IMPLEMENTATION OF BALANCED MIX DESIGN METHODS IN OREGON TO MEET LONG-TERM PERFORMANCE GOALS

Final Report

SPR 852

Oregon Department of Transportation

IMPLEMENTATION OF BALANCED MIX DESIGN METHODS IN OREGON TO MEET LONG-TERM PERFORMANCE GOALS

FINAL REPORT

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by

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17. Abstract

This study presents the development and implementation of a Balanced Mix Design (BMD) framework customized for Oregon's materials, traffic, and climate conditions, aiming to improve asphalt pavement durability, environmental performance, and cost-effectiveness. While traditional volumetric mix designs have been widely adopted, they may sometimes lead to premature cracking failures. To address this, performance tests, specifically the Indirect Tensile Cracking Test (IDT-CT) and Hamburg Wheel Tracking Test (HWTT), were incorporated into the mix design process to establish performance-based thresholds for rutting and cracking.

The research involved evaluating multiple IDT-CT testing protocols, ultimately recommending a practical approach balancing accuracy, repeatability, and feasibility. Laboratory investigations identified binder content ranges satisfying the proposed thresholds, which were validated through five pilot construction projects across Oregon. These BMD mixes demonstrated enhanced cracking resistance while maintaining comparable rutting performance relative to traditional volumetric designs.

To further assess field performance, a low-cost Accelerated Pavement Testing (APT) system was developed, and one year of field performance monitoring was conducted. Results showed that BMD sections maintained similar rut depths and surface smoothness, indicating strong in-service performance. Additionally, a life cycle assessment (LCA) revealed potential environmental benefits due to reduced maintenance frequency and extended pavement life.

The study provides a practical and data-driven framework to support ODOT's transition toward performance-based specifications, positioning BMD as a robust strategy for building longer-lasting, cost-efficient, and more sustainable asphalt pavements in Oregon.

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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	in2	square inches	645.2	square millimeters	mm2
Area	ft2	square feet	0.093	square meters	m2
Area	yd2	square yard	0.836	square meters	m2
Area	ac	acres	0.405	hectares	ha
Area	mi2	square miles	2.59	square kilometers	km2
Volume	fl oz	fluid ounces	29.57	milliliters	mL
Volume	gal	gallons	3.785	liters **	L
Volume	ft3	cubic feet	0.028	cubic meters	m3
Volume	yd3	cubic yards	0.765	cubic meters	m3
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/m2	cd/m2
Force and Pressure or Stress	lbf	poundforce	4.45	newtons	N
Force and Pressure or Stress	lbf/in2	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 m^3

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	mm2	square millimeters	0.0016	square inches	in2
Area	m2	square meters	10.764	square feet	ft2
Area	m2	square meters	1.195	square yards	yd2
Area	ha	hectares	2.47	acres	ac
Area	km2	square kilometers	0.386	square miles	mi2
Volume	mL	milliliters	0.034	fluid ounces	fl oz
Volume	L	liters	0.264	gallons	gal
Volume	m3	cubic meters	35.314	cubic feet	ft3
Volume	m3	cubic meters	1.307	cubic yards	yd3
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/m2	candela/m2	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/in2

For More Information see: https://www.fhwa.dot.gov/publications/convtabl.cfm

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DISCLAIMER

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1.0 INTRODUCTION

Roads play a vital role in interconnecting different parts of cities, states, and countries and have a significant economic impact by influencing trade, commerce, and regional development (FHWA 2021). Asphalt pavements constitute a substantial 94% of the total roadway infrastructure in the United States of America. (USDoT 2018). About 93-96% of the raw material for asphalt pavements consists of aggregates such as stone, gravel, or sand, which are bound together by an asphalt binder that forms the remaining 4-7%. These pavements are meticulously constructed to endure heavy and repetitive vehicular loads in various environmental conditions (Al Atroush, 2022). The design process involves a systematic approach to determine the appropriate asphalt mixtures, layer thicknesses, and overall pavement structure. Typically, asphalt pavements are designed to last 10-30 years; however, in many cases, due to cumulative traffic loading, severe environmental conditions, and material issues, these pavements may fail before reaching the design life (Bhandari et al., 2023). According to the Oregon Department of Transportation (ODOT) Pavement Management System (PMS), these pavements are susceptible to early failure and have a tendency to premature cracking within the first 6-7 years of their service life, in some cases before reaching the 15-20 year target design life.

The percentage of state highways in “fair or better” condition in Oregon is expected to fall from 89% in 2020 to 83% in 2024 (Pavement Condition Report 2022). The primary reason for this is limited investments due to constraints on funding and the continuously increasing cost of paving. In addition to this, based on the statistics reported by ODOT (MACMP- 2024), the price of liquid asphalt has increased from $350/ton in 2021 to around $520/ton in 2024, consequently increasing the overall material production costs. Thus, asphalt-surfaced pavements will likely deteriorate even further in the next decade due to inflation and the availability of funding. The leading cause of asphalt pavement failure is premature cracking, typically along the wheel paths and the longitudinal joints. For asphalt pavements with poor performance, micro-cracks start developing during the first couple of years, which begin widening and propagating throughout the entire pavement (Weaver et al., 2023). These distresses are not specific to a particular highway network; they are common and widespread on most of the asphalt pavements in Oregon (Sreedhar et al., 2019). Thus, expensive rehabilitation and maintenance will be required before the pavements last their intended life of 15-20 years, which causes strains on the underfunded Department of Transportation (DoT). To reduce the maintenance and enhance the durability of asphalt pavements, it is essential to determine the probable reasons for these cracking distresses and evaluate strategies to mitigate them.

The primary goal of asphalt pavement design is to resist cracking and rutting distresses to avoid premature failures (TRC 2014). This design is achieved by combining aggregates, recycled asphalt, and binder in appropriate quantities to provide structural integrity and stability under heavy traffic loading. However, the asphalt pavement design involves various components and is a complex process. In the past, the Marshall and Hveem methods were followed for designing pavements that were developed during the 1930s and 1950s. The Marshall mix design method uses a standardized hammer to compact specimens to a certain height. This approach primarily aimed to find a balance between the asphalt mixes' strength, durability, and flexibility. Additionally, it determined the optimum asphalt content that yields maximum stability and the desired flow. However, this method had a major limitation due to its reliance on volumetric assessments and experience, which may affect the accuracy of the results. Moreover, the preparation of the samples using a hammer did not effectively represent the field compaction conditions (Sousa et al., 1995). The Hveem method was also developed during the same timeline as that of the Marshall, but it was specifically designed for the state of California and did not have widespread use in the U.S. and the world. This method employs a kneading compactor for sample preparation and primarily focuses on the cohesion and internal friction of the mix to determine the stability. It was designed for a specific region, but it had limitations when applied to different climate and traffic conditions. Moreover, this method overlooks the critical aspects of cracking and flexibility, which are the primary reasons for the failure of asphalt pavements (Roberts et al., 2002). Neither the Marshall nor Hveem methods may accurately predict the long-term performance of pavements. Due to these limitations and frequent problems of cracking and rutting during those days, it was essential to develop a new system to resolve all these distresses.

A Superpave mix design system was established to overcome the challenges mentioned above. The Superpave is an acronym for Superior Performing Asphalt Pavements and was a product of the Strategic Highway Research Program. It was implemented in 1993 to develop a performance-based mix design method for asphalt pavements. The Superpave system builds from simple to complex, and the design is based on the traffic and environmental conditions where the pavement will be built. The design was comprised of three different levels, where Level 1 focused on low-traffic pavements, and the mix design was based on volumetric properties. Level 2 and Level 3 were envisioned for moderate and heavy traffic conditions. In these Levels, the asphalt mixtures were supposed to have mixture performance tests and were required to satisfy the volumetric parameters (Cominsky et al., 1994). However, due to the impracticality and high cost of conducting these performance tests routinely, the performance tests were never implemented (Yin et al., 2018). Hence, until now, the Level 1 approach has been followed for designing all the asphalt pavements in Oregon and several other states, primarily based on volumetric relations between different materials used in the mix. Although this method solved the rutting problem, most researchers and contractors believe that this mix design process does not reflect the long-term performance of asphalt pavements and results in early cracking.

Moreover, in the past 30 years, new materials have been found to be feasible for the construction of asphalt pavements, such as different types of polymer-modified binders, recycled tire rubber, plastic, fibers, and different chemical additives. Additionally, due to environmental benefits and energy efficiency, there is an increased demand to incorporate more Reclaimed Asphalt Pavements (RAP) in asphalt pavements. Due to all these issues and the complex nature of today’s asphalt mixtures, the simple traditional volumetric mix design may not generate high-performing asphalt mixtures. Hence, it is crucial to add performance tests to determine the susceptibility of the asphalt mix to cracking and rutting failures to fine-tune the mix components. The incorporation of performance tests to balance the cracking and rutting failure and prolong the life of the pavements is termed Balanced Mix Design (BMD). It is a well-known fact that the increase in the binder content increases the flexibility of the asphalt mix and may result in rutting failure along the wheel path. However, reducing the binder content to a level lower than the optimum makes the mix dry and stiff, which causes premature cracking failure. The primary goal of BMD is to fine-tune the binder content, gradation, RAP content, and other additive components in the mix to achieve the optimum asphalt mixture that will slow down cracking accumulation and avoid any early rutting failures on asphalt-surfaced roadways.

Oregon Department of Transportation (ODOT) initiated the first BMD research study in 2016 in collaboration with the Oregon State University-Asphalt Materials and Pavements (OSU-AMaP) research group. In this research study, Coleri et al. (2018) identified the potential cracking and rutting performance tests for incorporation into Quality Control (QC) and Quality Assurance (QA) processes. The study recommended using the Semi-Circular Bend (SCB) test (while the indirect tension test-IDT was also determined to be equally efficient) and the Hamburg Wheel Tracking Test (HWTT) as the performance tests to evaluate the fatigue cracking and rutting susceptibility for asphalt mixtures.

The second ODOT research study focused on developing a BMD framework to improve asphalt pavement durability by integrating performance testing for cracking and rutting with traditional mix design (Coleri et al., 2020). As part of the study, a long-term aging protocol was specifically developed to better simulate field aging conditions in the laboratory (Sreedhar and Coleri, 2020). Researchers evaluated mixtures from various Oregon projects using this protocol and advanced performance tests. The findings supported broader implementation of BMD to more accurately predict pavement performance and enhance long-term roadway quality across the state. However, preparing samples for the SCB test involves multiple cutting tools to meet standard protocol requirements, adding complexity to the overall process. As a result, the newly developed IDT-CT test was selected by ODOT to determine the cracking susceptibility of asphalt mixtures (Li et al., 2023). IDT was also determined to be equally effective in the previous ODOT research study (Coleri et al., 2018). Hence, in the current study, the suitability of the IDT-CT test was evaluated and further used to determine the cracking performance of the asphalt mixtures. HWTT was also used to determine the rutting resistance of asphalt mixtures.

Based on the findings from the two previous research studies and this research study, this report presents the findings of a comprehensive research effort aimed at developing and implementing a practical BMD framework tailored to Oregon’s materials, traffic, and climate conditions. The outcomes are intended to support ODOT’s transition toward performance-based asphalt mix design practices that not only enhance long-term pavement durability and reliability but also improve cost-effectiveness and reduce environmental impacts.

1.1 ORGANIZATION OF THIS RESEARCH REPORT

The research work demonstrates the implementation of a performance-based asphalt mixture through comprehensive laboratory and field testing to improve pavement longevity in Oregon. This research report comprises eight different chapters, whose organization is given below:

- Chapter 1.0: This chapter describes the need for research in this direction. In addition, it outlines the research problems and gaps along with the key objectives.

- Chapter 2.0: A state-of-the-art review of the development and use of the BMD approach is presented in this chapter.

- Chapter 3.0: The third chapter demonstrates the effect of test variables such as different aging conditions, temperature conditioning methods, sample sitting time, and device type on the IDT-CT results. It also provides recommendations on the most suitable testing approach and process based on a simple ranking framework.

- Chapter 4.0: This chapter focuses on establishing thresholds for characterizing the performance of asphalt mixtures in Oregon using statistical analysis. In addition, it validates the feasibility of performing BMDs in the laboratory. Based on the results of this part of the study, appropriate tentative thresholds were proposed to differentiate the asphalt mixtures concerning their rutting and cracking performance.

- Chapter 5.0: The validation of the developed thresholds for the characterizing performance of asphalt mixtures through field implementation in Oregon is shown in Chapter 5 of this report. The primary goal of this part was to determine the impact of BMD in terms of performance and environmental impact (through pavement life cycle assessment-LCA) and determine whether the BMD alternative would be better than the volumetric mix design.

- Chapter 6.0: The analysis of the post-monitoring of the pilot sections through Automated Pavement Condition Survey (APCS) data collection and accelerated pavement testing (APT) is highlighted in this chapter.

- Chapter 7.0: This chapter summarizes the key findings and states the conclusive remarks developed throughout the research work.

- Lastly, Chapter 8.0: The references used throughout the development of the present research report are listed in this chapter of the report.

1.2 OBJECTIVES OF THIS STUDY

The major objective of this study is to develop and implement a performance-based BMD framework tailored to Oregon’s unique materials, traffic, and climate conditions, with the goal of enhancing asphalt pavement durability, cost-effectiveness, and environmental sustainability through laboratory validation, field implementation, and performance benchmarking. The more specific objectives of this study are to:

- Assess the suitability of different testing and specimen preparation approaches for incorporating the Indirect Tensile Cracking Test (IDT-CT) into the BMD process;
- Benchmark the performance of asphalt mixes by establishing reasonable tentative rutting and cracking thresholds;
- Determine whether the established thresholds can be used in conducting the BMD through laboratory-produced asphalt mixtures;
- Validate the established thresholds by field implementation and pilot section construction;
- Collection and analysis of APCS data for the pilot sections constructed using volumetric and BMD approaches after 1 year of pavement construction and vehicle movement; and
- Develop and execute a low-cost Accelerated Pavement Testing (APT) system to compare the performance of the pilot sections prepared with volumetric and BMD approaches.

2.0 LITERATURE REVIEW

In this literature review, the effectiveness of the current volumetric mix design and the potential benefits of a new balanced mixture design method were evaluated by checking the past research studies and surveys conducted with the State Department of Transportation (DOTs) and asphalt paving contractors. Information related to the current balanced mix design procedures and the experiences of other state DOTs was adapted from the previous ODOT research project - SPR801 (Coleri et al. 2020). Research studies related to the more recent developments (since 2020) with Balanced Mix Design (BMD) procedures are also summarized in this literature review.

2.1 PERFORMANCE-BASED SPECIFICATIONS AND BALANCED MIX DESIGN PROCESS

Asphalt mixtures are designed to be used in pavements to withstand vehicular loads under different climatic conditions. Asphalt mixture design aims to develop an economical blend of aggregates and binder such that the resultant mixture provides sufficient stability to resist deformation under traffic loading and flexibility to withstand cracking. The most commonly used asphalt mix design methods are the Marshall, Hveem, and Superpave. Numerous research studies are currently being conducted to develop new asphalt mixture design processes with performance verification. To better understand the new BMD approach with performance verification, it is necessary to understand the history of the asphalt mix design process and historical efforts on this subject.

2.1.1 History of Asphalt Mix Design

In the late 1920s, the Hveem mix design method was developed for asphalt mixtures and was extensively used in some of the Western States. The objective of the entire process is to determine the optimum binder content (OBC), which is assumed to depend on aggregate surface area and absorption. The total aggregate surface area in an asphalt mixture is a function of the gradation (aggregate size distribution), aggregate shape, texture, and angularity. Also, this method assumes that the stability of the mixture is a function of aggregate particle friction and mix cohesion. The stability is measured using a Hveem stabilometer, which applies an increasing load to the compacted asphalt sample at a predetermined rate (Vallerga and Lovering 1985). As described by stability, mechanical properties are used to determine the optimum asphalt content. Although density is one of the most critical parameters controlling asphalt mixture design, parameters related to density (such as air voids) were not considered in the design process until the 1990s. The mixtures produced using the Hveem mix design method had lower binder contents than today's asphalt mixtures and are generally more susceptible to fatigue and thermal cracking (Harvey et al. 2015).

The Marshall method was developed in the early 1940s and was subsequently used by the U.S. Army Corps of Engineers in World War II for designing asphalt mixtures for airports (War Department 1943). Similar to the Hveem method, the primary objective of the Marshall method is to determine the optimum asphalt content. The optimum asphalt content is a function of air voids, maximum stability, and maximum density. It is subsequently validated by checking against flow and voids in mineral aggregate (VMA) (Department of the Army 1948). When compared to the Hveem method, the mixtures designed using the Marshall method possess higher asphalt contents with higher cracking resistance (Harvey et al. 2015).

Until the early 1990s, Hveem and Marshall mixture design methods were used by many states in the U.S. Superpave was developed as part of the Strategic Highway Research Program (SHRP) based on the knowledge gained from the Hveem and Marshall mixture design methods and the associated experiences. The development of the Superpave mixture design was completed in 1993. However, state-level implementations took several years. The major obstacle in the implementation process was the differences in climate, traffic, and materials between different states. For this reason, although a general mixture design method developed for all states started the beginnings of the implementation of a more comprehensive and scientific mixture design method at the state level, it took several years for states to adapt to this new method due to the missing performance data available at the state level.

The original objective of this innovative mixture design method (Superpave) was to develop and implement a performance-based mix design process. Although performance tests for asphalt mixtures were a part of the Superpave mix design process and several procedures were developed to predict mixture performance, the entire process turned out to be too complex and was never implemented by any state DOTs. Superpave mix design had three levels (Level 1, Level 2, and Level 3) with increasing complexity (Cominsky et al. 1994). The performance-based specifications were to be incorporated in Level 2 and Level 3 designs, but were never implemented.

The current asphalt mix design practice (Level 1) involves proportioning of the aggregates and the asphalt binder based on empirical properties of aggregates and volumetric properties such as densities, air voids, voids in the mineral aggregate (VMA), and voids filled with asphalt (VFA). To reach the optimum proportions for all materials, accurately measuring the specific gravity of the mixture components is critical. However, over the years, it has been observed that the measurement of these properties is highly variable, and measured properties vary from one agency to another. This high variability in the measured properties of the mixture constituents can result in highly variable OBC values that reduce the effectiveness and reliability of the followed mixture design process.

In addition to all those aforementioned issues with the Superpave mixture design method, the increased use of Reclaimed Asphalt Pavement (RAP), Recycled Asphalt Shingles (RAS), and several other additives complicated the mixture design process by introducing high variability and bias. The current simple volumetric mixture design method does not account for the highly complex microstructure of the asphalt mixtures with several different constituents and their interactions. ***Some asphalt mixtures with similar volumetric mixture designs were observed to provide completely different performances in the field (Harvey et al., 2015). This problem resulted in concerns with using the current simple volumetric mix design methods.***

Incorporating recycled materials into the asphalt mix created problems with accurately predicting the performance of the final asphalt mix based on the properties of the mix constituents. Besides, it is still not well understood how recycled binders interact with virgin binders (blending of the asphalt binder around the recycled asphalt aggregates and the virgin binder), which ultimately creates more doubt about how these materials affect field performance (West et al. 2018, Coleri et al. 2017a, and Coleri et al. 2017b). Furthermore, the effects of polymer modification in asphalt, rejuvenators, fibers, and warm-mix asphalt (WMA) additives cannot be assessed in the current volumetric mix design method. Therefore, performance tests need to be included as a part of the mix design procedure in addition to the volumetric properties to help ensure anticipated pavement performance in the field.

2.1.2 Balanced Mix Design Approach

The Expert Task Group formed by the Federal Highway Administration (FHWA) defines BMD as *"asphalt mix design using performance tests on appropriately conditioned specimens that address multiple modes of distress taking into consideration mix aging, traffic, climate and location within the pavement structure*" (West et al. 2018). Figure 2.1 illustrates the difference between the conventional volumetric mix design and the proposed balanced mix design process. In volumetric mix design, an OBC required to achieve 4% air-void content by applying a predetermined compactive effort (the number of gyrations in a Superpave Gyratory Compactor) is determined. However, the performance properties of asphalt mixtures are not accounted for in the design process. On the other hand, in a balanced mix design process, the performance properties of asphalt mixtures are evaluated in addition to volumetric properties. In general, the primary concept of the BMD is to overcome the issues with the Marshall and Hveem mix design concepts by optimizing asphalt binder content based on the rutting and fatigue cracking performance (Li et al. 2023). In the example presented in Figure 2.1, the binder content determined by the volumetric process is 5.1%. This binder percentage satisfies the rutting criteria for asphalt mixtures. However, this binder content does not satisfy the cracking performance requirements (flexibility index of 10 from the SCB test). On the other hand, the balanced mix design approach yields a binder content ranging between 5.2% and 5.65%. Within this range, both cracking and rutting criteria are met. Considering the asphalt mixture binder content production variability allowed in Oregon (±0.35%), the suggested design binder content can be recommended as 5.3% (5.65%-0.35%) to minimize the risk of rutting failure. Since rutting failures happen earlier than cracking failures, avoiding rutting failures can be considered to be more critical in a BMD approach.

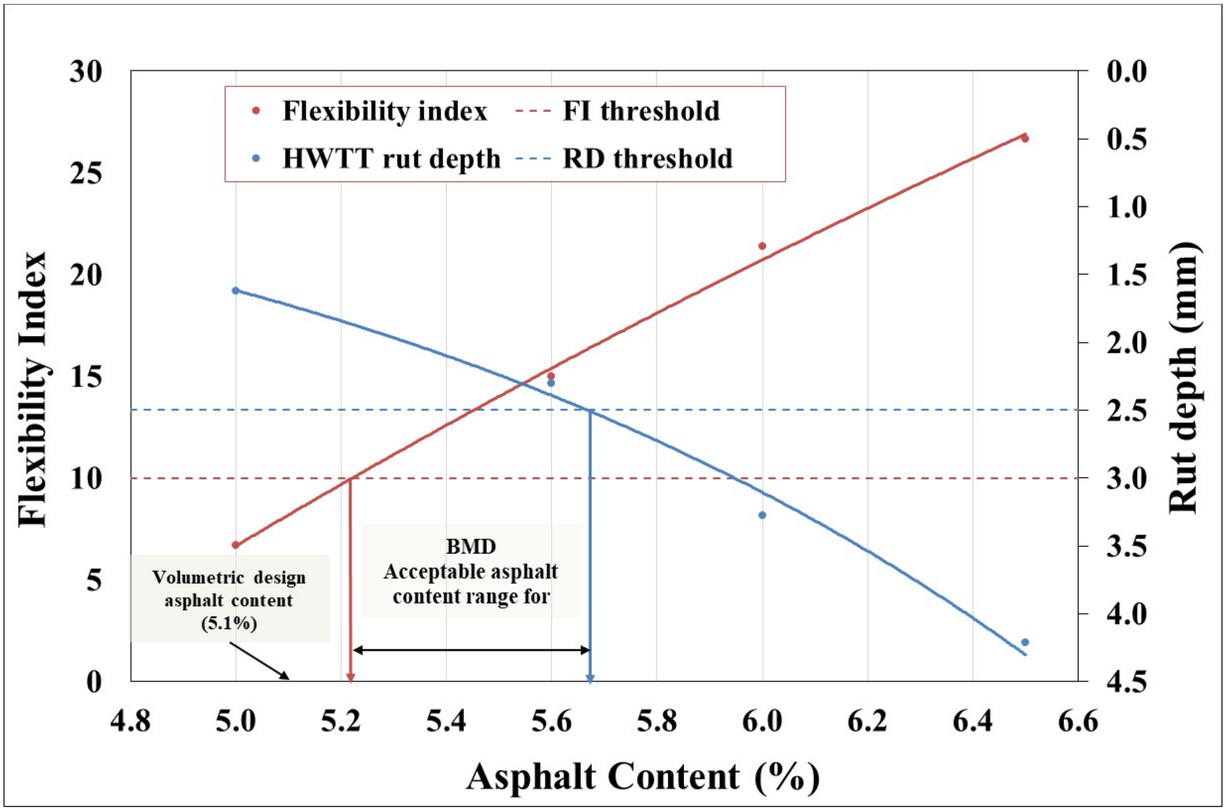


Figure 2.1: Volumetric mix design vs balanced mix design example.

The Association of State Highway and Transportation Officials (AASHTO) PP 105-20 Standard Practice for Balanced Design of Asphalt Mixtures laid down four approaches based on the recommendations from the National Cooperative Highway Research Program (NCHRP) Project 20-07/Task 406 - Development of a Framework for Balanced Mix Design (West et al. 2018). These approaches are comprehensively discussed in the balanced mix design resource guide published by the National Asphalt Pavement Association (NAPA) in 2021. The subsequent section shows the process and differences in these four approaches:

Approach A: Volumetric Design with Performance Verification: This is the most commonly used approach researched and employed by different agencies. In this approach, the mixture is designed based on Superpave specifications. Then, performance tests are conducted to validate whether the mix meets the performance requirements at the determined OBC. The mixture should satisfy both volumetric and performance testing criteria. If the mixture does not meet the requirements, the entire mix design process is repeated. The adjustments to the mixture can be made through the aggregate source, aggregate gradation, binder source, binder grade, and or additives. The process is illustrated in Figure 2.2.

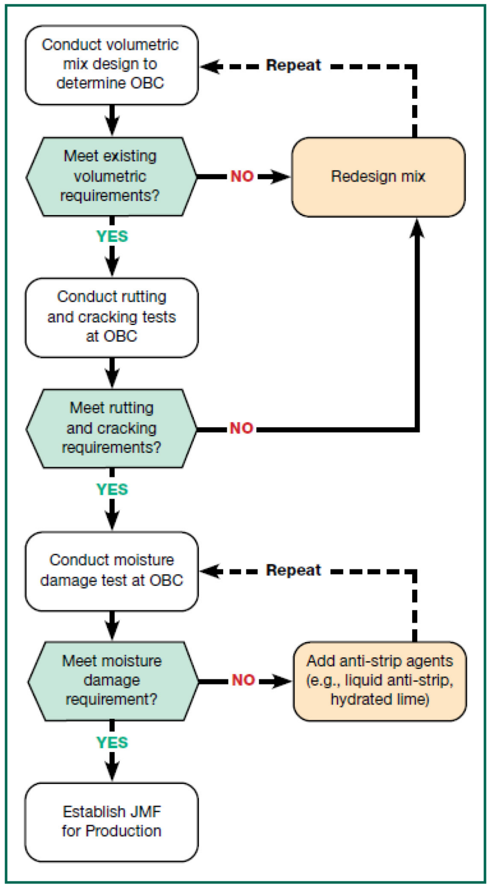


Figure 2.2: Approach A- Volumetric design with performance verification (Yin and West, 2021).

Approach B: Volumetric Design with Performance Optimization: It is a variant of Approach A in which the OBC is not determined through the volumetric mix design. Instead, samples are prepared with two or more binder contents (in addition to preliminary OBC), and then they are subjected to several performance tests (rutting, cracking, and moisture). The binder content that meets all the performance criteria is selected as OBC. Otherwise, changes are made in either materials or the mix proportions until all the performance criteria are met. Figure 2.3 illustrates Approach B of the balanced mix design process.

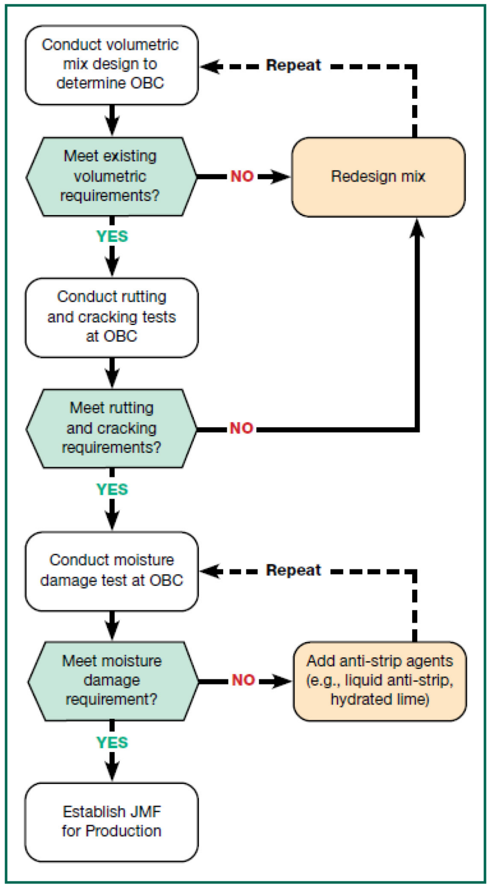


Figure 2.3: Approach B- Volumetric design with performance optimization (Yin and West, 2021).

Approach C: Performance-Modified Volumetric Design: In this method, the initial aggregate blend and asphalt content are determined using the Superpave mix design process. The mixture proportions are then adjusted to meet the requirements of performance tests. This method does not strictly enforce volumetric mix design requirements, while performance requirements must be met. If the mix design passes the moisture test criteria, a few volumetric properties are determined and validated as per the requirements of the agency. This approach is depicted in Figure 2.4.

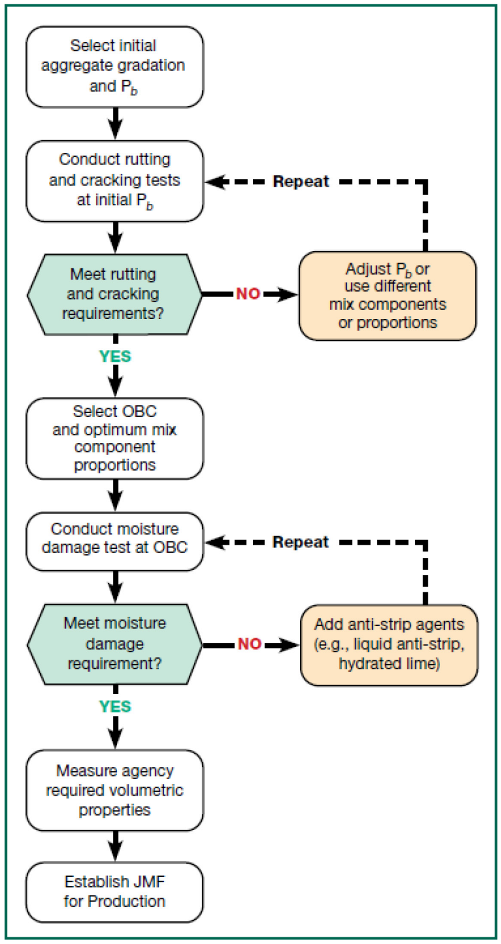


Figure 2.4: Approach C – Performance modified volumetric design (Yin and West, 2021).

Approach D: Performance Design: In this approach, the volumetric mix design process is limited or entirely skipped, and different trial mixtures are directly evaluated using performance tests, as illustrated in Figure 2.5. Here, the objective is to use different mixture components in proportion to satisfy the performance test criteria. Therefore, minimum volumetric design criteria may or may not be set for aggregate and binder properties. However, the volumetric criteria, such as air voids, minimum asphalt content, aggregate gradation, VMA, and VFA, may still be used as a guideline but not as a design criterion. This approach provides a lot of flexibility in design and can be quite rewarding for contractors and state DOTs. In this approach, the first objective is to select an initial gradation and a virgin binder grade. Thereafter, the designed mix is tested for performance at three or more binder contents. A binder content that satisfies the performance criteria is chosen as the OBC. If the binder content does not meet the criteria, then there is a need to adjust the initial mix design, which is similar to the previous approaches. This approach is expected to encourage innovation and direct producers and contractors to evaluate the impact of different additives, gradations, RAP contents, binder types, binder contents, and other variables on asphalt mixture performance. With the objective of reducing mixture costs while meeting the rutting, cracking, and moisture damage failure criteria, different combinations of additives, RAP/RAS contents, gradations, and binder types that will improve pavement longevity can be identified.

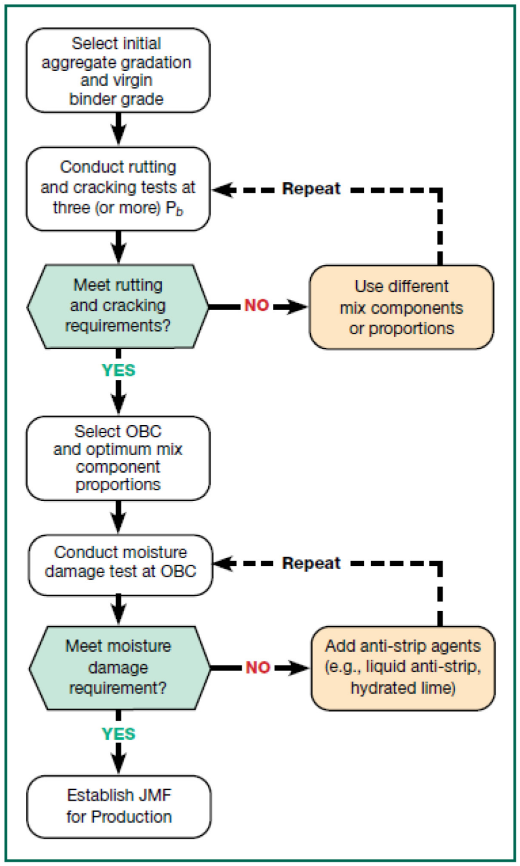


Figure 2.5: Approach D – Performance design (Yin and West, 2021).

As can be seen from the descriptions above, these new asphalt mix design approaches vary in terms of the weightage assigned to traditional volumetric requirements, performance verification, the scope for adjustments in mix components or proportions, and the scope for innovation. These differences are summarized in Table 2.1.

Table 2.1: Differences in BMD Approaches (Hajj et al. 2022a)

BMD Approach	Volumetric Requirements	Performance Requirements	Flexibility	Innovation Potential
A - Volumetric Design with Performance Verification	Full compliance	Full compliance	Most conservative	Lowest
B - Volumetric Design with Performance Optimization	Full compliance at preliminary OBC	Performance optimization through moderate changes in asphalt binder content	Slightly more flexible than Approach A	Limited
C - Performance Modified Volumetric Design	Some requirements relaxed or eliminated	Performance optimization by adjusting preliminary asphalt binder content or mixture component properties or proportions	Less conservative than Approach A and Approach B	Medium degree
D - Performance Design	Limited or no requirements	Performance optimization by adjusting mixture components and proportions[a]	Least conservative	Highest degree

[a] A state DOT may set minimum requirements for asphalt binder quality and aggregate properties. Once the laboratory test results meet the performance criteria, the mixture's volumetric properties may be checked for use in production.

2.1.3 Balanced Mix Design – Critical Steps

In a recent effort to gather information about BMD implementation efforts in the United States, FHWA conducted virtual site visits and interviews with some State DOTs. Seven key State DOTs were identified for this purpose based on their expertise and progress in this direction. In addition, the National Center for Asphalt Technology (NCAT) made similar efforts by organizing conferences, regional workshops, and other activities focused on BMD. The collaborative knowledge obtained from these efforts was distilled into a suggested process for incorporating BMD into the existing mix design method and quality assurance (QA) (Shaikh et al. 2024). This process consists of eight tasks that are further divided into subtasks. The tasks, subtasks, and activities are summarized in Table 2.2. The tasks that were already completed in Oregon are shown with a red check mark (✓) at the end of the task. The tasks that will be completed in this research project (SPR 852) and the research project awarded through the FHWA-AIDPT program are labeled with a hollow red check mark (✓) at the end of the task. Some notes are also entered in red color to provide more information.

Table 2.2: Tasks for BMD Implementation (Hajj et al. 2022a)

Task	Description
Introduction	Understanding the why and benefits of Performance Specifications ✓
Overall Planning 2.1	Identification of Champions ✓
Overall Planning 2.2	Establishing a Stakeholders Partnership ✓
Overall Planning 2.3	Doing Your Homework ✓
Overall Planning 2.4	Establishing Goals ✓
Overall Planning 2.5	Mapping the Tasks ✓
Overall Planning 2.6	Identifying Available External Technical Information and Support ✓
Overall Planning 2.7	Developing an Implementation Timeline ✓
Selecting Performance Tests 3.1	Identifying Primary Modes of Distress ✓
Selecting Performance Tests 3.2	Identifying and Assessing Performance Test Appropriateness ✓
Selecting Performance Tests 3.3	Validating the Performance Tests ✓
Performance Testing Equipment 4.1	Acquiring Equipment ✓ (existing systems to be checked)
Performance Testing Equipment 4.2	Managing Resources ✓
Performance Testing Equipment 4.3	Conducting Initial Training ✓
Performance Testing Equipment 4.4	Evaluating Performance Tests ✓
Performance Testing Equipment 4.5	Conducting Inter-Laboratory Studies ✓
Establishing Baseline Data 5.1	Reviewing Historical Data & Information Management System ✓ (partially done in SPR785)
Establishing Baseline Data 5.2	Conducting Benchmarking Studies ✓ (partially done in SPR785 and SPR801)
Establishing Baseline Data 5.3	Conducting Shadow Projects ✓
Establishing Baseline Data 5.4	Analyzing Production Data ✓
Establishing Baseline Data 5.5	Determining How to Adjust Asphalt Mixtures Containing Local Materials ✓
Specifications and Program Development 6.1	Sampling and Testing Plans ✓
Specifications and Program Development 6.2	Pay Adjustment Factors (Not currently part of the goals)
Specifications and Program Development 6.3	Developing Pilot Specifications and Policies ✓
Specifications and Program Development 6.4	Conducting Pilot Projects ✓
Specifications and Program Development 6.5	Final Analysis and Specification Revisions ✓
Training, Certifications, and Accreditations 7.1	Developing and/or Updating Training and Certification Programs ✓ (Training documentation&videos to be developed)
Training, Certifications, and Accreditations 7.2	Establishing or Updating Laboratory Accreditation Program Requirements (Not currently part of the goals)
Initial Implementation	**The decisions in terms of timing and the process for the actual implementation will be made by ODOT after the completion of this research project**

The eight major tasks shown in Table 2.2 are briefly described as follows (Hajj et al. 2022a).

Task 1: *Understanding the Why and Benefits of Performance Specifications* – This task involves bringing all the stakeholders on the same page about the shift in asphalt mix design and the resulting benefits.

Task 2: *Overall Planning* – In this task, the goals and timeline for the overall implementation process are chalked out.

Task 3: *Selecting Performance Tests* – This task involves the identification of the primary distress modes and selecting performance tests with an emphasis on a strong correlation with field performance.

Task 4: *Performance Testing Equipment: Acquiring, Managing Resources, Training, and Evaluating* – Apart from resource management, developing training programs, and purchasing equipment, this step encourages inter-laboratory studies (ILS) for developing precision and bias statements for the performance tests.

Task 5: *Establishing Baseline Data* – This task is concerned with collecting data to develop performance test criteria. Benchmarking of the test mix designs is also carried out in this step by validating the laboratory test results of the mixes with the known field performance. Results from shadow projects can also be utilized to validate laboratory test results. In addition, production variability and test sensitivity are also analyzed.

Task 6: *Specifications and Program Development* – This task is about drafting specifications using the developed mix design criteria and performance requirements based on the data obtained from benchmarking and validation studies. This task also involves selecting quality measures and other parameters to be incorporated into the existing QA/ QC program.

Task 7: *Training, Certifications, and Accreditations* – This task encompasses imparting training and developing certifications and accreditation programs. This is important for a seamless implementation of the BMD method as it requires trained engineers and technicians to properly test samples and collect and analyze data.

Task 8: *Initial Implementation into Engineering Practice* – This is the final step in the implementation process. In this task, BMD is integrated into the asphalt pavement program of a State DOT. The implementation can be phased in with a number of shadow projects and pilot projects. The process can be continuously evaluated, and adjustments can be made based on the lessons learned. This step relies heavily on the collaboration of the industry and ODOT, with potential guidance from OSU-AMaP. Full implementation is a time-intensive process and should be planned after the successful initial implementation. The decisions in terms of timing and the process for the actual implementation will be made by ODOT after the completion of this research project.

The above tasks follow a logical order; however, the suggested process also allows for carrying out some of the tasks in parallel or entirely in a different order. Moreover, since this is only a recommended approach for BMD implementation, DOTs can modify, adapt, or even not consider some of the tasks according to their convenience and other regional factors (Hajj et al. 2022a). Considerations are to be given to the organizational structure, staffing, workspace, quantity of asphalt production, etc., as well as industry experience and practices. Some of the tasks and subtasks are also interrelated and can be undertaken without affecting the overall progress of the implementation process. For example, subtasks 3.3 (validating the performance tests) and 4.1 (acquiring equipment) are independent and can be performed simultaneously without following the sequence. Similarly, task 4 (performance testing equipment: acquiring, managing resources, training, and evaluating) can be initiated in conjunction with performing benchmarking studies and establishing baseline data (task 5). Thus, the given implementation process provides great flexibility and tools for scheduling the BMD implementation in a state.

Figure 2.6 clearly presents specific challenges and themes mentioned in a report focusing on the recent outcomes of BMD in different states. As per the report, different challenges exist in different states, not limited to the ageing protocols, consistency of performance test methods, experienced workmanship, conducting upfront logistics preparations, lack of communication with contractors and consulting community during the mix design decisions, relaxation of volumetric criteria, etc (Bittner et al. 2024).

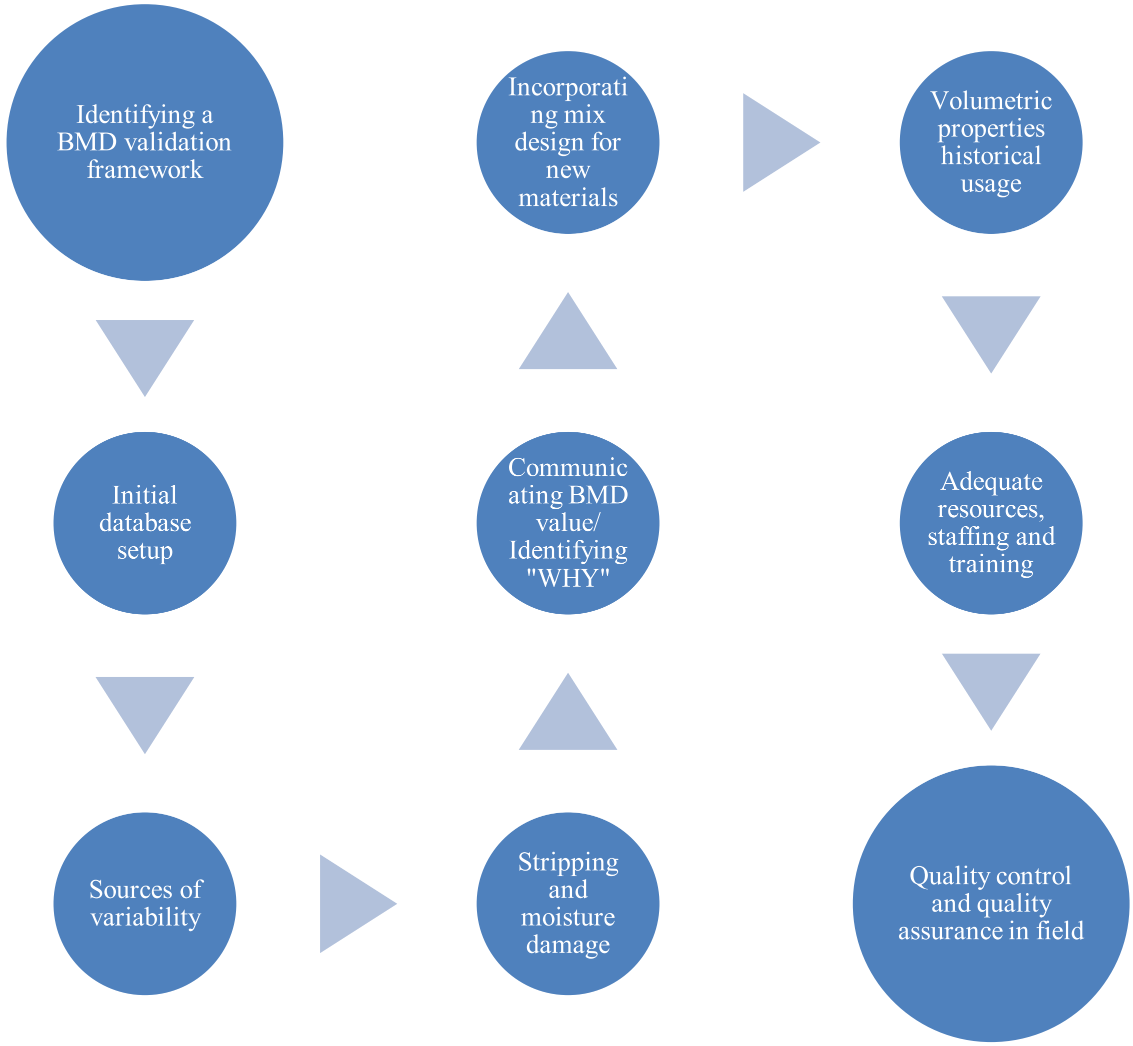


Figure 2.6: Summary of critical challenges in implementing BMD (Bittner et al. 2024)

2.1.4 The Practice of Balanced Mix Design in the U.S.

2.1.4.1 Initial development and progress in 2018 (ODOT research report SPR 801)

Back in 2018, several state agencies were investigating the feasibility of integrating performance testing into their mixture design methods. The FHWA's task force has identified several DOTs who have begun to implement BMD procedures. The research studies conducted to implement BMD methods are summarized in this section.

According to the survey conducted by the National Center for Asphalt Technology (NCAT) (West et al. 2018), 63% of the states think that the Voids Filled with Asphalt (VFA) requirement in the current volumetric mix design methods should either be eliminated or relaxed (Table 2.3) while this number increases to 69% when the responses from asphalt contractors are evaluated (Table 2.4). These results show that most asphalt specialists do not think VFA is an effective parameter controlling asphalt mixture performance. A similar conclusion is also valid for VMA when considering the asphalt contractor responses (Table 2.4). However, 67% of the state DOTs think that VMA is an effective parameter reflecting the long-term performance of the pavements and should not be eliminated or relaxed. It should be noted that VMA is a parameter calculated by using the total aggregate bulk specific gravity. However, problems (high variability) with accurate measurement of aggregate bulk-specific results in questionable VMA parameters (West et al. 2018). Thus, the use of VMA as a performance indicator can result in serious issues with projected in-situ mixture performance.

The majority of the state DOTs and asphalt contractors think that the Tensile Strength Ratio (TSR) is an effective parameter reflecting the moisture sensitivity of asphalt mixtures and should not be changed. About 67% of the asphalt contractors think that the dust-to-binder ratio should either be relaxed or eliminated, while this number drops to 46% when the DOT responses regarding the dust-to-binder ratio are evaluated.

Table 2.3: State DOT responses on existing mix design criteria (West et al. 2018)

Mix Design Criteria	No Change	Relaxed	Eliminated
%G_{mm} at N_i	19%	36%	45%
%G_{mm} at N_m	22%	37%	41%
VFA	37%	39%	24%
V_a	53%	42%	5%
D/A Ratio	54%	34%	12%
TSR	63%	15%	23%
VMA	67%	24%	10%

Table 2.4: Asphalt contractor responses on existing mix design criteria (West et al. 2018)

Mix Design Criteria	No Change	Relaxed	Eliminated
%G_{mm} at N_i	13%	28%	59%
%G_{mm} at N_m	19%	27%	54%
VFA	31%	43%	26%
V_a	47%	53%	0%
D/A Ratio	33%	49%	18%
TSR	51%	23%	26%
VMA	36%	53%	11%

Some of the BMD and performance-based specification development efforts in the U.S. as of 2018 are provided below:

The ***California Department of Transportation (Caltrans)*** was implementing a performance-modified volumetric design (Approach C outlined in the previous section) (West et al., 2018). The initial binder content is determined using the existing volumetric approach for a given aggregate gradation and binder grade. Performance tests, which included repeated shear, bending beam fatigue, frequency sweep testing, and HWTT, were carried out to determine the rutting, cracking, and stripping performance of asphalt mixtures. Short-term conditioning (four hours at

135 °C) was adopted for repeated shear and HWTT, while long-term conditioning, in addition to short-term conditioning, was used for bending beam fatigue and frequency sweep tests. Based on the results of these performance tests, adjustments to the binder content, binder source, aggregate source, or amount of material passing the No. 200 sieve were made. After these adjustments, the mixture was not required to satisfy the volumetric criteria. A performance-based specification developed for California has also been used to evaluate production-mix performance (Tsai et al. 2012). So far, at least seven interstate highways have been constructed using this approach.

The ***Illinois Department of Transportation (IDOT)*** also employs performance testing in addition to volumetric mixture design (Approach A) (West et al. 2018). The motivation behind implementing this approach was to address the use of higher contents of RAP/RAS. Binder content was determined using the Superpave volumetric mixture design process after selecting a suitable aggregate gradation and binder grade. I-FIT (Ozer et al. 2016) was used to evaluate the cracking performance after long-term conditioning (a long-term aging protocol was developed), while HWTT was used to evaluate the rutting resistance after short-term conditioning (Two hours of loose mix reheating at 132 ± 3°C). Different thresholds were used for the HWTT for mixes with different performance grades (PG), while a flexibility index of 8 was used as the threshold for the I-FIT cracking test. Different requirements for binder content adjustments, a change in binder source, or a reduction in quantities of recycled materials were made to achieve the desired mixture performance. However, the final volumetric properties of the mixtures were required to be within the Superpave volumetric mixture design criteria.

The ***Louisiana Department of Transportation and Development (LaDOTD)*** also used a volumetric design plus performance testing approach. This approach has already been implemented in the 2016 LADOTD asphalt specifications and is being used for high and low-volume roads on both wearing and binder courses. The optimum binder content is determined using the Superpave specification. Prepared mixtures are then subjected to performance tests, including HWTT after short-term conditioning for rutting resistance and SCB (ASTM D 8044-16) test after long-term conditioning for cracking resistance. Results of performance tests were used to determine the need to change any mixture properties. After modifying mixture properties to meet volumetric and performance requirements, the final set of performance experiments is conducted to validate the final mixture design. After the use of balanced mix design procedures, LADOTD decided to reduce the number of gyrations at N_{design} to increase the optimum binder content from the volumetric design (Cooper et al., 2014). The major reason for this change was the consistently lower optimum binder contents from the conventional volumetric design when compared to the binder contents suggested by the balanced mix design. It should be noted that LADOTD's balanced mix design has different requirements for two traffic levels. For instance, for lower traffic areas, SCB-J_c (cracking test parameter) should be more than 0.5kJ/$m^{2,}$ while this parameter was suggested to be more than 0.6kJ/m^2 for highways with high traffic levels.

The ***New Jersey Department of Transportation (NJDOT)*** also uses a volumetric design with performance verification (Approach A) (West et al., 2018). However, unlike other states, they have different performance thresholds for different asphalt mixture types. The five asphalt mixture types designed by using the BMD method are high RAP mixtures, bottom-rich base course, bridge deck waterproofing surface course, binder-rich intermediate course, and high-performance thin overlay. This approach is being implemented for about 10 percent of the state's total asphalt tonnage on these five mixtures that are subjected to high traffic volumes. For performance verification, Asphalt Pavement Analyzer (APA) (AASHTO T 340) tests on mixtures with short-term conditioning (2 hours at compaction temperature) are conducted to evaluate the rutting resistance and Texas overlay and bending beam fatigue tests (BBF) with again short-term conditioned specimens are conducted to evaluate cracking resistance. Mixture design adjustments generally suggest changes in binder content and the inclusion of polymers, rejuvenators, or WMA (warm mix asphalt) additives. Production mixtures are also sampled and tested for performance evaluation.

The ***Texas Department of Transportation (TxDOT)*** is also currently using volumetric design with performance verification (Approach A) to design specialty mixtures such as stone matrix asphalt and thin overlays. First, a conventional volumetric design is conducted to determine the optimum binder content. Then, specimens are prepared at optimum, optimum+0.5%, and optimum+1% binder contents to test for rutting and cracking resistance. HWTT and Texas overlay tests are both conducted on short-term conditioned mixtures (two hours at compaction temperature) for rutting and cracking resistance evaluation, respectively. HWTT results are also used to evaluate moisture susceptibility. If the mixture does not meet the performance criteria, a new volumetric mixture design is carried out by adjusting the binder content, changing the aggregate source, binder source, or the amount passing the No. 200 sieve.

The ***Wisconsin Department of Transportation (WisDOT)*** is also investigating the effectiveness of volumetric design with performance testing verification. HWTT after short-term conditioning of mixtures (four hours at 135°C) is used for rutting assessment, Disk-Shaped Compact Tension (DCT) and SCB after long-term conditioning (twelve hours at 135°C) are used for low-temperature and fatigue cracking performance evaluation, respectively.

2.1.4.2 Changes to Proposed Initial Processes and Implementation Progress

NCAT conducted a survey of State Highway Agencies (SHAs) and the industry about the BMD implementation efforts in May 2020. The survey revealed the approaches adopted by different states and those in the pre-implementation phase. Figure 2.7 shows the results of the survey on a U.S. map.

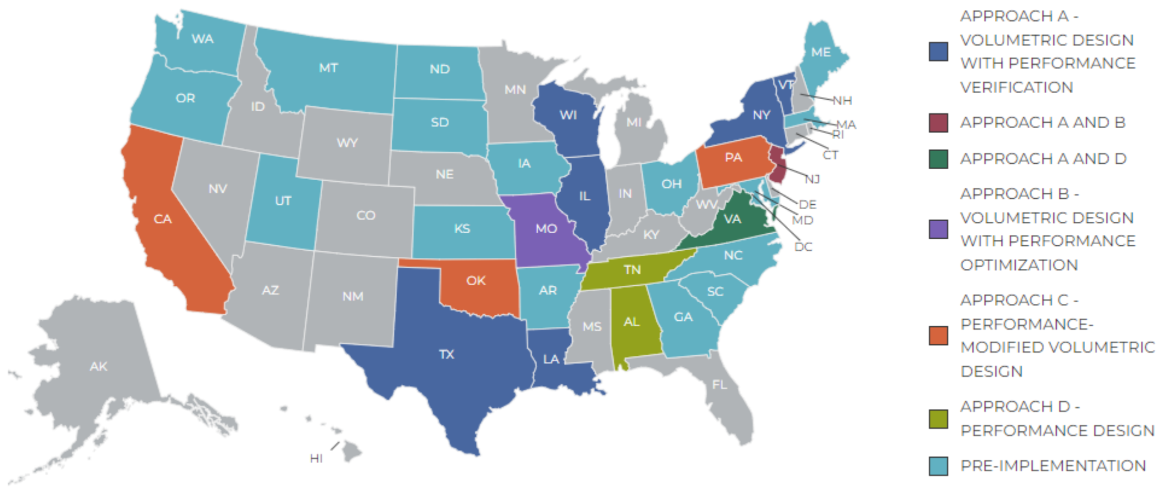


Figure 2.7: U.S. map of BMD implementation efforts in different states (NAPA 2022, Yin and West, 2021).

It can be seen from Figure 2.7 that 16 states (including Oregon) are in the pre-implementation phase. Oregon can be considered one of the *"pre-implementation"* states closest to *"initial implementation"*. Table 2.2 shows the BMD implementation tasks that were completed in Oregon (as of 2023, when this literature review was written) and the tasks planned to be completed after this research project. Only two states – Alabama and Tennessee have adopted Approach D, while other states have retained the volumetric mix design method in the BMD approach in one way or another (Approaches A, B, and C). The state-of-the-current practice on BMD for some of the states with completed implementations is summarized below.

This section summarizes the ongoing research efforts to implement balanced mix design procedures in California, Illinois, Louisiana, Maine, New Jersey, Texas, and Virginia as of 2021.

California

Since 2000, the University of California Pavement Research Center (UCPRC) and Caltrans have been developing, improving, and using the California Mechanistic-Empirical (CalME) design software for pavement design and performance evaluation. CalME was calibrated by using accelerated pavement tests and field performance data to improve the predictive capability of existing models. In addition, the software is capable of simulating pavement rehabilitation and maintenance scenarios. The developed software is also able to consider the impact of different variables on performance variability through a probabilistic model that uses Monte Carlo simulations (Ullidtz et al. 2010). Moreover, CalME enabled Caltrans to utilize non-traditional asphalt mixtures such as rubberized HMA and high RAP mixtures. A comprehensive material database (model coefficients calculated from repeated shear and BBF tests) was developed by UCPRC over the past 15 years to be able to predict in-situ performance for different case studies.

The predictions of this software for cracking and rutting performance have been used to evaluate the effectiveness of different asphalt mixtures for different traffic levels and climate regions. In addition to volumetric design, repeated simple shear tests (RSST) were generally conducted to determine the rutting performance of the asphalt mixtures at the design binder content. Recommendations to increase the binder content were provided based on the RSST results. This new mechanistic-empirical process, combined with laboratory test results, was reported to improve the performance of two pilot sections constructed in California (Red Bluff and Weed projects) (Tsai et al. 2012).

Caltrans introduced the Superpave mix design into the standard specifications in 2014. HWTT (AASHTO T 324 - Modified) and TSR were incorporated into the specifications, and the Job Mix Formula (JMF) was designed and approved using BMD Approach A (changed the approach proposed in 2018 for non-Performance Related Specifications-Non-PRS, which was Approach C), i.e., volumetric design with performance verification. This BMD approach applies to Rubberized Hot Mixed Asphalt Gap Graded (RHMA-G) and Type A HMA mixes. The BMD approach adopted by Caltrans for the Type A HMA mix is shown in Figure 2.8.

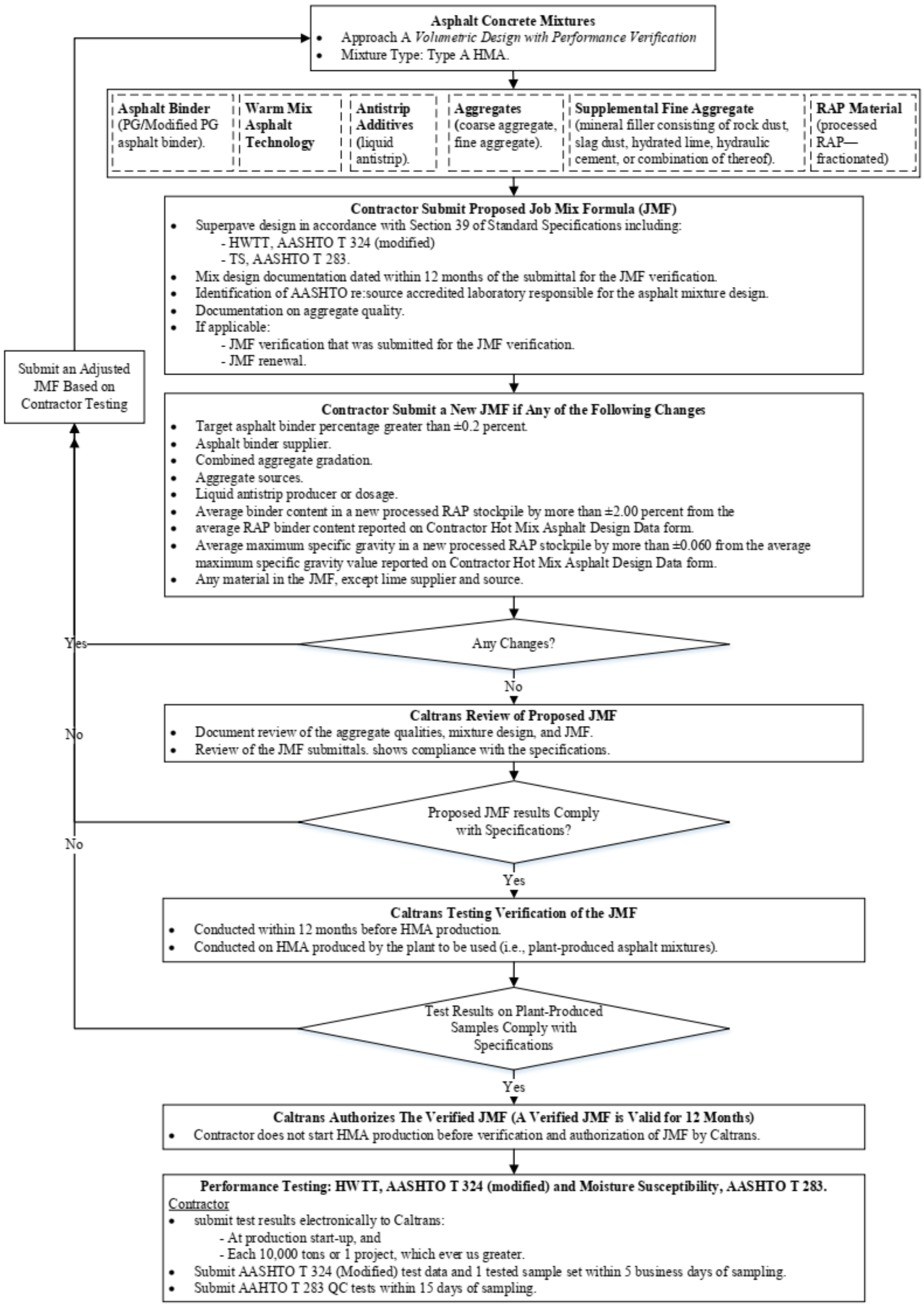


Figure 2.8: Flowchart of Caltrans Type A HMA mix design process (Hajj et al. 2021a)

It can be seen from Figure 2.8 that the type of binder has been considered in the HWT criteria, addressing both traffic and climate conditions. However, the cracking test has not been included in the specification for non-Performance Related Specification (non-PRS) projects.

Caltrans also has different BMD approaches based on the project type. The non-PRS projects follow Approach A, while PRS or long-life asphalt pavements (LLAPs) follow Approach C, i.e., performance-modified volumetric design. For LLAP projects, both the RSST test and flexural beam fatigue (FBF) are included in the performance-based specification (PBS) along with the HWT test for the evaluation of moisture susceptibility of the asphalt mixtures at the selected asphalt binder content (OBC). However, in the recent I-5 (Sacramento) project, RSST was replaced with a repeated load triaxial (RLT) test using an asphalt mixture performance tester (AMPT) due to issues observed with running and operating the RSST. Moreover, the PBS establishes criteria specific only to a project. To accommodate performance criteria in the specifications, Caltrans has modified some of the volumetric mix design criteria. For example, the required number of gyrations has been lowered, and VMA limits have been raised along with the dust-to-asphalt binder ratio upper limit for Type A HMA. The PBS applies directly to the plant-produced asphalt mixture, and the specification limits are set based on a 95% confidence interval for the given parameter after replicate tests.

Overall, Caltrans has made significant progress in implementing BMD for all the asphalt mixtures used in the state. Caltrans has carried out almost all the tasks shown in Table 2.2. According to the information gathered by FHWA's virtual sites, no problems were faced by the contractors or agencies following the BMD approach for asphalt pavement construction. Moreover, BMD mixtures helped in utilizing high RAP contents, achieving the target in-place density and compactability in the field (Hajj et al. 2021a). This adaptation also provides an approach to incorporate alternative materials, including plastic-modified binders, RAS, etc; necessitating further research and deployment. For large-scale implementation, Caltrans suggested working on the ruggedness of different testing equipment and the interpretation of results by encompassing non-traditional materials in the production of asphalt mixtures (Hajj et al. 2021a).

Illinois

IDOT primarily uses high Equivalent Single Axle Load (ESAL) and low ESAL mixtures that differ in their gradation and permissible binder contents. IDOT completely implemented HWT (Illinois-modified AASHTO T 324) into the specifications about a decade ago. From 2021, I-FIT has also been incorporated into the design verification and production testing of asphalt mixtures for all HMA mixtures. Historically, Illinois mixtures encountered rutting issues that were addressed by using RAP and RAS and stiffer PG binders. However, this led to durability issues in the mixtures over time. Thus, IDOT started exploring the use of cracking tests along with HWT tests during the mixture design and production stages. The cracking test was expected to address the commonly observed reflective cracking distress in asphalt pavement overlays. IDOT collaborated with the Illinois Center for Transportation (ICT) at the University of Illinois at Urbana-

Champaign (UIUC) for research to lay the foundation for incorporating performance testing into asphalt mixture design.

IDOT introduced the use of I-FIT as a special provision in 2016 for the purpose of collecting data (Flexibility Index or FI parameter) related to the cracking resistance of the HMA produced at the plant. The special provision was further expanded to long-term aged (LTA) HMA mixtures for information purposes only, and eventually, I-FIT was incorporated into the paving contracts in 2021 as a requirement. IDOT also adopted Approach A for BMD implementation (no change since 2018), and the process is shown in Figure 2.9.

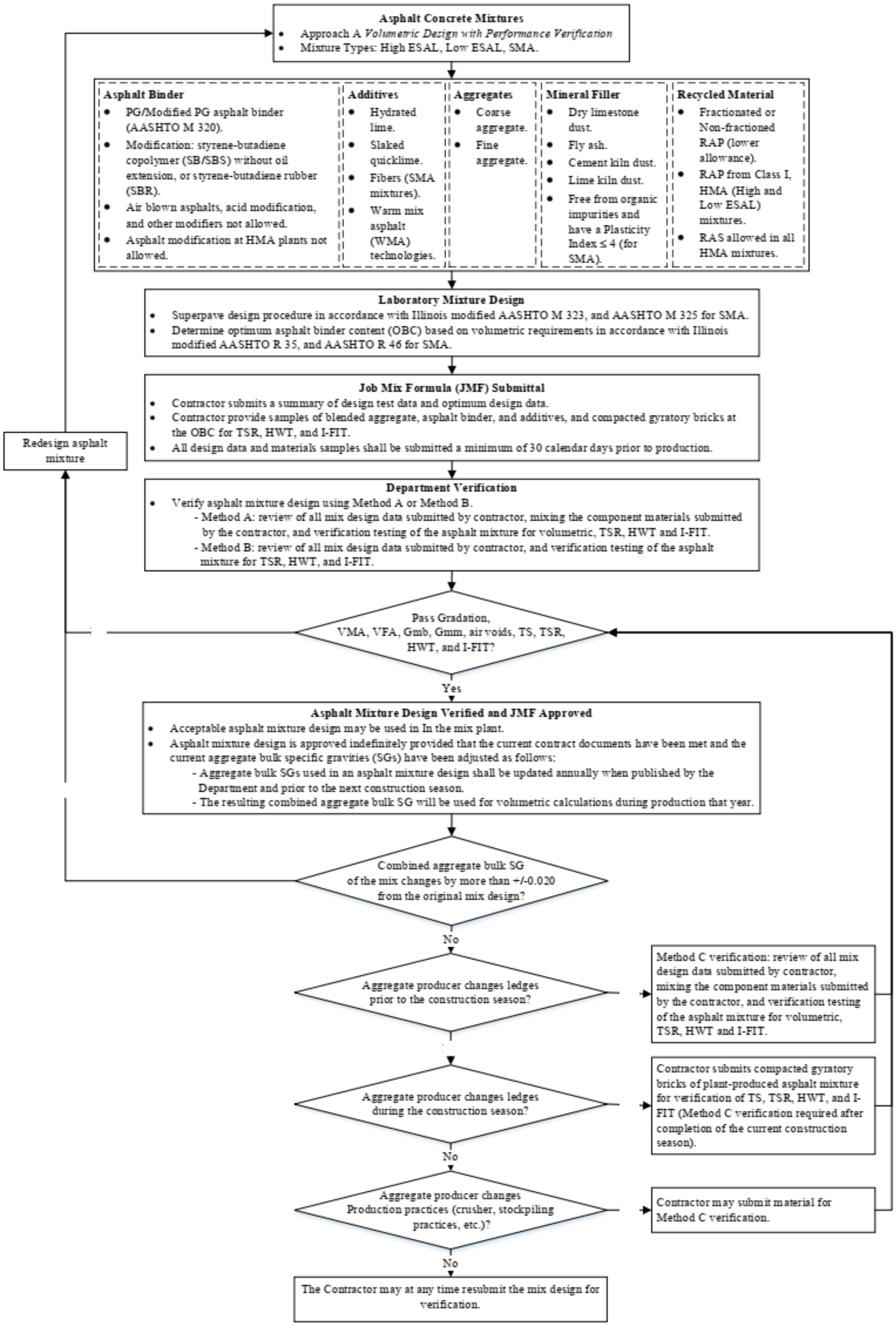


Figure 2.9: Flowchart of IDOT asphalt mix design process (Hajj et al. 2021b)

As mentioned before, IDOT conducted a series of research studies in association with UIUC to come up with a robust testing methodology for BMD. IDOT's criteria for the selection of a performance test were material sensitivity, field validation, and repeatability. In addition, sample preparation, conditioning, and testing were other important considerations. Based on the research recommendations, HWT (rutting), I-FIT (cracking), and TSR (moisture sensitivity) were selected as the performance tests for BMD. The performance testing requirements for all IDOT mixtures are shown in Table 2.5.

Table 2.5: IDOT mixture design performance testing requirements (Hajj et al. 2021b)

Mixture Type	HWT Thresholds[$] PG 58-xx (or lower)	HWT Thresholds[$] PG 64-xx	HWT Thresholds[$] PG 70-xx	HWT Thresholds[$] PG 76-xx (or higher)	FI[*] STA	FI[*] LTA[a]	TS[^] Conditioned Non-Polymer modified PG	TS[^] Conditioned Polymer modified PG[c]	TS[^] Uncon-ditioned	TSR
High ESAL IL-19.0	≥ 5,000	≥ 7,500	≥ 15,000	≥ 20,000	8	4.0[b]	≥ 60	≥ 80	≤ 200	≥ 0.85
High ESAL IL-9.5	≥ 5,000	≥ 7,500	≥ 15,000	≥ 20,000	8	4.0[b]	≥ 60	≥ 80	≤ 200	≥ 0.85
High ESAL IL-4.75	≥ 5,000	≥ 7,500	≥ 10,000	≥ 15,000	12.0	-	≥ 60	≥ 80	≤ 200	≥ 0.85
Low ESAL IL-19.0L	–	–	–	–	8	4.0[b]	≥ 60	≥ 80	≤ 200	≥ 0.85
Low ESAL IL-9.5L	–	–	–	–	8	4.0[b]	≥ 60	≥ 80	≤ 200	≥ 0.85
SMA ≤ 10 MESALs	≥ 5,000	≥ 7,500	≥ 15,000	≥ 20,000	16	10	≥ 60	≥ 80	≤ 200	≥ 0.85
SMA > 10 MESALs	≥ 5,000	≥ 7,500	≥ 15,000	≥ 20,000	16	10	≥ 60	≥ 80	≤ 200	≥ 0.85

[–]Not applicable.
[a]Required for surface courses only beginning in 2022.
[b]Production mixture requirement. Mixture design long-term aging FI is a minimum of 5.0.
[c]Except polymer modified PG XX-28 or lower asphalt binders shall have a minimum TS of 70 psi.
[$]Illinois Modified AASHTO T 324, ≤ 12.5 mm Rut Depth at a Minimum Number of Wheel Passes.
*Flexibility Index using llinois Modified AASHTO T 124.
[^] Tensile strength using Illinois Modified AASHTO T 283, psi

IDOT has also been performing round-robin studies of HWT and I-FIT every year since 2017. The round-robin studies shed light on the variability in the tests and provided contractors with data comparing different devices used by various agencies and contractors. This data has been used to develop precision statements for I-FIT based on four replicates per test. IDOT continues collecting performance test results and feeding them into the database that may be utilized in the future for further refinement and revision of testing methodology and criteria (Hajj et al. 2021b).

Similar to Caltrans, IDOT's experience with BMD mixtures has been positive so far, especially in fixing the poor cracking performance of higher RAP/ RAS asphalt mixtures. Incorporating I-FIT test criteria in mixture design and production stages in conjunction with HWT tests has resulted in asphalt mixtures that are balanced in their cracking and rutting performances (Hajj et al. 2021b). As per IDOT, there is a need to gather more information for the preparation of guidelines specifying the process of materials for large-scale production and integration of performance tests, which might be supportive of the implementation of BMD. Like Caltrans, they also suggested conducting ruggedness studies and analyses incorporating alternative materials (Hajj et al. 2021b).

Louisiana

LADOTD has been working to improve the performance of asphalt mixtures by adapting a balanced mix design procedure. Two comprehensive research studies were conducted by the Louisiana Transportation Research Center (Cooper et al., 2014; Mohammad et al., 2016) to determine reliable thresholds for HWTT (rutting) and SCB-J_c (cracking) tests. In these projects, the effects of switching from the 2006 volumetric design specification to the 2013 specification were evaluated by conducting these performance tests. The 2013 specification required a reduction in the number of gyrations at N_{design} to increase binder content and a slight increase in minimum VMA and VFA requirements. Results showed that asphalt mixtures designed with the 2013 specification have equal or better performance than the mixtures designed according to the 2006 specification. Results also showed that the new specification did not have a negative impact on the in-situ performance of evaluated asphalt mixtures.

LaDOTD emphasized the same factors as IDOT in selecting the performance tests. LaDOTD is using the loaded wheel test (LWT) (same as HWTT) and SCB tests for several reasons, summarized in Table 2.6.

Table 2.6: Comparison of the performance tests selected by LaDOTD (Hajj and Aschenbrener 2021c)

Factors	LWT (AASHTO T 324)	SCB (ASTM D8044)
Time for preparing samples	• Compact, cut, and perform volumetric measurements • 1 day for a set of 4 test specimens	• Compact, cut, notch, and perform volumetric measurements • 1 day for a set of 12 test specimens
Testing specimens	• 1 day for a set (2 samples = 4 test specimens)	• 1–2 hours for a set (12 test specimens)
Analyzing data	• Spreadsheet: 30 minutes	• Spreadsheet with cut/paste: 15 minutes
Technician training requirements	• Minimal • Several laboratories (State DOTs, Academia, Consultants)	• Minimal • Several laboratories (State DOTs, Academia, Consultants)

LaDOTD developed the performance test criteria based on the test results of field cores obtained from 9 field projects. The field performance indicators were compared with the laboratory mixture performance indicators. The developed test criteria were different for Level 2 (high traffic) and Level 1 (low traffic) asphalt mixtures. These test criteria were validated by the historical performance of the plant-produced mixtures across the state. However, no inter-laboratory study (round-robin) has been done to establish precision and bias information. This was observed as a potential issue for SCB test results, as they showed high variability with COV numbers approximately 30%, in the past. The issue was found to be related to sample fabrication and was later resolved by incorporating a QC form for specimen fabrication (Hajj and Aschenbrener 2021c).

The implementation of BMD by LaDOTD is backed by significant research efforts, pilot specifications, and field pavement trials. LaDOTD collaborated with academia as well as the industry and communicated thoroughly with the stakeholders to earn their confidence and support before fully switching to a performance-based mix design in 2016. In 2018, the PBS was amended and has been in practice since then, with scope for improvements based on any feedback from the industry. The result is the more effective utilization of innovative and recycled materials, such as warm mix additives and high RAP in asphalt mixture design, without compromising performance (Hajj and Aschenbrener 2021c). As per LaDOTD, BMD is a cost-effective approach that provides more flexibility to the contractors in terms of using recycled materials. LTRC is now working on evaluating the cost-benefit ratio of using the BMD approach in comparison to the traditional mix design approaches. Since the use of BMD imparts easier compactability, LaDOTD believes that there may be an improvement in the pavement durability. Considering SCB as an important performance test, they suggested developing a specified protocol for assessing the long-term aging effect on the fracture energy of short-term aged samples. Along with this, continuous monitoring is necessary to compile the data for the BMD improvement in terms of performance test criteria, validation, and modification in the BMD approach (Hajj and Aschenbrener 2021c).

Interestingly, the major reason for the successful process development and implementation stages for the LaDOTD experience was the strong collaboration between LaDOTD, industry, and academia (Hajj and Aschenbrener 2021c). It was stated that *"good communication and continuous dialogue with the industry, knowledge transfer, and necessary education and training with the support from academia"* were the major reasons for the successful implementation in Louisiana.

Maine

MaineDOT is also in the pre-implementation stage of incorporating BMD into the design and production of asphalt mixtures. The major pavement distress type in Maine has been identified as raveling, which is responsible for the asphalt mixtures' premature failures. For the past few years, Maine has been conducting direct tension cyclic fatigue (DTCF), and stress sweep rutting (SSR) tests with the asphalt mixture performance tester (AMPT) and collecting data for investigating the factors controlling pavement performance in Maine. Moreover, MaineDOT has also started testing mixtures for durability and raveling-related issues using the HWT tests. As a result of this ongoing effort, MaineDOT has been able to incorporate the HWTT in the asphalt mixture design and verification process and its specifications. Over the last few years, MaineDOT has also started envisioning a transition from the traditional volumetric mix design method to the BMD approach. Efforts have been made in this direction by evaluating mixtures for cracking and rutting resistance using IDEAL-CT (cracking) and IDEAL-RT (rutting) tests, respectively. Currently, the QA specification of MaineDOT does not have any performance requirements. However, the need for index-based performance tests has been felt, and some of the tasks from Table 2.2 are already in action, such as establishing a baseline database of the cracking index parameter. The implementation of BMD in Maine is supposed to be phased in using a tiered system from Approach A through to Approach C, with an end goal of moving towards Approach D over time (Hajj et al. 2021d). The need for this shift was also underscored by a recent study by Veeraragavan et al. (2022). In this study, 43 mixtures were tested for cracking and rutting performance using IDEAL-CT and HWTT, respectively. The index used for rutting resistance in Maine is called the normalized rutting resistance index (NRRI), which is the ratio of the actual rutting resistance index (RRI) to the minimum RRI (based on the specification criteria). The RRI is calculated using Equation (2-1) below:

$$\mathbf{RRI = N \times (25.0 - RD)} \tag{2-1}$$

Where
N = number of passes
RD = rut depth in mm

CT index was used as the cracking resistance index. The greater the CT index, the better the asphalt mixture against cracking. HWTT was conducted at two different temperatures of 45ºC and 48ºC, and the results of HWTT at these two temperatures were compared with the CT indices. As per the authors (Veeraragavan et al. 2022), a large number of mixes are highly rut resistant (NRRI>1) but are not performing well in terms of cracking resistance (CTindex <150). Thus, the BMD approach is expected to make the mixtures more 'balanced' by improving their cracking resistance.

It was reported in 2010 that raveling-related failures cost MaineDOT about $15 million a year. Although the adaptation of the HWTT for raveling performance evaluation started to reduce raveling-related failures for some roadway sections in Maine, the use of HWTT for raveling performance evaluation has still not been fully implemented. The reason for the delayed implementation was due to the poor performance of some of the field sections that had asphalt mixtures that passed the HWTT failure criteria (Hajj and Aschenbrener 2021c).

To improve the BMD approach and its implementation, MaineDOT recommended establishing a certification course on BMD, which should be mandatory for contractors and engineers for a successful implementation. As per the research professionals, among several available performance tests, there is a need to execute a screening process for the selection of the most appropriate performance test and its respective test parameters, which can directly simulate the field conditions. They also mentioned considering field traffic and environmental conditions for benchmarking the critical performance test thresholds. Following the selection of tests, parameters, and critical thresholds, additional test sections should be constructed and monitored to adjust the BMD process (Hajj and Aschenbrener 2021c).

New Jersey

As described in the previous section, the performance-based mix design method was used to design five special mixtures (about 10 percent of the state's total annual asphalt tonnage) for New Jersey roadways: i) high RAP mixtures or HRAP, ii) bottom-rich base course or BRBC, iii) bridge deck waterproofing surface course or BDWSC, iv) binder-rich intermediate course or BRIC, and v) high-performance thin overlay or HPTO (Bennert 2011). Field performance data collected since 2006 showed that the performance of asphalt mixtures designed with the new method has been exceptionally good. The BMD approach followed for designing five specialty asphalt mixtures is shown in Figure 2.10.

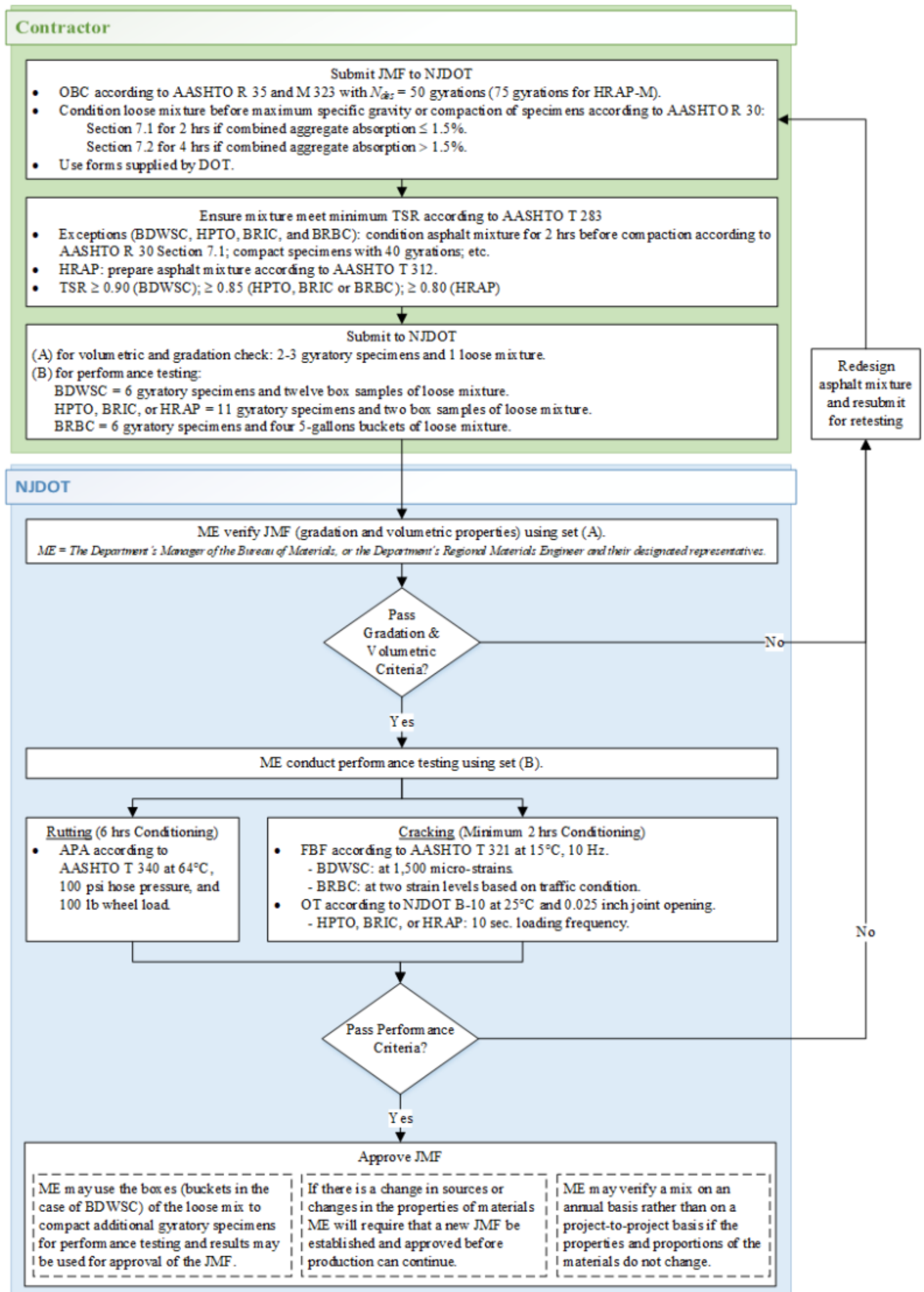


Figure 2.10: NJDOT BMD approach for the five specialty asphalt mixtures (Hajj and Aschenbrener 2021e)

As can be seen from Figure 2.10, NJDOT has implemented a combination of Approach A and Approach B for BMD. The designed asphalt mix has to first meet all the volumetric requirements (modified from the traditional mix design), and then the mix also needs to pass the cracking and rutting performance criteria. It should be noted that the volumetric design process followed in New Jersey generally results in binder contents that are significantly higher than in most other states. For instance, the upper limit for the dust-to-binder ratio for the majority of the mixtures in New Jersey is 1.2 (significantly less than the upper limit in Oregon, which is 1.6). The design number of gyrations for almost all the mixtures is 50. For this reason, most of the designed mixtures have asphalt binder contents higher than 7%.

For rutting evaluation, NJDOT uses APA, a switch-over from the Superpave Shear Tester (SST) that was costly and time-consuming. For cracking, NJDOT uses FBF for bridge deck waterproofing surface course and bottom-rich base course mixes and an overlay tester (OT) for all other mixes. The OT was found to be sensitive to the volumetric properties as well as differences in cracking performance between virgin mixtures and 30% RAP mixtures. The OT results were also determined to be correlated well with the field performance and were therefore selected as the cracking test. The baseline database was developed by Rutgers University and was later used to establish test criteria after field pavement performance. Owing to the factors related to cost, convenience, and duration of sample preparation (an important aspect in QA), Rutgers University has also started investigating the use of IDT tests as surrogate performance tests during production (Hajj and Aschenbrener 2021e).

Currently, NJDOT is in the process of implementing balanced mix design methods for all asphalt mixtures. The initial steps and timelines have already been chalked out, and a draft 5-year BMD implementation plan, as shown in Figure 2.11, is in the evaluation phase. The NJDOT PBS, in its current form, has helped the contractors explore the utilization of high RAP without any durability issues. This would facilitate a cost-effective and environmentally friendly mix design process. However, proper training is necessary for achieving satisfactory construction (Hajj and Aschenbrener 2021e).

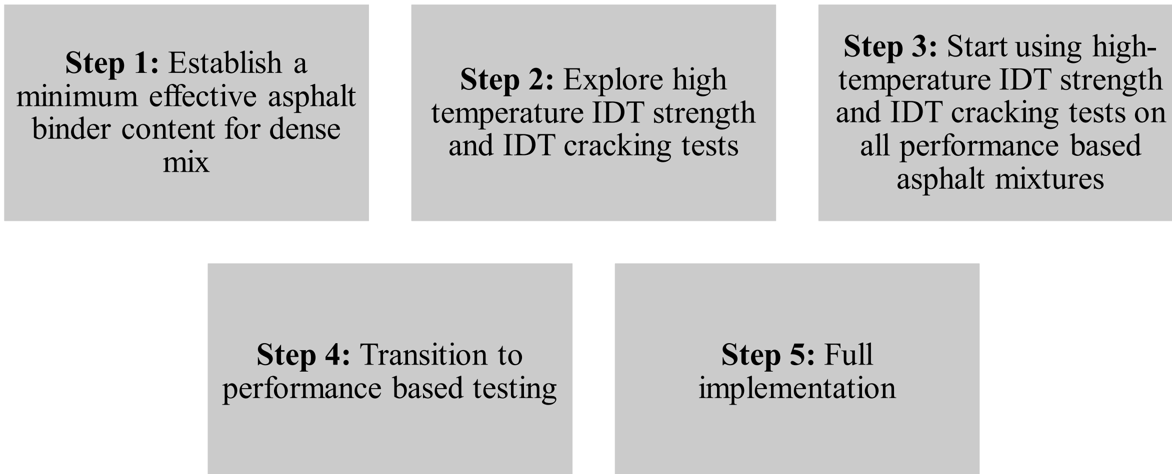


Figure 2.11: Five-year BMD implementation of NJDOT (Hajj and Aschenbrener 2021e)

Texas

The premature failures of asphalt pavements due to the use of RAP in asphalt mixtures motivated TxDOT to shift from the volumetric mix design method to BMD. There was also a motivation to incorporate higher RAP percentages in the mixtures considering the cost-effectiveness and environmental concerns. For the selection of performance tests, TxDOT relied on its history and experience with HWTT and OT for separating good and bad mixes in terms of rutting and cracking resistance, respectively. HWTT has been a part of the TxDOT process for mix design selection for several years and was also included in the standard specifications in 2004. Both HWTT and OT results are recorded, and the database has been well maintained. Since TxDOT is envisioning implementing BMD for all mixtures, a need for surrogate performance tests for acceptance has been realized. IDEAL-CT and IDEAL-RT are being evaluated as surrogate cracking and rutting tests, respectively. The TxDOT's BMD approach for surface asphalt mixtures is shown in Figure 2.12. The TxDOT follows Approach A, i.e., volumetric design with performance verification.

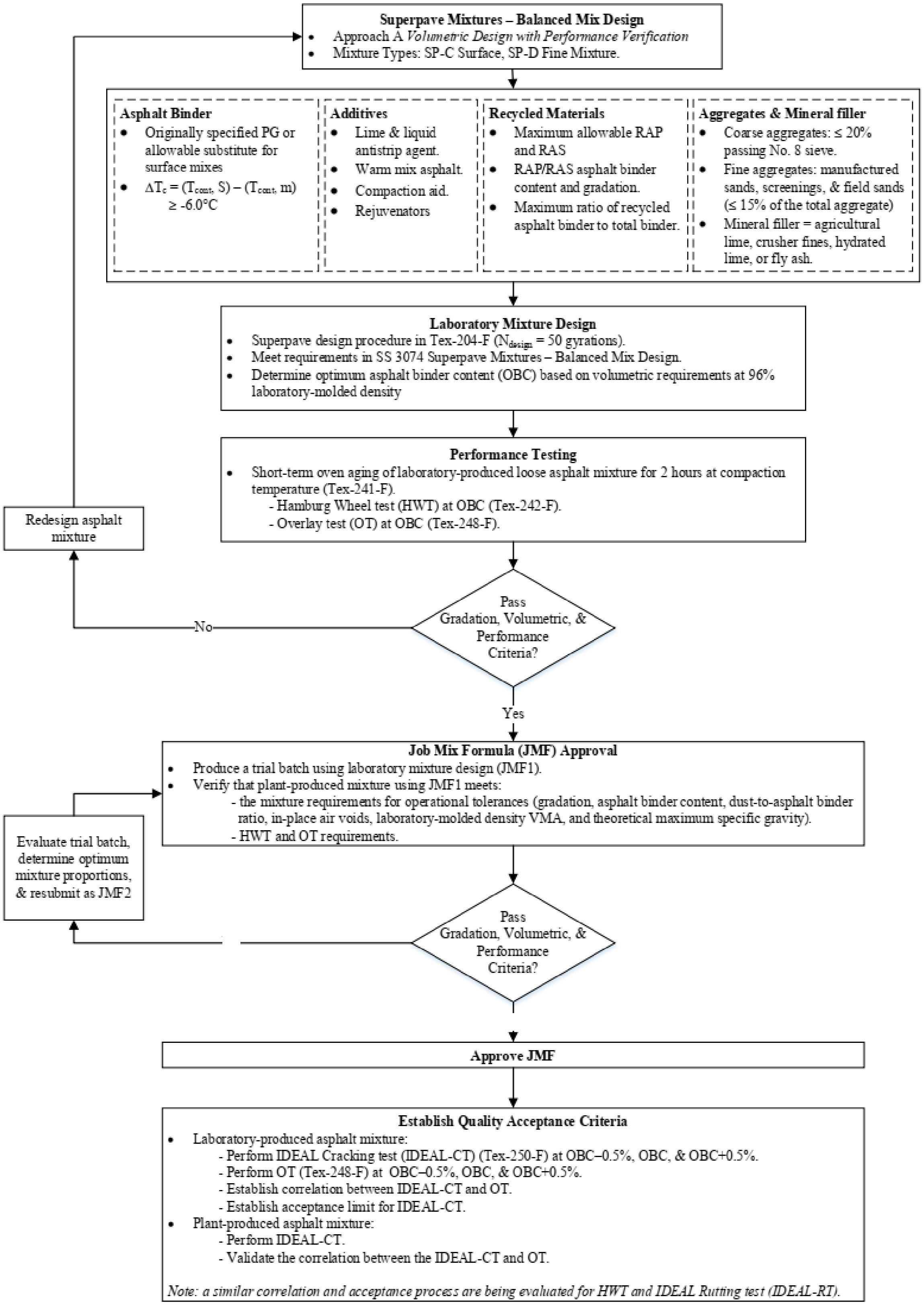


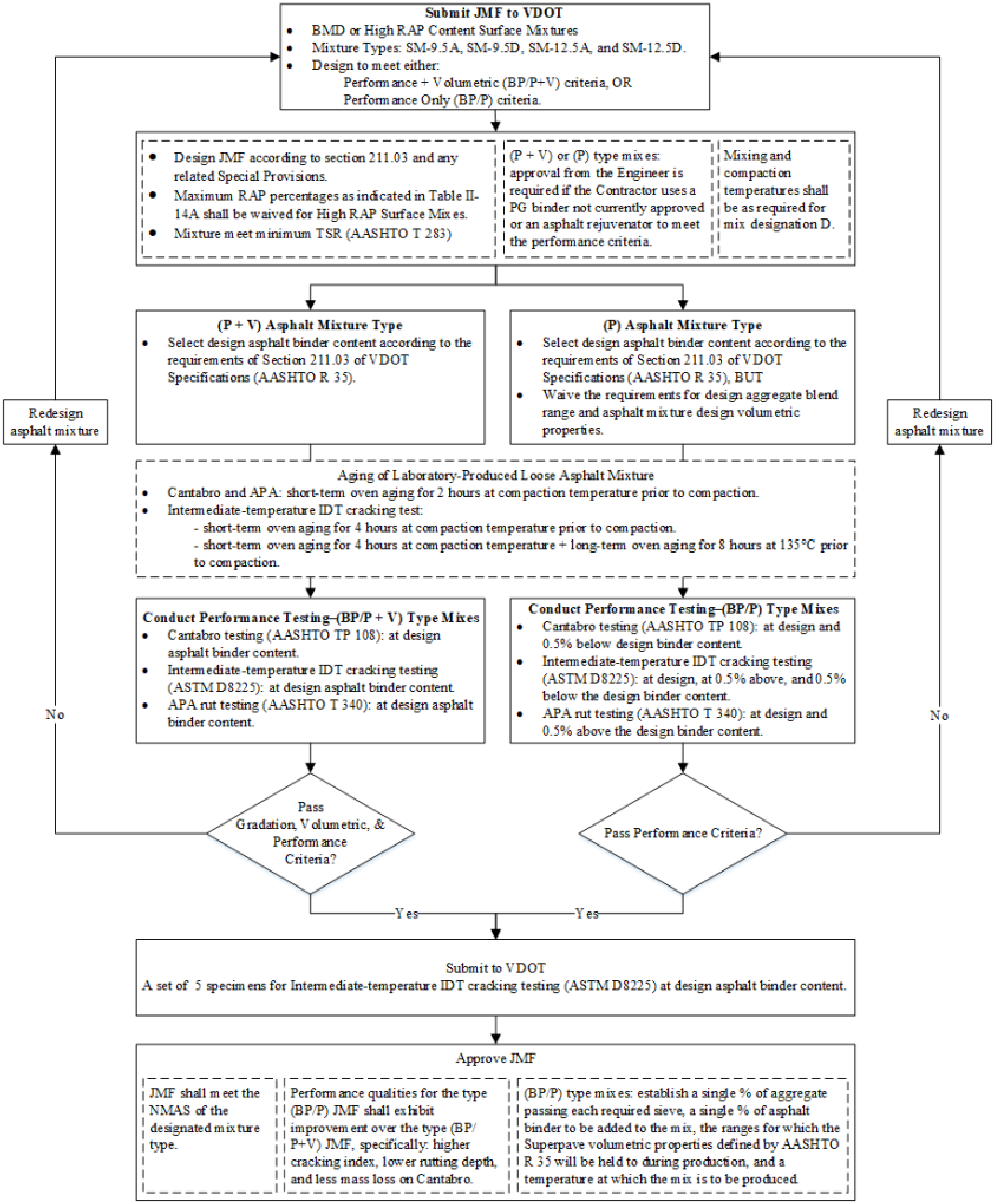
Figure 2.12: TxDOT's BMD approach (Hajj et al. 2021f)

TxDOT developed the preliminary test criteria based on the database of cracking and rutting test results. This historical database of results, in conjunction with the field performance of several funded projects, helped TxDOT in improving and updating the test criteria and methodologies. Currently, a round-robin study is also planned to develop precision and bias statements for HWT, OT, and IDEAL-CT (Hajj et al. 2021f).

The use of the BMD approach in Texas allowed contractors to develop more innovative asphalt mixtures that are more environmentally friendly and cost-effective (Hajj et al. 2021f). One major benefit of the implemented BMD approach is the ability to incorporate new additives and high RAP strategies without taking significant in-situ failure risks. This reduction in risk is a result of adapting experiments and procedures that properly characterize the in-situ performance of the Texas asphalt mixtures. TxDOT is expecting to save about $80 million annually after the full implementation of the BMD approach with performance verification. This significant saving is predicted to result from increased RAP usage without compromising performance and overall improvements in the longevity of asphalt pavements. Nevertheless, more test sections are essential to understand the influence of different materials on performance through periodic monitoring. As per TxDOT, further research is required to understand the cost-effectiveness of BMD compared to traditional methods. In addition, there is a need for the preparation of a data inventory to establish and validate the correlation between the outputs of available rutting and cracking performance tests. These future recommendations would support the implementation of BMD and fine-tune the performance test criteria for wide acceptance (Hajj et al. 2021f).

Virginia

When VDOT adopted the Superpave mix design method in the mid-1990s, the resulting asphalt mixtures did not perform well against cracking and developed durability issues. Mixtures with RAP performed worse, even though VDOT has been a leader in recycling efforts for more than four decades. Therefore, VDOT turned to the BMD approach to address this issue. The approach adopted by VDOT for BMD implementation is shown in Figure 2.13.



Note: TSR is part of asphalt mix design approval during production.

Figure 2.13: VDOT's BMD approach (Hajj et al. 2021g)

VDOT collaborated with the Virginia Transportation Research Council (VTRC), industry, and academia to select and implement performance tests. Moreover, a BMD advisory committee was also established to oversee the progress of the implementation efforts. A timeline was developed by VDOT for a statewide BMD implementation and is shown in Figure 2.14.

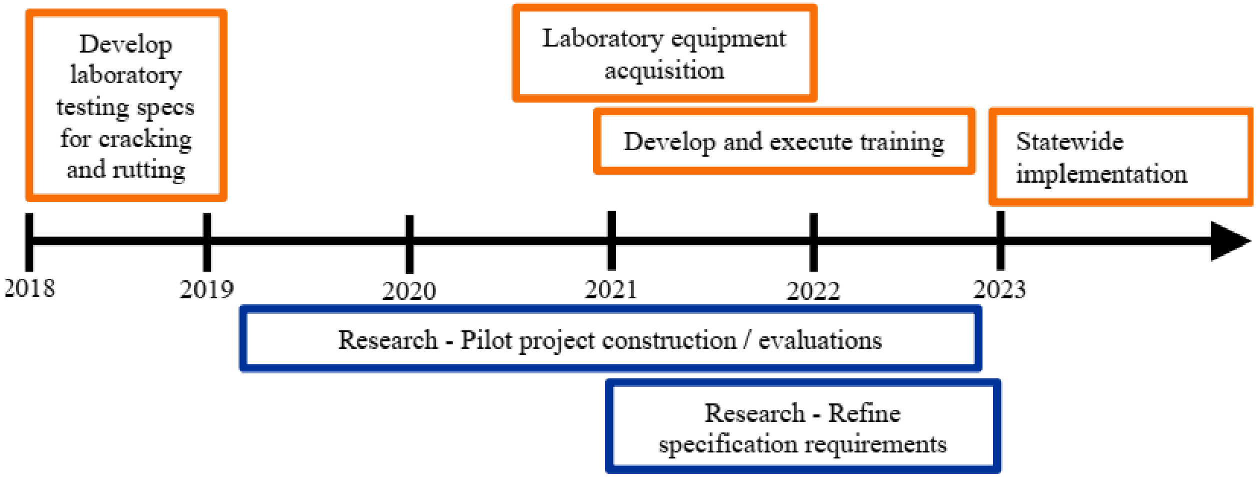
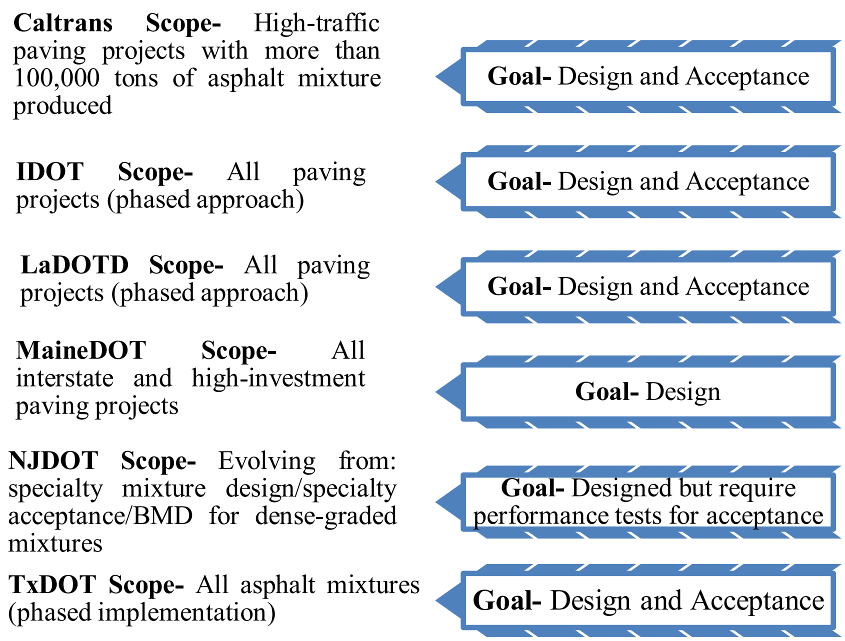


Figure 2.14: VDOT timeline for statewide BMD implementation (Hajj et al. 2021g)

During initial efforts, VDOT considered six tests for the benchmarking study. These were – Cantabro (durability), APA (rutting), OT (reflective cracking), I-FIT (cracking), N_{flex} factor (cracking), and IDT (cracking). After conducting the benchmarking study, only 3 out of 6 tests were selected to be included in specifications: Cantabro, APA, and IDT. These performance tests were used to develop test criteria by comparing the test results of the mixtures with known historical field performance. The adopted approach resulted in setting the thresholds as 7.5 percent for the Cantabro loss test, a maximum of 8 mm for APA rut depth, and a minimum of 70 for CT Index based on IDEAL-CT. VDOT plans to validate these performance test criteria by testing asphalt mixtures from 13 projects.

It should be noted that VDOT developed two different BMD provisions for mixes with a maximum of 30% RAP and mixes with a minimum of 40% RAP. Moreover, BMD Approach A (referred to as BP/P+V by VDOT) and BMD Approach D (referred to as BP/P by VDOT) will be utilized by VDOT, as can be seen in Figure 2.13. As per the initial implementation, the integration of BMD allows VDOT to use different sustainable, innovative, and recycled materials for the production of asphalt mixtures. BMD mixtures were easy to compact during the construction and resulted in consistent and improved in-place density throughout the construction compared to the section produced with a volumetric design. Such improvement often leads to pavement longevity. As a part of BMD implementation, VDOT recommends the construction and analysis of the pilot section and its periodic monitoring for validating and developing critical thresholds of performance tests. They also suggested developing a long-term aging protocol for the design of asphalt mixtures by incorporating the effect of materials variability as well as plant-level variability on the performance test results (Hajj et al. 2021g).

Overall, there are several reasons and benefits for integrating BMD for the production of asphalt mixtures, which lead to their widespread acceptance. Each DOT has its own project goal and scope. Figure 2.15 summarizes the project's goal and scope of a few DOTs in the United States (Hajj et al. 2022b). As per different DOTs, including Illinois, Texas, Louisiana, Virginia, Oregon, etc, the concept of BMD is valuable in applying recycled materials, while a few other DOTs, such as California, Maine, New Jersey, etc, suggested using BMD for improving the pavement longevity in terms of performance and raveling aspects (Hajj et al. 2022b). Considering such benefits, other DOTs are in the implementation phase to understand the BMD concepts through trial sections (Li et al. 2023, Bittner et al. 2024). In addition, due to the appreciable and promising results, the Federal Aviation Administration (FAA) is now planning to integrate the BMD process for airfield pavement design (Elias et al. 2024a, Elias et al. 2024b).



Note: Caltrans = California DOT; IDOT = Illinois DOT; LaDOTD = Louisiana DOT and Development; MaineDOT = Maine DOT, NJDOT = New Jersey DOT; TxDOT = Texas DOT

Figure 2.15: BMD goal and Scope for a few DOTs (Hajj et al. 2022b)

2.2 LABORATORY TESTS TO EVALUATE PERFORMANCE PROPERTIES OF ASPHALT MIXTURES

A major part of the BMD implementation process is dedicated to the selection of performance tests for rutting and cracking evaluation. Figure 2.16 and Figure 2.17 show, respectively, the different cracking and rutting tests considered by the SHAs and the asphalt paving industry for BMD implementation.

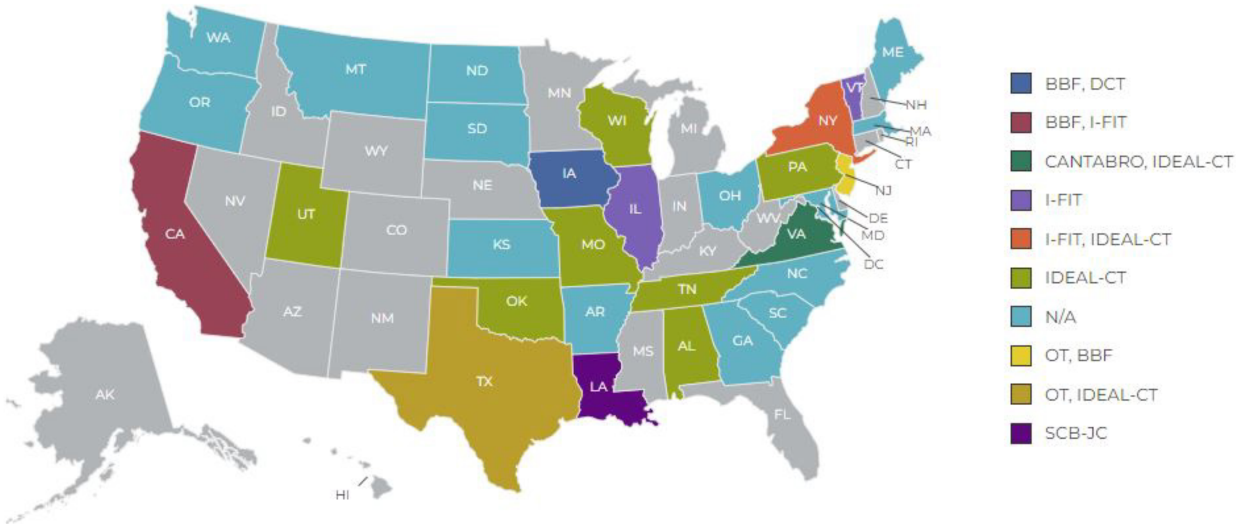


Figure 2.16: Different cracking tests used across the U.S. (NAPA 2022, Yin and West, 2021).

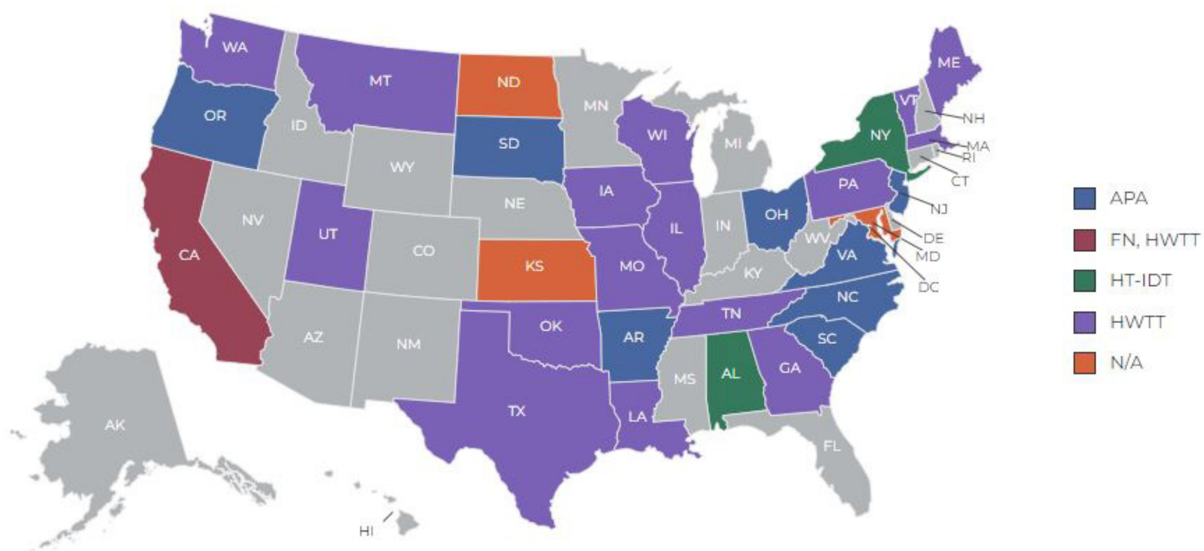


Figure 2.17: Different rutting tests used across the U.S. (NAPA 2022, Yin and West, 2021).

Some of the tests that have shown promising results in the laboratory may not be implemented for routine mix design due to practicality and cost issues. Such tests may also not be incorporated in quality control/quality assurance (QC/QA) because of the slow turnaround of results. The surrogate performance tests are widely considered to be included in the PBS and QA owing to factors such as cost, practicality, the time needed for sample preparation and conditioning, repeatability, and others, as listed in Table 2.7. As per NJDOT, specimen conditioning and testing are the key factors that need to be considered during the design and verification of BMD, while during the stage of implementation, sample preparation and equipment costs are also taken into account for the acceptance of asphalt mixtures. These factors depend on the intended use of performance tests and may evolve and change with time. Overall, among different influential factors, most of the DOTs consider repeatability/reproducibility, material sensitivity, and field validation to be the most crucial factors in selecting adequate performance tests for BMD.

Table 2.7: Factors considered for the selection of performance tests for BMD (Hajj et al. 2022b)

Influential Factors	Caltrans	IDOT	LaDOTD	MaineDOT	NJDOT Design	NJDOT Acceptance	TxDOT	VDOT
Specimen Preparation						×	×	×
Sample Conditioning and Testing					×	×	×	×
Training Needs and Applicability								
Instrument Cost								
Repeatability and Reproducibility	×	×	×	×	×	×		
Material Sensitivity	×	×	×	×			×	×
Field Validation	×	×	×	×	×			

Most of the tests shown in Figure 2.16 and Figure 2.17 have been investigated and discussed in detail in previous ODOT research project reports, SPR 801 (Development of A Balanced Mix Design Method in Oregon) and SPR 785 (Adjusting Asphalt Mixes for Increased Durability and Implementation of a Performance Tester to Evaluate Fatigue Cracking of Asphalt).

SPR 785 (Coleri et al. 2018) evaluated different test and data analysis methods for cracking performance quantification. The SCB test with the flexibility index parameter and the IDT test with the flexibility index parameter provided results that are 95% correlated. However, since four specimens can be cut from one gyratory core for the SCB testing, it was recommended as a more practical alternative, although all other factors for the IDT test with the flexibility index parameter were similar to the SCB with the flexibility index parameter. Based on the suggestions from ODOT and industry, the IDT test with a 62 mm-thick specimen from a Superpave Gyratory Compactor (SGC) will be used in this study. This suggestion was made to avoid any sawing and cutting at ODOT and industry laboratories, which also requires training and may result in safety issues. For all these reasons, OSU-AMaP is going to use the IDEAL-CT test with the CT Index parameter for cracking performance evaluation. IDEAL-CT specimens are identical in shape to the IDT specimens evaluated in SPR785, and preparation does not require any sawing or cutting in the laboratory. The CT Index parameter is different from the flexibility index parameter used in SPR785. However, both the flexibility index and CT Index parameters must be highly correlated due to the similar processes followed for the calculation of these two parameters. The flexibility index calculation procedure was provided in SPR785, while the CT Index calculation procedure is given in Section 2.2.1.

SPR 801 evaluated two tests for rutting performance evaluation, the Hamburg Wheel Tracking Test and the Flow Number (FN). It was determined that the differences between the laboratory and plant mixing processes directly control the FN test results. FN results for plant-mixed laboratory compacted (PMLC) mixtures are always significantly lower than the results for laboratory-mixed laboratory compacted (LMLC) mixes. This difference avoids any direct comparisons between the rut resistance of PMLC and LMLC asphalt mixtures. Through the statistical analysis, it was also determined that the correlations between asphalt mixture variables and FN are weak. For this reason, the FN test is not able to capture the impact of asphalt mixture properties, such as VMA, VFA, binder content, etc., on rutting resistance for Oregon asphalt mixtures. On the other hand, HWTT was determined to capture the impact of different mixture properties on rut resistance and was recommended as the rutting performance test for ODOT. Although the HWTT is an effective test for quantifying the rutting performance of asphalt mixtures, the high cost of the test system may not allow the use of this equipment at several locations. For this reason, the effectiveness of a surrogate rutting test (IDEAL-RT or HT-IDT, both described in this section) in identifying the rutting resistance of production asphalt mixtures should also be investigated in a future study.

2.2.1 IDEAL CT

IDEAL Cracking Test (IDEAL-CT) was developed by Zhou et al. (2017) and is an extension of the indirect tensile strength test. The test setup is shown in Figure 2.18. Cylindrical specimens of 150 mm diameter and 50 mm height are subjected to a loading rate of 50 mm/min, and the test is carried out at 25°C. Specimen thickness was later increased to 62mm to have identical specimens for both HWTT and IDEAL-CT testing. According to the previous experiences of OSU-AMaP, an excessive number of gyrations is required to compact a 24-hour-95 °C oven-aged loose asphalt mixture to 50mm thickness (about 300 to 500 gyrations were observed). For all these reasons, 62 mm-thick specimens were produced for testing in this research study for all IDEAL-CT and HWT tests. The different parameters utilized in calculating the CT Index from the load-displacement curve of IDT are shown in Figure 2.19.

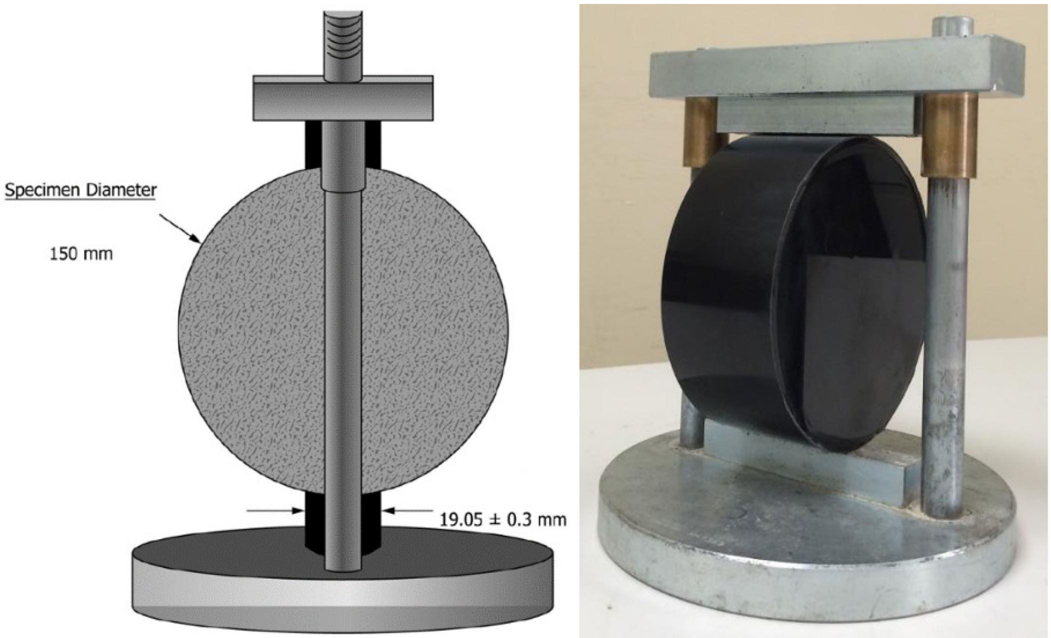


Figure 2.18: IDEAL-CT test frame (Zhou 2019a)

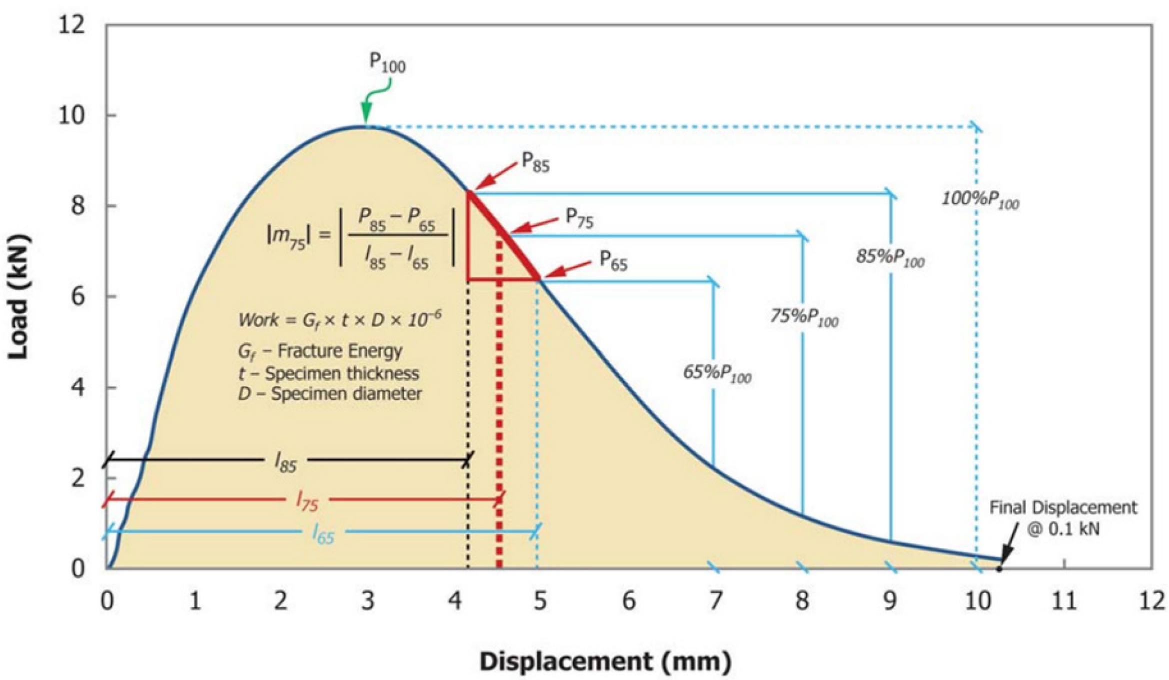


Figure 2.19: Typical load-displacement curves for IDEAL-CT (Zhou 2019a)

The parameters shown in Figure 2.19 are explained below:

G_f: is the area of the load vs. vertical displacement curve divided by the area of the cracking face.
P/l: is the slope of the load-displacement curve.
D: diameter.

L_{75}: the displacement at 75% of the peak load after the peak.
m_{75}: the slope of the tangential zone around the 75% peak load point after the peak; and
t: the thickness of the specimen

The CT-index is calculated using the Equations (2-2) and (2-3) below:

For 62 mm thick specimens:

$$\boldsymbol{CTindex} = \frac{G_f}{|m_{75}|} \times \left(\frac{L_{75}}{\boldsymbol{D}}\right)$$

(2-2)

For non-62 mm thick specimens:

$$\boldsymbol{CTindex} = \frac{t}{|62|} \times \frac{G_f}{|m_{75}|} \times \left(\frac{L_{75}}{\boldsymbol{D}}\right)$$

(2-3)

In this study, CT Index parameters were calculated using a code developed at OSU-AMaP. This code and the other software packages developed for the ODOT BMD process implementation are presented later in this report.

IDEAL-CT is a simple, practical, and rapid cracking performance test. It has been found to be sensitive to the volumetric properties of asphalt and often has a lower COV (<20%) that is better than many other traditional repeated load tests (Zhou et al. 2017). IDEAL-CT test results have been found to be highly correlated with the Texas OT and Illinois SCB (IFIT) tests. Zhou et al. (2017) used more than 25 mixtures to perform the correlation analysis of the tests. The tested asphalt mixtures were ranked based on their cracking resistance obtained from the three tests, and the resulting rankings were the same. Moreover, the IDEAL-CT has also been found to be correlated with the field performance of asphalt-surfaced pavements based on the data obtained from the Federal Highway Administration's accelerated loading facility (FHWA ALF) in McLean, Virginia.

2.2.2 IDEAL-RT

IDEAL Rutting Test (IDEAL-RT) was developed by Zhou et al. (2019) at Texas A&M University as a surrogate performance test to quantify the rutting resistance of asphalt mixtures. This test derives its concept from three-point bending and SCB tests and requires a testing frame similar to IDEAL-CT with a small modification. In IDEAL-CT, the boundary conditions of the test are provided by a rigid frame applying the load and a reaction frame in the opposite direction, as shown in Figure 2.18. The load and one-point support configuration create a dominant horizontal tensile stress in the sample, leading to cracking failure.

In IDEAL-RT, shear stress is introduced into the cylindrical sample by using two bottom supports, instead of one, as shown in Figure 2.20.

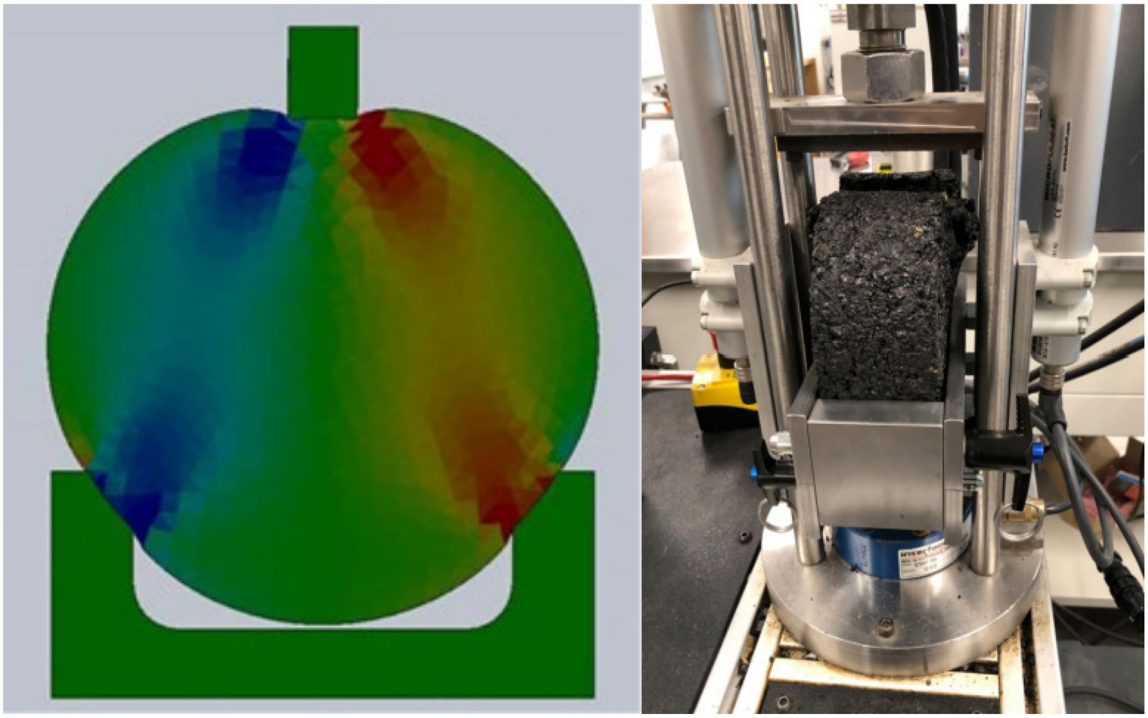


Figure 2.20: IDEAL RT test fixture and shear bands (shown in red and blue) formed due to the compressive load and two supports (Zhou 2021)

The compressive load applied from the top of the sample at the loading rate of 50 mm/min creates two shear bands on the sample, shown in red and blue colors in Figure 2.20. The test is conducted at 50ºC in Texas, and the test temperature can be modified depending on the regional conditions. The rutting parameter used in this test is Rutting Tolerance Index (RT_{Index}). The larger the RT_{Index} of the mix, the higher the rutting resistance. Both IDEAL-CT and IDEAL-RT involve simple test procedures and sample preparation processes. The samples to be tested can be prepared using a gyratory compactor and up to the required thickness without any need for cutting or trimming, unlike the SCB test or HWT test.

A correlation between IDEAL-RT and HWTT was developed in NCHRP 20-44 using 23 dense-graded mixtures, of which 11 were laboratory-mixed and laboratory compacted (LMLC) and the remaining 12 were plant-mixed and laboratory-compacted (PMLC). The test temperature for both the rutting tests was kept the same at 50ºC. To achieve better correlations, a new RRI parameter was defined as given in Equation (2-4) (Zhou 2021).

$$\boldsymbol{RRI = N^{0.3}\left(1 - \frac{\text{RD}}{25.4}\right)} \tag{2-4}$$

where,
RRI = Rutting resistance index.
N = 20,000, or the number of passes reaching 12.5-mm rut depth.
RD = Rut depth at 20,000 passes or 12.5 mm for those reaching 12.5-mm rutdepth before 20,000 passes.

As can be seen in Figure 2.21, a good correlation exists between IDEAL-RT and HWTT.

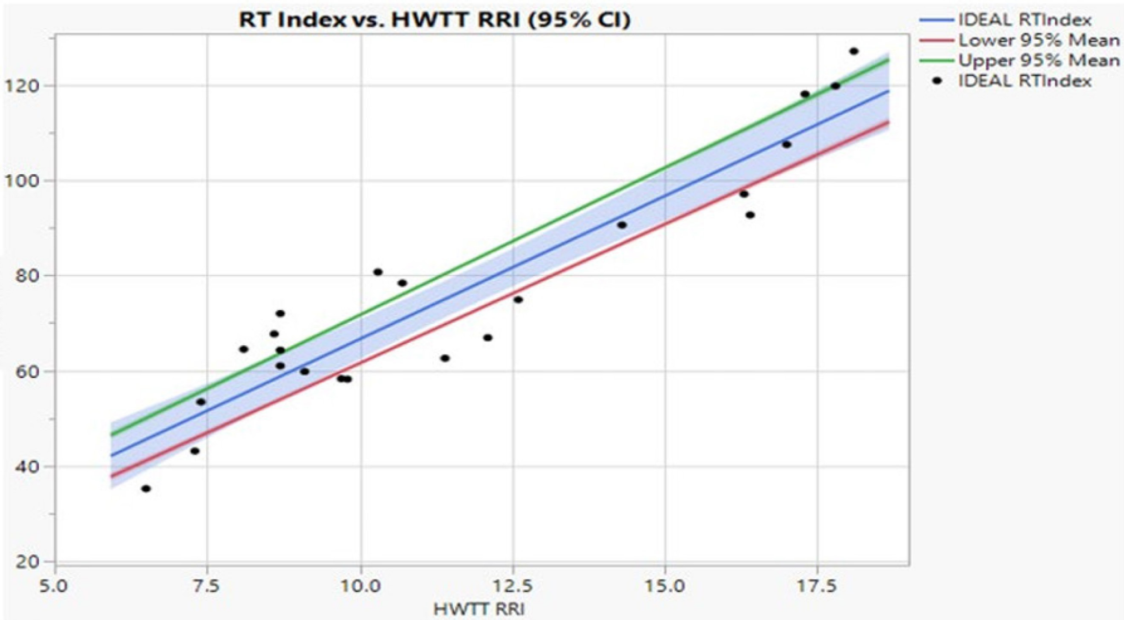


Figure 2.21: Correlation between IDEAL-RT and HWTT results (Zhou 2021)

In another study, Zhou et al. (2020) explored the relationship between IDEAL-RT and APA tests. A total of 18 mixes were selected for this purpose, differing in terms of binder type, aggregate types, gradations, and presence of RAP/RAS and rejuvenators. The test temperature for APA was 64ºC, and that for IDEAL-RT was 50ºC. The APA rut depth at 8,000 passes was compared with the average shear strength and the authors reported a good correlation between the two tests. However, the correlation was observed to be nonlinear. This nonlinear correlation suggests that the mix can be designed with an elaborate laboratory test (APA in this case), but IDEAL-RT can still be utilized as a production QC tool by using some conversion equations and models. **Since the major focus of the research study presented in this report is BMD, only HWT testing is used to evaluate the rutting resistance of asphalt mixtures.** However, the use of IDEAL-RT as a surrogate test in Oregon should be investigated in a future research study.

2.2.3 High-Temperature Indirect Tensile (IDT) Strength Test

High-Temperature Indirect Tensile (IDT) Strength test, or HT-IDT test, measures the shear strength of asphalt mixtures using the cohesion component instead of directly measuring shear strength as in IDEAL-RT. The HT-IDT strength is calculated using Equation (2-5).

$$\boldsymbol{HT-IDT\ Strength} = \frac{2 \text{ x Max Load}}{\pi \text{x D x H}} \qquad \textbf{(2-5)}$$

where:
HT-IDT Strength is in psi
Max Load is in pounds

D = average diameter in inches
H = average height in inches

This test is also simple, rapid, and repeatable, and has the potential to be included in production QC. Bennert et al. (2018) carried out a comparison between the APA tests and HT-IDT tests. NJDOT uses the APA tests for evaluating the rutting resistance of the mixtures, and they are conducted at 64ºC. For HT-IDT, Bennert et al. (2018) selected 54ºC as the test temperature. The results were also compared with the NCHRP Project 9-33 recommended HT-IDT strength threshold/acceptance criteria. The authors found a strong correlation between the two tests. Moreover, the COV for HT-IDT test results was 6.0% as opposed to 9.6% for APA test results (Bennert et al. 2018).

2.3 BMD IMPLEMENTATION EFFORTS IN OREGON

In this section, the tasks undertaken by ODOT in collaboration with OSU-AMaP and the asphalt paving industry to implement BMD in Oregon are described. Since Oregon is in the pre-implementation phase (see Figure 2.7), some of the tasks from Table 2.2 were conducted in this research project to prepare the entire process for the *"Initial Implementation"* stage. The tasks completed in the previous ODOT research projects (SPR 785 and SPR 801) and those completed in this research project are given in Table 2.2. The tasks completed before this implementation project are summarized in this section, with the expected benefits of BMD and PBS in Oregon.

2.3.1 Potential Benefits of BMD for Oregon

In Oregon, asphalt cracking is the major distress mode, necessitating costly rehabilitation and maintenance at intervals of less than half of the intended design lives in some cases. The simple volumetric mix design process may not always result in consistently high performance for asphalt mixtures (Coleri et al. 2017b) since no experiment is conducted in the process to evaluate the rutting and cracking performance of the asphalt mixture. The increased usage of recycled asphalt with higher binder replacement rates also reduces the ductility of the asphalt mixtures used in construction. Thus, incorporating performance verification into the current asphalt mix design process in Oregon will help ODOT address the durability issues in the asphalt mixtures by validating or revising the OBC determined by the volumetric mix design. Another motivation for implementing BMD in Oregon is to mitigate distresses from moisture damage commonly observed on roadways in Oregon. ODOT has been using hydrated lime, WMA additives, and anti-stripping agents to combat these distresses. However, the effect of these additives on the mix design and performance remains unexplored. The BMD approach may help to determine the binder content that can counter these issues without jeopardizing the performance of asphalt mixtures. In addition, the impact of new rejuvenator technologies to increase asphalt pavement recycling in Oregon can be quantified by using the developed BMD and PBS methods.

Performance testing with the production mixtures can also help ODOT develop a comprehensive materials database that can ultimately be used to understand the benefits of several different strategies (different mix designs with several additive types at different RAP contents). The reasons for unexpected early failures on some roadway sections can be further explored by using the information from the developed database. The developed database can be a powerful resource for identifying material-level failures. Integrating this database with the structural pavement designs and the pavement management system can help understand the actual failure mechanisms for several roadway sections in Oregon. Based on the findings, mix and structural design methods can be updated to reduce premature pavement failures in the long run.

According to the 2020 ODOT Pavement Condition Report, the current ODOT pavement program is underfunded, which is expected to result in a decline in pavement conditions in Oregon within the next decade. An estimated $220 million a year in funding is needed to repair pavements that are in poor condition while providing timely preventative preservation and maintenance on roads in fair or better condition. However, pavement program funding levels after 2021 are planned to be around $107 million (expected 21-24 annual STIP funding) per year, according to the report, which is less than half of the needed funding level. For this reason, implementing innovative strategies for asphalt mixture design is critical to improving long-term pavement performance in Oregon.

2.3.2 BMD Implementation Tasks Completed in SPR785 and SPR801

OSU-AMaP has been working on the development of a BMD method and PBS for Oregon since 2015. There were multiple stages in this research effort, which are shown on a flowchart in Figure 2.22. ODOT research project SPR 785, completed in 2017, was the preliminary step towards the development of a BMD approach for Oregon. The research by Coleri et al. (2017b) achieved the following:

- *Chapter 3 in SPR785-Coleri et al. (2017b)* – The SPR 785 evaluated different tests (four tests for cracking) and data analysis methods for cracking performance quantification. The SCB test with the flexibility index parameter and the IDT test with the flexibility parameter provided results that are 95% correlated. However, since four specimens can be cut from one gyratory core for the SCB testing, it was recommended to be a more practical alternative, although all other factors for the IDT test with the flexibility index parameter (a parameter similar to the CT Index) were similar to the SCB with the flexibility index parameter. Based on the suggestions from ODOT and industry, the IDT test with a 62 mm-thick specimen from a Superpave Gyratory Compactor (SGC) will be used in this study. This suggestion was made to avoid any sawing and cutting at ODOT and industry laboratories, which also requires training and may result in safety issues. For all these reasons, OSU is going to use the IDEAL-CT test with the CT Index parameter for cracking performance evaluation. IDEAL-CT specimens are identical in shape to the IDT specimens evaluated in SPR785, and preparation does not require any sawing or cutting in the laboratory. The CT Index parameter is different from the flexibility index parameter used in SPR785. However, both the flexibility index and CT Index parameters must be highly correlated due to the similar processes followed for the calculation of these two parameters. A related manuscript was published in the *"International Journal of Construction and Building Materials"* (Sreedhar et al. 2018b).

- *Chapter 4 in SPR785-Coleri et al. (2017b)* – This chapter presented the impacts of various mixture properties on the cracking and rutting resistance of asphalt mixtures. The sensitivity of the recommended laboratory experiments in identifying the impact of several different mixture variables on performance was also investigated. The impact of dust content and dust-to-binder ratio on the cracking and rutting performance of asphalt mixtures was also discussed in this chapter. The major goal was to provide a better decision-making structure for the asphalt mixture design stage to address fatigue cracking susceptibility, with the intent of avoiding premature pavement failures. The related manuscript was also published in the *"International Journal of Materials in Civil Engineering"* (Sreedhar and Coleri 2018a).

Utilizing the above outcomes from SPR 785, the research project SPR 801 (Coleri et al. 2020) formulated the BMD approach suitable for Oregon conditions and mixtures. BMD conceptualization and development steps are shown in Figure 2.22 with all other steps. In SPR801, the research by Coleri et al. (2020) achieved the following:

- *Chapter 3 in SPR801-Coleri et al. (2020):* In this part of the study, the most effective asphalt mixture long-term aging protocol was developed to achieve reliable cracking performance parameters that are correlated with in-situ cracking performance. The developed aging protocol was integrated into the BMD procedure that was developed in Chapter 4. The related manuscript was also published in the *"International Journal of Pavement Engineering"* (Sreedhar and Coleri 2022).

- *Chapter 4 in SPR801-Coleri et al. (2020):* The main objective of this chapter was to develop a BMD framework to be used in asphalt mixture design. Based on the findings from all work listed above (SPR 785 and SPR 801), a BMD process was developed and proposed for Oregon. This part of the study also focused on the selection of the most effective test for rutting performance evaluation in Oregon. Based on the findings, the HWTT was recommended. The related manuscript was published in the *"Transportation Research Record, Journal of the Transportation Research Board"* (Sreedhar et al. 2021).

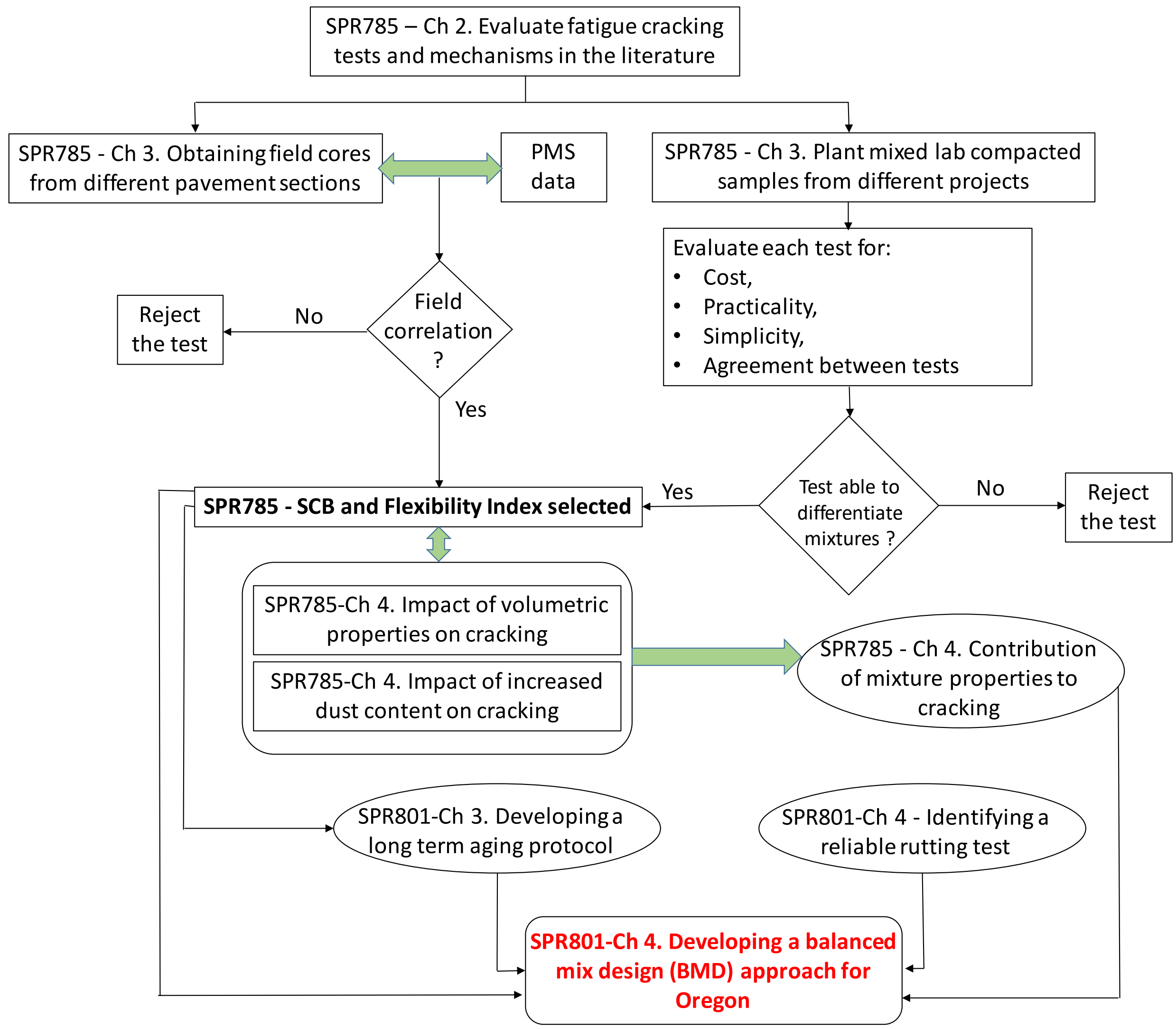


Figure 2.22: Flowchart for development of BMD approach for Oregon (Coleri et al. 2020)

2.4 SUMMARY

BMD is a recently developed mix design approach that determines the OBC based on the performance rather than the air voids, which is counted in the traditional volumetric mix design method. This approach has been adopted and further implemented by several DOTs. As per the literature review, the concept of BMD is valuable for designing mixtures that contain RAP material, modified binders, fibers, etc, for which the mix design is quite challenging. Currently, rutting and fatigue cracking are taken as the performance parameters for determining the OBC; however, in different BMD approaches, the asphalt mixtures designed at BMD OBC were also verified using the volumetric criteria. In BMD, binder content is provided in a range with balanced rutting and fatigue performance, thus imparting more flexibility in the selection of binder content than the traditional volumetric design. Various studies have stated that BMD is useful for producing long-lasting, cost-effective pavements.

Nevertheless, the selection of critical thresholds for determining OBC is not straightforward. This entails testing asphalt mixtures with different mix proportions, temperature conditions, binder grade, binder content, traffic conditions, etc., to benchmark the thresholds. Every state has its own specifications; thus, comprehensive experiments (in both laboratory and field) and parametric analysis are needed to develop the critical thresholds according to their state conditions, considering proper quality control and quality assurance. Apart from the testing and development of thresholds, the full implementation effort entails appropriate communication, training, and education activities for the contractors and engineers to make them understand the process of BMD and its benefits in making cost-effective decisions.

3.0 SENSITIVITY OF INDIRECT TENSILE CRACKING TEST (IDT-CT)

3.1 INTRODUCTION

Pavements are an essential part of the infrastructure, providing an interconnection between different parts of a nation. In the United States, around 94% of the pavements are paved with asphalt mixtures. These pavements, generally known as flexible pavements, are favored for medium to heavy traffic conditions due to their ease of construction, smooth rideability, and cost-effectiveness. Asphalt pavements are mainly composed of 93-95% mineral aggregates and 5-7% asphalt binder. To construct a conventional asphalt pavement, mineral aggregates and asphalt binder are heated, mixed, laid, and compacted to a particular density by following a mix design procedure. It is well known that the selection of these materials and the corresponding mix design considerably affect the durability of the asphalt mix. Over the decades, only the volumetric-mix design was adopted for the construction of asphalt pavements throughout the United States. However, the advent of new additives such as polymers, rubber, fibers, and warm mix additives, as well as the emphasis on the use of reclaimed asphalt material (RAM), has rendered the traditional volumetric mix design of asphalt mixtures inadequate (Newcomb and Zhou 2018). As a result, the need to incorporate performance tests in the mix design process and adopt a balanced mix design (BMD) approach is now widely recognized (Federal Highway Administration (FHWA) 2016). BMD is a step towards the design of pavement with balanced fatigue and rutting characteristics. It also satisfies the moisture sensitivity of the asphalt mixtures and volumetrics as per the requirements. The inclusion of performance tests was originally envisioned in the Superpave mix design in 1993, but it was never fully adopted by any agencies. The probable reasons for not adopting the BMD approach are high equipment cost, equipment complexities, and extensive time and labor requirements. However, with the recent technologies and developments, research and implementation efforts have recently gained momentum in this direction (Easa 2019; Hajj et al. 2021; Hajj and Aschenbrener 2021; Sreedhar et al. 2021; Veeraragavan et al. 2022).

One of the major challenges in adopting and implementing the BMD process is the selection of performance tests and the corresponding performance thresholds for rutting and cracking evaluation. So far, the state highway agencies (SHAs) and the asphalt paving industry have considered various cracking and rutting tests for BMD implementation. Examples include Direct Tension Cyclic Fatigue (DTCF) test, Disc-Shaped Compact Tension (DCT) test, Single-Edge Notched Beam Test (SENB), Flexural Bending Beam Fatigue (BBF) test, Illinois Flexibility Index Test (I-FIT), Indirect Tensile Cracking Test (IDT-CT) (formerly called IDEAL-CT), Overlay Test (OT), Semi-Circular Bend (SCB) test, Asphalt Pavement Analyzer (APA), Asphalt Mixture Performance Tester (AMPT), Hamburg Wheel Tracking Test (HWTT), Stress Sweep Rutting (SSR) Test and Indirect Tensile Rutting Test (IDT-RT). An overview of these test methods was presented by Zhou et al. (2020). Each test method has its own test attributes, such as sample dimensions, test temperatures, conditioning period, loading rate, and air voids, which lead to variations in performance characteristics. Some tests that have shown promising results in the laboratory may not be implemented for routine mix design due to practicality and cost issues. Such tests may also not be incorporated in quality control/quality assurance (QC/QA) because of the slow turnaround of results. Moreover, to ensure the robustness and ruggedness of the test, factors such as simplicity, practicality, efficiency, cost, repeatability, the sensitivity of mix properties, and correlation with field performance are important considerations (Coleri et al. 2017; Yin et al. 2020; Zhou et al. 2016).

Oregon is in the pre-implementation phase of BMD, and the Oregon Department of Transportation (ODOT) has been working on the development of a BMD method since 2015 in collaboration with Oregon State University (OSU). Coleri et al. (2017) and Sreedhar et al. (2018b) evaluated different test and data analysis methods for cracking and rutting performance quantification. The SCB test and the Indirect Tensile (IDT) test, both using the Flexibility Index (FI) parameter, showed a strong correlation with a 95% agreement in results. While the SCB test is considered more practical, allowing four specimens to be cut from a single gyratory core, both tests yielded similar outcomes. However, based on feedback from ODOT and industry partners, Oregon will adopt the IDT Cracking Test (IDT-CT) with the Cracking Tolerance Index (CT Index) for evaluating cracking performance. This decision aims to eliminate the need for sawing and cutting in laboratories, thereby reducing safety concerns, dust control issues, and training requirements.

The IDT-CT test procedure is laid out in ASTM D8225 (2019). It is a simple, practical, and rapid cracking performance test (Castillo-Camarena and Hall 2021). It is sensitive to the volumetric properties of asphalt and often has a lower coefficient of variation (COV) (<20%) that is better than many other traditional repeated load tests (Zhou et al. 2017). This test has also been found to be sensitive to the loading equipment, aging conditions, conditioning methods, and the specimen's air voids, among other factors (Elkashef et al. 2022; Habbouche et al. 2023; Wilhelm 2002; Zhou et al. 2017). These factors will play a crucial role in the QC/ QA program as samples will be prepared and tested in different laboratories. Another potential concern that has not been considered in the literature is the sample sitting time, i.e., the time that lapsed between the production of the sample and the cracking test. Thus, it is important to investigate the sensitivity of this test to the factors mentioned above before implementing it in Oregon. The primary objectives of this work are as follows:

- To identify the effect of test variables such as different aging conditions, temperature conditioning methods, sample sitting time, and device type on the IDT-CT results.
- To recommend the most suitable testing approach and process based on a ranking framework.

The present chapter involves testing two different plant-produced asphalt mixtures with different mix attributes. This study also conducted a statistical analysis to identify the difference in the testing approaches mentioned above. The output of this study would provide insight to the DOTs and concerned asphalt industries for conducting IDT-CT in a more suitable setting and process, which will result in less variability in test results.

3.2 MATERIALS AND METHODS

Loose production mixes were sampled in cardboard boxes from two construction projects before construction and brought to the laboratory. The asphalt binder contents of Mix 1 and Mix 2 were 5.7% and 6.1%, and the asphalt binder grades were PG76-22ER and PG70-28ER. These two binder types have polymer modification and are commonly used for construction in Oregon. In Oregon, Level 3 mixes are designed with 80 gyrations and are intended for use in pavements exposed to moderate to high truck traffic, ranging from 3 to 30 million equivalent single axle load (ESALs). On the other hand, Level 4 mixes are designed with 100 gyrations and are specifically designed for application on high-volume state highways and interstates with traffic exceeding 30 million ESALs. Mix 1 was a Level 4 ½" (12.5mm) dense graded mix, and Mix 2 was a Level 3 ½" (12.5mm) dense graded mix. The aggregates used in Oregon are generally defined as one type with almost one morphological characteristic: Oregon Basalt gravel. The theoretical maximum specific gravity (Gmm) of the sampled mixtures used for the weight calculation of the mixes was 2.466 for Mix 1 and 2.476 for Mix 2. As discussed in the subsequent section, this production mix was used for fabricating plant-mixed and laboratory-compacted (PMLC) specimens.

3.2.1 PREPARATION OF PMLC SPECIMENS

The loose material in the cardboard box was heated and split into specimen masses (using a splitter system) to achieve a more uniform mixture gradation by reducing segregation. These loose mixtures were then subjected to the long-term aging (LTA) protocol developed for Oregon mixes by Sreedhar and Coleri (2020). After LTA (24 hours at 95 °C), the mixtures were further heated at the compaction temperature for two hours. In previous studies (Sreedhar et al. 2018a, 2021), Superpave gyratory compacted samples of 150 mm diameter and 50 mm height were prepared for the IDT test. However, in this study, the specimen thickness was increased to 62 mm, consistent with the ASTM D8225 (2019) standard.

3.2.2 TEST METHODS

3.2.2.1 IDT-CT

Samples measuring 62 mm in height were compacted to 7±0.5% air voids in the laboratory, according to AASHTO T 312 (2019). Tests were conducted at 25°C with a 50 mm/min displacement rate as per ASTM D8225 (2019). The primary output of this test method is the "CT-Index", which was calculated as per the Equation (3-1) for 62 mm compacted asphalt mixtures. The CT-Index is a commonly used parameter whose higher value implies better-cracking resistance of the asphalt mixtures and, consequently, lower cracking in the field (Albayati et al., 2023). CT-Index was evaluated using different testing approaches described in the subsequent sections.

$$\boldsymbol{CT\ Index} = \frac{\mathrm{G_f}}{|\mathrm{m_{75}}|} \times \left(\frac{\mathrm{L_{75}}}{\boldsymbol{D}}\right) \tag{3-1}$$

Where
G_f: is the area of the load vs. vertical displacement curve divided by the area of the cracking face,
D: diameter,
L_{75}: the displacement at 75% of the peak load after the peak, and
m_{75}: the slope of the tangential zone around the 75% peak load point after the peak.

This study calculated the CT-Index parameter using a software package developed at Oregon State University (OSU). The software utilizes the load and displacement data to calculate different parameters of IDT-CT test. These test parameters include: IDT strength, fracture energy, fracture work, post-peak behavior at 75% peak load, displacement at 75% peak load, and CT Index. Figure 3.1 shows a screenshot of the final output file for any given asphalt mixture evaluation. The complete user manual of the developed software can be found in Appendix A of the report.

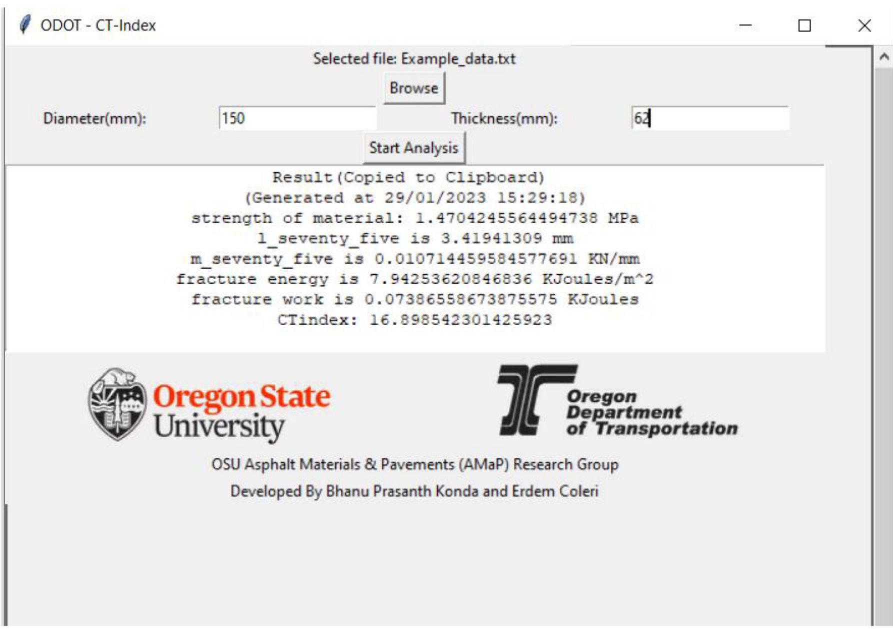


Figure 3.1: Screenshot of CT Index software final output

3.2.2.2 EXPERIMENTAL DESIGN

This study compared the impact of using different device types, temperature conditioning methods, aging methods, and sample sitting times on IDT-CT test results. This comparison serves as an indication of the sensitivity of IDT-CT to the factors mentioned above. The research outline of the present study is designed to improve processes in a QA/QC program. A cost-effective testing approach is a major factor that needs to be considered in this study. Therefore, a low-cost load frame (similar to the load frames used in the old Marshall mix design method) was used to test the samples of the remaining testing approaches. The test matrix adopted in the present study is shown in Table 3.1, and all the test approaches are further described in Table 3.2 for clarity. It should be noted that the CT-Index was determined using both UTM (Figure 3.3a) and load frame (Figure 3.3b), which are further compared with each other. Following the comparison of

CT-Index values, a statistical analysis was performed to determine whether the results were significantly different. Lastly, the ranking of test approaches was done considering the coefficient of variation between the results and the percentage difference in the average CT-Index value relative to those obtained from UTM. shown in Figure 3.2. For all the testing approaches, the value of CT-Index evaluated using the Universal Testing Machine (UTM) was taken as the reference in order to perform the sensitivity analysis. This reference was due to the expected higher accuracy, repeatability, and reliability of the UTM in the cracking test (Sreedhar et al. 2021; Walubita et al. 2014). However, UTM is costly, and incorporating this loading equipment in a balanced mix

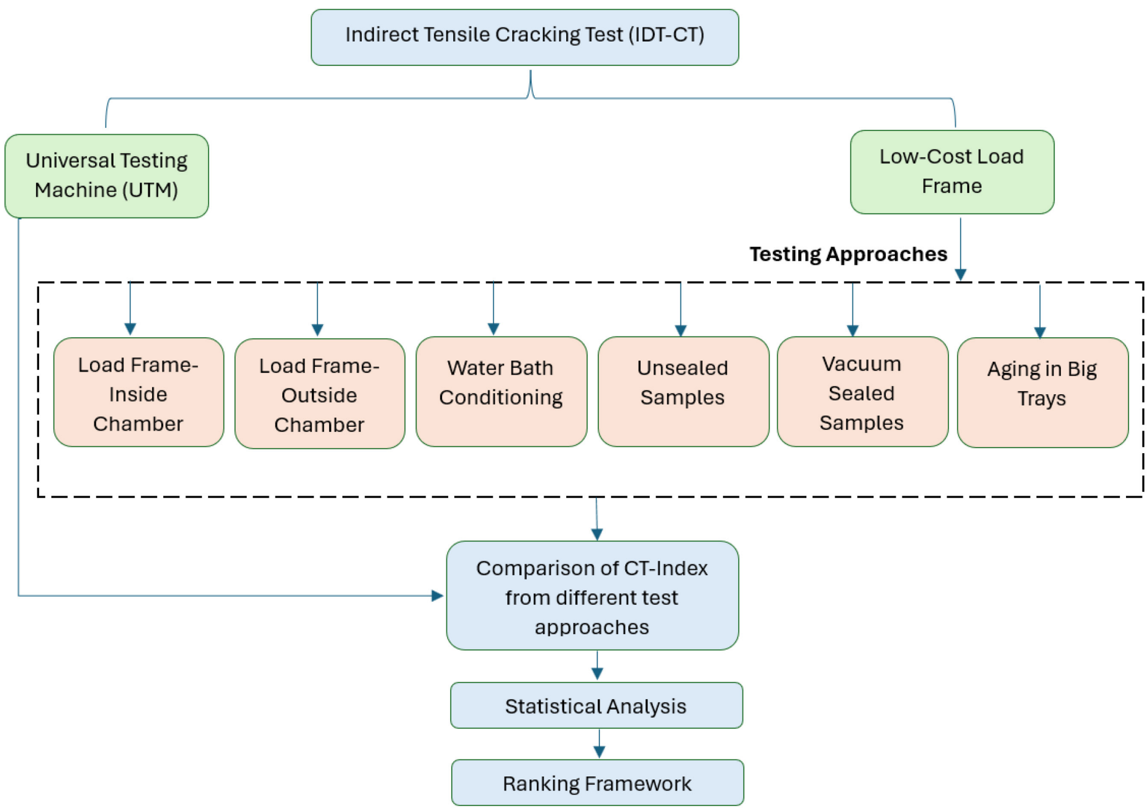


Figure 3.2: Experimental Plan

(a) **(b)**

Figure 3.3: Test Instruments (a) Universal Testing Machine (UTM), and (b) Lower cost load frame unit in an environmental chamber.

Table 3.1: Experimental plan to compare different testing, temperature conditioning, and specimen preparation approaches

No.	Testing Approach	Conditioning Temp.	Test System Used	Mix Type	Sample Sitting Time (No. of days between sample production and test)	Replicates
1	Universal Testing Machine (UTM) (Reference Approach)	25°C	UTM	Mix 1, Mix 2	3	5
2	Load Frame-Inside Chamber	25°C	Load Frame	Mix 1, Mix 2	3	5
3	Load Frame-Outside Chamber	Room Temp.	Load Frame	Mix 1, Mix 2	3	5
4	Water Bath Conditioning	25°C	Load Frame	Mix 1, Mix 2	3	5
5	Unsealed Samples	25°C	Load Frame	Mix 1, Mix 2	14	5
6	Vacuum Sealed Samples	25°C	Load Frame	Mix 1, Mix 2	14	5
7	Aging in Big Trays	25°C	Load Frame	Mix 1, Mix 2	3	5

Note 1: All samples were conditioned for 2 hours at 25°C before testing except #3, which is a room temperature test condition.
Note 2: Mix 1 was produced using PG76-22ER, while Mix 2 includes PG70-28ER.

Table 3.2: Rationale behind different testing approaches

No.	Testing Approach	Description
1	Universal Testing Machine (UTM)	Three days after the specimen production (two days after density measurement), specimens were placed in the UTM chamber and conditioned for two hours at 25°C before starting the test. The results obtained from UTM were taken as a reference (ground truth) to compare the output of different test approaches.
2	Load Frame-Inside Chamber	Three days after the specimen production, specimens were conditioned in a temperature-controlled chamber for two hours at 25°C. The load frame was also placed inside the chamber, and the specimens were tested in the load frame (Figure 3.3a).
3	Load Frame-Outside Chamber	The specimens were not subjected to any temperature conditioning and were directly tested in the load frame after production and density measurement at room temperature. Although the temperature of the room was controlled, it generally ranged from 20 °C to 28 °C throughout the year due to seasonal temperature variations.
4	Water Bath Conditioning	Three days after the sample production, specimens were conditioned in the water bath for two hours at 25°C. After removing them from the water bath, the specimens were immediately tested in the load frame.
5	Unsealed Samples	After the production and density measurement, the specimens were left sitting in the laboratory for two weeks (14 days) at room temperature. After two weeks, specimens were conditioned in a temperature-controlled chamber for two hours at 25°C before starting the test in the load frame.
6	Vacuum Sealed Samples	Same as #5, except that the specimens were placed in plastic bags and the bags were vacuumed and sealed to prevent exposure to air.
7	Aging in Big Trays	The loose asphalt mixtures were spread out in a single layer in big trays (26”x18”x3”) for more uniform heating during the LTA process and to avoid any periodic manual stirring of the mixtures required in standard-size trays (20”x12”x4”). The prepared specimens were tested in a load frame after conditioning them in a temperature-controlled chamber for two hours at 25°C.

Before testing, all the samples were dried for two days after measuring density by the saturated surface dry (SSD) method, according to AASHTO T 166 (2016). The entire process, from the splitting of the mix to the testing of samples, is shown as a flowchart in Figure 3.4.

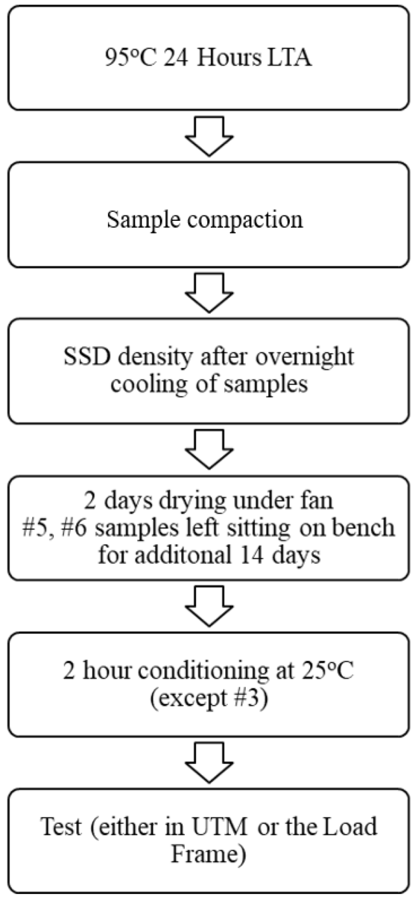
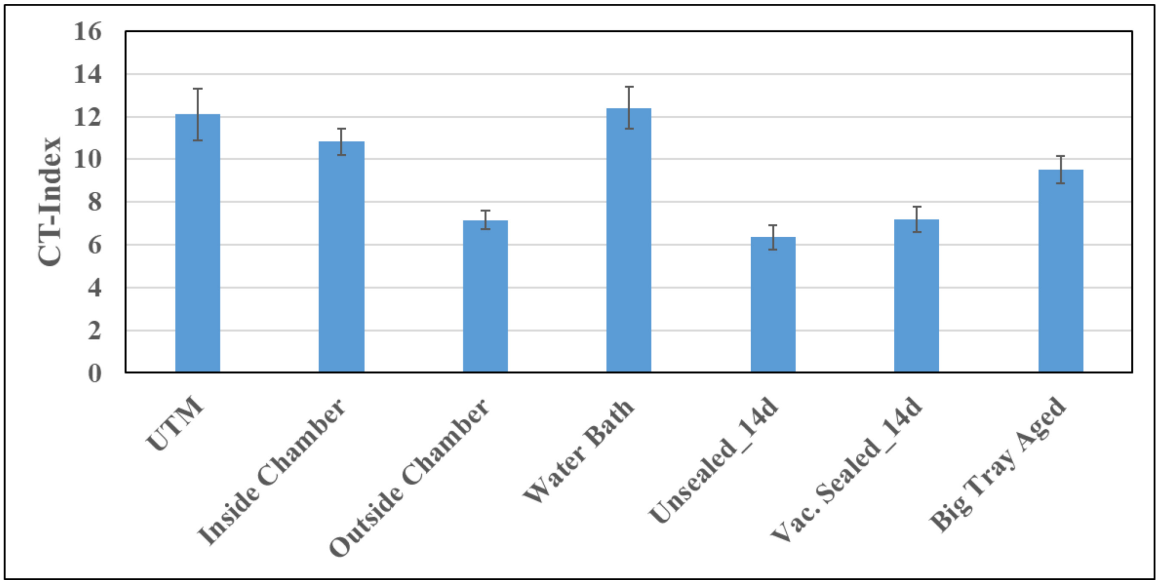


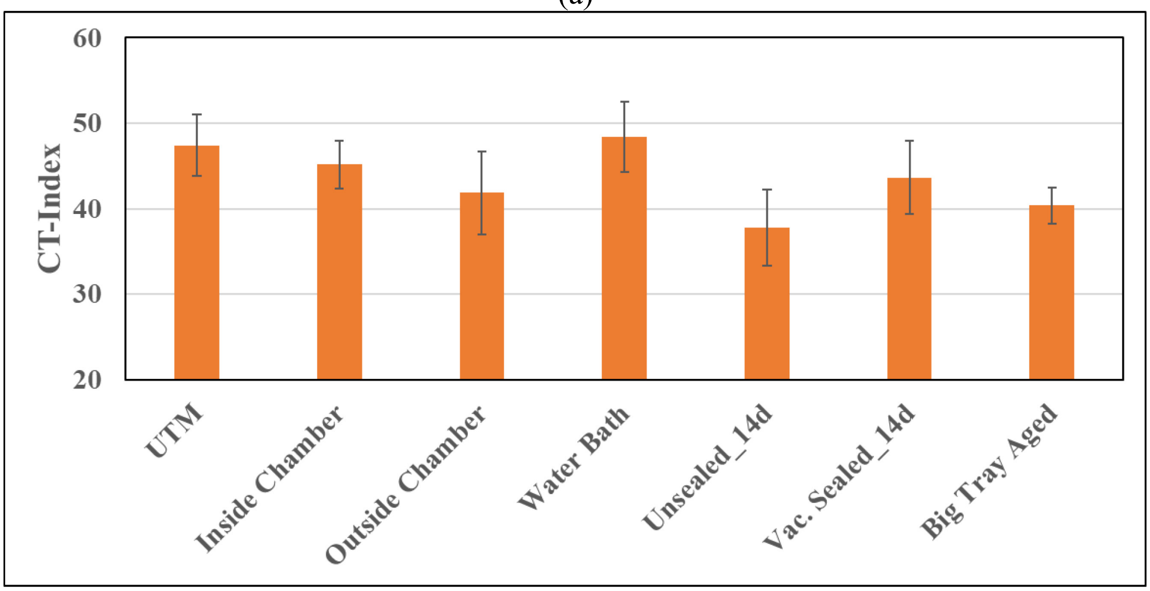
Figure 3.4: Flowchart of the steps followed in the experiment

3.3 RESULTS AND ANALYSIS

Loose production mixtures were sampled, split, and weighed into predetermined sample quantities. The fabricated IDT-CT samples were then subjected to different testing approaches and were eventually tested in either the UTM or the Marshall load frame as per the experimental plan. To eliminate any possible operator bias, all the tests were carried out by a single operator. One outlier from each set exhibiting a very high or low CT-Index value was excluded from the obtained results. The average CT-Index values for each testing approach are shown in Figure 3.5(a) for Mix 1, and Figure 3.5(b) for Mix 2.



(a)



(b)

Figure 3.5: IDT-CT test results for different testing approaches (length of the error bar is qual to one standard deviation) (a) Mix 1 (PG76-22ER) (b) Mix 2 (PG 70-28ER)

It can be observed from Figure 3.5 that for both the mixes, the average CT-Index values obtained from all the testing approaches tested in the load frame were found to be lower than those in the UTM. The only exception to this observation is the water bath conditioning approach. Nevertheless, the slightly higher average CT-Index of the water bath-conditioned samples can be due to water ingression in the samples, resulting in plastic deformation and creep (Dave et al. 2018) and not an accurate representation of fracture energy parameters. Irrespective of the mix type, the lower CT-Index was obtained for the samples placed at room temperature for 14 days. The lower CT-index was attributed to the atmospheric aging of the asphalt mixtures, resulting in stiffening of the asphalt binder and eventually lower cracking resistance. Consistent trends were observed in both mixes, with Mix 2 having higher CT-indices values, approximately four times higher than Mix 1. The reason behind this can be the higher binder content (6.1%) and softer binder grade (PG70-28ER) of Mix 2 than Mix 1 (5.7% binder content and PG76-22ER binder grade), although the comparison of the two mixes' cracking resistance is outside this study's scope.

Among all the testing approaches, the results obtained from the 'Inside Chamber' and 'Water Bath' methods are close to the reference UTM test results. In the 'Inside Chamber' testing approach, the samples were dry conditioned inside a temperature-controlled chamber at 25ºC. The UTM also has a similar conditioning process in the form of an environmental chamber. 'Outside Chamber' samples were not conditioned at 25ºC for 2 hours before the IDT-CT but were kept at room temperature. The low average CT-Index value for this testing approach indicates the importance of the conditioning process in a temperature-controlled environment. Therefore, it can be said that the load frame serves as a low-cost alternative to the expensive UTM assembly, provided a 2-hour at 25 °C (either dry or wet) conditioning protocol is followed before the test.

From the perspective of sample sitting time, the test results of the two approaches, 'Unsealed_14d' and 'Vac. Sealed_14d' shown in Figure 3.5, revealed that the sample sitting time plays a significant role in controlling the asphalt mixtures' cracking resistance. The average CT-Index value of the unsealed samples kept at room temperature for two weeks was comparatively lower than those kept sealed in a vacuum bag for the same period. This may be attributed to the over-atmospheric (oxidation and volatilization) aging of the unsealed samples, which results in the stiffening of the mix and, consequently, a lower CT-Index. Overall, both these testing approaches resulted in lower CT indices compared to other approaches. Although keeping the samples in a vacuum-sealed bag helps reduce the level of aging, some level of aging is still evident in the test results for the vacuum-sealed specimens, as proven by the CT-Index values lower than those of the UTM case. For this reason, it is recommended in this study that the produced samples must be tested within the first 3 days (including production, air void measurement, and drying of the sample), and testing should not be delayed for any reason. Using the test results from specimens kept in the laboratory for different durations after specimen production can result in significant levels of bias and may introduce significant errors in the balanced mix design methods. Similar variations may arise with the use of an aging tray with different dimensions in a single project. In this study, large-sized aging trays (26"x18"x3") were used to identify the effect of tray dimensions on the CT-Index of the asphalt mixtures. A lower CT-Index was observed with the use of big aging trays, indicating a higher aging effect during the LTA process. However, big trays result in a more uniform heating and aging effect as compared to the small trays. In addition, it avoids any periodic manual stirring of the mixtures, which is required in small-sized aging trays. Considering such variation, it has to be noted that a single tray dimension (particularly the big tray with dimensions: 26"x18"x3") should be used for all sample preparations to avoid any discrepancies in the results.

In order to determine whether the testing approaches considered in this study yielded significantly different CT-Indices, a Welch-modified two-sample t-test was performed between each approach. Suppose that the two mean CT indices for the testing approaches under comparison (say μ_1 and μ_2 are two mean CT-Indices) can be represented by the following null and alternative hypotheses:

$$H_0: \mu_1 = \mu_2$$

$$H_A: \mu_1 \neq \mu_2$$

A decision rule was adopted for the two-sample t-test. The decision rule is as follows:

- Reject H_0 if $p < 0.05$
- Fail to reject H_0 if $p \geq 0.05$

In the case where the null hypothesis was rejected (when the p value is less than 0.05), it was concluded that the mean CT-indices under comparison were significantly different from one another. Table 3.3 and Table 3.4 show the p-values returned for the two-sample t-test for each evaluated case at a 95% significance level for both Mix 1 and Mix 2, respectively.

Table 3.3 P-values from the two-sample t-test comparing the average CT-Index of each test case for Mix 1.

S. NO.	1	2	3	4	5	6	7
1	**1.0000**	0.3418	0.0072	0.8381	0.0032	0.0068	0.076
2		**1.0000**	0.0033	0.2351	0.0017	0.005	0.1627
3			**1.0000**	0.0084	0.2858	0.9516	0.0118
4				**1.0000**	0.0037	0.0067	0.0538
5					**1.0000**	0.3351	0.006
6						**1.0000**	0.0265
7							**1.0000**

Table 3.4 P-values from the two-sample t-test comparing the average CT-Index of each test case for Mix 2.

S. NO.	1	2	3	4	5	6	7
1	**1.0000**	0.5450	0.3204	0.8263	0.0643	0.4165	0.0692
2		**1.0000**	0.5225	0.4337	0.1153	0.716	0.1155
3			**1.0000**	0.2656	0.4815	0.7543	0.7568
4				**1.0000**	0.0553	0.3391	0.0674
5					**1.0000**	0.2576	0.5252
6						**1.0000**	0.4124
7							**1.0000**

From Table 3.3 and Table 3.4, it can be observed that both mixes #2 (Inside Chamber) and #4 (Water Bath) are closest to #1 (UTM) according to the t-test results (high p-values mean more similarity in the evaluated two cases). However, the water bath approach gives results slightly higher than the reference UTM approach (Figure 3.5), making it less conservative. #2 or the Inside Chamber approach is showing results close to the UTM results, and it is also more on the safe or conservative side (CT-Indices less than UTM results). There is also a statistical similarity between #5 and #6, as evidenced by high p-values for both mixes. The only difference between the two approaches was sealing the sample in a vacuum bag for #6. The average CT indices from the two approaches are also comparable, as shown in Figure 3.5. This indicates that vacuum sealing and testing the sample after a considerable time lapse is not an effective approach, even though it is a better approach than testing the unsealed sample after the same duration of time-lapse. Thus, samples must be tested within the next 1-2 days after production without waiting for extended periods.

3.3.1 RANKING FRAMEWORK

Based on the above results, selecting the most suitable testing approach is crucial for implementing IDT-CT as a balanced mix design and QA/QC test method. Therefore, an average ranking approach was adopted to rank different testing approaches based on two ranking predictors. A similar approach for ranking different asphalt mixtures can be found in the literature (Choudhary et al. 2020; Saboo et al. 2018; Sukhija et al. 2023a; Sukhija et al. 2023b). The ranking predictors considered in this study were the percent difference in the average CT-Index value of any testing approach concerning that of the UTM approach (% difference) and the coefficient of variation (COV) between the results of all the approaches except UTM tests because the variation with respect to the UTM results was already considered in the % difference ranking predictor.

The ranking framework utilized in this study is described in this section. The ranking of the approaches will change depending on the ranking predictor considered. A unique rank was assigned to each testing approach based on the value of each ranking predictor. The range of the rank values for each predictor is from 1 to 6, since there are six different approaches, excluding the UTM approach. Furthermore, a lower rank number indicates a better (more similar to the UTM results) testing approach for each ranking predictor. For example, rank 1 based on % difference ranking predictor means that the corresponding testing approach has the smallest percent difference in the mean CT-Index relative to the mean CT-Index of the UTM samples.

Similarly, rank 1 based on the COV ranking predictor indicates that the corresponding testing approach has the least COV value among all the testing approaches. Once the ranks were assigned to the testing approaches based on both the ranking predictors, those ranks were summed to obtain Σ Rank. The testing approaches are again ranked based on the Σ Rank value. This final ranking, based on the sum of the ranks, is called the average rank value (ARV). ARV was calculated for both mixes, as shown in Table 3.5. The ARVs of the two mixes were summed algebraically, and the resulting values were used to further rank the testing approaches. This final rank value, or Global Rank, is independent of other factors and can be used to determine the most suitable testing approach among all the strategies.

Table 3.5: Ranking of different testing approaches

Testing Approach	Load Frame-Inside Chamber	Load Frame-Outside Chamber	Water Bath Conditioning	Unsealed samples	Vacuum sealed	Aging in Big Trays
MIX 1 Ranking Predictors (% Difference)	10.46	40.91	2.56	47.56	40.54	21.38
MIX 1 Ranking Predictors (CoV)	11.26	11.97	16.02	17.76	16.19	13.68
MIX 1 $RV_{\% \text{ Difference}}$	2	5	1	6	4	3
MIX 1 RV_{CoV}	1	2	4	6	5	3
MIX 1 Σ Rank ($RV_{\% \text{ Difference}} + RV_{CoV}$)	3	7	5	12	9	6
MIX 1 ARV (rank based on Σ Rank)	**1**	4	2	6	5	3
MIX 2 Ranking Predictors (% Difference)	4.71	11.65	2.03	20.33	7.90	14.85
MIX 2 Ranking Predictors (CoV)	12.29	23.14	17.04	23.71	19.84	10.40
MIX 2 $RV_{\% \text{ Difference}}$	2	4	1	6	3	5
MIX 2 RV_{CoV}	2	5	3	6	4	1
MIX 2 Σ Rank ($RV_{\% \text{ Difference}} + RV_{CoV}$)	4	9	4	12	7	6
MIX 2 ARV (rank based on Σ Rank)	**1**	5	1	6	4	3
Global Rank Σ ARV (ARV (Mix1) + ARV (Mix 2))	2	9	3	12	9	6
Global Rank	**1**	4	2	6	4	3

Note: RV indicates the rank value and ARV denotes the average rank value

The ranking of the testing approaches for each mix changed with the different ranking predictors. While the water bath conditioning approach ranked higher than other approaches as per the % difference ranking, it ranked low when the repeatability of the test was considered in terms of the COV ranking. These observations are consistent for both the mixes used in this study. However, the overall ranking (i.e., Global Rank) indicated that 'Inside Chamber' is the most suitable approach as it ranked superior to its counterparts. Testing the samples in a load frame by conditioning them in a controlled-temperature chamber ranked 1 among the other strategies. As discussed before, this ranking methodology incorporates the variation of the results compared to the UTM and the repeatability compared to the other testing approaches. Since IDT-CT is a quick test, the load frame can also be kept outside the temperature-controlled chamber for testing the conditioned samples without any concern for a change in the test temperature of the specimens. This process makes the temperature conditioning in a smaller/low-cost chamber possible and improves practicality. As per the results, conditioning the specimens in a water bath and testing them in the load frame is another testing approach that can be adopted. Both these approaches are also more feasible options for implementation as a QC/QA tool compared to the UTM test system.

Figure 3.5 and Table 3.5 also highlight the relationship between tray dimensions and aging behavior in loose asphalt mixtures. The placement of loose asphalt mixtures in bigger trays (26"x18"x3") is associated with a more pronounced aging effect and a consequent reduction in CT-Index values. Moreover, the study demonstrates that the thickness of the loose asphalt mix within the trays plays a crucial role in controlling the aging process. **Consequently, to ensure the reliability and accuracy of the test outcomes, it is imperative to maintain consistent tray dimensions, as any variation in tray size may introduce aging-related bias in the test results.**

3.4 SUMMARY

This chapter compares different IDT-CT testing and specimen preparation approaches involving different device types, conditioning methods, aging methods, and sample sitting times. Two different asphalt mixtures were used for IDT-CT sample preparation. A simple ranking procedure and a Welch modified two-sample t-test were utilized for the comparison and sensitivity analysis. The major conclusions derived from this research work are as follows:

1. The IDT-CT results obtained from samples conditioned in either a temperature-controlled chamber or a water bath and tested in a load frame ('Inside Chamber' and 'Water Bath' approaches) were close to the reference UTM test results for both asphalt mixtures.

2. If the sample conditioning (either dry or wet) procedure is adopted, the load frame provides a low-cost alternative to the expensive UTM testing equipment.

3. Sample sitting time significantly affects the IDT-CT results. Irrespective of the mix type, a 2-week sample sitting time resulted in decreased CT-Index values of the samples of the same mix. Using the test results from specimens kept in the laboratory for different durations after specimen production can result in significant levels of bias and may introduce significant errors in the BMD methods.

4. Based on a simple ranking framework incorporating two ranking predictors – percent difference in the average CT-Index value of any testing approach concerning that of the UTM approach and coefficient of variation between the results of different approaches, testing the samples in load frame after conditioning them in a dry conditioning chamber can be considered as the most suitable testing approach with the lowest cost. Similar conclusions were also obtained statistically using the Welch-modified two-sample t-test.

5. The thickness of the loose asphalt mix in the tray controls the aging of the mix, and the size of the trays should not be varied to avoid any aging-related bias in the test results. Based on the obtained experimental results and ranking analysis, it is recommended to use bigger trays (26”x18”x3”) for more uniform heating and aging during the LTA process as compared to the small trays (20”x12”x4”).

4.0 BENCHMARKING THE PERFORMANCE OF ASPHALT MIXTURES FOR BALANCED MIX DESIGN (BMD) IN OREGON

4.1 INTRODUCTION

Asphalt pavements are meticulously engineered to endure heavy and repetitive vehicular loads in various environmental conditions. These pavements contain a heterogeneous blend of aggregates, binder, and recycled materials. The design process involves a systematic approach to determine the appropriate asphalt mixtures, layer thicknesses, and overall pavement structure. Achieving the optimal asphalt mix design entails selecting the proper aggregate gradation, asphalt binder type, and necessary additives or modifiers. The primary goal is to balance rutting resistance, increase fatigue tolerance and cracking resistance, enhance the pavement's durability, and prolong its lifespan. The asphalt content is an essential factor in attaining this balance. Deviating from the prescribed amount of binder can lead to pavement failure due to cracking or rutting (also called permanent deformation) distresses (Sreedhar et al., 2018a*)*. Moreover, introducing new modifiers and additives further complicates the mix design process, as it involves assessing their effects on performance characteristics (Sreedhar et al., 2021).

Until the early 1990s, asphalt mix designs relied on the Hveem and Marshall methods. However, these approaches lacked precision, leading to limited performance prediction and inaccuracies in assessing pavement fatigue life and cracking. Moreover, they did not explicitly account for the aging process of asphalt binders, which could impact long-term performance (Jianbing et al., 2018). To address these shortcomings, the Strategic Highway Research Program (SHRP) was initiated by FHWA between 1987 and 1993. The program aimed to design asphalt mixes tailored to specific traffic, climate, and material conditions to improve pavement durability. The SHRP mix design was categorized into three levels based on Equivalent Standard Axle Loads (ESAL). In simple words, ESAL is a concept used in roadway engineering to quantify the impact of different types of vehicles on the pavements. It expresses the damage caused by a vehicle as an equivalent number of standard 18,000-pound (single axle) load passes. This standardization helps in designing and evaluating pavement structures by comparing the effects of different vehicles based on their axle loads (Kawa et al., 1998).

The levels categorized by SHRP are Level II, Level III, and Level IV. A pavement with 20-year traffic of less than 1 million Equivalent Standard Axle Loads (ESAL) is classified as Level II. Level II focused on low traffic conditions, using empirical relations like voids in mineral aggregates and voids filled with asphalt for mix proportioning. The pavement with 20-year traffic between 1 million and 3 million ESAL is graded as Level III. This design level targeted roadways with moderate traffic and required a satisfying volumetric mix design, followed by a few performance tests. Meanwhile, pavements with traffic volume over 3 million were classified as Level IV. This Level of design targeted high traffic and included performance tests to evaluate mixes before paving. However, the complexity and high cost of these laboratory performance tests made them impractical for routine use, leading many transportation agencies to stick with just the basic volumetric mix designs. Although the solely volumetric-based design provided reasonable results for the simpler mixes of the past (less recycled asphalt, no additives, no fibers or other constituents), the new additives and complex asphalt binder types required the use of more comprehensive performance tests to evaluate and design today's high-performance asphalt mixtures. While the Superpave mix design method developed by the SHRP initiative improved rutting resistance, transportation agencies now identify fatigue and thermal cracking as primary sources of distress for asphalt pavements. Thus, there is a need to modify the volumetric mix design and develop practical and lower-cost testing methodologies to assess the long-term performance of asphalt mixes (West et al., 2018).

To integrate performance tests into the Balanced Mix Design (BMD) approach, researchers have developed and evaluated over a dozen tests to assess the cracking and rutting performance of asphalt mixes (Veeraragavan et al., 2022, Bowers et al., 2022, Zhou et al., 2017, Sreedhar et al., 2018b). For rutting, Hamburg Wheel Tracking Test (HWTT) is the most promising test method for assessing the rutting characteristics and is widely adopted throughout the globe. Based on the inferences shown in Chapter 3.0, IDT-CT can be considered a suitable test method for evaluating the cracking performance of asphalt mixes by testing the samples in a load frame after conditioning them in a dry conditioning chamber. The IDT-CT test's simplicity in sample fabrication and post-processing results has led some state Department of Transportation agencies (DoTs) to adopt it for evaluating the cracking performance of asphalt mixes (Veeraragavan et al., 2022; Bowers et al., 2022; Vivanco et al., 2022). Furthermore, the Oregon Department of Transportation (ODOT) is also considering using IDT-CT to quantify the performance of asphalt mixes.

Once the performance tests for evaluating asphalt mixtures are finalized, establishing specific thresholds becomes crucial to characterize the performance of the asphalt mixes. In 2015, the Maine Department of Transportation (Maine DOT) took the initiative to collect data from the Hamburg Wheel Tracking Test (HWTT) to create a substantial database for analysis. This dataset was then used to establish baseline thresholds. The researchers developed a parameter known as the normalized rutting resistance index (NRRI) based on the HWTT results. Asphalt mixtures with an NRRI value of less than 1 were identified as poor mixes with lower rutting resistance. Similarly, data analysis was conducted on the results of the IDT-CT test, which evaluates the cracking resistance of asphalt pavements. This analysis suggested a CT Index value of 150 as the threshold to classify the performance of asphalt mixes in Maine regarding their resistance to cracking (Veeraragavan et al., 2022). It has to be noted that the phenomenon of cracking generally occurs 5-6 years after the construction of the pavements. During this time, the asphalt pavement undergoes aging due to exposure to environmental conditions, resulting in stiffening of the binder. However, the long-term aging effect was not considered when determining the threshold of the asphalt mixes in Maine, which resulted in a very high CT Index (Veeraragavan et al., 2022). Hence, it is suggested that the asphalt mixes be subjected to a long-term aging process to evaluate the cracking performance in the laboratory.

Furthermore, the Connecticut DOT utilized field data from the pavement management system to establish thresholds for asphalt mix designs. They determined rutting along the wheel path as the critical parameter for threshold development. Asphalt pavements with rutting values less than 0.15 inches (3.81 mm) were classified as good performing, while those with rutting values exceeding 0.30 inches (7.62 mm) were labeled poor performers. For fatigue cracking evaluation, the percentage of cracking over the pavement was used as the baseline for thresholds (Mogawer et al., 2020). Similarly, the Virginia DOT conducted a research study to identify thresholds for characterizing asphalt mixtures in Virginia. They selected the Asphalt Pavement Analyzer (APA) and IDT-CT tests for performance measurement. According to the draft specification, recommended thresholds included an APA rutting value of less than 8.0 mm at 8,000 passes and a CT Index value of more than 70 (Bowers et al., 2022). Similar to the Maine DOT research work, the cracking performance of the asphalt specimens in this case was measured without following the long-term aging protocol. In Vermont, the Agency of Transportation employed the Hamburg Wheel Tracking Test (HWTT) to assess rutting resistance and the semi-circular bend Flexibility Index (FI) to evaluate cracking potential. A minimum FI value of 8 at 25°C was suggested for good performance. For HWTT, the rut depth for mixes with 50 and 65 design gyrations (a parameter from a laboratory compaction system correlated with the compactive effort during construction) should be less than 12.5 mm, while those mixes designed with 80 gyrations should have a rut depth of less than 6 mm for 20,000 passes to ensure long-term stability of the asphalt pavements (Mogawer et al., 2020).

As Oregon DOT has completed the finalization of performance tests to be integrated into the Balanced Mix Design (BMD) method (Sreedhar et al., 2018b), it is now imperative to establish specific thresholds for these tests to ensure the optimal performance of asphalt mixtures. The current study aims to determine Oregon's cracking and rutting thresholds, utilizing the IDT-CT and HWTT as performance evaluation methods, respectively. The results from IDT-CT and HWTT performed on 28 different plant-produced asphalt pavement projects in Oregon were provided by ODOT (tested by the ODOT Materials Laboratory in Salem, Oregon). A comprehensive statistical analysis was performed on these test results to determine the thresholds for performance parameters for upcoming BMD pilot sections. The established thresholds are essential in classifying the performance levels of asphalt mixes and guiding engineers in selecting appropriate mix designs that meet desired performance criteria. Balanced mix designs were developed for four projects using laboratory mixed and laboratory compacted (LMLC) specimens to validate these thresholds. By incorporating these performance tests and thresholds into the mix design process, ODOT intends to enhance the durability and longevity of asphalt pavements, ensuring they can withstand varying traffic conditions and environmental challenges across Oregon.

4.2 TEST METHODS

The Hamburg Wheel Tracking Test (HWTT) was utilized to assess the rutting performance of the asphalt mixtures. The newly developed IDT-CT test was used to conduct the cracking test and measure the susceptibility of the asphalt pavements to cracking failure. This section provides information on the test methods utilized in the current research study.

4.2.1 HAMBURG WHEEL TRACKING TEST (HWTT)

The Hamburg Wheel-Tracking Test (HWTT) system was developed to measure the rutting performance of asphalt specimens. The HWTT follows the AASHTO T 324 standard. According to the specification, a slab or a cylindrical specimen can be tested to assess the rutting performance. The current study conducted the test on cylindrical specimens measuring 150 mm in diameter and 62 mm in thickness. These specimens were later cut using a precision saw, and two specimens were connected edge to edge for the test, as shown in Figure 4.1. Tests were conducted by immersing the asphalt concrete sample in a hot water bath (at 50°C) and rolling a standard steel wheel across the sample's surface to simulate vehicular loading, as shown in Figure 4.2. Approximately 20,000 wheel passes are commonly used to evaluate the rutting resistance of a sample. The rut depth after 20,000 wheel passes was used to evaluate the rutting performance of the asphalt mixes. ODOT conducted HWTT tests on several projects, and the obtained results were further used for statistical analysis.

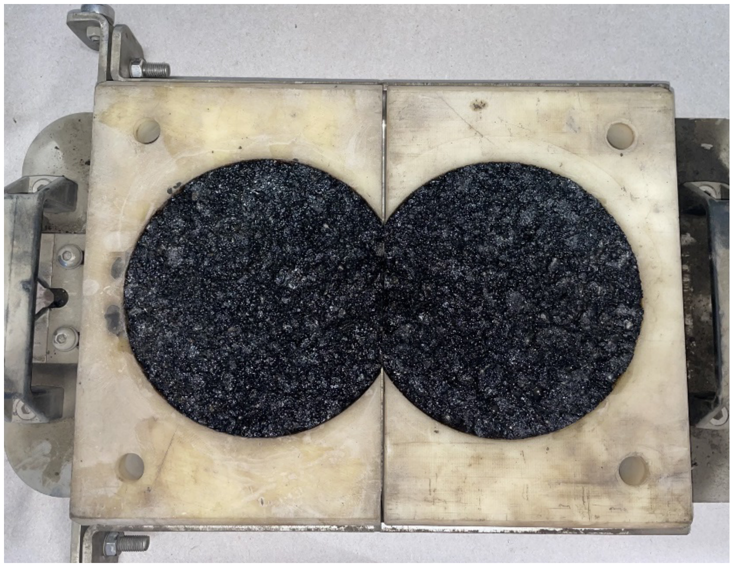


Figure 4.1: HWTT specimen in the mold.

Figure 4.2: HWTT set up.

4.2.2 INDIRECT TENSILE CRACKING TEST (IDT-CT)

The indirect tensile cracking test (IDT-CT) is a recently developed test to assess the cracking resistance of the asphalt mixtures. IDT-CT is conducted on the compacted samples to assess the susceptibility of asphalt mixtures to cracking by following the ASTM D8225-19. Figure 4.3 illustrates the test setup for the IDT-CT test. This test method utilizes cylindrical asphalt concrete specimens to determine the cracking tolerance index (CT Index) parameter from the load-displacement curve, as illustrated in Figure 4.4. Specimens with a diameter of 150 mm and a thickness of 62 mm were used for the test. After measuring the air voids, the specimens were conditioned at 25°C for 2 hours in the conditioning chamber and were instantly tested. A constant load line displacement rate of 50.0 ± 2 mm/min was maintained during the test. The post-peak slope of the load-displacement curve and deformation tolerance at 75% of the peak load were utilized to calculate the cracking tolerance index (CT Index) of the asphalt mixture. Six specimens were fabricated and tested for each binder content. Generally, a higher CT Index represents better cracking resistance (Zhou et al., 2017). Mathematically, the CT Index parameter is calculated by using the equation below (Equation (4-1)):

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

(4-1)

where:
CT Index = cracking tolerance index
G_f = failure energy (Joules/m^2)
$|m_{75}|$ = absolute value of the post-peak slope (N/m)
l_{75} = displacement at 75% of the peak load after the peak (mm)
D = specimen diameter (mm) and
t = specimen thickness (mm)

Figure 4.3: IDT-CT test setup.

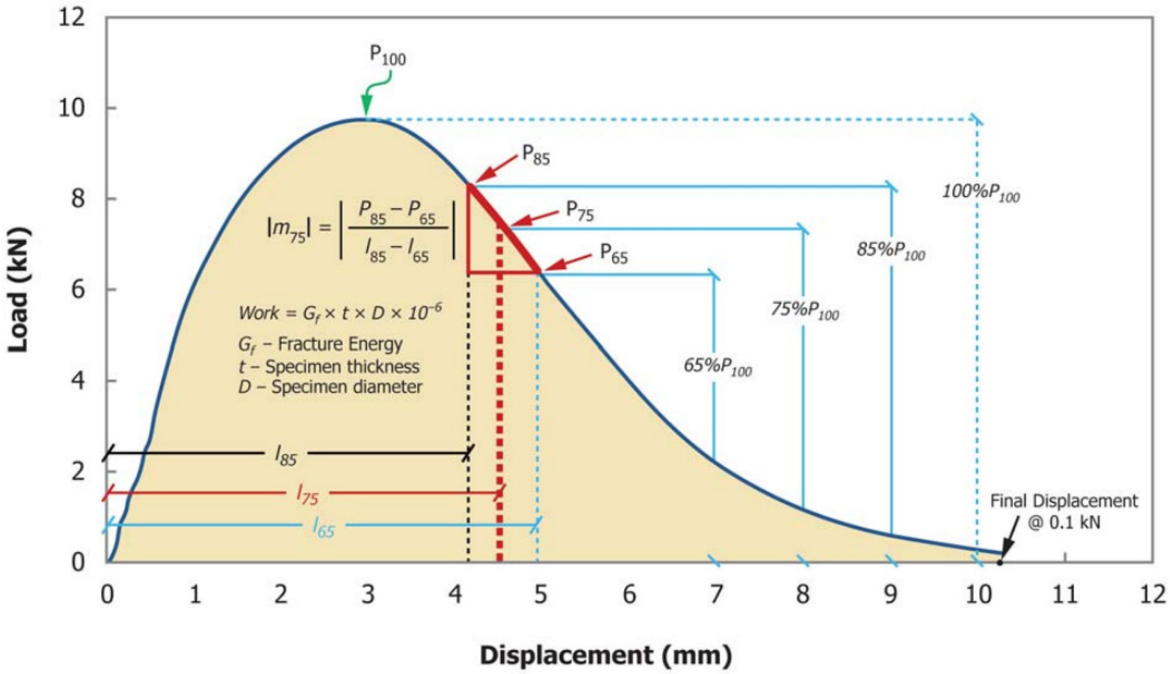


Figure 4.4: Load vs displacement curve from IDT-CT test (Zhou 2019a).

4.3 STATISTICAL ANALYSIS AND DISCUSSION

ODOT has been conducting IDT-CT and HWTT on asphalt mixtures from various projects since 2020. Loose asphalt mixtures (sampled from the plant during production for a construction project) were collected from the site and subjected to these tests. To ensure consistency, the loose mixtures were split and reheated at the compaction temperature to produce cylindrical specimens. Before compaction, the samples fabricated for IDT-CT tests were long-term aged at 95°C for 24 hours (Sreedhar et al., 2021). Meanwhile, the samples for HWTT tests were short-term aged for 2 hours at 135°C (Sreedhar et al., 2021). For each project, cylindrical specimens were compacted using the Superpave gyratory compactor, with the air voids controlled within an acceptable range of 7 ± 0.5%. The test results and other volumetric properties like mix type, binder grade, dust-to-binder ratio, effective asphalt content, and the amount of reclaimed asphalt pavement (RAP) were provided.

While ODOT currently does not have specific CT Index and HWTT rut depth requirements for asphalt mixtures, this study aims to establish appropriate CT Index and rut depth limits to classify the mixes' performance and incorporate these performance tests into the BMD approach. The data set used for establishing performance thresholds for BMD implementation is presented in Table 4.1. Data points from 28 projects were utilized for statistical analysis, providing a comprehensive dataset to determine the performance thresholds for the asphalt mixtures.

Table 4.1: Volumetric properties for projects analyzed in the present study.

Mix ID	Project Location	Level	Mix Type	AC	P_{200}/P_{be}	RAP
1	I-84: Meacham - Kamela	L2	3/8" D	PG64-28	1.54	30
2	OR140: Exit 35 - Blackwell Rd	L2	1/2" D	PG64-22	1.55	30
3	US395: Big Stick Creek - Alkali Lake	L2	3/8" D	PG54-34	1.19	30
4	OR42: Cedar Point Rd - Finley Lp	L3	1/2" D	PG64-22	1.63	30
5	US26: Necanicum - Nehalem	L3	1/2" D	PG64-22	1.42	30
6	US26 Hayward - Mountaindale	L3	1/2" D	PG64-22	1.4	30
7	OR42: Slater Creek - Hard Cash Lane	L3	1/2" D	PG64-22	1.36	30
8	OR140: Exit 35 - Blackwell Rd	L3	1/2" D	PG64-22	1.35	30
9	US101: Ecola Creek - Arcadia	L3	1/2" D	PG64-22	1.6	30
10	I-84: Meacham - Kamela	L3	1/2" D	PG64-28	1.35	30
11	OR58: Salt Creek Tunnel - MP 70	L3	1/2" D	PG64-28	1.57	30
12	US20: Warm Springs Rd. - Harper Junction	L3	1/2" D	PG64-28	1.33	0
13	I-84: Meacham - Kamela	L3	1/2" D	PG70-28ER	1.35	30
14	US26: Cornell - Sylvan	L4	1/2" D	PG70-22ER	1.47	20
15	US26: Weber - Cherryville	L4	1/2" D	PG70-22ER	1.39	20
16	I-5: Garden Valley - Roberts Creek	L4	1/2" D	PG70-22ER	1.4	20
17	I-84: Multnomah Falls - Toothrock Tunnel - Cascade Locks	L4	1/2" D	PG70-22ER	1.34	20
18	OR99W: McDougall - McDonald	L4	1/2" D	PG70-22ER	1.38	20
19	US30: Kittridge Ave - NW Bridge Ave.	L4	1/2" D	PG70-22ER	1.4	20
20	I-5: Roberts Creek Rd - S. Umpqua River	L4	1/2" D	PG70-22ER	1.49	20
21	I-84: Multnomah Falls - Toothrock Tunnel - Cascade Locks	L4	1/2" D	PG70-22ER	1.35	20
22	OR99W: 1st Ave. - Enid Rd.	L4	1/2" D	PG70-22ER	1.46	20
23	US395: SE 4th - I84 (Hermiston)	L4	1/2" D	PG70-28ER	1.45	20
24	I-84: Ladd Canyon - N. Powder	L4	1/2" D	PG70-28ER	1.48	20
25	OR140: Bear Cr. - 5th St.	L4	1/2" D	PG76-22ER	1.3	15
26	US199: Rogue Rvr Hwy - Applegate Rvr	L4	1/2" D	PG76-22ER	1.3	20
27	OR140: Exit 35 - Blackwell Rd	L4	1/2" D	PG76-22ER	1.38	15
28	OR140: Exit 35 - Blackwell Rd	L4	1/2" D	PG76-22ER	1.3	15

Note: Level - Project level based on traffic volume
Mix Type - 1/2, half inch dense mix
AC - Binder grade
P_{200}/P_{be} - Dust to binder ratio
RAP - Reclaimed asphalt pavement (%)

4.4 BENCHMARKING RUTTING THRESHOLDS

4.4.1 EFFECT OF MIX PROPERTIES ON HWTT RUT DEPTH

Table 4.2 presents a correlation matrix to examine the influence of various mixture properties on the rutting potential of asphalt mixes. It depicts the relation between different variables, and the values range from -1 to +1. Minus 1 represents the strongest inverse relation, while plus 1 represents the strongest direct relation between the two variables. The results presented in the correlation matrix show that they follow logical trends with respect to different fundamental mixture properties. The major parameters, such as the design level of the project, binder grade, binder content (P_b), dust-to-binder ratio (P_{200}/P_{be}) etc., were analyzed with a goal to determine a parameter for establishing thresholds for rutting.

The traffic volume over the pavement dictates the design level of the project. This is based on the ESAL over the pavement, as described in Section 4.1. From Table 4.2, it is evident that the design level and rut depth are negatively correlated. This suggests that as the design level of the project increases, the rut depth decreases. The primary reason for this is the use of polymer-modified binders and a higher number of gyrations to design Level 4 projects. These projects carry high traffic volume during their service life and, hence, are typically designed using stiff binders and lower binder contents to enhance the rutting susceptibility of the asphalt pavements.

In addition to this, it can be observed that the type of binder and rut depth are negatively correlated. The stiffness of the asphalt binder significantly influences the rutting potential of asphalt mixes. Generally, non-modified binders (e.g., PG64-22) are used for constructing Level 2 and Level 3 projects where the traffic volume is low to moderate. These binders are soft and flexible and thus are prone to higher rut depths; however, these binders serve the purpose for designated traffic on the pavements. Meanwhile, Level 4 projects employ polymer-modified binders (e.g., PG70-22ER), which have higher resistance to rutting due to their stiff nature. Thus, the correlation matrix accurately predicted that the increase in the binder grade would result in lower rutting of the pavements, as expected.

Moreover, the binder content (P_b) and the effective binder content (P_{be}) in the mix and the rut depth have a positive correlation, which suggests that increasing the binder content results in higher rut depth. Increasing the binder content increases the asphalt mix's flexibility and flowability, which results in higher rutting.

Similarly, the percentage of the aggregates passing the #200 sieve (0.075 microns) and the dust-to-binder ratio (P_{200}/P_{be}) resulted in a negative correlation, suggesting that the increase in these parameters would decrease the rut depth of the asphalt pavements. After studying the different parameters, it was determined that the design Level of the project and the binder type were found to be feasible for establishing the thresholds to characterize the rutting performance of asphalt mixtures.

Table 4.2: Correlation matrix showing the strength of correlations between HWTT rut depth and asphalt mixture properties.

	Rut Depth	Design Level	Binder Type	P_b	P_{be}	P_{200}	P_{200}/P_{be}	RAP
Rut Depth	**1**	-0.40	-0.38	0.30	0.12	-0.12	-0.21	0.15
Design Level	-0.40	**1**	0.86	-0.23	-0.09	-0.03	0.05	-0.54
Binder Type	-0.38	0.86	**1**	-0.07	0.15	0.13	-0.02	-0.61
P_b	0.30	-0.23	-0.07	**1**	0.64	0.38	-0.21	-0.02
P_{be}	0.12	-0.09	0.15	0.64	**1**	0.40	-0.52	-0.20
P_{200}	-0.12	-0.03	0.13	0.38	0.40	**1**	0.57	-0.09
P_{200}/P_{be}	-0.21	0.05	-0.02	-0.21	-0.52	0.57	**1**	0.10
RAP	0.15	-0.54	-0.61	-0.02	-0.2	-0.09	0.10	**1**

Note: Design Level - Project level based on traffic volume
RAP – Reclaimed asphalt pavement (%)
P_b – Binder content
P_{be} – Effective binder content
P_{200} – Dust passing 0.075µ sieve
P_{200}/P_{be} – Dust to binder ratio

4.4.2 INFLUENCE OF BINDER GRADE ON HWTT RESULTS

Figure 4.5 presents the box plots, which offer a concise summary of the HWTT results for specific binder grades, facilitating easy comparison of their performance characteristics. Notably, none of the mixes achieved a rut depth of 12.5 mm at 20,000 passes, indicating that the asphalt mixtures in Oregon generally exhibit significantly higher rutting resistance than those in other states (Veeraragavan et al., 2022). The median line in each box plot represents the central tendency of the rut depth for the specific binder type. A quick assessment reveals that non-modified binders yield higher rut depths than polymer-modified binders due to their lower stiffness. A statistically significant difference in rut depth between non-modified and polymer-modified asphalt mixes can be observed (p-value = 0.0059). Additionally, the box plots' widths for non-modified binders are wider, indicating more significant variability in rut depth performance among the mixes using these binders. Conversely, the box plots for HWTT results with polymer-modified binders (ending with ER) are narrower, suggesting the more consistent rutting performance of the asphalt mixtures. Notably, the PG76-22ER binder resulted in rut depths as low as 2 mm in some cases, with a maximum of 3.5 mm.

While the distribution statistics of rut depth can offer valuable insights into binder type effects, establishing a specific threshold based solely on binder type is not rational. Such an approach could lead to confusion and difficulty in accurately classifying the performance of asphalt mixes, especially for mixes prepared with RAP materials. Therefore, it is imperative to consider additional details and factors before designing the thresholds for HWTT rut depth.

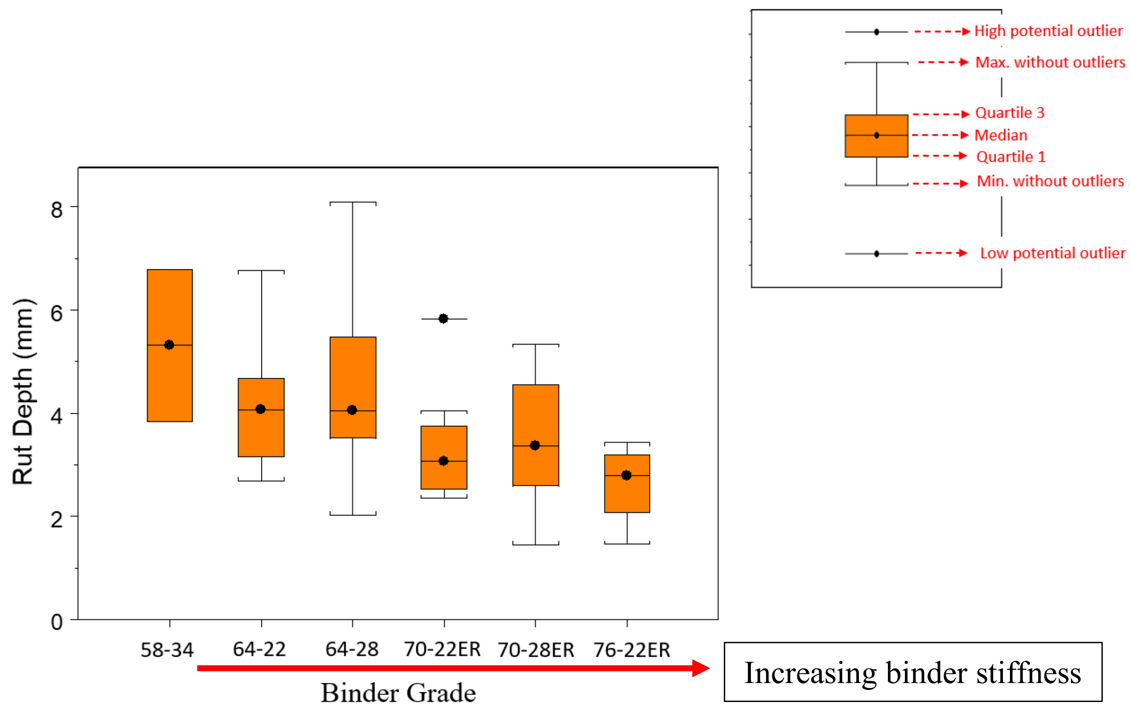


Figure 4.5: Box plots for HWTT results with specific binder grade.

4.4.3 INFLUENCE OF DESIGN LEVEL ON HWTT RESULTS

Figure 4.6 displays the rutting performance of asphalt mixes based on the design level of the project. The SHRP Superpave system defined the design levels by considering the traffic volume combined with vehicular loads expected on the asphalt pavements. As the ESALs increase, the design level of the project also increases, with Level 2 projects designed for low traffic (≤ 1 million), Level 3 referred to as moderate to high traffic (1 million to 3 million), and Level 4 pavements constructed to withstand the highest traffic volumes (≥ 3 million). The box plots clearly illustrate the distinct performance of asphalt mixes based on their design levels. Typically, Level 2 and Level 3 projects are designed with softer binders and may have higher binder contents and exhibit lower rutting resistance. In contrast, polymer-modified binders are utilized for Level 4 projects, which is the reason for the lower rut depth in the case of Level 4 mixes. The volumetric design also generally dictates a lower binder content for Level 4 mixes. The purpose of having more rut-resistant mixes for high ESAL highways is to avoid any early rutting failures in those critical roadways.

The whiskers in the box plots represent data variability outside the interquartile range. Wider whiskers for Level 3 and Level 4 projects indicate substantial dispersion of data points beyond the central range. This variability may be attributed to differences in climate conditions, pavement designs, and mixture properties and their constituents.

Establishing thresholds for the HWTT based on the design level is reasonable and practical. However, due to considerably lower rutting values obtained with the PG76-22ER polymer-modified asphalt binder compared to other binders used for Level 4 projects, it was decided to separate the Level 4 projects designed with PG76-22ER binders for more accurate analysis. PG76-22ER binder is commonly used in warmer regions in Oregon to avoid any rutting failures (for example, southern Oregon close to the California border)

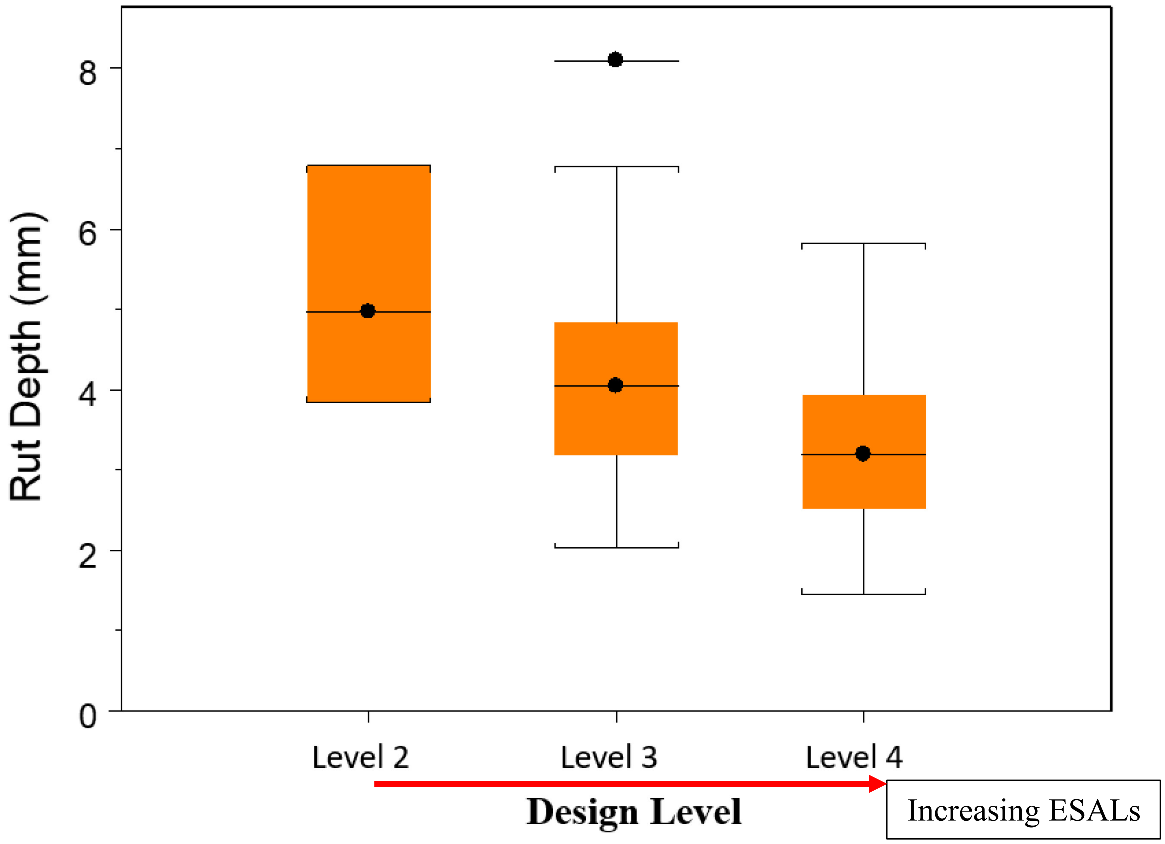


Figure 4.6: Effect of project design level on rutting performance.

Figure 4.7 describes the rut depth values after separating the Level 4 projects prepared with PG76-22ER binders. The values in red color indicate the rut depth for the first quartile, median, and third quartile. A significant difference in rut depth was observed between the median values for Level 3 projects, Level 4 projects excluding PG76-22ER binders, and Level 4 projects with only PG76-22ER binders. These observations suggest that the PG76-22ER binder exhibits superior rutting performance compared to other binders used for Level 4 projects, emphasizing the importance of considering binder type for Level 4 mixes in establishing performance thresholds for HWTT.

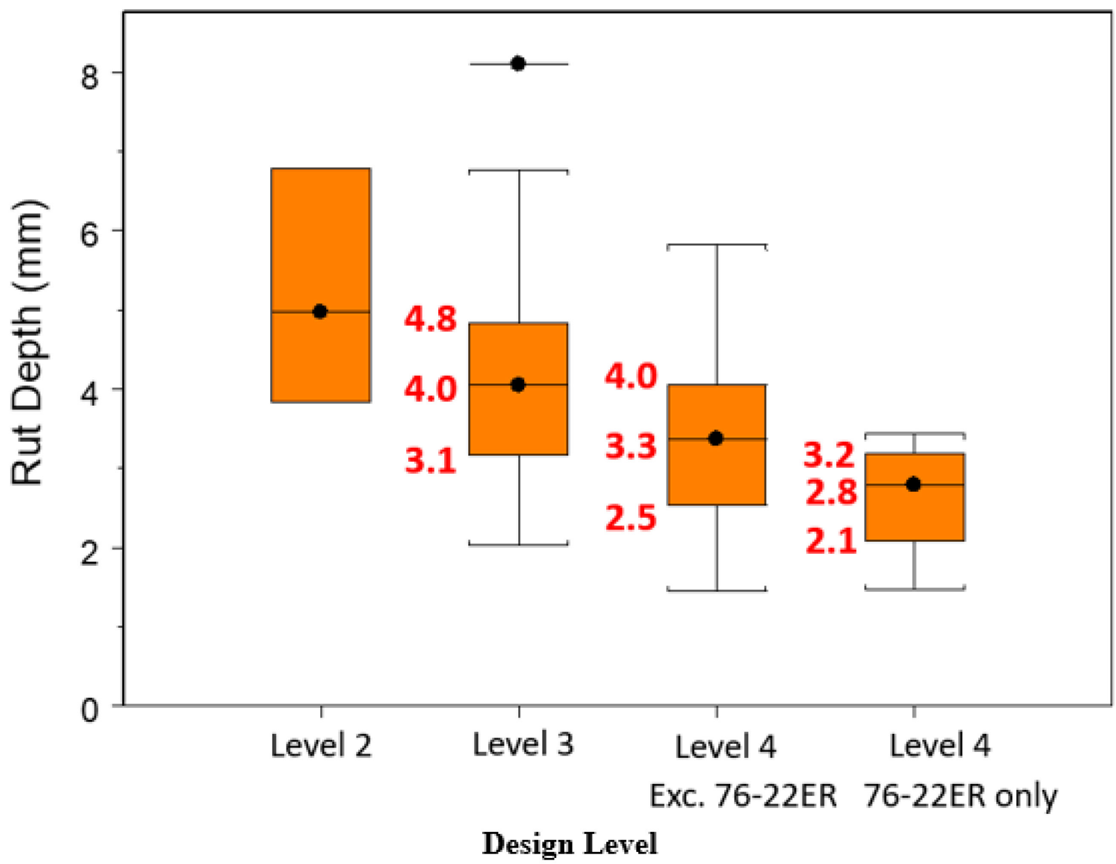


Figure 4.7: Boxplots after separating the PG76-22ER binder from the Level 4 projects.

Three rut depth values were considered for establishing the performance thresholds: Quartile 1, Quartile 2 (the median), and Quartile 3. Each quartile represents a specific percentage of the data points in the dataset.

- Quartile 1 indicates the value below which 25% of the data points fall. This represents the most conservative design threshold evaluated in this study to avoid any rutting failures in the field. Designing with a Quartile 1 threshold would imply that 75% of the asphalt mixtures at the particular design level will require binder content or volumetric properties adjustments to meet the desired performance criteria.

- Quartile 2, also known as the median, represents the middle value of the dataset. The 50th percentile indicates that 50% of the data points lie below and above this value. Using the median value as a threshold means that 50% of the projects must be adjusted to ensure the desired performance in the field. In other words, the adapted BMD process would push the mix designs with rut depths higher than the median values below that median threshold number.

- Quartile 3 represents the least conservative design for rutting in our evaluated cases and corresponds to the value below which 75% of the data points fall. It separates the lowest 75% of the data from the top 25%, defining the upper quartile.

In the present analysis, the three quartiles mentioned above were used to classify the rutting potential of the asphalt mixtures. As Oregon is in the early stages of implementing the BMD approach, more focus would be given to Quartile 2 (median) to present a conservative design and ensure the performance of the asphalt pavements under different loading and climatic conditions.

It is important to note that the rut depth values for all design Levels are significantly lower than the 12.5mm rut depth threshold targeted by various DoTs in the U.S.A. However, the thresholds given in Figure 4.7 were determined and used to start the BMD implementation process in Oregon. The rationale for choosing the statistics from current asphalt mixtures was to encourage the entire industry to move from stiff mixes with lower binder contents to softer ones that can resist premature cracking. To reduce the risk of any early rutting failures that can discourage the industry and agency from a larger-scale implementation, the conservative thresholds shown in Figure 4.7 were selected for different quartile levels to start the BMD mix production and pilot section construction trials in Oregon. As more data and experience are gathered with the BMD approach, further refinements to the thresholds and criteria should be made, by following the statistical analysis procedure described in this Section, to strike the right balance between conservative design and practical field performance. It should also be noted that asphalt mixtures that reached and exceeded the 8mm HWTT rut depth threshold resulted in early rutting failures in Oregon in the past. For this reason, the 12.5mm HWTT threshold commonly adopted by many state DoTs in the U.S. is expected to result in early rutting failures in Oregon and is not recommended to be adopted. **However, increasing those thresholds to a range of 5mm to 7mm for different design levels throughout the implementation efforts is recommended to increase the ductility and durability of the asphalt mixes to improve long-term cracking resistance.** In the future, alternative thresholds should be provided for areas with expected slow truck traffic speeds (areas likely to have significant traffic congestion) to avoid premature rutting failures.

4.5 BENCHMARKING CRACKING THRESHOLDS

4.5.1 EFFECT OF MIX PARAMETERS ON CT INDEX

Table 4.3 depicts the correlation matrix used to determine the correlations between fundamental mixture properties [design level, binder grade, binder content (P_b), effective binder content (P_{be}), percentage passing 0.075-micron sieve (P_{200}), dust to binder ratio (P_{200}/P_{be}) and reclaimed asphalt pavement (RAP)] and the CT Index results obtained from ODOT. The correlation matrix was developed using the S+ statistical analysis software.

It can be observed that the design level of the project and binder type are highly correlated with the CT Index. As the design level of the project increases from Level 2 to Level 4, they are specifically designed to carry higher traffic loads during their service life. Hence, polymer-modified binders are used to enhance the rutting performance of the asphalt mixes, as it typically occurs during the first 2 years of the service (Sreedhar et al., 2018a, Coleri et al., 2020, Lewis et al., 2023). This is also evident from the strong correlation between the type of binder used and the CT Index values. However, these statistically significant correlations between the design level and binder type suggest that the IDT-CT test effectively captures the performance of asphalt mixtures prepared using different binder types.

The positive correlation coefficients for the binder content (P_b) and effective binder content (P_{be}) suggest that increasing these parameters in the mix would result in a higher CT Index, as expected. Typically, the increase in the binder content would improve the ductility of the asphalt mix, and hence, higher cracking resistance can be observed. However, increasing the binder content over the prescribed amount would result in rutting failure. Therefore, it is important to strike the right balance for the binder content in the asphalt mixtures to enhance the performance. The balanced mix design process, after incorporating the performance tests, is expected to help determine the optimum binder content to improve the cracking and rutting resistance of the asphalt pavements.

It is important to note that the correlation matrix showed a high positive correlation between RAP and CT Index. This suggests that the increase in the percentage of RAP will improve the cracking resistance, but this is not accurate. One of the possible reasons for this trend is the use of softer binders for high RAP content mixes in Oregon (generally Level 3), which show a higher value of CT index with an increase in RAP compared to Level 4 mixes. On the other hand, Level 4 mixes use relatively stiffer binders and less binder content and generally have a low RAP percentage, resulting in a lower CT Index due to the pronounced influence of stiffer binders. The compilation of these two attributions aligns with the observed relationship between RAP content and the CT Index. Additionally, Level 4 mixes employ stiff binders and need higher gyrations to compact the specimens to ensure the desired air-void content. However, in actual practice, the RAP binder is already stiff due to its exposure to environmental conditions during its service life, which would decrease the cracking resistance. Thus, it is recommended that the data for each design level of the project and the binder grade be presented and analysed separately to determine their viability in establishing thresholds.

Table 4.3: Correlation matrix showing the strength of correlations between CT Index and asphalt mixture properties.

	CT Index	**Design Level**	**Binder Type**	**P_b**	**P_{be}**	**P_{200}**	**P_{200}/P_{be}**	**RAP**
CT Index	1	-0.68	-0.69	0.22	0.13	0.28	0.19	0.64
Design Level	-0.68	1	0.71	-0.53	-0.30	-0.60	-0.43	-0.88
Binder Type	-0.69	0.71	1	-0.15	-0.23	-0.18	-0.43	-0.84
P_b	0.22	-0.53	-0.15	1	0.49	0.75	0.42	0.42
P_{be}	0.13	-0.30	-0.23	0.49	1	0.57	-0.25	0.07
P_{200}	0.28	-0.60	-0.18	0.75	0.57	1	0.65	0.37
P_{200}/P_{be}	0.19	-0.43	-0.43	0.42	-0.25	0.65	1	0.37
RAP	0.64	-0.88	-0.84	0.42	0.07	0.37	0.37	1

Note: Design Level - Project level based on traffic volume
RAP – Reclaimed asphalt pavement (%)
P_b – Binder content
P_{be} – Effective binder content
P_{200} – Dust passing 0.075µ sieve
P_{200}/P_{be} – Dust to binder ratio

4.5.2 INFLUENCE OF BINDER TYPE ON CT INDEX

Figure 4.8 shows the box plot for the CT Index values for asphalt mixes prepared with different types of asphalt binders. As can be seen, the CT Index of mixes prepared with non-modified binders was higher than those with polymer-modified binders. Non-modified binders inherently possess more softness (due to lower PG), leading to better resistance against cracking compared to polymer-modified binders. In addition, softer binders are generally used for producing lower-level mixes, and those mixes have higher binder contents due to the lower gyration levels in the volumetric mix design. Interestingly, the CT Index values for mixes prepared with PG64-22 and PG64-28 binders were almost identical, indicating that the low-temperature binder grade did not considerably impact the fatigue cracking performance. Similarly, no statistically significant difference (p-value = 0.29) was observed in the CT Index values for mixes prepared with polymer-modified binders PG70-22, PG70-28, and PG76-22ER. These findings are consistent with the results from Maine DoT (Veeraragavan et al., 2022). They observed that mixes with 0% RAP are influenced by the change in binder type. However, after the addition of the RAP, the measured performance was found to be almost identical across all modified binder types. As the mixes used for the current statistical analysis were designed with RAP contents ranging from 15% to 30%, using the binder types to develop thresholds may not be a viable approach. However, it should also be noted that the binders with polymer modification (ER binders) are specifically used for Level 4 roads, and a higher number of gyrations (100) than the Level 3 mixes (80) were used during the volumetric mix design process to reduce the risk of early rutting failures in the field. This resulted in more binder in the Level 3 designs, making them more prone to rutting and more resistant to cracking.

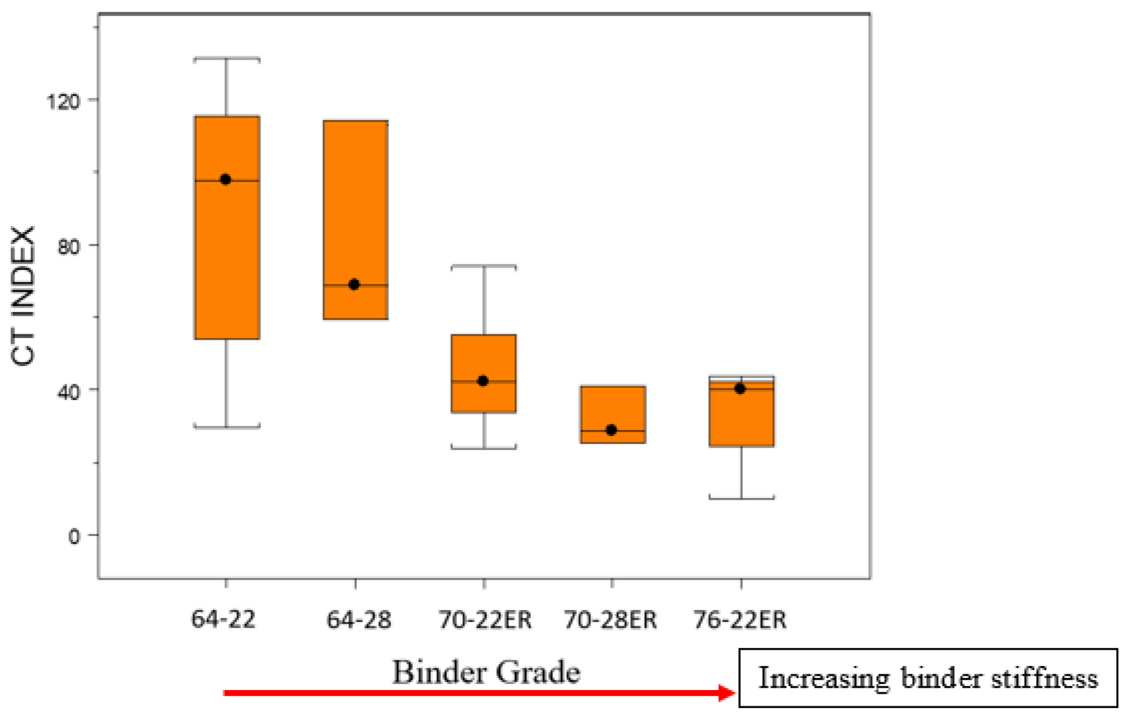


Figure 4.8: Variation of CT Index with respect to binder grade.

4.5.3 INFLUENCE OF DESIGN LEVEL ON CT INDEX

Figure 4.9 visually presents the relationship between the CT Index and the design level of the projects. The box plots effectively differentiate the CT Index values based on the design levels of the asphalt projects. The CT Index values decrease as the design level increases from Level 2 to Level 4. This observation can be attributed to the use of stiffer binders to prepare Level 4 mixes, which in turn reduces the cracking tolerance compared to Level 2 and Level 3 asphalt mixtures. However, since rutting can be considered a more critical distress mechanism than cracking due to its earlier occurrence, locations with heavy truck traffic requiring Level 4 are generally designed with stiffer asphalt mixtures. However, the low HWTT rut depth values shown in Figure 4.7 point out that the flexibility and cracking resistance of the asphalt mixtures can be improved for all design levels by increasing the binder content.

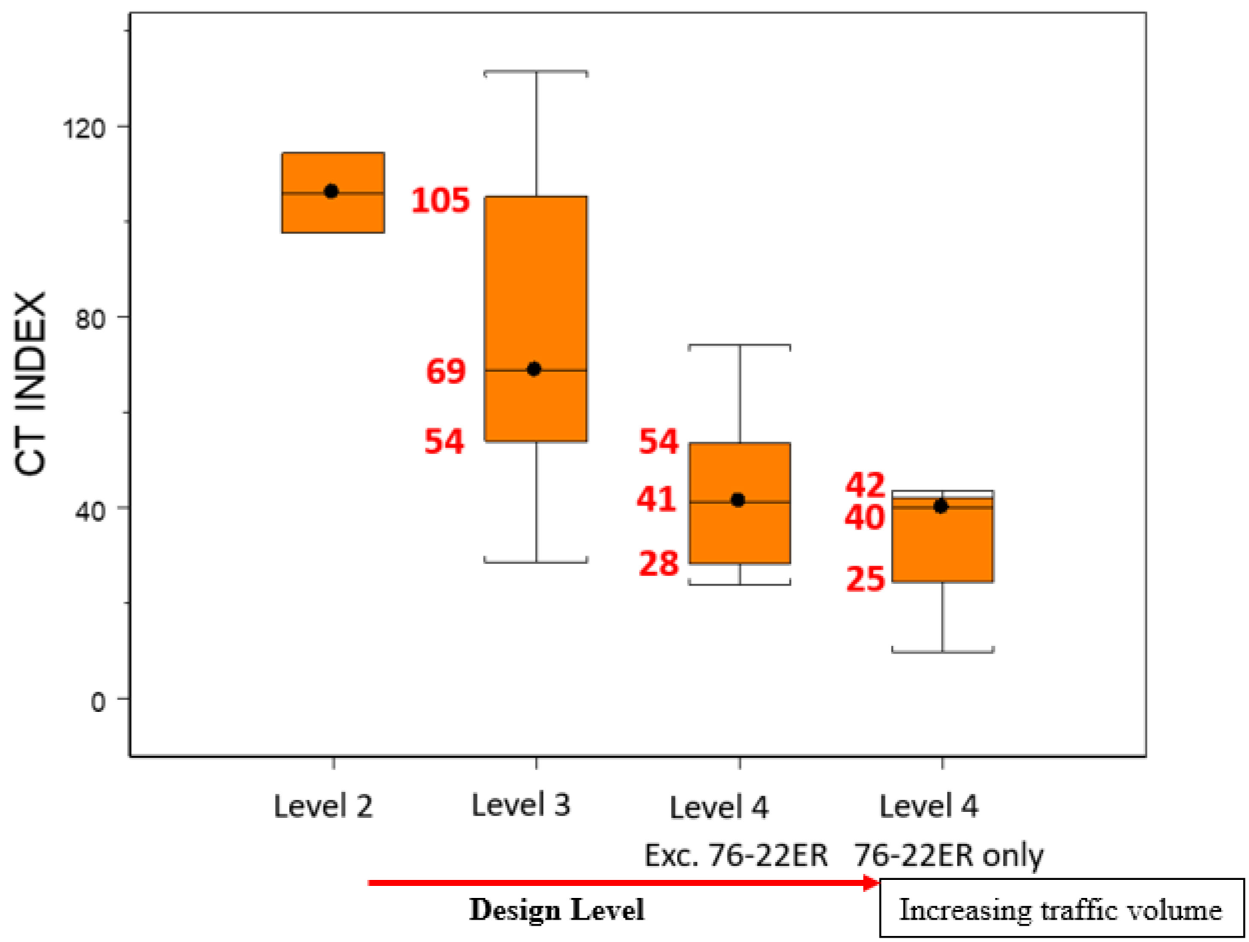


Figure 4.9 Comparison of the CT Index with the design level of the project.

Statistical analysis confirms a significant difference in the CT Index values among the different levels of projects. Level 2 projects exhibit CT Index values that are similar to Level 3 projects. However, only three test results were available for Level 2 mixes, and their distribution may not statistically represent Level 2 mixes. Since Level 2 mixes are generally used on low-volume roads with ESALs less than 1 million in a 20-year period, implementing the BMD method for

Level 2 mixes is not considered critical at this point. In addition, chip seals and emulsified asphalt mixtures (EAC), also called cold-mix asphalt, are more commonly used for paving low-volume roads in Oregon, and different approaches are needed to design those mixtures. For this reason, the implementation of the BMD process for Level 2 mixes is not within the scope of this study.

It is worth noting that projects using PG76-22ER polymer-modified binder in Level 4 designs showed slightly lower CT Index values compared to other Level 4 projects that did not use this binder type. However, the difference was not significant. To streamline the process of establishing CT Index thresholds and align with the HWTT thresholds, it was decided to separate the Level 4 projects that utilized the PG76-22ER binder from the remaining Level 4 projects that did not use this specific binder. This separation allows for more accurate and relevant threshold determination for the remaining Level 4 projects. The PG76-22ER binder is generally used in warmer regions in Oregon to improve rut resistance.

4.6 DISCUSSION ON THE STATISTICAL ANALYSIS AND THRESHOLD SELECTION PROCESS

It is important to note that rutting generally happens within the first summer if the asphalt mixture has any major design issues. However, an asphalt mixture poorly designed for cracking resistance may have a life significantly lower than the design life, but still, it generally would not fail within the next several years. For this reason, rutting is always considered to be a more critical distress. However, under-designing the asphalt mixture for cracking resistance may result in significantly earlier cracking failures and increase the life cycle cost of the asphalt mixture. For this reason, achieving an asphalt mixture with "balanced" cracking and rutting resistance is important. The purpose of the research efforts outlined in this chapter is mostly to develop an ideal method (BMD) for designing asphalt mixtures, which primarily aims at balancing the cracking and rutting distresses in the asphalt pavements.

This section presents the statistical approach to establish thresholds for the BMD implementation projects in Oregon. HWTT and IDT-CT results from 28 different projects comprising different mix properties and constituents were used to evaluate the cracking and rutting performance. Three different thresholds were developed for the CT Index and rut depth based on the design level of the project.

The final thresholds to evaluate the cracking and rutting performance of the asphalt mixtures for different quartile levels are shown in Table 4.4. It should be noted that the thresholds established for the CT Index and HWTT are also validated through actual field and accelerated pavement test section constructions (see Section 5.0 and Section 6.0). However, only one data point for the field performance data collected by Automated Pavement Condition Surveys (APCS) from the constructed pilot sections was available when this research report was written. However, field performance will be monitored for the next several years to determine the necessary adjustments required to improve the BMD process. This monitoring would provide valuable insights into the accuracy and effectiveness of the thresholds in predicting the performance of asphalt pavements. The experience gained from these pilot sections will be crucial in fine-tuning and refining the thresholds. Any necessary changes and adjustments to the established thresholds will be made based on the practical experience and observations gathered from the pilot sections. **The results of the field performance assessment are expected to support increasing the binder content of the asphalt mixes for all design levels. This observation is a result of the low rut depths achieved for all production mixes.** However, it is important to note that not all the binder around the RAP aggregates blends into the asphalt mixture due to the potential issues with RAP heating at the asphalt plants (RAP being indirectly heated by superheated aggregates during production). Lewis et al. (2024) conducted a RAP binder blending quantification study for Oregon asphalt mixes by using RAP from two different sources and with two different gradations. It was concluded that a significant percentage of the binder around the RAP aggregates (about 40% to 55%) does not blend into the mixture. This limited blending is expected to reduce the cracking resistance of the asphalt mixes while improving the rut resistance.

Table 4.4: Final thresholds for cracking and rutting.

Level	Binder Grade	Quartile 3 HWTT & CT Index	Median HWTT & CT Index	Quartile 1 HWTT & CT Index
3	ALL	4.8mm & 105	4.0mm & 69	3.1mm & 54
4	All except PG 76ER	4.0mm & 54	3.3mm & 41	2.5mm & 28
4	PG76ER	3.2mm & 42	2.8mm & 40	2.1mm & 25

4.7 LABORATORY INVESTIGATION OF ESTABLISHED THRESHOLDS

A case study was conducted to determine the effectiveness of the developed BMD thresholds. In this part of the study, four different projects (two Level 3 and two Level 4 mixes) were used for designing asphalt mixes by following the BMD method developed and described by Coleri et al. (2020). BMD approach B i.e., Volumetric Design with Performance Optimization, was used in this research work. The primary purpose of this part of the study was to determine if the thresholds established from the statistical analysis can be used to develop BMD mixes in the laboratory. This would set the foundation for further field pilot projects. Details of the process and the major findings are summarized in this section.

4.7.1 MATERIALS AND MIX DESIGN

The virgin aggregates, RAP, and virgin binder were sampled from asphalt plants supplying the mixes for four ODOT construction projects. Table 4.5 illustrates the details of these projects. The mixes include different amounts of binder content, RAP content, and RAP sources. The nominal maximum size of aggregates for all projects was 12.5 mm. The gradation curves for all four mixes are depicted in Figure 4.10.

Using a bucket mixer, all the mixes were prepared with three different binder contents (design binder content, −0.5%, +0.5%). Before compaction, the prepared asphalt mixture was subjected to short-term aging (STA) at 135°C for 2 hours (Newcomb et al., 2015). Following the STA, samples for IDT-CT testing were conditioned for 24 hours at 95°C to simulate long-term aging

(LTA) based on the aging protocol developed for Oregon (Shreedhar & Coleri 2020). After the aging process, the mixtures were placed in an oven at the compaction temperatures of the asphalt mixtures for two hours. Cylindrical specimens of 62 mm thickness were compacted using the Superpave gyratory compactor following AASHTO T312-12. Short-term aged samples were tested to assess the rutting resistance using HWTT (AASHTO T324-19), while IDT-CT (ASTM D8225-19) was conducted on long-term aged samples to determine the long-term fatigue cracking resistance.

Table 4.5: Mixture properties for different projects.

Project	Project Location	Level	Binder Grade	Additive	RAP (%)	OBC (%)	RAP Binder Content (%)
1	OR140: Exit 35 Blackwell Road	4	PG 76-22ER	-	15	5.7	5.1
2	I84: Meacham-Kamela	3	PG 70-28ER	WMA - 0.5%	30	6.1	7.2
3	I84: Ladd Canyon – North Powder	4	PG 70-28ER	Lime- 1%	20	6.1	5.5
4	OR58: Salt Creek Tunnel to MP70	3	PG 64-28	Lime- 1%	30	6.9	6.1

Note: RAP – Reclaimed asphalt pavement
WMA – Warm mix additive
OBC – Optimum binder content based on volumetric design

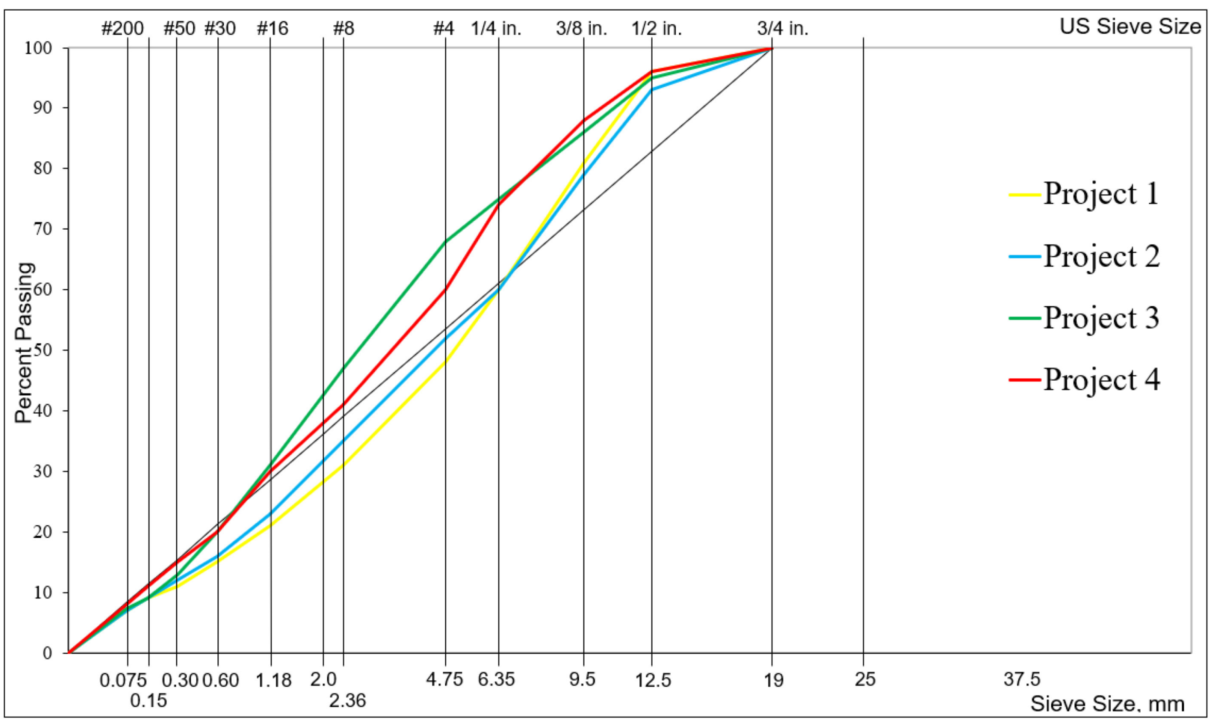


Figure 4.10: Gradation curves for asphalt mixtures for all four projects.

4.8 LABORATORY TEST RESULTS AND ANALYSIS

Figure 4.11 shows the CT Index value of all the asphalt mixtures used for the laboratory investigation. As can be seen, the CT Index proved to be effective in differentiating the cracking performance of the asphalt mixes based on their binder content. There are also significant differences in the CT Index values between the four projects. Notably, using PG76-22ER polymer-modified binder resulted in significantly lower CT Index values than other binder grades. Additionally, the CT Index values for Level 3 projects were higher than those for Level 4 projects since they were designed with 80 gyrations rather than 100 gyrations used for Level 4 (meaning a softer mix was achieved for Level 3 mixes from the volumetric design). This difference indicates that separate CT Index criteria may be needed for mix approval and acceptance for different levels of projects. Tailoring the CT Index thresholds based on the project level allows for a more accurate assessment and evaluation of the asphalt mixes' cracking potential for specific traffic conditions.

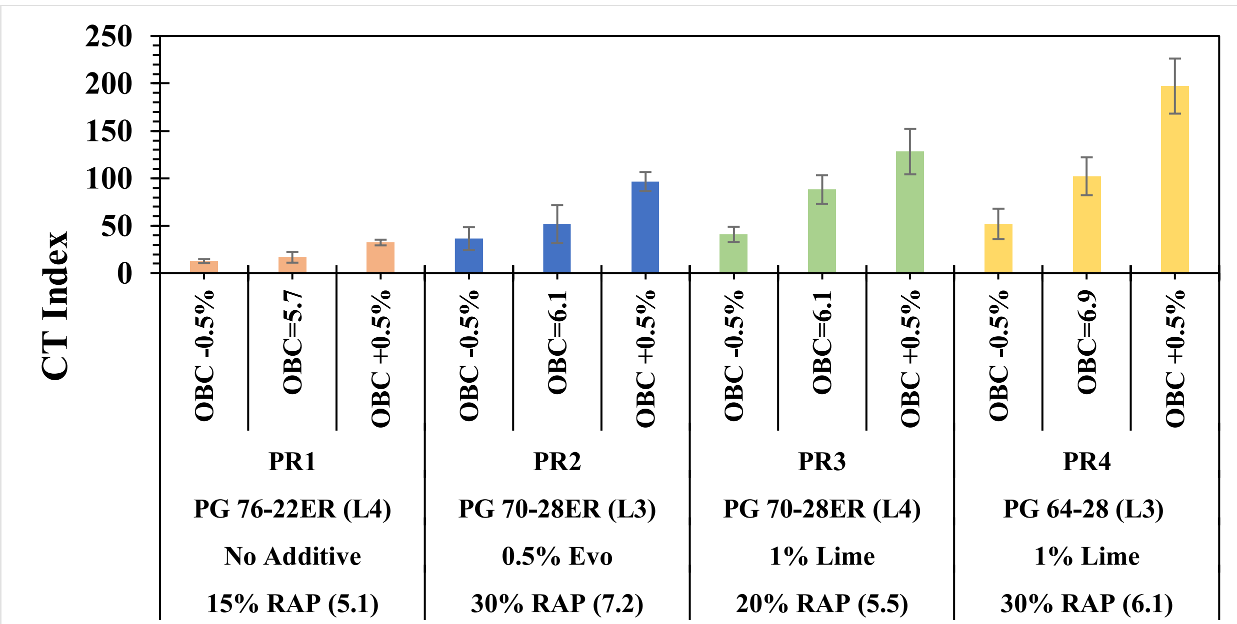


Figure 4.11: IDT-CT results from laboratory investigation (error bar = 1 standard deviation).

Figure 4.12 shows the HWTT rut depths of all the mixes utilized in the current laboratory investigation. The results indicate that the rut depth values for the asphalt mixes in Oregon are far lower than 12.5 mm, commonly used as a BMD threshold for several state DoTs in the U.S. The highest rut depth was found to be 7.25 mm, probably due to higher binder content, i.e., 7.4%, compared to other Level 3 and Level 4 projects. Additionally, the difference in rutting performance observed among projects with similar binder grades and content can be attributed to other factors, such as different additives in the mix or the percentage of Reclaimed Asphalt Pavement (RAP) utilized in those mixes. These variations in performance among similar mixes highlight the complex nature of asphalt mix design and the importance of considering a combination of factors to achieve desired performance outcomes. **This complex nature of today's asphalt mixes also proves the need to implement BMD approaches.**

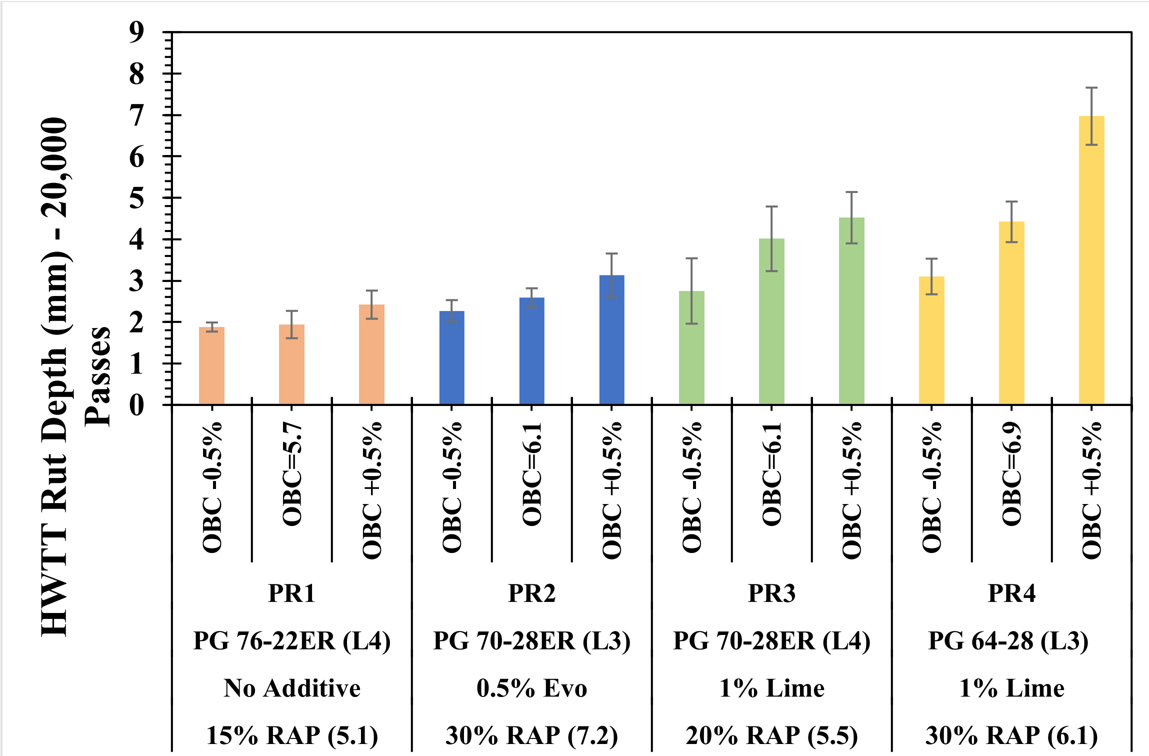


Figure 4.12: HWTT results from laboratory investigation (error bar = 1 standard deviation).

Table 4.6 displays the binder content range obtained using the BMD thresholds developed for IDT-CT and HWTT in the preceding sections (See Table 4.4). It is important to note that these binder contents were determined using the BMD software package developed by OSU-AMaP (Refer to Appendix B) and the values were further checked considering volumetric pass/fail criteria using another software package developed by the research team (detailed in Appendix C). As can be seen, the binder content range may change with the change in the choice of quartile, which controls the reliability level of the design for rutting and cracking.

Table 4.6: Binder content thresholds for the project used in laboratory investigation.

Projects	Level	Binder Grade	Additive %	OBC	Quartile 3 B.C. (%)	Median B.C. (%)	Quartile 1 B.C. (%)
1	4	PG76-22ER	-	5.7	6.50-7.62	6.45-6.87	5.72-5.72
2	3	PG70-28ER	WMA- 0.5%	6.1	6.05-7.79	5.75-6.85	5.40-5.91
3	4	PG70-28ER	Lime- 1%	6.1	5.8-6.22	5.56-5.84	5.24-5.44
4	3	PG 64-28	Lime- 1%	6.9	6.88-6.88	6.60-6.70	6.40-6.50

Note: OBC – Optimum binder content
WMA – Warm mix additive
B.C. – Binder content

4.9 CONCLUSIONS

In the present study, extensive statistical analysis was performed to determine the impact of various volumetric parameters on the IDT-CT and HWTT results and to validate the effectiveness of these two experiments in characterizing the cracking and rutting resistance of asphalt mixtures. Additional analysis was performed to establish the tentative performance thresholds for BMD to design the mixtures for the field pilot construction projects. These thresholds were further used to conduct a BMD case study with four asphalt mix types used for road construction in Oregon during the summer of 2022. IDT-CT and HWTT were conducted on laboratory-prepared samples to conduct the BMD process. The conclusions derived from this study are as follows:

- Based on the findings from this study and the previous research projects (Coleri et al. 2018, Sreedhar et al., 2018b), the indirect tensile cracking test (IDT-CT) and Hamburg Wheel Tracking Test (HWTT) are the most practical and reliable test methods to evaluate the cracking and rutting performance and can be incorporated into the BMD method for asphalt mixtures.

- The flexibility and cracking resistance of the Oregon asphalt mixtures can be improved for all design levels by increasing the binder content. The results of the field performance assessment are expected to support increasing the binder content of the asphalt mixes for all design levels. This observation is a result of the low HWTT rut depths achieved for all production mixes.

- Design levels were found to be the most reasonable and appropriate way to establish thresholds for BMD implementation, while only for the significantly stiffer PG76-22ER binder, a separate threshold is required under Level 4.

- Thresholds from the least conservative approach to the most conservative approach were determined to benchmark the cracking and rutting performance of asphalt mixtures for field implementation.

- The results showed that the BMD method of asphalt mixtures does not always increase the binder content; instead, it optimizes to balance the cracking and rutting performance of the mixes.

5.0 BMD PILOT SECTION CONSTRUCTION AND PERFORMANCE MONITORING - CASE STUDY ON BMD IMPLEMENTATION IN OREGON

5.1 INTRODUCTION

Traditionally, the design of today's asphalt mixtures is primarily based on volumetric relations (Diefenderfer et al., 2021). In this process, the air voids, voids filled with asphalt (VFA), and voids in mineral aggregate (VMA) play a vital role (Abdullah et al., 1998). The general process involves utilizing these volumetric values to predict the long-term performance of asphalt pavements. The majority of the Department of Transportation (DoT) agencies have set their thresholds for quality control and quality assurance (QC/QA) purposes and assume that adherence to these prescribed ranges would ensure the expected performance of the pavements. However, it was identified that the traditional volumetric mix design system with no performance testing failed to address cracking and rutting failures on asphalt-surfaced pavements (West et al., 2018). As a response, the Strategic Highway Research Program (SHRP) was initiated for the development of the Superpave asphalt mix design system, which aims to tailor asphalt pavement mixtures to the anticipated design traffic, categorizing pavements into three levels based on traffic volume (Cominsky et al., 1994). Level 1 focused on the low-traffic volume pavements and recommended that the volumetric properties would suffice to ensure the expected service of the pavements. Level 2 and Level 3 designs targeted the moderate and high traffic volume pavements and necessitated incorporating performance tests in the asphalt mixture design to ensure the long-term performance of asphalt pavements. However, these test methods were never implemented due to the complexity and high cost of the proposed performance tests (West et al., 2018).

In general, the Superpave mix design system reduced the susceptibility of the asphalt pavements to rutting failures; however, these pavements experienced premature cracking, leading to continuous maintenance and increased life-cycle costs. This persistent cracking issue has led researchers and agencies to shift towards the Balanced Mix Design (BMD) approach, integrating performance tests with volumetric mix design to balance the cracking and rutting susceptibility of today's complex asphalt mixtures (Zhou et al., 2021). It is well-known that adding an excessive amount of binder beyond the optimum amount will result in rutting failures on asphalt-surfaced pavements, and lower asphalt content will cause early cracking failures. Hence, it is essential to fine-tune the asphalt content in the mixture production to balance the cracking and rutting susceptibility of asphalt pavements. It is expected that incorporating the asphalt mix performance tests will assist in balancing the asphalt content and prolong the life of the pavements.

Oregon Department of Transportation (ODOT) started the BMD efforts in collaboration with the Oregon State University Asphalt Materials and Pavements (OSU-AMaP) group in 2016 (Sreedhar et al., 2018, 2021). In the prior studies, Coleri et al. (2020) focused on developing a long-term aging protocol for asphalt mixtures. Six different aging protocols were selected, and each was meticulously evaluated to compare the field aging levels with different laboratory-simulated aging conditions. The impact of different aging temperatures and durations on the cracking performance of asphalt mixtures with different mix design parameters was also evaluated. The conclusion drawn from these investigations recommended 24 hours of aging at 95°C as the most accurate and practical protocol. This protocol's ability to simulate 3-5 years of field aging stands out as a robust and practical method for predicting the long-term performance of asphalt mixtures. The cracking performance rankings of the most commonly used Oregon mixes were determined to be identical for the aging protocols with 24 hours and 72 hours of aging at 95°C, proving that the 24-hour aging would provide rankings that are identical to 72 hours of aging at 95°C. In addition, it was determined that aging the loose asphalt mixture at 135°C changes the binder properties and significantly reduces the compactability of the mix. This unrealistic binder state is expected to reduce the reliability of the field performance prediction based on the laboratory-measured performance.

The performance-based BMD aims to move beyond traditional volumetric design criteria by including tests that directly measure the potential performance of asphalt mixes under real-world conditions. Based on the previous chapters, it can be stated that the HWTT and IDT-CT tests could differentiate the rutting and cracking performance based on binder content and assess the impact of different mix design parameters on rutting and cracking potential, respectively. It is important to note that the IDT-CT cannot be considered a direct fracture test, while the SCB is. However, the high correlation between SCB-FI and IDT-CT Index values for Oregon asphalt mixes proves the effectiveness of the IDT-CT test for cracking performance assessment (Coleri et al. 2018, Sreedhar et al., 2018b)

In advancing the BMD method, establishing performance thresholds, also known as benchmarking the performance, is essential for distinguishing between well-performing and underperforming asphalt mixes. A previous component of this study (Section 4.0) provided detailed information on benchmarking the performance of asphalt mixes based on the IDT-CT and HWTT tests. IDT-CT and HWTT results from 28 different field projects in Oregon were utilized. Statistical analysis was performed using the laboratory test results (HWTT and IDT-CT) obtained from these construction projects to determine asphalt mix parameters, truck traffic, load levels, and climate effects that were significant and practical in developing thresholds for the classification of the mixes. The project design level emerged as a practical criterion for categorizing asphalt mix performance. However, the behavior of the PG76-22ER polymer-modified binder in Level 4 projects was distinct from that of other binders (due to being significantly stiffer to resist rutting in warmer regions in Oregon), necessitating a separate threshold for mixes using this binder grade.

The thresholds for evaluating the cracking and rutting susceptibility were determined from the least conservative to the most conservative approach, where quartile 1 represented the most conservative, while quartile 3 represented the least conservative for rutting. On the other hand, quartiles 1 and 3 represented the least conservative and most conservative regarding cracking, respectively. To validate these thresholds, specimens were fabricated and subjected to IDT-CT and HWTT tests, simulating various field project conditions. This validation process confirmed the thresholds' suitability for evaluating asphalt mix performance in the laboratory and determining the optimal binder content for the long-term durability of asphalt pavements. Hence, the above-developed thresholds were utilized for their validation and effectiveness in implementing the BMD process for Oregon.

Following the establishment of performance thresholds for the BMD process, a pivotal step was undertaken to validate these thresholds and assess their effectiveness in improving pavement quality beyond what is achievable with traditional volumetric mix design systems. This was accomplished through the strategic field implementation of pilot projects across Oregon. The study selected five distinct projects, each located in different parts of the state with different traffic and climates, to construct pilot sections. This initiative aimed to validate the established BMD thresholds and confirm their applicability across real-world conditions. The plan was to modify the volumetric mix design for the individual project and later recommend the optimum binder content, the aggregate gradation, and other mix components required for the mix generation according to the BMD approach. This BMD method is the "Volumetric Design with Performance Optimization" and is the most commonly used BMD method in the U.S. The refined mix design variables were then communicated to the asphalt contractors so they could produce the asphalt mix for the pilot section construction. Later, pilot sections of about 1 mile in length were constructed using this BMD job mix formula (JMF) while the rest of the construction project was completed using the conventional ODOT volumetric mix design method. Later, production asphalt mixes designed by following the volumetric and performance-based BMD approaches were obtained during the construction of these pilot sections to evaluate and compare their laboratory-measured rutting and cracking performance. The major objectives of this part of the research study were to:

- **Validate or Update the Cracking and Rutting Thresholds:** This objective focuses on confirming or updating the predetermined performance thresholds for cracking and rutting. By applying these thresholds to actual field projects, the study aims to determine their reliability in achieving asphalt-surfaced pavements with optimum rutting and cracking resistance without premature failures in real-world conditions.

- **Evaluate the Effectiveness of the Recommended Binder Type, RAP Content, and Gradation:** This objective involved a comparative analysis between the traditional volumetric mix design and the BMD approach, specifically looking at the binder type, RAP content, and aggregate gradation recommended for production. The goal is to determine if the BMD-recommended mixture properties offer superior performance and significant advantages over those designed using volumetric principles. In addition, an attempt was made to quantify the differences in the environmental impact of the asphalt mixtures produced using volumetric and BMD approaches through a cradle-to-gate life-cycle assessment (LCA) process.

- **Examine the Impact of BMD on Compaction during the Construction Process:** Understanding how the BMD method influences the compaction and constructability of the asphalt pavement during the construction process is crucial. This includes assessing any changes in compaction of the asphalt pavements. Identifying these impacts can help streamline the construction process and mitigate potential challenges associated with adopting BMD.

5.2 MATERIALS AND MIX DESIGN

This research aimed to evaluate the performance of the asphalt mixtures based on the volumetric mix design and BMD methods. It also aimed to determine the appropriate amount of binder, gradation, and RAP content necessary to develop the asphalt mixes that would satisfy the cracking and rutting thresholds developed from the statistical analysis (Chapter 4.0). For this reason, virgin aggregates, binder, and Reclaimed Asphalt Pavement (RAP) were sampled from 5 different locations in Oregon, as shown in Figure 5.1. These projects were strategically selected to maximize variability in material properties, traffic loads, and climatic conditions. The target gradation curves followed for the volumetric mix design of asphalt mixes for these projects are presented in Figure 5.2.

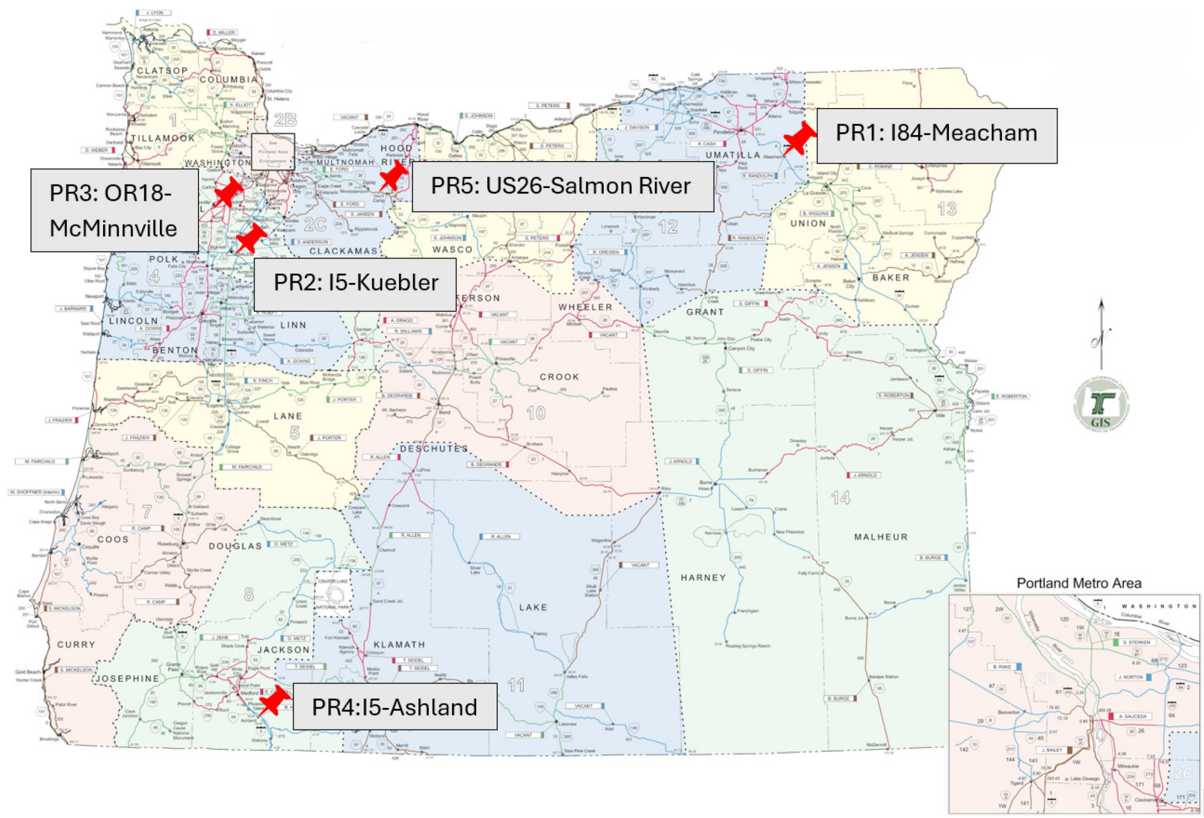


Figure 5.1: Approximate location of construction projects in Oregon. (Oregon Department of Transportation : Maps and GIS : Data & Maps : State of Oregon)

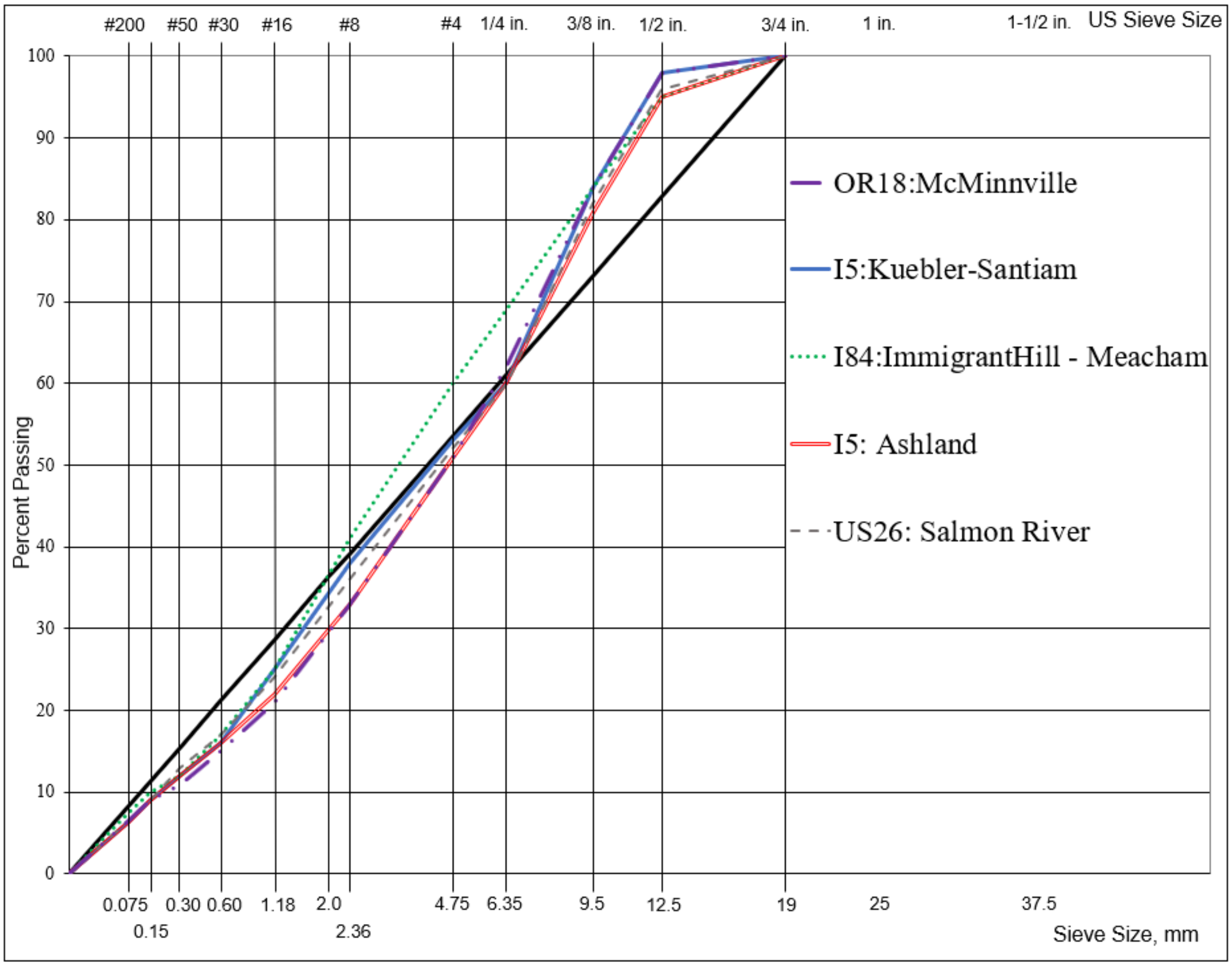


Figure 5.2: Gradation curves for all five projects on a 0.45 power chart.

Table 5.1 presents the mix design attributes for different projects utilized in this study. It can be observed that the combinations of asphalt mix constituents (asphalt binder grade, binder content, and RAP percentage) were different in all the projects. For all the projects, three different binder contents were used [design binder content (AC_{design}), AC_{design}−0.5%, AC_{design}+0.5%]. While mixing different constituents to prepare asphalt mixes in the laboratory, high-accuracy scales were used to measure the amount of binder content. Notably, ODOT allows a binder content variability of ±0.35% during asphalt mix production, a tolerance level that aligns with industry norms adopted by many other state agencies.

Table 5.1 Mix design parameters for all five projects.

Project	Highway ID	Project Level	Binder Grade	RAP[1] (%)	AC[2] (%)	RAM[3] AC (%)	Additive
PR1	I84: Immigrant Hill - Meacham	4	PG70-28ER	20	6.2	5.9	Evotherm P25 0.5%
PR2	I5: North Santiam-Kuebler	4	PG70-22ER	20	5.6	5.4	None
PR3	OR18: McMinnville	4	PG70-22ER	20	6.0	6.4	None
PR4	I5: North Ashland – South Ashland	4	PG76-22ER	15	6.2	6.0	Ultracote UP500 0.0375%
PR5	US26: Salmon River - Zigzag	3	PG64-22	30	5.3	5.6	None

Note: [1]RAP = Reclaimed asphalt pavement added by mass;
[2]AC = Asphalt content added by mass;
[3]RAM AC = Asphalt content by mass in reclaimed asphalt material.

5.2.1 FABRICATION OF ASPHALT MIX SPECIMENS

For this research study, two different techniques were followed to prepare asphalt mixtures. These techniques are categorized as Laboratory Mixed-Laboratory Compacted (LMLC) and Plant Mixed-Laboratory Compacted (PMLC). The description of sample preparation using these techniques is detailed in the subsequent sections:

5.2.1.1 LMLC specimens for BMD

LMLC specimens were prepared in the laboratory for BMD. For LMLC specimens, virgin aggregates, asphalt binder, and RAP materials were sampled a couple of weeks before the plant production and construction. Following the sampling, the materials were processed to meet the job mix formula (JMF). Processing involved sieving and batching the aggregates and the RAP in the laboratory. Thereafter, the batched aggregates and asphalt binder were placed in the oven at the mixing temperature (determined based on the relation between viscosity and temperature) along with the mixing bucket and the mixing arm for 2 hours. Additionally, the RAP aggregates were placed at 121°C in a forced draft oven by following the ODOT recommendations. After 2 hours, the preheated materials were thoroughly mixed in the mixing bucket for 2 minutes. It was determined by trial and error that 2 minutes of mixing in the bucket provided the appropriate coating to the aggregates. The time of mixing the material was kept constant for all the samples to avoid any inconsistency in the sample preparation and test results.

Further, the loose asphalt mixture was placed in the oven at a specified temperature of 135°C for 2 hours to simulate the short-term aging (STA), as recommended in NCHRP 815 (Newcomb et al., 2015). The primary reason for short-term conditioning is to simulate the early aging during the mix's production and transportation phase to the project site. As rutting is primarily observed during the initial phase of the pavement's life, the loose asphalt mix after STA was further kept in the oven for 2 hours at the compaction temperature before compaction. On the other hand, asphalt pavements tend to crack in the later years of their service life primarily due to aging. This aging process is referred to as long-term aging (LTA). For simulating the LTA of the specimens in the laboratory, the STA loose asphalt mixtures were further subjected to the draft oven at 95°C for 24 hours in accordance with Coleri et al. (2020). After LTA conditioning, the loose asphalt mixtures were kept in the oven for 2 hours at the compaction temperature to compact the asphalt mixtures. STA and LTA specimens were compacted to the required dimensions using the Superpave Gyratory Compactor (SGC).

5.2.1.2 PMLC specimens for BMD

For preparing PMLC samples, loose asphalt mixtures produced at the plant for the construction of BMD and volumetric sections were directly sampled in cardboard boxes and brought to the laboratory. Before the preparation of PMLC samples, the loose asphalt mixture was heated in a draft oven at 110°C for 2 hours, followed by the uniform sampling of the mix using a mechanical splitter. The theoretical maximum specific gravity (G_{mm}) of each mix was determined using the Rice method (ASTM D2041-03a). This was done to calculate the weight of the asphalt mixture required to achieve 7% air void content. This required amount of mix was weighed and placed in separate trays for sample preparation. It should be noted that the PMLC samples were not subjected to STA because these samples were already exposed to conditioning during production and storage. Thus, the loose asphalt mixtures were directly subjected to compaction temperatures for 2 hours after the splitting to assess the rutting performance. However, to determine the cracking performance of asphalt mixes, the LTA protocol of conditioning the production mix for 24 hours at 95°C, as recommended by Coleri et al. (2020), was followed. Similar to LMLC LTA specimens, the loose asphalt mix was placed in the oven at compaction temperature for 2 hours, followed by compaction using SGC.

5.3 EXPERIMENTAL DESIGN

LMLC and PMLC specimens prepared from the materials obtained from 5 different construction projects across the state of Oregon (shown in Table 5.1) were tested to assess the cracking and rutting performance. The IDT-CT and HWTT were conducted to assess the cracking and rutting performance of the asphalt mixtures, respectively. Section 4.2.1 and Section 4.2.2 of Chapter 4.0 describe the working principle and adopted test parameters for the HWTT and IDT-CT tests. These test methods are not presented here to avoid repetition. Table 5.2 demonstrates the experimental factorial design followed in this study. A total of 230 laboratory experiments were conducted for this part of the research study.

Table 5.2: Experimental plan to develop Balanced Mix Design.

Specimen Type[a]	Total Projects	Binder Contents	Replicates	Total Tests
LMLC IDT-CT	5	3 (AC_{design}, AC_{design} ± 0.5%)[b]	6	90
LMLC HWTT	5	3 (AC_{design}, AC_{design} ± 0.5%)[b]	4	60
PMLC IDT-CT	3 projects with both BMD and Volumetric Binder content[c] 2 projects with same binder content for Volumetric and BMD[d]	BMD and Volumetric	6	48
PMLC HWTT	3 projects with both BMD and Volumetric Binder content[c] 2 projects with same binder content for Volumetric and BMD[d]	BMD and Volumetric	4	32

a LMLC: Laboratory mixed and laboratory compacted; PMLC: Plant mixed and laboratory compacted.
b Binder content based on the volumetric mix design.
c Volumetric and BMD asphalt mixtures were obtained for three projects: I5-Kuebler Santiam, I5-North South Ashland, and US26-Salmon River Zigzag .
d. BMD and volumetric mix designs were accepted to be similar for I84-Meacham and OR18-McMinnville.

5.4 RESULTS AND DISCUSSIONS

5.4.1 Discussion on BMD testing (LMLC specimens)

As discussed previously, asphalt mix constituents for the five selected construction projects across Oregon were sampled, processed, mixed, and compacted to produce laboratory test specimens. Three different binder contents were used to determine the optimum BMD asphalt content: AC_{design} from volumetric mix design, AC_{design} - 0.5%, and AC_{design} + 0.5%. AC_{design} is the optimum asphalt binder content determined from the volumetric design method, which was conducted before the BMD specimen preparations started. AC_{design} is the volumetric design binder content needed to reach a 4% air void content after a specific number of gyrations (also called compactive effort) applied by the Superpave Gyratory Compactor (SGC) system. The number of gyrations was 80 and 100 for Level 3 and Level 4 asphalt mixture designs, respectively.

Six replicates were used for the IDT-CT tests, while four replicate tests (8 samples with four rut depth measurements) were used for HWTT to assess the rutting susceptibility of the asphalt mixtures. These results then formed the input for the software developed by the OSU-AMaP (refer to Appendix B), which determined the optimum binder content range based on the cracking and rutting performance threshold. The range determined by this software was conveyed to the plant, and a production mix with the BMD binder content was used to construct pilot sections at five locations. In addition, the aggregate gradation and RAP content for some of the designs were also changed to improve the performance of the BMD asphalt mixes.

5.4.1.1 Project 1: I84-Immigrant Hill – Meacham

The binder used in this mixture design was a PG70-28ER binder. The specific gravity for the binder was measured to be 1.033. The expected mix design was a Level 4 (highest ESALs) with ½" Nominal Maximum Aggregate Size (NMAS) dense gradation. The mix also had an Evotherm P25 additive in lieu of lime at a rate of 0.5% of virgin binder content. Mixes for the cracking and rutting tests were prepared at three binder contents, 5.7%, 6.2%, and 6.7%, where 6.2% was the optimum binder content based on the volumetric mix design method.

The average measured CT Index and HWTT rut depth values for all three binder contents and their corresponding error bars are illustrated in Figure 5.3 and Figure 5.4, respectively. As can be seen, the asphalt mix for this project already exhibited a high CT Index value at the volumetric binder content level, indicating a high level of resistance to cracking. In addition, the average rut depth measured for the volumetric binder content (6.2%) was 4.02 mm. These results point towards a relatively higher susceptibility to rutting when compared to the average performance of projects included in the prior statistical analysis (provided in Chapter 4.0).

Although a rut depth of 4 mm is not expected to provide a mix that will fail from rutting in the field, to reduce the risk of any early rutting failures that can discourage the industry and agency from a larger scale implementation, the conservative thresholds shown in the previous chapter were selected for different quartile levels to start the BMD mix production and pilot section construction trials in Oregon. As more data and experience are gathered with the BMD approach, further refinements to the thresholds and criteria should be made to strike the right balance between conservative design and practical field performance. It should also be noted that asphalt mixtures that reached and exceeded the 8mm HWTT rut depth threshold resulted in early rutting failures in Oregon in the past (previously communicated to the OSU research team by ODOT). For this reason, the 12.5mm HWTT threshold commonly adopted by many state DoTs in the U.S. is expected to result in early rutting failures in Oregon and is not recommended to be adopted. However, increasing those thresholds to a range of 5mm to 7mm for different design levels throughout the implementation efforts is recommended to increase the ductility and durability of the asphalt mixes to improve long-term cracking resistance.

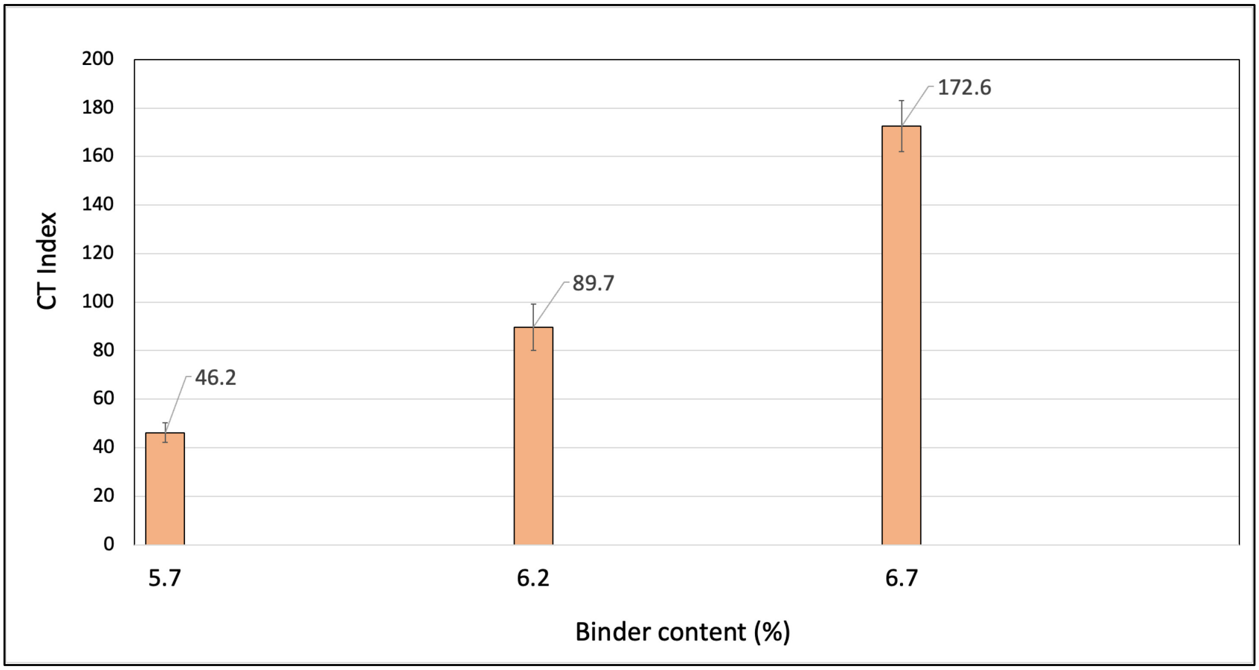


Figure 5.3: IDT-CT results for I84 – Immigrant Hill Meacham (error bar = 1 standard deviation).

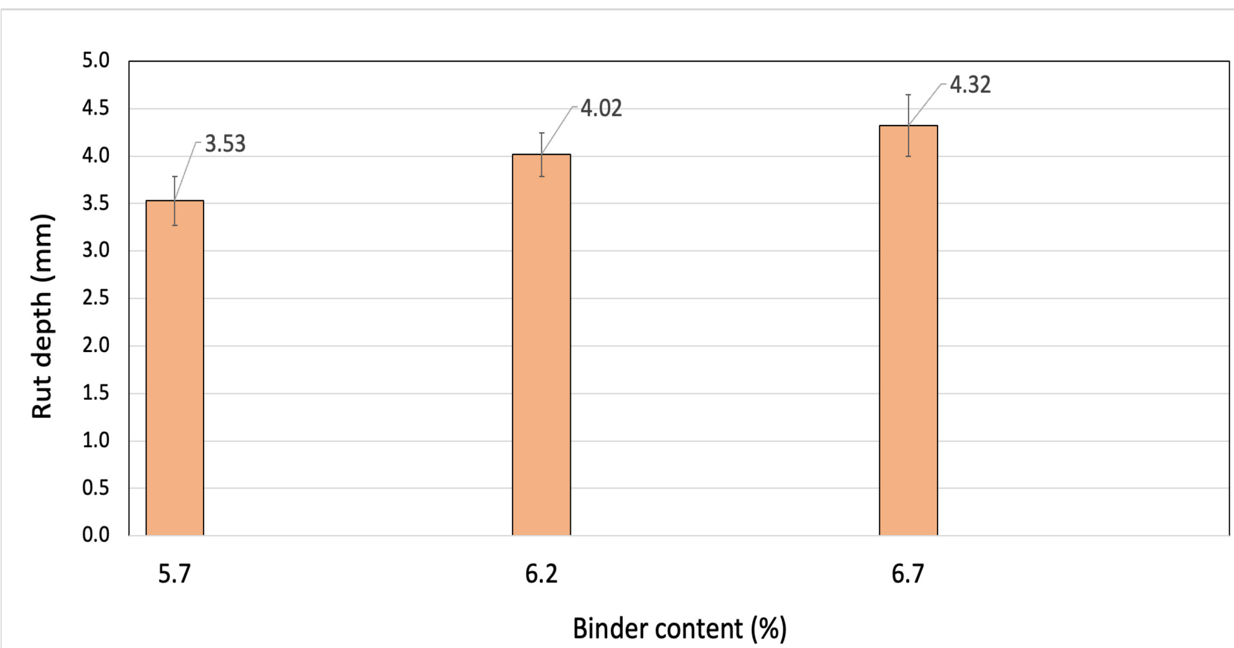


Figure 5.4: HWTT results for I84 – Immigrant Hill Meacham (error bar = 1 standard deviation).

The statistical analysis conducted in Chapter 4.0 determined that for a Level 4 mix without the PG76-22ER binder, the quartile 3 level (better than 75% of the asphalt mix pool in terms of cracking) threshold was selected. This project used 54 and 4.0mm thresholds for cracking (IDT-CT) and rutting (HWTT) to determine the optimum binder content range, respectively.

Figure 5.5 describes the software interface developed in this research project for BMD based on the IDT-CT and HWTT thresholds. The software uses the IDT-CT and HWTT results obtained from the laboratory testing as input files. Once the test files are uploaded to the software, the CT index and HWTT thresholds are entered to calculate the binder content range and other mix design suggestions. This binder content is expected to balance the cracking and rutting resistance of the asphalt pavements constructed with BMD. The user manual for the software is provided in the Appendix B.

Along with the binder content range, the software also describes the relationship between binder content with respect to the CT Index and HWTT rut depth. For this project, the lower binder content corresponds to the limit for the cracking resistance. In other words, it is the minimum amount of binder that needs to be added to the mix to avoid any cracking failures during the use phase. The higher binder content represents the maximum binder content percentage that can be added to the mix without any rutting failure. Using the software package developed by OSU-AMaP for the BMD design, the allowable binder content interval was determined to be 5.82% – 6.24%. Since a binder content variability of ±0.35% is currently allowed by ODOT during production, the BMD binder content was selected to be 6.24-0.35=5.89%. This number was revised to 5.9% for the final BMD mix design for simplicity. This process was followed to reduce the risk of rutting failure since it is a more critical failure due to the tendency to happen significantly earlier than cracking failures. The 5.9% binder content is expected to provide a CT Index that is around 54.

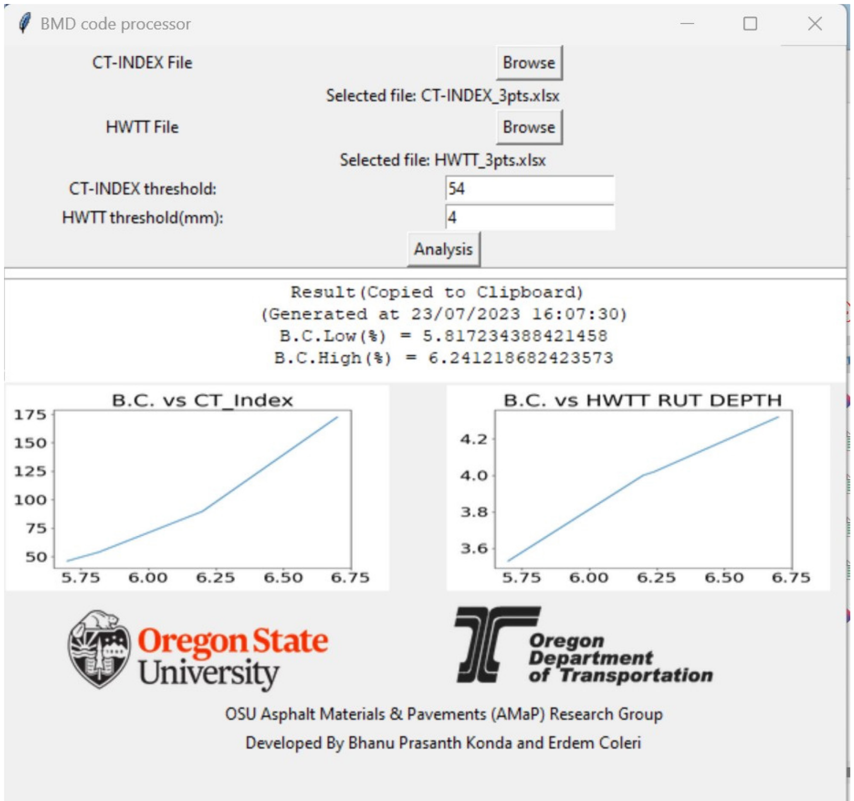


Figure 5.5: Binder content interval calculation based on quartile 3 IDT-CT and HWTT threshold.

The finalized BMD was also evaluated for its volumetric properties to ensure compliance with the ODOT specifications. To ensure the asphalt mix remains practical for construction, this step was necessary. **At the same time, ODOT is exploring the relaxation of specific volumetric requirements to support the development of more crack-resistant mixtures.** Figure 5.6 depicts the volumetric check conducted with the 3rd software package developed by OSU-AMaP and the corresponding pass and fail results (Appendix C). The software uses the mix design information such as the nominal maximum aggregate size (NMAS), the specific gravity of the aggregate (G_{sb}), the specific gravity of the binder (G_b), and the theoretical maximum specific gravity of the mix (G_{mm}). In addition, the total binder content and the dust percentage (percent passing the number 200 sieve) in the BMD mix were also entered into the software, along with the air voids. The user manual for the software is provided in the Appendix C. After performing the calculations, the software outputs the various volumetric properties for the "balanced" asphalt mixture. This includes the dust-to-binder ratio (P_{200}/P_{be}), voids in mineral aggregate (VMA), and voids filled with asphalt (VFA). These properties were later checked with the ODOT standards by the software algorithm, and a pass/fail criterion was allotted to each property depending on whether the values fell in the range. Figure 5.6 shows that the current BMD mix design successfully met all of ODOT's volumetric requirements.

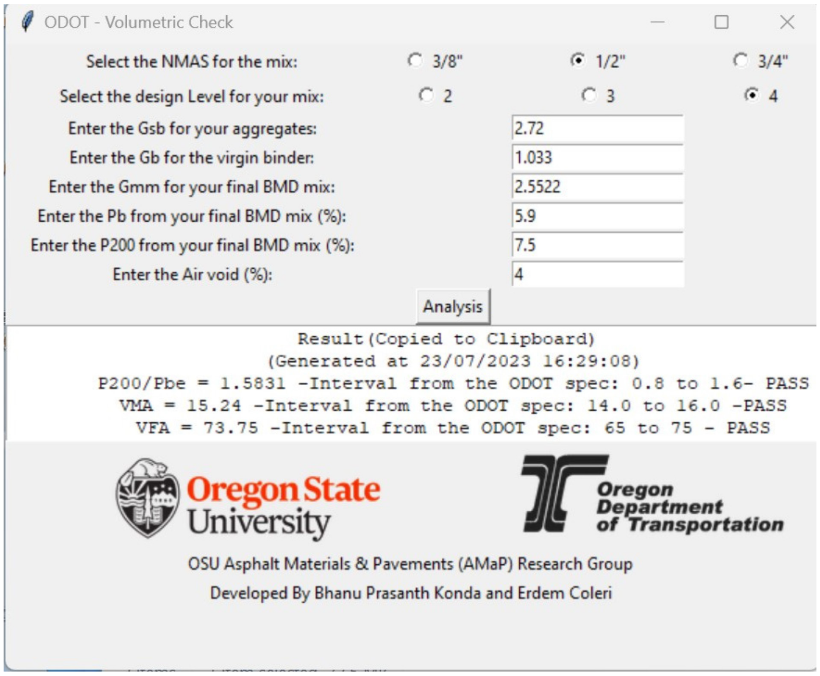


Figure 5.6: Volumetric check for the BMD mix.

This study's comprehensive analysis and results indicate a reduction in binder content from 6.2% to 5.9%. This suggests that the BMD does not always increase the binder content. Instead, incorporating performance tests in the asphalt mix design helps optimize the amount of asphalt content to provide adequate cracking and rutting performance of the asphalt mixtures. The aggregate gradations for BMD and volumetric mixes are shown in Table 5.3.

Table 5.3: Aggregate gradation for the volumetric and BMD method.

Sieve Size	Volumetric Gradation (% Passing)	BMD Gradation (% Passing)
3/4"	100	100
1/2"	95	95
3/8"	84	84.2
1/4"	69	68.6
#4	60	60
#8	41	41.4
#16	25	25.3
#30	17	16.5
#50	12	12.1
#100	10	9.6
#200	7.5	7.5
pan	0	0

Figure 5.7 shows the BMD performance diagram for the I84 - Immigrant Hill – Meacham project, which visually represents the variation of the CT Index and HWTT rut depth with respect to different binder contents. The black dashed lines on the graph represent the cracking and rutting thresholds used to determine the optimum binder content based on the BMD method. It can be observed that the CT Index threshold controls the minimum binder content required for the expected cracking performance, while the HWTT rut depth controls the maximum amount of binder content to avoid rutting failure in the asphalt pavement for this project.

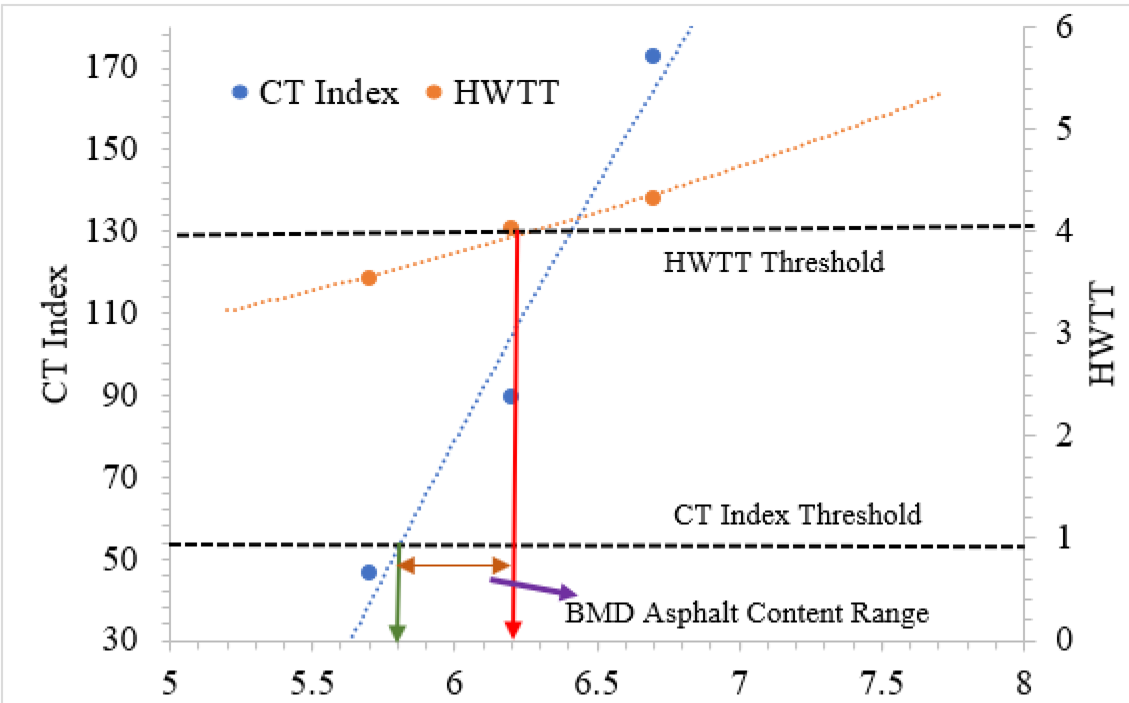


Figure 5.7: BMD performance diagram for I84 - Immigrant Hill – Meacham project.

5.4.1.2 Project 2: I5 - North Santiam – Kuebler

The binder used in this mixture design was a PG70-22ER binder. The expected mix design is a Level 4 (highest ESALs) with ½" NMAS dense gradation. Mixes for the cracking and rutting tests were prepared at three binder contents, namely 5.1%, 5.6%, and 6.1%. The 5.6% binder content was determined by the contractor as the design binder content based on the volumetric mix design process. A gradation optimization process was also followed to get closer to the ideal dense gradation. Figure 5.8 and Figure 5.9 depict the results from the IDT-CT and HWTT tests, respectively.

The asphalt mix at the volumetric mix design binder content had a low CT Index, which suggests it is highly susceptible to cracking failure. It also suggests that the binder content (5.6%) from the volumetric mix design process resulted in high (excessive) rutting resistance. Overall, the mixtures may be too dry if produced by following the volumetric mix design, leading to early cracking failure.

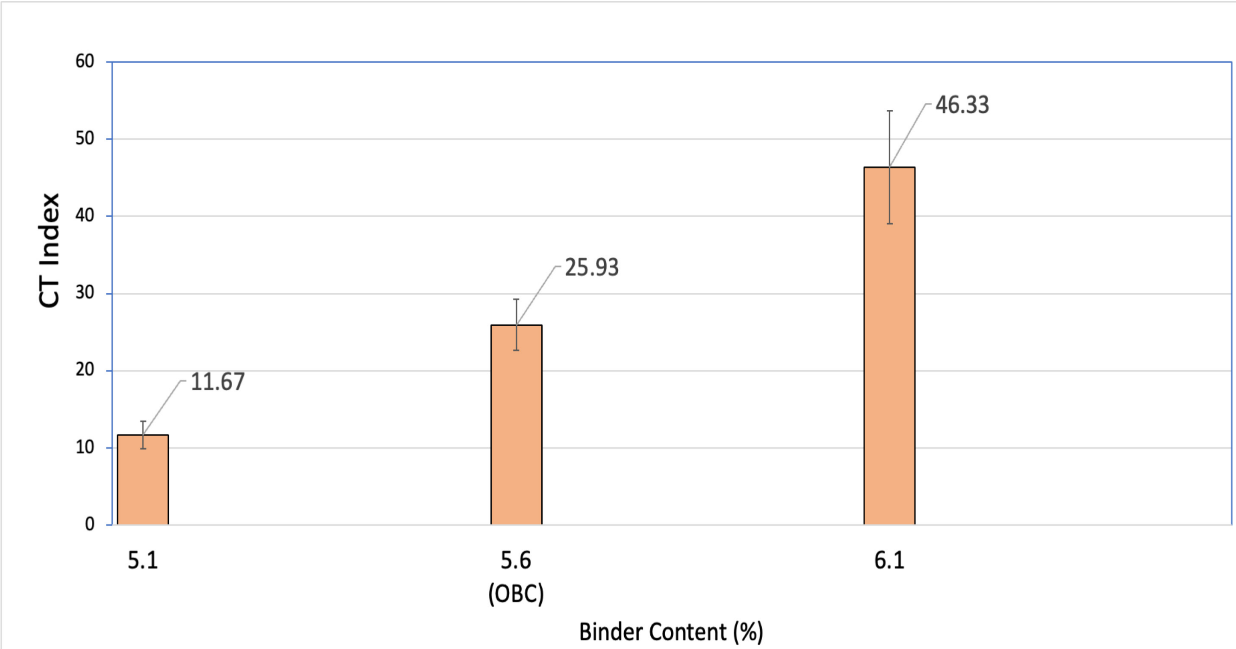


Figure 5.8: IDT-CT results for I5 - North Santiam – Kuebler (error bar = 1 standard deviation).

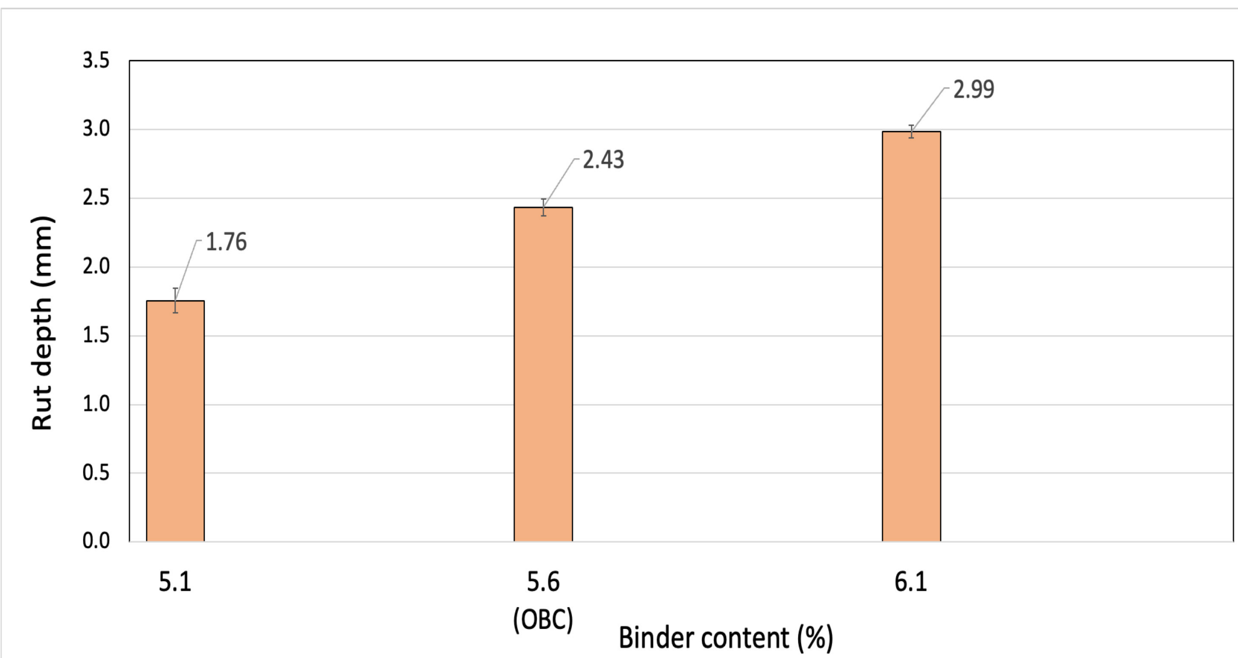


Figure 5.9: HWTT results for I5 - North Santiam – Kuebler (error bar = 1 standard deviation).

For this construction project, the values corresponding to the median (Quartile 2) threshold were used for the BMD process. This Quartile 2 threshold is more conservative for rutting-related failures (with a rut depth limit of 3.3mm) compared to the Quartile 3 BMD threshold (4mm) used for the I84-Meacham project. This Quartile was selected to have a variety of thresholds in this study to evaluate the impact of different design reliability levels on the long-term field performance of the pilot sections. The thresholds of 3.3 mm and 41 were selected for HWTT rut depth and CT Index, respectively, to calculate the required binder and RAP content, as well as gradation based on the BMD process.

Based on the BMD process, the allowable binder content interval was determined to be 5.96% – 6.28%. Since a binder content variability of ±0.35% is currently allowed by ODOT during production, the BMD design binder content was selected to be 6.28-0.35=5.93%. For simplicity, this number is revised to 5.9% for the final BMD mix design. Although 5.9% is expected to provide a CT Index slightly less than the cracking threshold (41) thresholds, it is expected to result in a mix with a lower likelihood of premature rutting failure.

Table 5.4 describes the aggregate gradation selected for the volumetric and BMD sections. Adjustments were made to the gradation from the volumetric process to get closer to the ideal target values and reduce the dust content (percent passing #200 sieve). Later, the impact of the gradation on potential cracking resistance was checked by running some trial IDT-CT tests and using the BMD software. Performance diagrams, similar to the I84-Meacham project, were developed using the software shown in Figure 5.5. The final BMD design was again checked for the ODOT's volumetric requirements using the software shown in Figure 5.6. The BMD mix met the volumetric requirements of ODOT. Software outputs for this BMD case are not shown here for brevity.

Table 5.4: Aggregate gradation for volumetric and BMD for I5 – Kuebler Santiam project.

Sieve size	Volumetric Gradation (% Passing)	BMD Gradation (% Passing)
3/4"	100	100
1/2"	98	97.4
3/8"	84	81.2
1/4"	60	59.2
#4	53	52.7
#8	38	35.9
#16	25	22.7
#30	16	15.1
#50	12	10.3
#100	9	7.4
#200	6.4	5.1
pan	0	0

5.4.1.3 Project3: OR18 – McMinnville

The binder used in this mixture design was a PG70-22ER binder. The expected mix design is a Level 4 (highest ESALs) with ½" NMAS dense gradation. Specimens for the cracking and rutting tests were prepared at three binder contents, 5.5%, 6.0%, and 6.5%, where 6.0% asphalt reflected the optimum binder content based on the volumetric mix design approach. Figure 5.10 and Figure 5.11 depict the IDT-CT and HWTT test results. The median threshold levels (Quartile 2) for Level 4 mixes were 41 and 3.3 mm for cracking (IDT-CT) and rutting (HWTT), respectively, selected for this construction project. From Figure 5.10 and Figure 5.11, it is seen that the 6.0% binder resulted in the CT index higher than the considered thresholds. Additionally, the HWTT rut depth is lower than 3.3 mm. This suggests that there is scope for a reduction in the binder content. The allowable binder content interval was 5.91% – 6.24%. Since a binder content variability of ±0.35% is currently allowed by ODOT during production, the BMD design binder content was selected to be 6.24-0.35=5.89%. This number was revised to 5.9% for the final BMD mix design for simplicity. Based on the volumetric mix design system, this binder content was 0.1% less than the optimum.

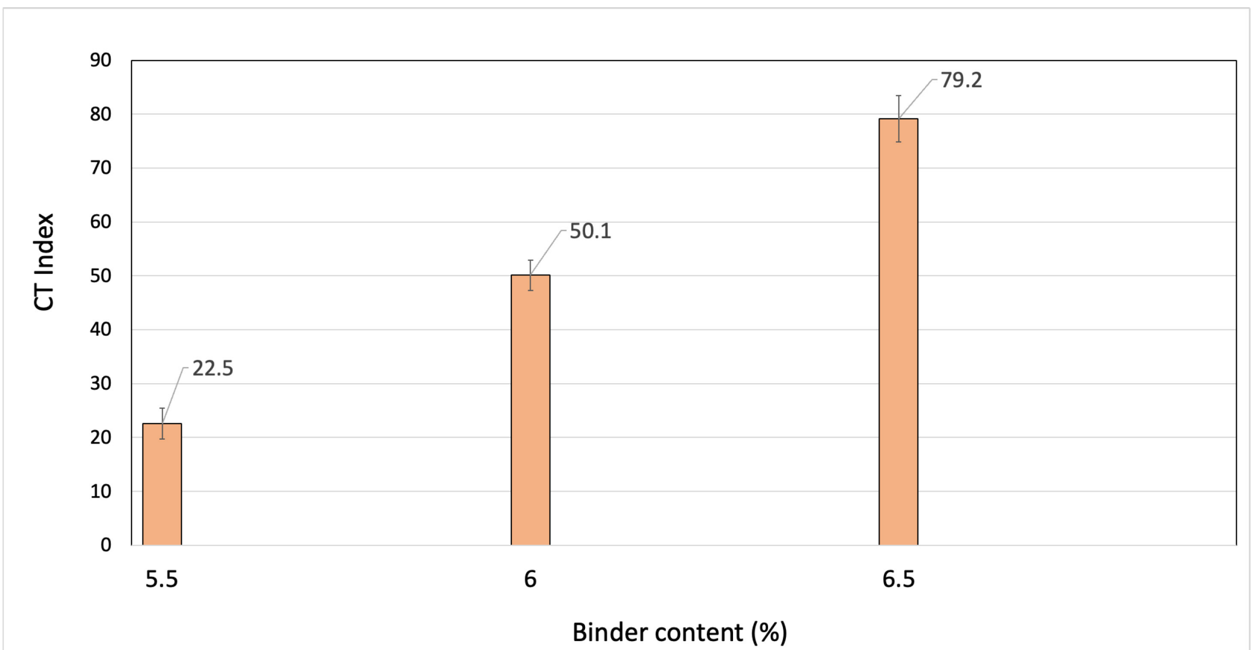


Figure 5.10: IDT-CT results for OR18-McMinnville (error bar = 1 standard deviation).

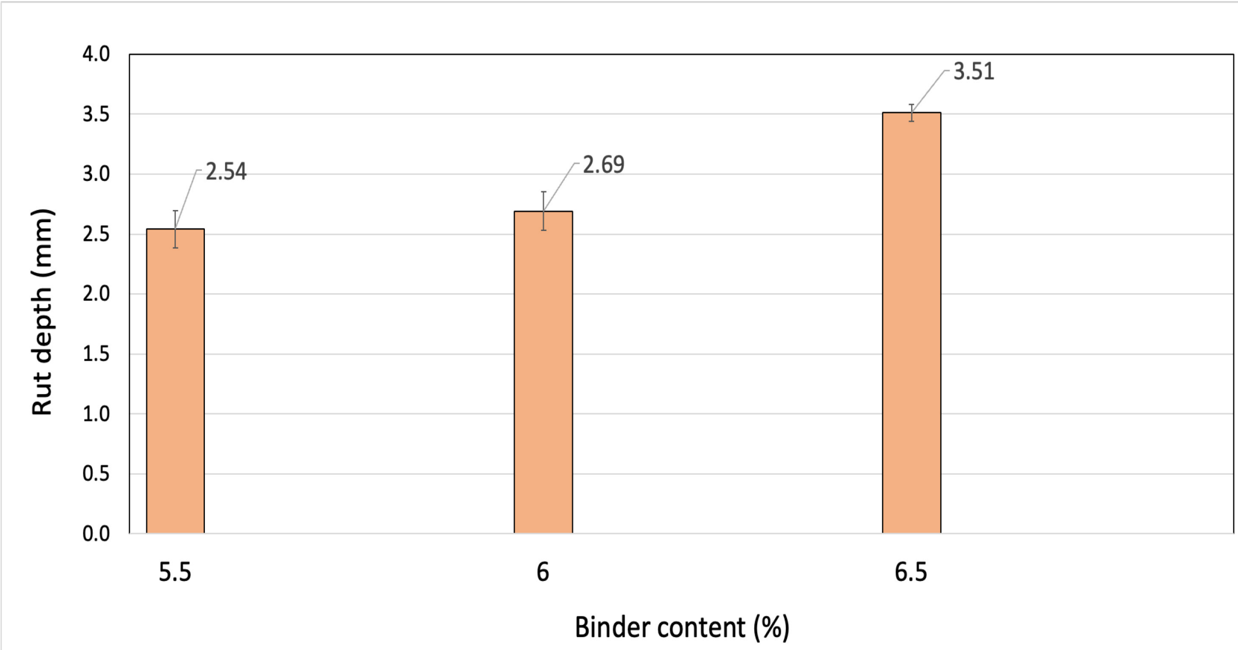


Figure 5.11: HWTT results for OR18-McMinnville (error bar = 1 standard deviation).

5.4.1.4 Project 4: I5 - North Ashland – South Ashland

The binder used in this mixture design was a PG76-22ER. This binder is significantly stiffer than those used for all four other construction projects. The reason for using this stiffer binder was to improve the rutting resistance to combat the warmer climate around the California border. The expected mix design is a Level 4 (highest ESALs) with ½" NMAS dense gradation. The specific gravity for the binder was measured to be 1.033. Specimens for evaluating the cracking and rutting tests were prepared at three binder contents: 5.7%, 6.2% (OBC), and 6.7%. In addition to this, the RAP percentage increased from 15% to 17.5%. Figure 5.12 and Figure 5.13 depict the IDT-CT and HWTT results.

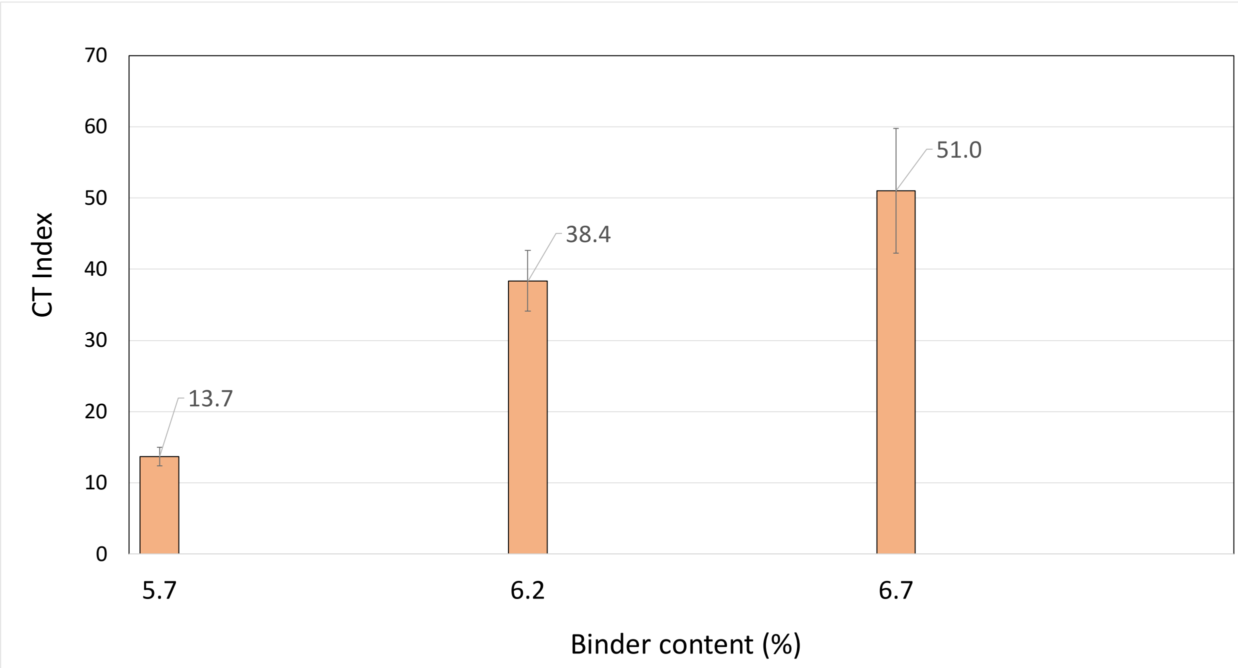


Figure 5.12: IDT-CT results for I5-North Ashland – South Ashland (error bar = 1 standard deviation).

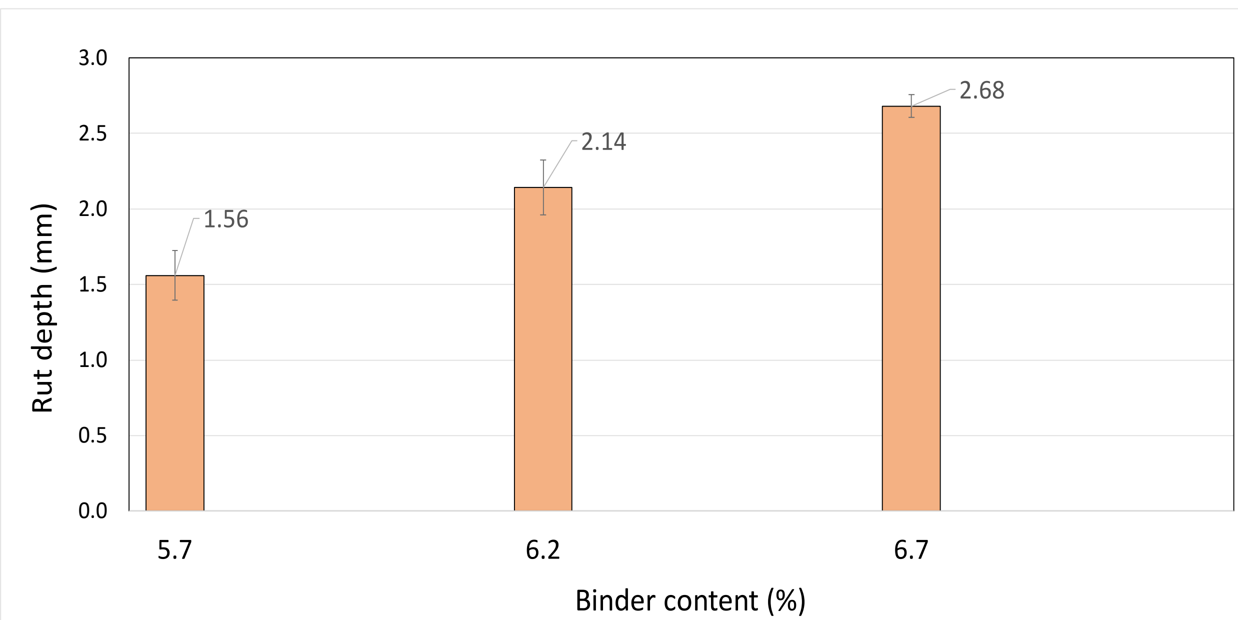


Figure 5.13: HWTT results for I5-North Ashland – South Ashland (error bar = 1 standard deviation).

The statistical analysis and laboratory testing determined that the PG76-22ER binder results in a low CT Index and is highly susceptible to cracking. However, this binder grade was found to enhance the rutting performance of the asphalt mix, resulting in a lower HWTT rut depth. However, the measured rut depths shown in Figure 5.13 prove that rut resistance is excessive (significantly lower rut depth than the 12.5mm threshold adapted by various state DoTs).

Based on the statistical analysis, the thresholds for Level 4 mixes with PG76-22ER binder corresponding to the median quartile (Quartile 2) were 40 and 2.8mm for cracking (IDT-CT) and rutting (HWTT), respectively. Using the BMD design software package developed by OSU-AMaP, the allowable binder content interval was determined as 6.40% – 6.82%. Since a binder content variability of ±0.35% is currently allowed by ODOT during production, the BMD design binder content was selected to be 6.82-0.35=6.47%. This number was revised to 6.4% for the final BMD mix design for simplicity.

The final BMD mix design was also checked in terms of volumetrics to ensure it follows all the volumetric requirements of ODOT standards. Figure 5.14 describes the results from the volumetric check. It was determined that the voids filled with asphalt (VFA) did not meet ODOT specifications and slightly exceeded the range. Since the BMD mix barely exceeded the voids filled with asphalt (VFA) limits set by ODOT, a binder content reduction of 0.1% was recommended, and the final design binder content was revised to 6.3%. This adjustment resulted in a mix that meets the VFA requirement. The recommended binder content was 0.1% higher than the volumetric binder content. Similar to some of the earlier projects, minor adjustments were made to the volumetric gradation to reach the target gradations. Table 5.5 illustrates the volumetric and the BMD aggregate gradation utilized for the current project.

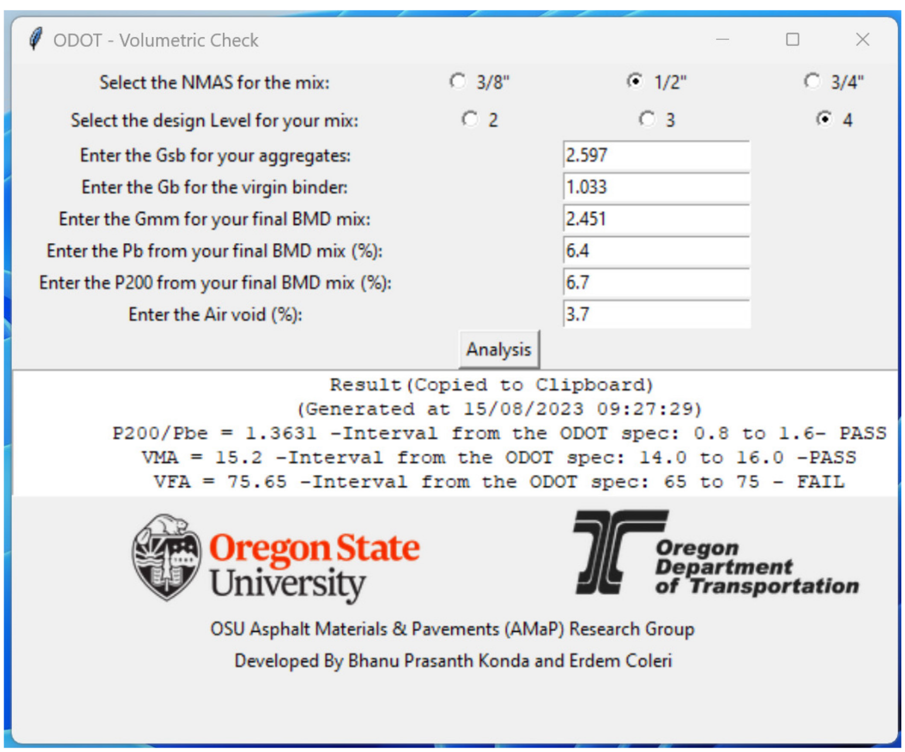


Figure 5.14: Volumetric check for I5-North Ashland – South Ashland.

Table 5.5: Aggregate gradation for volumetric and BMD for I5-North Ashland – South Ashland project.

Sieve size	Volumetric Gradation (% Passing)	BMD Gradation (% Passing)
3/4"	100.0	100.0
1/2"	95.0	94.4
3/8"	81.0	80.1
1/4"	60.0	60.0
#4	51.0	48.7
#8	33.0	31.6
#16	22.0	21.5
#30	16.0	15.3
#50	12.0	11.6
#100	9.0	9.0
#200	6.4	6.7
pan	0	0

5.4.1.5 Project 5: US26 - Salmon River – Zigzag

The binder used in this mixture design was a PG64-22 binder. This binder type is commonly used for Level 3 mixes in Oregon. The specific gravity for the binder was measured to be 1.035. The mix design is a Level 3 with ½" NMAS dense gradation. Specimens for the cracking and rutting tests were prepared at three binder contents: 5.3%, 5.8%, and 6.3%. The optimum binder content for this project, based on the volumetric approach, was 5.3%. This binder content was significantly lower than the other Level 3 projects, so the research team decided to use optimum binder content (OBC), OBC+0.5%, and OBC+1% as the trial BMD binder contents. Figure 5.15 and Figure 5.16 depict IDT-CT and HWTT results for those binder contents.

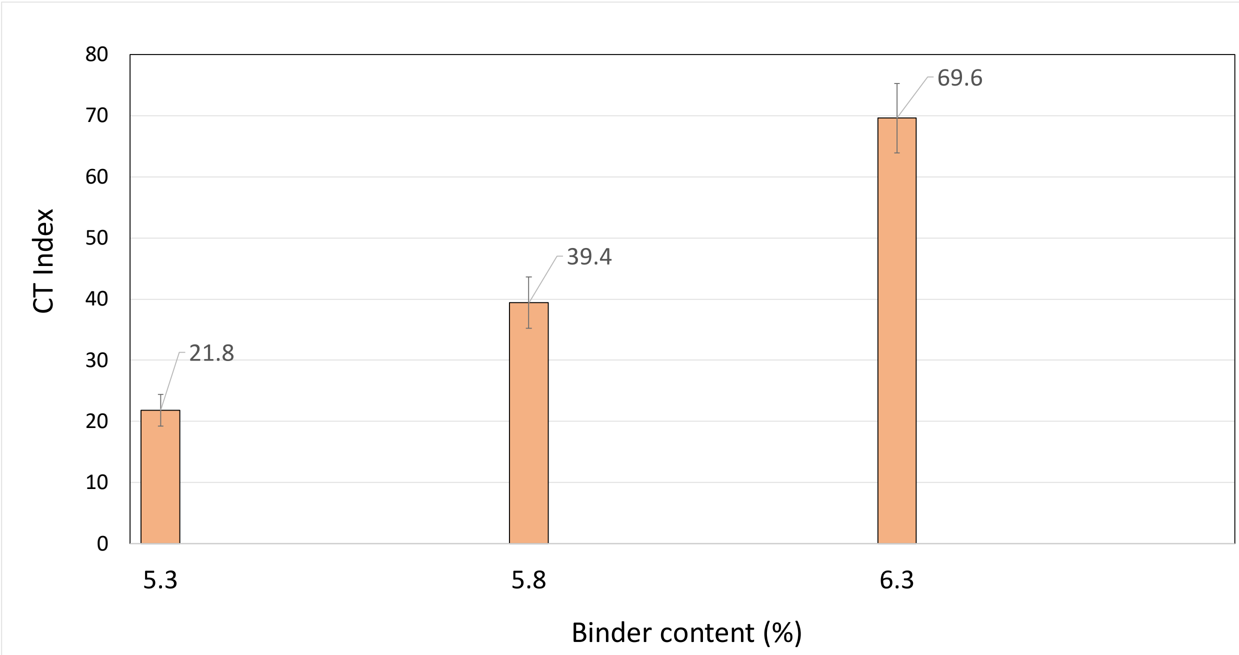


Figure 5.15: IDT-CT results for US26-Salmon River – Zigzag (error bar = 1 standard deviation).

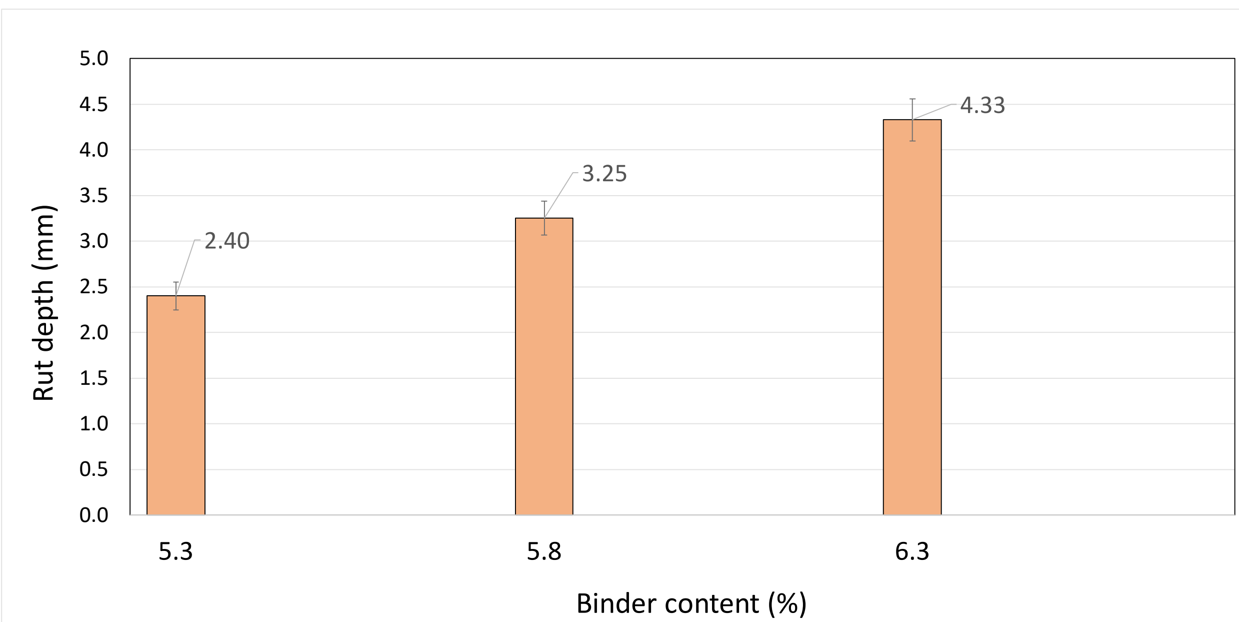


Figure 5.16: HWTT results for US26 - Salmon River – Zigzag (error bar = 1 standard deviation).

The thresholds for Level 3 mixes with the PG64-22 binder were 69 and 4.0mm for cracking (IDT-CT) and rutting (HWTT). These values were determined from the median quartile (Quartile 2) for Level 3 projects. Using the BMD design software package developed by OSU-AMaP, the allowable binder content was determined to be 6.14%.

Since a binder content variability of ±0.35% is currently allowed by ODOT during production, the BMD design binder content was selected to be 6.14-0.35=5.79%. This number was revised to 5.8% for the final BMD mix design for simplicity.

Table 5.6 describes the aggregate gradation utilized for the volumetric and BMD sections. As the volumetric gradation had a high dust content, adjustments were made to create a coarser gradation with less dust content. The final BMD mix design was also checked regarding volumetrics to ensure it follows all the volumetric requirements of ODOT. It was determined that the mix with 5.8% binder content did not meet the volumetric requirements and had a slightly higher VFA than the ODOT requirements (75.6%, exceeding the 75% ODOT limit). The binder content was revised to get the mix to satisfy the volumetric criterion, and the binder content was reduced by 0.1%. Thus, this project's final recommended BMD binder content was 5.7%. The suggested binder content was 0.4% higher than the volumetric binder content.

Table 5.6: Aggregate gradation for volumetric and BMD for US26 - Salmon River - Zigzag project.

Sieve size	Volumetric Gradation (% Passing)	BMD Gradation (% Passing)
3/4"	100	100
1/2"	96	95.9
3/8"	82	81.5
1/4"	60	61.5
#4	52	53.6
#8	36	38
#16	24	24.9
#30	17	17.2
#50	13	11.9
#100	9	8.6
#200	6.4	5.6
pan	0	0

5.4.1.6 Final recommendations based on the performance of LMLC specimens

Following the comprehensive testing of samples to evaluate cracking and rutting performance, the appropriate binder content range for each of the five projects was established, guided by thresholds derived from the initial statistical analysis conducted and presented in Chapter 4.0. This section summarizes the final recommendations provided to the contractors for all five projects. The pilot sections were constructed following the recommended binder contents and aggregate gradations. Table 5.7 summarizes the volumetric and BMD binder content for the pilot section construction. Moreover, it illustrates the different CT Index and HWTT rut depth thresholds utilized to develop the BMD binder content. From the table, it is evident that, among the five projects selected for the implementation phase of the BMD process, three required a substantial adjustment in binder content (≥0.3%). This adjustment was necessary to optimize the long-term performance and durability of the asphalt pavements. Interestingly, the required adjustment in two of these projects involved reducing the binder content. By fine-tuning the binder content based on performance testing rather than relying solely on traditional volumetric parameters, the BMD process ensures that pavements are designed with economic efficiency and longevity in mind. This approach represents a significant shift towards more sustainable and cost-effective pavement construction practices, demonstrating the BMD's ability to adjust mix designs to meet specific performance criteria while considering the economic implications.

However, it should be noted that the rut depth thresholds determined (Chapter 4.0) and used for the BMDs in this study were based on the statistics from the previous ODOT asphalt mixture designs by using the volumetric methods. Those rut depth thresholds were significantly lower than the national averages. It is recommended that for the next pilot projects during the summer of 2026, those rut depth thresholds should be increased to determine their in-situ rut resistance (to the levels ranging from 5mm to 7mm). **The OSU-AMaP research team strongly believes that the binder content of the Oregon asphalt mixes can be further increased to improve cracking resistance while still not observing any premature rutting failures in the field.**

Table 5.7: Final recommendations provided for the BMD asphalt mix.

Highway ID	Binder Types	Optimum Binder Content (OBC %)	BMD Binder Content (%)	Quartile	Thresholds CT Index	Thresholds Rut Depth (mm)
I84 - Meacham	PG70-28ER	6.2	5.9	3	54	4.0
I5 - Kuebler	PG70-22ER	5.6	5.9	2	41	3.3
OR18 - McMinnville	PG70-22ER	6.0	5.9	2	41	3.3
I5 - Ashland	PG76-22ER	6.2	6.3	2	40	2.8
US26 - Salmon River	PG64-22	5.3	5.7	2	69	4.0

5.4.2 DISCUSSION ON PMLC SPECIMENS

While the BMD process provided a recommended binder content designed to enhance field performance, verifying the expected mix performance with the actual production mix test results is crucial. This step is critical to assessing the real-world applicability of the BMD approach and its impact on the long-term performance of asphalt pavements. To ensure a comprehensive comparison, asphalt mixtures were either grade-sampled or plant-sampled during the construction of pilot sections. These samples allowed for a direct comparison between the mixes designed volumetrically and those designed using the BMD approach. They also allowed for a comparison between the expected laboratory performance of BMD mixes and the actual performance of the BMD production mixes. As stated previously, the sampling process involved collecting loose asphalt mixture in cardboard boxes, which were then transported to the laboratory for detailed testing and analysis.

It is important to note that the volumetric and BMD asphalt mixtures were obtained for three projects: I5-Kuebler Santiam, I5-North South Ashland, and US26-Salmon River Zigzag. However, for I84-Meacham, the volumetric optimum binder content of 6.2% resulted in some compaction issues during the initial construction phase. To address this issue, the contractor decided to follow the BMD recommendations and reduced the asphalt binder content to the BMD-recommended 5.9%. Consequently, for further laboratory testing, only the asphalt mix prepared following the BMD approach was collected for evaluation. Similarly, the OR18-McMinnville project had a 0.1% difference between the volumetric and BMD binder content, while the plant's expected production binder content variability was ±0.35%. Hence, the BMD and volumetric mix designs were accepted to be similar, and only the BMD mix was sampled from the plant. The performance of these projects, which utilized only BMD mixes, was assessed by comparing their outcomes considering the established cracking and rutting thresholds decided in Chapter 4.0. The outcomes of all the projects are described in the next sections.

5.4.2.1 Project 1: I84-Immigrant Hill – Meacham

Figure 5.17 depicts the BMD production mix outputs with respect to the BMD performance thresholds. The production mix passed the design threshold values for the HWTT rut depth and was lower than the established threshold. The BMD suggested binder content was expected to improve the cracking resistance and result in a higher CT Index. However, the production mix (PMLC samples) produced with the BMD binder content failed to pass the CT Index threshold criteria, even though the LMLC specimens passed. The potential reasons for the lower CT Index value can be the production binder content variability (±0.35% variability is currently allowed in Oregon) or the difference between the laboratory and plant mixture production processes. Since this type of lower CT Index value was commonly observed from the production mixes (PMLC samples) when compared to the laboratory-produced specimens (LMLC samples), the research team believes that the RAP blending issue is the major reason for getting lower CT Index values. Most of the asphalt plants in Oregon are indirectly heating the RAP using superheated aggregates coming from the drum. This process may not uniformly heat RAP material to the level (121ºC) achieved in the laboratory using calibrated ovens (or may excessively heat and burn the binder on the surface of the RAP aggregates). For this reason, alternative RAP heating methods should be investigated in a future study (which are currently being investigated in a recently awarded ODOT research project, SPR887). Running the RAP through a collar in the drum and heating it without exposing the material to direct drum flames might be one option to improve the production process and increase the RAP blending percentage. Another method might be to use a separate RAP heating system to reach the exact temperatures in a shorter period. The latter has a productivity advantage by not increasing the production time. However, separately heating the RAP also requires additional energy and creates emissions.

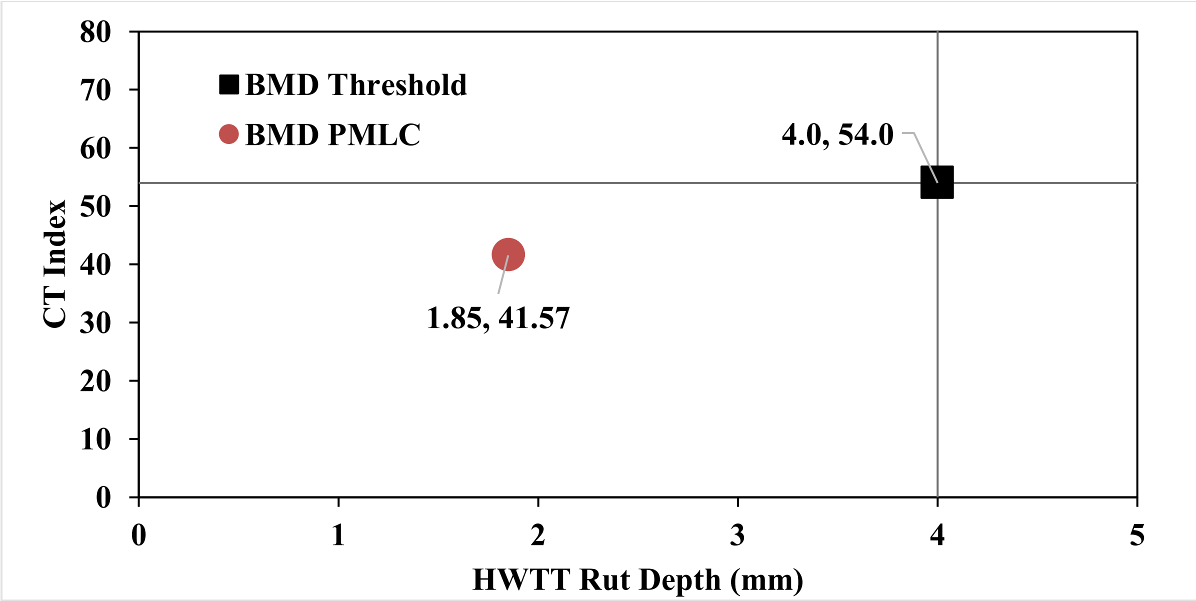


Figure 5.17: Performance diagram for production mix testing (I84-Meacham project).

5.4.2.2 Project 2: I5 – North Santiam - Kuebler

Figure 5.18 and Figure 5.19 show the CT Index and HWTT results for both volumetric and BMD production mixes. It was found that the BMD production mix achieved a significantly higher CT Index than the designed thresholds, underscoring an enhanced resistance to cracking due to the increased binder content. As stated previously, the BMD binder content based on the laboratory experiments was 5.9%. Considering a ±0.35% variability for the plant production, the plant-produced asphalt mix should have a binder content in the range of 5.55% - 6.25%. However, the production data obtained from the plant indicated that the plant-produced mixes exceeded this range and had 6.48% binder content in the mix (determined by laboratory binder extraction). This may be one of the primary reasons for a higher CT Index and, consequently, the cracking resistance for the production mix tested in the laboratory. Although the mix designed via the volumetric approach also surpassed the CT Index threshold, indicating satisfactory cracking resistance, it did so with a margin just above the design threshold of 41. This suggests that while both approaches yielded mixes with CT Index values above the suggested tentative thresholds, the BMD method provided a notably higher margin of safety against cracking failures.

Figure 5.19 reveals that the volumetric production mix exhibited a lower rut depth than the design expectation and the recommended value, indicating excessive rutting resistance. Despite having significantly high binder content in the BMD PMLC mixes, the rut depth for the BMD PMLC mix was found to be within the prescribed thresholds (i.e., 3.3 mm). Nevertheless, it should be noted that the 3.3 mm rut depth from the HWTT is still significantly lower than the national average and should be gradually increased in future pilot studies. **This result shows that Level 4 mixes can still take more asphalt binder without resulting in rutting failures.** The cracking and rut depth thresholds provided in this study (**Table 4.4**) should be gradually increased to improve long-term cracking resistance.

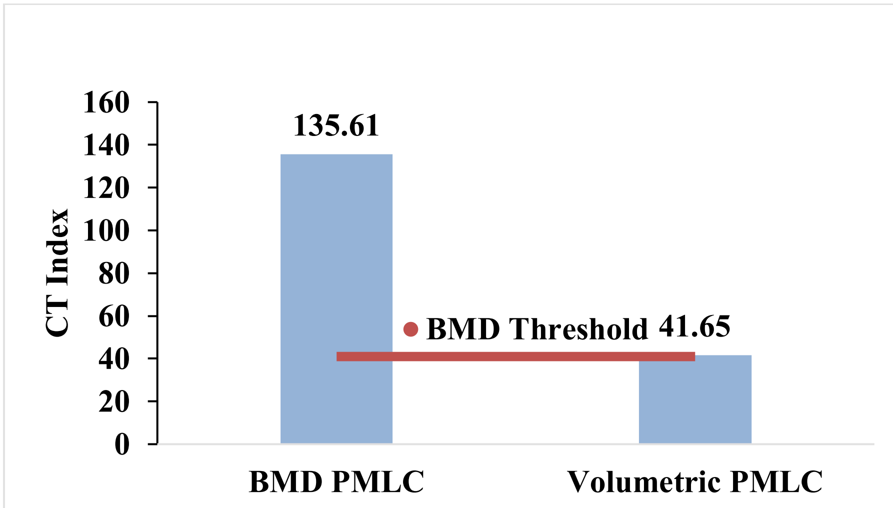


Figure 5.18: CT Index results for production mix from I5-Kuebler project.

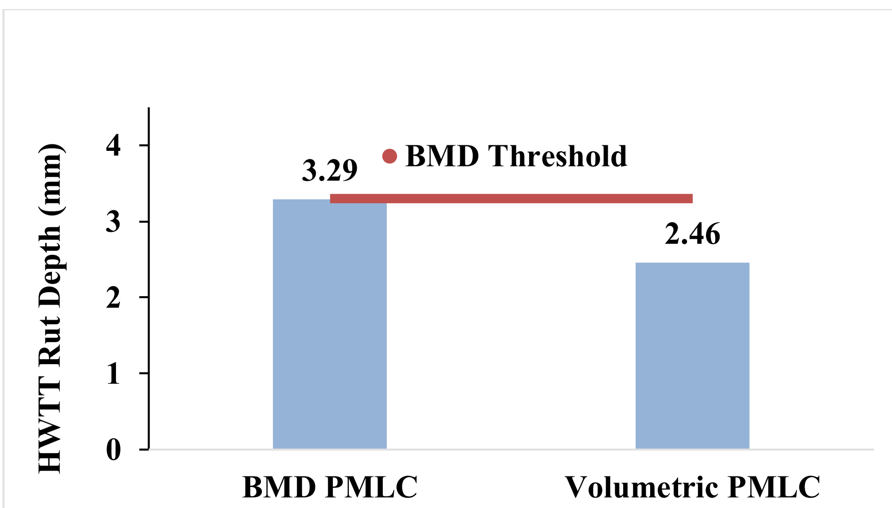


Figure 5.19: HWTT results for production mix from I5-Kuebler project.

Figure 5.20 presents a detailed performance analysis for Project 2, examining its compliance with established cracking and rutting thresholds. According to the diagram, the BMD mix meets the cracking resistance and rutting susceptibility criteria. The HWTT results were notably close to the rutting threshold, while the cracking resistance was significantly higher.

An intriguing observation from Figure 5.20 is the discrepancy in the Cracking Test (IDT-CT) performance between the laboratory-designed volumetric mix and its production counterpart. Initially, the volumetric mix failed to surpass the IDT-CT threshold during laboratory testing at its specified binder content (5.6%), suggesting inadequate cracking resistance. Contrarily, when produced and tested from actual production samples, the same mix passed the specified threshold value, demonstrating sufficient cracking resistance. This emphasizes the importance of validating laboratory mix designs with actual production and performance data to ensure that the designed mixes truly reflect their expected performance in the field. This approach can lead to more reliable and durable pavement structures, accommodating real-world variations that laboratory tests may not fully capture due to the production variability at the plant level. **That said, the production binder content that is about 0.6% higher than the BMD JMF (5.9% recommended versus the 6.5% from the plant) with no premature rutting failures with in the first two summers clearly tells us that the asphalt mixtures can still have significantly higher binder contents and the current BMD thresholds should be revised to achieve higher binder contents without having early rutting failures. However, lower binder contents can still be used for areas with slower traffic and expected traffic congestion.**

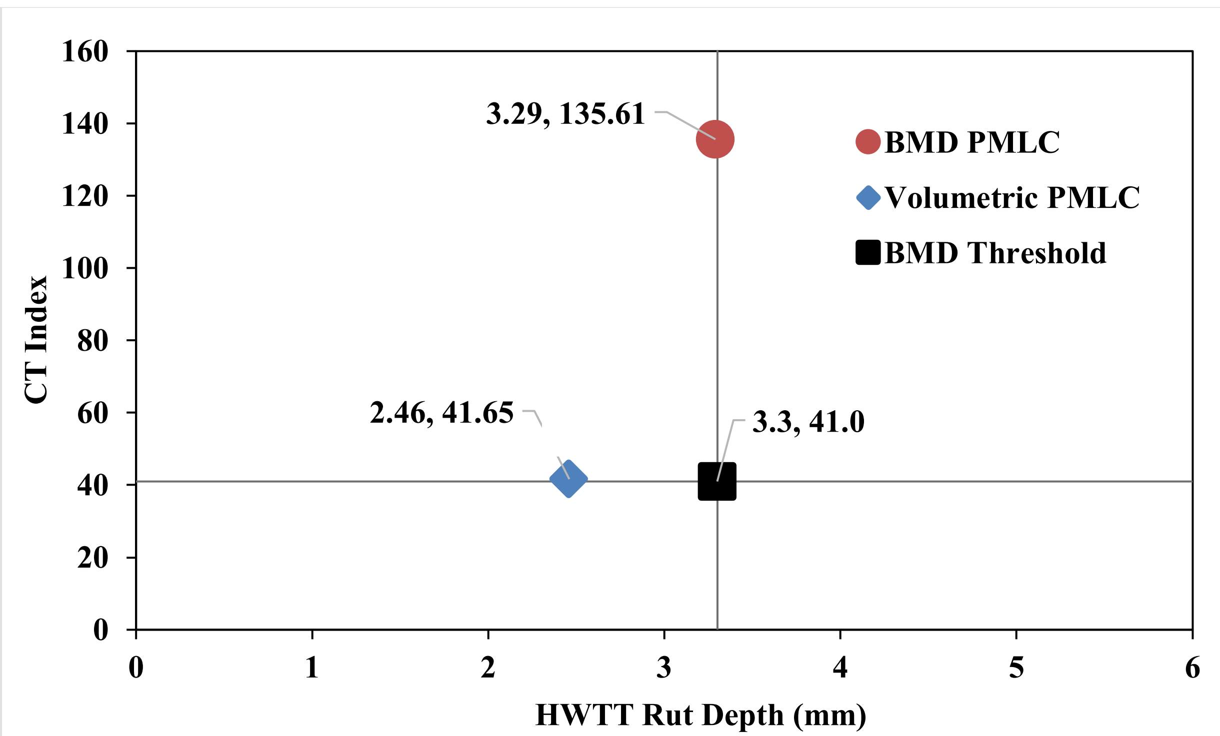


Figure 5.20: Performance diagram for production mix testing (I5-Kuebler project).

5.4.2.3 Project 3: OR18 – McMinnville

For the OR18 – McMinnville project, the CT Index for the samples from the production mixes did not meet the designed threshold of 41, as shown in Figure 5.21. However, these mixes passed the benchmarked rutting values (i.e., 3.3 mm) and exhibited an average rut depth of 2.38 mm. Since the rut depth of the BMD mixes was lower than the specified threshold value, there is a window for increasing the binder content, which eventually lowers the possibility of cracking on the pavement. However, cost being a concern, there can be further adjustments in the RAP content and binder grade, but the assessment of these variations is out of the scope of the research work and should be explored in the future for constructing durable as well as cost-effective asphalt pavements.

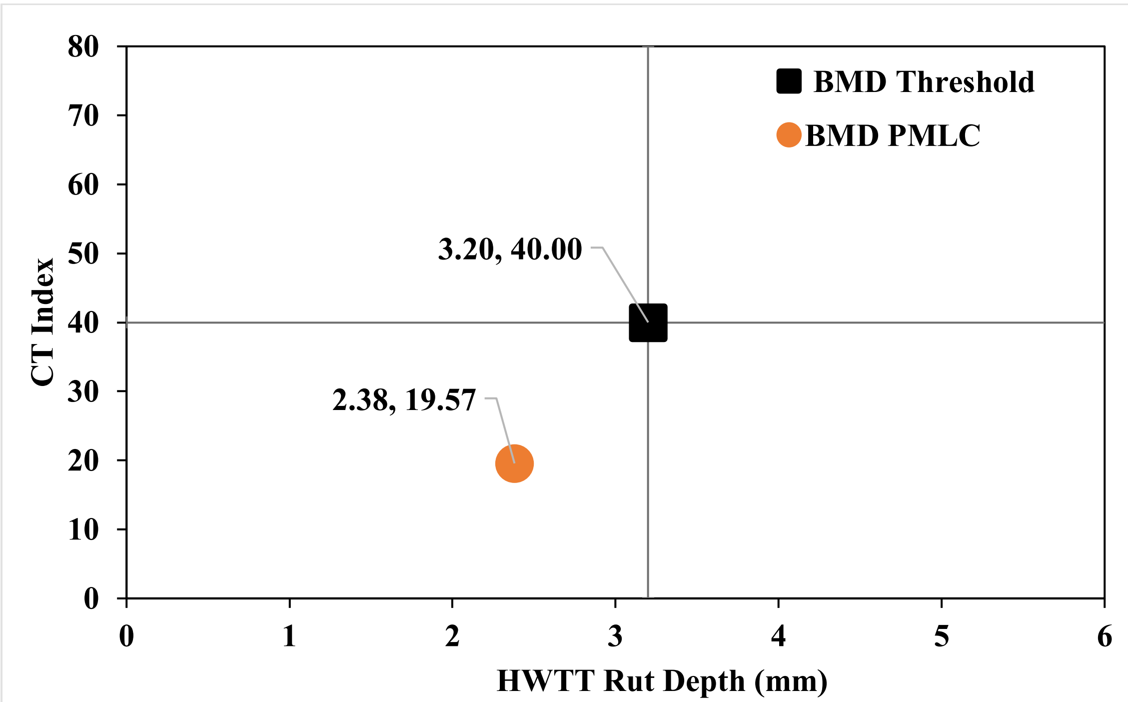


Figure 5.21: Performance diagram for production mix testing.

5.4.2.4 Project 4: I5–North Ashland – South Ashland

For the I5 North Ashland – South Ashland project, the volumetric binder content was 6.2%, and the BMD binder content was 6.3% after adjusting for the variability of the plant-produced mix. The volumetric mix design had a 15% RAP content, while the BMD had 17.5%.

Figure 5.22 and Figure 5.23 illustrate the production mix's IDT-CT and HWTT results. Similar to the previous project, this project also did not pass the CT Index threshold, while the HWTT rut depth values were lower than the designed threshold for both the volumetric and balanced mix design production mix. Figure 5.24 depicts the performance diagram for the production mix. From the figure, it is evident that the mix designed using a traditional volumetric process with a lower binder content exhibited a higher CT Index and HWTT rut depth than the mix optimized through the BMD approach. This result is expected to be a result of the plant production variability. The BMD mix's 0.1% higher binder content may be expected to compensate for the negative cracking resistance impact of the higher RAP content in the laboratory evaluations. However, in Oregon, a

±0.35% variability in binder content is allowed at the production. On the day of the BMD mix production, the binder content may be less than the 6.3% target, while the binder content for the volumetric mix could be higher than the 6.2% target. A similar variability is also expected for the RAP content in plant production, which might be affecting the results.

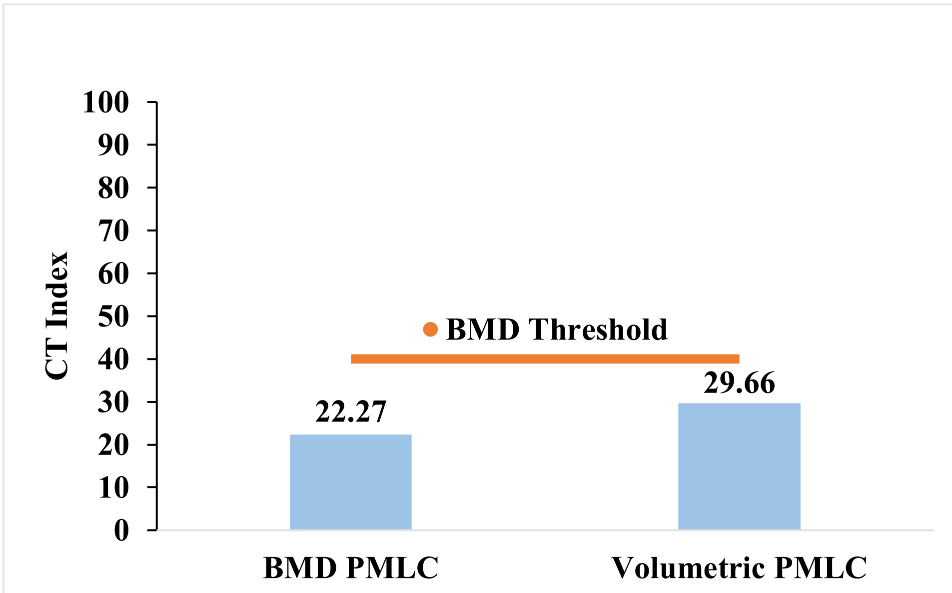


Figure 5.22: IDT-CT results for production mix from the I5-North – South Ashland project.

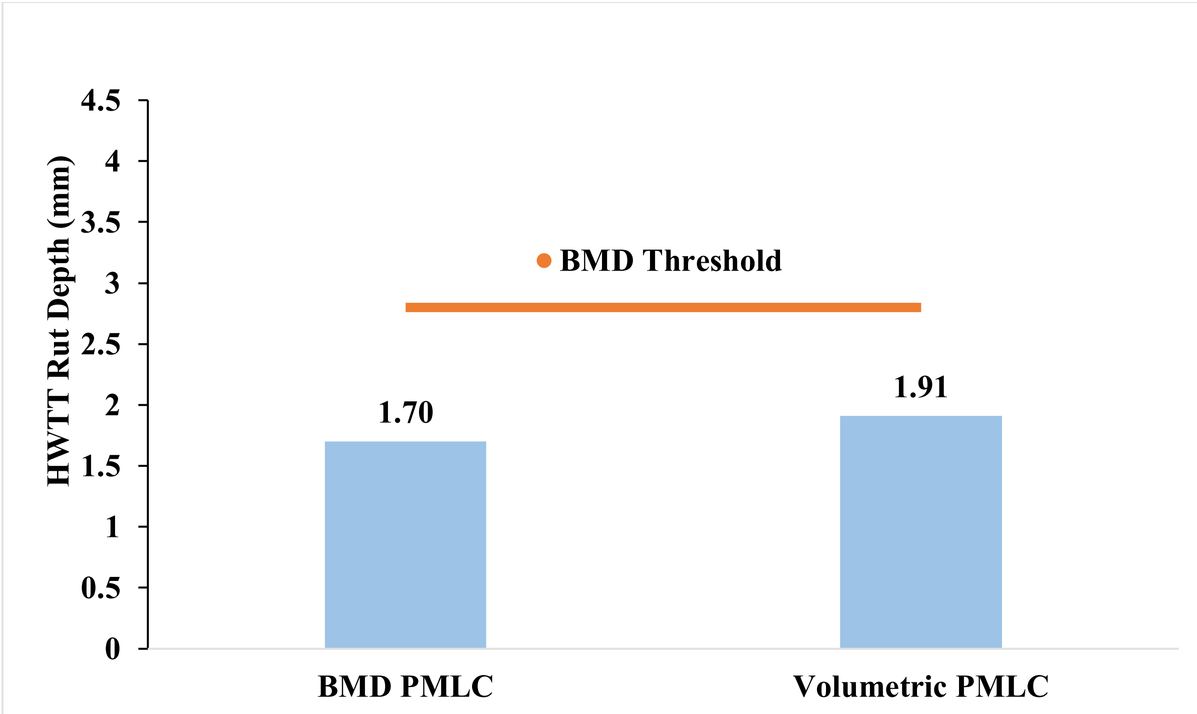


Figure 5.23: HWTT results for production mix from the I5 - North – South Ashland project.

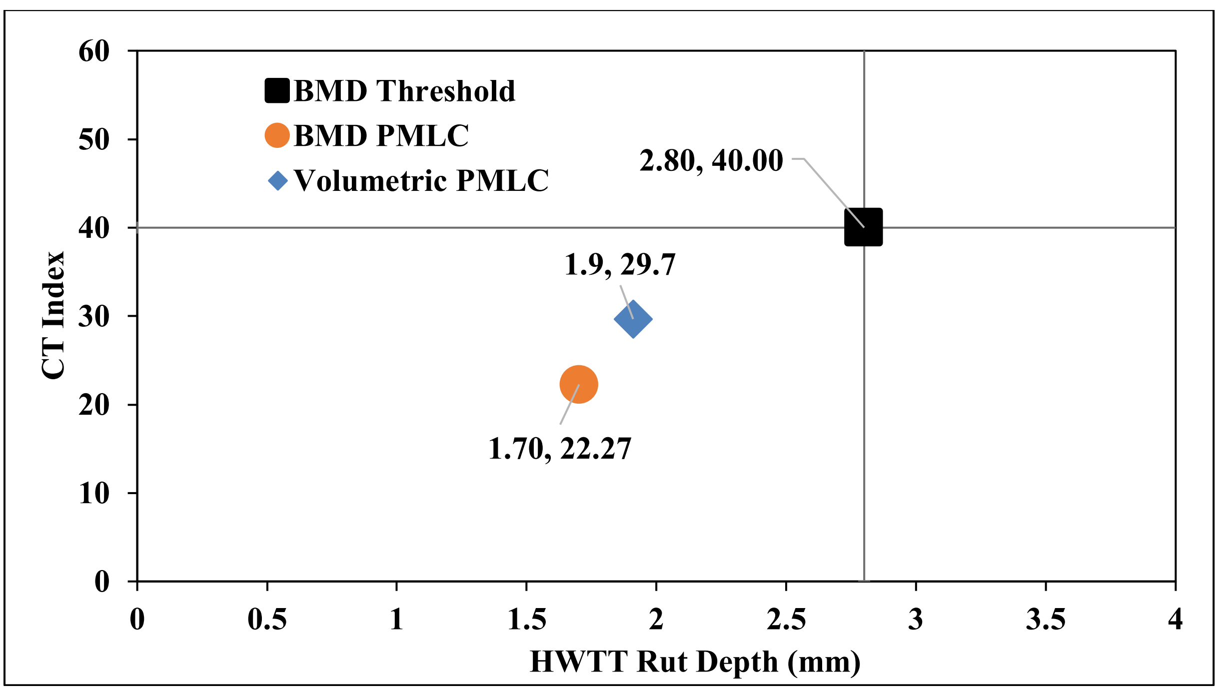


Figure 5.24: Performance diagram for production mix testing (I5 - North – South Ashland project).

5.4.2.5 Project 5: US26–Salmon River – Zigzag

Figure 5.25 and Figure 5.26 represent IDT-CT and HWTT results of the production mixes prepared for the US26 – Salmon River – Zigzag project. As is evident, the volumetric mix design resulted in a very low CT Index and high rut depth. On the contrary, the CT Index for the BMD PMLC mixes was lower than the designed threshold but higher than the PMLC mixes produced using the volumetric mix design approach. It was also found that the HWTT rut depth for the BMD production mix was lower than the threshold specified for this project, i.e., 4 mm, as presented in Figure 5.26. The results indicate that the BMD approach yields better performance in terms of cracking and rutting and is expected to survive longer than the volumetric mix design process.

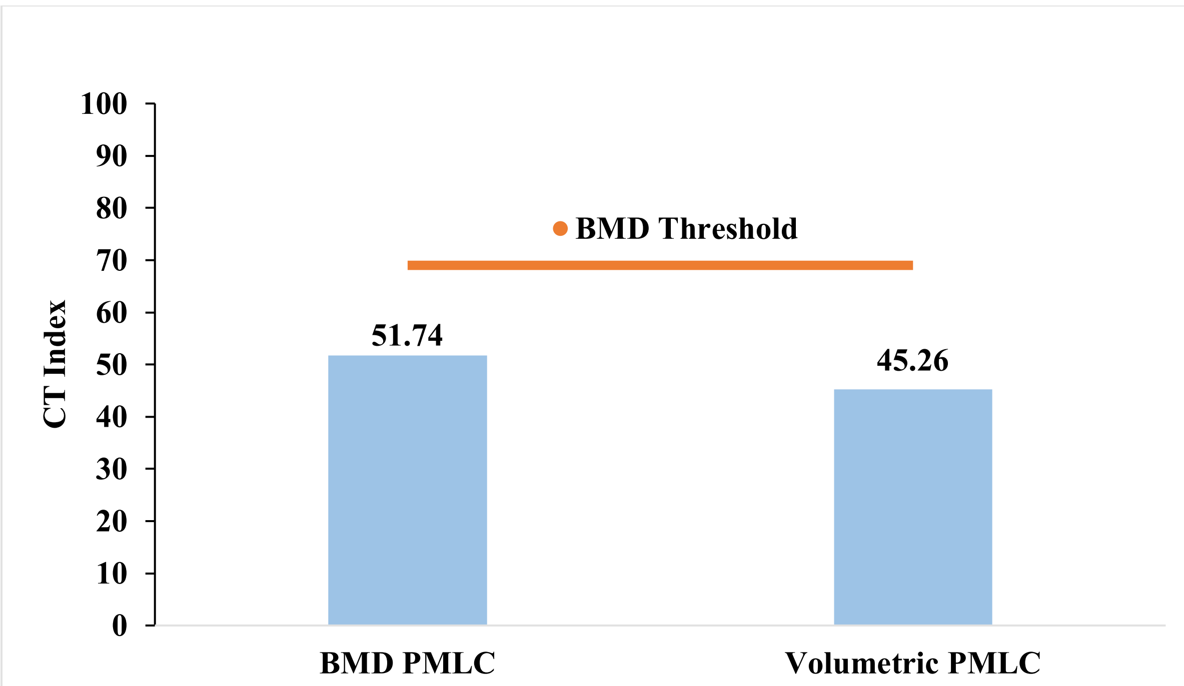


Figure 5.25: IDT-CT results for production mix from the US26–Salmon River – Zigzag.

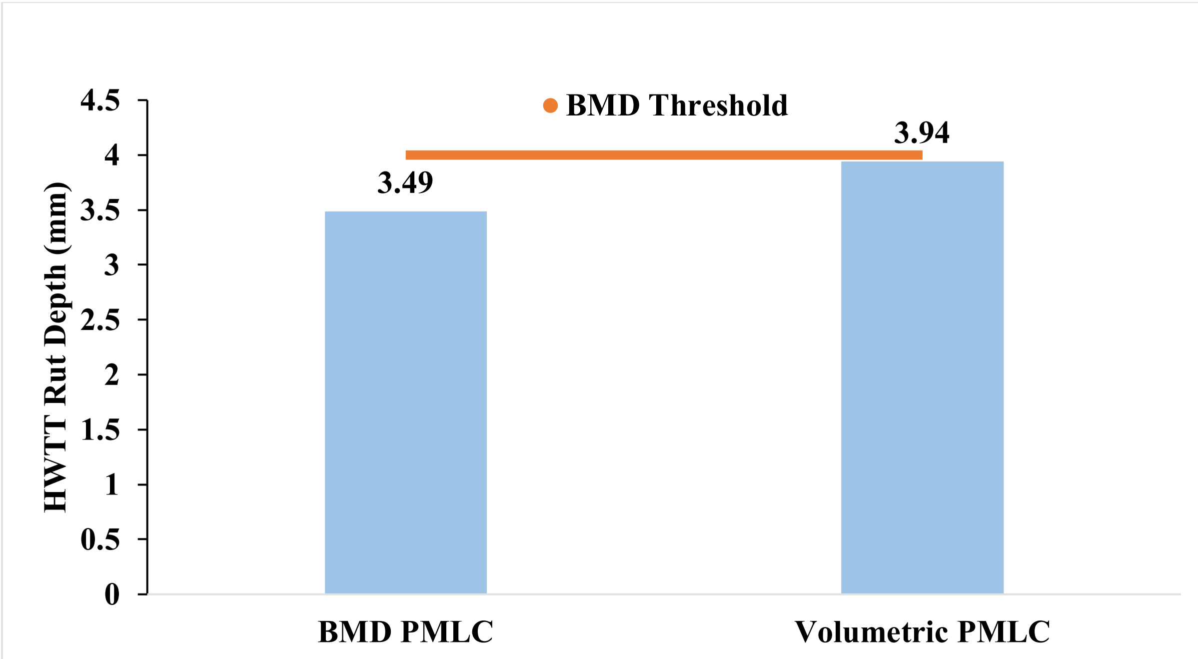


Figure 5.26: HWTT results for production mix from the US26–Salmon River – Zigzag.

Figure 5.27 describes the performance diagram for the US26 – Salmon River – Zigzag project. The production mix testing is close to falling in the sweet zone, but due to the lower CT Index, it did not pass the cracking threshold.

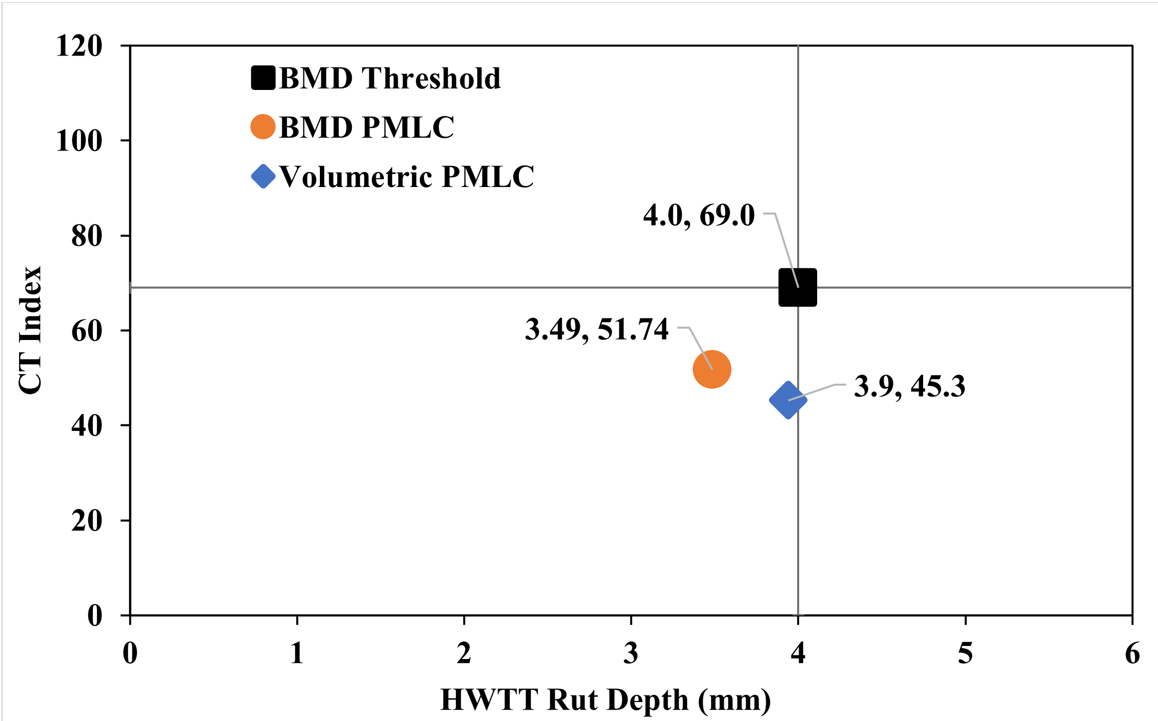


Figure 5.27: Performance diagram for production mix testing (US26–Salmon River – Zigzag).

5.4.3 DISCREPANCIES BETWEEN LMLC AND PMLC SPECIMENS

Confirming adequate performance of laboratory-mixed laboratory compacted (LMLC) samples is directly related to the performance of plant-mixed laboratory compacted (PMLC) samples. Figure 5.28 and Figure 5.29 illustrate the combined results of the rut depth and CT Index of all five projects evaluated in this study. Based on the evaluation of the PMLC specimens, it was evident that the asphalt mixtures of all five projects yield rut depths lower than their respective designed thresholds. However, 4 out of 5 projects did not meet the critical thresholds specified for the IDT-CT. Interestingly, LMLC specimens of all these projects passed their respective cracking and rutting thresholds. These findings are in line with the results observed in a few of the previous field projects in the United States (Coleri et al., 2020, West et al., 2021). The discrepancies can be attributed to various influential factors, including uncontrolled variations in plant production, errors in production temperatures, inaccuracy in the binder content measurement, and the temperature of heating the virgin and RAP aggregates.

Among the various factors listed above, preheating of RAP aggregates at the plant can be considered one of the significant factors contributing to the poor cracking performance of the asphalt mixtures (Prasad et al., 2023 and Antunes et al., 2019). In the laboratory, smaller quantities of virgin aggregates and RAP were heated separately in calibrated forced-draft ovens (necessary for each specimen). This process ensures uniform heating and activation of the RAP binder, potentially leading to a high CT Index. Conversely, during asphalt mix production at plants, RAP material is stored in large stockpiles in an open environment, leading to segregation and moisture retention issues. This environmentally exposed RAP is mixed with superheated aggregates, potentially lowering the overall temperature of the mix components. Thus, a decrease in production temperature may significantly affect the actual blending between the RAP binder and virgin binder (Lewis et al., 2024). In general, inappropriate blending leads to lower active binder content and, eventually, lower cracking performance for plant-produced mixes compared to those designed in the laboratory. However, the current Oregon Department of Transportation (ODOT) specifications assume that the RAP binder fully contributes to the mix, but the presumption of 100% blending between virgin and RAP binders does not hold in practice, resulting in significant implications for mix performance. This situation highlights the necessity for developing new processes and equipment to ensure the uniform preheating of RAP material at the plant level before its addition to the virgin aggregates. Specifically, there is a need to investigate the blending process followed in the laboratory, at plant conditions, and during actual production, considering varying aggregate types and binder grades.

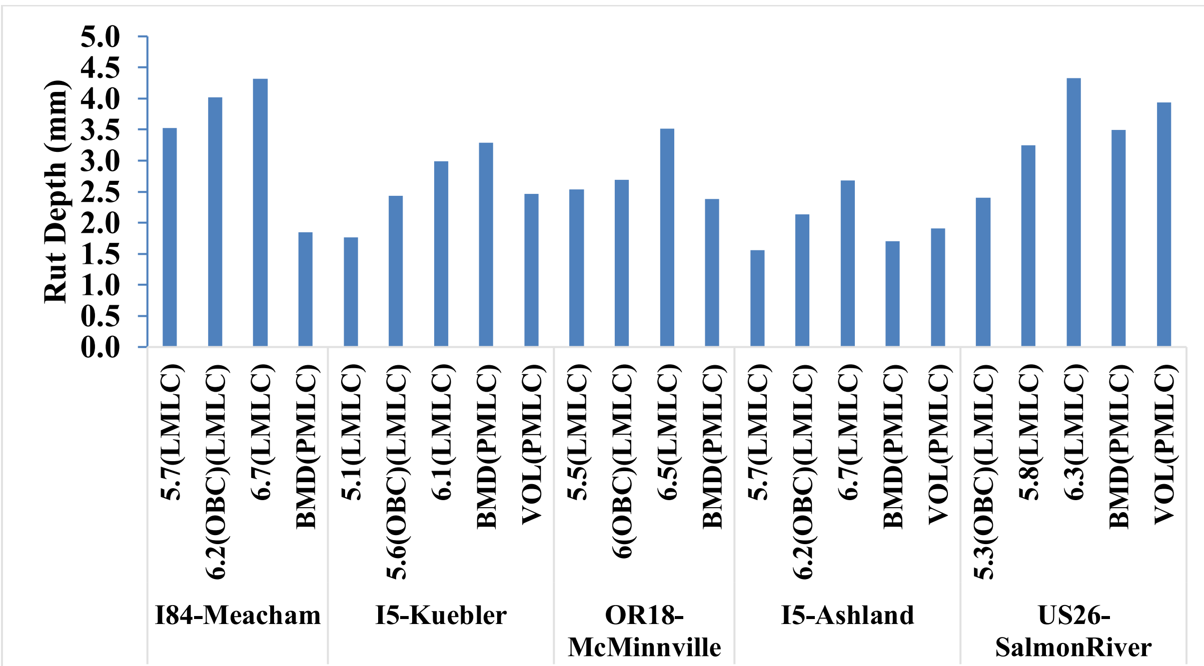


Figure 5.28: HWTT results for all the projects.

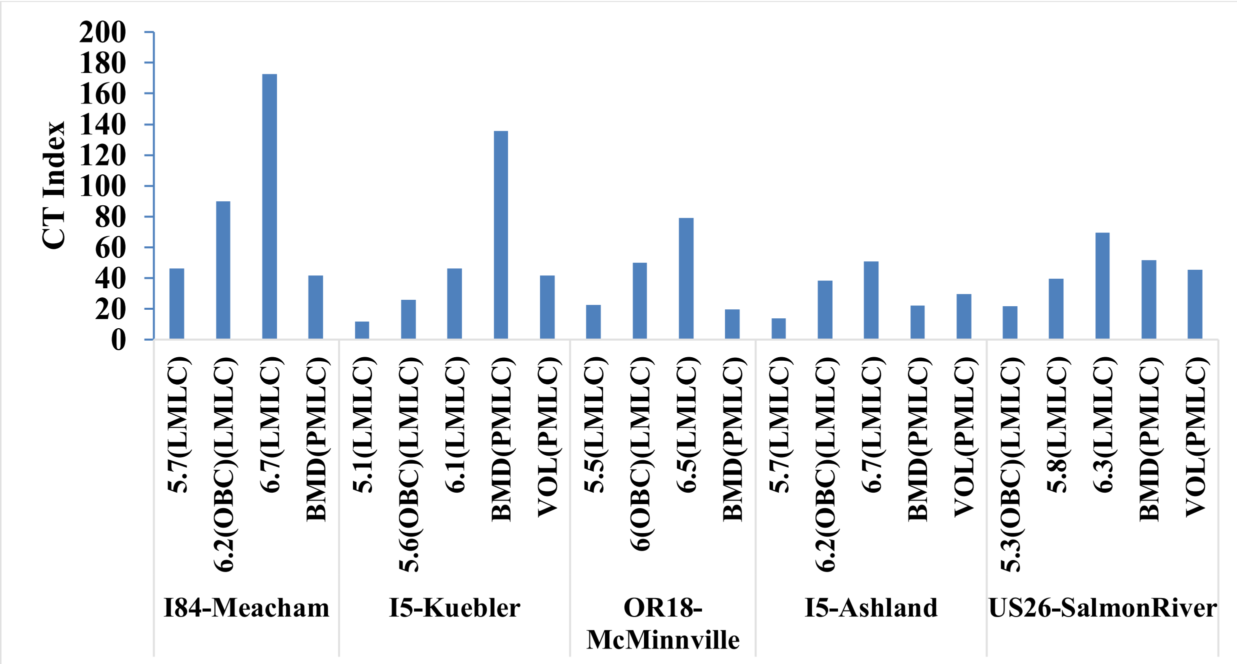


Figure 5.29: IDT-CT results for all projects.

5.4.4 CORRELATION BETWEEN THE DESIGNED THRESHOLDS AND PERFORMANCE TESTS

After conducting the cracking and rutting tests for the BMD production mix, it is essential to determine the correlation between the established thresholds and test results. The primary purpose is to check whether any relationship exists between them. In addition, these correlations may provide an effective way to understand if the BMD approach positively influences the cracking and rutting performance of the asphalt mixtures. The correlation values close to an absolute value of 1 represent a high degree of correlation, while a value close to 0 signifies no correlation.

Figure 5.30 describes the correlation between the established CT Index thresholds and the actual CT Index obtained from the BMD PMLC samples. For this purpose, only four projects out of 5 were chosen as the I5 – Kuebler BMD asphalt mixture had higher binder content than the suggested, resulting in an extremely high CT Index. The R^2 value of 0.961 suggests a strong correlation between the established thresholds and the laboratory test results for the production mixes. This validates the established CT Index thresholds and suggests that these thresholds can be further used for designing asphalt mixtures based on the BMD method.

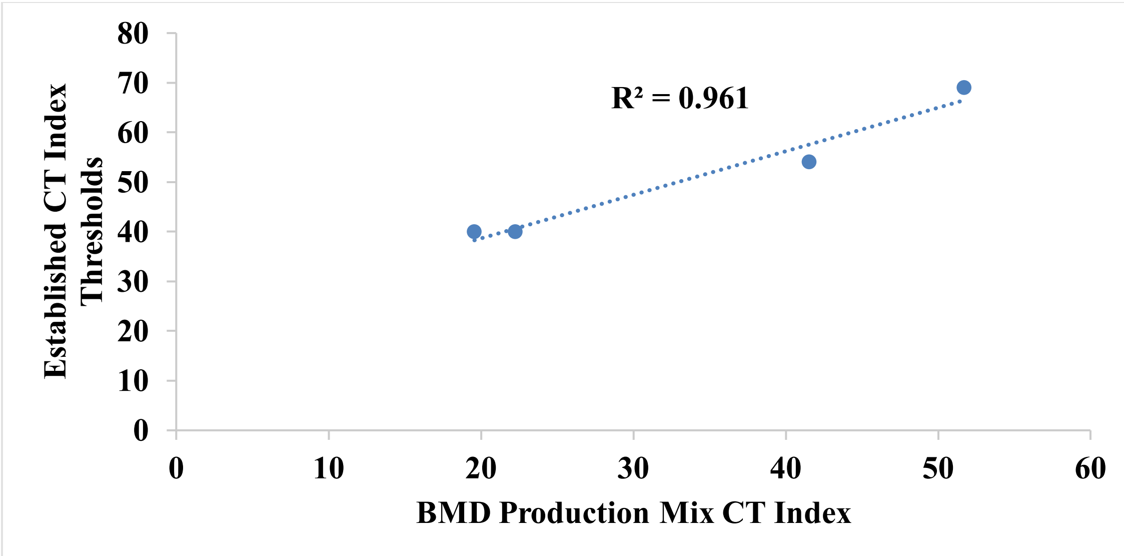


Figure 5.30: Correlation between benchmarked CT Index and BMD production mix results.

Figure 5.31 illustrates the correlation between the HWTT rut depth threshold and the rut depth of PMLC specimens produced following the BMD approach. As is evident, a weaker correlation exists between the established thresholds and the HWTT rut depths, indicated by an R^2 value of 0.393. The primary reason is the significantly lower rut depth for the I84-Immigrant Hill–Macham production mix. In addition, the measured rut depths for the production mixes were significantly lower than the rut depth thresholds for the BMD. This highlights that the designed mixes would experience less rutting and can last longer as far as rutting is concerned. In addition, it also indicates that there is significant scope for increasing the binder content in the asphalt mixes to meet the established thresholds and improve the cracking resistance.

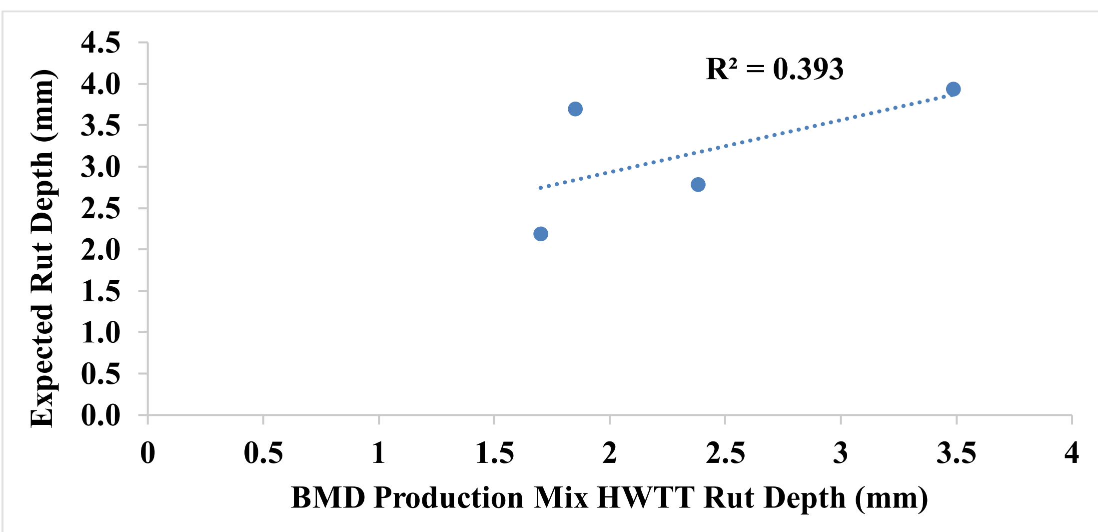


Figure 5.31: Correlation between expected HWTT rut depth and BMD production mix results.

5.4.5 LIFE CYCLE ASSESSMENT

Although BMD provides an effective means of optimizing asphalt binder content based on performance criteria, it can also influence the environmental burdens. The present study reveals that BMD can both increase and decrease the binder content relative to the optimum binder content determined through conventional volumetric mix design (refer to Table 5.7).

To assess the environmental implications of these design approaches, the Emerald Eco-Label tool was employed for the PMLC samples. Developed by the National Asphalt Pavement Association (NAPA), this tool facilitates life cycle assessment (LCA) of asphalt mixtures, enabling stakeholders to make informed decisions that promote sustainability. The tool evaluates environmental impacts from the cradle to gate (from raw material extraction up to the point the asphalt mix exits the production facility) (illustrated in Figure 5.32).

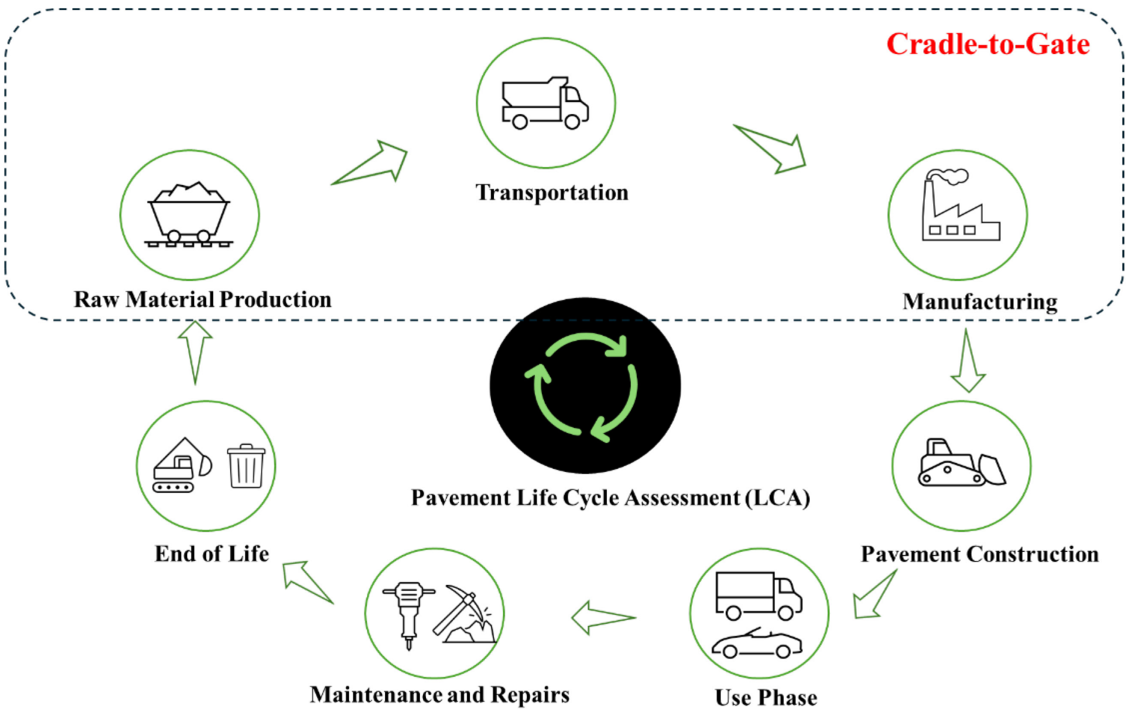


Figure 5.32: Cradle to gate pavement LCA (A1 to A3).

The life cycle stages assessed include:

- **Raw Materials Supply (A1)**: Accounts for environmental impacts associated with the extraction and processing of raw materials, including virgin aggregates, asphalt binder, and reclaimed asphalt pavement (RAP), based on their proportion in the mix.
- **Transportation Stage (A2)**: Includes impacts arising from the transport of all mix constituents (binder, aggregates, RAP), incorporating actual distances and modes of transportation.

- **Production Stage (A3)**: Encompasses the operational impacts of the asphalt plant during mix production. This includes energy consumption and emissions data, which are specific to the plant used in this study. The data inventory and impact assessment are based on information provided by the Asphalt Pavement Association of Oregon**.**

The declared unit for this LCA is 1 metric tonne (1 short ton) of asphalt mixture comprising virgin aggregates, RAP, and asphalt binder. The environmental impacts are calculated based on the annual average performance of the asphalt plant (as shown in Table 5.8) and do not reflect mix-specific production temperatures.

Table 5.8: Annual average data for asphalt production.

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

Key mix inputs considered in the assessment include (see Table 5.7 and Section 5.4.2 for detailed mix composition):

- Percentage of virgin aggregates by total mass,
- Percentage of RAP by total mass, and
- Percentage of asphalt binder by total mass

The environmental product declaration (EPD) was determined across multiple impact categories, including:

- **Global Warming Potential (GWP)-** It indicates the contribution of chemicals to the atmospheric greenhouse effect by trapping the Earth's atmosphere.
- **Ozone Depletion Potential (ODP)-** It reflects the damage caused to the earth's stratospheric ozone layer by the harmful chemicals viz., chlorofluorocarbons (CFCs). It is reported as an equivalent mass of CFC-11.
- **Eutrophication Potential (EP)-** This highlights the nutrient enrichment of water bodies caused by the release and subsequent deposition of chemicals in air or water. It is normalized to an equivalent mass of Nitrogen.

- **Acidification Potential (AP)-** This occurs due to the formation of acid rain as a result of chemical release into the atmosphere. AP is measured in terms of hydrogen ion formation per mass unit of chemical release as compared to SO_2.

- **Photochemical Ozone Creation Potential (POCP)-** This impact reflects the potential formation of photochemical oxidants caused due to the reaction between the hydrocarbons and nitrogen oxides with sunlight. POCP is normalized to an equivalent mass of O_3.

Figure 5.33 illustrates the environmental impacts of various asphalt mixtures designed using both volumetric mix design and BMD approaches per one metric tonne of asphalt mixture. To express the material quantity per 1 US short ton of asphalt mixture, the obtained values should be divided by 1.1023. Nonetheless, the observed trends remain consistent regardless of the unit of measurement.

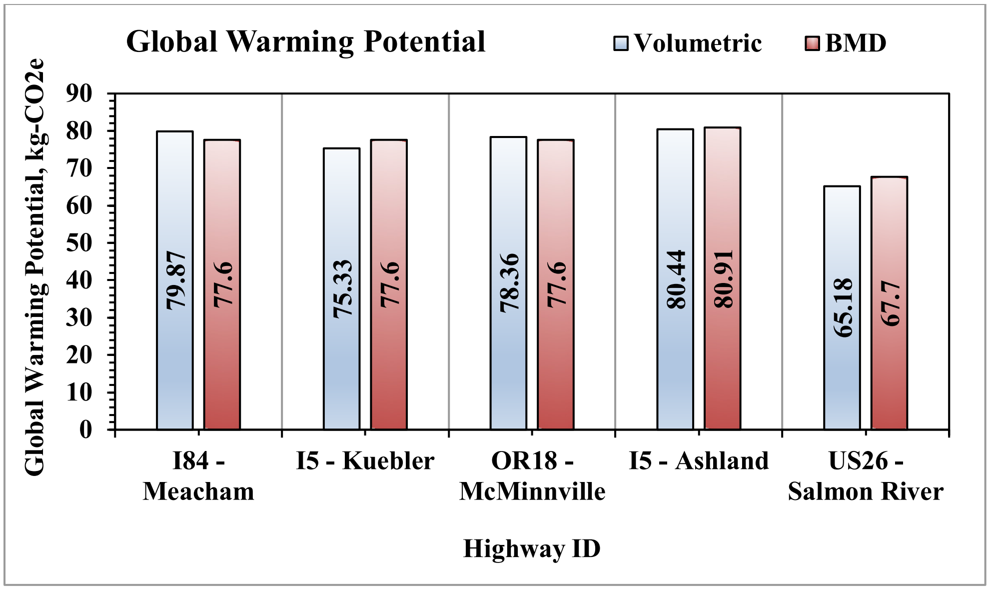
Due to project-specific variations in mix constituents, cross-comparison of all projects is not feasible, as also noted in the performance evaluation section. The asphalt binder content emerged as the most critical factor influencing environmental impacts, underscoring the importance of accurate determination of optimum binder content and the method employed for its selection.

For the I-84 Meacham and OR-18 McMinnville projects, GWP was marginally lower for BMD mixtures compared to their volumetric counterparts. In contrast, the BMD mixes for I-5 Kuebler and US-26 Salmon River exhibited slightly higher GWP, while the I-5 Ashland project showed a negligible difference between the two design approaches. These variations are attributed to differences in binder content, as presented in Table 5.7. Even in cases where BMD involved slightly higher binder content, the resulting GWP remained comparable, supported by higher CT Index values, indicative of improved cracking resistance and extended pavement longevity. It should be noted that the LCA conducted in this study only focuses on the A1-A3 stages and does not include the impact of improved performance on GHG emissions.

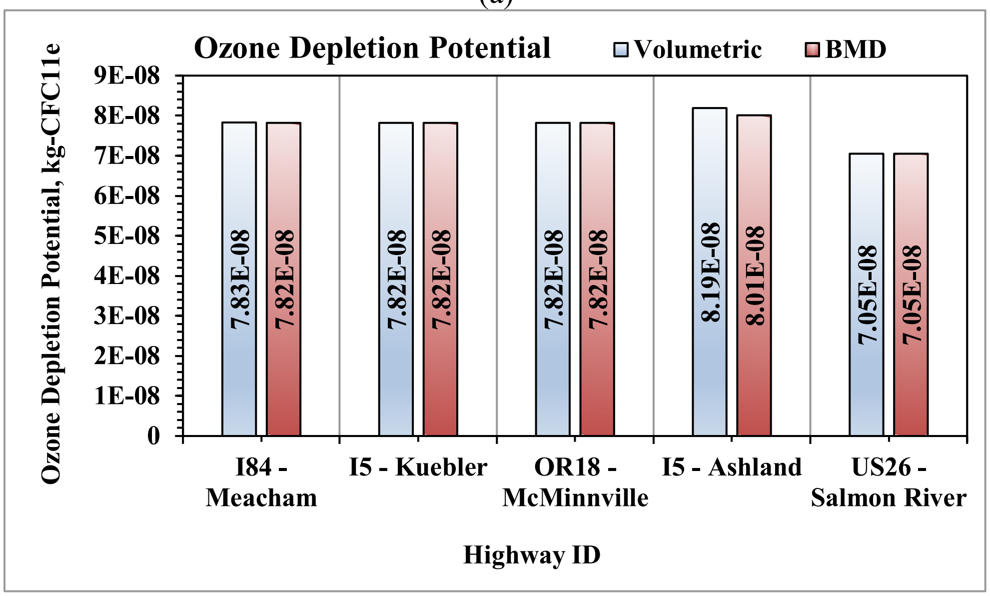
For ODP, both design methods generally resulted in similar impacts (almost identical), except for I-5 Ashland. The deviation here is attributed to the difference in RAP content: 15% in the volumetric mix and 17.5% in the BMD mix. This highlights the benefit of incorporating higher RAP content on the ODP.

Minimal differences were observed in EP across all mixtures, regardless of design method. Trends in AP and POCP were consistent with those seen in GWP, where mixtures with higher binder content generally exhibited greater environmental impact.

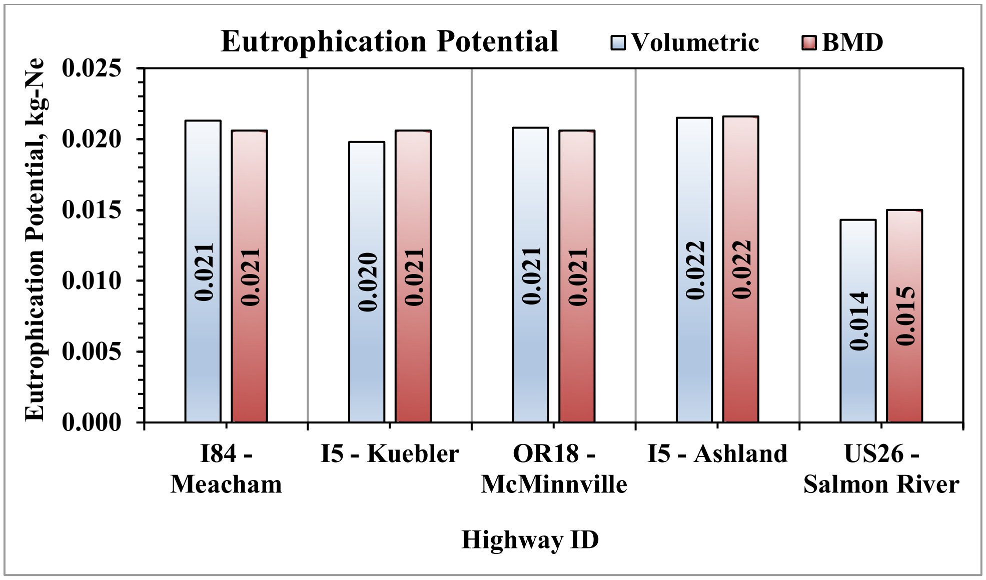
The cradle-to-gate LCA indicates that BMD does not significantly change the A1-A3 environmental impact. However, it is a preferable approach, as it enhances performance and pavement durability, thereby reducing the frequency of maintenance and repair activities and ultimately lowering the long-term emissions and pavement life cycle cost. Although the study did not directly quantify cost implications, the extended service life anticipated with BMD suggests improved economic and environmental outcomes over the conventional volumetric design method.


Global Warming Potential
Volumetric
BMD
Global Warming Potential, kg-CO2e
90
80
70
60
50
40
30
20
10
0
79.87
77.6
75.33
77.6
78.36
77.6
80.44
80.91
65.18
67.7
I84 - Meacham
I5 - Kuebler
OR18 - McMinnville
I5 - Ashland
US26 - Salmon River
Highway ID

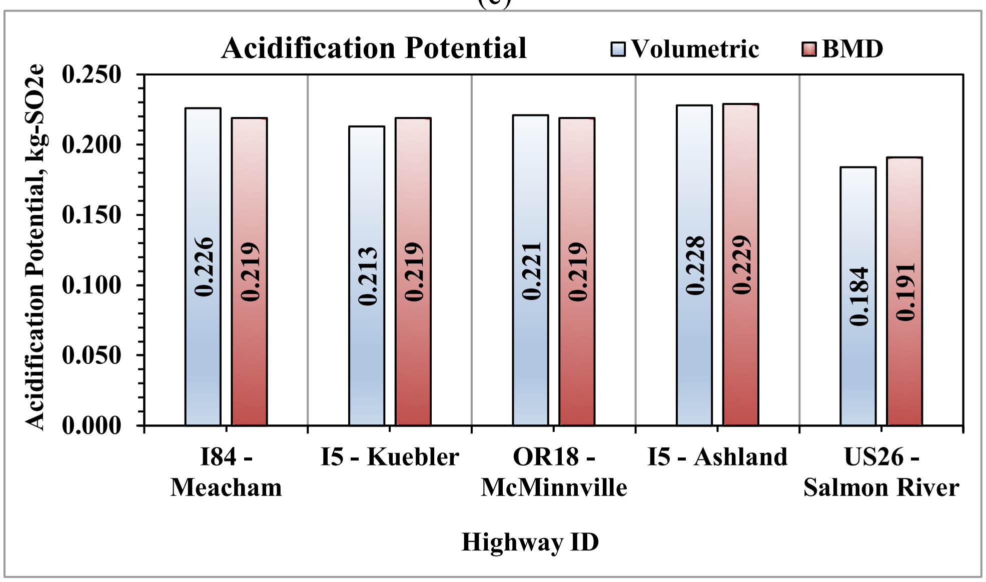
(a)


Ozone Depletion Potential
Volumetric
BMD
Ozone Depletion Potential, kg-CFC11e
9E-08
8E-08
7E-08
6E-08
5E-08
4E-08
3E-08
2E-08
1E-08
0
7.83E-08
7.82E-08
7.82E-08
7.82E-08
7.82E-08
7.82E-08
8.19E-08
8.01E-08
7.05E-08
7.05E-08
I84 - Meacham
I5 - Kuebler
OR18 - McMinnville
I5 - Ashland
US26 - Salmon River
Highway ID

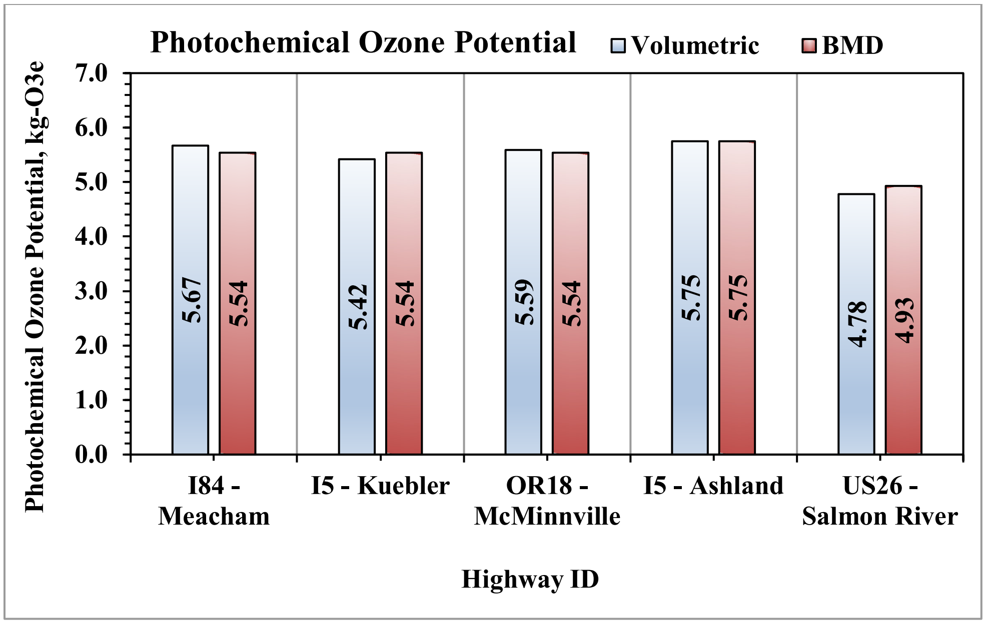
(b)


Eutrophication Potential
Volumetric
BMD
Eutrophication Potential, kg-Ne
0.025
0.020
0.015
0.010
0.005
0.000
0.021
0.021
0.020
0.021
0.021
0.021
0.022
0.022
0.014
0.015
I84 - Meacham
I5 - Kuebler
OR18 - McMinnville
I5 - Ashland
US26 - Salmon River
Highway ID

(c)


Acidification Potential
Volumetric
BMD
Acidification Potential, kg-SO2e
0.250
0.200
0.150
0.100
0.050
0.000
0.226
0.219
0.213
0.219
0.221
0.219
0.228
0.229
0.184
0.191
I84 - Meacham
I5 - Kuebler
OR18 - McMinnville
I5 - Ashland
US26 - Salmon River
Highway ID

(d)



(e)

Figure 5.33: Cradle to gate environmental impacts per 1 metric tonne of asphalt mixture.

5.4.6 DENSITY EVALUATION USING THE DENSITY PROFILING SYSTEM (DPS)

To understand the challenges associated with the BMD, it is imperative to monitor the construction of pilot sections. In this research work, the primary difference in BMD and volumetric mix design pilot sections was the binder content and aggregate gradation; however, the change in aggregate gradation is minimal. From this perspective, the research team visited one of the construction sites, i.e., I5-Kuebler, in order to understand the effect of a change in binder content. The research team observed the compaction process and further measured the density of the pavements (designed with BMD and Volumetric mix design) using a Density Profiling System (DPS). Figure 5.34 presents the DPS along with its different components. DPS emits electromagnetic waves in the pavement and captures the waves reflected from the pavement with the use of sensors mounted on the DPS cart. It measures the dielectric constant of the asphalt pavement, which is further used to determine the compaction achieved after construction in terms of air voids.

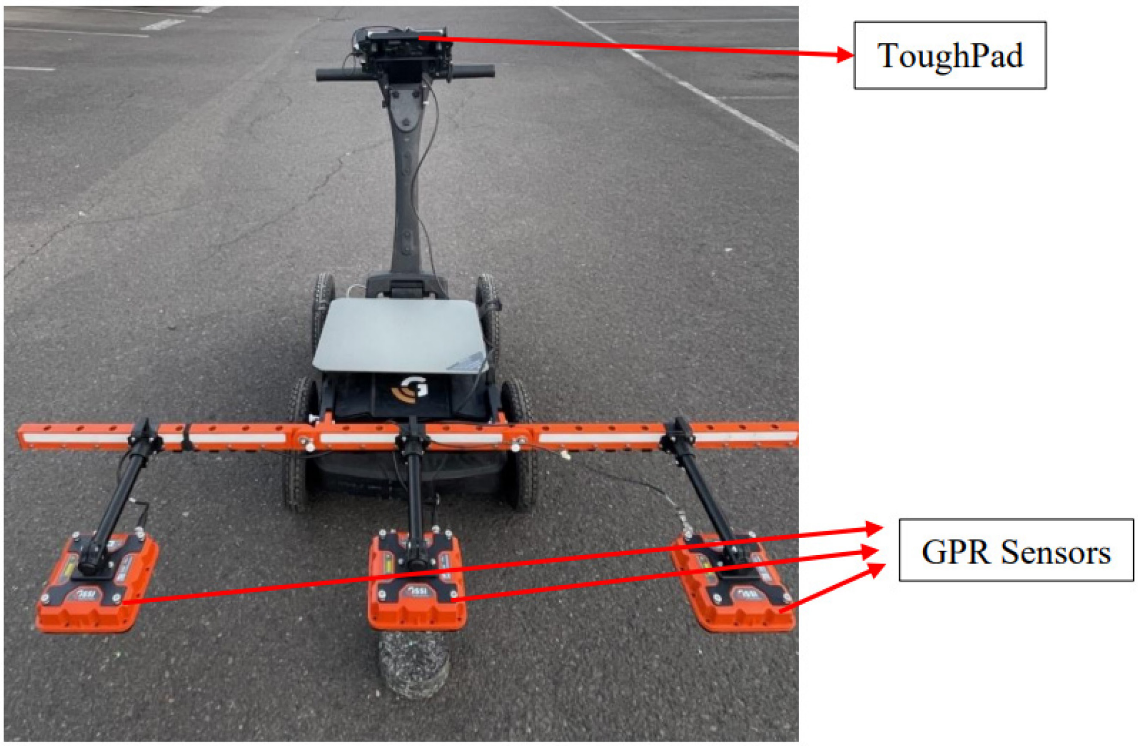


Figure 5.34: Density Profiling System used in this study.

During the initial phase of the BMD pilot section construction, density measurements were performed by the construction crew using the Nuclear Density Gauge (NDG). NDG is generally used to determine whether the density is in the range according to the Oregon Department of Transportation (ODOT) requirements. The density results obtained using the NDG during the initial construction phase were higher than expected.

Like the NDG results, the density/air voids of the same pilot section evaluated using the DPS also pointed the same way, as shown in Figure 5.35. As per the DPS results, the average air voids ranged from 4.8% to 5.5% for a 1,250-foot-long segment of the BMD mixture construction. The primary reason for low air voids can be attributed to adopting the same roller compactor patterns for the BMD section as those used for the volumetric section. The volumetric section had a 0.65% lower binder content than the BMD, requiring additional compaction effort to meet the expected density in the field. The incorporation of higher binder content in the BMD mix enhanced the flexibility of the asphalt mixture, necessitating less compaction effort compared to the traditional volumetric mix to achieve the targeted density. After the first 100 feet, the construction team modified the roller compaction patterns (significantly reduced the number of passes), which resulted in achieving air voids within the range of 6% - 7%, which is evident in the DPS results shown in Figure 5.36. It should be noted that adjusting roller patterns without performing a control strip at the beginning of new BMD mix production is not advisable. For the BMD mix, the construction process should have included a separate control strip, and the roller patterns and number of passes should have been revised accordingly to achieve the proper density without lowering compactive effort. For future projects, a control strip construction and assessment is recommended before construction of the BMD (or any) test section.

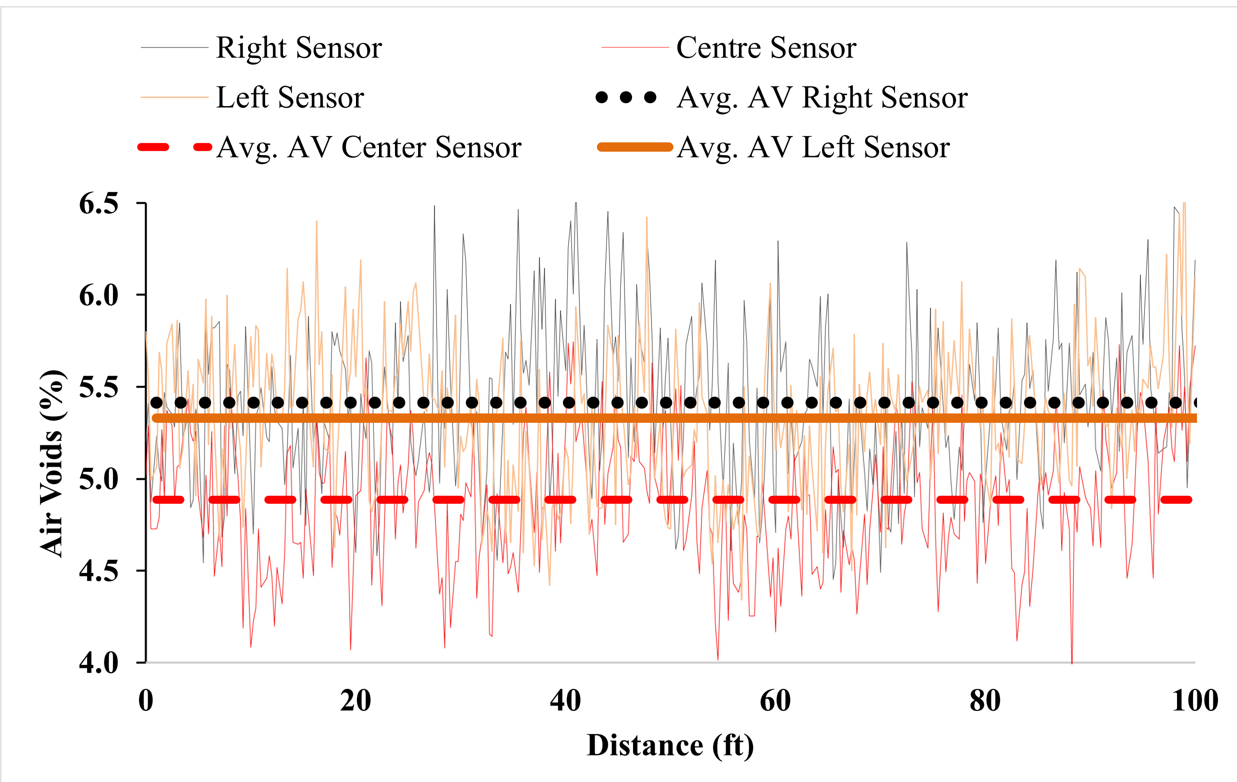


Figure 5.35: Initial BMD construction without adjusting the rolling patterns.

Avg. AV = Average air voids.

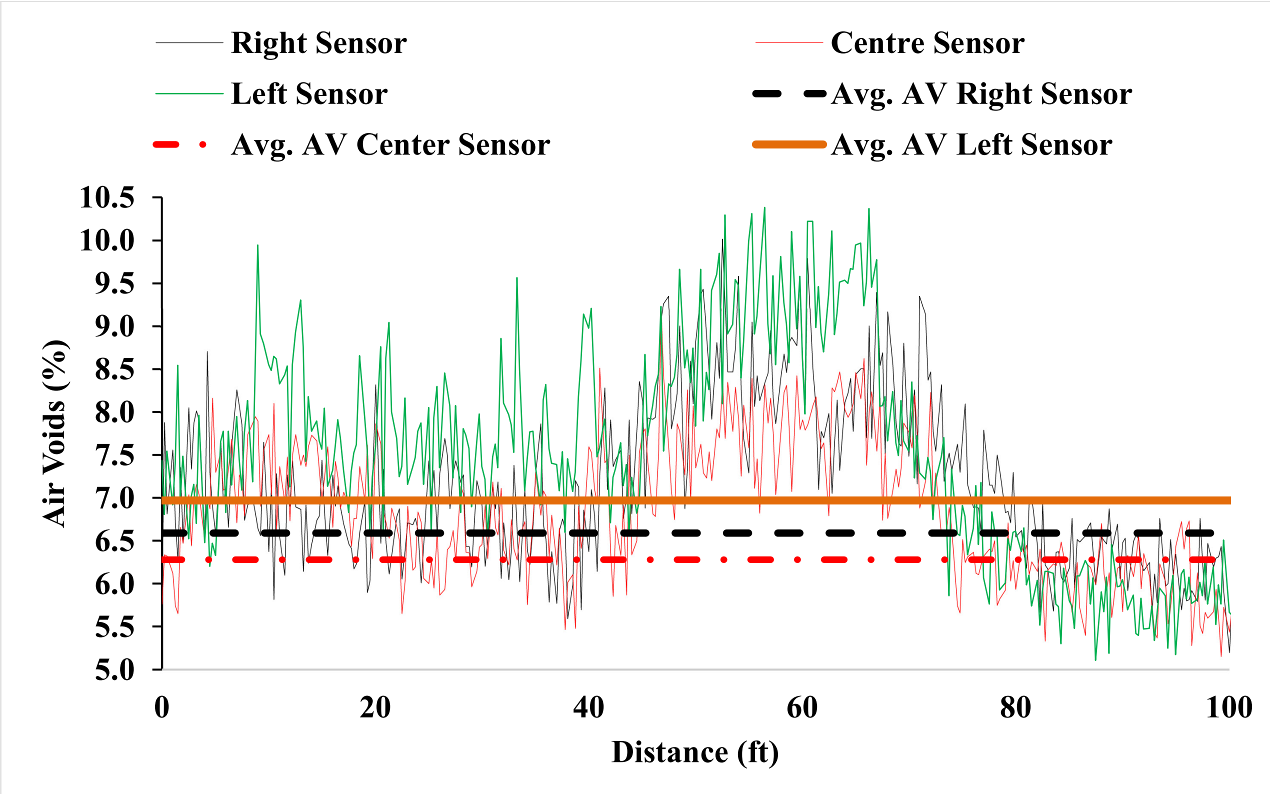


Figure 5.36: BMD section after adjusting the rolling patterns.

Avg. AV = Average air voids.

5.5 CONCLUSIONS

To determine the validity of the established thresholds and the effectiveness of the BMD method in developing long-lasting asphalt pavements for Oregon, five construction projects were selected in communication with ODOT Pavement Services and ODOT Research sections. IDT-CT and HWTT tests were conducted on the specimens prepared in the laboratory using three different binder contents to evaluate their cracking and rutting performance. The results from these tests were used to determine the optimum binder content for the BMD by using the software developed by the OSU AMaP research group. Pilot sections were constructed based on this binder content at 5 locations in Oregon. Volumetric and BMD plant production asphalt mixtures were sampled during construction to evaluate their performance. The major conclusions derived from this part of the study are as follows:

- Among the five field projects, the BMD approach indicated a lesser optimum binder content for two projects compared to the volumetric mix design method. This signifies that the BMD approach does not always increase the binder; however, it can help optimize the asphalt content, resulting in better field performance and lower project costs for some cases and definitely lower life-cycle costs for all.

- 4 out of 5 projects designed using the BMD approach failed to pass the CT Index threshold criteria; however, this value is higher than all the volumetric mixes. Therefore, better cracking performance is expected for the BMD pilot sections than for the volumetric sections.

- The BMD binder content resulted in low HWTT rut depths and passed the designated thresholds for all five projects, leading to the production of rut-resistant asphalt pavements. **However, low rut depths from both volumetric and BMD production mixes show that the rut depth and CT Index thresholds should be increased in a future study. Increasing binder content will improve fatigue cracking resistance, which is the major distress mode in Oregon.**

- The results suggest that the uniform heating of RAP material and the appropriate blending of the RAP binder with the virgin binder are vital to enhance the cracking performance. This was also the primary reason for the lower cracking performance of the plant-produced asphalt mixtures compared to those designed in the laboratory.

- There is a need to adjust rolling compaction patterns to ensure adequate field compaction based on the specific requirements of BMD sections. As per DPS observation, the incorporation of higher binder content in the BMD mix softened the asphalt mixture, suggesting significantly lower compactive effort compared to the conventional volumetric mix in order to achieve the targeted density.

6.0 ACCELERATED PAVEMENT TEST (APT) SECTION CONSTRUCTION AND TESTING AND FIELD PERFORMANCE MONITORING USING PMS DATA

6.1 INTRODUCTION

The BMD approach has, in some cases, indicated an increase in binder content, raising concerns about potential rutting in asphalt concrete. Laboratory studies conducted in this report have shown that while increased binder content slightly increased rutting (HWTT rutting), the values remained well below the commonly accepted threshold of 12.5 mm (≈0.5 in) in many states. However, the accuracy of the HWTT in simulating field conditions has been subject to debate (Tsai et al. 2016). To address this, evaluating asphalt mixes designed using BMD and volumetric principles under comparable conditions with an accelerated pavement test (APT) is recommended. This method is considered effective for rapidly assessing the cracking resistance and bleeding susceptibility of the mixes.

In this chapter, APTs were performed on two test sections at the Corvallis Knife River Asphalt Plant, designed following volumetric and BMD principles. A sensitive profilometer, including both hardware and software, was developed at OSU-AMaP to measure rutting deformations and bleeding. A dump truck, loaded to apply a back axle load of 40 kN on a dual tire, was driven repeatedly over both test sections. Deformations were measured at specified intervals using the OSU-AMaP profilometer. The collected data were processed using a custom-developed code to calculate rutting values for the volumetric and BMD mixes, facilitating a comparative analysis of their performance. In addition, the one-year rutting values of BMD pilot sections constructed at various locations in Oregon were compared with those of volumetric sections using rutting data obtained from ODOT Pavement Management System (PMS) records.

The major objectives of this part of the research study are as follows:

- To compare the deformation resistance of volumetric and BMD asphalt mixes via rutting values obtained from APT.
- To compare (using ODOT PMS data) the one-year rutting performance of pilot sections constructed using BMD and volumetric principles.
- To evaluate the constructability of the BMD compared to the volumetric mix design.

6.2 TEST SECTION CONSTRUCTION

Two 200-foot-long test sections were built at the Corvallis Knife River Asphalt Plant using both the conventional Volumetric and BMD design principles. The mix design was for a ½ inch Level 4 mix containing 20% RAP, with PG70-22ER asphalt binder used consistently across both sections. The design chosen for the trial section was based on project I-5: North Santiam – Kuebler mix (refer to sections 5.4.1.2 and 5.4.2.2), and the lift thickness was specified at 3 inches on top of a 3-inch-thick asphalt base course and a 6-inch-thick aggregate base layer.

Construction photos from July 2023 are shown in Figure 6.1. The same amount of tack coat was applied to each section before placing the new asphalt layer to eliminate potential bias in the results and ensure a reliable comparison of both design approaches. The Volumetric section had a binder content of 5.6%, while the BMD section used 5.9% binder. Thermal cameras were used to monitor the compaction temperature, which ranged between 135-145°C for both sections, as shown in Figure 6.2. ODOT personnel measured the density of both sections using a Nuclear Density Gauge. The average density (%Gmm) was found to be 93.4% for the Volumetric section and 93.6% for the BMD section, indicating comparable compaction levels at the end of construction despite the different binder contents and design approaches. Accelerated Pavement Testing (APT) was conducted on both sections throughout the summer to evaluate the performance of each design, with further details on the APT provided in subsequent sections.

(a) Dust removal from the adjoining pavement

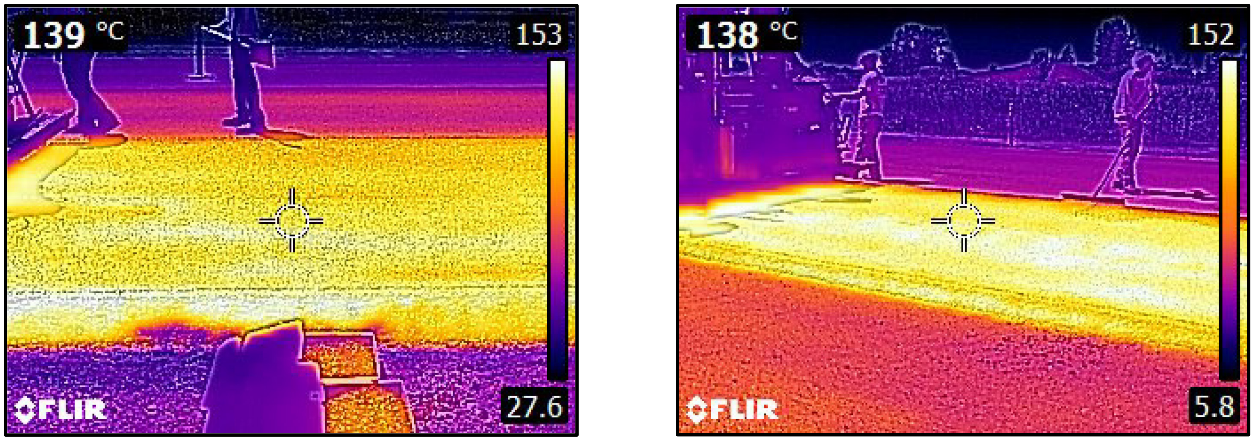
(b) Application of tack coat on the old pavement

(c) Paving process

(d) Compaction process

(e) Final test sections with markings

Figure 6.1: Construction process of Volumetric and BMD test sections



(a) (b)

Figure 6.2: Thermal camera showing compaction temperature (a) Volumetric Section and (b) BMD section

6.3 DEVELOPING THE NEW OSU-AMaP ACCELERATED PAVEMENT TEST SYSTEM

Accelerated Pavement Test (APT) systems often consist of large vehicles equipped with full-scale truck wheels, hydraulic systems to adjust loading, deformation measuring systems, and an automated motor for back-and-forth wheel movement. These systems are typically expensive to purchase and maintain, making them challenging for agencies to adopt. This study utilized a cost-effective alternative to make the testing process more accessible.

6.3.1 APT Test Setup

A dump truck with an empty weight of 14,500 lb was obtained to load the test sections. The front axle of the truck was equipped with single tires, while the rear axle featured dual tires on both sides. This truck was specifically chosen to evaluate the impact of full-scale truck tires on pavement performance, as most rutting and cracking damage is predominantly load-driven (are due to Truck loads). The truck was loaded with sand, increasing its total weight to 26,100 lb, with a measured load of 17,600 lb (≈40 kN on the dual wheel) applied to each rear axle. This load was selected to match the load levels commonly used for APT in the U.S. The truck was operated in shifts, and the number of passes was recorded using a mobile application operated by a research team member seated in the passenger seat. The temperature profile and the thermal gradient for the test sections were recorded using a thermocouple system developed by OSU-AMaP.

The test section was initially cleared of debris and thoroughly cleaned. Figure 6.3 provides photographs of the cleaned test section. Following the cleaning, the areas where the wheels would traverse were marked on the test sections (Figure 6.4). In this study, loading was conducted over a 12 ft-long area. This distance was selected to ensure that the tandem wheels on the rear axle did not intersect with the deformations caused by the front single wheel.

Figure 6.3: Cleaned test section (BMD and volumetric mixes)

Figure 6.4: Marked the Volumetric section and loading the section with the dump truck

Precise measurement of deformations is critical for the successful execution of APT. To achieve this, a sensitive profilometer (both hardware and software) was developed by OSU-AMaP to measure deformations across the lane width. The profilometer is capable of capturing precise coordinate measurements over a 9-foot length. A photograph of the profilometer is provided in Figure 6.5. As shown in the figure, the system consists of a high-precision laser mounted on a 12 ft-long frame, a motor control unit, a power supply unit, and two laptops-one for processing laser coordinate data and the other for controlling motor operations.

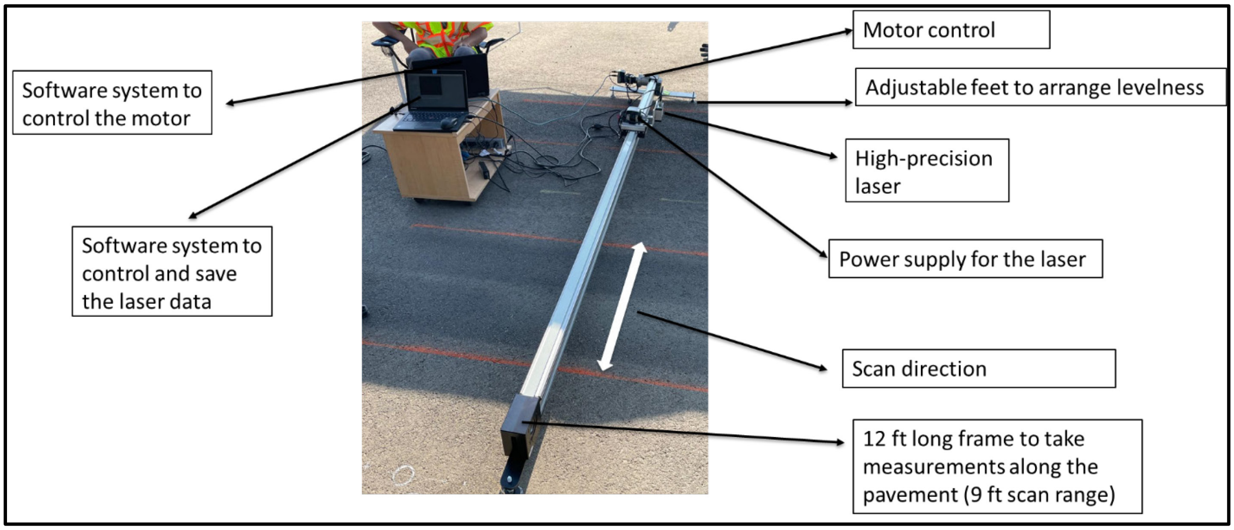


Figure 6.5: Laser Profilometer system developed by OSU-AMaP

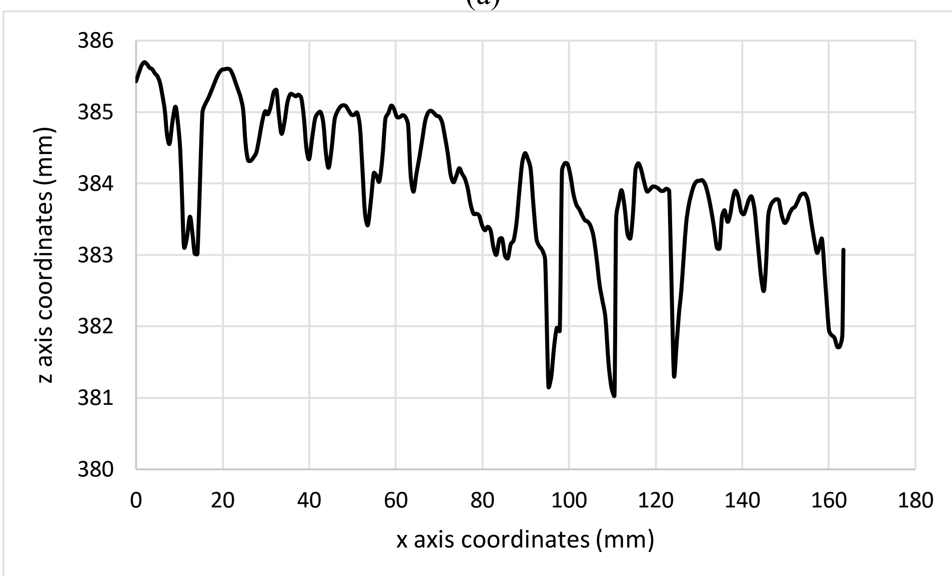
Deformation measurements were collected using the profilometer at 11 stations along the 12-foot test section. These stations included three at the start, three at the end of the section, and five midpoint locations, all arranged at equal intervals. The stations were marked on the pavement using a permanent marker to ensure measurements were taken at the exact same locations after a certain truck passes (Figure 6.6). Deformation data were recorded at these stations after 0, 10, 20, 50, 100, 200, 500, 1,000, 2,000, 5,000, 10,000, and 20,000 truck passes. It was anticipated that the truck would decelerate near the start and end points in the section. The loading time would be increased at the beginning and the end, which can result in inconsistent and excessive rutting values. Therefore, rutting values were calculated using the coordinate data from the five middle stations, where the truck maintained a relatively consistent speed. Rutting values were determined for each of the specified passes (with 0 mm rutting at 0 passes), and passes versus rutting curves were obtained for both the BMD and volumetric sections.

Figure 6.6: Profilometer measuring stations marked on the BMD section and coordinates used in this study.

6.3.2 Processing Deformation Data to Calculate the Rutting Values

At each station, the profilometer was operated across the lane width, recording x and z values at approximately 5 mm (4.82 mm) intervals along the y-axis (as shown in Figure 6.6). Figure 6.7 illustrates the laser scan direction and a typical x-z scan obtained at a random y location.

(a)



(b)

Figure 6.7: (a) The laser texture scanner setup showing the scanning direction and axes (x, y, z) during surface profile measurement (b) The corresponding surface profile (z-axis coordinates versus x-axis coordinates)

After collecting profilometer data along the entire y-axis, the scans were sequentially numbered with a spacing of 4.82 mm between each scan. The average z-coordinate values for each scan were calculated and recorded as the baseline condition (0 passes) before truck loading. These baseline values were used as the reference. For each subsequent pass, the average z-coordinate values were subtracted from the baseline average z-values to calculate the deformation values at each station.

An example is provided below: Table 6.1 shows the first five scans of the 0-pass data from the volumetric section for the first three stations (There are a total of 565 scans for each station).

Table 6.2 presents the average z-coordinate values for 10 passes for the first five scans of the same stations. Table 6.3 displays the calculated deformation values, derived by subtracting the coordinates of 10 passes from 0 passes, using the formulation provided in Equation (**6-1**). The deformation profile obtained for the volumetric section at 0, 10, and 2,000 passes is provided in Figure 6.8. As shown in the figure, rutting tracks were clearly visible, and rutting values increased progressively with the number of truck passes.

$$\boldsymbol{Deformation_{10\ Passes} = Average\ of\ Z_{10\ Passes} - Average\ of\ Z_{0\ Passes}} \quad \textbf{(6-1)}$$

Table 6.1: Scan data at first 3 stations for first 5 scans at 0 passes.

Scan No	Y Location	1_Average of Z	2_Average of Z	3_Average of Z
1	0	395.0533	396.3886	395.3657
2	4.8157	395.6866	396.8107	396.0165
3	9.6314	395.6684	396.7989	396.0470
4	14.4471	395.6828	396.6611	395.9459
5	19.2628	395.4809	396.5380	395.7810

Table 6.2: Scan data at first 3 stations for first 5 scans at 10 passes.

Scan No	Y Location	1_Average of Z	2_Average of Z	3_Average of Z
1	0	395.4693	396.6096	395.6996
2	4.8157	396.0659	397.0099	396.2988
3	9.6314	396.0546	396.8686	396.3288
4	14.4471	396.0622	396.9353	396.2494
5	19.2628	395.8283	397.0601	396.0400

Table 6.3: Deformation values at first 3 stations for first 5 scans for 10 passes.

Scan No	Y Location	1_Average of Z	2_Average of Z	3_Average of Z
1	0	0.4160	0.2210	0.3340
2	4.8157	0.3794	0.1992	0.2823
3	9.6314	0.3863	0.0697	0.2818
4	14.4471	0.3794	0.2742	0.3035
5	19.2628	0.3474	0.5221	0.2589

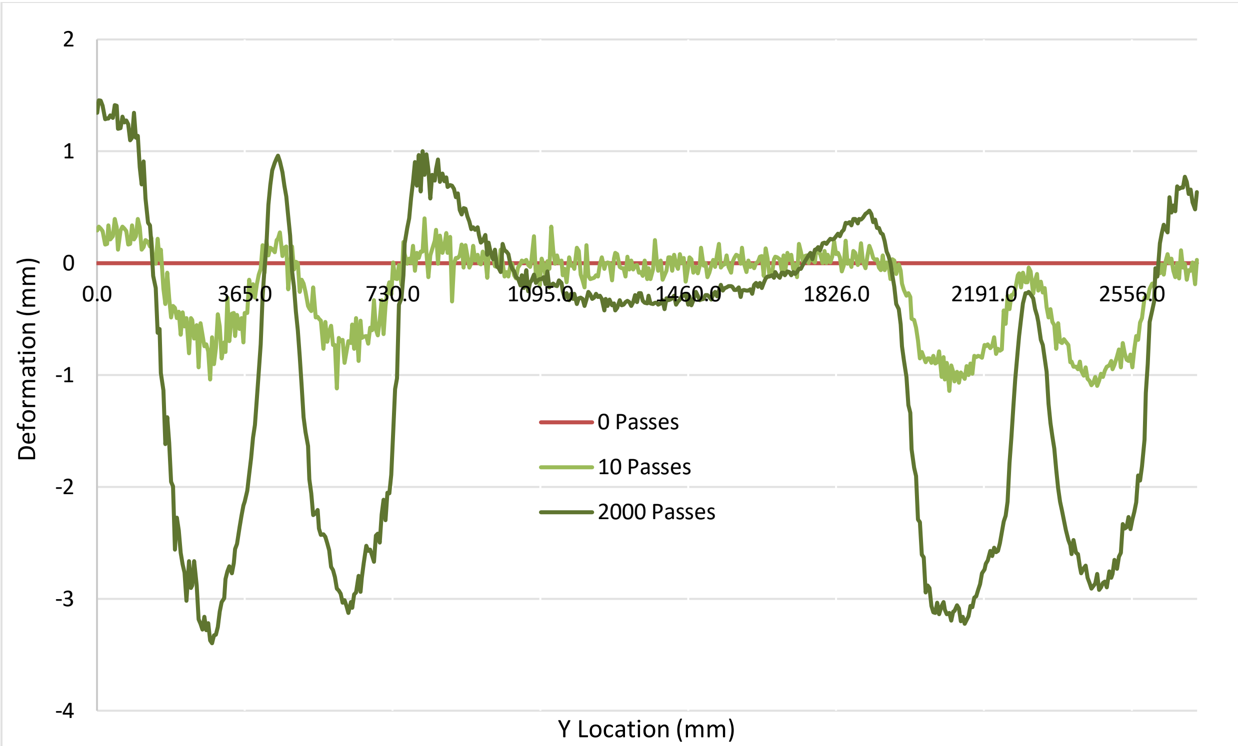


Figure 6.8: The deformation profile obtained for the volumetric section after 0, 10, and 2,000 truck passes

When the deformation profile presented in Figure 6.8 was analyzed, it was observed that the data contained significant noise, particularly for relatively low passes. To address this, a noise reduction (filtering) algorithm was applied to the data (exponential smoothing with a damping factor of 0.5). This noise reduction process produced a smoother deformation profile (Figure 6.9) and allowed for more accurate rutting calculations.

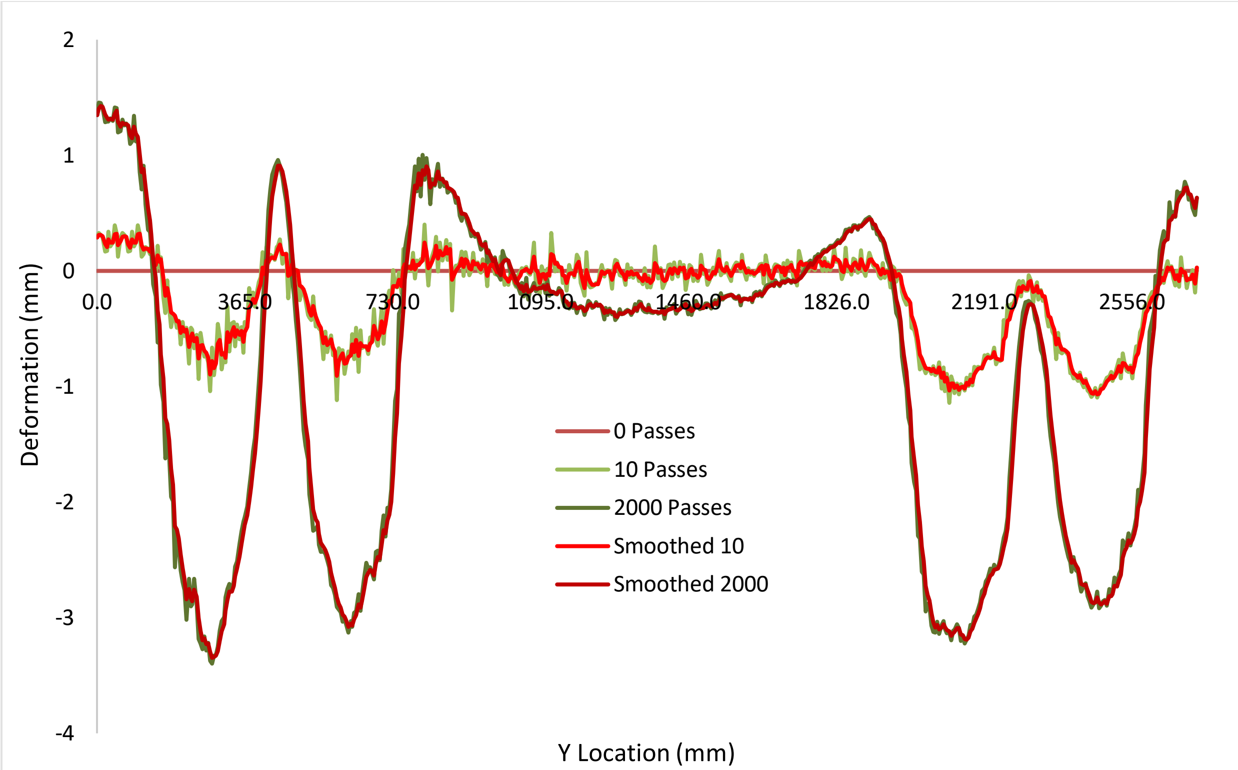


Figure 6.9: Deformation data after the noise reduction algorithm was applied

After the deformation data was obtained from all 11 stations and the noise reduction process was completed, the rutting values were calculated. In this study, the method described by Garg et al. (2018) was used for the rutting calculations. As described in Garg et al. (2018), two types of rutting values can be calculated: straightedge rutting and rutting from zero elevation. In this report, straightedge rutting (max rutting) values were calculated as they hold greater critical importance.

6.3.3 Temperature Monitoring of APT Section

Considering the viscoelastic-plastic properties of asphalt, rutting values are significantly influenced by pavement temperature. The asphalt's viscosity (resistance to flow) decreases significantly with increasing temperature, making the mix more susceptible to rutting. For this reason, the pavement temperature was recorded at the APT section. The pavement temperature was measured at the surface and at depths of 1 in, 2 in, 3 in, 4.5 in, and 6 in below the surface. A photograph of the thermocouple systems used for measuring pavement temperature is provided in Figure 6.10.

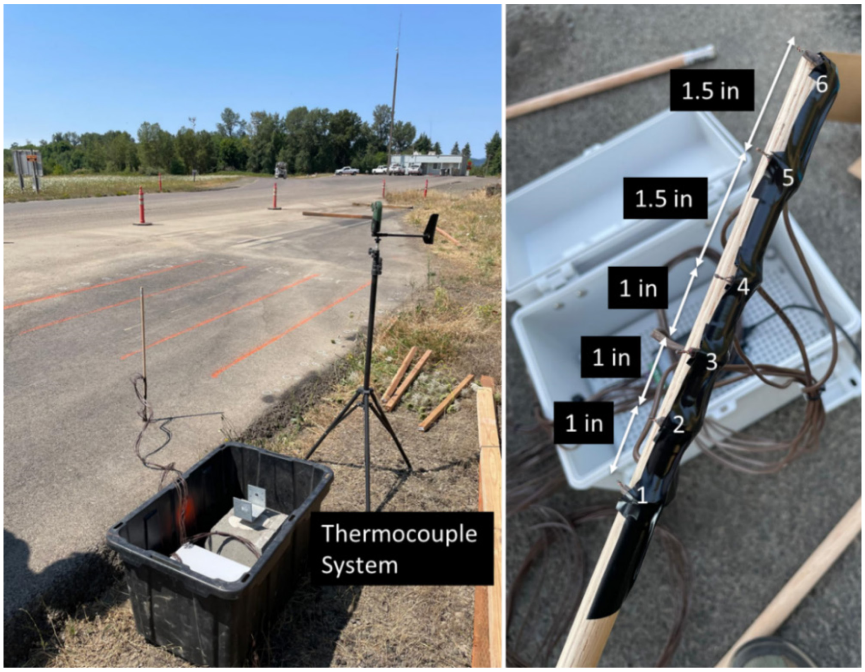


Figure 6.10: Thermocouple system to measure pavement temperature in the APT section

A typical temperature dataset obtained from the section is presented in Figure 6.11. The first thermocouple (Number 1) shown in Figure 6.10 measured the surface temperature, while thermocouples 2, 3, 4, and 5 measured temperatures at depths of 1 in, 2 in, 3 in, 4.5 in, and 6 in, respectively. As shown in Figure 6.11, the surface temperature peaked around 4-5 pm, while during the night, the maximum temperature was recorded at relatively deeper layers within the pavement, as expected.

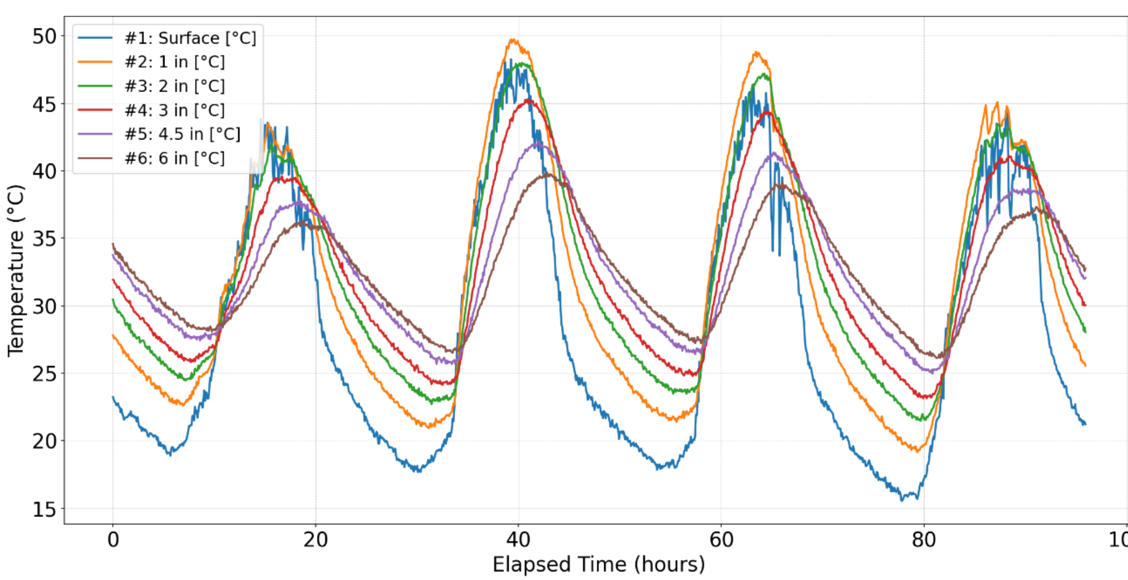


Figure 6.11: A typical temperature dataset recorded from the pavement in the test section

Figure 6.12 presents the temperature data recorded during the APT tests. It is important to note that testing began with the volumetric section in August 2024 and was completed in the same month. Testing for the BMD section started at the end of August and was completed by September 23, 2024. As seen in the graph, lower peak temperature values were generally observed in September. The average temperatures recorded during truck loading for the volumetric and BMD test sections are shown in Figure 6.13. As shown in the figure, the average temperature (calculated from all six pavement measurements during the corresponding tests) observed for the volumetric section was 35.1°C, while for the BMD section, it was 32.7°C.

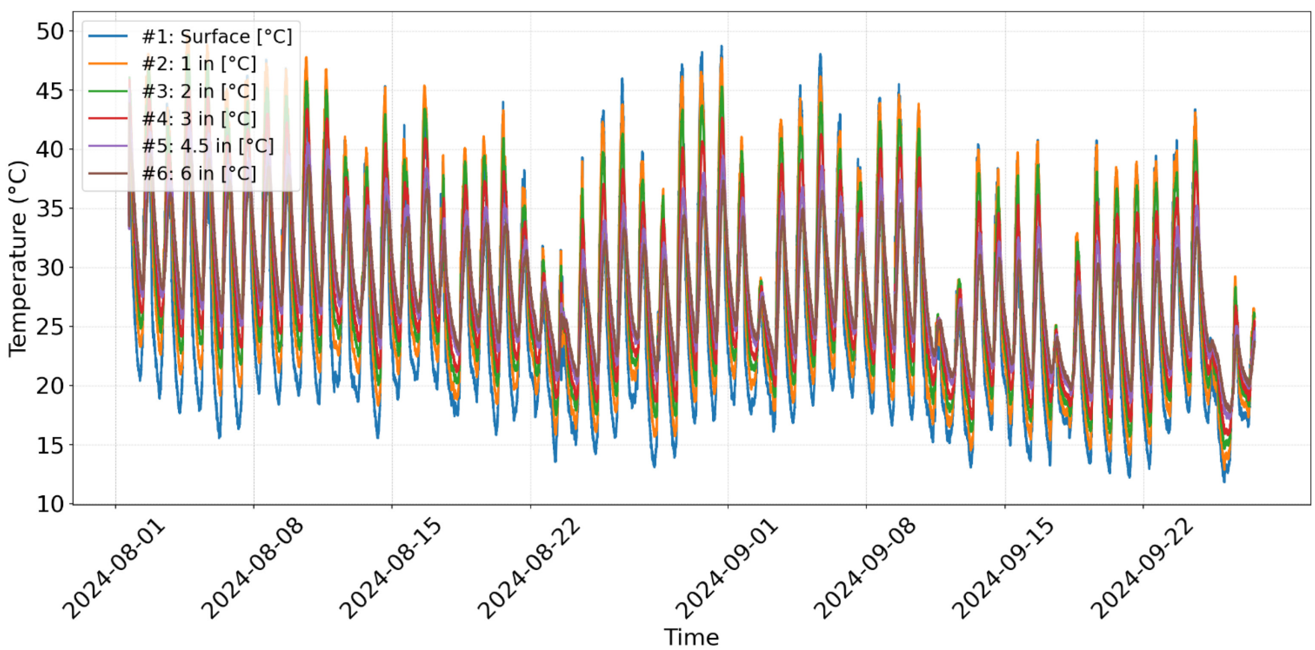


Figure 6.12: Pavement temperature data during APT testing

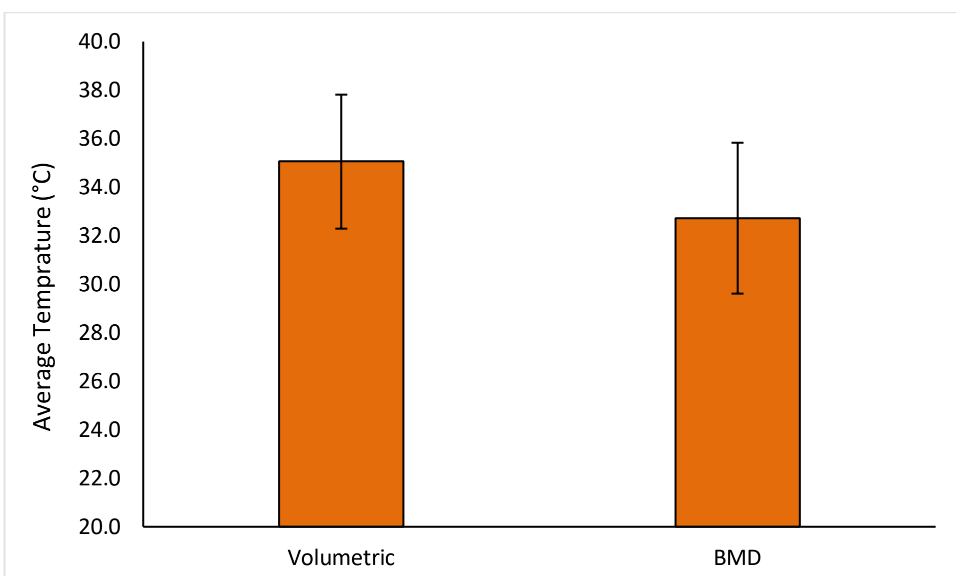


Figure 6.13: Average temperature recorded during truck loading

6.4 ACCELERATED PAVEMENT TEST RESULTS

At both test sections, the rutting became noticeable after a certain number of trucks passes. The visual state of the volumetric and BMD test sections following 10 and 20,000 passes is shown in Figure 6.14 and Figure 6.15, respectively.

Volumetric Test Section (After 10 Passes) Volumetric Test Section (After 20,000 Passes)

Figure 6.14: Volumetric section after 10 and 20,000 truck passes

BMD Test Section (After 10 Passes) BMD Test Section (After 20,000 Passes)

Figure 6.15: BMD section after 10 and 20,000 truck passes

Figure 6.16 presents the deformation profile for the volumetric section. As shown in the graph, rutting became more pronounced with increased truck passes, and shear heaves (a.k.a. deformation humps) also became more noticeable. Rutting values were calculated using the deformation profile data provided in Figure 6.16. The rutting values calculated are provided in Figure 6.17. As expected, the rutting values increased dramatically at the initial truck passes (secondary compaction or densification stage), and the increase in rutting slowed down at later truck passes. The deformation profile and rutting calculations were obtained using the average data from the middle five stations (Stations 4, 5, 6, 7, and 8).

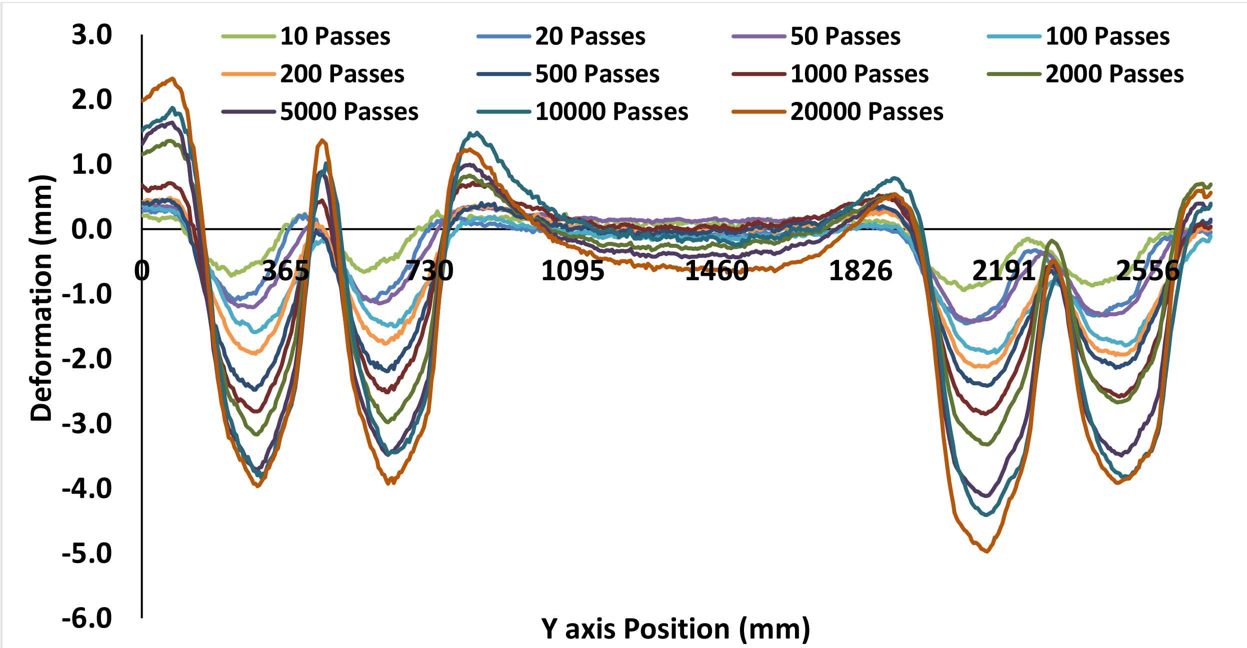


Figure 6.16: Deformation profile obtained for volumetric test section

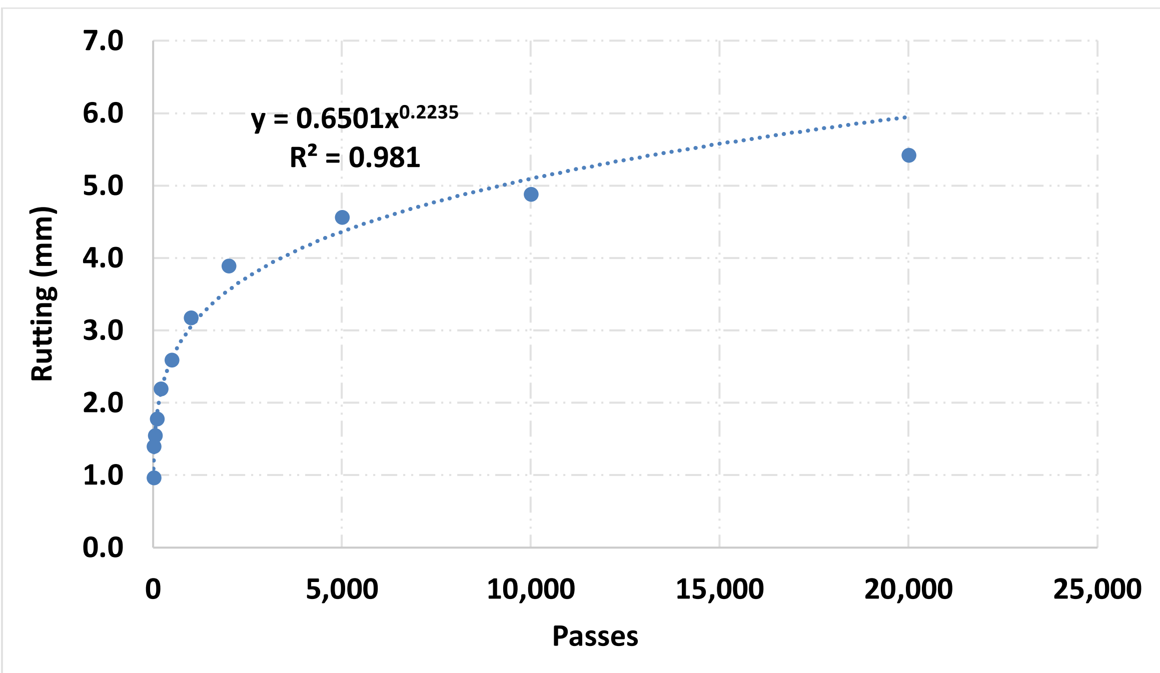


Figure 6.17: Rutting values obtained for the volumetric test section

The deformation profile obtained for the BMD section is presented in Figure 6.18. The rutting values calculated using this profile are provided in Figure 6.19.

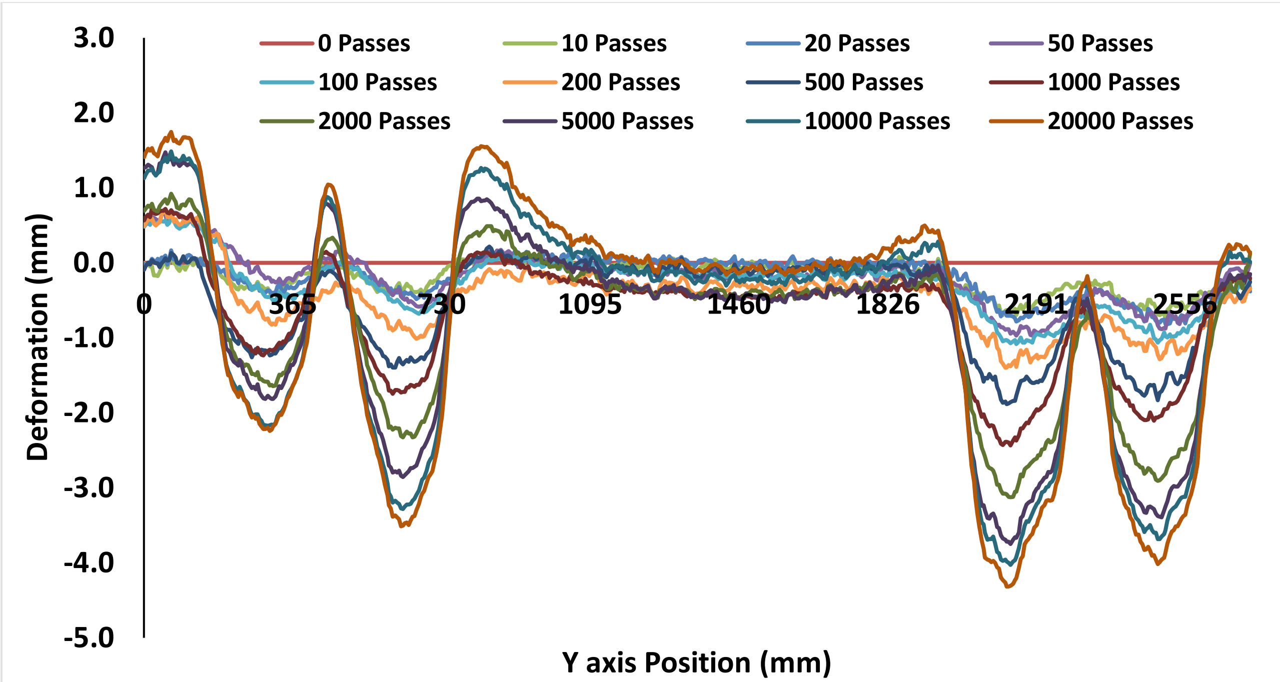


Figure 6.18: Deformation profile obtained for the BMD test section

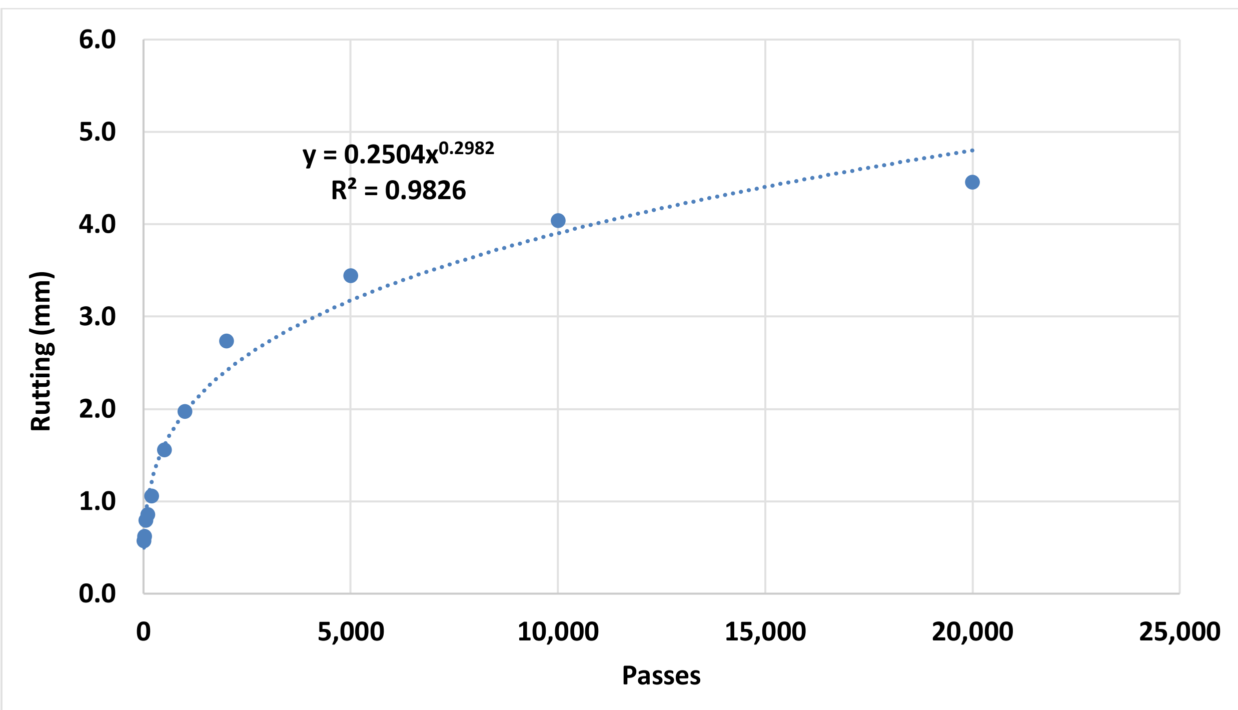


Figure 6.19: Rutting values obtained for the BMD test section

The rutting values for the BMD and volumetric test sections are presented in Figure 6.20 and Figure 6.21. As shown in the graphs, although the binder content in the BMD section (5.9% by weight of mixture) was slightly higher than in the volumetric section (5.6% by weight of mixture), the rutting values observed for the BMD section were slightly lower. This difference is thought to be due to the volumetric tests being conducted on warmer days (Figure 6.13). It should also be noted that an attempt was made to induce failure in both the volumetric and BMD sections by increasing the truck load. The load on the rear axle was raised to 60 kN (previously 40 kN), and 2,000 passes were conducted over each section at the end of both tests. The average rutting for the volumetric section increased from 5.41 mm to 5.85 mm, while for the BMD section, it increased from 4.46 mm to 4.89 mm. Despite the significant increase in load, the slight increase in rutting suggests that the mixes are very dense, preventing further compaction. Additionally, the high shear resistance of the mixes was sufficient to prevent a dramatic increase in rutting. **These results indicate that a slight increase in binder content did not significantly affect rutting values, which were observed to be around 4-5 mm. Considering that the rutting threshold for many states is 12.5 mm, it is suggested that binder content could be further increased to enhance the cracking resistance of asphalt mixes to extend the longevity of flexible pavements.**

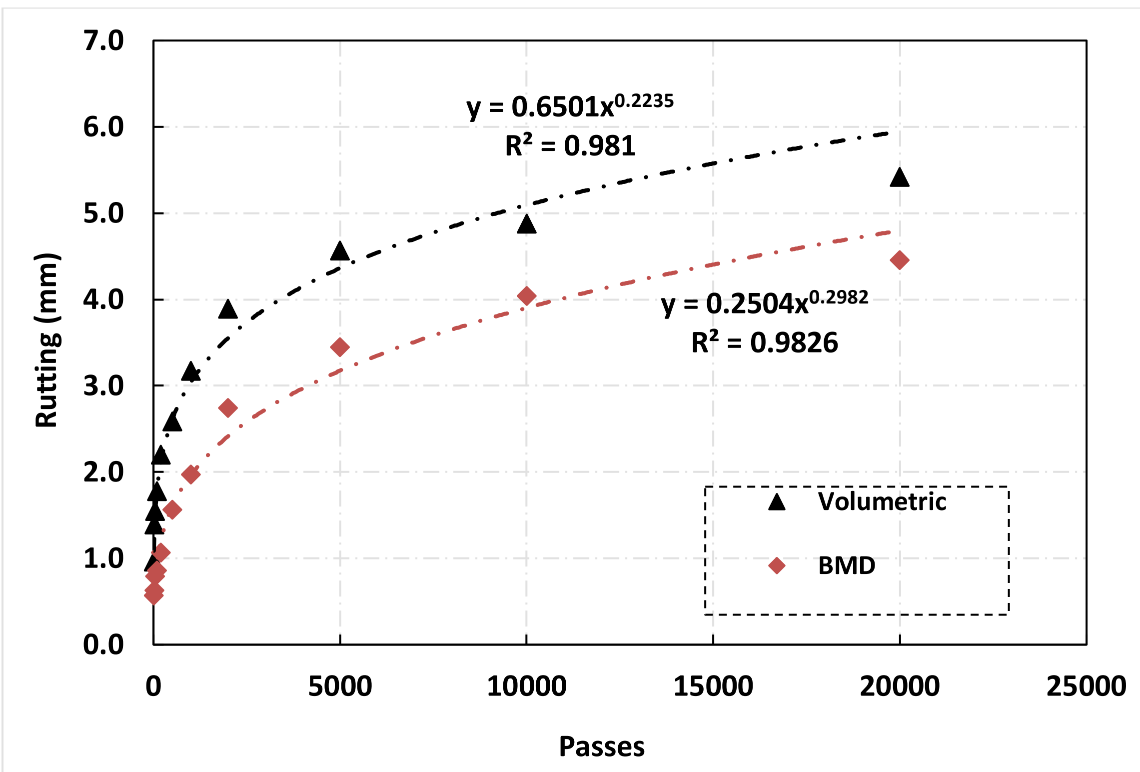


Figure 6.20: Rutting versus Truck Passes graph for volumetric and BMD section

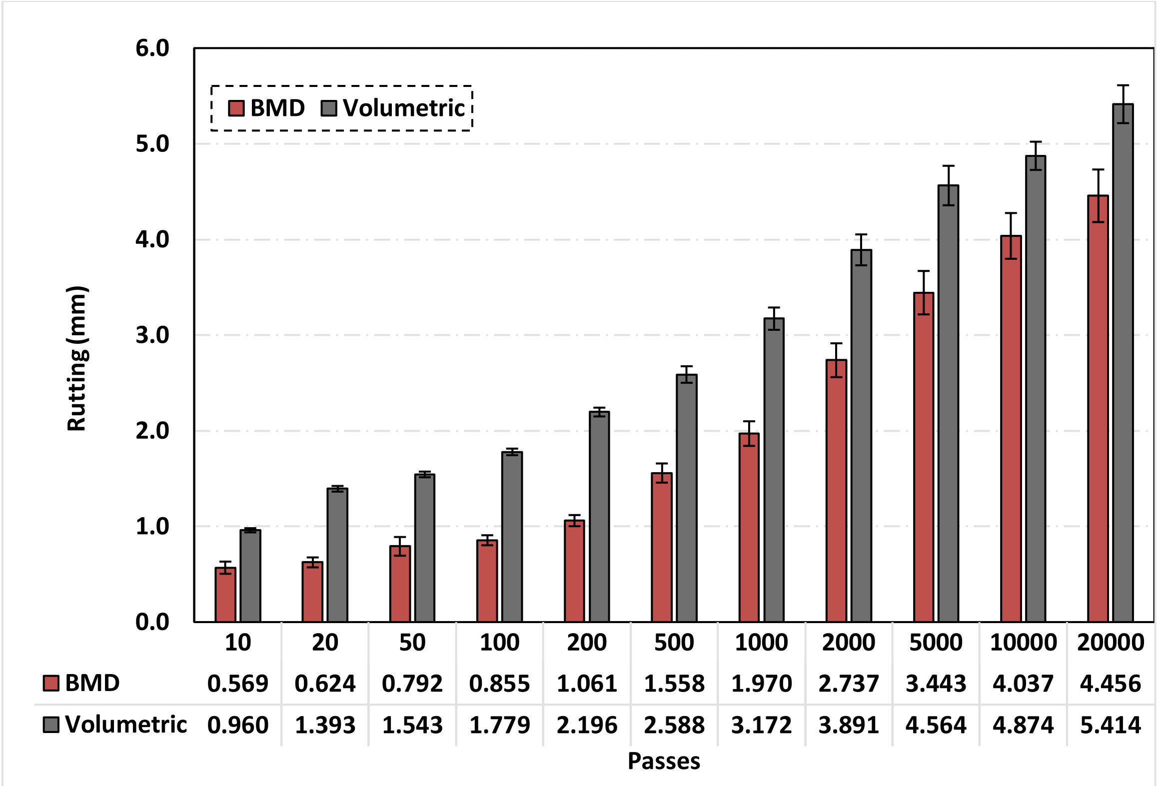


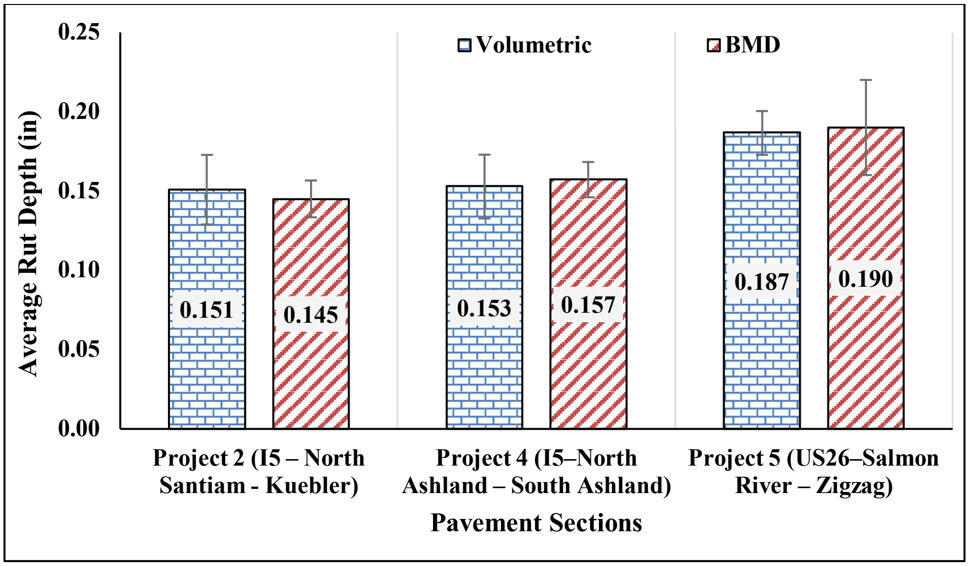
Figure 6.21: Rutting value comparison between volumetric and BMD test sections

6.5 COMPARISON OF ONE-YEAR RUTTING PERFORMANCE OF FIELD PILOT SECTIONS CONSTRUCTED USING BMD AND VOLUMETRIC MIX DESIGNS

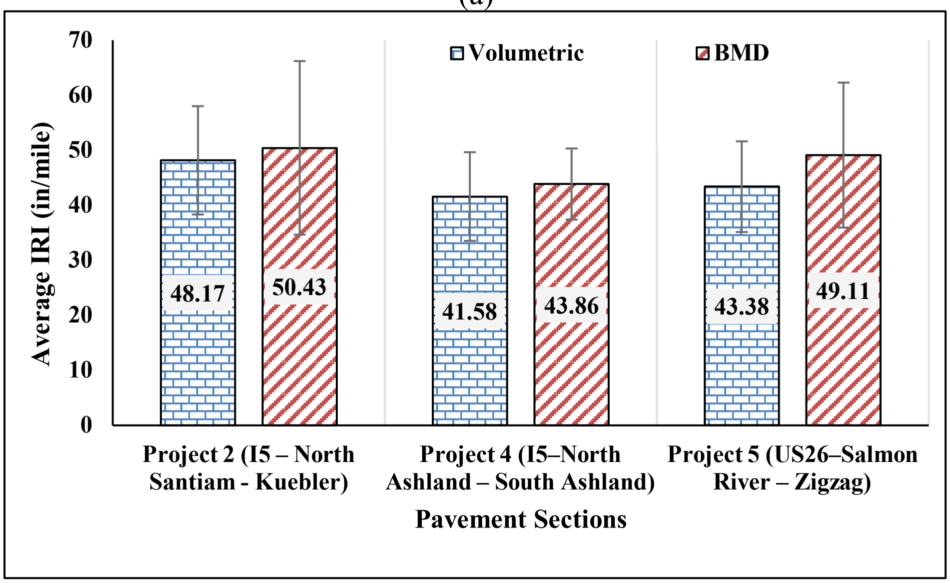
Post-monitoring of the field pilot projects is crucial as a part of the Pavement Management System (PMS) to support the implementation of new technologies (here, the BMD approach). From this perspective, the ODOT and OSU-AMaP research laboratory are working collaboratively to analyze the behavior of pilot sections constructed with volumetric and BMD approaches. This would facilitate directly comparing the typically adopted and recently developed design approaches. An attempt has been made to collect 1-year post-monitoring data regarding deformation and surface roughness. Deformations were reported in the form of rut depth, while surface roughness was reflected by a commonly used International Roughness Index (IRI). IRI is typically reported in inches/mile or m/km, and its roughness scale range varies with the type of pavement. In general, a pavement section with an IRI > 170 inches/mile or 2.7 m/km is not acceptable for users and entails early routine repairs, while an IRI < 95 inches/mile is recommended for a “good” or “very good” pavement segment (Perrone et al. 2015). It is important to note that the IRI significantly influences vehicle fuel efficiency and greenhouse gas emissions related to fuel consumption during the use phase. These concerns are generally neglected while making decisions for pavement construction, maintenance, and rehabilitation (Ghosh et al. 2015).

In the present study, the PMS data of the sections developed with the volumetric and BMD approach (Projects 2, 4, and 5) are collected over a range of stations, and the average values are shown in Figure 6.22. With the movement of vehicular traffic, there is some deformation on the pavement, regardless of the type. However, the difference in rut depth of pavement segments produced with volumetric and BMD approaches is insignificant. It has also been confirmed using a student t-test, where the p values corresponding to rut depth values of Project 2, 4, and 5 data values are calculated to be 0.42, 0.39, and 0.75 (if the p value is higher than 0.05, it suggests that the difference between the observations are insignificant), respectively, suggesting similar rutting performance of the BMD and volumetric design pavement segments. Like rutting characteristics, IRI data offer significantly similar surface roughness for all the monitored pavement segments with a p-value of 0.66, 0.41, and 0.24 for projects 2, 4, and 5, respectively. Nevertheless, there seems to be a remarkable difference between the rut depth and IRI when comparing different projects. Such discrepancies are attributed to the variable design binder content, RAP proportion, binder grade, additive, and RAP asphalt content, suggesting the inapplicability of ground-level comparison between the projects.

Despite higher binder content in BMD-based pavements, the rut depth and IRI are quite comparable. Similar to results obtained in APT tests, in Project 2, the BMD section yielded slightly lower (yet comparable) rut depth values. This suggests the importance of integrating performance-based mix design over traditional volumetric-based mix design. Further long-term monitoring of these pavement segments is necessary to evaluate cracking behavior. However, the cracking test results presented in this report indicated a significant improvement in cracking resistance with increased binder content. Therefore, it is estimated that the BMD mix design would result in more durable and crack-resistant asphalt surfaced pavements.



(a)



(b)

Figure 6.22: Pavement management system data after 1 year of pavement construction (a) Rut depth and (b) IRI

6.6 CONCLUSIONS

In this section, two different asphalt concrete test sections, produced using the volumetric and BMD mix design approaches, were tested using a low-cost, practical APT method. The rutting values obtained for the volumetric and BMD sections were compared. In addition, the one-year post-construction rutting and IRI values of sections constructed using the volumetric and BMD approaches in three regions of Oregon were compared using ODOT PMS data. Based on the results obtained, the following conclusions can be drawn:

1. The APT test results showed that the volumetric and BMD sections produced comparable rutting values. The BMD section exhibited slightly lower rutting, which was attributed to the slightly lower temperatures observed during the BMD APT testing.

2. ODOT PMS data from three different locations revealed no statistically significant differences in rutting and IRI values between pavements constructed using the volumetric and BMD approaches.

3. The results indicated that potential increases in binder content with BMD had no significant impact on rutting values. Considering that laboratory results suggested a significant improvement in cracking resistance with increased binder content, the BMD approach appears to enable the construction of more durable pavements.

As part of future work, long-term monitoring of sections constructed using volumetric and BMD mix designs is recommended to evaluate the impact of the improved crack resistance provided by the BMD mix design.

7.0 SUMMARY, MAJOR CONCLUSIONS, AND FUTURE RECOMMENDATIONS

The research work presented in this report aims to mitigate performance-related issues of asphalt-surfaced pavements. To achieve this objective, this research study was divided into laboratory, APT, and field components. The report centers on the development of a new asphalt mix design approach that integrates performance-based testing. Initially, the previous literatures in this direction were compiled, reviewed, and summarized in Chapter 2.0 to provide background knowledge to understand the research work and its importance. The literature review also highlights existing knowledge gaps and proposes how the information and technologies generated in this study can effectively bridge them.

Chapter 3.0 focuses on determining the reliability of the IDT-CT test and the testing approach for assessing the cracking performance of asphalt mixtures in a more robust and practical way. Following the selection of an appropriate testing approach, Chapter 4.0 focuses on the determination of practical parameters to quantify the performance of asphalt mixtures based on the data obtained from 28 field projects in Oregon. A statistical analysis was performed on the obtained performance testing data, and the critical thresholds were established to benchmark the performance of asphalt pavements in Oregon. In addition, four different projects were chosen to determine if the established thresholds are reliable and can be used to design asphalt mixtures with better performance in the laboratory.

However, validating these thresholds through field investigation is important to confirm their reliability. Hence, the next part of this report (Chapter 5.0) focused on validating the developed thresholds by field implementation. For this purpose, five different projects were chosen in Oregon, and the asphalt mixtures were designed based on the Balanced Mix Design (BMD) method in the laboratory. The BMD approach intends to determine the optimum binder content based on the asphalt mixture performance testing results. Later, this binder content was used to produce asphalt mixes for the construction of five pilot projects in Oregon.

During the construction of pilot projects, plant-produced asphalt mixtures were also obtained and tested in the laboratory to determine the effectiveness of BMD with respect to the traditional volumetric design. Testing the plant-produced mixes also allowed for the development of an understanding of the differences between LMLC and PMLC specimen performance and the effectiveness of laboratory specimen production in simulating plant production. Plant-produced asphalt mixtures were also assessed through cradle-to-gate LCA to identify the change in environmental impact with the application of BMD. The Emerald Eco-label tool of the National Asphalt Pavement Association (NAPA) was used to quantify the environmental burdens associated with BMD and traditional volumetric-based mix design. Along with the experimental testing, the Density Profiling System (DPS) obtained from FHWA was utilized to determine the change in compactive efforts for volumetric and BMD sections for a nearby field project located at I-5-Kuebler. In addition, pavement performance monitoring was done after 1 year of construction and traffic movement. The observations and findings of collected APCS data, in terms of rut depth and International Roughness Index (IRI), have been highlighted in Chapter 6.0 of this report. To understand the long-term effectiveness of the BMD method, the research team also proposed and developed a low-cost accelerated pavement testing (APT) system. The working of APT and their observations were recorded on one of the test sections prepared using volumetric and BMD production mixes of the I5-Kuebler project. This section of the report (Chapter 6.0) helps in comparing the rutting characteristics of the volumetric and BMD production mixes.

Overall, this research study will support the Oregon Department of Transportation (ODOT) in making informed decisions regarding the adoption of a long-term, performance-oriented asphalt mix design approach to enhance pavement durability across the state. Additionally, the findings provide valuable insights into potential challenges related to production and compaction during field implementation.

Conclusions based on the laboratory and field tests, along with the analytical findings, recommendations, and suggested future research, are discussed in the following sections.

Sensitivity of Indirect Tensile Cracking Test (IDT-CT)

- The IDT-CT results from samples conditioned in either a temperature-controlled chamber or a water bath, and tested in a load frame (referred to as the 'Inside Chamber' and 'Water Bath' approaches), closely aligned with the reference UTM test results for both asphalt mixtures. Considering the cost of UTM, the load frame offers a cost-effective solution if the sample conditioning (either dry or wet) procedure is adopted.

- The duration of sample sitting time has a notable effect on the IDT-CT results. For both mix types, a 2-week sitting period resulted in significantly lower CT-Index values for the same mix. Relying on test results from specimens stored in the laboratory for different lengths of time after production can lead to significant bias and potential errors in the balanced mix design methods.

- A simple ranking framework, which considers two predictors – the percent difference in the average CT-Index value between each testing approach and the UTM approach, and the coefficient of variation across results from different approaches – suggests that conditioning samples in a temperature-controlled chamber (25°C) and running the test quickly in a load frame is the most suitable and cost-effective method. These findings were also supported by statistical analysis using the Welch-modified two-sample t-test. Table 7.1 presents the final global ranking of the test approaches. Preliminary research suggests that the position of the load frame, whether inside or outside the temperature-controlled system, has minimal impact on test results, provided the test is conducted promptly after conditioning.

Table 7.1: Final global ranking of the IDT-CT testing approaches.

Testing Approach	Load Frame-Inside Chamber	Load Frame-Outside Chamber	Water Bath Conditioning	Unsealed samples	Vacuum sealed	Aging in Big Trays
Mix 1 ARV (rank based on Σ Rank)	**1**	4	2	6	5	3
Mix 2 ARV (rank based on Σ Rank)	**1**	5	1	6	4	3
Σ ARV (ARV (Mix1) + ARV (Mix 2))	2	9	3	12	9	6
Global Rank	1	4	2	6	4	3

Note: RV indicates the rank value and ARV denotes the average rank value

- The thickness of the loose asphalt mix in the tray influences the aging process, and changing the tray size could lead to aging-related bias in the test results. Based on the experimental findings and ranking analysis, it is advised to use larger trays (26”x18”x3”) for more consistent heating and aging during the LTA process, compared to smaller trays (20”x12”x4”). Consistency in tray size was determined to be critical to avoid any aging-related bias for the asphalt mixes.

Benchmarking the Performance of Asphalt Mixtures for BMD in Oregon

- The correlation matrix accurately predicts the effect of different influential parameters (design level, binder grade, binder content, effective binder content, dust content, and dust-to-binder ratio) on the performance of asphalt mixtures. From the correlation matrix, the design level of the project and binder grade were found to be the most significant factors controlling the cracking and rutting resistance.

- The flexibility and cracking resistance of the Oregon asphalt mixtures can be improved for all design levels by increasing the binder content. The results of the field performance assessment are expected to support increasing the binder content of the asphalt mixes for all design levels. This observation is a result of the low HWTT rut depths achieved for all production mixes.

- The design level based on traffic volume is the most efficient parameter for characterizing the performance of asphalt mixtures. However, Level 4 mixes (high traffic volume) designed with PG76-22ER polymer-modified asphalt resulted in high rutting performance but are prone to early cracking compared to all other Level 4 mixes designed with other binder grades. Hence, a separate threshold was established for Level 4 projects incorporating the PG76-22ER binder. These thresholds are listed in Table 7.2.

Table 7.2: Final thresholds for cracking and rutting.

Level	Binder Grade	Quartile 3 HWTT & CT Index	Median HWTT & CT Index	Quartile 1 HWTT & CT Index
3	ALL	4.8mm & 105	4.0mm & 69	3.1mm & 54
4	All except PG 76ER	4.0mm & 54	3.3mm & 41	2.5mm & 28
4	PG76ER	3.2mm & 42	2.8mm & 40	2.1mm & 25

- Based on the statistical analysis, different threshold levels were recommended for different quartiles to account for different reliability levels for the BMD. Different quartiles were used to design asphalt mixes for pilot section constructions to determine the impact of those quartiles on long-term performance.

- PG76-22 polymer-modified binder has a significantly higher stiffness than all other binder types, and it provides asphalt mixes with high rut resistance. However, it resulted in low CT Index values due to the lower ductility of the binder. More research in this area should be performed to accurately assess the cracking performance of the mixes with PG76 polymer-modified binder.

- The BMD approach developed by Coleri et al. (2020) can be implemented with the tentative thresholds proposed in this study to design and construct the BMD pilot sections for the field validation of the entire process.

Implementation of BMD in Oregon

- The thresholds developed in the previous phase of the study were validated by constructing pilot sections in the field. Three out of five projects needed significant adjustments to the binder content, while only slight adjustments in the binder content were needed for the remaining two projects. Table 7.3 presents the final recommended binder contents for different field projects.

Table 7.3: Final recommendations provided for the BMD asphalt mix.

Highway ID	Binder Types	Optimum Binder Content (OBC %)	BMD Binder Content (%)	Quartile	Thresholds CT Index	Thresholds Rut Depth (mm)
I84 - Meacham	PG70-28ER	6.2	5.9	3	54	4.0
I5 - Kuebler	PG70-22ER	5.6	5.9	2	41	3.3
OR18 - McMinnville	PG70-22ER	6.0	5.9	2	41	3.3
I5 - Ashland	PG76-22ER	6.2	6.3	2	40	2.8
US26 - Salmon River	PG64-22	5.3	5.7	2	69	4.0

- Although the laboratory mixed laboratory compacted (LMLC) specimens passed the cracking and the rutting thresholds, the plant mixed laboratory compacted (PMLC) specimens failed to pass the critical thresholds. Four out of five mixes failed to pass the cracking thresholds; however, all five mixes passed the rutting threshold criteria.

- Four out of five mixes designed based on the BMD method outperformed the asphalt mixtures compared to the asphalt mixtures designed based on the traditional volumetric approach and are expected to perform better in the long run. One project did not perform better than the volumetric method, and the potential cause for this can be the increase in the RAP in the BMD mix. However, it is essential to note that the IDT-CT test effectively captured this increased RAP, which was evident from the lower CT Index values compared to the volumetric mixes.

- A high correlation was obtained between the established thresholds for IDT-CT and the IDT-CT of PMLC mixes (Figure 5.30), suggesting that these thresholds can be used for future projects. However, the rutting observed from the PMLC mixes was considerably lower than the thresholds, resulting in a low HWTT correlation. (Figure 5.31). These findings suggest that Oregon asphalt mixes tend to be dry and vulnerable to cracking, indicating a substantial opportunity to enhance performance by adopting the BMD process and increasing binder content.

- For the I5-Kuebler project, the PMLC mix had significantly higher binder content, resulting in a higher CT Index and rut depths. However, the rut depths were still under the established thresholds. **This suggests that the BMD thresholds followed in this study should be revised to improve cracking resistance.**

- The field observation from the I5-Kuebler project determined that adjusting roller compactor patterns was important while constructing the asphalt pavements designed using the BMD approach. The roller compaction patterns used for the mixes designed with a volumetric approach should not be used for constructing pavements designed with BMD. A new control section must be constructed, and the new compaction process should be developed for the new mix. Based on the field observations and according to the contractors and ODOT engineers, the pilot section construction using the BMD was quick and efficient. The benefits of a more compactable asphalt mixture should also translate into improved long-term performance by enabling the achievement of higher in-place density during construction. Achieving higher density not only enhances structural capacity and load resistance but also reduces air voids, thereby limiting oxidative aging of the binder and decreasing susceptibility to moisture-related damage.

- LCA indicates a marginal difference between the environmental impacts in asphalt mixtures produced using volumetric and BMD approaches, which is primarily due to the slight difference in the binder content determined through both approaches.

- The BMD method assists in optimizing the binder content that would result in better field performance and lower project costs for some projects and definitely lower life-cycle costs for all.

Accelerated Pavement Testing (APT) and Field Performance Data Collection through APCS

- The APT test results indicated that the volumetric and BMD sections displayed similar rutting values. However, the BMD section showed slightly lower rutting, which was likely due to the slightly lower temperatures observed during the BMD APT testing.

- The APCS data collected from three distinct locations showed no statistically significant differences in rutting or IRI values between pavements built using the volumetric and BMD approaches.

7.1 MAJOR CONTRIBUTIONS TO KNOWLEDGE AND PRACTICE

- The suitability of a cost-effective load frame, compared to an expensive UTM instrument, for conducting IDT-CT was explored through a sensitivity and ranking analysis. The contribution, presented in Chapter 3.0, also detailed the sensitivity of IDT-CT test results using different testing and sample conditioning approaches.

- Critical thresholds were established for evaluating the performance of asphalt mixes with different mix properties. The adopted procedure and parametric values can be found in Chapter 4.0 of the report.

- BMD process for the asphalt pavement construction in Oregon was implemented, and the associated environmental burdens were determined. Chapter 5.0 includes the complete details for this contribution.

- The effectiveness of Volumetric and BMD processes was also tested by conducting full-scale accelerated pavement tests via a low-cost APT system developed by OSU-AMaP. This information is given in Chapter 6.0 of this report.

- Rut Depth and International Roughness Index, 1 year post-construction, on several volumetric and BMD sections were measured and evaluated. This is also reported in Chapter 6.0 of the report.

7.2 DEVELOPMENT OF SOFTWARE PACKAGES, TRAINING VIDEOS, AND SPECIFICATION UPDATE

Software Packages

- **Three valuable software packages were developed in this research work**:
    - The first software was proposed to determine the CT Index values using the load and displacement values from the experimental results. The user manual of this software can be referred to in the Appendix A.
    - The second software was developed to calculate the BMD binder content range based on the rutting and cracking test parameters. The user manual of this software can be found in the Appendix B.
    - Another software was developed to perform the volumetric checks on the calculated binder content. This software was equipped with the critical thresholds of ODOT and determined whether the mix is suitable based on the ODOT volumetric criteria. The user manual for volumetric check software is detailed in the Appendix C.

Training Videos

- **Several training videos were prepared as a part of this research work**:
    - These videos illustrate the procedures for conducting key performance tests, including the Indirect Tensile Cracking Tolerance Test and the Hamburg Wheel Rut Test.
    - Additionally, they provide a step-by-step guide for performing data analysis using the developed software tools. The goal is to offer a more accessible and practical understanding of these processes, supplementing conventional training methods.

Specifications Update

- **Three ODOT specifications were updated using the outcomes of the present study**. These specifications include:
    - Contractor Mix Design Guidelines for Asphalt Concrete.
    - Supplemental ACP Test Procedures.
    - Oregon Standard Specifications for Construction.

7.3 POTENTIAL FUTURE WORK

- Since two mixture types were evaluated in the sensitivity analysis of the IDT-CT test (Chapter 3.0 of the report), it is suggested that the testing approaches be validated based on more laboratory and field compacted mixtures. This would aid in providing firm conclusions about the testing approach and its ranking. In addition, future work should be conducted to identify and specify the ideal sitting time of the samples for accurate testing and the practical applicability of the test results. Along with sitting time, the effect of aging tray dimensions on the cracking resistance of asphalt mixtures should be studied on a wider scale in order to enhance the replicability of the testing methodology.

- An additional ruggedness study to determine the between-lab and within-lab precision and bias and the reasons for differences is currently being conducted in a study funded by the FHWA-Accelerated Implementation and Deployment of Pavement Technologies (AID-PT) program to support the BMD implementation effort of ODOT.

- More pilot sections incorporating the BMD method for producing asphalt mixtures should be constructed and periodically monitored for cracking and rutting performance. Based on these periodic observations, the current BMD thresholds should be revised to increase flexibility and ensure the asphalt pavements' long-term performance.

- The effectiveness of the IDEAL-RT test in assessing the rutting behavior should be studied in a future study to potentially replace the current HWTT method, which involves more samples for testing and more expensive test equipment.

- Blending between the RAP binder and virgin asphalt binder for the laboratory and plant mixes should be further investigated to determine the effective binder available from RAP aggregates for asphalt mixture proportioning. This effort and the associated adjustments to the BMD and volumetric processes should be provided to account for the RAP blending effect.

- Results of this study show that there may be a RAP blending issue due to nonuniform and inaccurate heating at the plant level, which negatively contributes to the cracking resistance of the asphalt mixtures that are produced. Thus, the RAP heating process at the plant level should be evaluated in a future study to determine the uniformity and accuracy of the current heating process. *This will directly affect the blending of the RAP binder.*

- Periodic monitoring of the pilot sections for the next several years is necessary to determine the effectiveness of BMD asphalt mixtures in achieving asphalt mixes with higher performance.

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APPENDICES

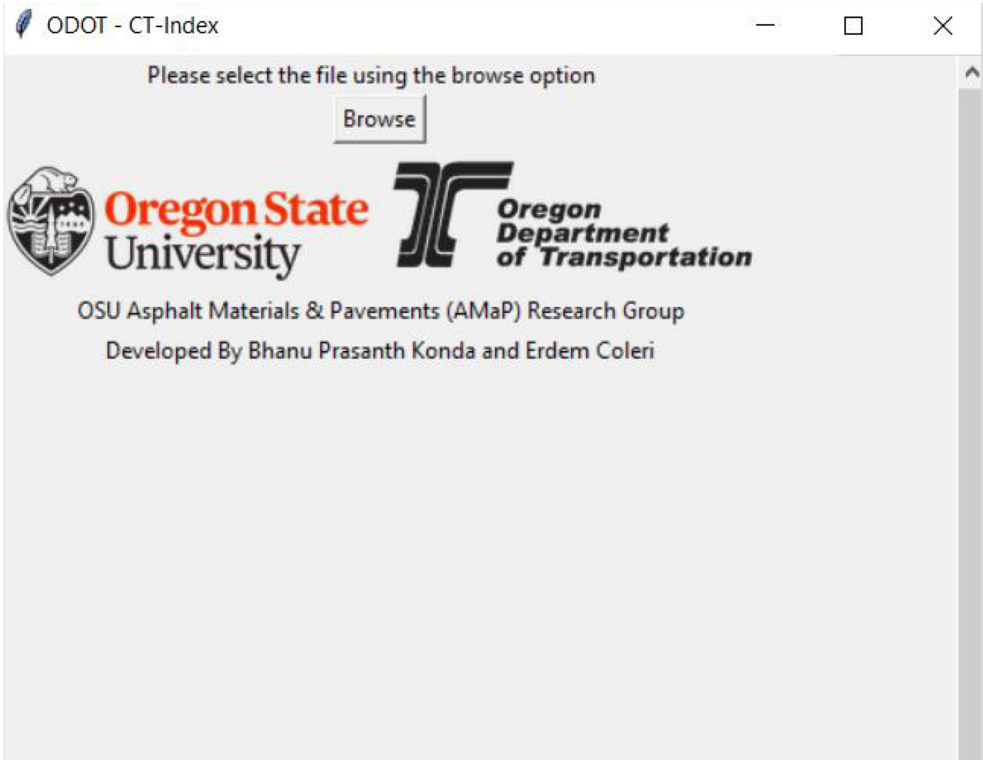
A. USER MANUAL FOR CT INDEX SOFTWARE

OSU – Asphalt Materials and Pavements (AMaP) Research Group
School of Civil and Construction Engineering
Oregon State University
DEVELOPED BY BHANU PRASANTH KONDA AND ERDEM COLERI

Step 1: Make a text file(.txt) or csv file (.csv) and copy and paste the Load and Displacement data from your original test system output data to this text or csv file and save it. The load must be in kN, and Displacement must be in mm. Please do the required unit conversions before pasting your data to text or csv file. The first and second columns must be separated by space, not by comma or dot. An example test system output and the example text file prepared from it for data processing are available in the software .zip file. Your data in the text or csv file should look like the following:

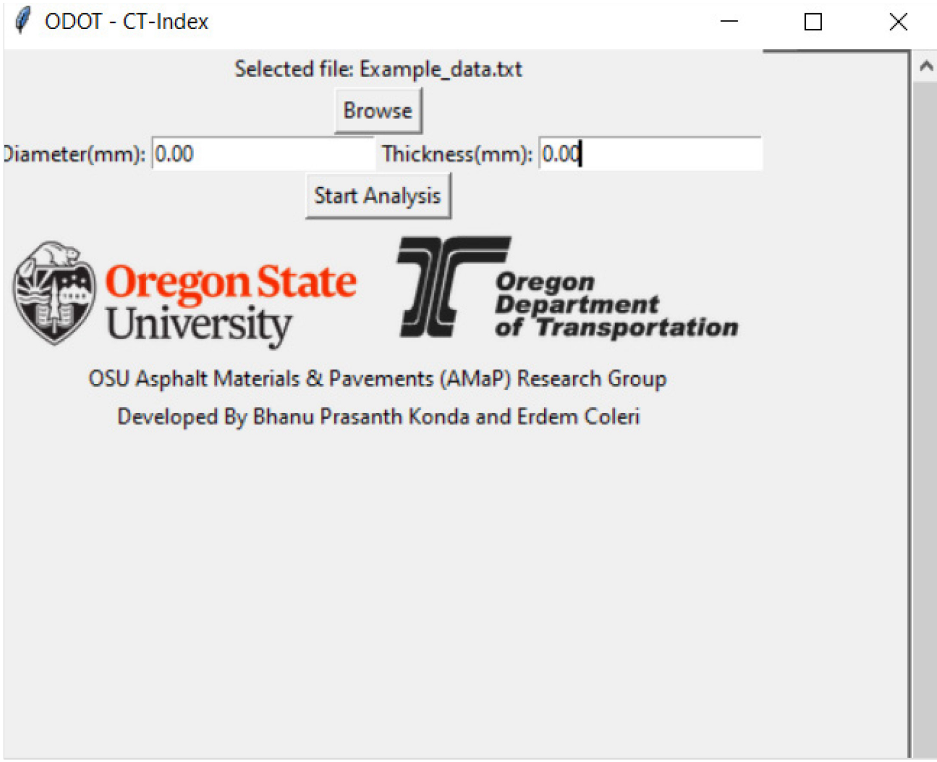
```
0.146974117 0.000552848
0.18731983  0.007482802
0.21421729  0.010259005
0.225744635 0.012808472
0.2315083   0.018430052
0.249759763 0.028194791
0.291066408 0.038309172
0.359270006 0.050406292
0.457252443 0.061366998
0.584053695 0.073549621
0.779058576 0.087548763
0.936599612 0.102569044
```

Step 2: Open the application by double-clicking on the executable file (.exe file). Software installation is not needed. Depending on the computer, it may take 10 seconds to 2 minutes for the software to start after double-clicking. It should appear with a feather logo on your taskbar.

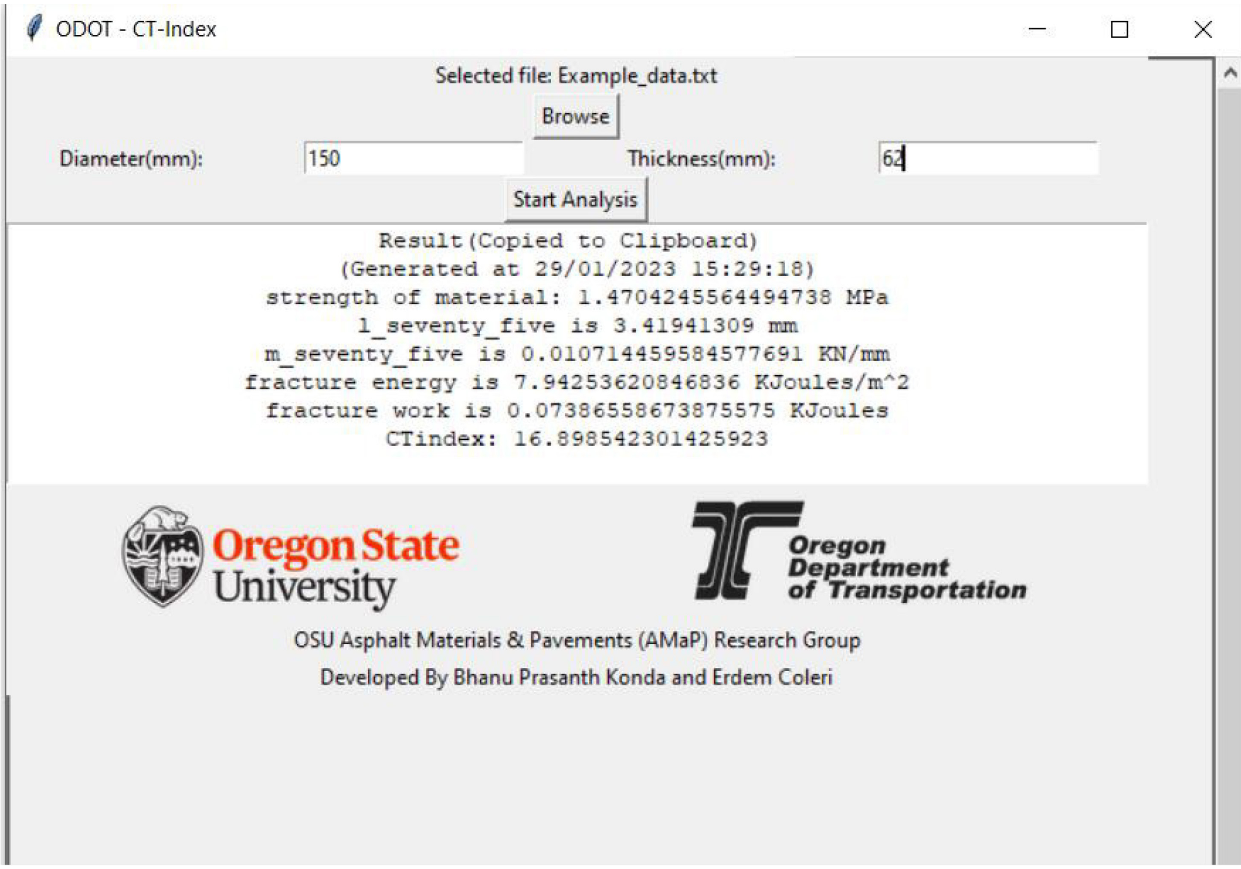


Step 3: Click on the Browse option and select the text file or CSV file previously created in Step 1.

Step 4: Enter the diameter and thickness of your tested specimen (measured before starting the test) in mm into the two boxes that will appear.



Step 5: Once you start the analysis, several calculated parameters should appear at the bottom. "CTindex" at the bottom of the list is the parameter that will be used for Balanced Mix Design (BMD). The result will also be copied to your clipboard, so you can use CTRL + V to paste it anywhere.


ODOT - CT-Index
Selected file: Example_data.txt
Browse
Diameter(mm):
150
Thickness(mm):
62
Start Analysis
Result(Copied to Clipboard)
(Generated at 29/01/2023 15:29:18)
strength of material: 1.4704245564494738 MPa
l_seventy_five is 3.41941309 mm
m_seventy_five is 0.010714459584577691 KN/mm
fracture energy is 7.94253620846836 KJoules/m^2
fracture work is 0.07386558673875575 KJoules
CTindex: 16.898542301425923
Oregon State University
Oregon Department of Transportation
OSU Asphalt Materials & Pavements (AMaP) Research Group
Developed By Bhanu Prasanth Konda and Erdem Coleri

B. USER MANUAL FOR BALANCED MIX DESIGN

OSU – Asphalt Materials and Pavements (AMaP) Research Group

School of Civil and Construction Engineering

Oregon State University

DEVELOPED BY BHANU PRASANTH KONDA AND ERDEM COLERI

This software was developed to perform the Balanced Mix Design (BMD) process using the rutting (Hamburg wheel tracking test - HWTT) and cracking (Ideat CT Index) test outputs. Using the test results as inputs, the software will perform the analysis and provide a binder content interval that will satisfy the requirements for rutting and cracking resistance. To be able to find the binder content interval, cracking, and rutting test thresholds must be entered. Those thresholds will be determined by the OSU AMaP research group and will be provided in the final ODOT research report for project SPR852. Tentative numbers were used in this user manual for developing the example cases.

Step 1: Prepare two Excel .xlsx files with CT-Index and HWTT test results. The number of columns in your test result files will vary depending on how many binder contents you used for preparing the BMD specimens. The software is capable of processing any number of binder content trials and any number of columns. The required minimum number of binder content levels will be provided in the final ODOT research report SPR852.

Two example datasets were provided with the software package (in the software .zip file), one with three binder contents and one with four. The example input Excel file screenshots with four binder contents for CT-Index and HWTT are provided below. In the provided example, there are replicate tests conducted for every binder content. Although OSU AMaP suggested conducting 5 replicate tests for the IDT-CT tests, this number may vary depending on the availability of the mix's constituents. For this reason, in this hypothetical example, we have five replicate test results for 5% and 6% binder contents, while we have four replicate test results for 5.6% and 6.5% binder content levels. The trial binder contents and the corresponding CT Index and HWTT rut depth values should be carefully entered to avoid any errors in the BMD process. It should be noted that the CT Index values will be calculated from the Indirect Tension (IDT) test results using the data processing software provided by the OSU AMaP in another software package. HWTT test results are the rut depths in mm provided by the test system output file at 20,000 repetitions and at a test temperature of 50oC (tests conducted in water).

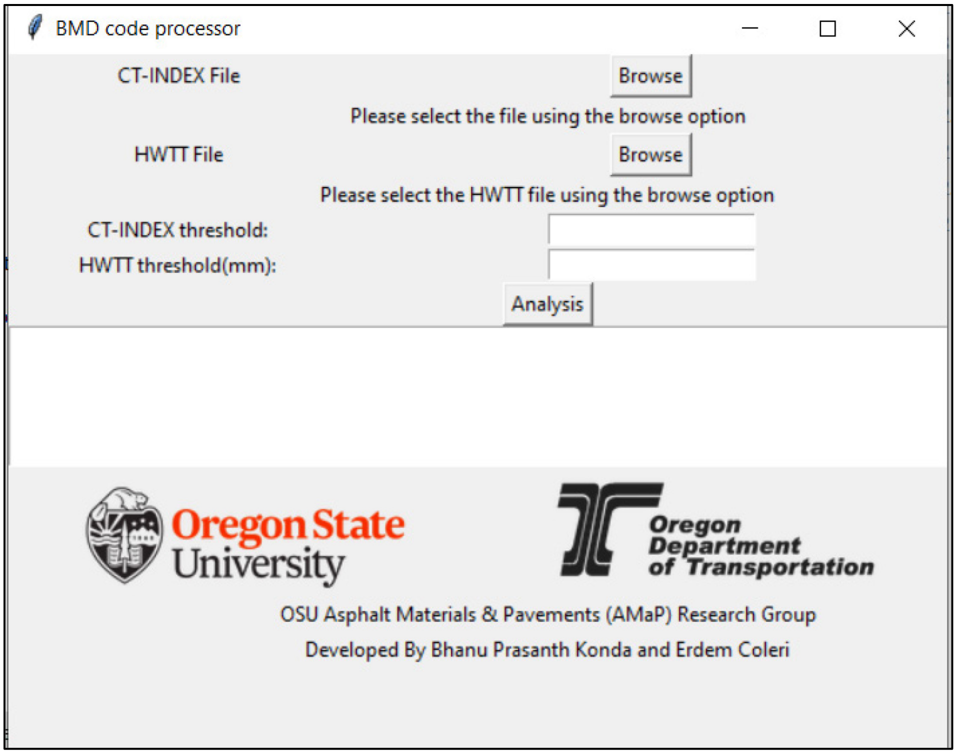
CT Index input file for four binder contents for BMD:

Replicates	5	5.6	6	6.5
1	35.6	73	104.2	131.1
2	32.4	76.3	107.4	136.2
3	34.2	71.3	105.1	132.4
4	37.1	78.1	105.3	135.2
5	33.2		108.3	
6				
7				

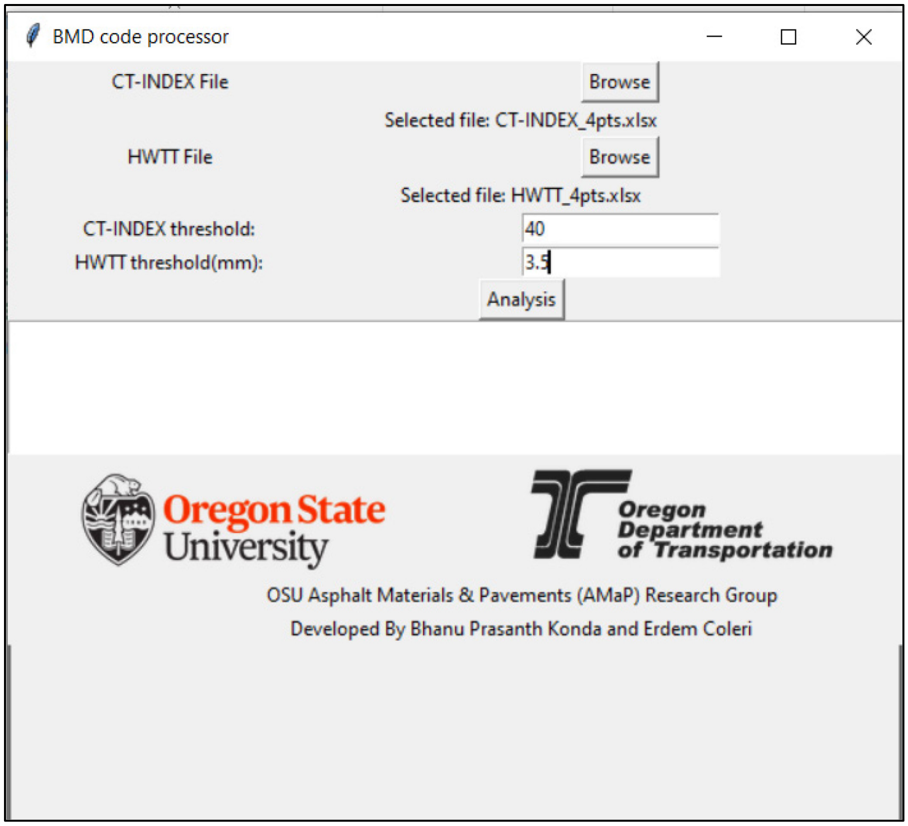
HWTT rut depth input file for four binder contents for BMD:

Replicates	5	5.6	6	6.5
1	1.66	2.25	3.2	4.2
2	1.6	2.35	3.3	4.3
3	1.61	2.32	3.19	4.12
4	1.64	2.2		4.25
5		2.4		4.22
6				
7				

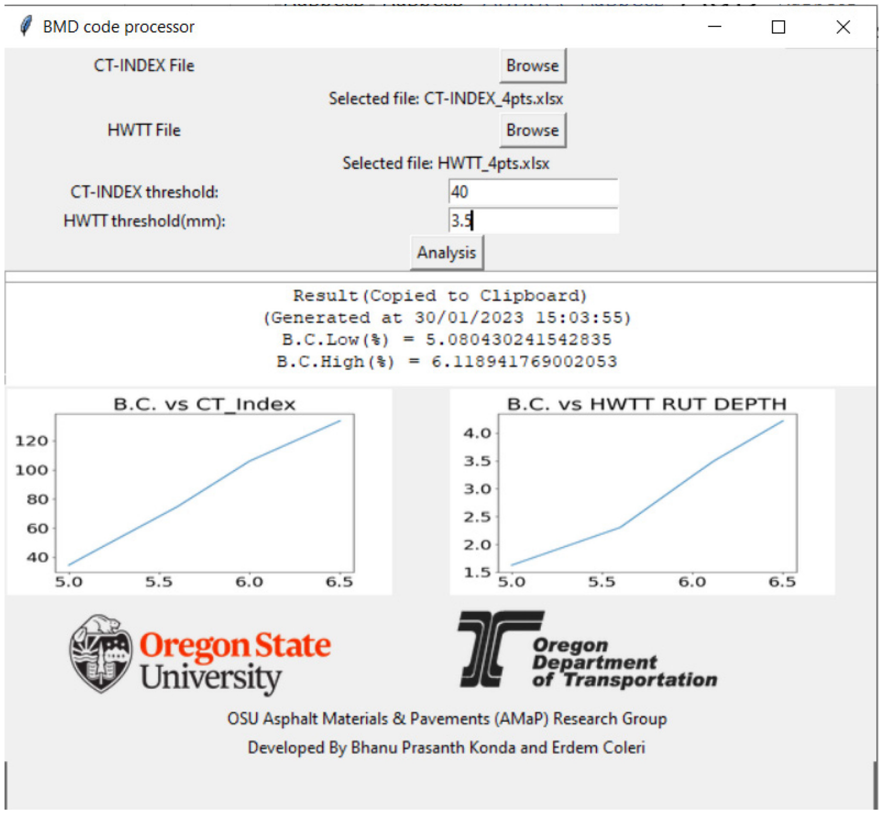
Step 2: Open the software by double-clicking on the executable file (.exe file). Software installation is not needed. Depending on the computer, it may take 10 seconds to 2 minutes for the software to start after double-clicking. It should appear with a feather logo on your taskbar.



Step 3: Click the Browse option and select the Excel file previously created in Step 1. The CT-Index file must be uploaded to the CT-Index part at the top. HWTT file must be uploaded by clicking the corresponding Browse option under the Browse option for the CT-Index. The thresholds for CT Index and HWTT should also be entered in the correct cells in the software. As mentioned above, those thresholds will be provided in the final research report for the ODOT Research project SPR852. In this example, only tentative numbers were used. After browsing all input files and the thresholds, a screenshot of the software is given below.

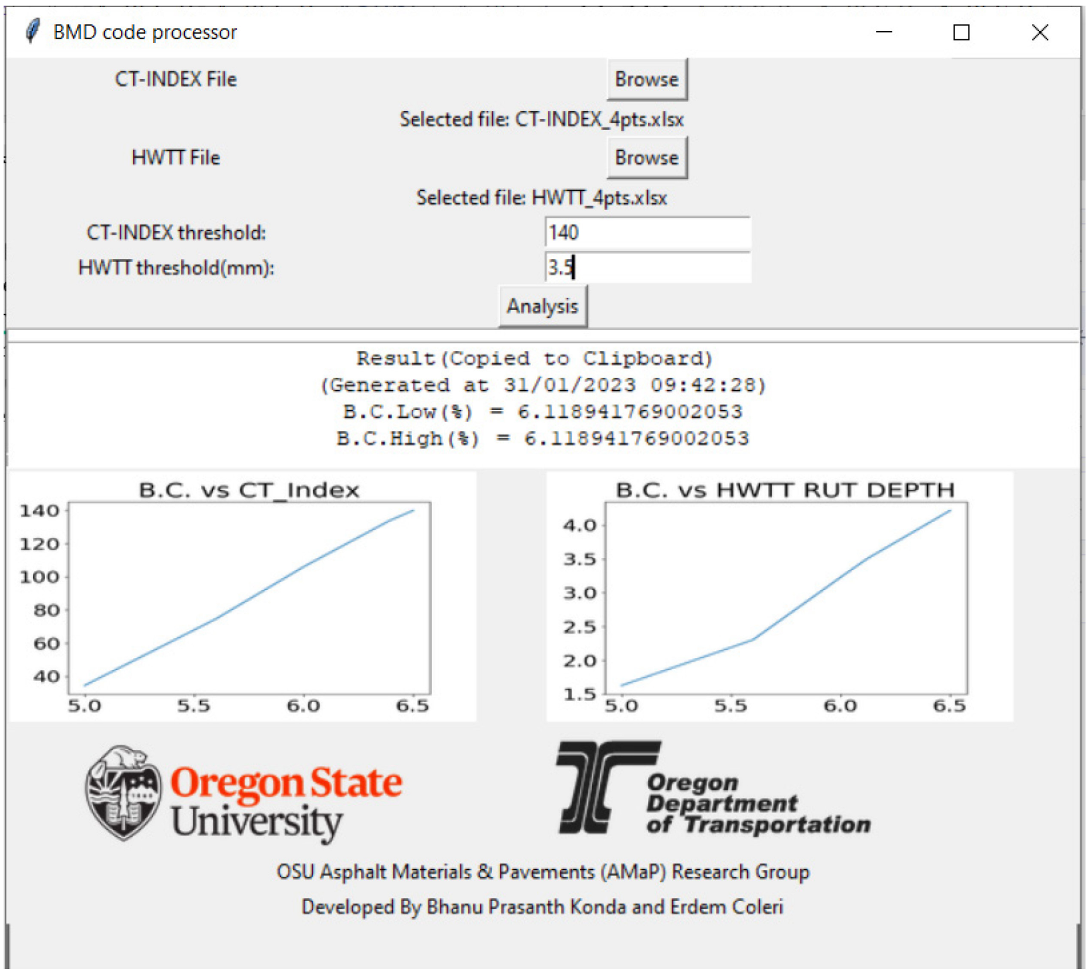


Step 4: Click on the "Analysis" to start the calculation process. Once you start the analysis, it may take 15 seconds to 3 minutes (depending on the computer) to get the results. The software may look like it is not responding during that period, but it will be internally performing the calculations. After the "Analysis" was completed, several calculated parameters and two plots (one for CT Index and one for HWTT results) should appear at the bottom. The result will also be copied to your clipboard, so you can use CTRL + V to paste it anywhere. B.C. Low (%) is the lowest binder content allowed that will provide an acceptable cracking performance according to the process. B.C. High (%) is the highest binder content allowed that will provide an acceptable rutting performance according to the process. The process for selecting the final BMD design binder content (by considering the actual binder content variability during production at the plant) by using this provided acceptable binder content interval is explained in the final research report for the ODOT research project SPR852. The software includes the data point for the calculated binder content level for the given threshold number while plotting the input data for CT Index and HWTT in two separate plots. For this reason, changing the thresholds also changes the plots.



IMPORTANT NOTE: The BMD process is expected to get an acceptable binder content interval that will satisfy both rutting and cracking performance requirements. This interval in the previous example is determined to be [5.08%, 6.12%]. The low 5.08% binder content comes from the CT Index values (the minimum binder content needed to avoid premature cracking), while the high 6.12% binder content comes from the HWTT test results (the maximum binder content allowed to avoid early rutting failures). Depending on the selected thresholds and the properties of the tested asphalt mixtures, the binder content value suggested by the CT Index results may rarely be higher than the highest allowed binder content that will be coming from the HWTT results. For those cases, the algorithm is setting the lower and upper limit for the binder content threshold to be the one suggested by the HWTT test results. This decision is made by considering the fact that rutting failures happen significantly earlier than cracking failures, and rutting failures are more critical. To avoid early rutting failures, the algorithm suggests only one number for the binder content that should avoid any early rutting failures. However, it should be noted that the cracking resistance of the mix for that particular case would be lower than the resistance required by the CT Index threshold. For this reason, a redesign might be necessary.

An example case is also provided below. It is the exact same case as the one on the previous page, except the CT Index threshold is increased from 40 to 140. Since the 140 threshold for the CT Index suggests a binder content level higher than the highest allowed by the HWTT results (which is 6.39%), the binder content allowed for BMD is set to 6.12% (one number, not an interval) based on the HWTT results to avoid any early rutting failures. As also mentioned above, the thresholds given in this user manual are hypothetical, and the actual thresholds will be selected at the end of the ODOT research project SPR852. These issues are expected to be avoided by setting thresholds suitable for Oregon asphalt mixtures. However, it should always be required to adjust the design to meet the rutting resistance requirements first (by also considering the ±0.35% allowed binder content variability at the plant) since the rutting failures will be more costly for the agency.



C. USER MANUAL FOR VOLUMETRIC CHECK SOFTWARE FOR BMD

OSU – Asphalt Materials and Pavements (AMaP) Research Group

School of Civil and Construction Engineering

Oregon State University

DEVELOPED BY BHANU PRASANTH KONDA AND ERDEM COLERI

The major purpose of this software is to perform a final volumetric check for the selected balanced mix design (BMD) to ensure that the design still meets all the volumetric design requirements. Some of the parameters required for calculating critical parameters can be estimated based on the BMD mix information or directly measured after preparing specimens with the selected BMD. The recommended process is available in the final SPR852 research report.

The software calculates the critical parameters for volumetric properties and checks them against the following ODOT requirements:

Property	Level 1	Level 2	Level 3	Level 4
Design Method	Superpave	Superpave	Superpave	Superpave
Compaction Level	65 Gyrations	65 Gyrations	80 Gyrations	100 Gyrations
Air Voids, %	3.5	4.0	4.0	4.0
VMA, % minimum	1/2 inch - 14.0; 3/8 inch - 15.0	3/4 inch - 13.0; 1/2 inch - 14.0; 3/8 inch - 15.0	3/4 inch - 13.0; 1/2 inch - 14.0; 3/8 inch - 15.0	3/4 inch - 13.0; 1/2 inch - 14.0; 3/8 inch - 15.0
VMA, % maximum	min + 2.0%	min + 2.0%	min + 2.0%	min + 2.0%
P No. 200 / Eff. AC ratio	0.8 to 1.6	0.8 to 1.6	0.8 to 1.6	0.8 to 1.6
TSR, % minimum	80	80	80	80
VFA, %	70 - 80; 3/8 inch: 70 - 80	65 - 78; 3/8 inch: 70 - 80	65 - 75; 3/8 inch: 70 - 80	65 - 75; 3/8 inch: 70 - 80

The input and output parameters are:

NMAS=Nominal Maximum Aggregate Size

Design level for the mix

Gmm=Maximum specific gravity

Gsb= Bulk Specific Gravity of the Combined Aggregate

Gb=Specific gravity of virgin binder

Pb=Asphalt content in the mix %

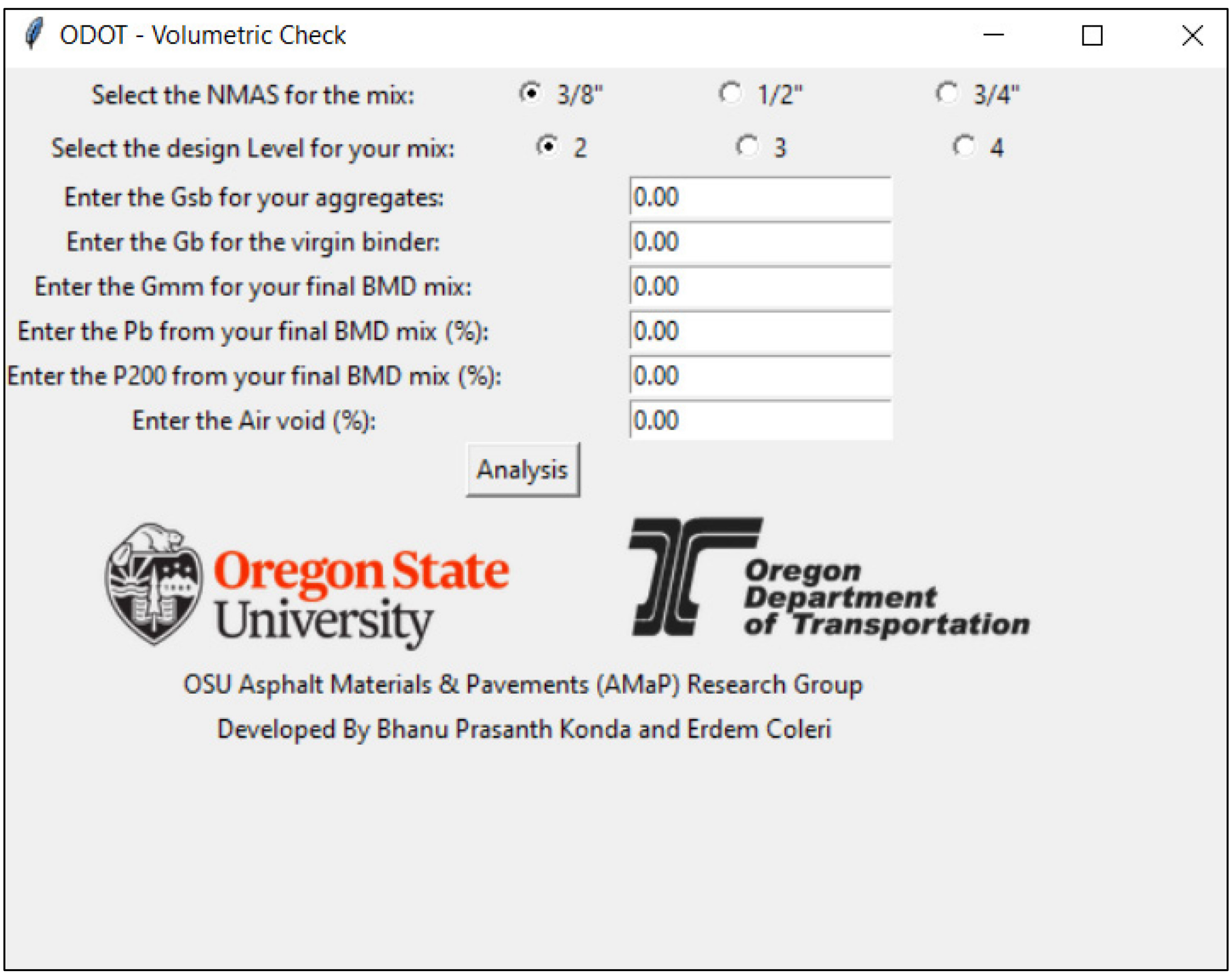
P200=Percent passing #200 sieve

VMA=Voids in mineral aggregate %

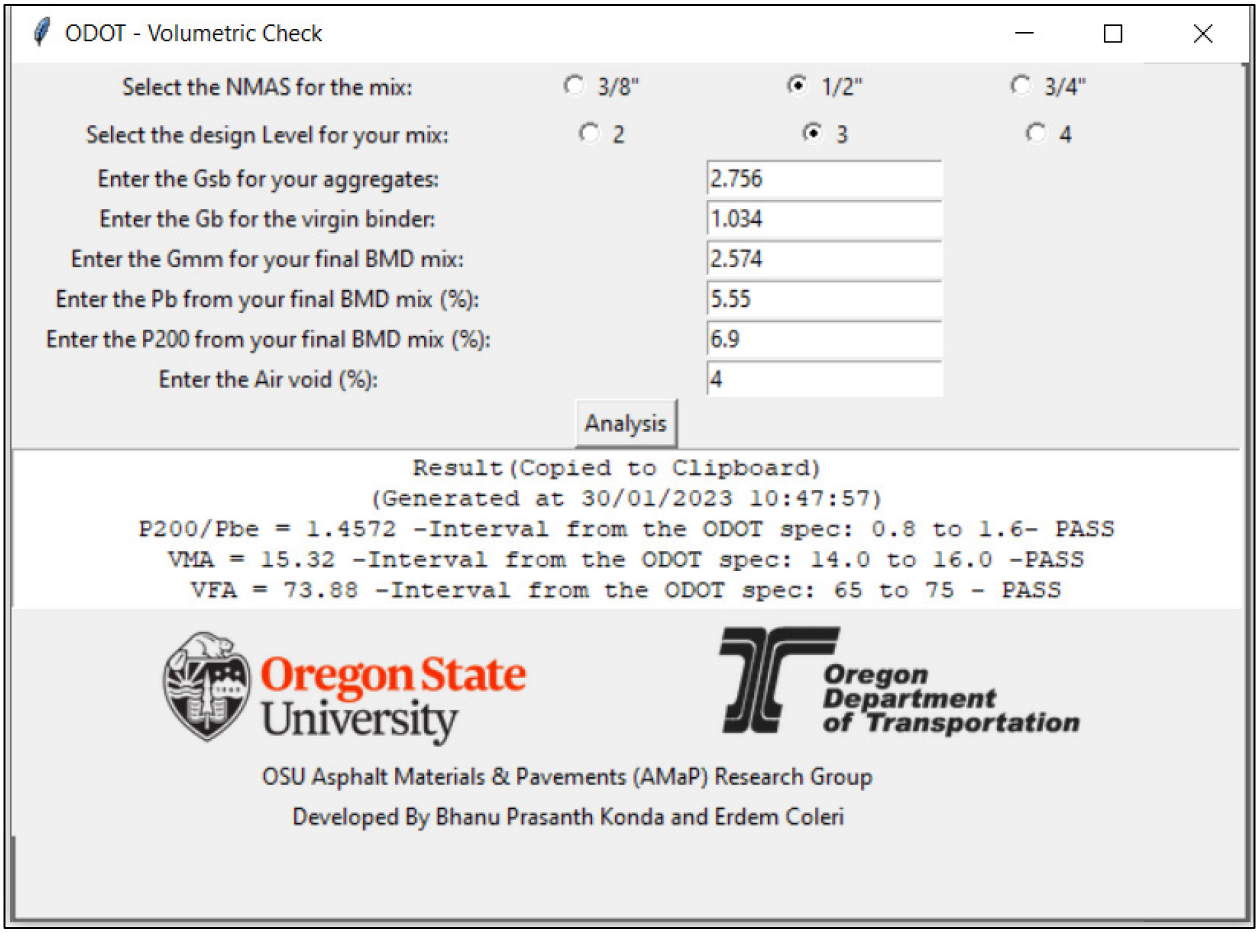
VFA=Voids filled with asphalt %

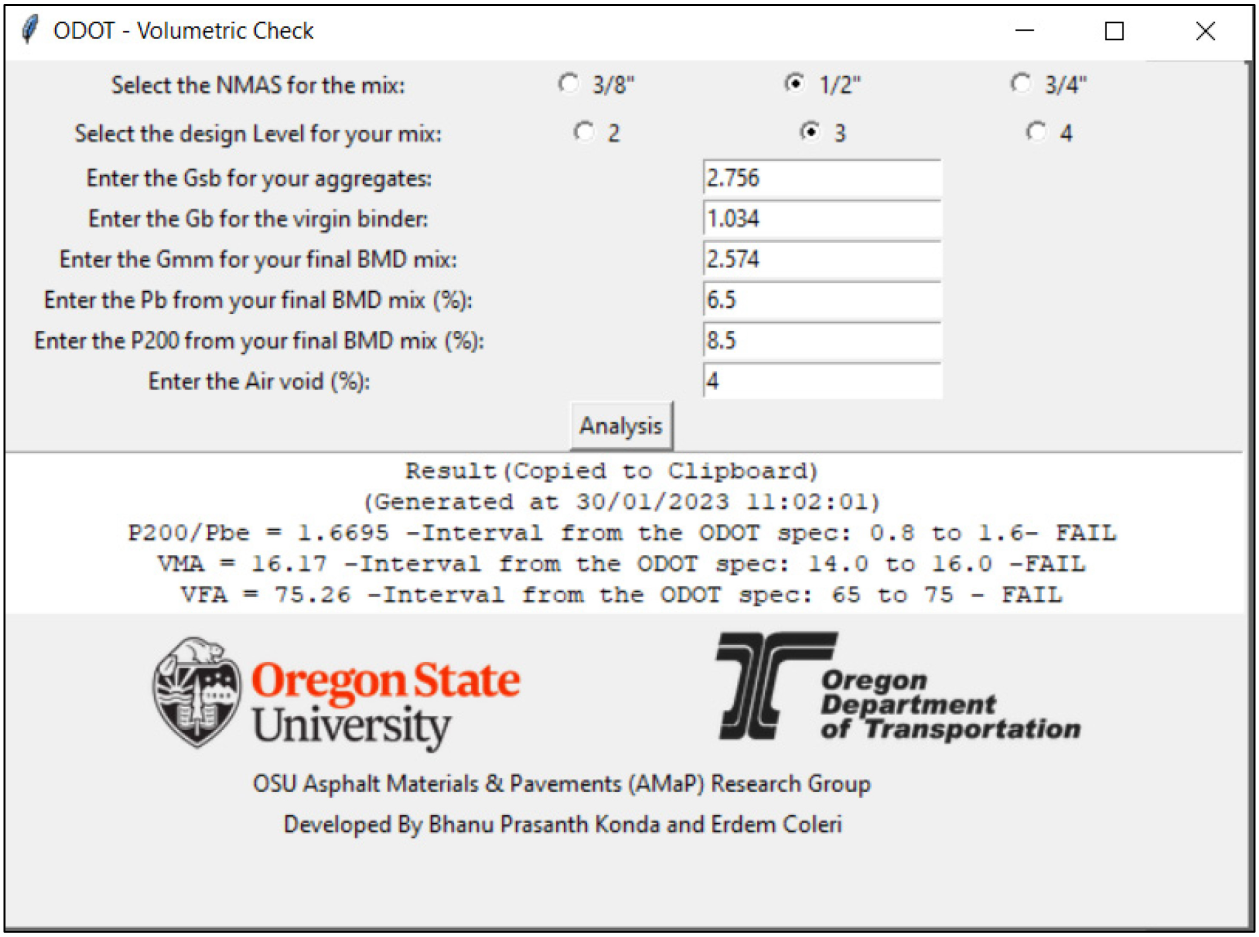
An example case with all the equations used for the calculations in the software is provided at the end of this manual in the Appendix section.

Step 1: Open the application by clicking on the executable file (.exe file).



Step 2: Enter all the values for the new BMD mix and click on the analysis to get the result. There are two example cases provided below. The first one is for a mix that meets all P200/Pbe (dust-to-binder ratio), VMA, and VFA requirements. It can be seen from the output that the mix passed all the volumetric design requirements (with "PASS" near all requirements). The second one is for a mix that does not meet any of those requirements (with "FAIL" near all requirements).





Example calculations for volumetric parameters

The major parameters used for the calculations are:

Gmm=Maximum specific gravity

Gmb=Bulk specific gravity

Gsb= Bulk Specific Gravity of the Combined Aggregate

Gse=Effective specific gravity of the mixture

Gsa=Combined apparent gravity

Gb=Specific gravity of virgin binder

Pba=Absorbed asphalt %

Pbe=Effective asphalt content %

Pb=Asphalt content in the mix %

P200=Percent passing #200 sieve

Pa=Air voids %

VMA=Voids in mineral aggregate %

VFA=Voids filled with asphalt %

Example:

Enter the NMAS for the mix: **½"**

Enter the design Level for your mix: **3**

Enter the Gsb for your aggregates: **2.756**

Enter the Gb for the virgin binder: **1.034**

Enter the Gmm for your final BMD mix: **2.574**

Enter the Pb from your final BMD mix (%): **5.55**

Enter the P200 from your final BMD mix (%): **6.9**

The Gse for the BMD mix is:

The software will calculate the Gse using this equation:

$$G_{se} = \frac{100 - P_b}{\frac{100}{Gmm} - \frac{P_b}{G_b}}$$

=(100-5.55)/(100/2.574-5.55/1.034)= 2.8209

The Pba for the BMD mix is:

The software will calculate the Pba using this equation:

$$P_{ba} = G_b \times \left[(100 - P_b) \times \frac{G_{se} - G_{sb}}{G_{se} \times G_{sb}}\right]$$

=1.034*[(100-5.55)*(2.8209-2.756)/(2.8209*2.756)]=0.815

The Pbe for the BMD mix is:

Pbe = Pb - Pba = 5.55-0.815=4.735

The P200/Pbe (dust-to-binder ratio) for the BMD mix is:

P200/Pbe = 6.9/4.735 = 1.4572

The Gmb for the BMD mix for 4% air-void content is:

Gmb=Gmm-[4*Gmm/100]=2.471

The VMA for the BMD mix is:

$$\% \, VMA = 100 - \left(\frac{G_{mb} \times (100 - P_b)}{G_{sb}} \right)$$

=100-[(2.471*(100-5.55))/2.756]=15.32

The VFA for the BMD mix is:

$$\% \, VFA = 100 \times \left(\frac{\%VMA - P_a}{\%VMA} \right)$$

=100*[(15.32-4)/15.32]=73.89

ODOT requirements for the volumetric design are provided below:

	Level 1	**Level 2**	**Level 3**	**Level 4**
Design Method	Superpave	Superpave	Superpave	Superpave
Compaction Level	65 Gyrations	65 Gyrations	80 Gyrations	100 Gyrations
Air Voids, %	3.5	4.0	4.0	4.0
VMA, % minimum	1/2 inch – 14.0 3/8 inch – 15.0	3/4 inch – 13.0 1/2 inch – 14.0 3/8 inch – 15.0	3/4 inch – 13.0 1/2 inch – 14.0 3/8 inch – 15.0	3/4 inch – 13.0 1/2 inch – 14.0 3/8 inch – 15.0
VMA, % maximum	min + 2.0%	min + 2.0%	min + 2.0%	min + 2.0%
P No. 200 / Eff. AC ratio	0.8 to 1.6	0.8 to 1.6	0.8 to 1.6	0.8 to 1.6
TSR, % minimum	80	80	80	80
VFA, %	70–80 3/8 inch: 70–80	65–78 3/8 inch: 70–80	65–75 3/8 inch: 70–80	65–75 3/8 inch: 70–80

The final outputs and checks for the example case are:

P200/Pbe = 1.4572 - Interval from the ODOT spec: 0.8 to 1.6 - PASS

VMA=15.32 - Interval from the ODOT spec: 14 to 16 - PASS

VFA=73.88 - Interval from the ODOT spec: 65 to 75 - PASS