limits. The optimized dosage and production temperatures for different mixes are presented in Table 9.1.

Table 9.1. Optimized additive dosages and production temperatures of the asphalt mixtures for performance evaluation

Test Samples	Additive Dosages	Temperature Condition	Mix Material	Level 3 MT	Level 3 CT	Level 4 MT	Level 4 CT
Control Reference Samples	No Additive	HMA	Asphalt Binder	153-160°C	140-145°C	165-171°C	152-157°C
Control Reference Samples	No Additive	HMA	Aggregate	163-170°C	140-145°C	175-181°C	152-157°C
Rejuvenator Samples	1.5% by weight of the total binder	HMA	Asphalt Binder	153-160°C	140-145°C	165-171°C	152-157°C
Rejuvenator Samples	1.5% by weight of the total binder	HMA	Aggregate	163-170°C	140-145°C	175-181°C	152-157°C
WMA Samples	0.5% by weight of the total binder	WMA (HMA-25°C)	Asphalt Binder	128-135°C	115-120°C	140-146°C	127-132°C
WMA Samples	0.5% by weight of the total binder	WMA (HMA-25°C)	Aggregate	138-145°C	115-120°C	150-156°C	127-132°C

Note: In all the mixtures, RAP was heated to 121°C for two hours before mixing. MT and CT represent mixing and compaction temperatures, respectively. Dosages should be adjusted depending on the RAP content and total binder content, as per Equation 3.1 (Chapter 3.0).

- At optimum dosages, both rejuvenators and WMA additives enabled a 10% increase in RAP content while maintaining satisfactory cracking and rutting performance. These changes can be attributed to modifications in the asphaltene-to-maltene ratio and enhanced binder flexibility with rejuvenators, or to reduced production temperatures and mitigated ageing effects with WMA.
- Statistical analysis indicated that nearly all high RAP mixtures performed comparably to or better than the control mixtures, with the sole exception of WMA2 at 6% binder content in Level 4 mixtures, which showed a slight reduction in both cracking and rutting performance. These findings confirm that RAP contents can be increased by about 10% beyond current

allowable limits through the use of rejuvenators or WMA technologies, with the rate and extent of improvement influenced by mix design level, binder content, and binder grade. With a little adjustment in the mix design attributes and additives dosages, RAP proportions could be increased even more than the current expectations (say, 50% in Level 3 and 40% in Level 4). However, those additives generally do not provide significant improvements in cracking resistance when the binder content is low at around 5.5% or lower. For this reason, the thresholds for the recently proposed BMD approach should be modified to achieve a binder content of at least 6% for both Level 3 and Level 4 mixtures.

- Among the evaluated strategies, rejuvenators consistently outperformed WMA additives, with the ranking order: REJ1 > REJ2 > WMA1 > WMA2. REJ1 provided the best balance of cracking resistance and rutting performance, followed by REJ2, while WMA1 performed better than WMA2. This can be clearly depicted in the ranking table shown below (Table 9.2).

Table 9.2. Average ranking of the strategic techniques for high RAP mixtures

Strategic Techniques	Level 4 CT Index	Level 4 Rut Depth	Level 3 CT Index	Level 3 Rut Depth	Average Rank
WMA1	3	3	2	3	3
WMA2	4	4	4	4	4
REJ1	1	1	1	1	1
REJ2	2	2	3	2	2

9.1.4 Economic and Environmental Burdens

- Preliminary analysis showed that all key mix design attributes, binder type, binder content, and RAP content, affect greenhouse gas (GHG) emissions, though their relative influence varies by emission category. For instance, in the case of global warming potential (GWP), binder content was the most significant factor, while RAP content had the greatest impact on Ozone depletion potential (ODP).
- Within the cradle-to-gate system boundary, the material production stage contributed the largest share of emissions (49–72%), followed by the mix production stage (16–32%) and transportation (10–22%). In contrast, for ODP, transportation accounted for the majority of emissions (61%). The contributions of different phases are shown in Figure 9.1.

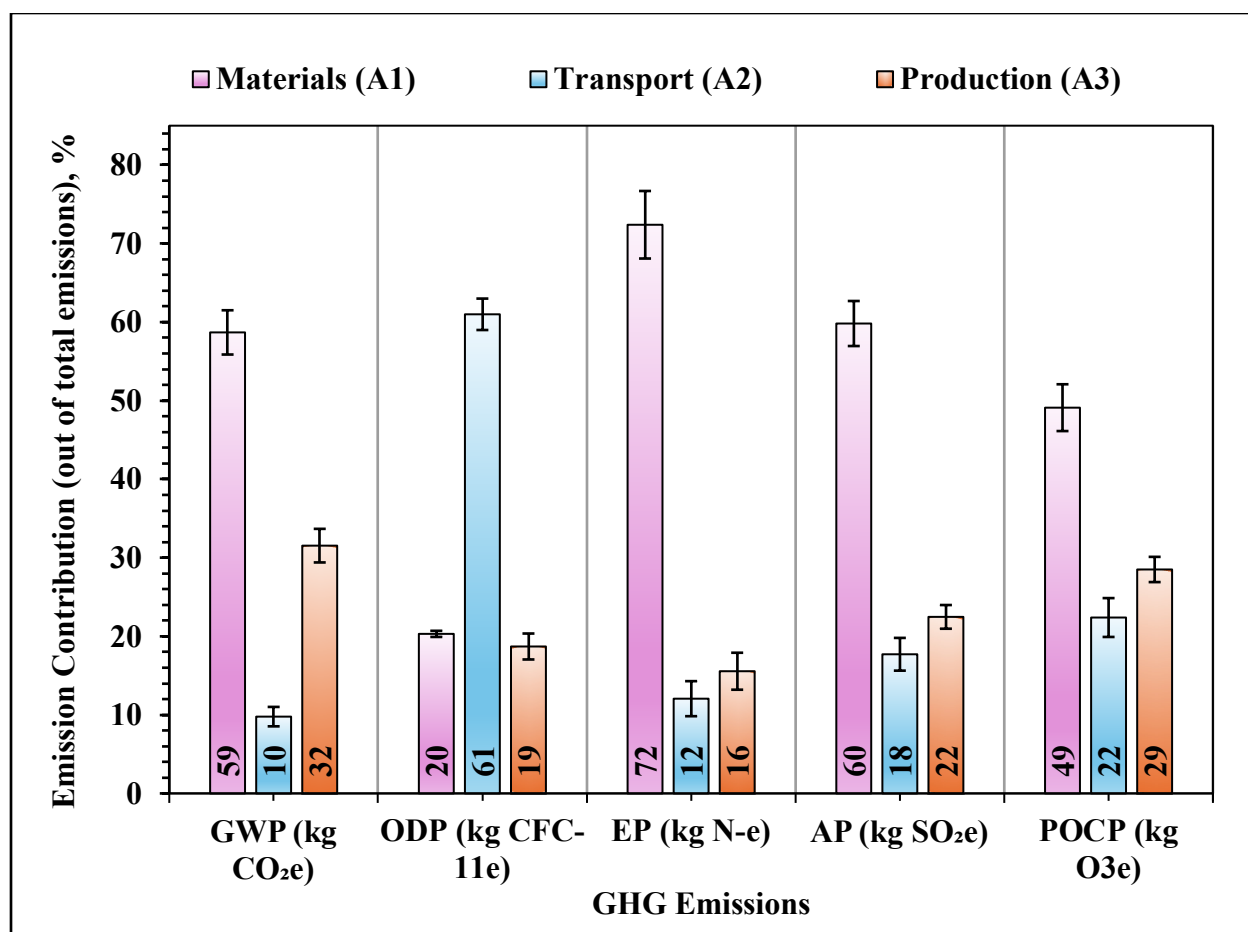


Figure 9.1. Contribution of different cradle-to-gate phases to the total GHG emissions

- In Level 3 mixtures, WMA technologies lowered total GWP by 7–8% compared to control mixtures, primarily due to reduced burner fuel and oil heating from lower production temperatures. In Level 4 mixtures, the most environmentally favourable strategy was binder grade bumping, which achieved about a 12% GWP reduction by replacing polymer-modified PG70-22ER with unmodified PG64-22, thereby avoiding the higher emissions associated with polymer modification. This was followed in effectiveness by WMA, rejuvenators, and increased binder content.
- RAP pricing significantly influenced overall cost and the cost-effectiveness of different strategies, as illustrated in Table 9.3. At \$30/ton, only binder grade bumping and WMA technologies were cost-effective in Level 4 mixtures, while no strategies were economical in Level 3. However, reducing the RAP price to \$17.5/ton resulted in cost savings for all strategies (improvements ranging from 1% to 14.7%), depending on mix design level and selected strategy, underscoring the importance of carefully evaluating RAP material costs during decision-making.

Table 9.3. Percent change in total cost relative to control mixtures based on the cost of RAP material

Mix Design Level	Strategic Techniques	RAP Cost 30\$/ton	RAP Cost 17.5\$/ton
Level 3	Increased Binder Content	1.40%	-1.50%
Level 3	WMA1	1.30%	-1.60%
Level 3	WMA2	0.30%	-2.70%
Level 3	REJ1	1.80%	-1.00%
Level 3	REJ2	1.50%	-1.40%
Level 4	Increased Binder Content	-0.30%	-3.00%
Level 4	Binder Grade Bumping	-11.40%	-14.70%
Level 4	WMA1	-0.90%	-3.70%
Level 4	WMA2	-0.60%	-3.30%
Level 4	REJ1	0.60%	-2.10%
Level 4	REJ2	0.90%	-1.80%

Note: Positive value indicates an increase in cost, while a negative value indicates a reduction in cost.

9.1.5 RAP Management Strategy: Effect of RAP Source and In-plant Variability

- Findings demonstrated significant influence of binder grade and RAP source on the performance of asphalt mixtures, whereas RAP sampling location (within-plant variability) showed no significant impact, as performance metrics across locations largely overlapped.
- Despite varying significance levels, rejuvenator and WMA mixtures showed consistent trends. Specifically, the combination of PG64-22 binder and RAP Source 2 produced the most favorable performance outcomes in terms of both cracking and rutting. Due to the softer binder in RAP2, CT Index values were 1.35–1.85 times higher, whereas rut depths were 1.2–1.7 times greater compared to RAP1 mixtures. This result highlights the importance of RAP binder properties in achieving a high-performance mix.
- While the measured CT Index and rut depths varied with the use of WMA additives and rejuvenators, the relative trends between RAP sources remained consistent. RAP1 mixtures showed better rutting resistance but lower cracking resistance than RAP2. Rejuvenators significantly improved the CT Index, enhancing cracking resistance with minimal effect on rutting. In contrast, WMA mixtures, influenced by reduced oxidative ageing at lower production temperatures, exhibited similar or slightly higher rut depths than the control, while their CT Index values remained statistically comparable. These additives enhanced the ductility and flexibility of the asphalt mixtures, contributing to better cracking resistance with acceptable rutting levels (< 12.5 mm).
- Variability in CT Index with WMA or rejuvenator inclusion was strongly governed by the Asphalt Flexibility Ratio (AFR) (L75/m75) parameter, highlighting the importance of post-

peak behavior (the behavior after crack initiation) in the IDT-CT load–displacement curve. An example showing the sensitivity of the CT Index is presented in Table 9.4. A strong correlation ($R^2 = 0.97$; Pearson = 0.98) confirmed that the CT Index is more sensitive to AFR than to fracture energy.

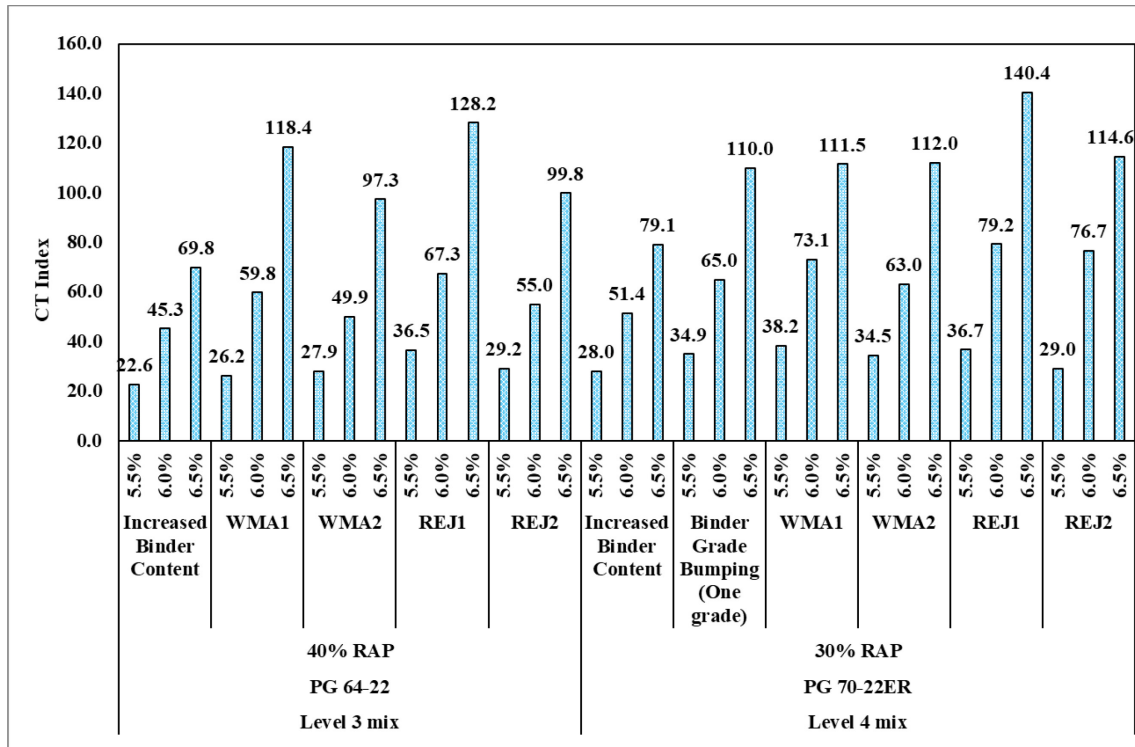
Table 9.4. Example of the sensitivity of the CT Index to fracture energy and AFR

Mix Combination	CT Index	Fracture Energy (J/m ²)	AFR
PG70-22ER (RAP1)- Control	51.39	9713.63	0.79
PG70-22ER (RAP1)- REJ1	79.23	9725.86	1.22

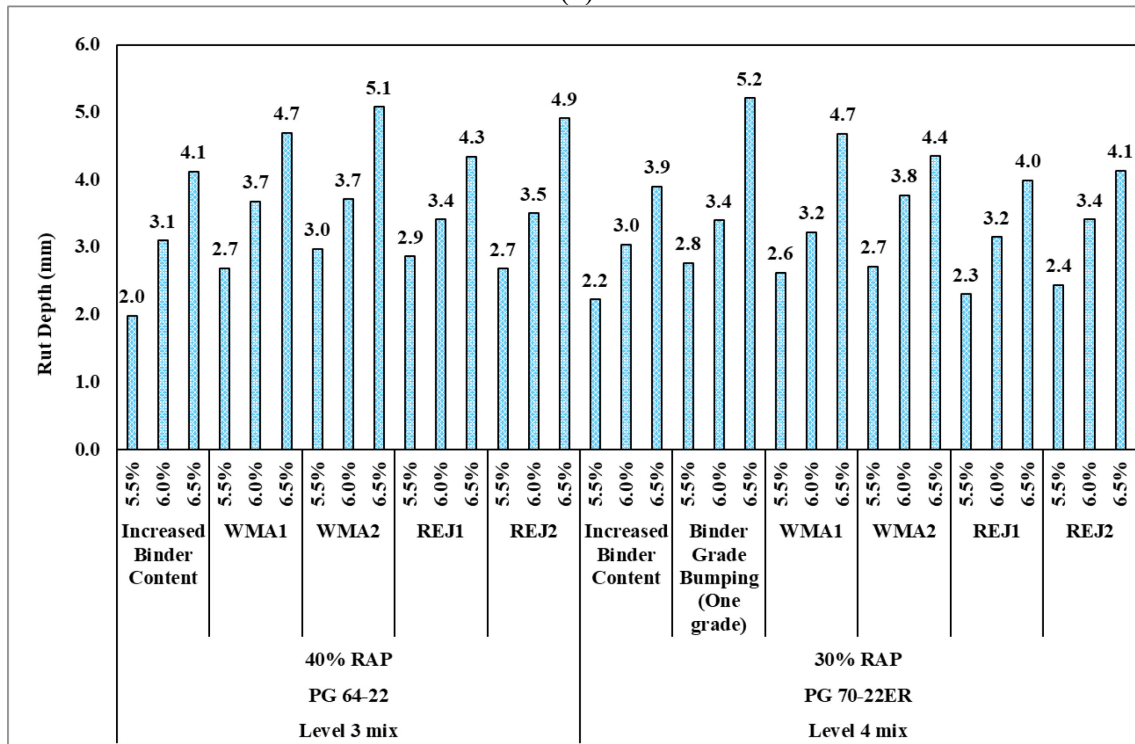
9.2 CONTRIBUTIONS OF THE STUDY

The key contributions of the research work are as follows:

- The study provides insights into adjustments in mix design attributes and their suitability for high RAP incorporation. A comprehensive evaluation demonstrated how strategic techniques, such as rejuvenators and WMA additives, interact with asphalt binders and aggregates under varying conditions of binder grade, binder content, and RAP source. Figure 9.2 presents the comparison of the performance of all the high RAP mixtures prepared using different strategic techniques adopted in the present study. As per the results, the use of these strategic techniques enables 10% higher RAP material than the current allowable limit in Oregon, with REJ1 showing the superior balanced performance in terms of cracking and rutting. These findings were validated through rigorous statistical analyses.



(a)



(b)

Figure 9.2. Comparison of performance of high RAP mixtures prepared using different strategic techniques adopted in the present study (a) CT Index and (b) Rut depth

- A promising methodology was recommended for optimizing the dosage of WMA additives and rejuvenators, as well as identifying reliable WMA production temperatures using a workability-based approach.
- Findings revealed that the application of WMA technologies can reduce the production temperatures by 25 °C, ensuring satisfactory performance as that of conventional hot mix asphalt, despite higher RAP proportions. Their use was also found to be cost-effective and environmentally friendly.
- A cradle-to-gate life cycle assessment (LCA) was conducted to evaluate the environmental implications of increased RAP usage and strategic measures. The cost-effectiveness analysis revealed that RAP cost significantly influences the overall material costs for all strategies, underscoring the need for careful consideration by decision-makers.
- The research determined the influence of RAP source and in-plant variability, highlighting how these factors affect mixture performance, particularly when WMA additives and rejuvenators are integrated. The stiffness of the RAP binder (which varies from source to source) significantly affects the cracking performance of the produced asphalt mixtures.

9.3 FUTURE DIRECTIONS

Comprehensive testing confirmed the feasibility of increasing RAP and suggested the possibility of achieving a higher RAP percentage, but further exploration is required. Some of the future directions include:

- Determine the impact and consequences of very high RAP mixtures (say, 50% in Level 3 and 40% in Level 4) using the strategic techniques discussed in this study. This would provide more clarification on the effectiveness of the strategic techniques and their capability of improving RAP utilization in asphalt mixtures with desirable performance.
- Conduct detailed evaluations of WMA- and rejuvenator-modified binders to better understand the interaction mechanisms among virgin binder, RAP binder, aggregates, and additives, thereby clarifying their influence on mixture performance trends.
- Although the benefits of strategic measures were identified across binder contents in this study, future work should integrate the BMD framework to more comprehensively assess mix performance attributes.
- Since RAP mixture performance depends on RAP source, binder grade, and binder content, it is recommended to include multiple material sources and aggregate gradations in the

experimental design. This will improve the insights and validate the conclusions of the present study. It is expected that the stiffness of the RAP binder is highly influential on the long-term cracking resistance of the asphalt mixtures.

- Construct and monitor field trial sections incorporating the promising strategies identified in this work. Long-term performance monitoring will be crucial for validating laboratory findings under real-world conditions. As a part of the present research work, a tentative conceptual pilot section construction and performance monitoring plan is also provided in Chapter 8.0.
- Plant-level investigations are crucial for understanding RAP blending and the interactions between asphalt binder, aggregates, and potential additives. These studies provide valuable insights into their effectiveness and help clarify the underlying mechanisms of their performance. Future research should focus on expanding plant-level evaluations to optimize these interactions and to better understand how they influence the workability and long-term performance of asphalt mixtures
- While this study focused on Oregon mixes, the framework and statistical analysis approach can be applied by other DOTs and agencies to evaluate the suitability of strategic techniques for high-RAP mixture production.

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