Design Requirements for High Traffic Asphalt Mixes to Ensure Pavement Performance

Final Report

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16. Abstract

High-traffic (HT) asphalt mixtures in Wisconsin are designed using 100 gyrations, however concerns have been raised regarding the ability to achieve balanced performance and adequate field compaction using such a high gyration level. This research aims to propose modification to WisDOT's HT mix design specifications to improve constructability while maintaining or enhancing performance. The study began with a synthesis of HT mix design requirements in several states. A benchmarking study was then conducted using eight HT mixes, sampled from different projects in Wisconsin, using the Indirect Tensile Asphalt Cracking Test (IDEAL-CT) and Hamburg Wheel Tracking Test (HWTT) to assess cracking and rutting resistance, respectively. The mixes underwent extraction and recovery, and the recovered binders were evaluated for Performance Grade (PG) and Multiple Stress Creep Recovery (MSCR). The virgin binders and recycled asphalt materials (RAM) used in the mixes were also collected and evaluated to determine their PG and MSCR. Mix results were benchmarked against WisDOT HT mixes, leading to the selection of three mixes for redesign and further testing. The mixes were reproduced as lab-mixed lab-compacted (LMLC) specimens, redesigned using the Bailey Method and Asphalt Film Thickness (AFT), and compacted at 75 gyrations to 4.0% air voids without air-void regression. Overall, it was noted that the cracking resistance was significantly influenced by the stiffness of the recovered binder's PG, and the recycled binder ratio. Performance testing showed that the redesigned mixes achieved similar or improved cracking resistance, rutting resistance, and compactability compared to baseline HT mixes designed at 100 gyrations with air-void regression. To evaluate the impact of air-void regressed design accompanied with reduced gyration level, a fourth mix was selected for redesign using 3.0% regressed air voids and 75 gyrations, resulting in improved cracking and rutting resistance. The findings of this study support using 75 gyrations at 4.0% air voids for HT mixes in Wisconsin with air-void regression. The study also highlighted the impact of the recovered binder's PG on the mixture cracking resistance. Additionally, the Bailey Method and AFT can be used to guide the selection of aggregate gradation, and asphalt binder content. A special provision is proposed for initial implementation.

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EXECUTIVE SUMMARY

The design number of gyrations (N_{des}) in the Superpave method is meant to provide a compaction effort that matches the ultimate field density. The N_{des} parameter is important because it largely controls the asphalt binder content in the mix. A high N_{des} typically results in asphalt mixes with a strong rut-resistant aggregate structure but low asphalt binder content, which may be difficult to compact in the field and may exhibit reduced cracking resistance and durability. The Wisconsin Department of Transportation (WisDOT) developed a regressed air-void approach in which Superpave mixes are initially designed using the Superpave method at 4.0% air voids, then the binder content is increased during production to reduce the air voids to 3.0%. A key advantage of the regressed air-void approach is its ability to maintain a strong aggregate structure while accommodating higher asphalt binder contents.

The objective of this study is to benchmark existing WisDOT high traffic (HT) mixture designs using volumetric, mixture content analysis and performance testing and propose modifications to existing HT mixture designs to improve mix performance. Additionally, the study aims to summarize existing mix design requirements for HT mixtures in states with similar climates ("Wet-Freeze") and aggregate sources for Wisconsin to identify potential areas for improvement.

The research began with a synthesis that included a review of state DOT specifications and a survey sent to various state DOTs to identify their HT mix design practices, aggregate requirements, binder specifications, and challenges related to the design and construction of HT mixes. For the survey, HT mixes were defined as those designed for traffic levels exceeding 8 million ESALs. The survey results indicate that the traffic level used to define HT mixes varies across states, and that N_{des} vary significantly across states. Two states, e.g., Wisconsin and Michigan, utilize a regressed air-void approach. It was also shown that all states surveyed specify a minimum VMA criteria except for Minnesota, which uses AFT, and Iowa, which uses both VMA and AFT. Several states have adopted the minimum VMA criteria specified in AASHTO M 323, whereas some states have increased the minimum VMA requirement from those in AASHTO M 323. The Wisconsin DOT uses the regressed air void approach where mixes are designed at 4.0% air voids and regressed to 3.0% during production. WisDOT specifies an N_{des} of 40, 75, and 100 gyrations for low traffic (LT), medium traffic (MT), and HT mixes, respectively. The minimum VMA criterion for WisDOT follows AASHTO M 323.

The benchmarking phase included eight HT mixes that were sampled from different projects representing different mix types, e.g., 3HT with a 19 mm NMAS and 4HT with a 12.5 mm NMAS. Source materials including virgin aggregate, Reclaimed Asphalt Pavement (RAP), Reclaimed Asphalt Shingles (RAS), and virgin binder were also sampled during production. The sampled mixes used different binder grades, e.g., PG 58-28 S and PG 58-28 H. Production data was also collected to determine any changes made to the aggregate proportions during production. The performance and volumetrics of the sampled plant mixes were verified. Indirect Tensile Asphalt Cracking Test (IDEAL-CT) and Hamburg Wheel Tracking Test (HWTT) were conducted on plant-mixed lab-compacted (PMLC) specimens to determine cracking and rutting resistance, respectively. The mixes were subjected to extraction and recovery, and the as-recovered binder was tested to determine their PG and MSCR. A washed gradation was done on the recovered aggregates to verify gradation against the mix design. The RAP binder and virgin binder were tested to determine their PG and MSCR. The performance of the eight mixes was compared with those of HT mixes from the WisDOT database, and based on the comparison, three of the eight mixes were selected for the next phase of the study, which involved a redesign of the HT mixes using the same source materials. The performance of the selected mixes was considered more representative of HT WisDOT mixes.

The redesign phase included further testing and analysis of the three mixes selected in the benchmarking phase. The three mixes were recreated in the lab using the sampled raw materials, to produce lab-mixed lab-compacted (LMLC) specimens. The rutting and cracking resistance of the LMLC were determined, and the results were compared with those of the PMLC specimens. The results show distinct differences between the LMLC and PMLC specimens. The LMLC results were used as a baseline for the redesign of the mixes. For the redesign, the Bailey Method was utilized to optimize aggregate packing and gradation. In addition, a virtual design approach incorporating Asphalt Film Thickness (AFT) was used alongside the Bailey Method to refine further and optimize the mix design. The redesigned mixes underwent a few iterations to improve performance. A target air void content of 4.0% and an N_{des} of 75 gyrations were used for the redesigned mixes. The objective was to reduce the number of design gyrations for HT mixes from 100 to 75 to improve field compaction, while maintaining balanced performance. The three redesigned mixes were not regressed to 3.0% air voids to evaluate whether satisfactory performance can be achieved without air-void regression. To evaluate the impact of air-void regression, a fourth mix was selected for redesign using 75 gyrations and air-void regression to ensure balanced performance following WisDOT regressed approach.

Based on the results of this study, the three HT mixes redesigned at 4.0% air voids and 75 gyrations provided balanced performance with respect to both rutting and cracking resistance. Additionally, the redesigned mixes had similar or better compactability compared to baseline mixes designed at 100 gyrations. The compactability of the mixes was assessed using the compaction slope and locking point from the Superpave Gyratory Compactor (SGC) data. The results also revealed that improved rutting and cracking resistance can be achieved using 75 gyration levels along with a 3.0% air-void regressed design. Hence, the results of this study support using a reduced gyration level of 75 for HT mixes in Wisconsin.

It was also shown that the AFT can be used successfully to guide the selection of the asphalt cement (AC) content during the design process to improve performance. The cracking resistance, as measured by the CT_{index}, was shown to be significantly influenced by the stiffness of the recovered binder. A strong correlation was noted between the CT_{index} and both the high-temperature PG and low-temperature PG. Mixes with a recovered binder having a high-temperature PG above 80 showed CT_{index} values below 50.

CHAPTER 1. INTRODUCTION

Background

Superpave asphalt mix design has been used in the US since 1993. The Superpave system has gone through developments since its introduction with different and refined test procedures and material specifications. The FHWA recommends carefully evaluating any proposed specification changes to fully understand their impact (FHWA 2010). In Superpave, the aggregate gradation and properties affect how easily the mix compacts, which in turn controls the air voids and the amount of binder needed (Christensen and Bonaquist 2006). The Superpave specifications are tailored to different traffic levels of a roadway. High traffic (HT) level is defined as the roadways with large volumes of traffic. Different state agencies have defined high traffic as those roadways with more than 8 to 10 million Equivalent Single Axle Loads (ESALs). The traffic level is used to define the number of gyrations used for design.

For Superpave mix design, the design number of gyrations (N_{des}) is meant to provide the compaction effort that matches the ultimate field density. During the Strategic Highway Research Program (SHRP) project in 1994, the original N_{des} specification was introduced and developed using field densities of 15 field projects that were in service for at least 12 years (Cominsky et al. 1994). The SHRP project proposed twenty-eight design gyration levels based on the traffic level and pavement climate. Further research led to the reduction of the number of gyration levels to four based on the traffic level, which was later adopted by AASHTO R 35 (Anderson et al. 2000). Table 1 shows the N_{des} values based on traffic from AASHTO R 35.

Table 1: Superpave gyration levels (From AASHTO R 35)

Design Traffic Level (Million ESALs)	**Gyration Levels**		
	$N_{initial}$	N_{design}	$N_{maximum}$
<0.3	6	50	75
0.3 to <3.0	7	75	115
3.0 to < 30.0	8	100	160
>30.0	9	125	205

Several state DOTs raised concerns about whether the AASHTO gyration levels accurately reflected the level of compaction and densification in the field. The NCHRP Project 9-09(1) included forty projects from sixteen states to verify design gyration levels based on field density after a few years of construction (Prowell and Brown 2007). It was determined that the ultimate field density of the surveyed projects was less than the design densities. Based on the findings of the NCHRP 9-09(1), it was recommended to reduce the AASHTO design gyrations and eliminate the N_{max} and N_{min} requirements.

Several states validated the NCHRP 9-09(1) project recommendations using local mixes, which resulted in different states adopting different N_{des} values. Several states have also adopted volumetric properties, including Voids in Mineral Aggregate (VMA), Voids Filled with Asphalt (VFA), and design air voids, which differ from those given by AASHTO M 323, as shown in

Table 2. Other criteria, such as minimum Asphalt Film Thickness (AFT) and minimum asphalt content (AC), were also adopted by some states.

Table 2: Superpave HMA design requirements (From AASHTO M 323)

Design ESALs, millions	Required Relative Density, % Theoretical Maximum Specific Gravity			Voids in the Mineral Aggregate (VMA), % Minimum						Voids Filled with Asphalt (VFA), % Range	Dust to Binder Ratio, range
				Nominal Maximum Aggregate Size, mm							
	$N_{initial}$	N_{design}	N_{max}	37.5	25	19	12.5	9.5	4.75		
<0.3	≤91.5	96	≤98	11	12	13	14	15	16	70-80	0.6-1.2
0.3 to <3	≤90.5	96	≤98	11	12	13	14	15	16	65-78	0.6-1.2
3 to <10	≤89	96	≤98	11	12	13	14	15	16	65-75	0.6-1.2
10 to < 30	≤89	96	≤98	11	12	13	14	15	16	65-75	0.6-1.2
≥30	≤89	96	≤98	11	12	13	14	15	16	65-75	0.6-1.2

Design Gyrations

Several state DOTs have conducted research to validate N_{des} and evaluate its impact on performance. A study was conducted in Georgia where it was shown that pavements reached an air void level of 5.7% after five years of construction, which indicates that the design air void of 4.0% was unlikely to be achieved in the field, using the N_{des} levels at the time (Watson et al. 2008). The locking point was shown to provide better correlation with field density with an average locking point of 65 gyrations. Based on the results of this study, the Georgia DOT changed their specifications to use a design gyration level of 65 for all traffic levels. A considerable increase in fatigue life was noted using the reduced gyration level due to an increase in optimum asphalt binder content.

The Virginia Transportation Research Council conducted a study to evaluate the impact of using a reduced N_{des} of 50 on the binder content, gradation, and other volumetric properties (Diefenderfer et al. 2018). The study showed that the amount of increase in binder content from using a lower gyration level was dependent on the mix type. It was also shown that mixes designed using lower gyration levels were easier to compact in the field. The study, however, did not evaluate the impact of using different aggregate gradations and volumetrics on the performance of the mixes such as rutting and cracking.

The Iowa DOT performed a study to validate the N_{des} parameter for Iowa mixes and to assess the impact of using different design gyration levels (Williams et al. 2021). The study compared the old (high) and new (low) design gyration levels using performance testing including dynamic modulus, flow number, Disk-shaped Compact Tension (DCT), HWTT, and beam fatigue. The mixes designed using the lower gyrations levels had better cracking and fatigue performance. No statistical difference was noted in rutting performance of old and new mixes based on the HWTT results. A reduced gyration level of 50, 75, and 95 was proposed for standard, high, and very high traffic, respectively. It was also proposed to use a design air void of

4.0% for surface mixes, 3.0% for base mixes with standard traffic, and 3.5% for base mixes with high and very high traffic.

The Colorado DOT initially adopted the design gyrations proposed by the SHRP research , however mixtures prepared using the high design gyrations failed prematurely because of moisture damage and cracking (Harmelink et al. 2007). A field study in Colorado including 39 projects showed that pavements do not densify to the design air void after more than 6 years of construction. Using lower design gyrations resulted in better compaction and lower pavement air voids.

The Indiana DOT adopted a variation of Superpave called Superpave5. In Superpave5, mixes are designed and compacted at 5.0% air voids. The design is conducted using lower gyrations to yield mixes that are easier to compact in the field (Montoya et. al. 2018). Following successful field trials and demonstration projects, Indiana DOT changed their specifications to use Superpave5. A study was conducted by Purdue University documenting the implementation of Superpave5 on 12 trial projects in six Indiana DOT districts (Haddock et al. 2020) It was concluded that the field densities do not always match the design densities and local contractors need to undergo training on Superpave5 design and construction methods to ensure mixes are not over-compacted in the field.

WisDOT Approach

Wisconsin DOT (WisDOT) uses a unique approach where Hot Mix Asphalt (HMA) mixes are designed at 4.0% air voids and regressed to 3.0% air void during production. The regressed air void approach maintains the same aggregate structure while allowing for additional binder content. An illustration of the air-void regressed air approach is shown in Figure 1. The relationship between AC content and air voids is used to determine the optimum binder content during the design process. The binder content is adjusted during production to regress the air voids to 3.0%. In the example shown in Figure 1, the design AC content at 4.0% air voids is 5.4% and the production AC content at 3.0% air voids is 5.7%. WisDOT uses 100 design gyrations for HT mixes compared to 75 gyrations for medium traffic (MT) mixes. The HT and MT mixes have comparable aggregate requirements, with HT mixes having higher requirements on fractured faces, FAA, and sand equivalency.

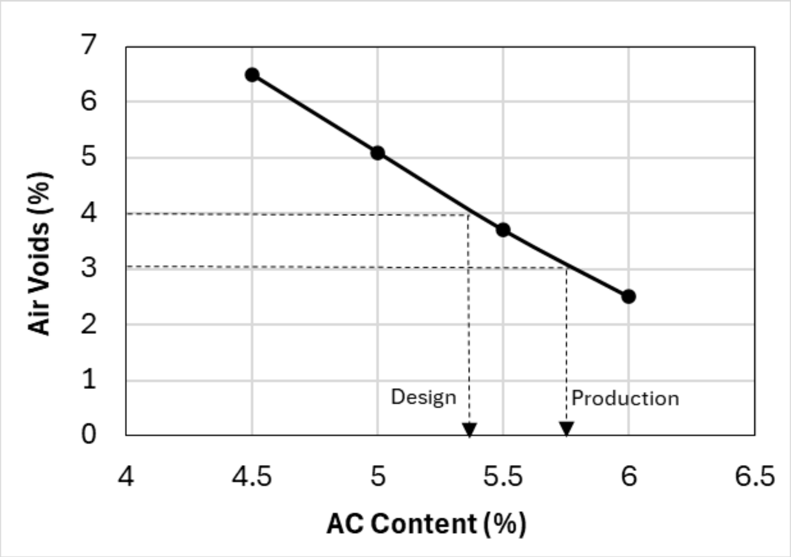

Figure 1. Air-void regression approach

Figure 2**Error! Reference source not found.** illustrates the effect of air-void regression on mix compactability. HT mixes are designed at the optimum binder content given by Point 1 in Figure 2**Error! Reference source not found. Error! Reference source not found.**. A "3.0% air-void regressed" binder content, given by Point 2, is used for production. The higher binder content used during production results in better densification in the field, which corresponds to a low gyration level of N_{des-av}, at an air void content of 4.0%, as given by Point 3.

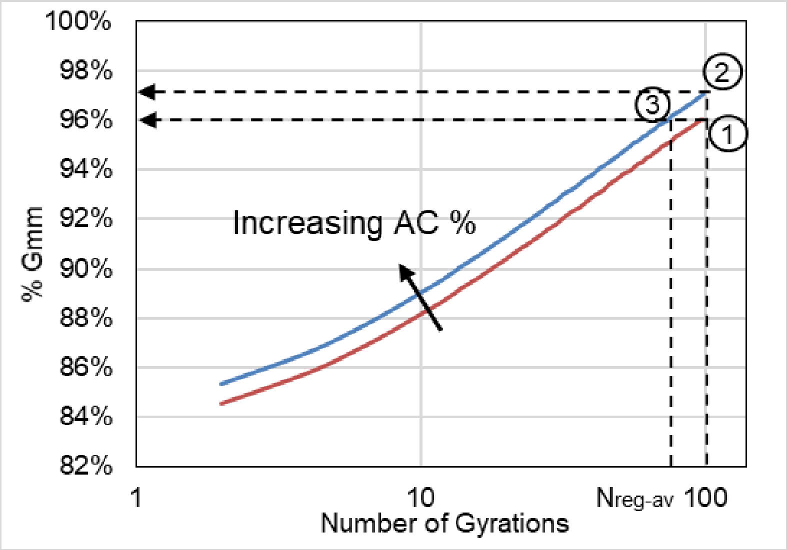

Figure 2. Gyration levels corresponding to regressed air-void design

A research study was performed by the National Center for Asphalt Technology (NCAT) to investigate the effect of air-void regression on rutting, cracking, and moisture susceptibility of low-traffic (LT), medium-traffic (MT), and HT mixes in Wisconsin (West et al. 2018). The study included six mixes with various Reclaimed Asphalt Pavement (RAP) and Reclaimed Asphalt Shingles (RAS) contents. The mixes were tested for intermediate-temperature cracking using the Illinois Flexibility Index Test (IFIT), low-temperature cracking using the Disk-shaped Compact Tension (DCT), and rutting using the HWTT. It was shown that air-void regression resulted in a 0.3-0.4% increase in binder content and a notable increase in the flexibility index (FI) using the IFIT. The DCT results, however, did not show significant improvement with air-void regression. The Corrected Rut Depth (CRD) at 20,000 passes from the HWTT increased slightly with air-void regression, however the results were within acceptable criteria.

A previous benchmarking study was conducted by WisDOT to support the implementation of BMD (West et al. 2021). The study included one stone matrix asphalt (SMA) mix, three HT mixes, nine MT mixes, and five LT mixes. The results showed a wide range of CT_{index} ranging from 25 to 128. It was shown that MT mixes had higher binder content and CT_{index} values than HT mixes. The difference in binder content and performance between the MT and HT mixes was mainly attributed to the difference in design gyrations. The MT mixes had an average binder content of 5.9% which was 0.3% higher than HT mixes. The results also showed no statistically significant difference between the rutting resistance of HT and MT mixes as measured by the HWTT using the CRD at 20,000 passes.

Balanced Mix Design (BMD)

The introduction of the Balanced Mix Design (BMD) has led to the use of performance testing in the design protocols of various transportation agencies. Performance-related testing involves testing mixtures for cracking, rutting, and moisture susceptibility. Currently, WisDOT employs the IDEAL-CT and the HWTT for cracking and rutting, respectively.

IDEAL-CT The IDEAL-CT test utilizes an indirect tensile strength configuration. Testing is performed in accordance with ASTM D8225. The test is conducted to obtain the cracking tolerance index (CT_{index}). It is designed to evaluate an asphalt mixture's resistance to cracking under a steadily increasing load; and it is performed at 25ºC. The specimen geometry is cylindrical and the test is run at a loading rate of 50 mm/min (Zhou 2019). Higher CT_{index} values indicate better cracking resistance. A study by (Zhou et al. 2019) further validated the test. The IDEAL-CT showed good correlation with field performance in terms of fatigue, reflective, and thermal cracking. The test also correlated well with the Texas Overlay Test and Illinois Flexibility Index Test (I-FIT). All three tests had the same rankings for ten asphalt mixes regarding cracking resistance. WisDOT has introduced modifications to the IDEAL-CT test in their Manual of Test Procedures (MOTP) (WisDOT 2025). Procedures and standards in the MOTP are referred to as WTM. The WTM D8225 provides specifications on specimen thickness, conditioning, and aging procedure.

Aging, particularly long-term aging, is a critical factor in the implementation of the IDEAL-CT. Several research studies have been conducted to identify a lab-aging protocol that accurately simulate field aging. The SHRP Project A-003A provided recommendations for long-term aging using compacted mixes at 85°C for 5 days (Bell et al. 1994). Further research was conducted under the NCHRP 9-52 and the NCHRP 9-54 studies highlighting the significance of climatic conditions and the need to identify different aging levels based on location (Newcomb et al. 2015 and Kim et al. 2017). NCHRP 9-52 used the cumulative degree days concept, whereas the NCHRP 9-54 introduced a climate aging index which combines the effect of climate and pavement depth. The shortcomings of lab-aging compacted mixes were also identified, and it was proposed to use loose-mixture aging instead. The NCHRP 9-54 study provided recommendations not to use temperatures above 100°C for long-term aging because of the effect of high temperatures on the chemical composition of the asphalt binder. A cracking experiment was conducted by NCAT and the Minnesota DOT to evaluate different cracking tests, and aging protocols. The study proposed 6 hours at 135°C and 8 hours at 135°C long-term aging procedure using loose mixes for Minnesota and Alabama climates, respectively (Chen et al. 2018). Bahia et al. (2018) investigated long-term aging of Wisconsin mixes using 6 and 14 hours at 135°C and concluded that 14 hours was too severe to effectively differentiate mixtures based on cracking performance. The recommendations of this study were adopted by WisDOT to use 6 hours at 135°C long-term aging procedure as per WTM R121. The long-term aging procedure is preceded with a short-term aging procedure as per WTM R30. It should be noted that plant-produced mixes do not require short-term aging.

Hamburg Wheel Tracking Test (HWTT)

The Hamburg Wheel Tracking Test (HWTT) evaluates rutting resistance and stripping potential caused by moisture damage. It simulates both repeated traffic loading and water-induced damage, which is the loss of adhesion between the asphalt binder and aggregate due to water. Several agencies use the total rut depth (TRD) at a specified number of passes to evaluate rutting resistance. Other rutting parameters were proposed by several researchers including the Rutting Resistance Index (RRI), the Creep Slope (CS), and the Corrected Rut Depth (CRD). The CRD was proposed by researchers at NCAT as an alternative criterion for rutting (Yin et al. 2014). It evaluates the rutting that occurs solely due to plastic deformation without the effect of moisture stripping. A study was conducted by Yin et al. (2020) using 70 mixtures with a wide range of materials to investigate the correlation between different HWTT parameters and field performance. The study showed good correlation between CRD and field rutting. Another parameter, stripping number (SN) was also proposed in lieu of the stripping inflection point (SIP). A typical curve showing the different rutting and stripping parameters proposed by NCAT is shown in Figure 3. The study conducted by West et al. (2021) has proposed a rutting criterion for Wisconsin mixes using CRD at 20,000 passes, based on traffic level. To further refine this criteria, WisDOT continues to collect mixtures during production and monitor performance using IDEAL-CT and HWTT testing.

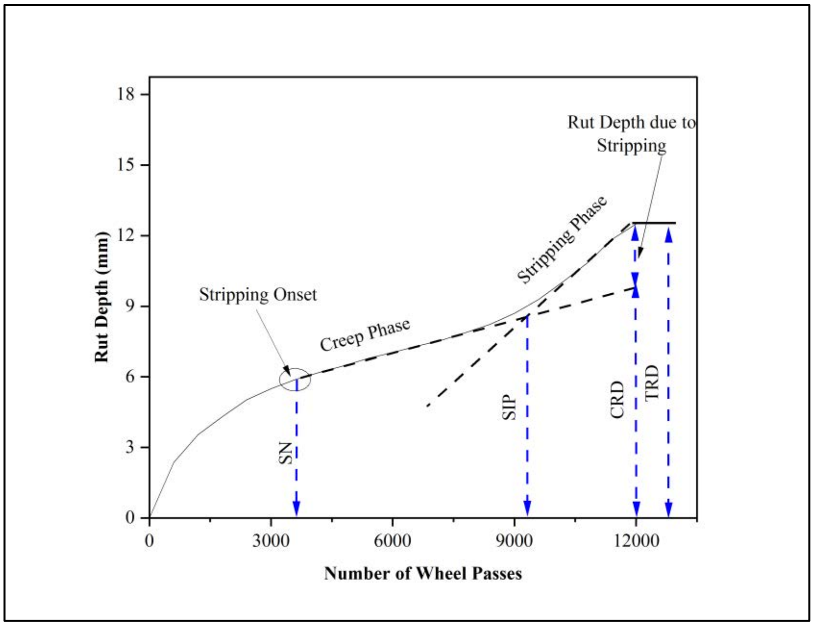

Figure 3. Typical rut-depth curve showing CRD versus TRD

Bailey Method

The Bailey Method is a tool used to achieve proper aggregate packing and optimize gradation balance for better mix performance (Vavrik et al. 2002). The method was developed by Robert Bailey of the Illinois DOT in the early 1980s based on his extensive experience designing asphalt mixtures. The objective was to create a method that could effectively combat rutting while maintaining the durability of asphalt pavements. The Bailey Method focuses on optimizing the aggregate structure by ensuring adequate coarse aggregate interlock and fine aggregate packing, providing a balance between strength and flexibility in asphalt mixtures (Thompson 2007). The Method has been used to troubleshoot problems during mix design. It introduces different aggregate size ratios to define aggregate packing in the fine and coarse portions of the gradation. The packing of the coarse portion is determined using the Coarse Aggregate (CA) ratio, which describes how coarse aggregate particles pack together and indicates how the coarse aggregates compact and confine the fine aggregate that fills their voids. The packing of the fine portion is characterized by the FA_c ratio and the FA_f ratio, which describe the packing behavior within the coarser and finer fractions of the fine portion, respectively. The FA_c ratio describes how the coarser fraction of the fine aggregate packs together and shows how these particles compact the finer material filling their voids. The FA_f ratio, describes how the finest particles of the fine aggregate pack together and determines the remaining voids within the fine-aggregate blend (Aschenbrener et al. 2002). Several studies have used the Bailey Method to improve performance. A study was carried out by Daniel and Rivera (2008) using the Bailey Method as a tool for improving the rutting resistance of asphalt mixes in New Hampshire. The method accurately predicted the increase in VMA for mixtures containing angular aggregates and Reclaimed Asphalt Pavement (RAP), however inaccurate predictions were noted for mixtures with round aggregates. Mixes designed using the Bailey Method had better or similar rutting resistance to baseline mixes. Hassan and Elkashef (2025) conducted a study using Oklahoma mixes to evaluate the effect of Bailey ratios on the cracking and rutting resistance of asphalt mixes. It was shown that coarser mixes with better aggregate interlock and higher VMA had higher CT_{index}. However, there was no direct correlation between the Bailey ratios and the rut depth. Overall, the study demonstrated that the Bailey Method can be used to optimize mix design within a BMD framework.

Research Objectives

The objectives of the current study, as stated in the request for proposal, are as follows:

- Summarize existing mix design requirements for high traffic (HT) mixtures in regions with similar climates ("Wet-Freeze") and aggregate sources to WisDOT. Identify potential areas of improvement.
- Benchmark existing WisDOT HT mixture designs using volumetric and performance testing; proposed testing must include consideration of prior and ongoing WHRP HMA performance testing research.
- Propose modifications to the existing HT mixture design based on available data, benchmarking, and testing, and determine whether improvements to constructability and performance can be achieved using the proposed mix design procedure changes.

Research Plan

The objectives of this research were addressed by focusing on the research activities presented in Figure 4 below.

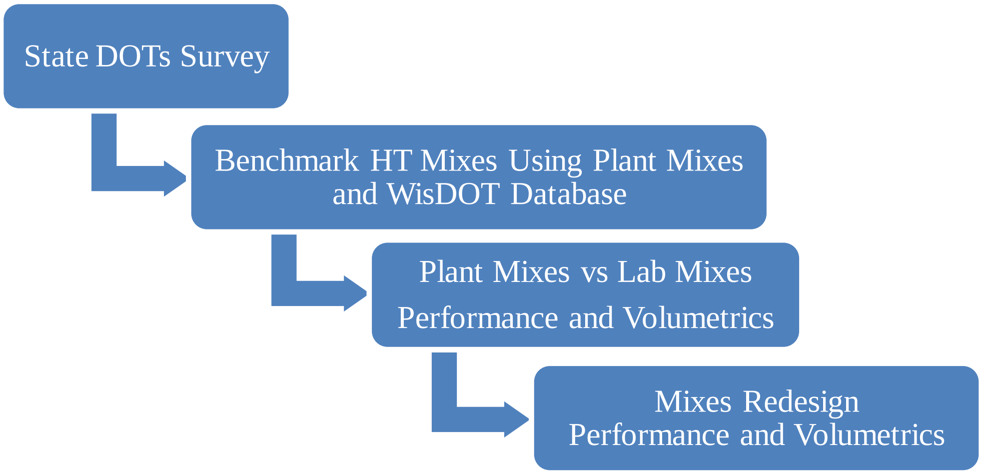

Figure 4. Schematic of proposed research activities

CHAPTER 2. SYNTHESIS OF AGENCY PRACTICE AND LANDMARK RESEARCH

Synthesis Approach

In this phase of the study, the research team conducted a synthesis of specifications from different agencies for high-traffic (HT) mixes in states in the wet-freeze region and in the Combined State Binder Group (CSBG). The agencies included in this study are shown in Figure 5. The survey includes a total of twenty-five states and Washington, DC.

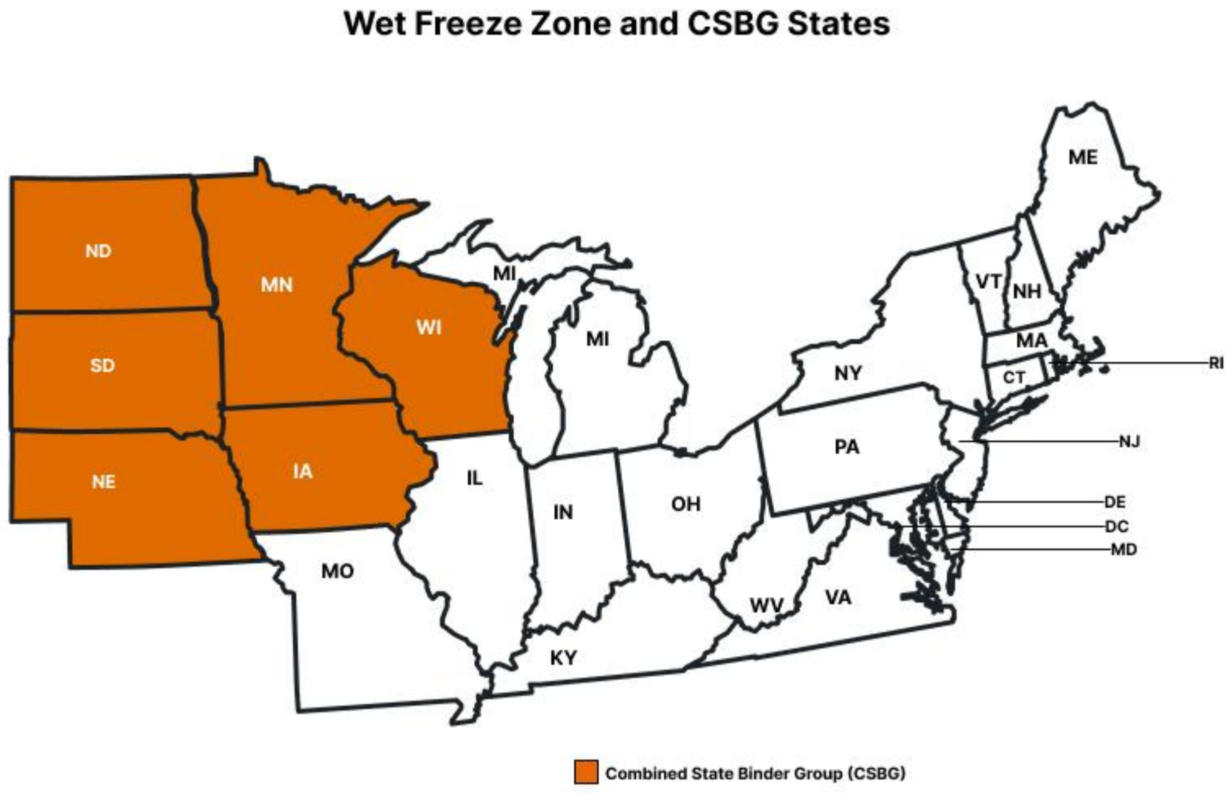

Figure 5. Agencies in the wet-freeze zone and CSBG states

The first phase of the synthesis included a comprehensive review of the agencies' standard specifications. The results of this review are provided in the following sections. The second phase of the synthesis involved sending a survey to the agencies to collect additional information on the high-traffic mixes. The research team put together a survey, as shown in Appendix A. The TOC reviewed and approved the proposed survey. The results of this survey were collected and analyzed.

Review of State Specifications

This task included a review of the standard specifications for all states in the wet-freeze zone and for states in the Combined State Binder Group (CSBG). A total of twenty-five states and Washington, DC were included in this survey. The standard specifications were reviewed to determine the N_{des} values used by those agencies and the relevant selection criteria.

Table 3 presents the N_{des} values by traffic level. The traffic level categories listed are based on AASHTO R 35 where low traffic is defined as less than 0.3M ESALs followed by medium traffic with less than 3M ESALs, and high traffic with less than 30M ESALs. Traffic exceeding 30M ESALs is classified as very high traffic. A few states adopted different traffic limits from those defined by AASHTO R 35. For example, Wisconsin defines low traffic as less than 1M ESALs, medium traffic as less than 8M ESALs, and high traffic as more than 8M ESALs. Table 4 provides information on the traffic limits used by the various states.

Based on the information in Table 3, most of the surveyed states have implemented lower gyration levels than those specified in AASHTO R 35. Among all the states included in this study, Michigan and Delaware are the only states that still adopt AASHTO R 35 gyrations. Figure 6 provides a map showing all N_{des} values across different agencies.

Table 3: The N_{des} values for the agencies included in this survey.

State	ESALs (million)				Notes
	<0.3	0.3 to <3	3 to <30	≥30	
AASHTO R 35	50	75	100	125	
Wisconsin	40	40 75	75 100	100	N_{des}=40 for ESALs<1M N_{des}=75 for 1M≤ESALs≤8M N_{des}=100 for ESALs>8M
Michigan	50	75	100	125	Follows AASHTO R 35
Delaware	50	75	100	125	Follows AASHTO R 35
Washington DC	50	75	100	125	HMA follows AASHTO R 35
Pennsylvania	50	75	100	100	
Connecticut	50	75	75	75	
New York	50	75	75	100	
New Jersey	50	75	75	75	
Maryland	50	65	80	100	
Virginia	50	50	50	50	Fixed N_{des}
Rhode Island	50	50	50	50	Fixed N_{des}
Ohio	65	65	65	65	Fixed N_{des}
Maine	65	65	65	65	Fixed N_{des}
Kentucky	65	65	65	65	Fixed N_{des}
North Dakota	75	75	75	75	Fixed N_{des}
New Hampshire	50	50	50 75	75	N_{des}=50 for ESALs <5M N_{des} = 75 for ESALs ≥ 5M
Massachusetts	50	75	75 100	100	N_{des}=75 for 0.3M<ESALs<10M N_{des}=100 for ESALs≥10M
Iowa	50	50 75	75 95	95	N_{des}=50 for ESALs<1M N_{des}=75 for 1M≤ESALs≤10M N_{des}=95 for ESALs>10M
Minnesota	40	40 60	90 100	100	N_{des} =40 for ESALs<1M N_{des} =60 for 1M≤ESAL<3M N_{des} =90 for 3M≤ESALs<10M N_{des} =100 for 10M≤ESALs≤30M.
Missouri	50	75	80* 100	125	*N_{ini} and N_{max} do not apply if N_{des} =80 is used.
Illinois	30	30	50 70 90	50 70 90	N_{des}=30 for LT. N_{des}=50,70,90 for HT mixes and varies with RAP content.
Indiana	30* 75**	50* 100**	50* 100**	50* 100**	Uses Superpave5. *For all other mixes. **For mixes with NMAS = 4.75 mm.
West Virginia	50	65	65* 80**	80* 100**	*For mix in top two lifts or binders stiffer than PG 76-XX. ** For mixes not in top two lifts or binder softer than PG 76-XX.
Vermont	50	65	80	80	Mixes with NMAS = 1" use N_{des}=50 for all traffic levels. Type IVSB asphalt mix with NMAS= 3/8" is designed at 3% AV and N_{des}=65 for all traffic levels.
Nebraska	40,65, and 95				N_{des} is based on mix type. Mixes SPS, SPR, and SPH are HMA with N_{des}=40,65, and 95 respectively. Mixes SLX and SRM are WMA with N_{des}= 50 and 65, respectively.
South Dakota	40,50,60,70, and 80				N_{des} is based on mix type. Mix classes Q1, Q2, Q3, Q4, and Q5 use N_{des}=40,50,60,70, and 80 respectively.

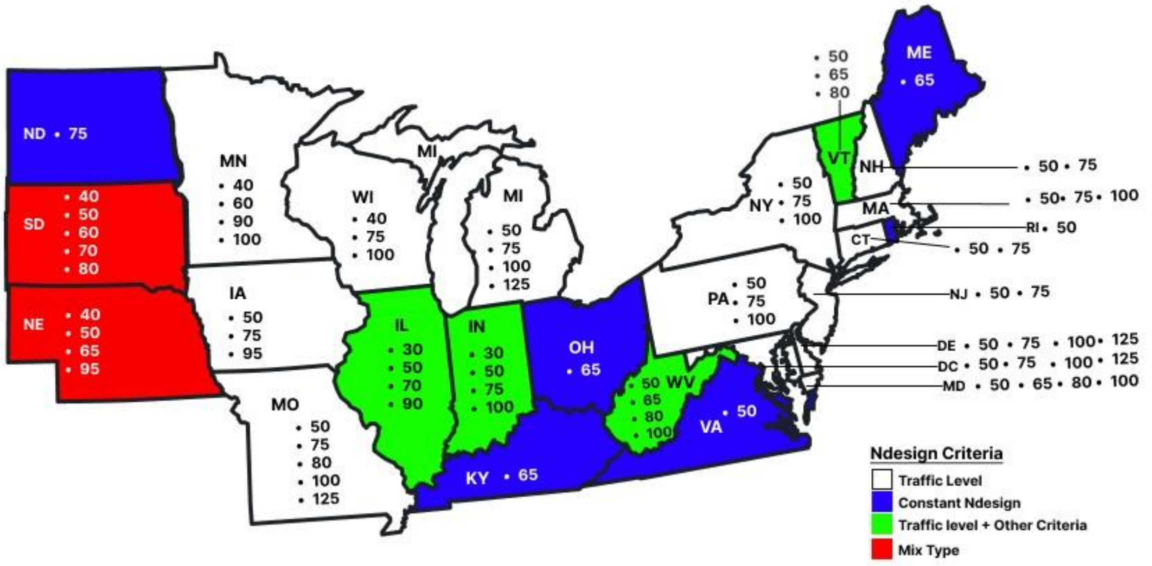

Figure 6. N_{des} values for the agencies in the CSBG and wet freeze zone

Based on the information presented in Table 3 and Figure 6, the surveyed agencies have adopted one of the following approaches for the selection of N_{des}:

- Using a fixed N_{des} irrespective of traffic level and mix type.
  - This approach was followed by states such as Virginia, Rhode Island, Ohio, Maine, Kentucky, and North Dakota.
- Using traffic level to specify N_{des}.
  - This approach was followed by many states, for example, Wisconsin, New Hampshire, Massachusetts, etc. The traffic-level limits varied slightly across states. Some states followed the same traffic-level limits defined by AASHTO R 35, while other states have specified their own traffic-level limits. For example, Wisconsin defines high traffic as more than 8M ESALs, whereas Iowa and New Hampshire define high traffic as more than 10M and 5M ESALs, respectively.
- Using traffic level along with other criteria to specify N_{des}.
  - This approach was followed by states such as Illinois, West Virginia, Indiana, and Vermont. For example, Illinois uses an additional criterion based on the RAP and RAS content to specify the N_{des} for high-traffic mixes. West Virginia uses the mix depth from the surface and the binder's PG as additional criteria to select N_{des} for high-traffic mixes. Indiana and Vermont use the traffic level and the nominal maximum aggregate size (NMAS) to define N_{des}.
- Using mixture type to specify N_{des}.
  - Nebraska and South Dakota followed this approach. Both states define N_{des} by mix type or mix class. These agencies define mix types and classes intended for use in different applications. There is no explicit reference to traffic levels in the Nebraska DOT and South Dakota DOT specifications.

The Superpave specifications relevant to high traffic mixes are shown in Table 4 for the agencies included in this survey. Figures 5 through 7 show the N_{des} values, VMA, and air voids (Va) criteria for high-traffic mixes, respectively. It is shown that there is wide variation in N_{des} values across high-traffic mixes used by the various states.

It should be noted that Wisconsin and Michigan adopted a regressed air-void approach, which involves designing the mix with 4.0% Va and increasing the binder content during production to reduce air voids. Most states use 4.0% design Va criteria; however, a few states, such as North Dakota, New York, Kentucky, and Indiana, have implemented different design air voids. Indiana uses a Superpave5 mix design, in which mixes are designed and compacted in the field at 5 % Va. As shown in Figure 7, New York and Kentucky use a 3.5 % Va, while Nebraska and Virginia use a different design Va based on mix type. Virginia uses 4.0% Va for mix type A using PG 64-22 and mix type D using PG 70-22, and 3.5% Va for mix type E using PG 76-22. Nebraska uses 4.0% for Superpave Heavy-traffic (SPH) mixes, 1.5–5.0% Va for Superpave Paved Shoulders (SPS) mixes, and 3.0% for Superpave Recycle (SPR) mixes. A few states specify a minimum AFT, including Indiana, Iowa, Minnesota, and North Dakota. Table 4 shows that ten states specify a minimum asphalt content. With respect to the VMA criteria, all agencies except Minnesota and Iowa specify a minimum VMA. As noted above, Minnesota and Iowa specify a minimum AFT. Most of the agencies use the minimum VMA criteria specified in AASHTO M 323. In contrast, some agencies have increased the minimum VMA requirement from that in AASHTO M 323 as given in Table 4.

Table 4: Volumetric properties of HT mixes for agencies in the wet freeze zone and CSBG.

State	ESALs (millions)	N_{des} values	Design Va	Min. AC	Other (VFA, film thickness, etc.)	Notes
Wisconsin	ESALs>8	100	4.0%	N/A	VFA, VMA	Regressed Va at 3.0%.
Michigan	3≤ESALs<30 ESALs≥30	100 125	4.0%	N/A	VFA	Regressed Va at 3.0%.
Delaware	3≤ESALs<30 ESALs≥30	100 125	4.0%	N/A	VFA	VMA is 0.5% higher AASHTO M 323.
Washington DC	3≤ESALs<30 ESALs≥30	100 125	4.0%	N/A	VFA	
Pennsylvania	ESALs≥3	100	4.0%	N/A	N/A	
Connecticut	ESALs≥3	75	4.0%	Yes	VFA	VMA is 0.5% higher than AASHTO M 323.
New York	0.3≤ESALs<30 ESALs≥30	75 100	3.5%	Yes	VFA	
New Jersey	ESALs≥0.3	75	4.0%	N/A	VFA	
Maryland	3≤ESALs<30 ESALs≥30	80 100	4.0%	N/A	VFA	
Virginia	All	50	4.0% 3.5%	N/A	VFA	VMA is 1% higher than AASHTO M 323. Va= 4.0% (PG 64-22, and PG 70-22) and Va= 3.5% (PG 76-22).
Rhode Island	All	50	4.0%	Yes	VFA	VMA is 0.5% higher than AASHTO M 323.
Ohio	All	65	4.0%	Yes	N/A	
Maine	All	65	4.0%	N/A	VFA	
Kentucky	All	65	3.5%	Yes	N/A	
North Dakota	All	75	3.0%	N/A	VFA, Film thickness	
New Hampshire	ESALs≥5	75	4.0%	Yes	N/A	
Massachusetts	ESALs≥10	100	4.0%	N/A	VFA	VMA is 1% higher than AASHTO M 323.
Iowa	1≤ESALs≤10 ESALs>10	75 95	4.0%	Yes	Film thickness	No VMA requirement.
Minnesota	3≤ESALs<10 10≤ESALs≤30	90 100	4.0%	N/A	Film thickness	No VMA requirement.
Missouri	3≤ESALs<30 ESALs≥30	80/100 125	4.0%	N/A	VFA	See note in Table 3.
Illinois	ESALs≥3	50 70 90	4.0%	N/A	N/A	See note in Table 3 2.5% Higher than AASHTO M 323.
Indiana	ESALs≥0.3 ESALs≥0.3	50 100	5.0%	Yes	VFA, Film thickness	VMA is 1% higher than AASHTO M 323. See note in Table 3.
West Virginia	3<ESALs<30 ESALs ≥ 30	65/80 80/100	4.0%	N/A	VFA	See note in Table 3. 0.5% higher than M323,
Vermont	ESALs≥3	50,65, or 80	4.0% 3.0%	Yes	N/A	See note in Table 3.
Nebraska	N/A	40,50,65, or 95	4.0%, 3.0%, 1.5-5.0%	Yes	N/A	No VMA. Va% based on mix type. See note in Table 3.
South Dakota	N/A	40,50,60,70, or 80	4.0%	N/A	VFA for class Q mixes	See note in Table 3.

Note: For the VMA, AASHTO M 323 is followed unless otherwise noted.

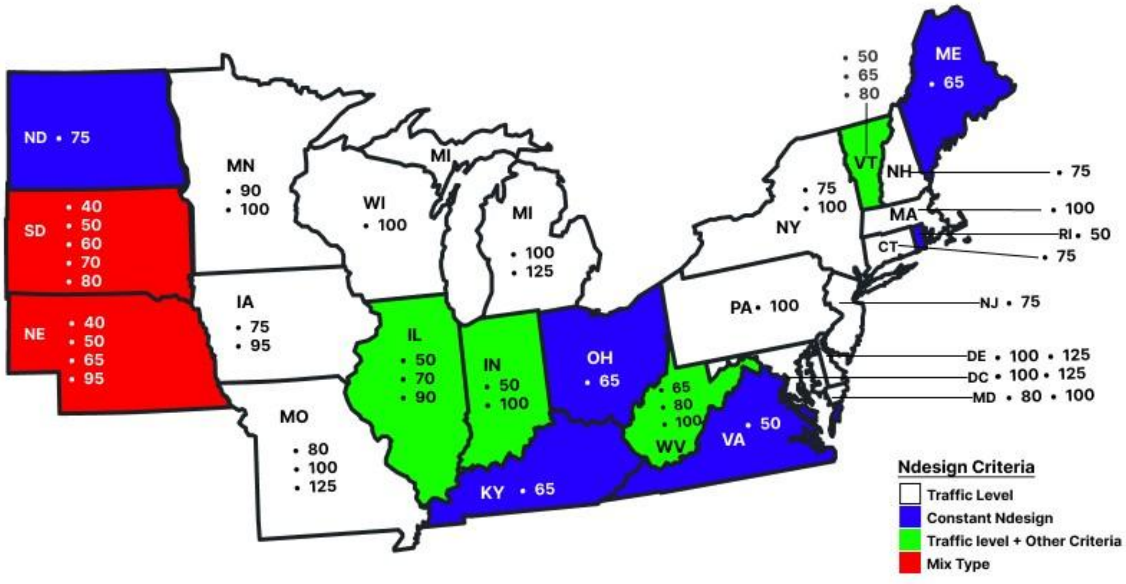

Figure 7. N_{des} of HT mixes for the agencies in the wet freeze zone and CSBG.

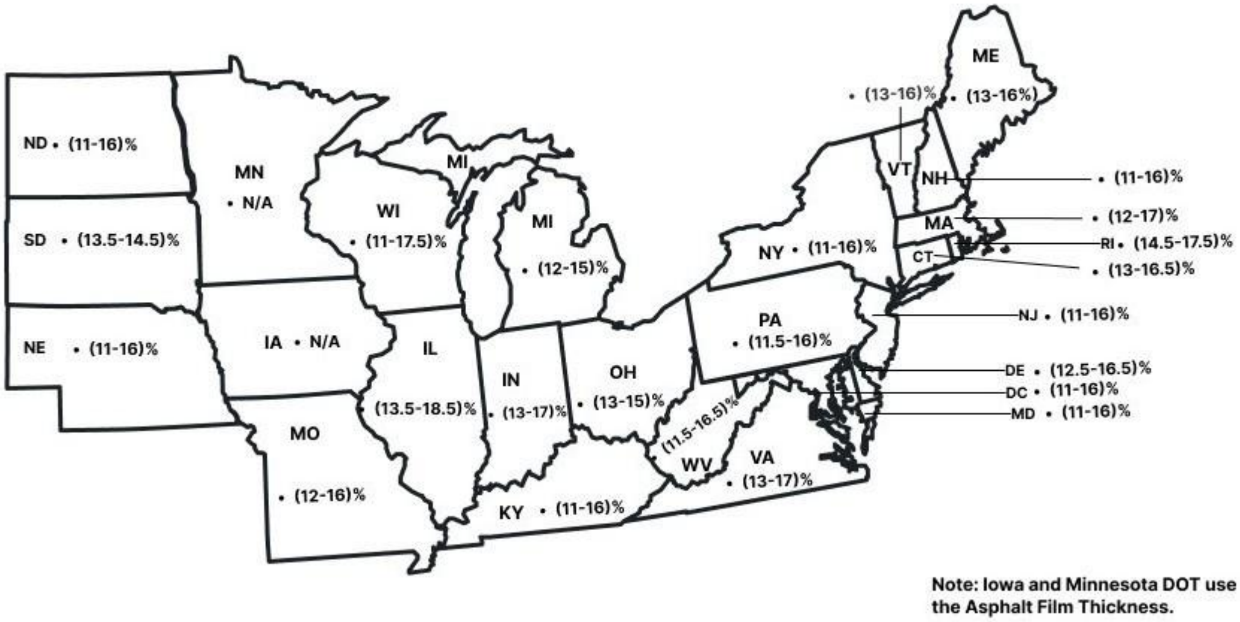

Figure 8. Minimum VMA of HT mixes for the agencies in the wet freeze zone and CSBG

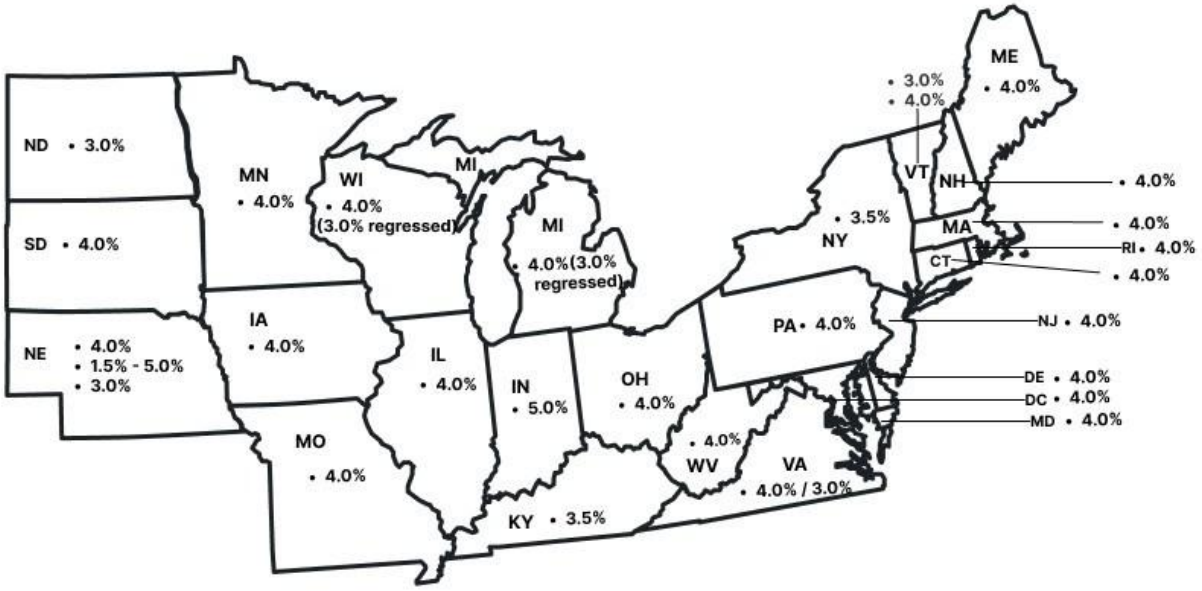

Figure 9. Design air voids of HT mixes for the agencies in the wet freeze zone and CSBG

Highlights of the States Surveyed

This section provides a summary of the volumetrics and N_{des} criteria for the surveyed agencies.

Wisconsin: The Wisconsin DOT uses the regressed air void approach. Superpave mixes are compacted at N_{des} values of 40, 75, and 100 gyrations based on traffic level. A design air void of 4.0% and a regressed air void of 3.0% are used. The minimum VMA criterion follows AASHTO M 323. SMA mixes are designed at 4.5% air voids using 65 gyrations. SMA mixes have higher minimum VMA requirements based on NMAS. WisDOT does not use a regressed air void approach for SMA mixes.

Michigan: Michigan DOT uses the regressed air void method, where mixes are designed at 4.0% air voids and regressed to 3.0% Va by adding more binder content during production. The N_{des} values used are in accordance with AASHTO R 35, and the minimum VMA criteria are in accordance with AASHTO M 323.

Delaware: Delaware DOT uses N_{des} values in accordance with AASHTO R 35 at a design air void level of 4.0%, with a minimum VMA that is 0.5% higher than AASHTO M 323.

Washington, DC: N_{des} values are based on AASHTO R 35, with a design air void level of 4.0% and a minimum VMA in accordance with AASHTO M 323 for HMA mixes. The SMA mixes are designed with a minimum of 4.0% to 10.0% air voids and a minimum VMA of 20%. For the warm mix asphalt (WMA), a N_{des} value of 100 is used for traffic levels between 3 and 30 million ESALs at a design air void of 4.0%, with a minimum VMA that follows AASHTO M 323.

Pennsylvania: Pennsylvania DOT uses N_{des} values in accordance with AASHTO R 35 for all traffic levels except for ESAL ≥ 30M where a 100 gyration is specified instead of 125. A design air void of 4.0% and a minimum VMA in accordance with AASHTO M 323 is used. In the PennDOT specifications, special mix types have different design air voids and N_{des} values. SMA mixes have a N_{des} of 100 gyrations and a design air void of 3.5 – 4.0%, while asphalt-rich base course mixes use N_{des} of 50 gyrations and a 2.5% design air void.

Connecticut: Connecticut DOT uses N_{des} values in accordance with AASHTO R 35 for all traffic levels except for ESAL ≥ 30M where a 100-gyration is specified instead of 125. A 4.0% design air void is used. The minimum VMA is 0.5% higher than AASHTO M 323.

New York: New York DOT uses N_{des} values of 50, 75 and 100 gyrations depending on the traffic level, at a design air void level of 3.5%. The minimum VMA is in accordance with AASHTO M 323.

New Jersey: New Jersey DOT uses N_{des} values of 50 and 75 gyrations, depending on the traffic level, at a design air void of 4.0%. The VMA is provided in accordance with the AASHTO M 323 specification. SMA mixes are designed at an air void level of 4.0% with a minimum VMA of 17%.

Maryland: Maryland DOT uses 50, 65, 80, and 100 gyrations depending on traffic level with a design air void of 4.0%, with a minimum VMA in accordance with AASHTO M 323. The SMA mixes use a design air void level of 3.5% and N_{des} value of 100 gyrations, with a minimum VMA of 18%.

Virginia: Virginia DOT uses a constant N_{des} value of 50 gyrations for all traffic levels at an air void level of 4.0% for A and D mixes and 3.5% for E mixes. For Virginia DOT mixes, the 'A' designation corresponds to a PG 64-22 binder, the "D" designation corresponds to a PG 70-22 and the "E" designation corresponds to a PG 76-22 binders.

North Dakota: North Dakota DOT is a member of the CSBG, North Dakota DOT specifies a N_{des} of 75 gyrations for all the traffic levels at a design air void level of 3.0%, with a VMA in accordance with AASHTO M 323. They are among the few states specifying the AFT in their hot mix asphalt (HMA) mix design requirements.

Ohio: The Ohio DOT uses 65 gyrations irrespective of the traffic level at a design air void of 4.0% and the minimum VMA is provided, following the AASHTO M 323 specification. The minimum asphalt content for surface content is 5.8%, 5.4% for 12.5 mm nominal maximum aggregate size (NMAS) and 4.6% for 19 mm NMAS. For the SMA mixes, they are designed using 3.5% air void with a N_{des} of 65 gyrations. The minimum VMA is specified is between 16%

to 19%. Marshall mix design properties are provided in the specification. The Marshall method is still in use in this state.

Maine: Maine DOT provides N_{des} value of 65 gyrations for all traffic levels at a design air void level of 4.0%, with the minimum VMA in accordance with AASHTO M 323.

Kentucky: In 2012, the Kentucky Transportation Cabinet (KYTC) used N_{des} values of 50, 75, and 100 gyrations regardless of the traffic level. However, in 2019, they adopted 65 gyrations for all traffic levels. They also reduced the design air void from 4.0% to 3.5%. The VMA complies with AASHTO M 323. Moreover, the asphalt content was increased from 5.0% to 5.3% by weight of total mixtures for all 0.5-inch and from 5.3% to 5.6% by weight of total mixtures for all 0.38-inch nominal surface mixtures. The SMA mixes are designed at an air void level of 4.0%, with an N_{des} of 100 gyrations, and a minimum VMA of 16% to 17% based on the NMAS.

Rhode Island: Rhode Island DOT uses a constant N_{des} of 50 gyrations for all traffic levels at an air void of 4.0% and the minimum VMA required is 0.5% higher than AASHTO M 323. Marshal mix design method is also still applicable.

New Hampshire: The New Hampshire Department of Transportation (NHDOT) uses 50 gyrations for ESALS < 5 million and 75 gyrations for ESALs ≥5 million. A design air void of 4.0% is used and the VMA follows AASHTO M 323. NHDOT uses a minimum asphalt content for different Superpave mixes with different NMAS, 3/8 inch for 6%, ½ inch for 5.5% and ¾ inch for 4.6%.

Missouri: Missouri DOT uses N_{des} values in accordance with AASHTO R 35 but adopts 80 or 100 gyrations for mixes between 3 and 30 million ESALs. When 80 gyrations are used, the N_{ini} and N_{max} do not apply. A design air void of 4.0% is used, and the minimum VMA follows AASHTO M 323.

Massachusetts: Massachusetts DOT uses N_{des} values of 50, 75, and 100 gyrations depending on the traffic level, at a design air void of 4.0% and the minimum VMA required is 1% higher than AASHTO M 323 specifications.

Iowa: Iowa DOT provides N_{des} of 50, 75, and 95 gyrations depending on the traffic level at a design air void of 4.0%. The AFT specified is between 8 to 15µm and the minimum VMA and the VFA properties are not specified.

Minnesota: Minnesota DOT provides N_{des} of 40, 60, 90, and 100 gyrations, depending on the traffic level, at a design air void level of 4.0%. The minimum film thickness is specified as 8.5 µm. SMA mixes use N_{des} of 75 gyrations at a design air void level of 4.0%, with a minimum VMA of 17%.

Illinois: Illinois DOT provides its N_{des} value based on the traffic level and RAP content. For low ESAL mixes, the N_{des} used is 30 gyrations. For high ESAL, the N_{des} values provided are 50, 70, and 90 gyrations based on the amount of recycled material (i.e., RAP and RAS). The N_{des} decrease with recycled content. The design air void used is 4.0%. For the SMA mixes 50 gyrations is used at a minimum VMA of 16% and 80 gyrations is used at a minimum VMA of 17%.

Indiana: Indiana DOT provides N_{des} at 30, 50, 75, and 100 gyrations depending on the traffic level and NMAS at a design air void level of 5.0%. The minimum VMA is 1% higher than AASHTO M 323 specification. SMA mixes use a design air void level of 4.0%, N_{des} of 75 gyrations and a minimum VMA of 15% to 17%.

Vermont: Vermont DOT provides N_{des} 50, 65 and 80 gyrations depending on the traffic level. The design air void used is 4.0% and the minimum VMA adopted is in accordance with AASHTO M 323. For mix type IS the NMAS is 1", when this mix type is used a N_{des} of 50 gyrations is adopted for all traffic levels. Type IVSB mix is specifically designed with a minimum of 65 gyrations and requires an air void level of 3% but does not permit the use of RAP.

West Virginia: West Virginia DOT provides 50, 65, 80 and 100 gyrations at a design air void level of 4.0% and a minimum VMA that is 0.5% higher than AASHTO M 323. For ESALs $\geq$ 3 million, when the mix is not in the top two lifts, or the binders used are stiffer than PG 76-XX a reduced N_{des} of 65 and 80 gyrations is adopted.

Nebraska: Nebraska is a member of the CSBG. Nebraska DOT provides N_{des} values for their Superpave mixes based on the mix type. SPS, SPR, and SPH use N_{des} values of 40, 65, and 95 gyrations, respectively. The different mixes are used based on their application and RAP content. The SPS mix is designed as a shoulder mix with a PG 52-34 binder at an air void level of 1.5% to 5.0%. SPR mix is designed with a N_{des} of 65 gyrations and a target design air void level of 3.0%. SPH mix, used with heavy truck applications, is designed at a N_{des} of 95 gyrations, a target air void of 4.0%. The SLX and SRM are WMA mixes with N_{des} values of 50 and 65 gyrations, respectively.

South Dakota: South Dakota is another member of the CSBG. They provide N_{des} of 40, 50, 60, 70, and 80 gyrations depending on the mix class Q1, Q2, Q3, Q4 and Q5 respectively, at a design air void level of 4.0% and a minimum VMA in accordance with AASHTO M 323. SMA mixes are designed in accordance with AASHTO R 46.

Agencies' Survey on HT mixes

A survey was created to get feedback from the states' bituminous engineers to provide a better perspective and understanding of the design practices for HT mixes. The survey questions were meant to request additional information on the mix design of HT mixes in these states, and to gather insight from state bituminous engineers regarding their experience with HT mixes in their states. The survey questionnaire is provided in the Appendix section. The questions focused on HT mix design requirements, aggregate requirements, binder specifications, and any concerns regarding the performance or compaction of HT mixes. A total of ten states responded to the survey, including Connecticut, Indiana, Iowa, Michigan, North Dakota, South Dakota, New Jersey, Ohio, Vermont, and Virginia. A summary of the responses is provided in Tables 5 through 7.

Table 5: Summary of Survey Responses on Design Requirements for HT Mixes

State	HT Mixes	Design Requirements	Mix Size
Connecticut	>3M ESALs	N_{des}=75, Va=4%, VMA=14–16% (1/2” NMAS), VFA= 65 – 75 Minimum AC content based on mix type and level.	Leveling Course (1/4” NMAS) Surface (1/2” NMAS)
Indiana	>3M ESALs Category 3 >10M ESALs Category 4	For Dense graded NMAS=3/8”, N_{des}= 50, Va=5%, and VMA= 16% Often, for high traffic interstates, we specify SMA NMAS=3/8”. SMA is N_{des}= 75, Va= 4%, VMA=17%.	3/8” NMAS, but 1/2” NMAS is used occasionally.
Iowa	1-10M ESALs	N_{des}=75 Surface, Intermediate, Base Va=4.0% Surface, Intermediate Va=3.5% Base VMA – No criterion AFT = 8.0-15.0 μ Minimum AC content based on mix NMAS and asphalt layer	Surface and intermediate (1/2” NMAS) Base (3/4” NMAS)
Michigan	>10M ESALs	N_{des}=100 for 10 to 30M N_{des}=125 for 30 to 100M Va=4.0% regressed to 3.0% at production Maximum RAP is 27%	3/8” (5 designation) 1/2” (4 designation)
North Dakota	Based on daily ESALs	N_{des}=75, Va=3%, VMA=14%	1/2"
New Jersey	≥ 0.3 million ESALs	N_{des}=75, Va= 4%, VMA based on NMAS Other requirements for specialty mixes on high-volume roads.	1/2" or 3/8” NMAS. Intermediate course 1/2" or 3/4" NMAS.
Ohio	>1500 trucks on the opening day	N_{des}=65, Va=4%, VMA based on NMAS Minimum AC content based on mix NMAS and asphalt layer	Surface 1/2" NMAS Intermediate 3/4" but switching to 1/2" NMAS
South Dakota	Based on the no. of trucks. Class Q5 >1200 trucks	N_{des} range from 40 to 80 based on class. Va=4.0%, VMA=14.5%, VFA based on class.	1/2" NMAS.
Vermont	≥ 3M ESALs	N_{des}=80, Va=4%, VMA based on NMAS.	Leveling 3/8” NMAS Surface 3/8” and 1/2" NMAS
Virginia	> 10M ESALs	N_{des}=50, Va=3.5%, VMA and VFA based on NMAS, Va ranges from 2 to 5% during production.	Surface 1/2" and 3/8” NMAS Leveling 3/8” NMAS

Table 6: Summary of Survey Responses on Aggregate Requirements for HT Mixes

State	Gradation	Aggregate requirements	Special aggregate requirements to HT mixes
Connecticut	Fine gradations	Coarse Aggregate Angularity (CAA)- Fine Aggregate Angularity (FAA) – Flat and Elongated- Sand Equivalent	Yes, based on ESALs
Indiana	Less than or equal to 58% passing No.8 for 3/8” NMAS	FAA - CAA	Friction, durability, and polish-resistant.
Iowa	No. 30 sieve is used to control HT mix gradation	FAA- CAA- Sand Equivalent	Yes, based on ESALs and asphalt layer
Michigan	Fine gradations	Based on specifications	Yes, based on ESALs
North Dakota	Both coarse and fine.	FAA	Yes, based on ESALs
New Jersey	Specialty mixes for high volume have finer gradations.	Based on specifications.	Specialty mixes such as Bottom Rich Intermediate Course (BRIC), High-Performance thin overlays (HPTO), and Stone Matrix Asphalt (SMA) have specific requirements.
Ohio	Fine gradations	FAA and CAA	Marshall's mix design method is used for low and medium traffic
South Dakota	Coarse gradation	FAA- CAA- Soundness- LA Abrasion	Requirements based on Mix Class.
Vermont	Fine gradations	Based on specifications	Based on specifications
Virginia	Fine gradations	FAA – FAA – Sand equivalent	Based on specifications

Table 7: Summary of Survey Responses on Binder Requirements and Any Concerns Related to HT Mixes

State	Asphalt Binder	Concerns
Connecticut	Polymer modified for level 3 mixes	BRIC and SMA are used in areas with very high, slow-moving traffic.
Indiana	High-grade binder typically PG 76-22 or a PG 58E-28	No concerns
Iowa	No requirements to use a polymer-modified binder.	No concerns
Michigan	Polymer modified required, such as PG 70-28P or PG 76-28P	No concerns.
North Dakota	Based on ESALs-MSCR, grading is used.	Incentives were added to improve in-place density.
New Jersey	Neat or polymer-modified, based on the type of mix.	Tack coat application. Specification for bond strength using shear testing of cores.
Ohio	Base binder is PG 70-22M. Grade bumping for high traffic areas.	No concerns. Mixes with high-grade binders such as PG88-22M have been laid down successfully.
South Dakota	No requirement to use polymer-modified binder.	No concerns.
Vermont	SBS polymer modified binder.	HT mixes tend to have lower asphalt content because of N_{des}. Concerns regarding adequate compaction. Adequate compaction because of the high $N_{des.}$ Use regressed air void to increase asphalt content and use of SMA mixes.
Virginia	Use PG 64E-22 / PG 76-22	Considering lowering Va to 3.0%

CHAPTER 3. MATERIAL AND METHODS

Eight asphalt mixes were sampled from several Wisconsin projects paved during the 2024 construction season. The sampled mixes represented different mix types, e.g., 3HT and 4HT, binder grades, aggregate types, and recycled binder replacement, as shown in Table 8. All eight mixes contained RAP, whereas only three mixes contained RAS. The recycled binder replacement, defined as the percentage of RAP and RAS binders to the total binder, ranged from 14.7% to 33.0%. All mixes used a PG 58-28 binder with either an S or H traffic designation. The test procedures used are based on the modified Wisconsin DOT procedure in the Manual of Test Procedures (MOTP); the procedures and standards are referred to as WTM.

Table 8: List of Plant-produced Mixes

Mix ID	Virgin Binder's PG	Design AC Content (%)	RAP	RAS	Binder Replacement	Mix Type
A	PG 58-28 S	4.9	12%	4%	33.0%	3HT
B	PG 58-28 S	5.8	23%	0%	20.1%	4HT
C	PG 58-28 S	5.9	18%	0%	14.7%	4HT
D	PG 58-28 S	5.7	18%	3%	27.2%	4HT
E	PG 58-28 S	5.8	25%	3%	31.6%	4HT
F	PG 58-28 S	5.9	22%	0%	21.6%	4HT
G	PG 58-28 S	5.0	20%	0%	23.5%	3HT
H	PG 58-28 H	5.0	20%	0%	23.5%	3HT

Mixes G and H share the same mixture design but use different virgin binders.

The loose mixtures were sampled, in coordination with contractors, in cardboard boxes in accordance with WTM R97. The source materials, aggregates, asphalt binders, RAP and RAS, used for the subsequent lab verification and redesign, were collected along with the loose mixes. The sampled materials represented both the Northern and the Southern regions of Wisconsin. The asphalt binders were sampled in accordance with Wisconsin DOT CMM 836.

The source aggregate gradation, RAP gradation, and RAS gradation, for all the material used in all eight mixes, mixes A through G and H are shown in Tables 9 through 15. It should be noted that mixes G and H used the same mix design, aggregate source, and gradation but different binder grades.

Table 9: Source Aggregate Mix A

Sieve sizes		Aggregate Sources Gradations (%)						
Sieve	**(mm)**	**7/8 Chips**	**5/8 Chips**	**3/8 Chips**	**Man Sand**	**Natural Sand**	**RAP**	**RAS**
1"	25	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/4"	19	80.0	70.0	100.0	100.0	100.0	100.0	100.0
1/2"	12.5	10.0	12.0	97.0	100.0	100.0	97.0	100.0
3/8"	9.5	1.0	1.0	17.0	98.0	98.0	78.0	96.0
#4	4.75	1.0	1.0	1.0	67.0	85.0	59.0	93.0
#8	2.36	1.0	1.0	1.0	35.0	71.0	44.0	76.0
#16	1.16	1.0	1.0	1.0	16.0	54.0	33.0	57.0
#30	0.6	1.0	1.0	1.0	7.0	24.0	22.0	50.0
#50	0.3	1.0	1.0	1.0	3.0	6.0	16.0	42.0
#100	0.15	1.0	0.5	0.5	1.0	2.5	12.2	35.4
#200	0.075	0.5	0.4	0.5	2.5	1.5	11.2	30.4

Table 10: Source Aggregate Mix B

Sieve sizes		Aggregate Sources Gradations (%)				
Sieve	**(mm)**	**5/8 Chips**	**3/8 Chips**	**Man Sand**	**Natural Sand**	**RAP**
1"	25	100.0	100.0	100.0	100.0	100.0
3/4"	19	70.0	100.0	100.0	100.0	100.0
1/2"	12.5	12.0	97.0	100.0	100.0	100.0
3/8"	9.5	1.0	17.0	100.0	100.0	97.0
#4	4.75	1.0	1.0	98.0	98.0	78.0
#8	2.36	1.0	1.0	67.0	85.0	59.0
#16	1.16	1.0	1.0	35.0	71.0	44.0
#30	0.6	1.0	1.0	16.0	54.0	33.0
#50	0.3	1.0	1.0	7.0	24.0	22.0
#100	0.15	0.5	1.0	3.0	6.0	16.0
#200	0.075	0.5	0.5	1.0	2.5	12.2

Table 11: Source Aggregate Mix C

Sieve sizes		Aggregate Sources Gradations (%)				
Sieve	**(mm)**	**5/8 Chips**	**3/8 Chips**	**Man Sand**	**Natural Sand**	**RAP**
1"	25	100.0	100.0	100.0	100.0	100.0
3/4"	19	100.0	100.0	100.0	100.0	100.0
1/2"	12.5	54.8	100.0	100.0	100.0	100.0
3/8"	9.5	6.0	84.7	100.0	100.0	97.2
#4	4.75	1.5	8.3	91.6	100.0	78.9
#8	2.36	1.3	3.4	51.8	97.0	62.4
#16	1.16	1.2	2.2	25.7	88.4	49.9
#30	0.6	1.2	2.1	12.0	66.0	40.3
#50	0.3	1.2	2.0	6.1	22.2	28.2
#100	0.15	1.1	1.9	3.0	5.6	18.7
#200	0.075	1.0	1.6	1.6	2.8	12.8

Table 12: Source Aggregate Mix D

Sieve sizes		Aggregate Sources Gradations (%)					
Sieve	**(mm)**	**5/8 Stone**	**3/8 Stone**	**Man Sand**	**Natural Sand**	**RAP**	**RAS**
3/4"	19	100.0	100.0	100.0	100.0	100.0	100.0
1/2"	12.5	82.3	100.0	100.0	100.0	100.0	100.0
3/8"	9.5	31.2	98.0	100.0	100.0	96.5	99.9
#4	4.75	1.9	23.0	98.0	97.0	44.2	99.4
#8	2.36	1.7	2.0	69.0	84.0	57.8	98.8
#16	1.16	1.6	2.0	43.0	72.0	44.1	81.3
#30	0.6	1.6	2.0	27.0	53.0	33.5	57.9
#50	0.3	1.4	2.0	14.0	16.0	20.9	50.1
#100	0.15	1.4	2.0	5.0	3.1	13.6	41.8
#200	0.075	1.2	1.7	2.3	1.1	9.0	30.4

Table 13: Source Aggregate Mix E

Sieve sizes		Aggregate Sources Gradations (%)					
Sieve	**(mm)**	**5/8 Chips**	**3/8 Chips**	**Man Sand**	**Natural Sand**	**RAP**	**RAS**
1"	25	100.0	100.0	100.0	100.0	100.0	100.0
3/4"	19	100.0	100.0	100.0	100.0	100.0	100.0
1/2"	12.5	59.1	99.9	100.0	100.0	98.4	100.0
3/8"	9.5	5.2	80.4	100.0	100.0	94.4	99.9
#4	4.75	0.9	10.4	95.7	95.5	76.1	99.4
#8	2.36	0.7	1.1	67.3	84.7	59.5	98.8
#16	1.16	0.6	0.8	39.3	69.0	49.3	81.3
#30	0.6	0.6	0.7	26.6	57.1	40.5	57.9
#50	0.3	0.5	0.6	16.8	29.4	24.4	50.1
#100	0.15	0.4	0.6	7.0	5.8	15.2	41.8
#200	0.075	0.4	0.5	2.5	1.5	11.2	30.4

Table 14: Source Aggregate Mix F

Sieve sizes		Aggregate Sources Gradations (%)				
Sieve	**(mm)**	**7/8x3/8 Bit Agg**	**3/8x1/4 Washed Chips**	**1/4 Washed Man Sand**	**3/16 Screening Sand**	**RAP**
1"	25	100.0	100.0	100.0	100.0	100.0
3/4"	19	100.0	100.0	100.0	100.0	100.0
1/2"	12.5	82.0	100.0	100.0	100.0	96.0
3/8"	9.5	39.0	100.0	100.0	100.0	84.0
#4	4.75	3.0	25.0	96.0	95.0	50.0
#8	2.36	2.0	2.0	63.0	88.0	35.0
#16	1.16	1.8	1.5	34.0	77.0	27.0
#30	0.6	1.7	1.2	18.0	48.0	22.0
#50	0.3	1.5	1.0	9.0	14.0	18.0
#100	0.15	1.4	0.9	3.5	1.8	15.0
#200	0.075	1.2	0.9	1.5	0.9	11.7

Table 15: Source Aggregate Mixes G and H

Sieve sizes		Aggregate Sources Gradations (%)			
Sieve	**(mm)**	**7/8x3/8 Bit Agg**	**3/8x1/4 washed Chips**	**1/4 Washed Man Sand**	**RAP**
1"	25	100.0	100.0	100.0	100.0
3/4"	19	95.0	100.0	100.0	100.0
1/2"	12.5	46.0	100.0	100.0	96.0
3/8"	9.5	29.0	100.0	100.0	84.0
#4	4.75	2.8	25.0	96.0	50.0
#8	2.36	2.5	2.0	63.0	35.0
#16	1.16	2.5	1.5	34.0	27.0
#30	0.6	2.4	1.2	18.0	22.0
#50	0.3	2.3	1.0	9.0	18.0
#100	0.15	2.0	0.9	3.5	15.0
#200	0.075	1.6	0.9	1.5	11.7

The volumetrics and performance of the sampled plant mixes were determined as shown in Chapter 4. The G_{mm} of the plant mixes were determined and compared with mix design values. To evaluate the performance of the plant mixes, the IDEAL-CT and the HWTT were conducted for cracking and rutting resistance, respectively. In addition, extraction and recovery tests were performed to determine the binder content and the recovered aggregate gradation of the field mix. The recovered binder was subsequently graded to verify their Performance Grade (PG) and Multiple Stress Creep Recovery (MSCR) properties and assess any potential aging or effects from field production.

Based on the initial evaluations, three mixes were identified as candidates for improvement, with more details on their selection in Chapter 4. The selected three mixes were recreated in the lab using the sampled raw materials, and comprehensive performance testing was conducted. The findings from this stage served as the baseline for the mixes’ performance and for the subsequent redesign to enhance their performance characteristics, as described in Chapter 5.

During the redesign process, a combined approach using both the Bailey Method and virtual mix design was utilized to optimize aggregate packing and interlock, aggregate surface area, and AFT to ensure an appropriate balance between stability, cracking resistance, and workability. The redesign includes changes to aggregate gradation and binder content. Additionally, the compaction effort was changed by reducing the design gyration from 100 to 75. The redesigned mixes targeted 4.0% air voids at a design gyration level of 75. The reduction in the design gyration level was meant to improve the field compactibility. The three redesigned mixes were not air-void regressed to examine whether improvement in performance can be achieved using reduced gyrations without air-void regression. A fourth mix was selected for redesign at a subsequent stage to investigate the impact of air-void regression along with reduced gyrations. For each mix, at least two redesigned mixes were developed. The first redesigned mix involved using the Bailey Method to optimize aggregate gradation. Based on the performance results of the first redesigned mix, a second redesigned mix was developed by incorporating both the Bailey Method and a virtual mix design approach**,** enabling refinement of mix performance to target a specified AFT**.** This approach ensured that the desired film thickness, critical for durability and moisture resistance, was achieved without compromising volumetric properties.

The tests done for this project are outlined below:

- G_{mm} and G_{mb} were used to determine the volumetrics of all the mixes in this study.
- For performance testing, IDEAL-CT and HWTT were utilized.
- Performance grading of the binders was determined using the Dynamic Shear Rheometer (DSR) and Bending Beam Rheometer (BBR)
- Extraction and recovery were used to determine the binder contents of the plant mixes and to recover binder for further testing.

CHAPTER 4. BENCHMARKING AND MIX VERIFICATION

For all mixes, the sampled virgin and RAP binders were tested to determine their PG as shown in Table 16. It is noted that, for most mixes, the virgin binder used in production had a higher MSCR designation than the mix design. Further, WisDOT specifications allow contractors to switch to a higher MSCR during production without revising the mixture design. The MSCR designation, shown in Table 16, was determined according to WTM M332 based on $Jnr_{@3.2kPa}$, Jnr_{diff}, and percent (%) $recovery_{@3.2kPa}$. The percent recovery, which indicates the extent of polymer modification in the binder, was the controlling parameter for the MSCR designation. According to Wisconsin DOT WTM M322, a minimum percent recovery of 30% is required for heavy traffic “H”, and a minimum percent recovery of 55% is required for very heavy traffic “V”. The testing of the RAP binders reveals notable aging with a low-temperature PG of -6°C for all RAP sources, and a high-temperature PG of 82°C and 76°C, based on the RAP source. The RAP source used in Mix C showed excessive aging, and its PG could not be determined. The RAP binder from Mix C was too stiff to pour even at elevated temperatures to make BBR specimens for low temperature testing, and its high temperature could not be determined due to DSR test limitations, as it was not possible to test the RAP binder above 116°C.

Table 16: PG of Virgin and RAP binders

Mix ID	Virgin Binder’s PG	Virgin Binder’s Continuous PG	Virgin Binder’s MSCR PG	Virgin Binder’s % Recovery @3.2 kPa	RAP Binder’s PG
A	PG 64-28	PG 68.9-32.0	PG 58-28 V	61.0%	PG 82-6
B	PG 64-28	PG 69.0-31.2	PG 58-28 H	36.4%	PG 82-6
C	PG 64-28	PG 69.0-31.2	PG 58-28 H	38.0%	PG 116+*
D	PG 58-28	PG 60.4-29.8	PG 58-28 S	0.4%	PG 82-6
E	PG 64-28	PG 67.2-32.8	PG 58-28 V	60.0%	PG 82-6
F	PG 64-28	PG 67.7-29.6	PG 58-28 H	31.0%	PG 70-6
G	PG 58-28	PG 60.0-30.3	PG 58-28 S	0.8%	PG 70-6
H	PG 64-28	PG 67.7-31.8	PG 58-28 V	65.0%	PG 70-6

*High temperature DSR testing stopped at 116 °C

The plant-produced mixtures were tested to verify their G_{mm} as per AASHTO T209-20 and Wisconsin DOT WTM T209 specifications. The asphalt cement (AC) content was determined using extraction (toluene as the solvent) and recovery. The G_{mm} and AC content of the plant mixes are shown in Table 17, along with the design G_{mm} and AC content. For most mixes, the plant AC content was equal to or higher than the design AC content.

Table 17: Design and Field G_{mm} and AC Content

Mix ID	Design G_{mm}	Plant G_{mm}	Design AC Content (%)	Plant AC Content (%)
A	2.566	2.558	4.9	5.3
B	2.543	2.537	5.8	6.0
C	2.521	2.518	5.9	5.9
D	2.514	2.490	5.7	6.0
E	2.503	2.519	5.8	6.0
F	2.487	2.490	5.9	5.8
G	2.516	2.531	5.0	4.9
H	2.516	2.526	5.0	5.0

The recovered binders from all eight mixes were tested to determine their PG according to AASHTO M 320 and AASHTO M 332, as shown in Table 18. It should be noted that the recovered binder was assumed to be in RTFO-aged condition, so the high-temperature PG was determined using the as-recovered binder. For the low-temperature PG, the recovered binder was subjected to pressure aging vessel (PAV) aging before testing. The results of the recovered binder reflect the stiffening effect of the RAP and RAS in the mix. It should be noted that Mix H had a 54.4% recovery, which was slightly below the minimum criterion of 55% for very heavy traffic (V) and was thus designated as heavy traffic (H). It is interesting to note that the MSCR designation for the recovered binder followed the same MSCR designation as the virgin binder, except for Mix F, which showed a very low % recovery$_{@3.2kPa}$ compared to that of the virgin binder.

Table 18: Recovered binder's PG and MSCR results

Mix ID	Recovered Binder's PG	Recovered Binder's Continuous PG	Recovered Binder's MSCR PG	% Recovery @3.2 kPa
A	PG 76-22	PG 81.9-24.2	PG 58-22 V	60.4%
B	PG 70-22	PG 72.4-27.2	PG 58-22 H	39.7%
C	PG 70-28	PG 71.2-29.6	PG 58-28 H	33.5%
D	PG 70-22	PG 73.7-26.9	PG 58-22 S	18.6%
E	PG 76-22	PG 80.2-26.1	PG 58-22 V	55.5%
F	PG 64-28	PG 64.7-30.0	PG 58-28 S	3.5%
G	PG 64-28	PG 65.8-29.8	PG 58-28 S	5.1%
H	PG 76-22	PG 79.7-23.4	PG 58-28 H	54.4%

The recovered aggregate from the plant mixes was tested to determine the field aggregate gradation for all mixes. The field gradations were plotted alongside the design gradations, as shown in Figures 8 through 15. It was noted that the field gradations were slightly finer than the design gradations for all mixes. However, the differences noted were mostly within production tolerance limits. The control points shown are design requirements, and those do not reflect the production tolerances for those sieves.

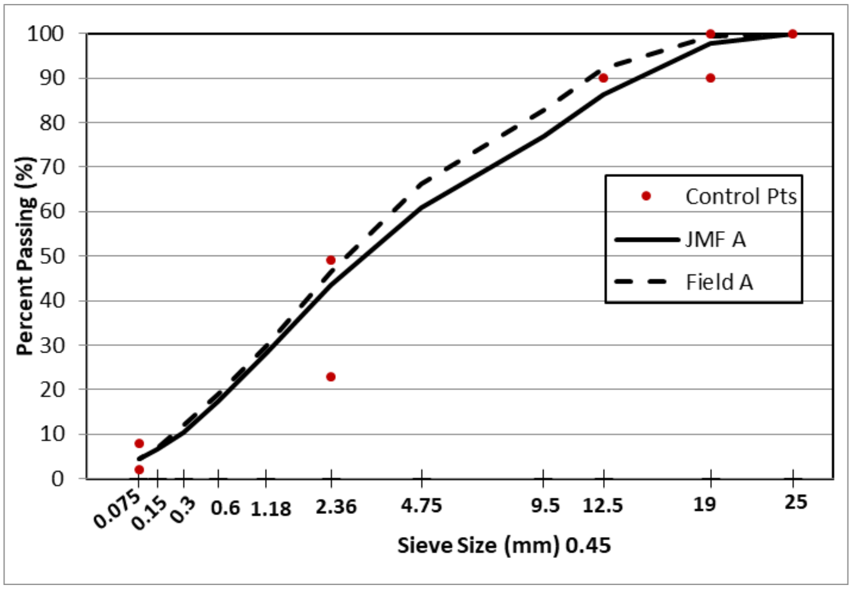

Figure 10. Field and design aggregate gradations for Mix A

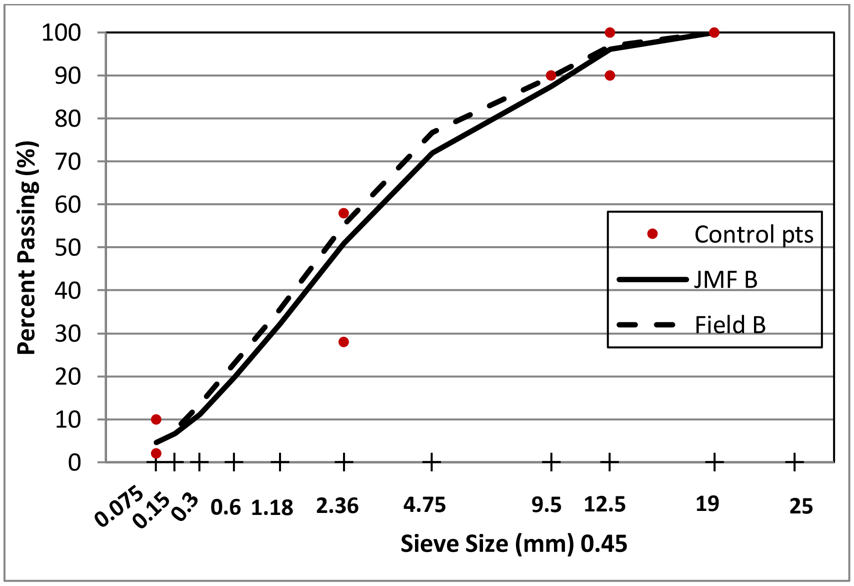

Figure 11. Field and design aggregate gradations for Mix B

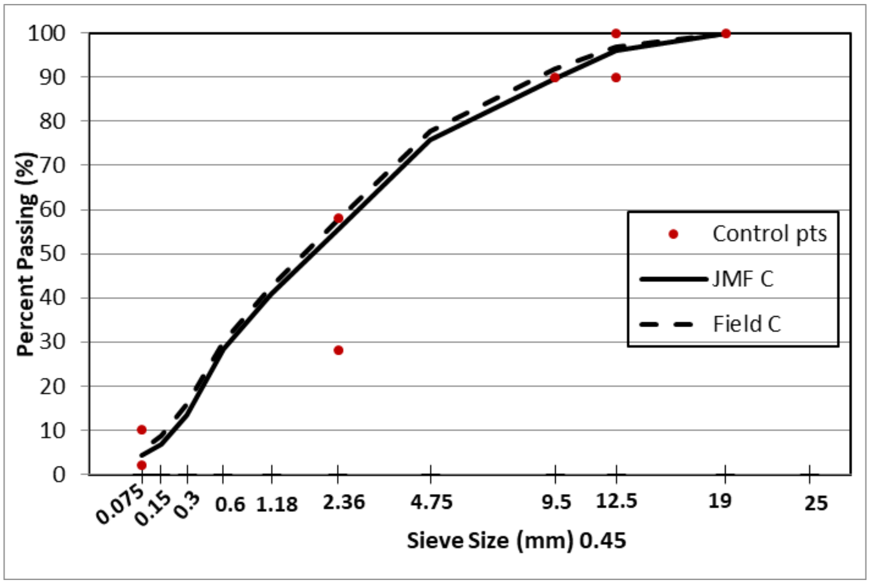

Figure 12. Field and design aggregate gradations for Mix C

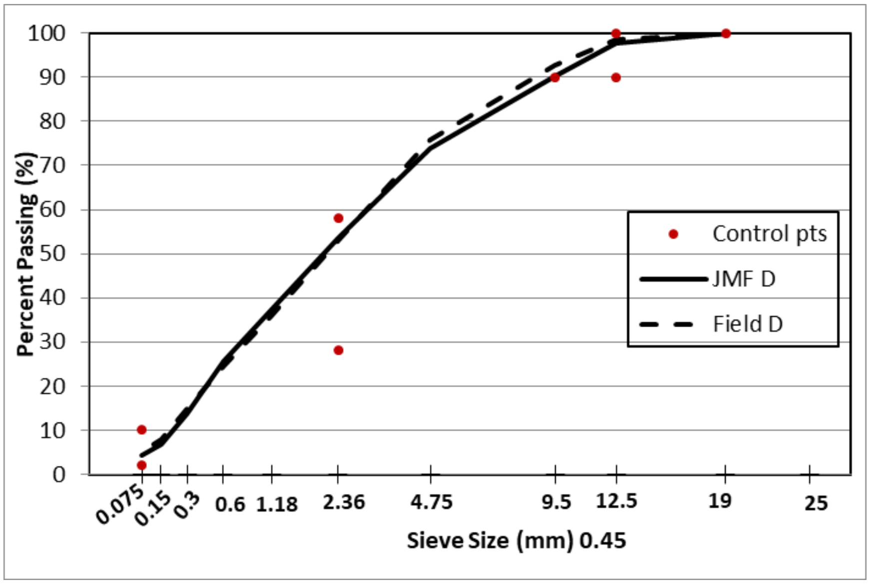

Figure 13. Field and design aggregate gradations for Mix D

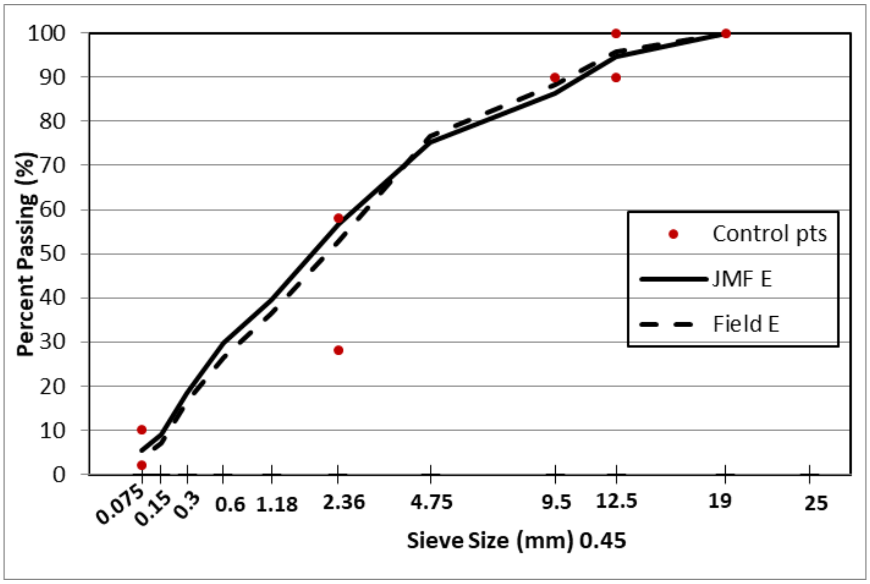

Figure 14. Field and design aggregate gradations for Mix E

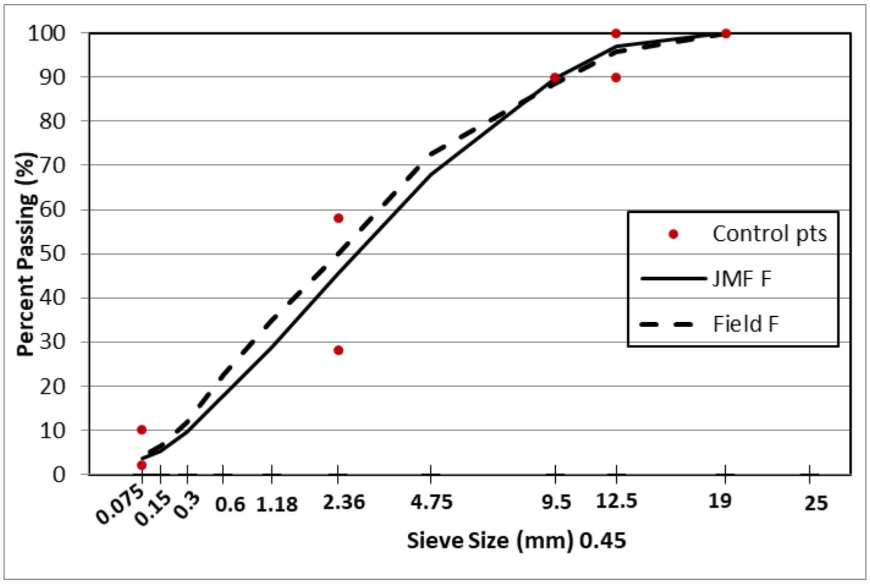

Figure 15. Field and design aggregate gradations for Mix F

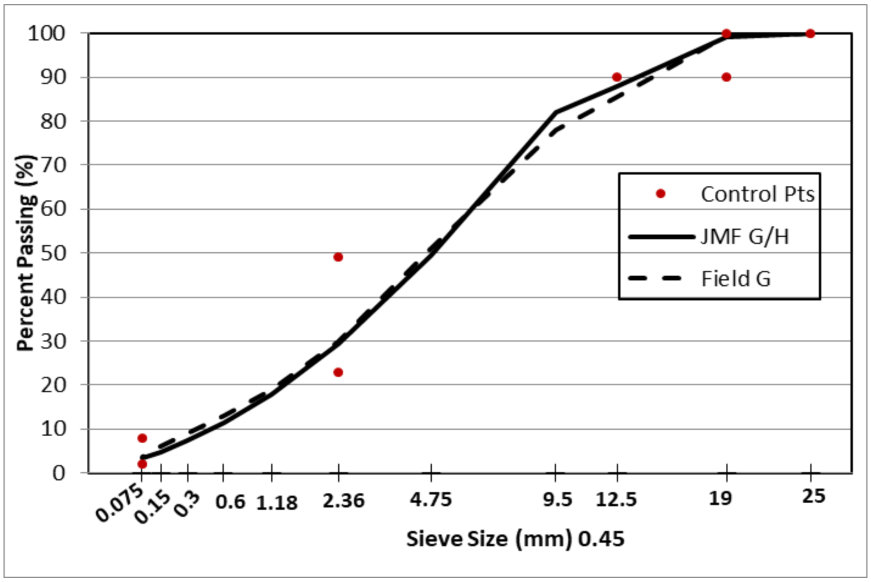

Figure 16. Field and design aggregate gradations for Mix G

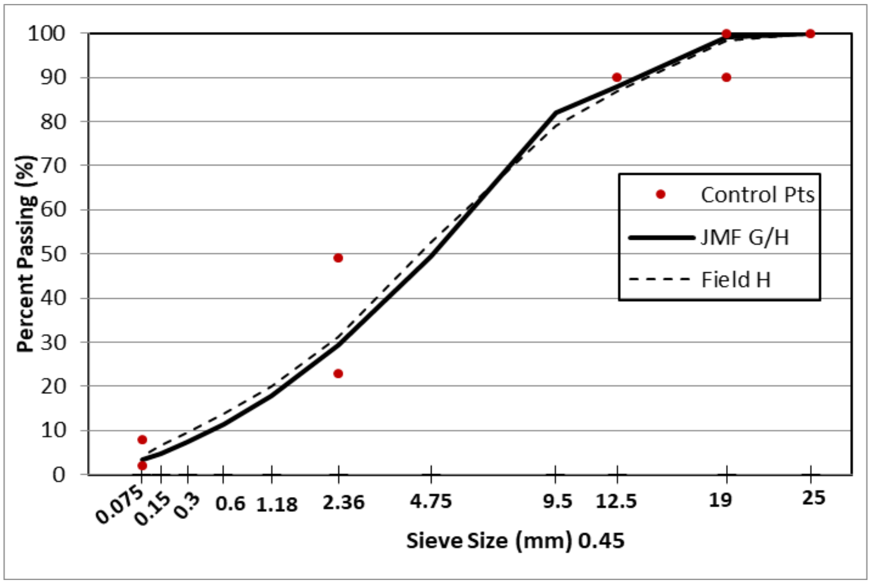

Figure 17. Field and design aggregate gradations for Mix H

Plant-produced lab-compacted (PMLC) specimens were prepared and tested to determine their cracking and rutting resistance using the IDEAL-CT and the HWTT, respectively. The loose mixes were received in cardboard boxes and reheated for 1 hour at compaction temperature to split the mix into test-size samples before conditioning. For the IDEAL-CT, mixtures were long-term aged for 6 hours at 135°C before compaction. The IDEAL-CT specimens were compacted to a height of 62 mm and a target air void of 7.0 ± 0.5%. For the HWTT, mixtures were reheated at compaction temperature and compacted to a height of 62 mm with 7.0 ± 0.5%

air voids. IDEAL-CT testing was conducted at 25ºC following WTM D8225, whereas HWTT was conducted at 46ºC following WTM T324.

The rut depth versus the number of wheel passes from the HWTT was plotted for all mixtures, as shown in Figure 18. The rutting resistance of the mixes was assessed using the total rut depth (TRD) and corrected rut depth (CRD) at 20,000 passes, as shown in Table 19. Moreover, the stripping number (SN), denoting the rut depth curve's inflection point, was calculated and used as a measure of stripping potential. The TRD includes the mixture rutting due to plastic permanent deformation and stripping, whereas the CRD excludes the effect of stripping. Hence, only mixtures that exhibited an inflection point as measured by the SN, e.g., Mixes B, C and F, showed differences between the CRD and TRD at 20,000 passes. The test for mixtures C and F reached 12.5-mm rut depth before 20,000 passes; hence, the rut depth curves were extrapolated using the stripping slope to calculate the TRD at 20,000 passes.

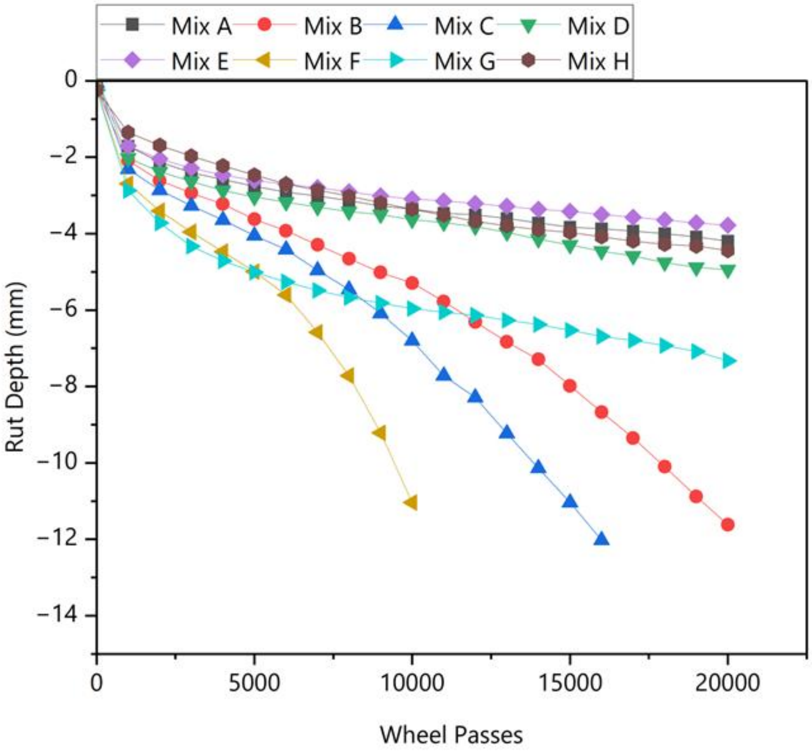

Figure 18. Rut Depth versus Number of Wheel Passes from HWTT for Plant Mixes

Table 19: HWTT results of all plant mixes

Mix ID	TRD_{20k} (mm)	CRD_{20k} (mm)	SN
A	4.2	4.2	N/A
B	11.6	4.8	4,936
C	16.6*	5.5	3,303
D	4.9	4.9	N/A
E	3.8	3.8	N/A
F	29.8*	5.7	2,935
G	7.3	7.3	N/A
H	4.4	4.4	N/A

*Test stopped before 20,000 passes

The CT_{index} results of the long-term aged plant mixes are shown in Table 20. The results show a wide range of cracking resistance among the mixes. The results highlight the effect of the recovered binder grade on the cracking resistance. Mixes A, E, and H, with a stiff binder having a high-temperature PG close to or above 80°C, showed the lowest CT_{index} values of 42, 47, and 37, respectively. Mixes F and G, with a soft binder having a high-temperature PG of 64.7°C, and 65.8°C showed the highest CT_{index} values of 145 and 131, respectively. It was noted that mixes B, C, F, and G showed very high CT_{index} which were not typical of long-term aged plant mixes in Wisconsin. To verify the IDEAL-CT results, additional specimens were compacted and tested for mixes C, F, and G at Oklahoma State University (OSU). Mix B was not retested due to limited material availability. The results conducted at OSU were comparable to those reported by Iowa State University (ISU), particularly for mixes F and G. Mix C had slightly lower CT_{index} of 70. It should be noted that the CT_{index} results from OSU are only reported here for comparison, and are not used in subsequent analysis, to avoid introducing multilaboratory variability.

Table 20: IDEAL-CT results of all plant mixes

Mix ID	CT_{index}	COV (%)
A	42	12%
B	104	22%
C	101 70*	18% 24%
D	74	22%
E	47	14%
F	145 147*	19% 14%
G	131 118*	20% 10%
H	37	27%

*Additional specimens tested at OSU.

To further analyze the IDEAL-CT results, an IDEAL-CT interaction diagram showing the relationship between the fracture energy and the l75/m75 parameters is presented in Figure 19. The contour plots on the interaction diagram represent different CT_{index} values, with CT_{index} increasing toward the upper-right corner. Based on the results of the plant-produced mixes, the impact of l75/m75 is significant on the CT_{index}, whereas the impact of the fracture energy parameter does not appear to be as substantial. Mixes F and G had the lowest fracture energy among all mixtures, yet they showed the highest cracking resistance, due to their high l75/m75 parameters.

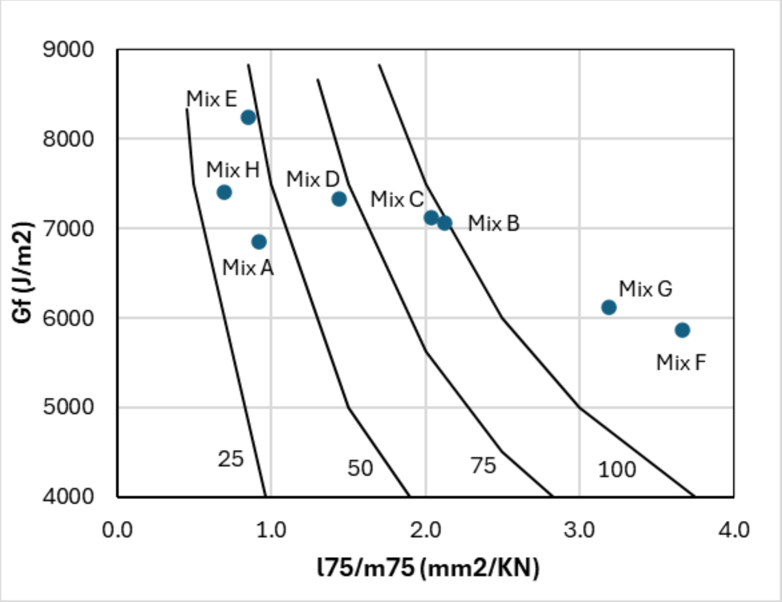

Figure 19. IDEAL-CT interaction diagram for plant mixes

The CT_{index} results show a strong correlation with the recovered binder's high-temperature and low-temperature PGs, as shown in Figures 18 and 19. Mixes A, E, and H with a high-temperature PG at or higher than 80°C and a low-temperature PG at or higher than -26°C have CT_{index} values lower than 50.

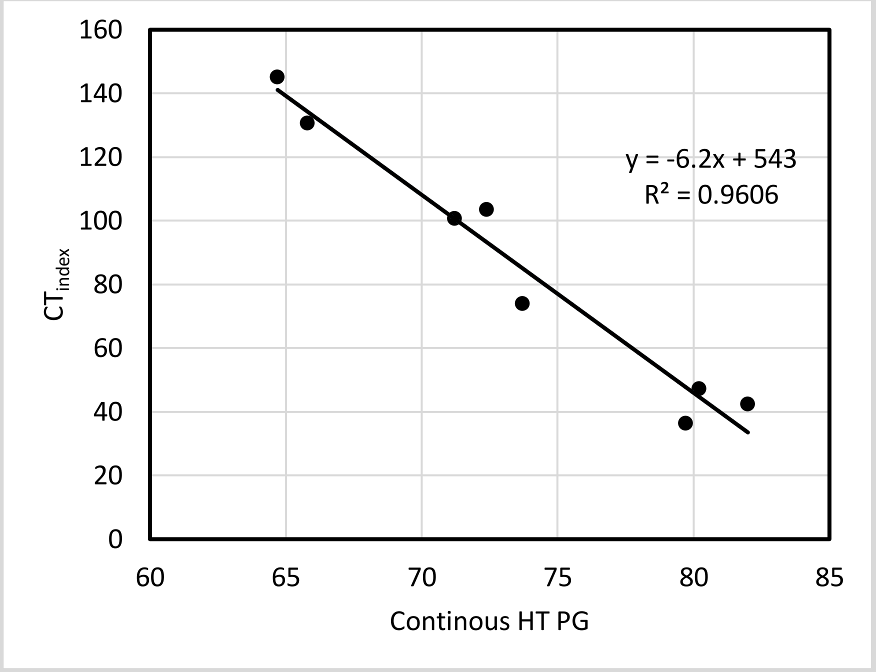

Figure 20. Effect of recovered binders' HT PG on CT_{index}

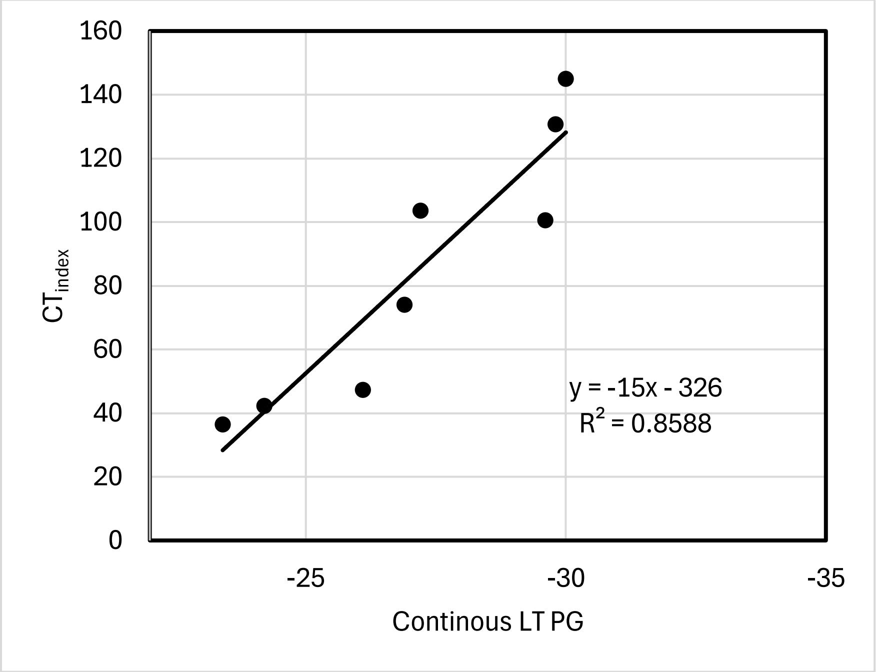

Figure 21. Effect of recovered binders' LT PG on CT_{index}

The overall rutting and cracking resistance of the plant mixes is shown in Figure 22 using a performance space diagram. Using a maximum CRD at 20,000 passes of 5 mm as a passing rutting criterion for HT mixes, mixes C, F, and G appear not to meet that criterion. On the other hand, all mixtures satisfy the minimum criterion of 30 for the CT_{index}.

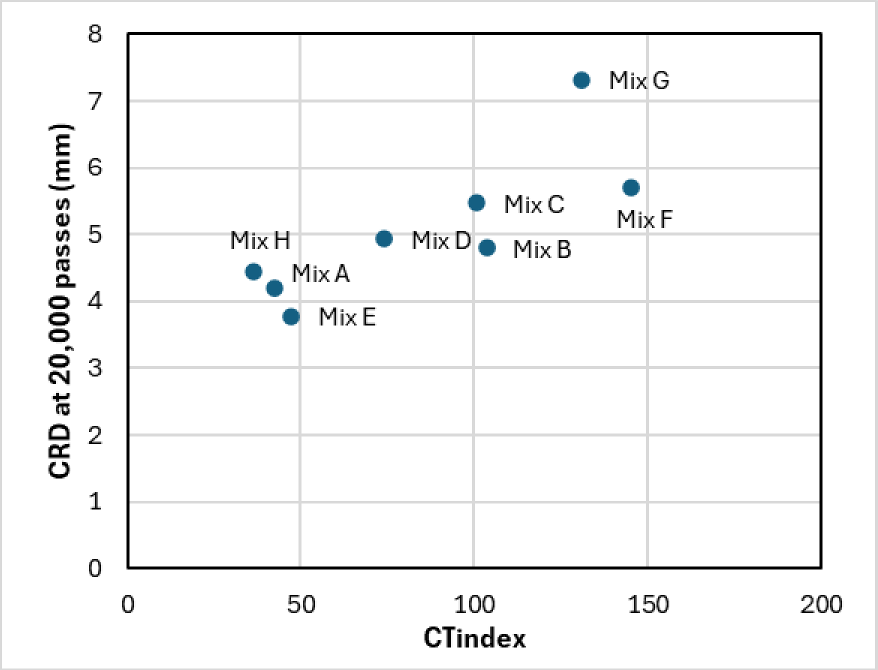

Figure 22. Performance space diagram for plant mixes

The Wisconsin DOT has an extensive database of plant-mix test results for IDEAL-CT and HWTT. The database includes different mix types: low-traffic, medium-traffic, and high-traffic. The results for the high-traffic mixtures were extracted from the database for CT_{index} and CRD at 20,000 passes and plotted in Figure 23 and Figure 24, respectively. The results are grouped based on MSCR designation (i.e., binder traffic level) and RAP content. The results do not show any clear trends by binder's MSCR designation, possibly because these designations do not necessarily reflect the binder used in production. With increasing RAP content, the CRD and the CT_{index} appeared to decrease, denoting lower cracking and higher rutting resistance.

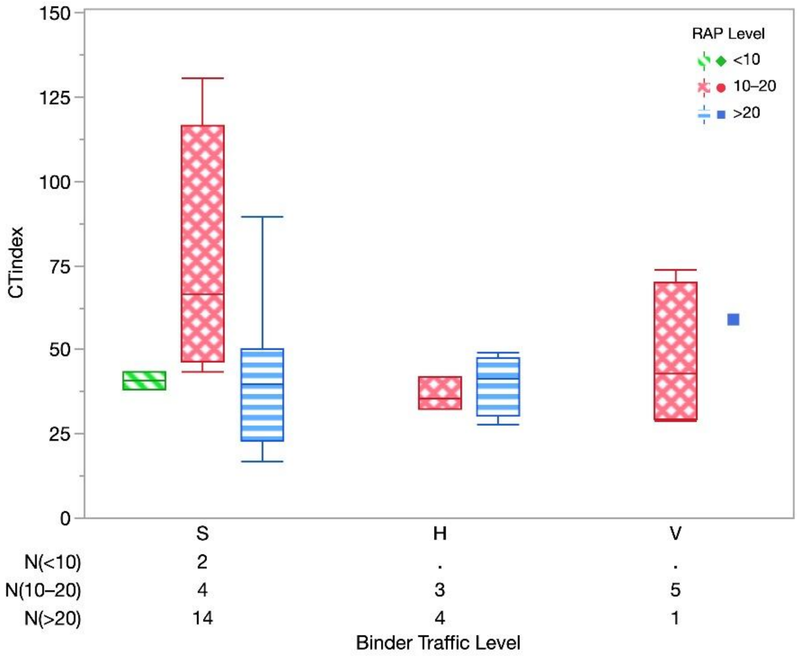

Figure 23. CT_{index} for Wisconsin HT mixes

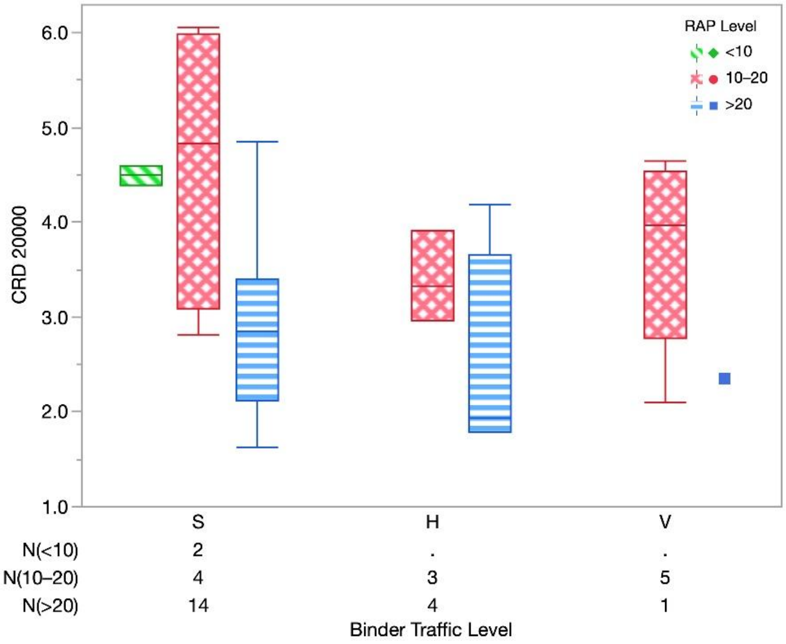

Figure 24. CRD at 20,000 passes for Wisconsin HT mixes

The performance of the eight plant mixes included in this study is compared with the HT mixes from the Wisconsin database, as shown in Figure 25. According to Figure 25, Mixes B, C, F and G showed high CT_{index} which is not representative of the average performance of Wisconsin HT mixes. On the other hand, Mixes A, E, and H provide good rutting and cracking resistance, and they fell within the average performance of Wisconsin HT mixes, thus it was decided to procced with these mixes for redesign. The redesign objective was to determine if adjusting compaction criteria and gradation could improve the overall mixture performance. The redesign of Mixes A, E, and H was done using a reduced number of gyrations without air void regression with the objective of assessing whether performance can be improved with reduced gyration only. To assess the combined effect of reduced gyration and air void regression on performance, Mix D was selected for redesign and testing.

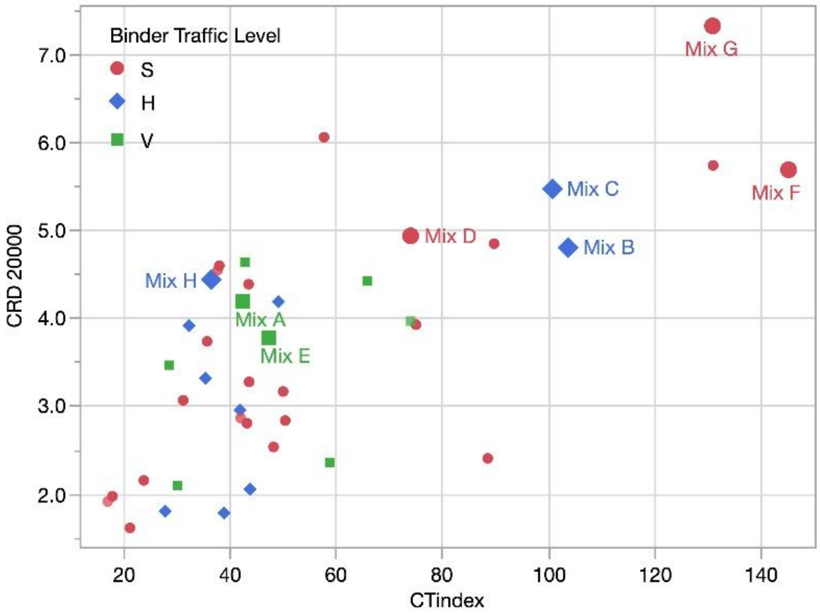

Figure 25. Performance space diagram for Wisconsin HT mixes

CHAPTER 5. LAB MIX TESTING AND REDESIGN

The objective of this part of the experimental plan was to verify Mixes A, E, and H in the lab using the collected raw materials to produce lab-mixed lab-compacted (LMLC) specimens. The performance of the lab mixes was compared with that of the plant mixes. The performance of the lab mixes was then used as a baseline for subsequent mix redesigns. As explained previously, the redesign involved using both the Bailey Method and virtual mix design to achieve a target design air void of 4.0% using a design gyration of 75. As noted previously, the redesign of Mixes A, E, and H did not follow the air-void regressed approach with the objective of assessing whether performance improvement could be achieved through reduced number of gyrations only without air void regression. To investigate the combined effect of air-void regression and reduced gyrations, Mix D was selected for redesign and testing, and the results are presented at the end of this chapter.

Lab Mix Verification

Raw materials collected during production were used to prepare LMLC specimens for Mixes A, E, and H. The specimens were compacted at 100 gyrations to match mix design gyrations. The volumetrics of the LMLC specimens were compared with those of the plant mixes, e.g., PMLC specimens, using G_{mm} and air voids at 100 gyrations. Following mix verification, HWTT and IDEAL-CT specimens were prepared and tested to establish the baseline performance of the LMLC mixes as compared to the PMLC mixes.

Table 21 shows the volumetrics and binder content of the PMLC and the LMLC specimens. During lab verification, the same amount of binder was used as in the field, and samples were compacted using 100 gyrations. The air voids in the LMLC specimens ranged from 2.5% to 3.7%. The difference between the G_{mm} values of the PMLC and LMLC specimens was within the multilaboratory precision limit of 0.0193 as outlined in AASHTO T 209.

Table 21: Volumetric properties for the lab and plant mixes

	PMLC Mix A	LMLC Mix A	PMLC Mix E	LMLC Mix E	PMLC Mix H	LMLC Mix H
G_{mm}	2.558	2.547	2.519	2.507	2.531	2.526
G_{mb}	2.495	2.461	2.436	2.440	2.437	2.440
Air Voids @ N_{des}=100	2.5%	3.4%	3.3%	2.5%	3.7%	3.4%
Binder Content	5.4%	5.4%	5.8%	5.8%	5.0%	5.0%

The CT_{index} results of the lab mixes, i.e. LMLC specimens, along with those of the plant mixes, i.e. PMLC specimens, are shown in Figure 26. It was noted that the lab mix results did not align with those of the plant mixes, with no clear trend observed between the two. Similarly, the CRD at 20,000 passes from the HWTT of the lab mixes was compared with the plant mixes, as shown in Figure 27. It was noted that the lab mixes exhibited better rutting resistance than the plant mixes.

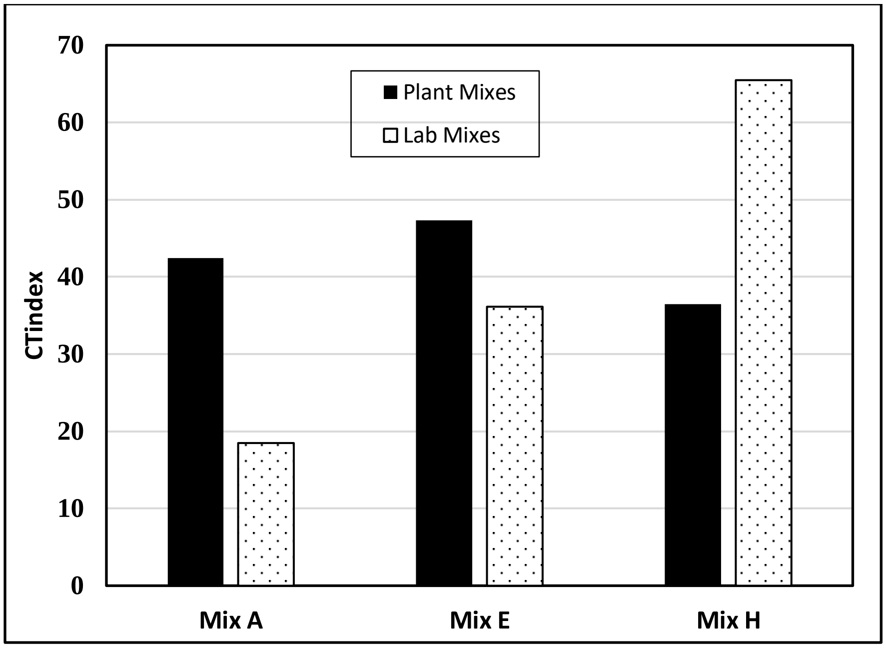

Figure 26. CT$_{index}$ results for lab and plant mixes

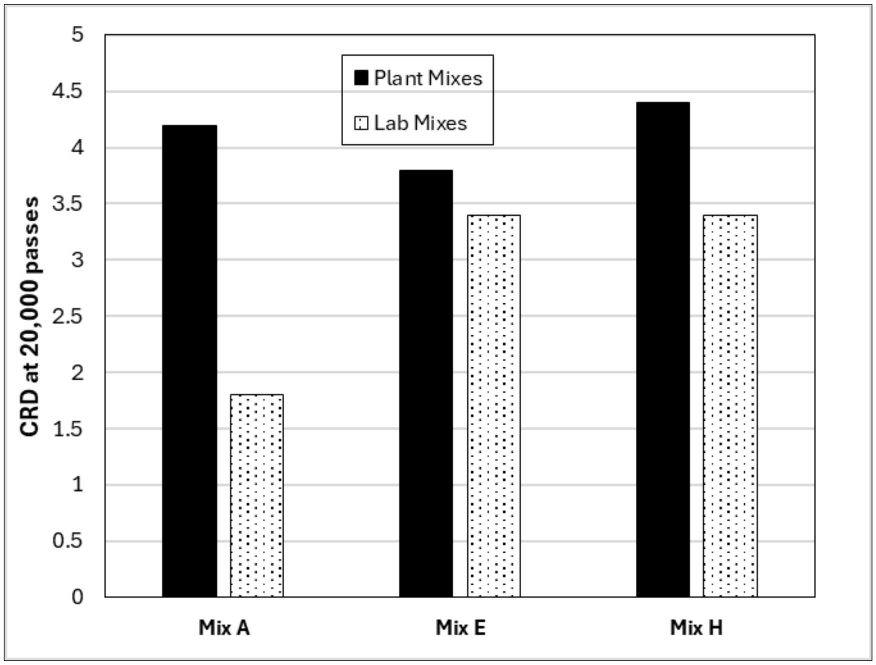

Figure 27. CRD at 20,000 passes for lab and plant mixes

Redesign of HT Mixes

Using the results of the lab mixes for Mixes A, E, and H, as a baseline, multiple variations of these mixes were designed using the principles of the Bailey Method and virtual mix design. The Bailey Method was used to optimize aggregate packing by varying ratios to describe the packing of the coarse and fine aggregate fractions. The virtual mix design method was used to optimize the AFT. The RAP and RAS content were kept the same among all mix variations. The redesigned mixes used the same aggregate source as the baseline mixes. The redesigned mixes targeted a 4.0% air void using 75 gyrations.

The mix redesign was conducted through multiple iterative steps to systematically improve performance. In the initial iteration, the Bailey Method was employed to establish the aggregate gradation for the redesigned mixture, followed by adjustment of binder content to achieve targeted performance criteria. Subsequent iterations incorporated both the Bailey Method and a virtual mix design approach to further refine mixture properties. The virtual mix design tool, developed by the Iowa DOT, is based on AFT and was used to modify aggregate gradation and predict volumetric properties, including VMA. The tool utilizes a comprehensive database containing aggregate gradations, binder characteristics, and material property data to estimate design parameters for trial aggregate proportioning.

The redesign of Mix A involved three different iterations, whereas the redesign of Mixes E and H involved two different iterations. Tables 22 to 24 show the aggregate proportions for the baseline and redesigned Mixes for Mix A, E, and H, respectively. The baseline mixes represent the LMLC presented in the previous section.

Table 22: Aggregate percent proportions for Mix A baseline and redesigned mixes

Aggregates	Mix A	Mix A-1	Mix A-2	Mix A-3
7/8"	8%	14%	10%	8%
5/8"	13%	15%	10%	15%
3/8"	15%	19%	15%	16%
Man Sand	41%	29%	40%	35%
Natural Sand	8%	8%	10%	11%
RAP	11%	11%	11%	11%
RAS	4%	4%	4%	4%
Total	100%	100%	100%	100%

Table 23: Aggregate percent proportions for Mix E baseline and redesigned mixes

Aggregates	Mix E	Mix E-1	Mix E-2
5/8"	12%	18%	20%
3/8"	5%	8%	16%
Man Sand	45%	36%	31%
Natural Sand	9.75%	10%	5%
Dust	0.25%	0%	0%
RAP	25%	25%	25%
RAS	3%	3%	3%
Total	100%	100%	100%

Table 24: Aggregate percent proportions for Mix H baseline and redesigned mixes

Aggregates	Mix H	Mix H-1	Mix H-2
7/8 x 3/8	21%	21%	23%
3/8 x 1/4	21%	14%	10%
1/4 sand	33%	40%	42%
RAP	25%	25%	25%
Total	100%	100%	100%

The aggregate gradation for the baseline and redesigned mixes is presented in Tables 25 to 27 for Mixes A, E, and H, respectively.

Table 25: Aggregate gradations for Mix A baseline and redesigned mixes

Sieve sizes		% Passing			
Sieve	**(mm)**	**Mix A**	**Mix A-1**	**Mix A-2**	**Mix A-3**
1"	25	100.0	100.0	100.0	100.0
3/4"	19	97.8	99.0	98.5	99.0
1/2"	12.5	86.2	87.9	88.2	87.7
3/8"	9.5	76.9	81.9	80.6	81.1
#4	4.75	60.9	49.5	64.1	52.3
#8	2.36	43.4	29.4	45.3	30.5
#16	1.16	27.7	17.9	28.8	18.8
#30	0.6	17.0	11.3	17.5	12.2
#50	0.3	9.6	7.4	9.4	8.2
#100	0.15	5.6	4.8	5	5.5
#200	0.075	3.7	3.4	2.9	3.9

Table 26: Aggregate proportions for Mix E baseline and redesigned mixes

Sieve sizes		% Passing		
Sieve	**(mm)**	**Mix E**	**Mix E-1**	**Mix E-2**
3/4"	19	100.0	100.0	100.0
1/2"	12.5	93.7	93.0	93.7
3/8"	9.5	85.5	80.5	85.5
#4	4.75	74.6	67.3	72.7
#8	2.36	53.6	49.8	50.7
#16	1.16	36.2	35.7	33.3
#30	0.6	26.4	26.6	24.0
#50	0.3	16.7	15.9	14.9
#100	0.15	8.3	7.2	7.4
#200	0.075	4.5	3.8	3.8

Table 27: Aggregate gradation for Mix H baseline and redesigned mixes

Sieve sizes		% Passing		
Sieve	**(mm)**	**Mix H**	**Mix H-1**	**Mix H-2**
1"	25	100.0	100.0	100.0
3/4"	19	98.8	99.0	98.9
1/2"	12.5	88.5	87.7	88.8
3/8"	9.5	78.3	81.1	78.3
#4	4.75	53.8	50.0	51.2
#8	2.36	31.3	30.5	30.5
#16	1.16	19.2	18.8	18.8
#30	0.6	13.2	12.2	13.0
#50	0.3	9.4	8.2	9.2
#100	0.15	6.7	5.5	6.4
#200	0.075	4.7	3.9	4.9

Figure 28 through Figure 30, show the corresponding aggregate gradation curves. It should be noted that Mix A baseline and redesigned mixes, and Mix H baseline and redesigned mixes all have a NMAS of 19 mm, whereas Mix E baseline and redesigned mixes have a NMAS of 12.5 mm. All mix gradations are within the control points, indicating the mixes have adequate inter-particle contact and minimal potential for segregation. Figure 29 shows the gradation curve of Mix E-2 is slightly coarser than that of Mix E-1, indicating higher stone-on-stone contact, which is expected to increase rutting resistance. Mix A and Mix A-2 have fine gradations, while Mix A-1 and Mix A-3 are coarse mixes. All variations of Mixes E and H are coarse-graded mixes.

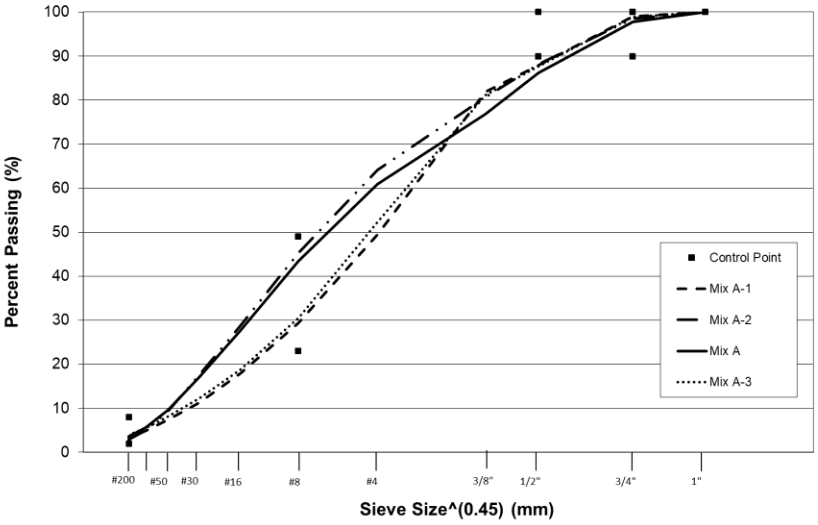

Figure 28. Gradation curves for Mixes A

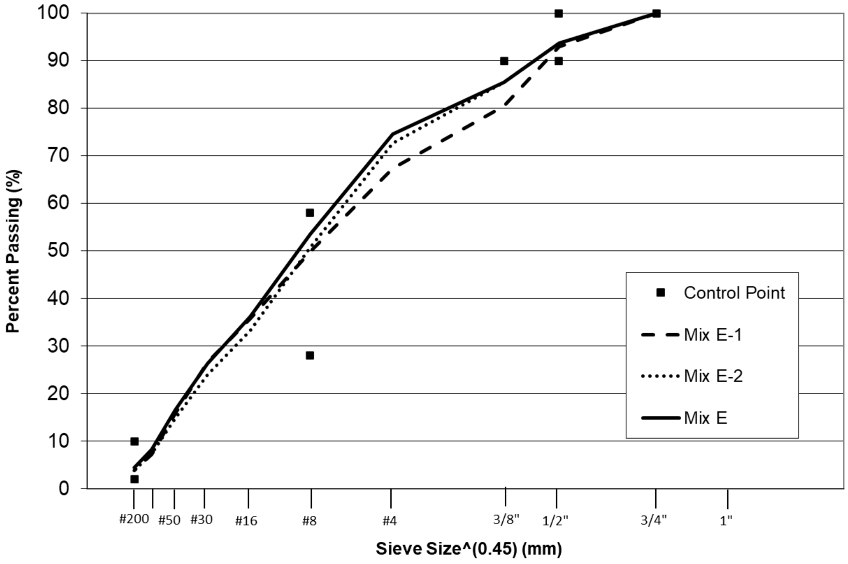

Figure 29. Gradation curves for Mixes E

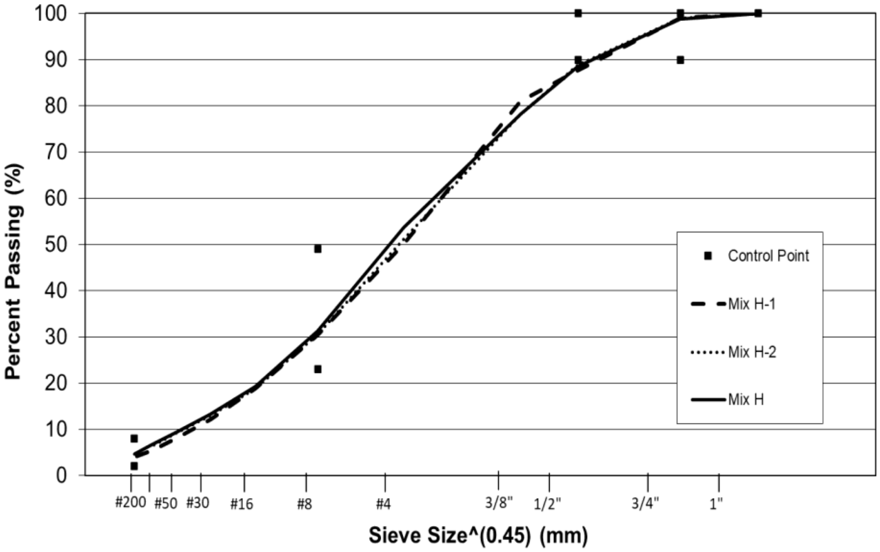

Figure 30. Gradation curves for Mixes H

The Bailey ratios for the baseline mixes and redesigned mixes are shown in Figure 31, Figure 32, and Figure 33 for Mixes A, E, and H, respectively. The CA ratio shows the structure of coarse aggregates and the fine aggregate ratios; FA_C ratio shows the structure of the coarse portion of fine aggregates, and the FA_F ratio shows the packing of the fine within the fine aggregates.

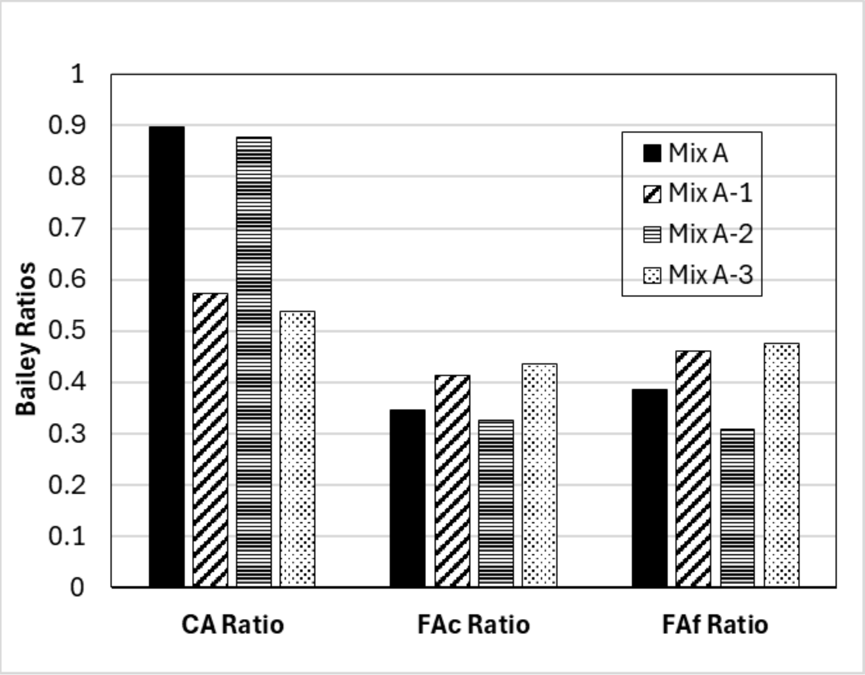

Figure 31. Bailey ratios for baseline and redesigned mixes for Mixes A

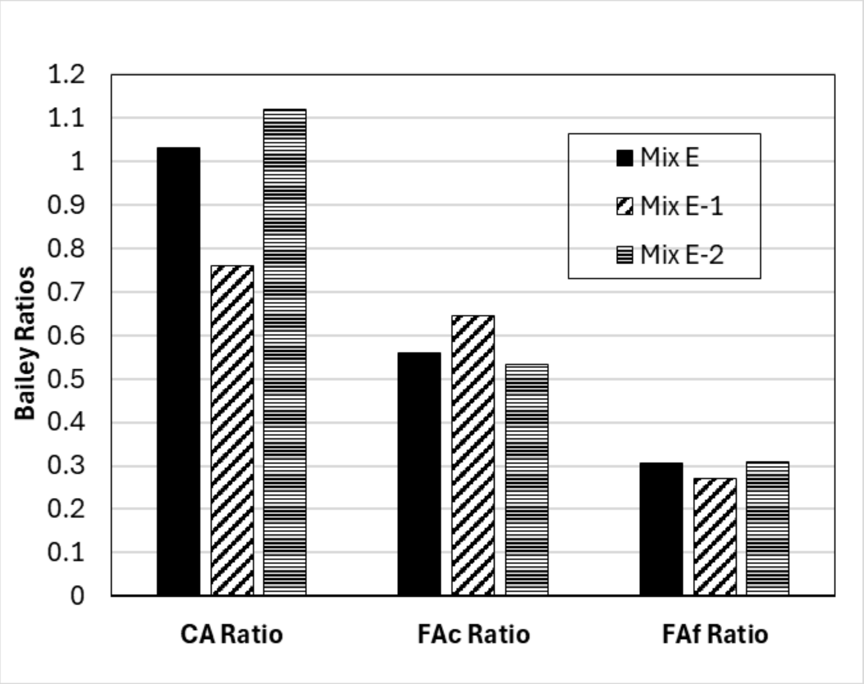

Figure 32. Bailey ratios for baseline and redesigned mixes for Mixes E

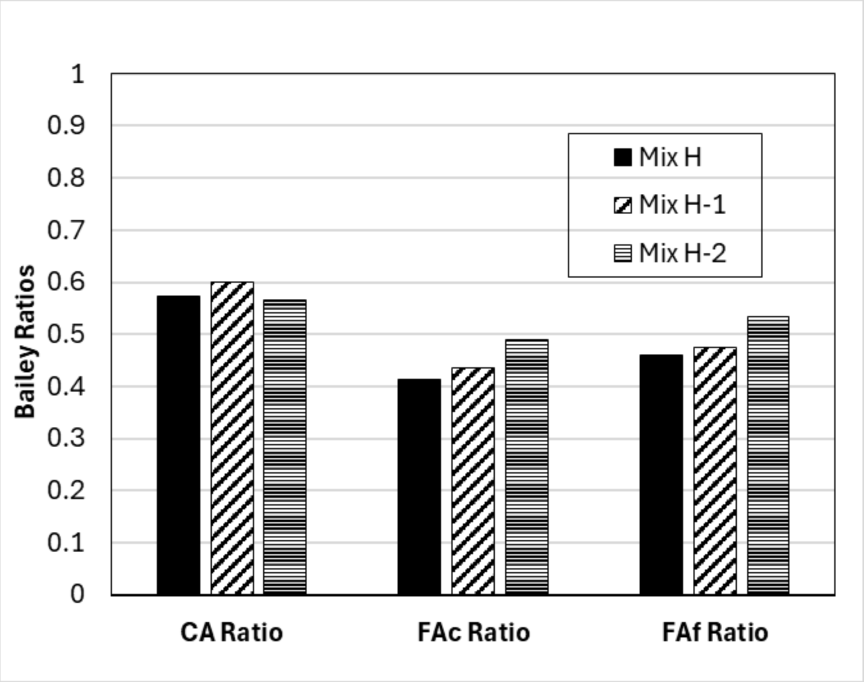

Figure 33. Bailey ratios for baseline and redesigned mixes for Mixes H

Table 28 through Table 30 show the volumetrics and binder content of the baseline and redesigned Mixes A, E, and H, respectively. It should be noted that the volumetrics of the baseline mix were determined at an N_{des}=100 and Va=3.0%, whereas the volumetrics of the redesigned mixes were determined at an N_{des}=75 and Va=4.0%. The redesigned mixes show increases in VMA for Mixes E and H, while Mix A shows a decrease in VMA compared to the baseline mixes. The VMA for all redesigned Mixes A, E and H met the minimum criterion for their NMAS as per WisDOT specification manual Table 460-1 on aggregate gradation. Mixes A and H with NMAS of 19.0 mm met the minimum VMA of 13% while Mix E, met the minimum VMA criterion of 14% for the 12.5 mm NMAS. The VFA for all 12.5 mm NMAS mixes fell within the specified WisDOT range of 70-76%, and the VFA for all 19 mm NMAS was within 65-75% for HT mixes as per WisDOT specifications. The AFT for all mixes was above 8 µm.

Table 28: Volumetrics and mix properties - Mixes A

Volumetrics	Mix A	Mix A-1	Mix A-2	Mix A-3
G_{mm}	2.547	2.573	2.557	2.556
N_{des}	100	75	75	75
Binder content (%)	5.4	5.0	5.4	5.4
Air Voids (%)	3.0	4.0	4.0	4.0
VMA	15.3	14.4	14.8	14.9
VFA (%)	73.8	72.2	73.1	73.2
AFT (µm)	9.7	12.4	12.0	12.5

Table 29: Volumetrics and mix properties - Mixes E

Volumetrics	Mix E	Mix E-1	Mix E-2
G_{mm}	2.507	2.523	2.531
N_{des}	100	75	75
Binder content (%)	5.8	5.4	5.4
Air Voids (%)	3.0	4.0	4.0
VMA	14.4	14.7	14.6
VFA (%)	72.3	72.8	72.6
AFT (µm)	8.4	8.7	8.8

Table 30: Volumetrics and mix properties - Mixes H

Volumetrics	Mix H	Mix H-1	Mix H-2
G_{mm}	2.526	2.503	2.515
N_{des}	100	75	75
Binder content (%)	5.0	5.7	5.3
Air Voids (%)	3.0	4.0	4.0
VMA	13.5	15.2	14.3
VFA (%)	70.3	73.7	72
AFT (µm)	9.5	12.7	10.3

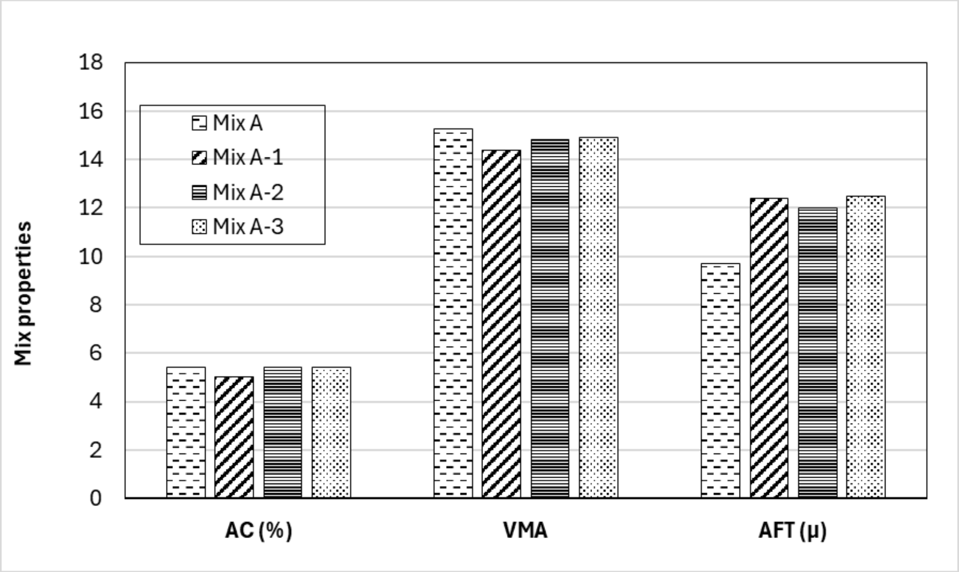

Figure 34. Mixes A design properties

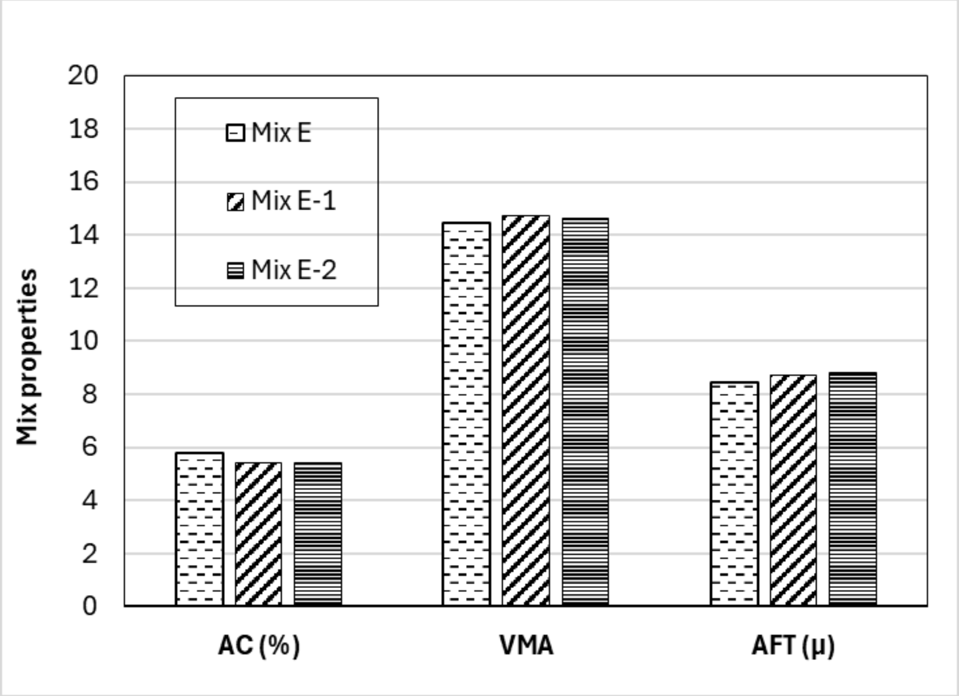

Figure 35. Mixes E design properties

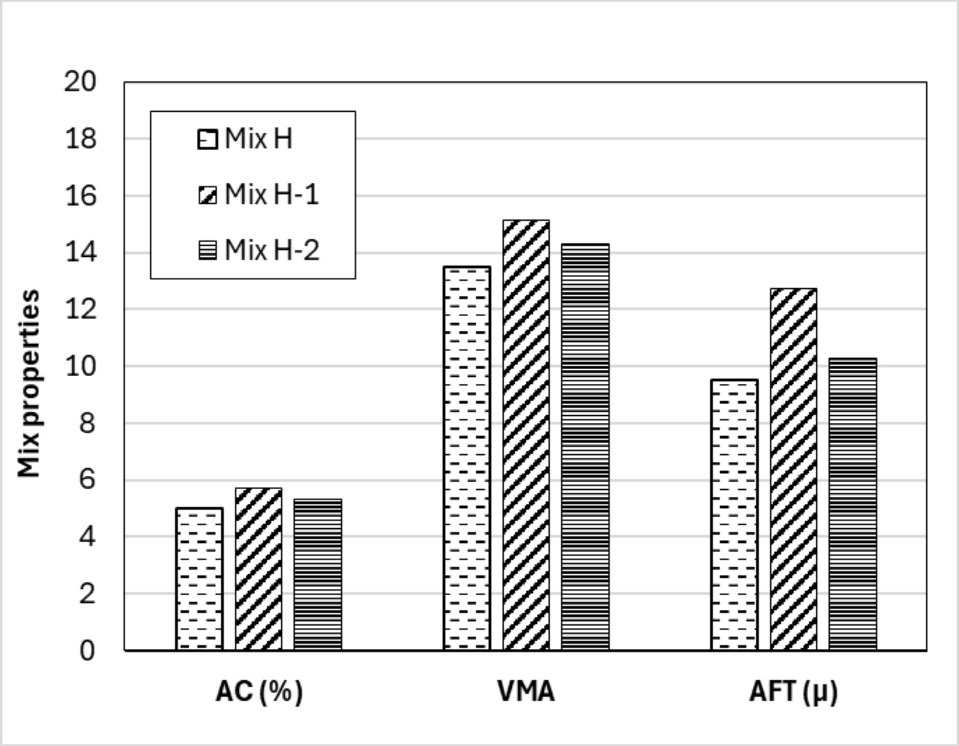

Figure 36. Mixes H design properties

Performance of baseline and redesigned mixes

Table 31 shows the CT_{index} results of all three mixes. For Mix A, the redesigned mixes showed a notable improvement in CT_{index} compared to the baseline mix. For Mix E, the first iteration yielded a lower CT_{index} compared to the baseline, whereas the second iteration resulted in a slight improvement compared to the baseline. For Mix H, both redesigned iterations resulted in a significant increase in the CT_{index} compared to the baseline. The CT_{index} results are also plotted in Figure 37.

Table 31: CT_{index} for baseline and redesigned mixes

Mix ID	Baseline	Redesign #1	Redesign #2	Redesign #3
A	18.5	30.4	24.1	31.4
E	36.1	28.6	45	N/A
H	65.5	139.8	129.7	N/A

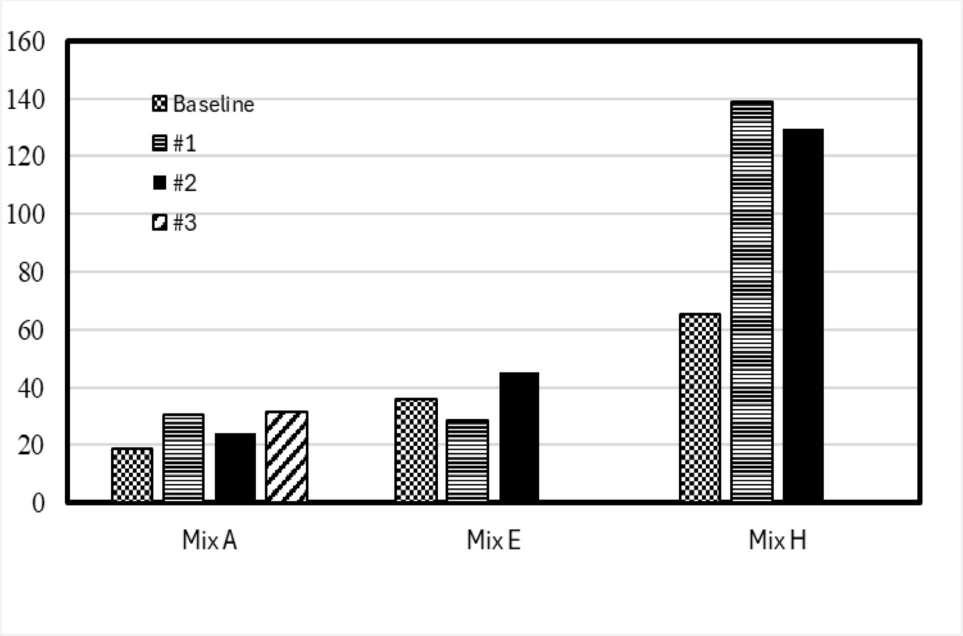

Figure 37. CT_{index} for baseline and redesigned mixes

The CRD at 20,000 passes calculated using the HWTT results for all mixes is shown in Table 32. The CRD results were below the 5 mm threshold as specified by WisDOT for HT mixes. It should be noted, however, that the second redesigned Mix H, Mix H-2, had a CRD of 4.7 mm which is close to the maximum threshold of 5 mm. On the other hand, Mix H-2 had a notably high CT_{index} of 139.8 as shown in Table 31. None of the mixtures showed any signs of stripping, hence the CRD should be the same as the TRD.

Table 32: CRD@20,000 for baseline and redesigned mixes

Mix ID	Baseline	Redesign #1	Redesign #2	Redesign #3
A	1.8	2.6	2.2	2.1
E	3.8	2.2	3.3	N/A
H	3.9	4.8	3.8	N/A

Figure 38 shows a performance space diagram of the CRD and the CT_{index}, with a vertical line representing the minimum CT_{index} and a horizontal line showing the maximum CRD specification values. The gradations for the different redesigned mixes for Mix H were not significantly different; however, an increase in binder content led to a considerable increase in the CT_{index} and a higher CRD. For Mix E, a reduction in binder content in the redesigned mixes improved rutting resistance compared to the baseline mix. Additionally, it was noted that making the mix coarser increased cracking resistance.

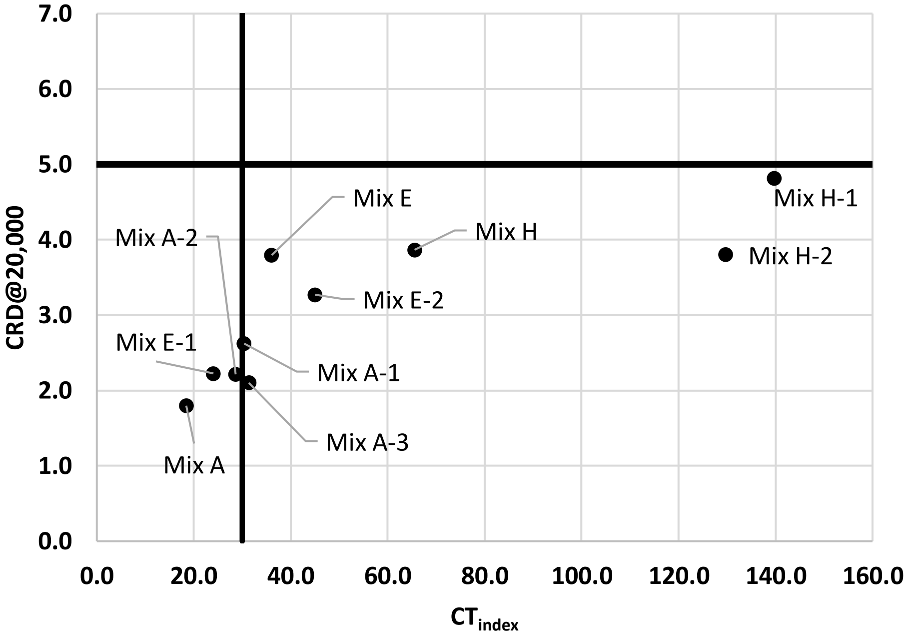

Figure 38. Performance space diagram for Mixes A, E, and H

The relationship between the AFT and the CT_{index} is shown in Figure 39 for all redesigned mixes. The data points are labeled with the Mix ID and the percentage recycled binder replacement. It is noted that the CT_{index} increases with the AFT; however, the relationship between the AFT and the CT_{index} is controlled by the percentage binder replacement. For Mixes A and E with a binder replacement ranging from 31.6% to 35.6%, the CT_{index} did not exceed 45; however, for Mixes H with lower binder replacement rates ranging from 20.6% to 23.5%, the CT_{index} ranged from 65 to 140.

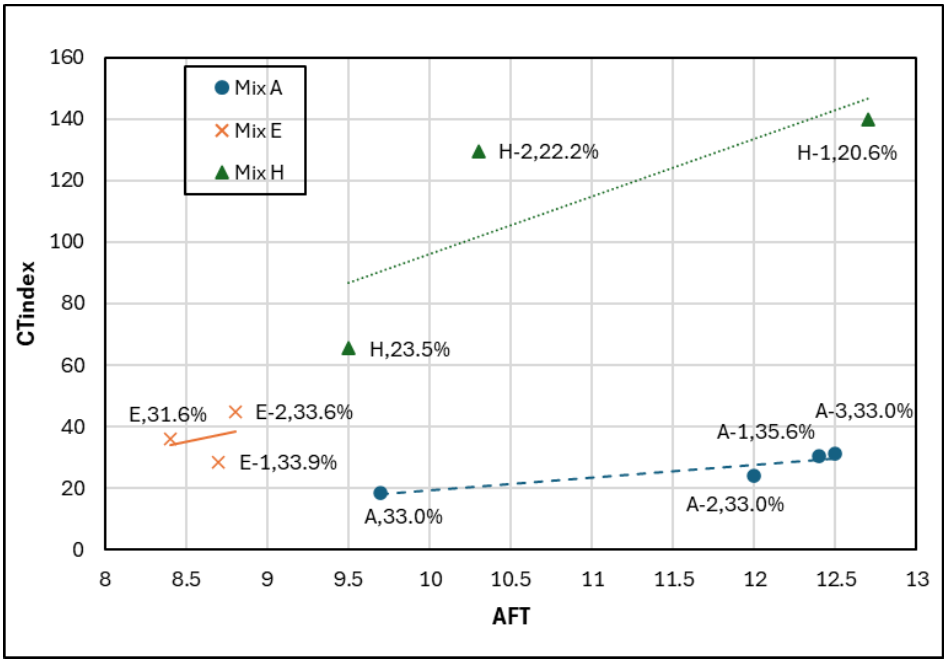

Figure 39. Relationship between AFT and CT$_{\text{index}}$

Compactability of Mixes

The compaction data obtained from the Superpave Gyratory Compactor (SGC) for all LMLC specimens were analyzed to evaluate the compatability of the redesigned mixes in comparison with the baseline mixes. Two key compaction parameters were calculated: the Locking Point (LP), and Compaction Slope (CS). The LP corresponds to the number of gyrations at which two consecutive height measurements are identical, indicating the onset of aggregate locking (Leiva and West 2021). The CS represents the rate of densification over the linear portion of the compaction curve and is calculated using the following equation (Kandhal et al. 2001).

$$CS = 100 * \frac{\%G_{mm}\ at\ N_{des} - \%G_{mm}\ at\ N_{ini}}{\log(N_{des}) - \log(N_{ini})} \qquad (1)$$

The CS and LP results for all mixes are shown in Figures 38 and 39, respectively. For Mix A, the third redesigned mix, Mix A-3, exhibits the highest CS and LP, indicating the best compactability among all Mix A variants. For Mix E, the CS and LP results show different trends among the redesigned mixes; however, neither of the redesigned mixes showed a significant difference in compactability compared to the baseline mix. For Mix H, both redesigned mixes showed improved compactablity compared to the baseline as evidenced by their higher LP. At the same time, the CS values indicate no notable differences among all Mix H variants.

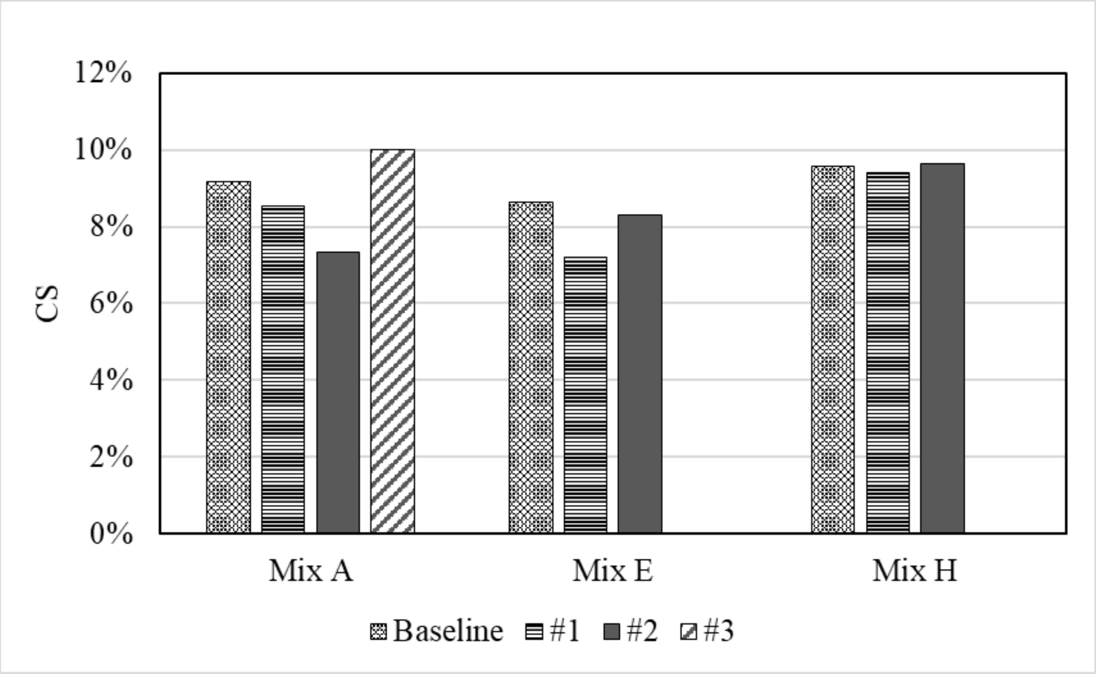

Figure 40. CS for all mixes

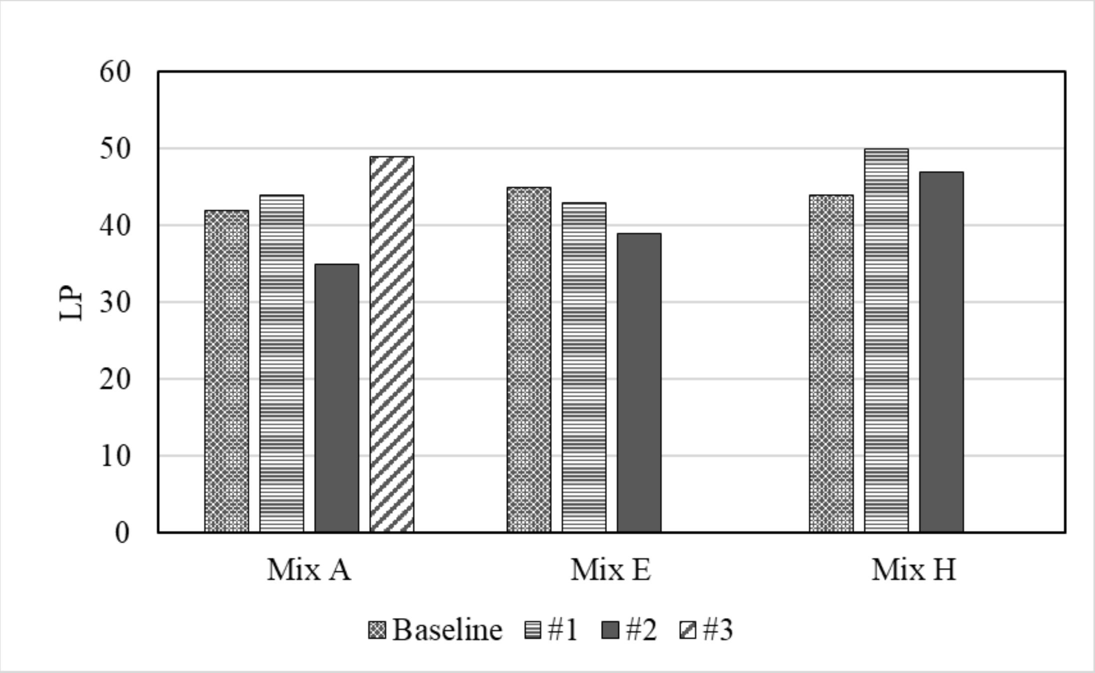

Figure 41. LP for all mixes

Impact of reduced gyrations and air-void regression

To evaluate the impact of air-void regression and reduced gyration level on the rutting and cracking resistance, Mix D was selected for redesign using 75 gyrations and 3.0% regressed air voids. The intention of redesigning Mix D was to determine if Mix D could be improved under the same process as was used for Mixes A, E, and H. In statistics, it is akin to determining if an independent set of data (a point estimate but specifically Mix D) conforms to that of criteria established by multiple sets of data (distribution of data established by Mixes A, E, and H). It is not intended to provide the validation for adopting a specification but verification. Validation for adopting a specification should be done using a special provision and subsequently evaluating it on actual mix designs and field projects. A baseline mix was produced in the lab based on the WisDOT-approved mix design using 100 gyrations and 4.0% air voids and tested for rutting and cracking performance. The mix was then redesigned using 75 gyrations at 4.0% air voids and the binder content increased to achieve 3.0% regressed air-voids. Table 33 summarizes the resulting volumetric properties of the baseline and redesigned mixes compared to the plant mix.

Table 33: Volumetrics and mix properties – Mixes D

Volumetrics	Plant mix	Lab mix – Baseline	Lab mix – Redesign
G_{mm}	2.534	2.541	2.523
Binder content	6.0	5.5	5.9
Number of Gyrations	100	100	75
Air Voids	3.0	4.0	3.0
VMA	14.9	14.6	13.9
VFA	79.9	72.7	84.9
AFT	8.7	8.5	9.35

The mix gradations for the baseline and redesigned mixes are shown in Figure 42.

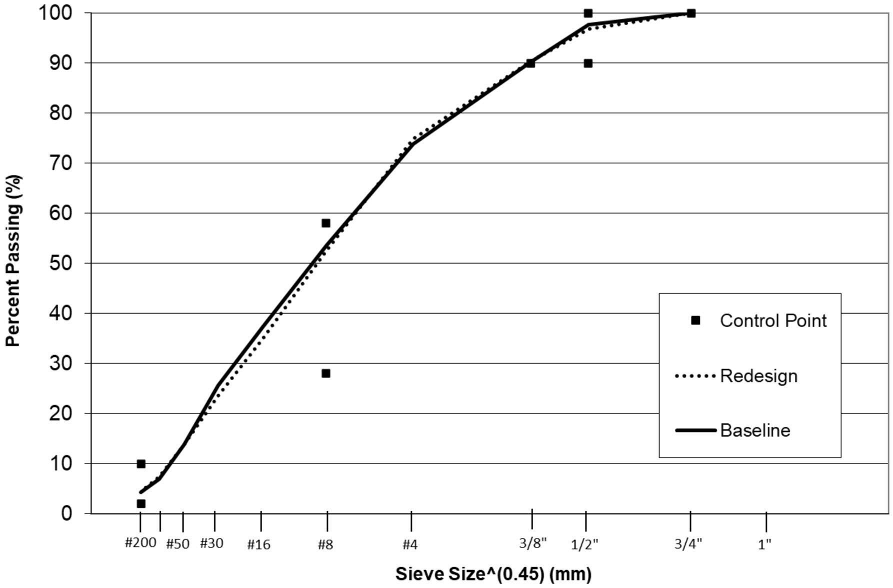

Figure 42. Gradation Curves for Mixes D

The results of the CT_{index} and the CRD at 20,000 passes are shown in Figure 43 and Figure 44, respectively. The results indicate that the redesigned mixes using 75 gyrations and 3.0% regressed air voids showed better cracking and rutting resistance compared to the baseline mix. The results of the redesigned mix also met the minimum CT_{index} criterion of 50 and the maximum CRD at 20,000 passes criterion of 5 mm. These results show that balanced performance can be achieved using a reduced gyration level of 75 and a 3.0% regressed air-voids.

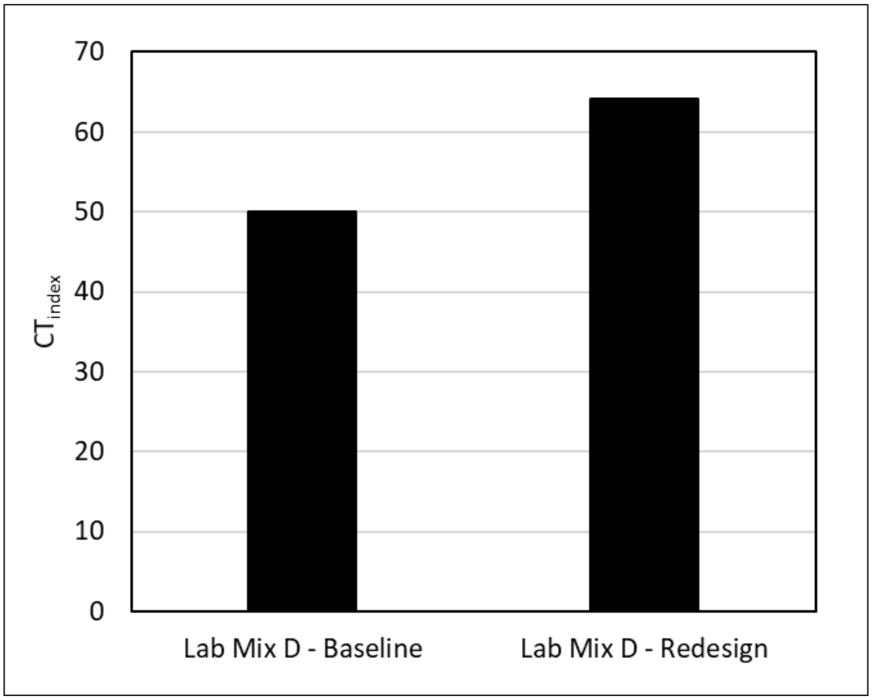

Figure 43. CT_{index} for Mixes D

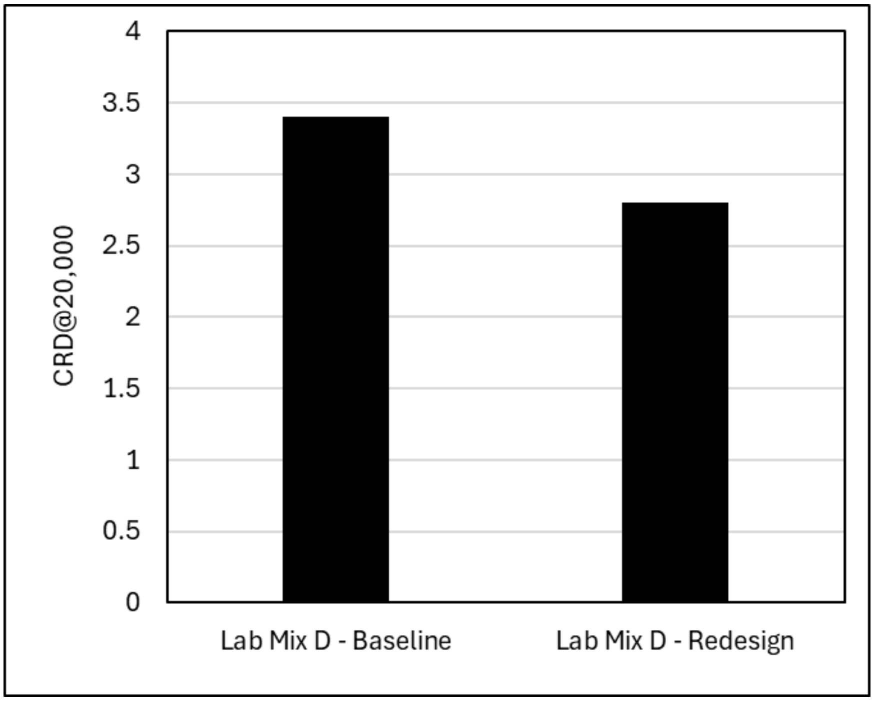

Figure 44. CRD at 20,000 passes for Mixes D

CHAPTER 6. SUMMARY AND RECOMMENDATIONS

The synthesis of the agencies' specifications shows that the N_{des} vary by state. Additionally, it was shown that different states use varying traffic levels to define high traffic. The synthesis also revealed that two out of twenty-six states use a regressed air void design. The synthesis also showed that most of the agencies use the minimum VMA criteria specified in AASHTO M 323 for their mix design. In contrast, some agencies have increased the minimum VMA requirement from that in AASHTO M 323. Iowa and Minnesota DOTs use Asphalt Film Thickness as a mix design criterion. The survey shows that most of the states surveyed have implemented lower gyration levels than those specified in AASHTO R 35. Among all the states included in this study, Michigan and Delaware are the only states that still adopt AASHTO R 35 gyrations.

Eight plant mixes were sampled from different asphalt plants representing different mix types and materials. The volumetrics of the plant mixes, such as G_{mm} and air void at N_{des}, were verified. The performance of the plant mixes was evaluated using the IDEAL-CT and HWTT to determine CT_{index} and CRD, respectively. The binder content of the plant mixes was determined using extraction and recovery. The performance grades of the recovered binder, virgin binder, and RAP binder were determined for all mixes. Based on the performance of the eight plant mixes relative to HT mixes from the WisDOT database, three mixes were considered representative of HT mixes in Wisconsin and selected for further testing.

The three mixes selected for the redesign were recreated in the lab, and the performance of the lab mixes was compared with that of the plant mixes. The performance of the lab mixes was then used as a baseline for the redesign of the three mixes. The redesign involved using different approaches, including adjusting the gradation using the Bailey Method and modifying the binder content to optimize AFT, thereby improving cracking resistance without compromising rutting resistance. The redesigned mixes met the volumetric criteria of the WisDOT specifications for VMA and VFA. Increasing the AFT increased cracking resistance; however, the improvement was limited at a high recycled binder replacement rate.

The research demonstrated that a design with 4.0% air voids at $N_{des} = 75$ gyrations can provide similar or better performance than the control mixes, which were designed at $N_{des} = 100$ and 3.0% regressed air voids. The performance results for the redesigned mix D show that using a reduced gyration level of 75 and 3.0% regressed air voids can provide improved cracking and rutting resistance, which further support the recommendations to lower the N_{des} from 100 to 75 gyrations.

Based on the results of this research, the following recommendations can be made and need to be validated:

- Implementing a new N_{des} value of 75 gyrations for the HT mixes.
- With reduced N_{des}, an aggregate optimizing using tool such as Bailey Method can be used. Care should be taken to ensure the gradations allow for changes that may arise during field production.

- Introduce guidance on binder bumping, especially when recycled binder replacement exceeds 30% to mitigate the reduction in cracking that could result from increased stiffness.
- Using a minimum AFT of 8.0 microns as part of the design approval. This could help improve cracking resistance without compromising rutting resistance that could result from regressing the design to 3.0% air void by using additional asphalt binder.

Based on the research completed in this project, the research team has provided a verified set of criteria but needs to be validated before implementation. Proposed updates to the Wisconsin DOT Special Provision HMA Pavement Balanced Mix Design are provided in Appendix B and should be field validated in actual mix designs and field produced mixes.

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APPENDIX A: SURVEY INSTRUMENT

Survey Questions

This survey is conducted as part of a research project funded by the Wisconsin Highway Research Program (WHRP) on the design of high traffic (HT) mixes. Your participation in this survey would be highly appreciated.

Please provide your answers to the following questions related to the Superpave mix design of HT mixes in your state. Please provide reference to standard specifications or provisional specifications if appropriate.

Name: **State:**

E-mail address: **Phone no.:**

Q1. What is the traffic criterion for HT mixes?

Q2. What are the N_{des}, AV, and VMA requirements for HT mixes?

Q3. Are there any additional volumetric requirements for HT mixes such as VFA, asphalt binder film thickness, etc.?

Q4. Does the specification include a minimum asphalt content for HT mixes? If yes, please specify.

Q5. What are the typical NMAS used with HT surface and leveling course mixes?

Q6. Do aggregate gradations for HT mixes typically fall on the coarse or fine side?

Q7. Are there any special aggregate requirements for HT surface and leveling course mixes?

Q8. How are the aggregate requirements for HT surface and leveling course mixes different from other mixes used in this state?

Q9. Is there any requirement to use polymer-modified binders for HT mixes?

Q10. Are there any concerns regarding the performance and compaction of HT surface or leveling course mixes? If yes, please specify if the DOT is considering implementing any future changes to address those concerns

APPENDIX B: PROPOSED WISCONSIN DOT SPECIAL PROVISION FOR HMA MIXES USING BMD

A Description

Conform to standard specification 450, 460, and STSP 460-050, as applicable, except as modified in this special provision.

This special provision incorporates Balanced Mix Design (BMD) with Percent Within Limits (PWL) into the design and testing of HMA and SMA mixtures. This provision applies to the following bid item(s)**: Enter Bid Item #.**

B Materials

*Append the Maximum Allowable Percent Binder Replacement t***able** *in 460.2.5 with the following:*

RECYCLED ASPHALTIC MATERIAL COMBINATION	LOWER LAYER	UPPER LAYER
RAS	25%	20%
RAP and FRAP	40%	50%
RAS, RAP, and FRAP[1][2]	35%	50%

[1] When used in combination, the RAS component cannot exceed 5 percent of the total weight of the aggregate blend.

[2] The maximum allowable percent binder replacement from RAS, RAP, and FRAP, in combination, in an SMA mixture, is 40 percent.

Append **Table** *460-2 with the following:*

TABLE 460-2 Addendum

Mixture Type	LT	MT	HT	SMA
Hamburg Wheel Track Test (HWTT) (WTM T324) Corrected Rut Depth @ 20,000 Passes (mm) Stripping Number (LC_{SN})	≤ 12.0 ≥ 3,000	≤ 7.5 ≥ 3,000	≤ 5.0 ≥ 3,000	≤ 4.0 ≥ 3,000
Indirect Tensile Cracking Testing at Intermediate Temperature (IDEAL-CT) (WTM D8225) CT-Index	≥ 30	≥ 30	≥ 30	≥ 80
Ideal Rutting Test (IDEAL-RT) (ASTM D8360) RT-Index	Report	Report	Report	Report

Add the following to standard specification 460.2.7:

(2) Proposed additives or alternative materials must be submitted with the mix design submission along with samples of all other mix design materials.

Append **CMM** *Table 866-2 with the following:*

HMA TEST	TEST PROCEDURE
Hamburg Wheel-Track Testing of Compacted Asphalt Mixtures	WTM T324
Indirect Tensile Cracking Test at Intermediate Temperature	WTM D8225
Ideal Rutting Test	ASTM D8360

Modify the following in CMM 866.2.2:

5. Complete a mix design report identifying materials used and summarizing volumetric and performance properties in meeting required specifications in 866.2.4 with the gyration levels for the HT mixes will be Nini = 7, Ndes = 75, and Nmax = 115. The volumetric calculations shall include the Asphalt Film Thickness as determined by the following table and calculations.

Table XXX Surface Area Factors for Determination of Asphalt Film Thickness

Total Percent Passing Metric Sieve No. (English Sieve No.)	***Maximum Size, mm***	***4.75 mm (No. 4)***	***2.36 mm (No. 8)***	***1.18 mm (No. 16)***	***600 µm (No. 30)***	***300 µm (No. 50)***	***150 µm (No. 100)***	***75 µm (No. 200)***
Surface Area Factor, m2/kg	***0.41***	***0.41***	***0.82***	***1.64***	***2.87***	***6.14***	***12.29***	***32.77***

The Surface Area (SA) is determined by taking the % Passing times the Surface Area Factor for all sieve sizes. The Surface Area for the material above the 4.75 mm (No. 4) sieve is a constant 0.41. The total surface area is determined by adding all of the individual surface area values for each sieve.

The Asphalt Film Thickness (AFT) is determined by the percent of the effective binder contact (P_{be}), dividing by the total surface area and multiply by 10.

AFT = (P_{be}/SA)x10

Add the following in CMM 866.2.4.2:

Mixture Properties (3.0% “Air-Void Regression” asphalt binder content):

- **Hamburg Wheel-Track Test**
    - **Corrected Rut Depth at 20,000 Passes**
    - **Stripping Number**
- **IDEAL-CT**
    - **CT-Index**
- **IDEAL-RT**
    - **RT-Index**

Modify the following in CMM 866.2.5.1

(1) Mix design summary reports and either individual or batches of blended aggregates (if required or requested), are submitted to BTS before paving, using the comparison level method.

Add the following in CMM 866.2.5.1:

(15) **The department’s performance test results for the Hamburg Wheel-Track Test, IDEAL-CT, and IDEAL-RT will be used for informational purposes only to determine reproducibility tolerances and will not be used to reject mix designs that are less than the values in Table 460-2 as modified in this special provision.**

Append Table 866-4 with the following:

Test	Allowable Difference
Hamburg Wheel-Track Testing of Compacted Asphalt Mixtures	N/A
Indirect Tensile Cracking Test at Intermediate Temperature	N/A
Ideal Rutting Test	N/A

Modify the following to CMM 866.2.5.2:

This process requires submittal of the mix design summary report and blended aggregates representing the mix design job mix formula (JMF). The contractor needs to submit materials to the department a minimum of 10 working days before paving.

- **The contractor must include four 6,800g (15 lb.) batches of the blended aggregate, representing the mix design JMF, (inclusive of any components containing recycled asphaltic materials or stabilizing agents) and either three full 1-quart containers or one full 1-gallon container of design PG binder. Virgin blended aggregate is submitted separately from RAM and both must be dried before sending to BTS. The contractor must also include four 16,000g (approx. 35 lb) batches of unaged, batched HMA material representing the JMF for the department performance testing described herein.**
- **BTS may request individual aggregate/RAM samples for each component and either three full 1-quart containers or one full 1-gallon container of the design PG binder in place of the composite aggregate samples.**

Remove CMM 866.2.5.3.

Modify the following in STSP 460-050 460.2.8.2.1.3.1:

(3) Perform sampling from the truck box according to WTM R97 and four-part splitting of HMA samples according to WTM R47. Sample size must be adequate to run the appropriate required tests in addition to one set of duplicates that may be required for dispute resolution (i.e., retained). This requires sample sizes which yield four splits for all random sampling per sublot. All QC samples shall provide the following: QC, QV, Retained, and Extra. Take possession of the QC and Extra split samples intended for QC testing. The department will observe and take possession of the QC and Retained split samples intended for QV testing. Additional sampling details are found in Appendix A. Label samples according to WTM R97.

Additionally, collect additional HMA material along with the standard QC sample to be used for balanced mix design testing. Perform a 2-part split of the material yielding four (4) 16,000g (35lb.) boxes of HMA. Label samples according to WTM R97 with an additional note identifying the samples for performance testing. The performance testing samples may only be used for the performance testing required by this special provision.

(4) Test the QC split sample using the test methods identified below at a frequency greater than or equal to that indicated. The Extra split sample shall be tested only when the Gmm and/or Gmb replicate tolerances are exceeded according to WTM T166 section 13.1.4 and WTM T209 section 14.1.1. When testing the Extra split sample, only the results from the test which the tolerances were exceeded may replace the results from the QC split sample. The Rule of Retained according to CMM 836.1.2 applies.

- Blended aggregate gradations according to WTM T30.
- Asphalt content (AC) in percent.
  - Determine AC using one of the following methods:
    - AC by ignition oven according to WTM T308. If the department is using an ignition oven to determine AC, conform to WTP H-003. If the department is not using an ignition oven to determine AC, IOCFs must still be reverified for any of the reasons listed in WTP H-003 Table 2 and conform to WTP H-003 section 3.
    - AC by chemical extraction according to AASHTO T 164 Method A or B.
    - AC by automated extraction according to WTM D8159.
- The Design Asphalt Thickness shall be 8.0 or more.
- Bulk specific gravity (Gmb) of the compacted mixture according to WTM T166.
- Maximum specific gravity (Gmm) according to WTM T209.

- Air Voids (Va) by calculation according to WTM T269.
- Voids in Mineral Aggregate (VMA) by calculation according to WTM R35 section 9.2.

Test the split samples for balanced mix design using the latest BMD Sample Preparation guidance (consult BTS) and the test methods identified below at a frequency greater than or equal to that indicated.

- Indirect Tensile Cracking Testing at Intermediate Temperature according to WTM D8225.
- Ideal Rutting Test according to ASTM D8360.

(5) Lot size shall consist of 3,750 tons with sublots of 750 tons. Test QC samples for each design mixture at a frequency of 1 test per 750 tons of mixture type produced and placed as part of the contract. Test balanced mix design samples at a frequency of 3 tests per 3,750 tons of mixture type produced and placed as part of the contract. Add a random sample for any fraction of 750 tons at the end of production for a specific mixture design. Partial lots with less than three sublot tests will be included into the previous lot for data analysis and pay adjustment. Volumetric lots will include all tonnage of mixture type under specified bid item unless otherwise specified in the plan.

Append the limits in STSP 460-050 460.2.8.2.1.7 with the following:

ITEM	ACTION LIMITS	ACCEPTANCE LIMITS
CT-Index	- 5.0	-
RT-Index	- 5.0	-

Modify the* following *in STSP 460-050 460.2.8.2.1.7:

(3) Notify the engineer if any individual test result falls outside the action limits, investigate the cause and take corrective action to return to within action limits. For individual CT-Index and RT-Index test results outside of the action limits, perform dispute resolution according to 460.2.8.3.1.8 in this special provision. If two consecutive test results, excluding CT-Index and RT-Index, fall outside the action limits, stop production. Production may not resume until approved by the engineer. Additional QV samples may be collected upon resuming production, at the discretion of the engineer.

Modify the* following *in STSP 460-050 460.2.8.3.1.4:

(1) HTCP-certified personnel will obtain QV random samples by directly supervising HTCP-certified contractor personnel sampling from the trucks at the plant. Sample size must be adequate to run the appropriate required tests in addition to one set of duplicate tests that may be required for dispute resolution (i.e., retained). This requires sample sizes which yield four splits for all random sampling per sublot. All QV samples shall furnish the following: QC, QV, Retained, and Extra. The department will observe the splitting and take possession of the QV, Retained, and Extra split samples intended for QV testing. The department will take possession of retained samples accumulated to date each day QV samples are collected. The department will retain samples until surpassing the analysis window of up to 5 lots, as defined in standard spec 460.2.8.3.1.7(2) of this special provision. Additional sampling details are found in Appendix A.

Additionally, the department will collect additional HMA material along with the standard QV sample for balanced mix design testing. From the additional material collected, perform a 2-part split of the material yielding eight 16,000g (35lb.) boxes of HMA. Four of the boxes shall be designated as the QC Performance sample and four boxes shall be designated as the QV Performance sample.

The department will perform testing conforming to the following standards:

- Bulk specific gravity (Gmb) of the compacted mixture according to WTM T166.
- Maximum specific gravity (Gmm) according to WTM T209.
- Air voids (Va) by calculation according to WTM T269.
- VMA by calculation according to WTM R35.

- Asphalt content by ignition oven according to WTM T308, chemical extraction according to AASHTO T164 method A or B, or automated extraction according to WTM D8159.

The department will test the split samples for balanced mix design using the latest BMD Sample Preparation guidance and the test methods identified below:

- Indirect Tensile Cracking Testing at Intermediate Temperature according to WTM D8225.
- Ideal Rutting Test according to ASTM D8360.

Add section 460.2.8.3.1.8 Data Analysis for Balanced Mix Design to STSP 460-050 with the following:

(1) The engineer, upon completion of the first 3 lots, will compare the variances (F-test) and the means (t-test) of the QV test results with the QC test results for IDEAL-CT and IDEAL-RT. Additional comparisons incorporating the first 3 lots of data will be performed following completion of the 4th and 5th lots (i.e., lots 1-3, 1-4, and 1-5). A rolling window of 5 lots will be used to conduct F & t comparison for the remainder of the contract (i.e., lots 2-6, then lots 3-7, etc.), reporting comparison results for each individual lot. Analysis will use a set alpha value of 0.025. If the F- and t-tests report comparable data, the QC and QV data sets are determined to be statistically similar and QC data will be used to calculate a PWL value for the CT- and RT-Indices.

(2) If the F- and t-tests result in non-comparable data or an individual QC or QV performance test result is outside of the action limits, follow the *dispute resolution* steps below:

1. The retained portion of the split from the lot in the analysis window as determined by BTS will be referee tested for IDEAL-CT, and/or IDEAL-RT and HWTT. Referee test results will replace the QV data of the sublot(s).
2. F- and t-tests will be conducted again with the referee test results replacing the QV results.
   a. If the F- and t-tests indicate variances and means compare, no further testing is required for the lot and QC data will be used for PWL calculations.
   b. If the F- and t-tests indicate non-comparable variances or means, the retained portion of the random QC sample will be tested for IDEAL-CT and/or IDEAL-RT by the department's regional lab for the remaining 4 sublots of the lot which the F- and t-tests indicate non-comparable datasets. The department's regional lab and the referee test results will be used for PWL calculations.
3. The contractor may choose to dispute the regional test results on a lot-basis within 7 days after receiving the results from the region. In this event, the retained portion of each sublot will be referee tested by BTS. The referee test results will supersede the regional lab results for the disputed lot.

(3) The department will notify the contractor of the referee test results within 14 working days after receipt of the samples by the department's laboratory.

(4) The department will determine mixture conformance by analyzing referee test results, reviewing mixture data, and inspecting the completed pavement.

C (Vacant)

D (Vacant)

E Payment

(1) **Costs for all sampling, testing, and documentation required under this special provision are incidental to the work.**