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Strategies for Improving the Cracking Resistance of Alabama Mixes

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16. Abstract

This project evaluated practical strategies for improving the cracking resistance of asphalt surface mixtures in Alabama while ensuring adequate resistance to rutting. The study focused on Superpave surface mixtures commonly used by the Alabama Department of Transportation (ALDOT) and examined three types of adjustments: binder content and grade, aggregate gradation and nominal maximum aggregate size, and chemical additives.

Laboratory testing included the IDEAL-CT (i.e., AL-CT, outlined in ALDOT-459) for cracking resistance, as well as high-temperature indirect tensile strength (ALDOT-458) and Hamburg wheel-tracking tests for rutting resistance. The results indicated that decreasing the design air voids to increase the binder content led to incremental improvements in cracking resistance. While using a softer binder enhanced cracking performance, it reduced resistance to rutting. Alternatively, employing a polymer-modified binder improved both cracking and rutting performance, achieving a balanced outcome.

Adjustments in aggregate gradation revealed that coarser gradations significantly enhanced cracking resistance while maintaining acceptable rutting performance. Strong correlations were observed between cracking performance and intermediate sieve sizes. Additionally, chemical additives improved cracking resistance in surface mixtures; however, their effectiveness varied based on the specific mixture.

These strategies can be applied individually or combined to further enhance cracking performance while maintaining a balance in rutting resistance.

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Asphalt Mixture Performance, Cracking, Rutting, IDEAL-CT, H-IDT, HWTT

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List of Acronyms

AASHTO – American Association of State Highway and Transportation Officials
ALDOT – Alabama Department of Transportation
AL-CT – Alabama Cracking Test
ANOVA – Analysis of Variance
ASTM – ASTM International (formerly American Society for Testing and Materials)
Bailey Method – Aggregate packing method for gradation analysis
BHF – Baghouse Fines
BMD – Balanced Mix Design
BPN – British Polishing Number
CA – Coarse Aggregate Ratio (Bailey Method)
CT_{Index} – Cracking Tolerance Index
Ctrl – Control Mixture
COV – Coefficient of Variation
DCT – Disk-Shaped Compact Tension Test
D/P – Dust-to-Binder Ratio
ESAL – Equivalent Single Axle Load
FAc – Coarse Portion of Fine Aggregate Ratio (Bailey Method)
FAf – Fine Portion of Fine Aggregate Ratio (Bailey Method)
FAA – Fine Aggregate Angularity
FDOT – Florida Department of Transportation
FHWA – Federal Highway Administration
FI – Flexibility Index
Gf – Failure Energy
H-IDT – High-Temperature Indirect Tensile Test
HMA – Hot Mix Asphalt
HT-IDT – High-Temperature Indirect Tensile Test
HT-ITS – High-Temperature Indirect Tensile Strength
HWTT – Hamburg Wheel-Tracking Test
IDT – Indirect Tensile Test
IDEAL-CT – Indirect Tensile Asphalt Cracking Test
I-FIT – Illinois Flexibility Index Test
JMF – Job Mix Formula
LMLC – Laboratory-Mixed Laboratory-Compacted
LTA – Long-Term Aging
NMAS – Nominal Maximum Aggregate Size
NAPA – National Asphalt Pavement Association
NCAT – National Center for Asphalt Technology
PCS – Primary Control Sieve
PG – Performance Grade
P_8 – Percent Passing No. 8 Sieve
RAP – Reclaimed Asphalt Pavement
RAS – Recycled Asphalt Shingles

RAV – Regressed Air Voids
RBR – Reclaimed Binder Ratio
SCB – Semi-Circular Bend Test
SBS – Styrene-Butadiene-Styrene
SCS – Secondary Control Sieve
SGC – Superpave Gyratory Compactor
STA – Short-Term Aging
Superpave – Superior Performing Asphalt Pavements
TCS – Tertiary Control Sieve
TSRST – Thermal Stress Restrained Specimen Test
Va – Air Voids
VBE – Voids Filled with Binder Effective
VFA – Voids Filled with Asphalt
VMA – Voids in Mineral Aggregate
WMA – Warm Mix Asphalt

1. INTRODUCTION

1.1 Transition from Volumetric to Balanced Mix Design

Asphalt pavements are used in most roadways within the United States transportation network, and state departments of transportation invest significant resources each year to maintain this infrastructure. The long-term performance of these pavements depends on their resistance to two types of distress: rutting and cracking. Rutting occurs as a progressive accumulation of permanent deformation in pavement layers under repeated traffic loading (Tayfur et al., 2007). Aggregate structure—through internal friction, shape, angularity, and gradation—provides the skeleton to rutting resistance, while the asphalt binder adds cohesion and stiffness to resist deformation (Asphalt, Institute 2014). Cracking, which encompasses both top-down and bottom-up fatigue cracking, as well as thermal cracking, arises from complex interactions among aggregate structure, binder properties, traffic loading, environmental conditions, and binder aging (Tangella et al., 1990).

The Superpave mix design system, implemented in the 1990s, introduced improvements to binder specifications and compaction protocols. However, the Superpave mix design method relies almost entirely on volumetric properties—air voids, voids in mineral aggregate, and voids filled with asphalt—as surrogates for performance (Kandhal et al., 1998). This volumetric approach does not directly measure how mixture components interact to influence cracking and rutting resistance. Consequently, some mixtures that satisfy volumetric criteria still exhibit inconsistent performance, particularly when incorporating recycled materials (Cooper III et al., 2014). Agencies have reported that the Superpave volumetric mix design often produces mixtures with increased stiffness, thereby reducing the occurrence of rutting. However, this design often has insufficient binder content, leading to issues such as premature cracking and raveling (Tran et al., 2022). These issues are not adequately addressed within the volumetric mix design system (Yin & West, 2021).

Due to the limitations, state agencies have considered adopting Balanced Mix Design (BMD), an approach that directly measures both rutting and cracking resistance during the design process (West et al., 2018). BMD evaluates multiple performance characteristics simultaneously, rather than relying solely on volumetric properties. The Federal Highway Administration (FHWA) has established a framework for BMD implementation that incorporates performance testing at the mix design stage, allowing engineers to optimize mixtures for both high-temperature rutting resistance and cracking resistance at intermediate and/or low temperatures (FHWA, 2022). This approach has been formalized in AASHTO R 132, which provides standardized procedures for BMD (AASHTO, 2025).

1.2 Incorporating BMD Elements into Practice

Like other state departments of transportation, the Alabama Department of Transportation (ALDOT) has begun incorporating elements of BMD into its practices. ALDOT first incorporated performance testing by requiring the Hamburg Wheel Tracking Test (HWTT) for stone matrix asphalt and dense-graded mixtures subjected to high traffic with 10 million or more equivalent single axle loads (ESALs). ALDOT has adopted the Indirect Tensile Asphalt Cracking Test (IDEAL-

CT), also known as the AL-CT test, as outlined in ALDOT-459 (ALDOT, 2022b) and the High-Temperature Indirect Tensile (HT-IDT) test, described in ALDOT-458 (ALDOT, 2022a). These tests were initially used for benchmarking and evaluation rather than acceptance, allowing ALDOT to assess variability, aging effects, and sensitivity using Alabama materials and production practices.

Additionally, ALDOT developed project-specific BMD special provisions to support implementation. These provisions enable the design of mixtures directly to performance thresholds for cracking and rutting resistance, while selectively relaxing volumetric limits. This shift places design emphasis on mechanical performance while maintaining constructability and quality control. Performance thresholds for IDEAL-CT and HT-IDT in these provisions were established using a large database of Alabama-approved mix designs and refined through collaboration among ALDOT, industry representatives, and NCAT researchers. Thresholds were categorized into performance levels to support validation and the development of future specifications (Tran et al., 2023).

A more recent implementation milestone was a full-scale field validation project on State Route 55 in Covington County. Six asphalt mixtures were designed to meet distinct combinations of cracking and rutting performance targets and constructed as adjacent test sections under uniform conditions. This layout allowed for a direct comparison between performance indicators in the laboratory and those in the field. After one year of service, no cracking was observed, and rutting trends aligned closely with HT-IDT results. Strong laboratory–field correlations confirmed that HT-IDT is an effective indicator of early rutting resistance, while volumetric properties showed limited predictive value. Ongoing field monitoring will be used to validate cracking thresholds and refine specifications before wider implementation. This measured approach allows ALDOT to modernize mixture design practice while maintaining confidence in long-term pavement performance (Sadeghi et al., 2025).

Following the abovementioned implementation efforts, the next step is to gain a better understanding of how the material components affect the mix resistance to cracking and rutting. This understanding will allow engineers to make informed adjustments during the optimization of the mixture. Instead of relying on trial-and-error testing of numerous candidate mixtures, designers can focus their modifications on the components most likely to enhance cracking resistance while maintaining adequate rutting performance.

2. PROJECT OBJECTIVES AND SCOPE

The present study is designed specifically to address the need for improving cracking resistance by identifying mixture characteristics that contribute to cracking susceptibility and proposing adjustments that could enhance performance across Alabama mixtures. This study aims to:

- Determine which mixture components affect the cracking resistance of Alabama asphalt mixtures, and
- Propose mixture adjustments and additive technologies that could improve cracking performance statewide.

The scope of mixture adjustments evaluated in this study includes: (1) binder-related parameters, such as increasing binder content through the Regressed Air Voids (RAV) approach and adjusting binder grade; (2) aggregate gradation changes, assessed through six systematically designed fine- and coarse-graded alternatives; and (3) the use of performance-enhancing additives, specifically two chemical warm mix asphalt (WMA) additives and two recycling agents.

3. LITERATURE REVIEW

The successful implementation of a balanced mix design requires an understanding of how individual mixture components influence cracking and rutting resistance. While the general principles governing these relationships are established, the specific effects depend on material properties, environmental conditions, and the interactions among components. This literature review synthesizes research on the effects of binder properties, aggregate gradation, chemical WMA additives, and recycling agents on the performance of asphalt mixtures. The review identifies critical knowledge gaps that motivate the present investigation and establishes the technical foundation for evaluating mixture adjustments in Alabama materials.

3.1 Binder Content, Binder Grade, and Polymer Modification

Binder properties represent the most influential mixture variables affecting both cracking and rutting resistance. The amount of binder, its grade, and whether it contains polymer modification collectively determine how mixtures respond to traffic loading and environmental stresses. Understanding these effects provides essential context for optimizing mixture performance through BMD.

3.1.1 Binder Content Effects

Research demonstrates that binder content critically affects the balance between cracking and rutting resistance. Mixtures with insufficient binder—often characterized as "dry" or brittle—exhibit poor cracking resistance across multiple testing protocols. Studies using the Semi-Circular Bend (SCB) test, Disk-Shaped Compact Tension (DCT) test, Illinois Flexibility Index Test (I-FIT), and related methods have documented that increasing binder content improves intermediate-temperature and low-temperature cracking performance (Bennert & Davis, 2019; Dave et al., 2019; Ghafari & Nejad, 2021; Ling et al., 2023; Mivehchi et al., 2022). Higher binder content enhances stress relaxation capacity, increases flexibility, and provides greater resistance to crack initiation and propagation.

However, this improvement in cracking resistance could potentially influence rutting resistance. The same studies report that higher binder content tends to reduce rutting resistance in wheel-tracking tests such as the Hamburg Wheel-Track Test (HWTT) (Ling et al., 2023; Mivehchi et al., 2022). Excess binder reduces the stiffness of the mixture, allowing for greater accumulation of permanent deformation under repeated loading. These competing effects illustrate why it can be challenging to optimize mixture performance solely through volumetric design—achieving the optimal binder content requires measuring both performance characteristics directly.

The magnitude of these effects depends on the specific range of binder content evaluated. Small increases in binder content can improve cracking resistance without creating unacceptable rutting susceptibility, particularly when combined with the selection of an appropriate binder grade or optimization of the aggregate structure. Identifying the optimal binder content, therefore, requires systematic evaluation using performance tests rather than reliance on volumetric properties alone.

3.1.2 Binder Grade Selection

Binder grade selection provides another mechanism for balancing cracking and rutting resistance. Stiffer unmodified binders—those with higher high-temperature performance grades—increase mixture modulus and generally improve rutting resistance. Studies measuring dynamic modulus and Flow Number have documented these benefits (Abdulmajeed & Muniandy, 2017; Junaid et al., 2018; Li et al., 2008). The increased stiffness at high temperatures reduces the accumulation of permanent deformation under traffic loading.

Conversely, softer binders are typically adopted to enhance intermediate-temperature and low-temperature cracking performance, particularly in mixtures containing significant amounts of recycled asphalt pavement (RAP). The aged binder in RAP increases overall mixture stiffness, and using a softer virgin binder helps provide adequate flexibility. Agencies may specify binders one grade softer than normal when incorporating high RAP contents to counteract the stiffening effect and improve cracking resistance. However, some research has reported that stiffer unmodified binders can achieve acceptable or even improved fatigue life when overall mixture design is properly optimized (Bennert & Davis, 2019; Junaid et al., 2018; Li et al., 2008; Mivehchi et al., 2022). These findings suggest that the relationship between binder grade and cracking performance is more complex than simple softening strategies might suggest. The aggregate structure, binder content, and other factors interact with the binder grade to determine the performance. This complexity reinforces the need for mixture performance testing rather than prescriptive binder grade selection.

3.1.3 Binder Modification

Polymer modification, particularly with Styrene-Butadiene-Styrene (SBS), has been widely adopted to improve both rutting and cracking performance. SBS-modified binders exhibit increased high-temperature stiffness, enhanced elastic recovery, and improved Flow Number values, resulting in reduced rutting potential and extended service life in both laboratory and field evaluations (Behnood et al., 2016; Kök & Çolak, 2011; Tayfur et al., 2007; Veeraragavan, 2011; Von Quintus et al., 2007). The elastic properties of SBS allow binders to recover from deformation rather than accumulating permanent strain.

Simultaneously, SBS modification tends to increase fracture energy, improve fatigue life, and enhance resistance to thermal cracking (Ho & Zanzotto, 2005; Kim et al., 2003; Kök & Çolak, 2011; Lundström & Isacsson, 2004). These improvements occur because polymer modification maintains flexibility at lower temperatures while providing adequate stiffness at high temperatures. These dual benefits make polymer-modified binders particularly attractive for BMD applications where both cracking and rutting resistance must be optimized.

However, recent research has identified a concerning measurement issue. Common intermediate-temperature cracking indices, such as the CT_{Index} from IDEAL-CT or the Flexibility Index (FI) from I-FIT, sometimes appear insensitive to the benefits of polymer modification. Several studies have reported that SBS-modified mixtures show similar or even lower index values compared to unmodified mixtures, despite demonstrating clear improvements in fatigue behavior and fracture properties measured through other protocols (Pei et al., 2025; Yin et al., 2025). This discrepancy raises important questions about which performance tests best capture the actual cracking resistance benefits of different mixture components. These findings have significant implications for the implementation of BMD. If commonly used cracking tests do not adequately reflect the benefits of certain mixture components, agencies may make suboptimal decisions during mixture optimization. This concern highlights the importance of validating laboratory test results against field performance.

3.2 Effect of Aggregate Gradation

Aggregate gradation has a significant influence on the internal particle structure, mixture stiffness, and resistance to both rutting and cracking. Unlike binder properties, which can be relatively easily adjusted through specification changes, gradation effects are more complex because they depend on aggregate source characteristics, particle shape and angularity, and how particles pack together to form the mixture skeleton. Understanding these effects is crucial for assessing whether gradation adjustments can enhance the performance of Alabama mixtures.

Early Superpave guidance favored coarse gradations based on stone-on-stone contact concepts, which emphasized aggregate interlock and load distribution through a strong aggregate skeleton (Kandhal & Cooley Jr, 2002). This approach assumed that maximizing contact between larger particles would provide superior rutting resistance by creating a more stable structure. However, later field validation programs demonstrated that actual performance often differed from predicted behavior.

The WesTrack experiment, the National Center for Asphalt Technology (NCAT) Test Track, and the Florida Department of Transportation (FDOT) accelerated pavement testing program provided critical field performance data across various mixture designs. These studies have shown that fine-graded Superpave mixtures often exhibit better rutting performance than their coarse-graded counterparts (Choubane et al., 2006; Epps, 2002; Kandhal & Cooley Jr, 2002). The field evidence prompted researchers to reevaluate the role of gradation in mixture performance and to examine the mechanisms by which fine and coarse gradations influence both rutting and cracking.

3.2.1 Effect of Fine Gradations

Research has reported that finer gradations can provide better rutting resistance and, in many cases, similar or improved cracking performance. Fine-graded mixtures have been associated with lower rut depths, higher Flow Number values, reduced permanent strains, and improved Marshall stability and resilient modulus (Buttlar et al., 2015; Ghuzlan et al., 2020; Golalipour et al., 2012; Kim et al., 2009). These benefits likely result from the denser particle packing that fine gradations create, which increases interparticle contact and distributes loads more effectively throughout the mixture.

Fine gradations also offer practical production advantages. Mixtures with more material passing through intermediate sieves can facilitate greater use of natural sand, which may be more readily available and less expensive than manufactured fine aggregate in some regions. Fine gradations can also improve mixture workability and compactability when properly controlled, potentially reducing construction-related variability (Alsheyab & Khasawneh, 2024).

However, the cracking performance of fine gradations appears more variable. Some studies have reported that fine gradations maintain adequate cracking resistance (Kasu et al., 2019; Lv et al., 2020; Thushara & Krishnan, 2025), while others have documented reduced fatigue life or increased cracking susceptibility compared to coarser alternatives (Ma et al., 2016; Valdés-Vidal et al., 2015). These conflicting results suggest that gradation effects on cracking depend on other factors such as binder content, binder grade, and air void content (Sreedhar & Coleri, 2018; Thushara & Krishnan, 2025)—reinforcing the need to evaluate gradation adjustments within the context of complete mixture designs rather than in isolation.

3.2.2 Effect of Coarse Gradations

Other research has documented advantages for coarse-graded mixtures under certain conditions. Coarse gradations have resulted in lower rut depths in HWTT across various air void levels and temperatures in some studies (Larrain & Tarefder, 2016; Pan et al., 2023). Mixtures with coarser aggregate structures have also shown improved resistance to moisture damage and enhanced fatigue life, particularly when evaluated through four-point bending beam tests (Alsheyab & Khasawneh, 2024; Hasan et al., 2019).

Overall, the literature suggests that gradation influences cracking and rutting in ways not fully explained by conventional volumetrics. Finer gradations often improve rutting and sometimes cracking, while coarser gradations can provide fatigue and structural benefits. The findings underscore the need for controlled studies where gradation, binder content, and binder grade are varied systematically rather than independently.

3.3 Effect of Chemical Warm-Mix Asphalt Additives

Chemical WMA additives—typically surfactants or organic compounds—enable the production of asphalt mixtures at reduced temperatures by improving workability and aggregate coating (Cheraghian et al., 2020; Sukhija et al., 2022). Their use has grown rapidly and now accounts for most of the WMA production in recent U.S. surveys (Williams et al., 2024).

Most studies report similar or slightly better fatigue resistance for chemical WMA compared to conventional HMA in flexural beam fatigue and repeated-load indirect tensile tests (Ahmed et al., 2013; Diefenderfer & Hearon, 2008; Fakhri et al., 2013; Norouzi et al., 2021; Silva et al., 2010). The magnitude and direction of change appear sensitive to strain level, mixture characteristics, and testing protocols. Low-temperature cracking performance generally compares favorably between chemical WMA and HMA. Studies using the Indirect Tensile Test (IDT) and the Thermal Stress Restrained Specimen Test (TSRST) protocols have reported similar resistance between the two mixtures (Das et al., 2012; Yoo et al., 2011).

The primary performance difference between chemical WMA and HMA is in rutting resistance. Lower production temperatures reduce binder oxidative aging, resulting in a softer binder that is susceptible to permanent deformation at elevated service temperatures. Studies using wheel-tracking tests report higher rut depths for chemical WMA compared to conventional HMA (Fakhri et al., 2013; Jamshidi et al., 2013; Malladi et al., 2015; Moghadas Nejad et al., 2014; Zhao et al., 2012). These differences become more evident when production temperatures decrease significantly or when mixtures already exhibit marginal rutting resistance.

Chemical WMA performance characteristics create both opportunities and challenges for BMD implementation. While reduced aging during production may help maintain binder flexibility—particularly valuable for mixtures containing recycled materials—the tendency toward reduced rutting resistance may require adjustments.

3.4 Effect of Recycling Agents

Recycling agents are often used in mixtures with RAP and RAS to restore the properties of aged binder by replenishing lost maltenes and aromatics (Sabaei et al., 2025). At the binder level, these agents help to reduce stiffness and increase ductility. At the mixture level, studies report notable improvements in cracking and fatigue performance, although the effects on rutting can vary.

Bio-based and organic recycling agents such as waste vegetable oils, bio-oils, tall oils, and paraffinic oils generally increase fatigue life and improve low-temperature cracking resistance in high-RAP mixtures, as demonstrated in flexural beam fatigue, overlay tests, and SCB-type fracture evaluations (Espinoza-Luque et al., 2018; Mogawer et al., 2013; Pan et al., 2018; Podolsky et al., 2020; Pradhan, 2023; Shen et al., 2007; Zaumanis et al., 2014; Zhang et al., 2019).

Rutting behavior is highly influenced by the chemistry and dosage of the recycling agent. Studies on binders have shown a reduction in $G^*/\sin\delta$ and an increase in non-recoverable creep compliance after rejuvenation, indicating a softer binder and a potential increase in rutting (Chen et al., 2014; Elkashef et al., 2018; Ji et al., 2017; Pradhan, 2023; Shen et al., 2007). Research involving wheel-tracking tests often indicates greater rut depths for rejuvenated mixtures, especially with high dosages (Espinoza-Luque et al., 2018; Shen et al., 2007; Zaumanis et al., 2014). Overall, recycling agents effectively reduce cracking in mixtures rich in RAP, but it is crucial to carefully optimize their type and dosage to prevent a potential increase in rutting.

3.5 Summary and Knowledge Gaps

Across the reviewed research, several consistent patterns emerge regarding how mixture components affect performance:

- Higher binder contents improve cracking resistance but tend to reduce rutting resistance.
- Selecting a softer binder grade can improve cracking resistance but may increase rutting susceptibility.
- Polymer-modified binders can improve resistance to both cracking and rutting, although certain cracking indices, such as the CT_{Index}, may not fully reflect these advantages.
- Aggregate gradation significantly affects cracking and rutting resistance; fine and coarse gradations have advantages under varying conditions, which volumetric parameters alone do not fully capture.
- Chemical WMA additives can improve cracking resistance but often decrease rutting resistance due to reduced aging.
- Recycling agents improve cracking resistance in recycled mixtures, but they may decrease resistance to rutting.

Despite the extensive information available, significant gaps hinder the practical application of research findings for mixture optimization.

- Limited integrated studies that examine the impacts of binder content/grade, aggregate gradation, chemical WMA additives, and recycling agents under consistent materials and test methods.
- No guidance on which combinations and magnitudes of adjustments can significantly improve cracking resistance for typical Alabama surface mixtures without causing unacceptable rutting.

The experimental program in this project aims to evaluate mixture components and additives systematically, using a controlled set of Alabama materials. The goal is to identify practical adjustment strategies that enhance cracking resistance while maintaining satisfactory rutting performance.

4. METHODOLOGY

4.1. Materials and Control Mixture

4.1.1. Aggregate Sources and Properties

All asphalt mixtures tested in this study were prepared using a blend of reclaimed asphalt pavement (RAP), baghouse fines (BHF), and virgin aggregates from four stockpiles. RAP content was fixed at 20% and BHF at 1% across all mixtures to maintain consistency in recycled materials and isolate the effects from other mixture variables. Virgin aggregates included #89LS limestone, Shot gravel, Coarse Sand, and #8910G gravel, each contributing distinct physical and packing characteristics to the blended gradations.

Table 1 presents key properties of the virgin aggregates. Some of these properties were measured in the laboratory, while others were obtained from ALDOT's Materials Sources and Devices with Special Acceptance Requirements (MSDSAR) list and Materials data sheets (ALDOT, 2023). Loose and rodded unit weights were determined in accordance with AASHTO T19 (AASHTO, 2024b) using a 2.8-liter (1/10 ft^3) measure bucket. Bulk specific gravity (G_{sb}) and water absorption were measured per AASHTO T85 (AASHTO, 2022b) for coarse aggregates and AASHTO T84 (AASHTO, 2022a) for fine aggregates. These values were then used to calculate void contents under both loose and rodded conditions following AASHTO T19 procedures (AASHTO, 2024b). Fine Aggregate Angularity (FAA) was assessed according to AASHTO T304 (AASHTO, 2022c) and reported as uncompacted void content. Among the aggregates, Shot gravel had the highest loose unit weight and absorption, but the lowest G_{sb} and void content, suggesting a packed structure with limited angularity. Water absorption was below 1% for all the virgin aggregates, indicating minimal absorption in the blended mixtures. The #8910G aggregate exhibited a relatively high L.A. abrasion value and the largest difference between loose and rodded voids, potentially having greater susceptibility to degradation.

Table 1 Virgin Aggregate Properties

Properties	#89LS	Shot	Coarse Sand	#8910G
Loose Unit Weight (gr/cm^3)	1.534	1.620	1.550	1.613
Rodded Unit Weight (gr/cm^3)	1.666	1.713	1.687	1.880
Voids at Loose Unit Weight (%)	43.7	37.4	39.5	40.6
Voids at Rodded Unit Weight (%)	38.9	33.8	34.1	30.7
Bulk Specific Gravity	2.727	2.586	2.562	2.715
Absorption (%)	0.6	1.0	0.6	0.6
Uncompacted Void of Fine Aggregate (%)	N/A	N/A	46.781	45.646
Percent Flat and Elongated[1] (3:1 / 5:1)	2.2 / 0.5	N/A	N/A	3.3 / 0.6
L.A. Abrasion[1] (%)	19	N/A	N/A	35.9
Micro Deval[1]	8	N/A	N/A	Na
British Polishing Number[1] (BPN)	27	N/A	N/A	Na
Sodium Sulfate Soundness[1] (% Sound)	99.7	N/A	N/A	99.9
Total Silica Content[1] (%)	1.8	N/A	N/A	N/A

[1] From ALDOT's Approved Sources and Materials list for the sampling period (ALDOT, 2023).

Table 2 presents percent passing for individual virgin and reclaimed aggregate stockpiles (Dry gradation). Among the virgin aggregates, Shot gravel and #8910G exhibited finer gradations, whereas Coarse Sand and #89LS showed coarser gradations with material concentrated in larger size fractions. The #8910G stockpile contributed the greatest portion of dust (percent passing the No. 200 sieve, P200) and thus served as the primary source of P200 in the overall blended gradations.

Table 2 Percent Passing for Aggregate Sources

Sieve	Percent Passing				
	#89LS	Shot	Coarse Sand	#8910G	RAP
1/2"	100.0	100.0	100.0	100.0	100.0
3/8"	99.0	100.0	100.0	100.0	94.0
#4	42.0	96.0	96.0	65.0	73.0
#8	7.0	75.0	86.0	33.0	59.0
#16	3.0	55.0	73.0	18.0	45.0
#30	2.0	42.0	51.0	5.0	33.0
#50	1.7	31.0	12.0	1.0	18.0
#100	1.2	20.0	4.0	0.8	11.0
#200	0.8	13.4	1.0	0.2	6.3

4.1.2. Control Mixture Design and Performance

The control mixture used in this study was an ALDOT-approved 9.5-mm NMAS Superpave surface mix design, compacted to 65 gyrations in the Superpave Gyratory Compactor (SGC) and targeting 4.0% design air voids. The mixture utilized an unmodified PG 67-22 asphalt binder, which represents the binder performance grade commonly used in Alabama (ALDOT, 2022c), with an optimum binder content of 5.6%. To enhance moisture resistance, a liquid anti-stripping agent was incorporated at a dosage of 0.5% by weight of the virgin binder. The RAP binder content, measured using the ignition oven method without correction factors, was 4.07%, corresponding to a Reclaimed Binder Ratio (RBR) of 14.5%. The aggregate structure of the control mixture, referred to as “Fine 3”, is shown in Figure 1.

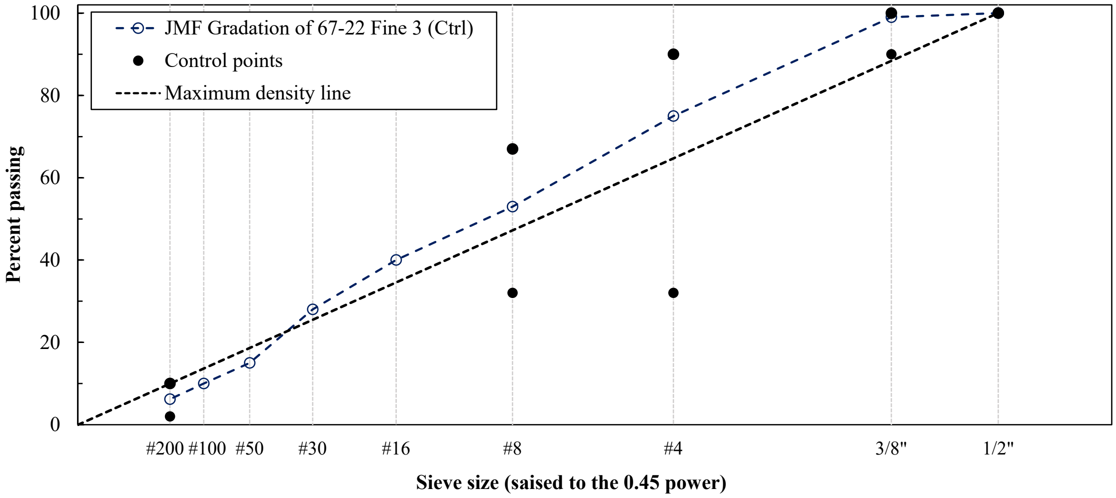


Figure 1. Control mixture gradation

Table 3 summarizes the volumetric and performance properties of the control mixture. The volumetric requirements and maximum allowable HWTT rut depth are based on ALDOT’s Standard Specifications (ALDOT, 2022c). According to results from the Alabama BMD benchmarking study (Tran et al., 2023), the control mixture performed below the statewide average mix design validation data in both cracking and rutting resistance.

Recent ALDOT BMD special provisions established minimum thresholds of $CT_{Index} \geq 50$ and *HT-ITS* ≥ 17 psi (NAPA, 2024), while an earlier (2020) special provision specified traffic-level-dependent CT_{Index} requirements of 55, 83, and 110 for low-, medium-, and high-traffic mixtures, respectively, along with a minimum *HT-ITS* value of 20 psi. Moreover, ALDOT specifies a maximum 10 mm rut depth for Superpave mix designs (ALDOT, 2022c). Given all the requirements, this study set a target CT_{Index} of 55.0, a minimum HT-ITS value of 20.0, and a maximum allowable HWTT rut depth of 10.0 mm. Based on these criteria, the control mixture meets the rutting resistance requirements but fails the cracking threshold. This outcome underscores the need for enhanced cracking resistance as the primary focus of the BMD framework evaluated in this study.

Table 3. Volumetric and Performance Properties of the Control Mixture

Property	Average Value	Target or Limit
Volumetric Properties (N_{des} = 65)		
Air Voids (%)	4.0	4.0
VMA (%)	16.5	Min 15.5
Dust-to-Binder Ratio (D/P)	1.16	0.6 – 1.4
Performance Properties (V_a = 7%)		
CT_{Index}	40.8	55.0
HWTT Rut Depth (mm)	5.4	Max 10.0
HT-ITS (psi)	24.4	20.0

4.2. Experimental Plan

This study conducted an experimental program to evaluate how adjustments to mixture components and the addition of performance-enhancing additives affect the cracking and rutting resistance of representative asphalt mixtures from Alabama. The study followed a two-experiment approach designed to identify practical strategies for improving cracking resistance while maintaining adequate rutting performance.

Experiment 1: Mixture Component Adjustment. This experiment evaluated changes to the binder component in the mixtures, including binder content using the regressed air void method, performance grade, and polymer modification, as well as changes to aggregate characteristics, such as aggregate gradation and nominal maximum aggregate size. For each adjustment, an asphalt mixture was prepared in the laboratory and assessed using three performance tests: the IDEAL-CT (AL-CT) for cracking resistance, the HT-IDT for rutting resistance, and the HWTT for evaluating combined rutting and moisture damage.

Experiment 2: Use of Additives. In this experiment, specific combinations of component adjustments were evaluated using two recycling agents and two chemical WMA additives to determine if they could provide additional improvements in cracking beyond those achieved through component adjustments alone.

Figure 2 illustrates the experimental plan for this study, with further details provided in the subsequent sections.

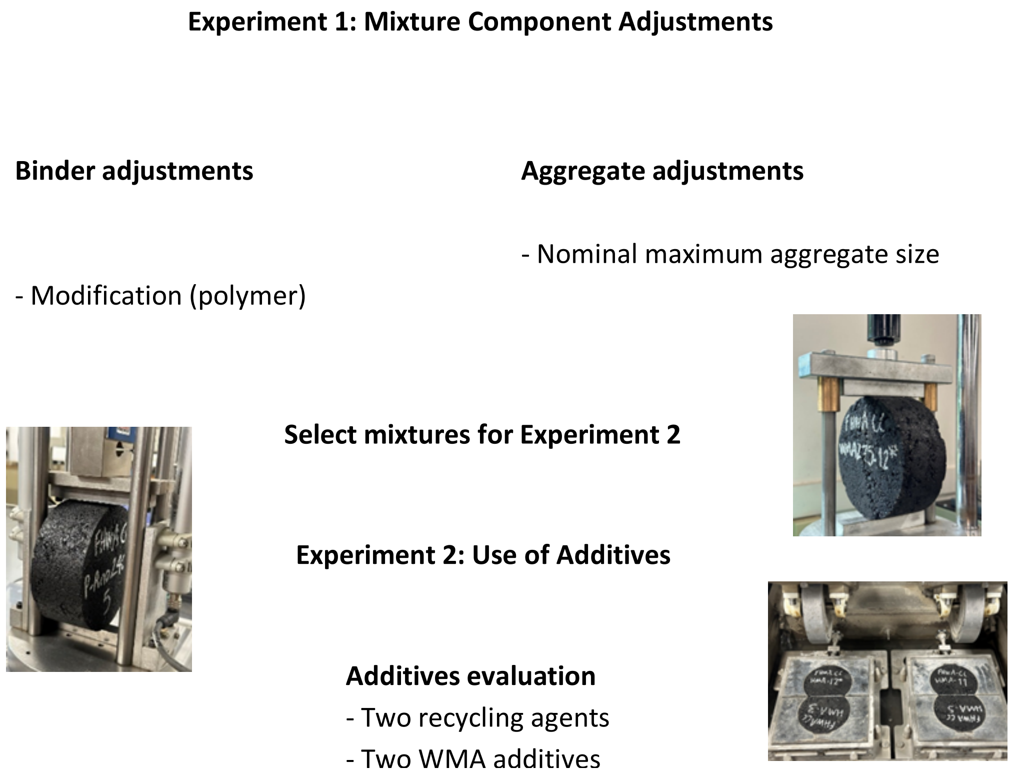


Figure 2. Experimental Plan

4.2.1. *Mix Component Adjustment*

Four approaches were employed to adjust the mixture components while maintaining consistency in the overall material composition, as follows.

- **Regressed air voids**: In this approach, the target design air voids of the control mixture were reduced by increasing the asphalt binder content while keeping the design gyrations and aggregate gradation constant. This adjustment directly reflects the effect of increasing binder content without altering other mix design parameters. In this study, the design air voids were reduced from 4.0% to 3.0%, corresponding to a 0.3% increase in total binder content relative to the control mixture.
- **Binder grade adjustment**: The unmodified PG 67-22 binder was replaced with either a softer unmodified binder (PG 58-22) or a polymer-modified binder (PG 76-22) to evaluate the impact of binder stiffness and modification on the cracking and rutting resistance.
- **Aggregate gradation adjustment**: Six alternative aggregate blends were developed by systematically varying the proportions of virgin aggregate while maintaining a constant nominal maximum aggregate size (NMAS = 9.5 mm), RAP content, and total binder

content. These gradations ranged from fine-graded to coarse-graded, allowing assessment of how particle size distribution influences performance.

- **NMAS adjustment**: A fine-graded blend was developed by replacing the virgin #89LS aggregate fraction with an equivalent proportion of the coarser #78LS fraction from the same source. This modification changed the NMAS from 9.5 mm to 12.5 mm, while maintaining the same RAP content and total binder content; however, the design air voids decreased to 2.8% due to altered packing characteristics.

4.2.2. Use of Additives

Two types of additives representing distinct performance modification mechanisms were evaluated:

- **Recycling agents (R1 and R2)**: Bio-based additives designed to restore aged binder functionality and improve mixture flexibility, particularly beneficial for mixtures containing recycled materials.
- **Chemical WMA additives (WMA1 and WMA2)**: Chemical additives that reduce production temperatures and aging levels, potentially affecting both cracking and rutting resistance.

The dosages of these additives were selected based on manufacturer recommendations and confirmed through laboratory evaluations. The details are summarized in Table 4. Also, to explore potential synergistic effects, selected combinations of component adjustments and additives (e.g., binder grade modification combined with gradation changes or use of additives) were evaluated.

Table 4. Additive Dosages

Additive	Dosage (by weight of virgin binder)
Recycling agent 1 (R1)	2.6
Recycling agent 2 (R2)	
WMA additive 1 (W1)	0.5
WMA additive 2 (W2)	

4.3. Mixture Identification and Coding Scheme

Each mixture evaluated in this study was assigned a unique identifier based on the following nomenclature. In this format, α represents the binder performance grade (PG) and regressed air void condition (if applicable), β denotes the aggregate gradation designation, and γ specifies the additive incorporated ("R" and "W" denote recycling agents and WMA additives).

$$\alpha\,\beta + \gamma$$

Table 5 presents the material components for each naming variable. For example, the control mixture is designated "67-22 Fine3," indicating PG 67-22 binder, Fine3 gradation, and no additives. When all mixtures within an experimental subset share common characteristics (e.g., the same binder grade), redundant variables may be omitted for brevity. For instance, when evaluating gradation effects using a fixed PG 67-22 binder, mixtures are referred to simply as

"Fine3," "Fine4," etc. Throughout this report, the control mixture is frequently abbreviated as "Ctrl" for conciseness.

Table 5. Acceptable Inputs for Naming Variables

Naming Variable	Material Components
α	"58-22", "67-22", "76-22", "67-22RAV"
β	"Fine1" through "Fine5", "Coarse1”, "Coarse2", or "Fine 12.5mm"
γ	"R1", "R2", "W1", "W2"

4.4. Laboratory Mixing and Conditioning Variables

Laboratory-mixed and laboratory-compacted (LMLC) specimens were prepared following standardized procedures to ensure consistency. The mixing temperatures, short-term laboratory conditioning (STA), and long-term laboratory conditioning (LTA) used for all mixtures are summarized in Table 6. Regardless of the performance optimization strategy evaluated, all mixtures with a given binder type were treated identically with respect to mixing and conditioning. The only exceptions were WMA mixtures, which required reduced temperatures.

Table 6. Mixing and Aging Conditions for HMA and WMA Samples

Stage	HMA			WMA		
	PG 58-22	PG 67-22	PG 76-22	PG 58-22	PG 67-22	PG 76-22
Mixing	300 ± 5°F	310 ± 5°	330 ± 5°F	N/A	275 ± 5°F	275 ± 5°F
STA	2hrs@275°F	2hrs@275°F	2hrs@275°F	N/A	2hrs@240°F	2hrs@240°F
LTA	8hrs@275°F	8hrs@275°F	5days@203°F	N/A	8hrs@275°F	5days@203°F

Note: N/A = Not Applicable

Mixing temperatures for HMAs were determined based on the recommended ranges for each asphalt binder grade, while those for WMAs were set according to guidance from the additive supplier and prior experience. After mixing, LMLC specimens were STA-conditioned for 2 hours at 275°F (135°C) for all HMA mixtures and at 240°F (116°C) for WMA mixtures, as specified in AASHTO R30-22 (AASHTO, 2023a).

For LTA-conditioning, all mixtures containing unmodified binders (PG 58-22 and PG 67-22) were conditioned for 8 hours at 275°F (135°C) in accordance with AASHTO R121, Method E (AASHTO, 2024a). This conditioning level corresponds to approximately five to seven years of field aging under warm-climate conditions (AASHTO, 2024a). For the PG 76-22 polymer-modified binder, however, prior experience has shown that elevated temperature aging leads to polymer degradation; therefore, a lower temperature aging protocol—5 days at 203°F (95°C), following AASHTO R121, Method C (AASHTO, 2024a)—was adopted. This duration and temperature combination represent approximately eight years of field aging at a depth of 20 mm, as recommended by the specification (AASHTO, 2024a). All performance test specimens were compacted to a target air void content of 7.0 ± 0.5% to ensure consistent conditioning across test methods.

4.5. Gradation Adjustments

As described earlier, six experimental gradations were developed to investigate how aggregate gradation affects mixture performance by systematically varying virgin aggregate proportions while maintaining constant NMAS (9.5 mm), RAP content (20%), and total binder content (5.6%). These gradations were not designed to meet specific volumetric or performance targets; rather, they were developed to span a range of gradation characteristics and allow assessment of how these characteristics influence resulting volumetric properties and performance.

Each gradation was named using the naming convention “TYPE NUM,” where “TYPE” denotes gradation classification (Fine or Coarse) and “NUM” represents a ranking based on percent passing the #8 sieve (P_8), which served as the primary control sieve (PCS). Lower P_8 values correspond to coarser gradations and thus higher ‘NUM’ values. The control mixture was designated “Fine 3,” with Fine 1 and Fine 2 representing finer gradations and Fine 4 and Fine 5 representing progressively coarser gradations. Coarse 1 and Coarse 2 represented the two coarse-graded alternatives in the experimental plan. Figure 3 shows the gradation curves for all mixtures.

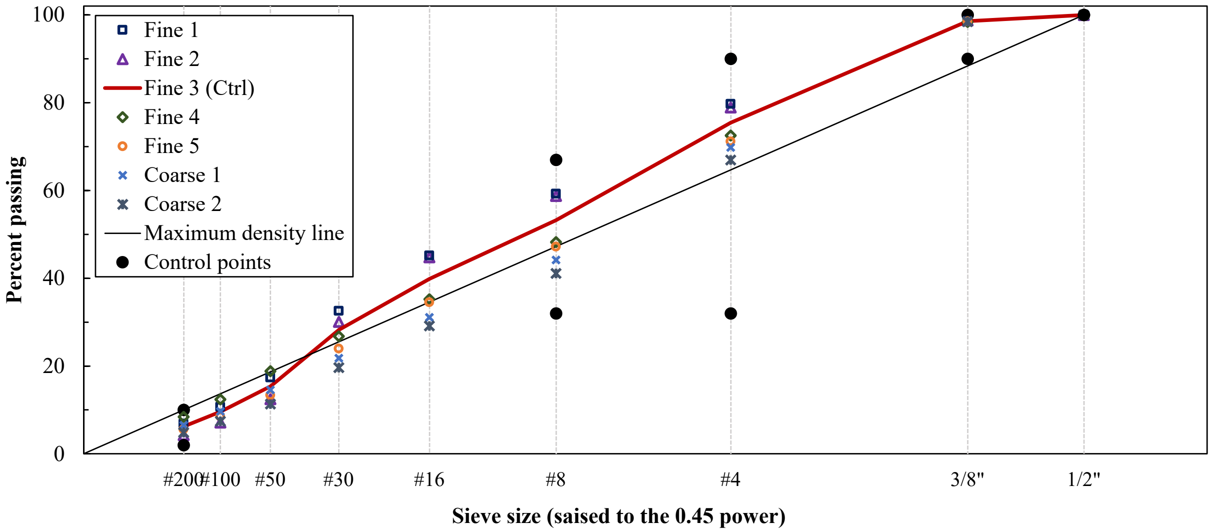


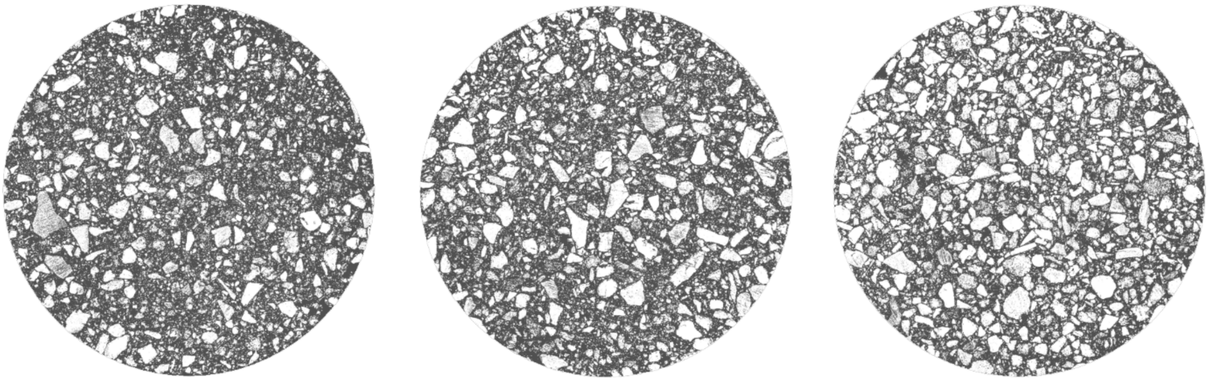
Figure 3. Gradation curve for experimental Mixtures

Table 7 details the virgin aggregate blending proportions used to create each gradation. Although some aggregate combinations would not typically comply with standard Job Mix Formulas (JMF) under DOT specifications, they were deliberately chosen in this study to evaluate the influence of varying consensus properties on mixture volumetric and performance properties.

Table 7. Blending Percentage of Aggregates for Different Experimental Mixtures

Experimental Mixtures	Percentage of Virgin Aggregates in the Blend by Weight					
	#89LS	Shot	Coarse Sand	#8910G	Baghouse fine	RAP
Fine 1	16%	10%	21%	32%	1%	20%
Fine 2	6%	30%	31%	12%	1%	20%
Fine 3 (Ctrl)	**21%**	**15%**	**16%**	**27%**	**1%**	**20%**
Fine 4	35%	0%	0%	44%	1%	20%
Fine 5	26%	20%	11%	22%	1%	20%
Coarse 1	28%	21%	0%	30%	1%	20%
Coarse 2	31%	25%	6%	17%	1%	20%

Figure 4 visually compares the mid-depth cross-sections of selected samples (Fine 1, Fine 3, and Coarse 2), processed using a Python-based image analysis technique that converts grayscale images at a brightness cutoff of 70% in the HSV color space. White regions represent visible aggregate particles, with black regions corresponding to mastic and fine materials. The visual contrast between Fine 1 and Coarse 2 illustrates the structural differences in aggregate packing and stone-to-stone contact.



a) Fine 1 b) Fine 3 (Ctrl) C) Coarse 2

Figure 4. Cutting surface for different gradations

4.5.1. Aggregate Packing Bailey Parameters

The Bailey Method (Vavrik et al., 2002) parameters were used to evaluate aggregate packing for different gradation alternatives. There are four key gradation-based parameters within the Bailey method, which are defined by specific sieve sizes.

Primary Control Sieve (PCS): The PCS represents the boundary between the 'coarse' and 'fine' portions of the overall aggregate structure. It is defined as the sieve size closest to the value calculated using Equation (1).

$$PCS = 0.22 \times NMAS \tag{1}$$

The method also defines three additional sieve sizes—Half Sieve, Secondary Control Sieve (SCS), and Tertiary Control Sieve (TCS)—as shown in Equations (2) through (4). These are used to calculate the subsequent gradation-based parameters.

$$Half\ Sieve = 0.5 \times NMAS \tag{2}$$

$$SCS = 0.22 \times PCS \tag{3}$$

$$TCS = 0.22 \times SCS \tag{4}$$

Coarse Aggregate ratio (CA ratio): Calculated using Equation (5), this parameter characterizes the packing behavior of the coarse fraction within the aggregate gradation

$$CA\ ratio = \frac{\%\ passing\ half\ size - \%\ passing\ PCS}{100 - \%\ passing\ half\ size} \tag{5}$$

The CA ratio represents the proportion of smaller coarse aggregates (interceptors) to larger coarse aggregates (pluggers). Interceptors are particles that pass the Half Sieve and interfere with the dense packing of larger single-sized aggregates, thereby affecting the overall packing efficiency (Vavrik et al., 2002).

Coarse Portion of Fine Aggregate ratio (FAc ratio): The fine aggregate fraction can be viewed as a blend of courser and finer particles. The coarser particles form voids that are filled by the finer particles. The FAc ratio, calculated using Equation (6), represents the proportion of the fine coarse within the fine aggregate relative to the total fine aggregate (Vavrik et al., 2002).

$$FA_c\ ratio = \frac{\%\ passing\ SCS}{\%\ passing\ PCS} \tag{6}$$

Fine Portion of Fine Aggregate ratio (FAf ratio): The FAf ratio calculated using Equation (7), characterizes the fineness of the fine aggregate fraction by quantifying the proportion of its finest particles (Vavrik et al., 2002).

$$FA_f\ ratio = \frac{\%\ passing\ TCS}{\%\ passing\ SCS} \tag{7}$$

4.6. Laboratory Performance Testing

4.6.1. Indirect Tensile Asphalt Cracking Test (IDEAL-CT)

IDEAL-CT tests were conducted at 25°C in accordance with ASTM D8225-19 (ASTM, 2019) using four cylindrical specimens (150 mm diameter, 62 mm height, 7 ± 0.5% air voids) per mixture. Specimens were conditioned for two hours before testing at a monotonic loading rate of 50 mm/min. Figure 5 shows a typical IDEAL-CT specimen in the test frame used in this study. The cracking tolerance index, CT_{Index}, was calculated using Equation (8):

$$CT_{Index} = \frac{t}{62} * \frac{G_f}{|m_{75}|} * \frac{l_{75}}{D} \tag{8}$$

Where:

G_f = Failure energy (J/m^2)
m_{75} = Slope at 75% of post-peak load (kN/mm)
l_{75} = Displacement at 75% post-peak load (mm)
t = Specimen thickness (mm)
D = Specimen diameter (mm).

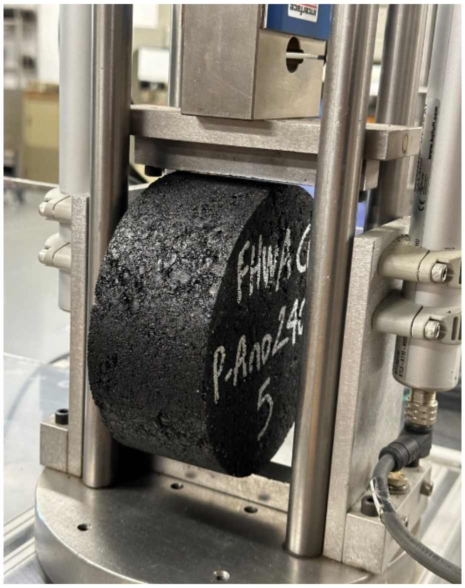


Figure 5: The IDEAL-CT Setup

4.6.2. High-Temperature Indirect Tensile Test (HT-IDT)

HT-IDT tests were performed following ALDOT-458 (ALDOT, 2022a) at 50°C using four gyratory-compacted samples per mixture. Specimens (150 mm × 62 mm, 7 ± 0.5% air voids) were conditioned in a water bath for one hour. Tests were conducted at a loading rate of 50 mm/min, and the resulting High-Temperature Indirect Tensile Strength (*HT-ITS*) values were used to evaluate rutting resistance. A higher *HT-ITS* value is desired for better resistance to rutting. Figure 6 shows an HT-IDT test specimen and the test frame.

Figure 6: The HT-IDT Setup

4.6.3. Hamburg Wheel-Tracking Testing (HWTT)

HWTT was conducted in accordance with AASHTO T 324 (AASHTO, 2023b) to evaluate rutting and moisture induced damage susceptibility. A 158-lb steel wheel passed over submerged specimens at 52 ± 2 passes/min. Each test included two pairs of 150 mm diameter specimens (62 mm height, 7 ± 0.5% air voids) at 50°C. Data were used to determine deformation and stripping inflection points. Figure 7 shows the laboratory setup of HWTT testing.

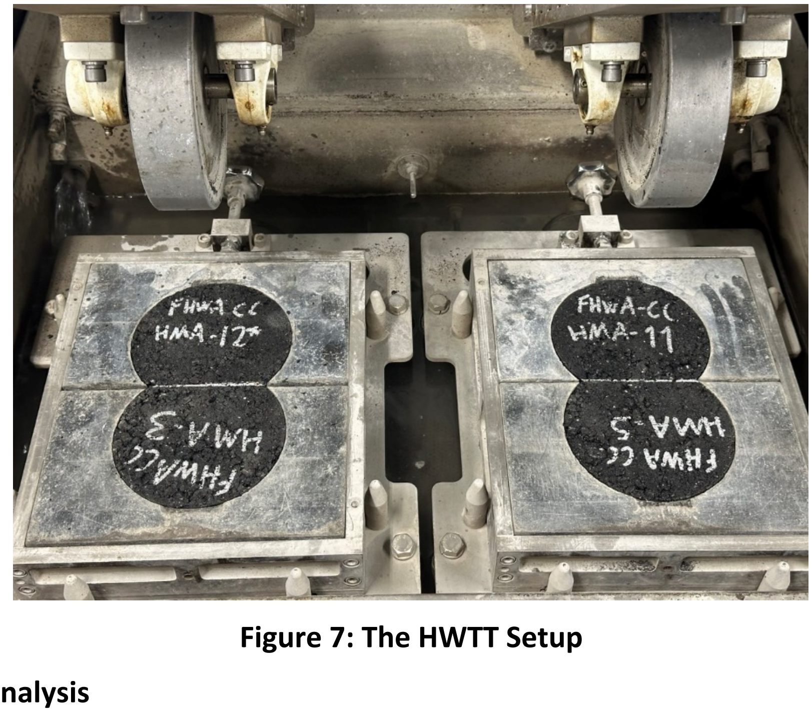


Figure 7: The HWTT Setup

4.7. Statistical Analysis

Statistical comparisons were performed using one-way ANOVA followed by Tukey’s Honestly Significant Difference (HSD) test at a 95% confidence level. Assumptions of normality and homogeneity of variance were verified using the Anderson-Darling and Levene's tests, respectively. Statistical groupings are indicated by letter labels, and mixtures sharing no common letters differ significantly.

5. RESULTS OF EXPERIMENT 1 - EFFECT OF MIXTURE COMPONENT ADJUSTMENTS

This chapter examines the impact of material components on the cracking and rutting performance of asphalt mixtures. The results are presented in two main evaluations: (1) binder adjustments, which include increasing binder content by regressing air voids, changing binder grades (either to softer grades or polymer-modified options), and examining their combinations; and (2) aggregate gradation and NMAS adjustments, which are achieved by varying the proportions of virgin aggregate while keeping the binder content constant.

For each evaluation, performance is measured using three tests: IDEAL-CT for cracking resistance, HT-IDT for high-temperature strength, and HWTT for resistance to rutting and moisture damage. The findings for each testing method are presented, followed by an assessment of their implications for balancing cracking and rutting performance.

5.1. Effect of Binder Content and Grade Adjustments

Three strategies related to asphalt binder were evaluated to assess their individual effects on mixture performance. The strategies included: increasing binder content through regressing air voids (RAV), using a softer unmodified binder (PG 58-22), and incorporating a polymer-modified binder (PG 76-22). Table 8 summarizes performance test results for the control mixture, as well as those of the three alternatives.

Table 8. Summary of Volumetric and Performance Test Results

Test Method	**Property**	**Mixtures**			
		67-22 Fine3	**67-22 RAV Fine3**	**58-22 Fine3**	**76-22 Fine3**
IDEAL-CT (STA)	CT_{Index}	40.8	49.2	61.2	59.6
	G_f (J/m^2)	6368.7	6329.5	5009.6	8859.8
	L_{75}/m_{75} (mm^2/kN)	0.960	1.163	1.835	1.008
IDEAL-CT (LTA)	CT_{Index}	12.0	15.2	25.5	23.4
	G_f (J/m^2)	5834.0	5834.2	6256.1	8237.6
	L_{75}/m_{75} (mm^2/kN)	0.308	0.390	0.611	0.427
HT-IDT (STA)	*HT-ITS* (psi)	24.4	23.9	17.9	29.4
HWTT (STA)	Rutting at 10,000 passes (mm)	4.874	4.1	>12.5	1.868
	Passes to 12.5 mm	15850	17050	14850	>20000

All mixtures in this section share the same gradation (Fine 3), so this part of the mix identifiers was omitted for brevity. However, the figures still indicate the common property that has been removed across all mixtures.

5.1.1. IDEAL-CT Results

Figure 8 shows CT_{Index} values for binder adjustment strategies under two aging conditions, based on four to six replicates per mixture. Error bars represent ±1 standard deviation. STA specimens were conditioned for 2 hours at 135°C (275°F) after mixing and prior to compaction, while LTA specimens received extended conditioning: 8 hours at 135°C for unmodified binders (PG 58-22 and PG 67-22) or 5 days at 95°C (203°F) for the polymer-modified binder (PG 76-22). Detailed conditioning methods and variables are provided in Table 6. It is essential to note that LTA protocols differ between polymer-modified and unmodified binders, so their effects may be different.

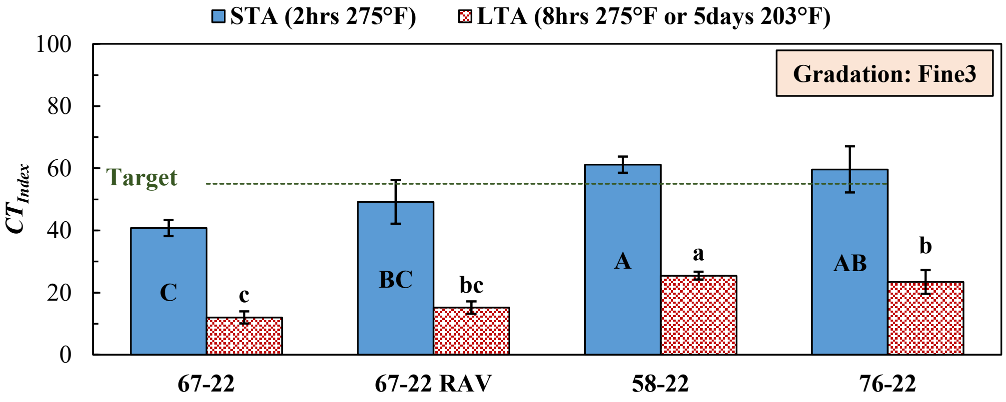


Figure 8 Binder adjustment: IDEAL-CT CTIndex results

The average coefficient of variation (COV) for CT_{Index} was 11.0% for both STA and LTA, indicating good test repeatability. Statistical groupings are labeled with uppercase letters for STA and lowercase letters for LTA, where mixtures sharing no common letters differ significantly at the 95% confidence level.

All three strategies increased CT_{Index} relative to the control under both aging conditions. The softer binder (58-22) and polymer-modified binder (76-22) produced statistically significant gains under both STA and LTA, with both mixtures exceeding the CT_{Index} target of 55. The regressed air void approach generated a smaller improvement, which was less pronounced than that of binder grade modifications, although it still provided measurable enhancement in cracking resistance.

To understand the mechanisms driving CT_{Index} changes, the two component parameters—failure energy (G_f) and the ratio $l_{75}/|m_{75}|$—were further examined (Figure 9 and Figure 10). These variables represent mixture cracking toughness and relative ductility, respectively (Yin, Chen, et al., 2023; Yin, West, et al., 2023), with higher values for both corresponding to increased CT_{Index}.

Failure Energy (G_f). Figure 9 indicates that G_f changed minimally with the regressed air void approach (67-22 RAV), remaining statistically equivalent to the control under both STA and LTA. This statistical equivalence indicates that increasing binder content through air void regression primarily affects ductility rather than toughness.

In contrast, binder grade adjustments had a significant effect on failure energy. The softer binder (58-22) significantly reduced G_f, while the polymer-modified binder (76-22) significantly increased G_f, demonstrating the strong dependence of toughness on binder grade. Among all alternatives evaluated, the polymer-modified binder (76-22) achieved the highest G_f values under both aging conditions.

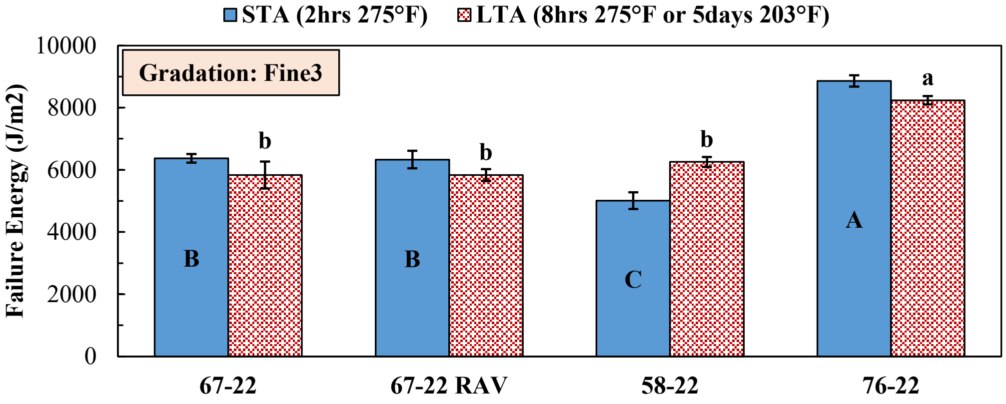


Figure 9. Binder adjustment: IDEAL-CT failure energy results

Ductility Parameter (l_{75}/|m_{75}|). Figure 10 presents the ductility component of CT_{Index}. The RAV mixture produced a statistically insignificant increase in l_{75}/|m_{75}| relative to the control, consistent with its modest CT_{Index} gain. The softer binder (58-22) yielded a statistically significant increase in l_{75}/|m_{75}|, which explains its substantial improvement in CT_{Index} despite reduced toughness. In contrast, the polymer-modified binder (76-22) showed no statistically significant change in this parameter, indicating that its CT_{Index} improvement resulted entirely from increased toughness rather than enhanced ductility.

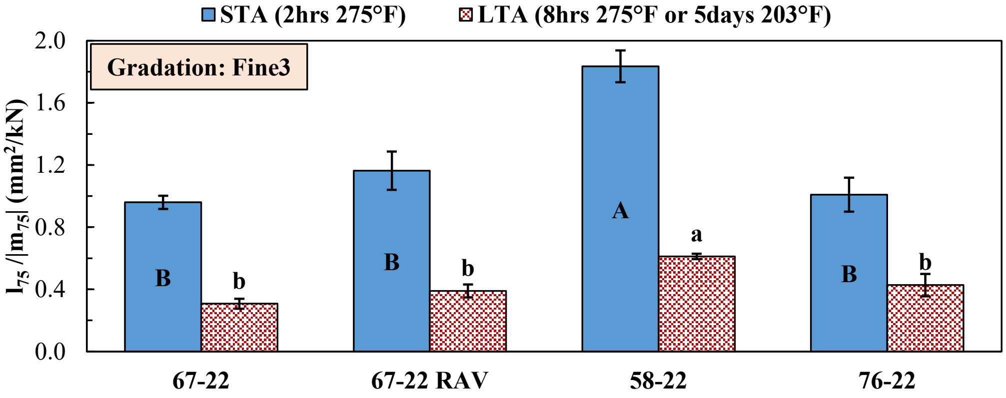


Figure 10. Binder adjustment: IDEAL-CT l75/|m75| results

Overall, these component analyses show that the three binder strategies improve CT_{Index} through different mechanisms:

- Increasing binder content using regressing air voids (67-22 RAV): Primarily increases ductility with minimal change in toughness, resulting in moderate CT_{Index} gains.
- Using a softer binder (58-22): Substantially increases ductility ($l_{75}/|m_{75}|$) but decreases toughness (G_f), producing significant CT_{Index} improvement through the ductility pathway.
- Polymer-modified binder (76-22): Substantially increases toughness (G_f) with no change in ductility, achieving CT_{Index} improvement through enhanced energy absorption capacity.

These differences explain the relative magnitudes of CT_{Index} improvements observed in Figure 8 and have important implications for mixture optimization. The results demonstrate that multiple pathways exist for improving cracking resistance, depending on which strategy has the most effect for a given application.

5.1.2. HT-IDT Results

The HT-IDT test evaluates rutting resistance through high-temperature tensile strength measurement, providing a complementary assessment to the IDEAL-CT cracking results. Figure 11 presents HT-ITS values from four replicates per mixture under STA. The average COV across all mixtures was 2.8%, indicating excellent test repeatability. Statistical groupings are shown with letter labels, where mixtures sharing no common letters differ significantly at the 95% confidence level.

The regressed air void strategy resulted in a statistically insignificant reduction in HT-ITS relative to the control (24.4 psi versus 23.9 psi), indicating that the modest increase in binder content (0.3%) does not substantially compromise high-temperature strength. This finding is important because it indicates the regressed air void approach can improve cracking resistance without creating rutting concerns.

Binder grade changes produced the expected trends based on stiffness differences. The softer binder (58-22) significantly reduced HT-ITS to 17.9 psi, falling below the 20-psi minimum threshold and indicating unacceptable rutting susceptibility. In contrast, the polymer-modified binder (76-22) significantly increased HT-ITS to 29.4 psi, providing the largest margin above the minimum requirement among all mixtures evaluated.

Except for the softer binder mixture (58-22), all alternatives satisfied the specified minimum HT-ITS threshold. The polymer-modified binder (76-22) not only met both performance criteria but also provided substantial margins above both thresholds, achieving a CT_{Index} of 59.6 (versus the target of 55) and an HT-ITS of 29.4 psi (versus the minimum of 20 psi). This dual performance improvement makes the 76-22 Fine3 mixture a candidate for additional cracking evaluation, which is explored in the latter part of this study.

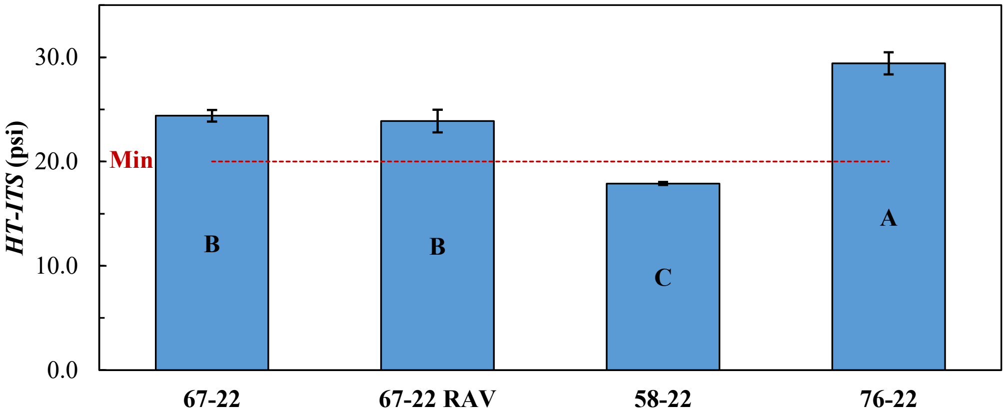


Figure 11. Binder adjustment: HT-ITS results

5.1.3. HWTT Results

The HWTT provides an assessment of rutting resistance through repeated wheel loading under submerged conditions. Figure 12 presents HWTT rut depth at 10,000 passes under STA conditioning, based on two pairs of specimens per mixture.

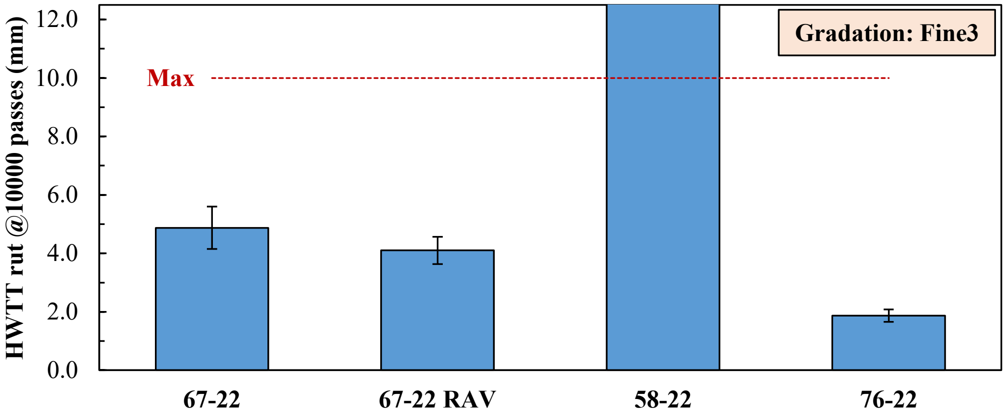


Figure 12. Binder adjustment: HWTT results

The regressed air void approach exhibited slightly improved rutting resistance compared to the control, with a decrease in rut depth from 4.87 mm to 4.10 mm. This finding suggests that moderate increases in binder content can improve cracking resistance without compromising rutting performance.

Binder grade changes exhibited trends similar to those of HT-IDT. The polymer-modified binder (PG 76-22) significantly enhanced rutting resistance, with rut depth remaining below 2 mm after 10,000 passes and requiring over 20,000 passes to reach the 10 mm failure criterion. This performance, coupled with improved cracking resistance, highlights the dual benefits of polymer modification.

The softer binder (PG 58-22) demonstrated the highest susceptibility to rutting, surpassing the 10 mm threshold in fewer than 10,000 passes. This finding indicates that although the softer binder significantly enhanced the CT_{Index} from 40.8 to 61.2, this improvement comes with a risk of rutting. As a result, this mixture may not be suitable for typical surface course applications unless additional mitigation strategies are implemented.

5.1.4. Summary

The test results show that different binder strategies affect cracking and rutting performance in varying ways. Figure 13 illustrates these relationships by plotting CT_{Index} against HT-ITS, with target thresholds indicated as dashed reference lines ($CT_{Index} \geq 55$, HT-ITS ≥ 20 psi). This diagram highlights three pathways for optimizing performance.

- The polymer-modified binder (PG 76-22) enhances resistance to cracking and rutting, effectively moving the mixture toward the upper-right region of the plot. This indicates the ideal outcome for BMD, fulfilling all performance criteria with good margins.
- The regressed air voids (RAV) method offers moderate cracking improvement while ensuring sufficient rutting resistance, providing a cost-effective alternative when polymer modification is not financially feasible.
- The softer binder (PG 58-22) significantly enhances resistance to cracking but increases the risk of rutting. This approach needs additional mitigation strategies, such as optimizing gradation or reducing binder content, to ensure balanced performance.

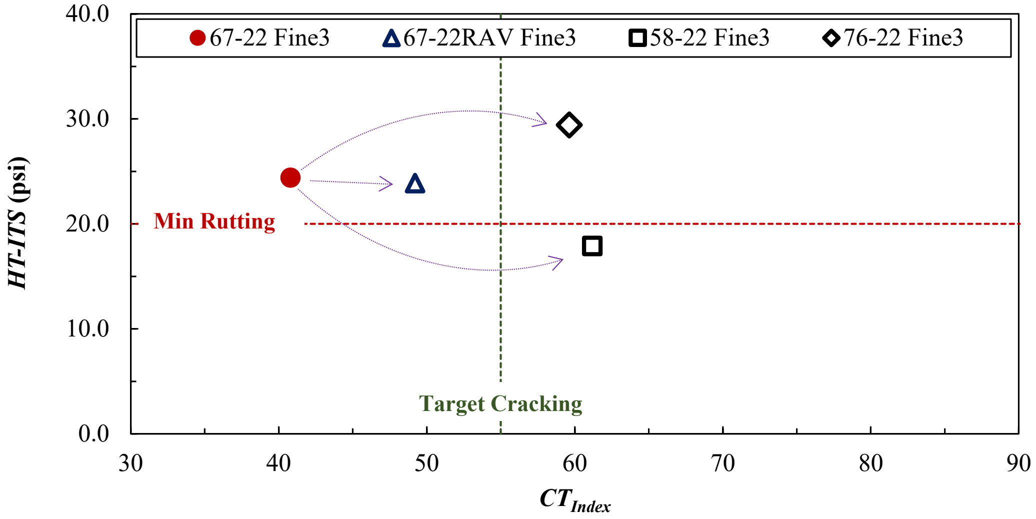


Figure 13. Effect of Binder Adjustments on Cracking and Rutting Performance

These results demonstrate that agencies can select binder strategies tailored to project-specific requirements, material availability, and economic constraints, while also considering the associated performance trade-offs.

5.2. Effect of Aggregate Gradation Adjustments

Seven different gradations were developed to investigate how aggregate gradation affects mixture performance while maintaining a constant NMAS of 9.5 mm, using a binder grade of PG 67-22, with 20% recycled asphalt pavement (RAP) content, and a total binder content of 5.6%. The gradations ranged from fine (Fine1, Fine2) to the control (Fine3), and then to progressively coarser alternatives (Fine4, Fine5, Coarse1, Coarse2). Table 9 summarizes the volumetric properties, gradation parameters, and performance test results for all mixtures. Since all mixtures utilized the same binder grade, the binder identifiers are omitted from the figure labels in the following subsections for brevity.

Among the seven mixtures, Fine5 and Coarse2 exhibited volumetric properties most similar to those of the control mixture (Fine3), with both air voids and VMA within ±0.5 percentage points. Although these gradations were not specifically designed to meet particular volumetric targets, the similarities among Fine3, Fine5, and Coarse2 allow for direct performance comparisons while minimizing potential confounding effects from volumetric differences.

Table 9. Gradation adjustment: Summary of volumetric and BMD results

Test Methods	Property	Experimental Mixtures						
		Fine1	**Fine2**	**Fine3**	**Fine4**	**Fine5**	**Coarse1**	**Coarse2**
Volumetric Properties	Va (%)	1.8	7.5	3.9	6.6	3.7	2.9	3.6
	VMA (%)	13.9	18.3	15.8	18.5	15.4	14.9	15.3
	VFA (%)	87.1	59.0	75.4	64.3	76.0	80.5	76.5
	VBE (%)	12.1	10.8	11.9	11.9	11.7	12.0	11.7
Gradation Parameters	P_8 (%)	59.3	58.8	53.2	48.3	47.2	44.2	41.1
	CA	1.01	0.95	0.91	0.89	0.83	0.85	0.78
	FA_c	0.55	0.51	0.53	0.56	0.51	0.49	0.48
	FA_f	0.33	0.24	0.34	0.46	0.36	0.45	0.38
IDEAL-CT (STA)	CT_{Index}	27.9	25.8	40.8	44.4	58.5	61.4	65.4
	G_f (J/m^2)	5887	5945	6369	6521	6928	6449	6979
	L_{75}/m_{75} (mm^2/kN)	0.89	0.65	0.96	1.02	1.26	1.41	1.40
IDEAL-CT (LTA)	CT_{Index}	N/A	N/A	12.0	N/A	12.5	N/A	18.1
	G_f (J/m^2)	N/A	N/A	5834	N/A	6054	N/A	6395
	L_{75}/m_{75} (mm^2/kN)	N/A	N/A	0.31	N/A	0.31	N/A	0.42
HT-IDT (STA)	*HT-ITS* (psi)	31.2	27.1	24.4	24.4	25.8	24.7	22.6
HWTT (STA)	Rutting at 10,000 passes (mm)	N/A	N/A	4.874	N/A	3.831	N/A	4.332
	Passes to 12.5 mm	N/A	N/A	15850	N/A	17700	N/A	18950

5.2.1. IDEAL-CT Results

Short-Term Aged Test Results. Figure 14 presents the average CT_{Index} results for each mixture based on four replicates under STA conditions (2 hours at 135°C following AASHTO R 30 (AASHTO, 2023a). Error bars represent ±1 standard deviation, and the average COV was 9.2%. Statistical groupings are indicated by uppercase letters.

The results indicate that the CT_{Index} value generally increased as the percentage of material passing the #8 sieve (P_8) decreased, meaning that the mixtures became coarser. The highest CT_{Index} values were observed for Fine5 (CT_{Index} = 58.5), Coarse1 (CT_{Index} = 61.4), and Coarse2 (CT_{Index} = 65.4). All of these mixtures had coarser gradations compared to the control mixture, which had a CT_{Index} of 40.8. Among them, Coarse2, the coarsest blend evaluated (with P_8 = 41.1%), achieved the highest CT_{Index} value. The three coarsest gradations surpassed the target CT_{Index} of 55, demonstrating that adjusting the gradation alone—without altering the binder grade or content—can lead to significant improvements in cracking performance.

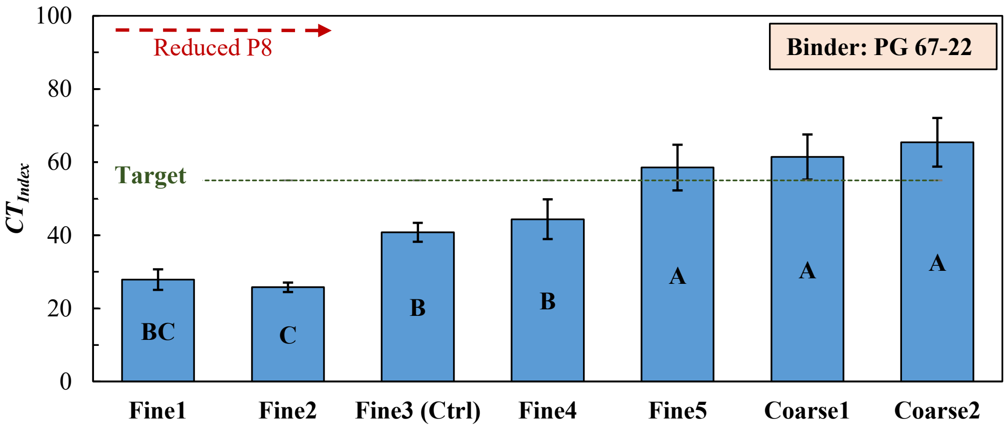


Figure 14. Effect of Gradation Adjustment on STA CT_{Index} Results

Long-Term Aged Test Results. To assess whether the improvements in cracking resistance are maintained after prolonged aging, three mixtures were tested under LTA conditioning: the control mixture (Fine3) and two alternatives (Fine5 and Coarse2). These mixtures were chosen due to their enhanced resistance to cracking, comparable resistance to rutting, and similar volumetric properties. Figure 15 illustrates the average CT_{Index} results based on four replicates. The average coefficient of variation (COV) for the LTA specimens was 16.4%, which is higher than that observed in the STA samples.

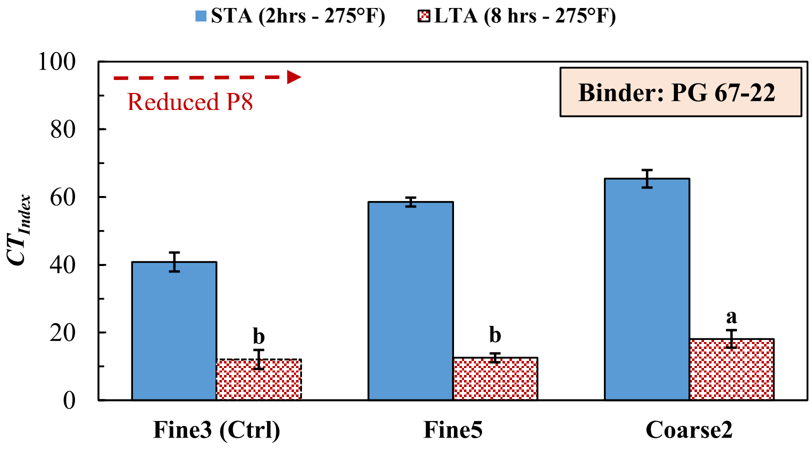


Figure 15. Effect of Gradation Adjustment on LTA CT_{Index} Results for Selected Mixtures

The results indicated that Fine5 maintained a CT_{Index} similar to the control under long-term aging conditions, while Coarse2 showed a statistically significant improvement, achieving a CT_{Index} of 18.1. This trend is consistent with the short-term aging results, suggesting that the cracking resistance benefits of coarser gradations remain effective even after long-term aging; however, the extent of improvement is reduced compared to short-term aging conditions.

Interaction Diagram Analysis. To understand the mechanisms driving CT_{Index} variability across different gradations, an interaction diagram was developed by plotting the average G_f against $l_{75}/|m_{75}|$ for each mixture. Higher values for both variables indicate an increased CT_{Index}, which positions the mixtures toward the upper-right corner of the diagram. Figure 16 displays the results for both STA and LTA conditions, with contour lines representing constant CT_{Index} values ranging from 10 to 70.

Both aging conditions exhibit a systematic shift toward the upper-right region (indicating higher G_f and $| m_{75} |/|m_{75}|$) as the mixtures become coarser. This shift demonstrates simultaneous improvements in both toughness and ductility. Notably, the increase in $l_{75}/|m_{75}|$ (horizontal displacement) is more pronounced than the increase in G_f (vertical displacement), suggesting that enhanced ductility is the primary mechanism by which coarser gradations improve the CT_{Index}.

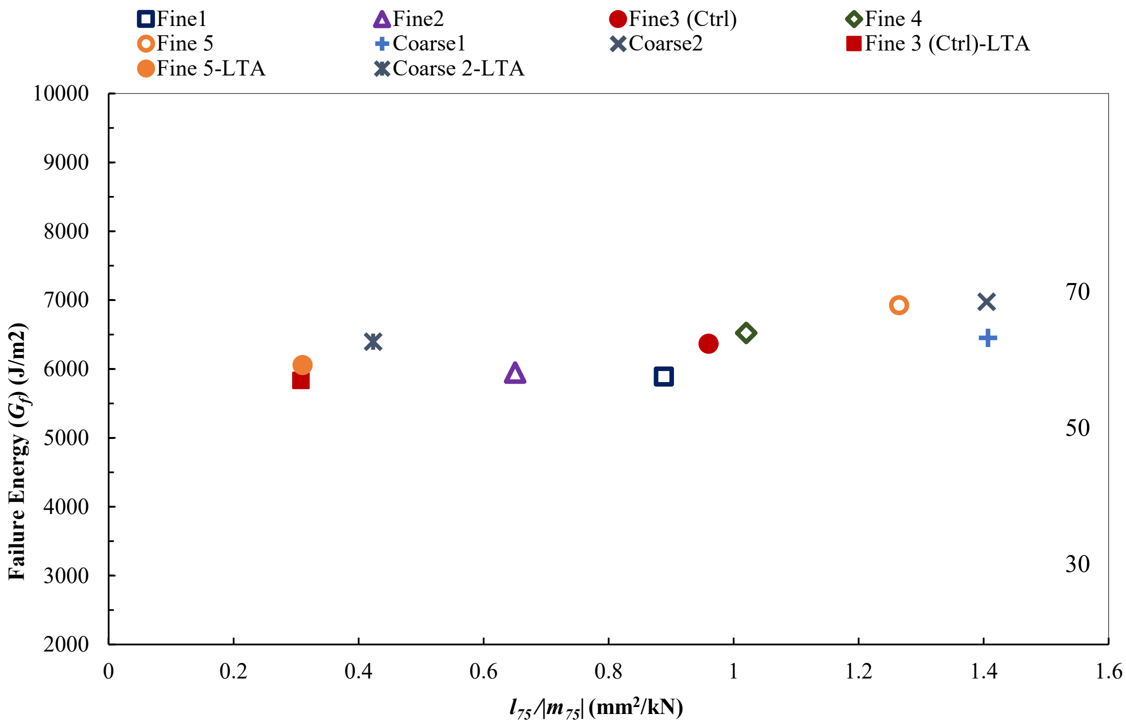


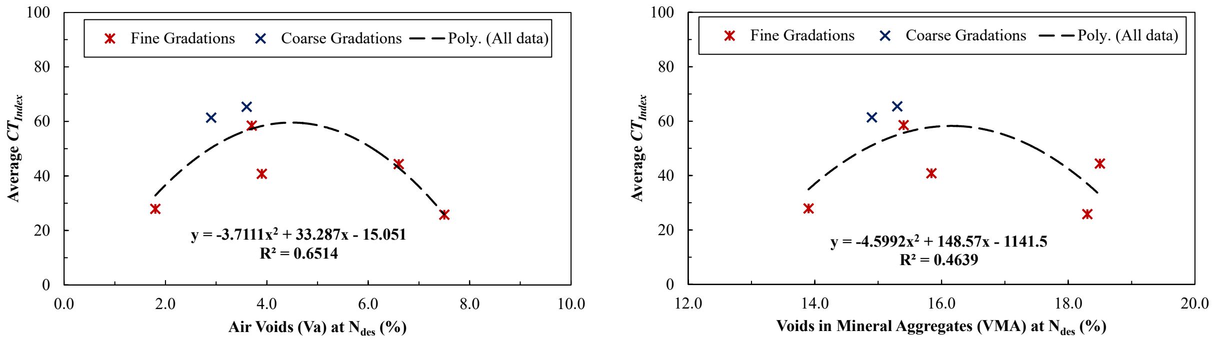
Figure 16. IDEAL-CT Interaction Plot (contour lines representing CT_{Index} values)

Correlation with Volumetric Properties. Figure 17 illustrates the relationships between the CT_{Index} (STA) and key volumetric properties measured on specimens compacted to 60 design gyrations. Although different markers are used to represent fine and coarse gradations, regression analyses utilized the entire dataset because there were no systematic differences between the gradation types.

All four volumetric parameters showed moderate to good second-order polynomial correlations with the CT_{Index}. Each correlation showed a peak in CT_{Index} at intermediate volumetric values—

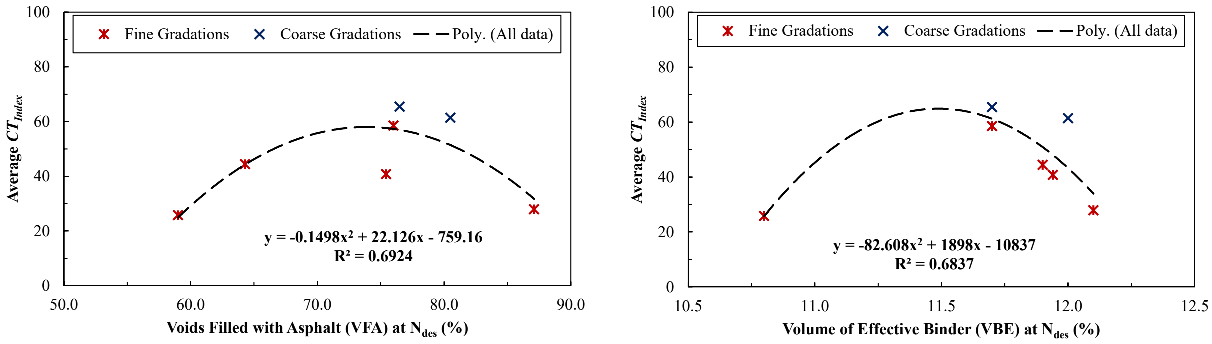
approximately 4% air voids, 16% VMA, 75% VFA, and 11.8% VBE. This suggests that too low or too high volumetric values negatively impact cracking resistance.

These findings suggest that there is an optimal volumetric range for maximizing the *CT_{Index}*, although this range may depend on other mixture characteristics. It is essential to note that since only aggregate proportions were varied while keeping other design variables constant, these relationships should not be universally generalized. Instead, they should be viewed as evidence that volumetric properties influence cracking resistance in complex and non-linear ways.



(a) Air Voids (Va)

(b) Voids in Mineral Aggregates (VMA)



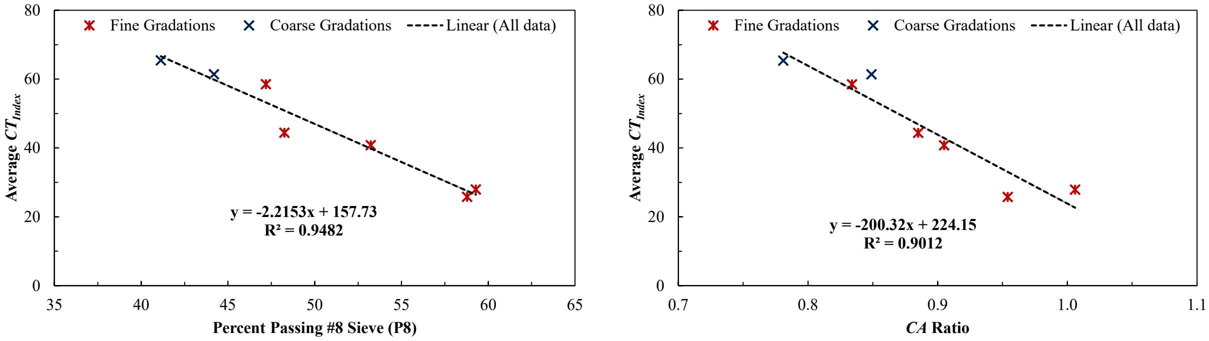
(c) Voids Filled with Asphalt (VFA)

(d) Volume of Effective Binder (VBE)

Figure 17. Correlation of STA CT_{Index} with Volumetric Properties

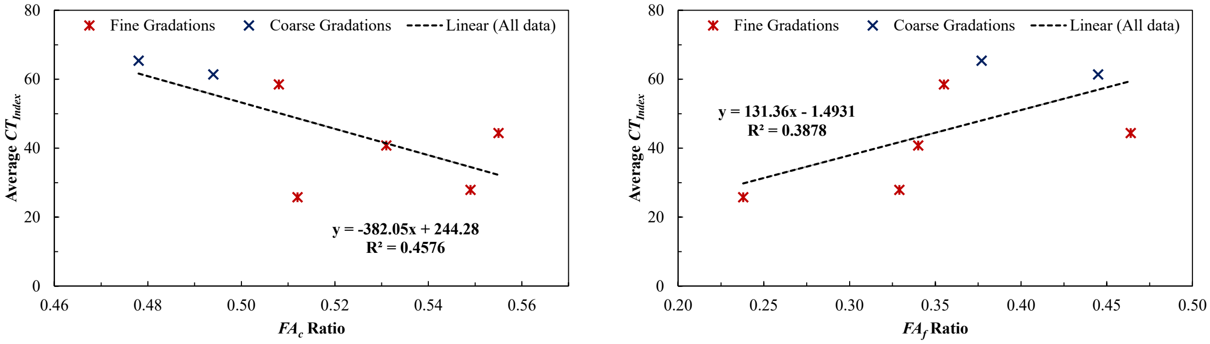
Correlation with Gradation Parameters. Figure 18 illustrates the correlations between the CT_{Index} (STA) and gradation parameters, specifically the percent passing the #8 sieve (P_8) and the three ratios defined by the Bailey Method. The P_8, which represents the primary control sieve (PCS), shows a very strong negative correlation with the CT_{Index} (R^2 = 0.95). This indicates that as the mid-size fraction decreases, the cracking resistance significantly increases. Additional analysis (not shown) revealed similarly strong correlations (R^2 = 0.94–0.95) for percent passing sieve sizes from #4 to #30, which corresponds to the Half Sieve through the Secondary Control Sieve (SCS) range. These findings suggest that the mid-range portion of gradation—comprising the fine fraction of coarse aggregate and the coarse fraction of fine aggregate—has the greater influence on cracking resistance.

Among the parameters of the Bailey Method, the Coarse Aggregate (CA) ratio demonstrated a very strong positive correlation (R^2 = 0.90), indicating that lower relative proportions of interceptors (coarse particles that pass the Half Sieve but are retained on the PCS) enhance cracking resistance. In contrast, the fine aggregate ratios (*FA_c* and *FA_f*) showed weak to moderate correlations (R^2 = 0.39 and 0.46, respectively), suggesting that the characteristics of the fine aggregate fraction play a secondary role in determining cracking resistance.



(a) Percent Passing #8 Sieve (P_8)

(b) CA Ratio



(c) FA_c Ratio

(d) FA_f Ratio

Figure 18. Correlation of STA CT_{Index} with Gradation Parameters

5.2.2. HT-IDT Results

Short-Term Aged Test Results. Figure 19 presents the average *HT-ITS* values for all gradations under STA conditioning, based on two replicates per mixture, with error bars indicating ±1 standard deviation. The COV for *HT-ITS* across all mixtures was 3.5%. Due to the limited number of replicates, statistical comparisons were not performed.

The results show a general decrease in *HT-ITS* as the P_8 value decreases, indicating that coarser gradations result in lower high-temperature strength. However, the change in strength is modest, with most mixtures falling within a relatively narrow range of 22.6 to 27.1 psi. The finest gradation evaluated, referred to as Fine1 (P_8 = 59.3%), exhibited the highest HT-ITS at 31.2 psi.

It is important to note that all experimental gradations exceeded the minimum threshold of 20 psi. This indicates that the improvements in cracking resistance achieved through coarser gradations did not result in unacceptable reductions in high-temperature strength. This finding suggests that the aggregate gradation adjustment has a relatively limited effect on laboratory-measured rutting resistance, as quantified by the HT-IDT, especially when compared to its significant impact on cracking resistance.

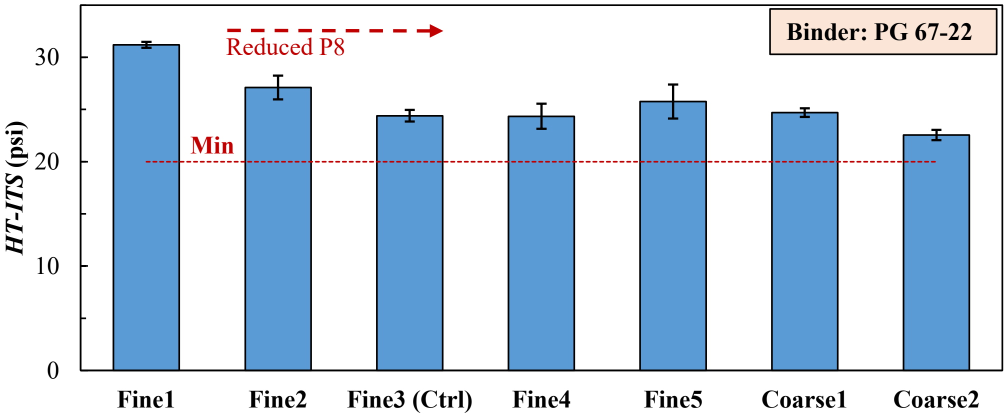


Figure 19. Effect of Gradation Adjustment on STA HT-ITS Results

Correlation with Gradation Parameters. Figure 20 shows the relationship between *HT-ITS* and selected gradation parameters. While fine and coarse blends are indicated separately, all regression lines were developed using the full dataset.

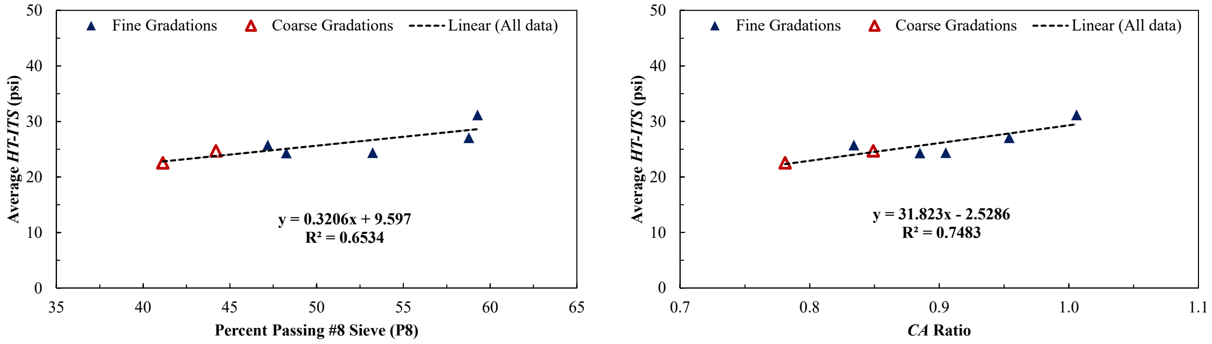
P_8 showed a strong positive correlation with HT-ITS ($R^2 = 0.78$), suggesting that finer gradations enhance high-temperature strength. Similar correlations ($R^2 = 0.64–0.65$) were found for sieve sizes ranging from #4 to #30, confirming that mid-range gradation fractions influence both cracking and rutting resistance, albeit in opposite ways.

Among the Bailey parameters, only the coarse aggregate (CA) ratio demonstrated a strong correlation with HT-ITS ($R^2 = 0.78$). This positive relationship indicates that higher proportions of interceptors improve rutting resistance. However, this finding contradicts the trend observed for cracking resistance, where lower CA ratios resulted in improved CT_{Index}.

These opposing trends highlight that aggregate gradation characteristics that enhance cracking resistance may reduce rutting resistance, and vice versa. This fundamental trade-off emphasizes the importance of gradation in BMD. Without directly evaluating both performance characteristics, optimizing one could inadvertently compromise the other.

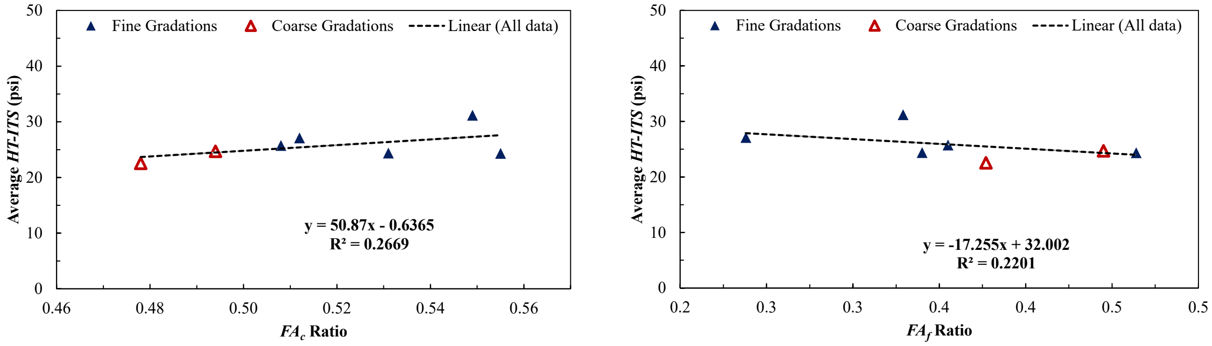
The strong correlations between performance indices and gradation parameters suggest that the gradation of aggregates may be the primary factor influencing outcomes when the binder content is held constant. However, interpreting this alone would be an oversimplification. In practical applications, various aggregate characteristics—such as strength, angularity, texture, and morphology—also play a significant role in performance. The pronounced correlations observed in gradation highlight the need to maintain appropriate consensus property limits that align with known field performance. It is essential to acknowledge that current laboratory tests may not fully capture all the relevant effects of aggregates.

Based on the combined STA results, the Fine5 and Coarse2 mixtures demonstrated significantly improved CT_{Index} values, with HT-ITS values comparable to those of the control. Therefore, these two mixtures were advanced for further testing, specifically LTA IDEAL-CT (Section 5.2.1.2) and HWTT evaluation (Section 5.2.3).



(a) Percent Passing #8 Sieve (P_8)

(b) CA Ratio



(c) FA_c Ratio

(d) FA_f Ratio

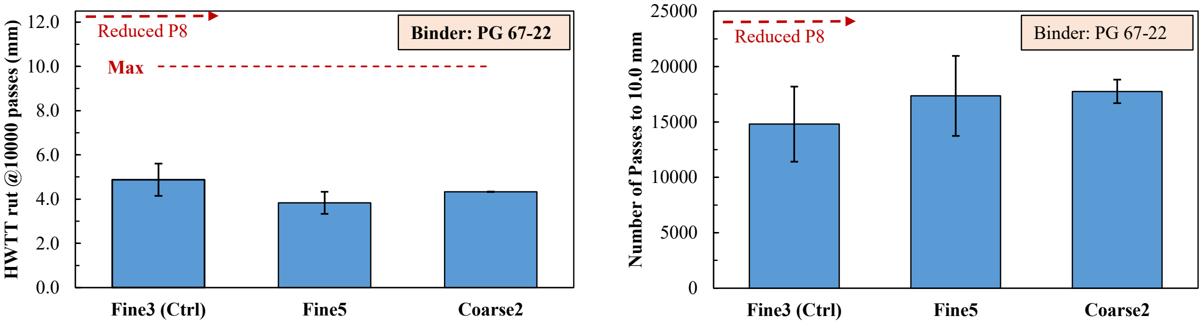
Figure 20. Correlation of HT-ITS with gradation-based parameters

5.2.3. HWTT Results

Figure 21 presents the HWTT results for three selected mixtures under STA conditioning: the control mixture (Fine3), Fine5, and Coarse2. Two pairs of specimens were tested for each mixture. In Figure 21(a), the average rut depth after 10,000 passes is shown, while Figure 21(b) displays the number of passes required to reach a rut depth of 10.0 mm. The average COV is 9.4% for rut depth and 16.6% for the number of passes to reach 10.0 mm.

All three mixtures demonstrated acceptable rutting performance, with rut depths remaining well below ALDOT's threshold of 10 mm after 10,000 passes. Notably, Coarse2—despite being the coarsest gradation—exhibited slightly better rutting resistance compared to the control mixture, requiring approximately 17,750 passes to reach 10.0 mm, compared to 14,800 for the control. Fine5 performed similarly to Coarse2.

These findings highlight an important difference between HT-IDT and HWTT results: while HT-ITS decreased with coarser gradations, the rutting resistance of HWTT either improved or remained equivalent. This suggests that the two tests measure different aspects of rutting resistance. HT-ITS primarily assesses material strength at a single temperature and loading rate, whereas HWTT evaluates cumulative deformation under repeated loading with exposure to moisture. The HWTT results may better capture the benefits of enhanced aggregate interlock and stone-on-stone contact in coarser gradations, which provide structural rutting resistance independent of binder-dominated strength.



(a) Rut depth after 10,000 passes

(b) Number of passes to 10 mm

Figure 21. Effect of Gradation Adjustment on HWTT Rut Depth Results for Selected Mixtures

5.2.4. Summary

Figure 22 summarizes the cracking and rutting performance of the gradation study by plotting the CT_{Index} against HT-ITS for all seven mixtures. Target thresholds are indicated by dashed reference lines.

A clear distinction is observed between finer and coarser gradations: finer mixtures show lower CT_{Index} values combined with higher HT-ITS, while coarser mixtures display the opposite trend. The variation is more pronounced along the horizontal axis (CT_{Index}), ranging from approximately 26 to 65, compared to the vertical axis (*HT-ITS*), which ranges from about 23 to 31 psi. This asymmetry suggests that adjustments in gradation can effectively enhance cracking resistance, while having only a modest effect on high-temperature strength.

Notably, the three coarsest gradations (Fine5, Coarse1, and Coarse2) all achieved CT_{Index} values exceeding the target threshold of 55, while also maintaining *HT-ITS* above the minimum of 20 psi. This suggests that optimizing gradation can significantly improve cracking resistance without compromising rutting performance, provided that rutting criteria are met through appropriate performance testing.

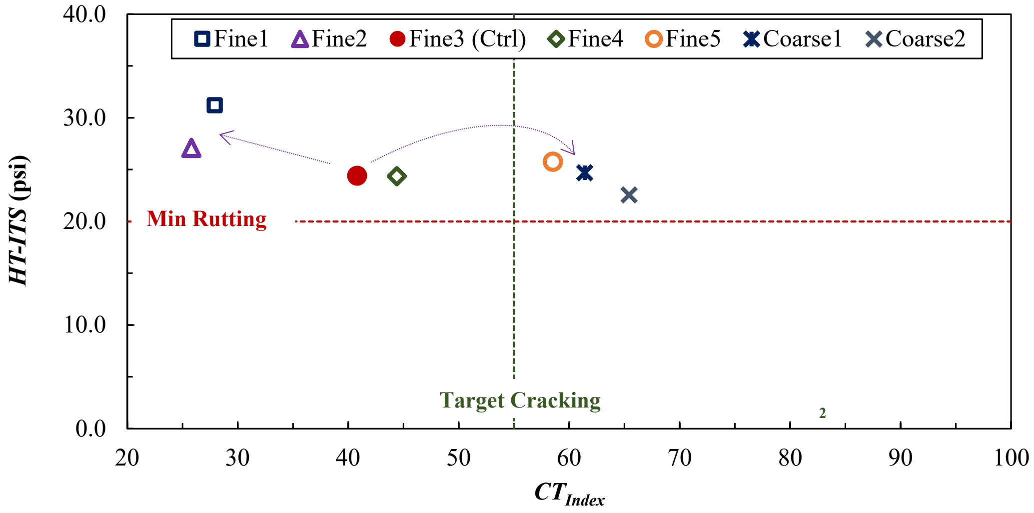


Figure 22. Effect of Gradation Adjustments on Cracking and Rutting Performance

5.3. Effect of Nominal Maximum Aggregate Size

In addition to gradation adjustment, NMAS represents another potential variable for performance optimization. One additional mixture was evaluated to determine whether increasing NMAS from 9.5 mm to 12.5 mm influences cracking and rutting performance. This adjustment was achieved by replacing the #89LS limestone fraction with an equivalent proportion of coarser #78LS limestone from the same source, while maintaining constant RAP content and total binder content.

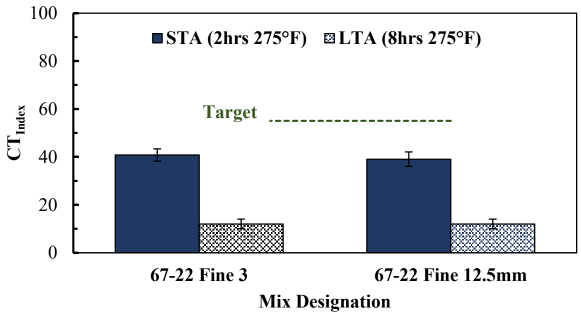
5.3.1. IDEAL-CT Results

Figure 23 presents the IDEAL-CT results comparing the control mixture (PG 67-22 Fine3, NMAS = 9.5 mm) with the larger NMAS mixtures (PG 67-22 Fine 12.5mm) under STA conditioning. Statistical comparisons indicated that both mixtures belonged to the same statistical grouping for all cracking metrics (CT_{Index}, G_f, and $l_{75}/|m_{75}|$). These findings suggest that increasing NMAS within the range evaluated did not produce measurable changes in cracking resistance.

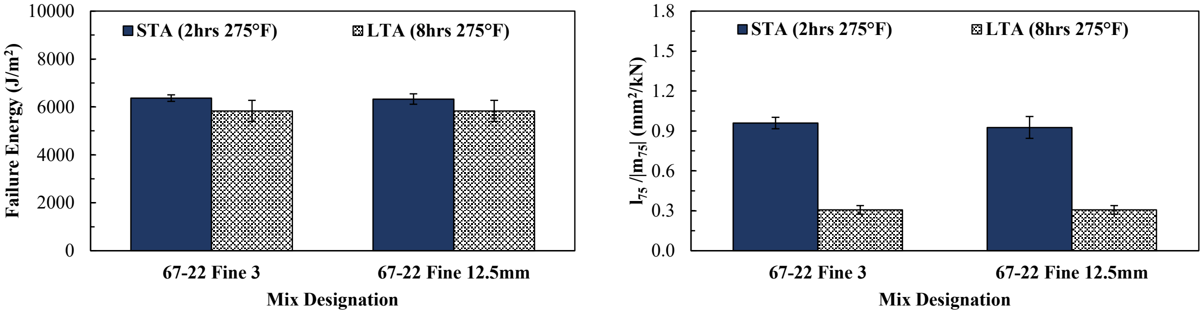
5.3.2. Rutting Resistance Test Results

Figure 24 presents the rutting performance results comparing the two mixtures under STA conditioning. The larger NMAS mixture exhibited slightly improved performance in both HT-IDT and HWTT tests, though the *HT-ITS* improvement was not statistically significant.

Overall, these results indicate that NMAS adjustment within the evaluated range (9.5 to 12.5 mm) had a minimal influence on both cracking and rutting resistance. However, because only one NMAS alternative was evaluated and volumetric properties changed simultaneously, these findings should not be broadly generalized. Additional research with systematic NMAS variations and controlled volumetrics would be necessary to draw conclusions about the effects of NMAS on cracking and rutting performance.



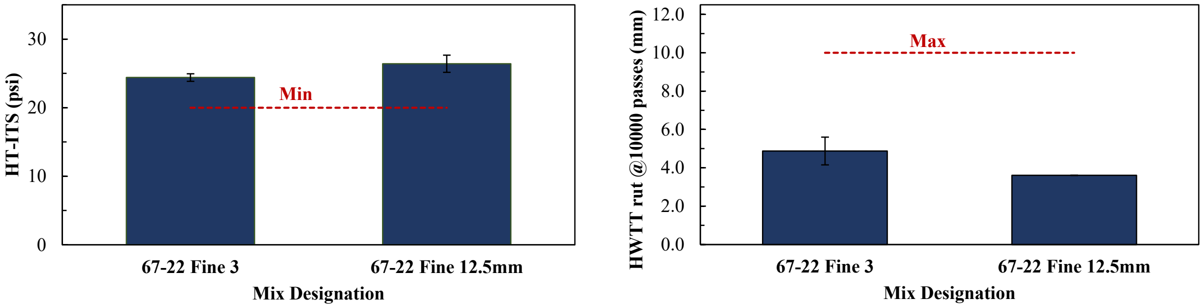
(a) CT_{Index}



(b) G_f

(c) $l_{75}/|m_{75}|$

Figure 23. Effect of NMAS on IDEAL-CT Results



(b) HT-IDT results

(b) HWTT results

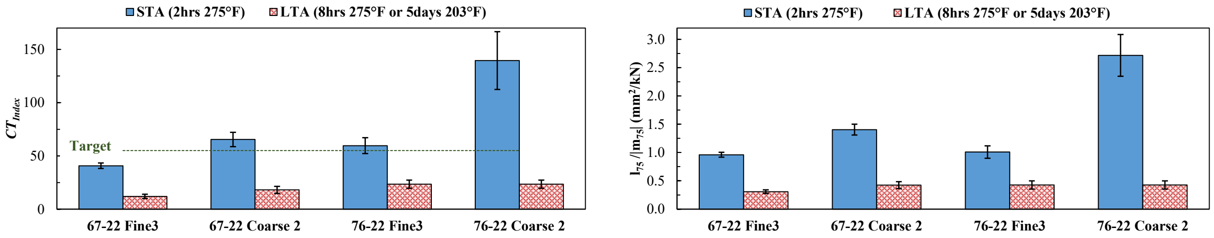
Figure 24. Effect of NMAS on Rutting Test Results

5.4. Combined Effects of Binder Grade and Gradation

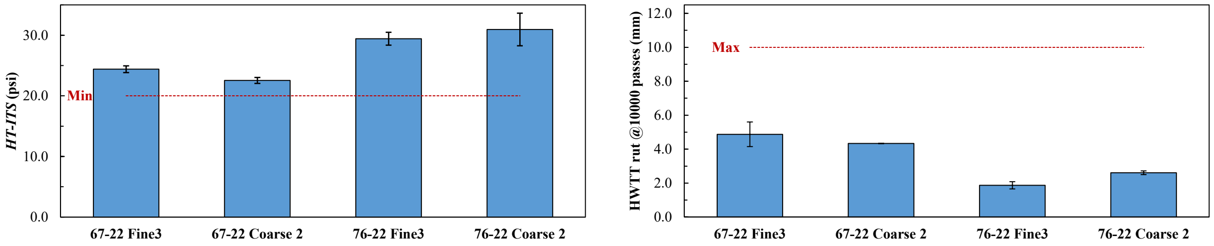
The earlier results indicated that the polymer-modified binder (PG 76-22) and the coarse gradation (Coarse2) provided the best individual improvements while maintaining or enhancing rutting resistance. This section examines the combination of these two strategies (PG 76-22 Coarse2) to determine whether they produce combined effects when applied together. The performance of this mixture is compared to that of the control (PG 67-22 Fine3) and the single-factor alternatives (PG 67-22 Coarse2 and PG 76-22 Fine3).

Figure 25 presents comparative results for the CT_{Index} and the l75/|m75| ratio under both STA and LTA conditions, as well as *HT-ITS* and HWTT rut depth under STA conditioning. Under the STA condition, the coarse gradation (Coarse2) significantly increased the CT_{Index} for both binder types, with the combined strategy (PG 76-22 Coarse2) achieving the highest value. However, this improvement did not result in similarly large improvements under the LTA condition. One possible explanation for this is that the LTA may have changed the polymer network in the PG 76-22 binder, significantly stiffening it and reducing its resistance to cracking. As a result of this alteration, both mixtures containing the PG 76-22 binder experienced a similar reduction in their CT_{index} value after the LTA.

These observations highlight that the performance changes between STA and LTA conditions can differ significantly. This finding has important implications for the implementation of BMD: selecting the appropriate laboratory aging protocols is crucial for accurately predicting field performance, and validation through field correlation studies is essential for interpreting laboratory improvements within the context of BMD.



(a) CT_{Index} (b) $l_{75}/|m_{75}|$



(c) HT-ITS (d) HWTT rut depth after 10000 passes

Figure 25. Comparison of best-performing mix component adjustment strategies

5.5. Summary of Findings (Effects of Binder and Aggregate Adjustments)

Table 10 synthesizes the effects of binder and aggregate adjustments on volumetric and performance properties relative to the control. Upward and downward arrows indicate increases and decreases, respectively; a dash represents no significant change. Green highlights desired changes, and red highlights undesirable changes. Where applicable, symbols indicate statistical significance; in other cases, they represent subjective trends observed across replicates.

The RAV approach yielded marginal benefits in terms of cracking, with negligible effects on rutting, offering a cost-effective option for modest performance improvement. Binder grade changes created more pronounced effects: the softer binder (PG 58-22) substantially improved cracking resistance but noticeably reduced rutting performance, while the polymer-modified binder (PG 76-22) enhanced both cracking and rutting performance characteristics simultaneously. Gradation adjustments demonstrated that coarser blends (Fine5, Coarse1, Coarse2) consistently improved cracking indices while maintaining acceptable rutting resistance, with Coarse2 showing good balanced performance.

Table 10. Summary of Effects of Binder and Aggregate Gradation Adjustment

Design or Performance Properties		**Selected Mixtures**					
		67-22 Fine3 (Ctrl)	**67-22 RAV Fine3**	**58-22 Fine3**	**76-22 Fine3**	**67-22 Fine5**	**67-22 Coarse2**
Design and volumetrics	Total Binder Content	—	⇧	—	—	—	—
	Percent air voids	—	⇩	—	—	—	—
Cracking Resistance	CT_{Index} (STA)	—	—	⇧	⇧	⇧	⇧
	CT_{Index} (LTA)	—	⇧	⇧	⇧	—	⇧
Rutting Resistance	*HT-ITS* (STA)	—	—	⇩	⇧	—	⇩
	HWTT (STA)	—	—	⇩	⇧	⇧	—

The findings reveal several effective approaches to enhance cracking performance. These include selective adjustments to binder grades, optimization of aggregate gradation, or a strategic combination of both. The choice of method will depend on specific project requirements, the availability of materials, economic considerations, and the desired performance levels. Building on these results, the next phase of this study will focus on investigating recycling agents and chemical WMA additives, aiming to further increase cracking resistance beyond what can be achieved through adjustments to the components alone.

6. RESULTS OF EXPERIMENT 2 - EFFECT OF ADDITIVES

The previous section demonstrated that adjusting binder grades and optimizing gradation can significantly improve cracking resistance, although these changes can have varying effects on rutting performance. This chapter explores whether chemical additives—specifically recycling agents and WMA additives—can further enhance cracking resistance beyond what is achievable through component adjustments alone.

For the evaluation of additives, two baseline mixtures were selected: PG 67-22 Coarse2, which has good cracking resistance after gradation optimization, and PG 76-22 Fine3, which offers good performance through polymer modification. Each baseline mixture was tested with four additives: two recycling agents (R1 and R2) and two chemical WMA additives (W1 and W2). The additives were applied at dosages of 2.6% and 0.5% by weight of binder, respectively. The results are categorized into two groups, each corresponding to one of the baseline mixtures. For each group, performance data for IDEAL-CT, HT-IDT, and HWTT are presented, followed by an evaluation of the balance between cracking and rutting performance.

6.1. Effects of Additives on PG 67-22 Coarse2 Mixtures

This section evaluates the impact of four additives on performance when applied to the PG 67-22 Coarse2 baseline mixture, which already has a significant improvement in cracking (CT_{Index} = 65.4) due to gradation optimization. Table 11 summarizes the performance test results for the control mixture (PG 67-22 Fine3), the baseline mixture (PG 67-22 Coarse2), and the four mixtures with additives. The detailed results are discussed in the following subsections.

Table 11. Effects of Additive on BMD Test Results (PG 67-22 Coarse 2 Baseline Mixture)

Test Method	**Property**	**Experimental Mixtures (All using a PG 67-22 binder)**					
		Fine3	**Coarse2**	**Coarse2+ R1**	**Coarse2+ R2**	**Coarse2+ W1**	**Coarse2+ W2**
IDEAL-CT (STA)	CT_{Index}	40.8	65.4	88.1	69.0	87.1	90.8
	G_f (J/m^2)	6368.7	6979.0	5114.6	5296.2	6618.5	6243.5
	L_{75}/m_{75} (mm^2/kN)	0.960	1.405	2.636	1.956	1.973	2.185
IDEAL-CT (LTA)	CT_{Index}	12.0	18.1	34.1	27.9	27.4	21.9
	G_f (J/m^2)	5834.0	6395.5	5905.4	5807.9	6785.9	6381.6
	L_{75}/m_{75} (mm^2/kN)	0.308	0.423	0.87	0.72	0.605	0.515
HT-IDT (STA)	*HT-ITS* (psi)	24.4	22.6	15.8	17.3	18.7	19.5
HWTT (STA)	Rutting at 10,000 passes (mm)	4.874	4.332	6.626	8.574		7.358
	Passes to 12.5 mm	15850	18950	10500	11450		10000

6.1.1. IDEAL-CT Results for PG 67-22 Coarse2 Mixtures

Figure 26 presents the CT_{Index} values for the control mixtures and those based on the PG 67-22 Coarse2 baseline mixture, evaluated under both STA and LTA conditions. Each data point represents the mean of four replicates, with error bars indicating ±1 standard deviation. The average COV was 9.6% for both conditioning levels, suggesting good test repeatability. Statistical groupings are shown using uppercase letters for STA and lowercase letters for LTA.

The mixtures containing additives demonstrated a higher CT_{Index} compared to the Coarse2 baseline mixture under both conditioning levels. Under STA conditions, recycling agent R1 and both WMA additives (W1 and W2) showed statistically significant improvements relative to the Coarse2 baseline mixture, with CT_{Index} values ranging from 87.1 to 90.8. This represents an enhancement of 33% to 39% over the Coarse2 baseline mixture. Although the recycling agent R2 also increased the CT_{Index} to 69.0, this improvement was less pronounced and not statistically significant. These results suggest that combining additives with gradation optimization can lead to significant improvements in cracking performance.

Under LTA conditions, the CT_{Index} values for all mixtures decreased significantly due to oxidative aging, as expected. However, the Coarse2 mixtures with additives retained higher CT_{Index} values. Mixture R1 showed the highest overall LTA performance with a CT_{Index} of 34.1, followed by R2 with a CT_{Index} of 27.9, and W1 with a CT_{Index} of 27.4. The greater reduction in CT_{Index} seen with the WMA additives is likely due to their lower STA conditioning temperature of 240°F, compared to the LTA conditioning temperature of 275°F. This lower STA conditioning temperature minimizes initial aging, resulting in greater changes brought about by the LTA process.

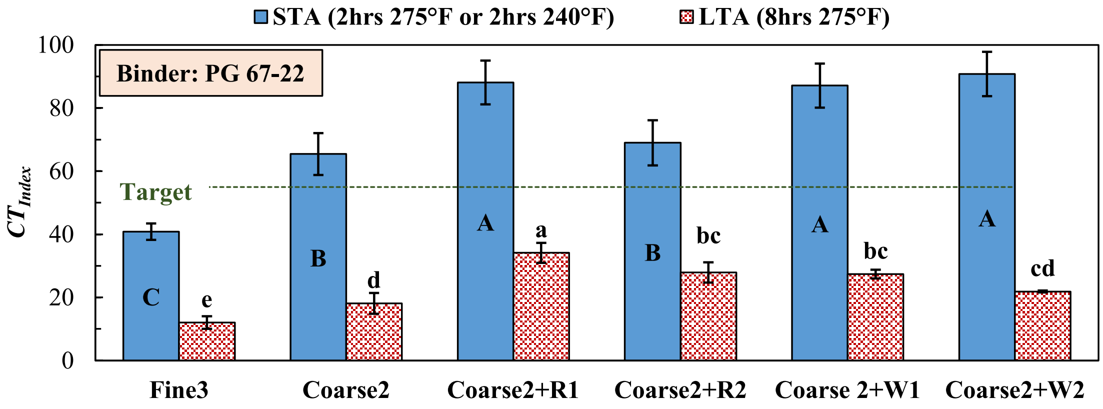


Figure 26. Effects of Additives on CT_{Index} Results for PG 67-22 Coarse2 Mixtures

***CT_{Index}* Component Analysis.** To understand the mechanisms driving these CT_{Index} improvements, the failure energy (G_f) and ductility ratio (l75/|m75|) were examined independently.

Figure 27 shows that additives reduced G_f of the Coarse2 mixtures under STA, with reductions being most pronounced for recycling agents (R1, R2). Statistical analysis confirmed that both recycling agents caused significant decreases in G_f, whereas reductions associated with WMA additives were smaller and not statistically significant. Under LTA, G_f increased for all the mixtures with additives, with W1 showing a statistically significant increase. This pattern suggests that while additives initially soften the binder (reducing G_f), extended aging partially enhances toughness.

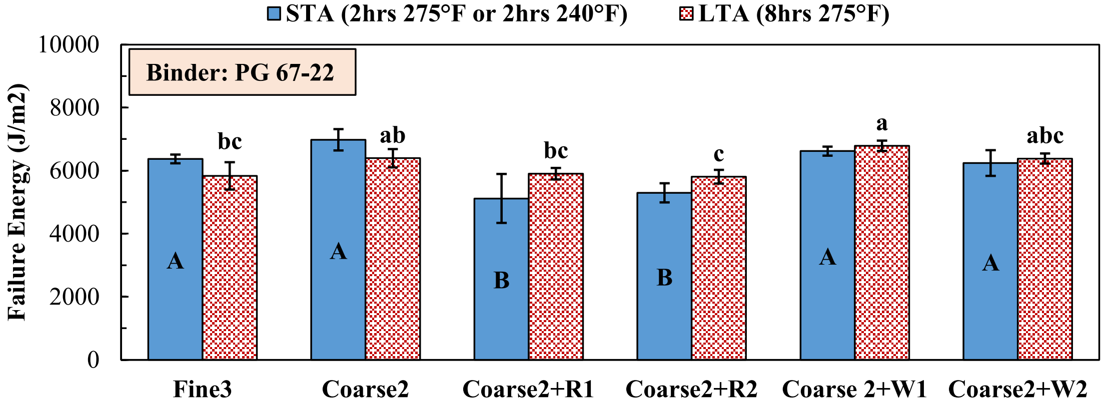


Figure 27. Effects of Additives on G_f results for PG 67-22 Coarse2 Mixtures

Figure 28 shows that the additives substantially increased the ductility parameter l75/|m75|, with improvements observed for all additives under both STA and LTA. The magnitude of this increase was most notable for recycling agents, particularly R1, which achieved values of l75/|m75| more than double those of the Coarse2 baseline mixture under STA (2.636 versus 1.405). These results confirm that additives improve CT_{Index} primarily through enhanced ductility rather than increased toughness—a mechanism similar to that observed for softer binders earlier.

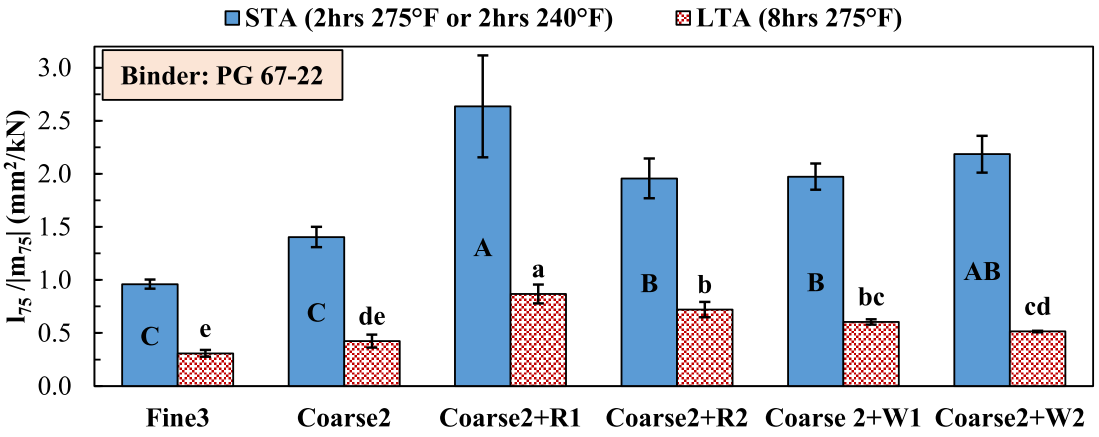


Figure 28. Effects of Additives on I75/|m75| Results for PG 67-22 Coarse2 Mixtures

6.1.2. HT-IDT Results for PG 67-22 Coarse2 Mixtures

Figure 29 presents HT-ITS values under STA. All the mixtures with additives exhibited reduced *HT-ITS* compared to the Coarse2 baseline mixture, with recycling agents producing the largest and statistically significant decreases (R1: 15.8 psi, R2: 17.3 psi). WMA additives also reduced *HT-ITS*, though these reductions were smaller in magnitude and not statistically significant (W1: 18.7 psi, W2: 19.5 psi). All mixtures containing additives did not meet the minimum threshold of 20 psi. Additives enhance cracking resistance and ductility, but they lower the material's strength at high temperatures, as shown by the HT-IDT test results.

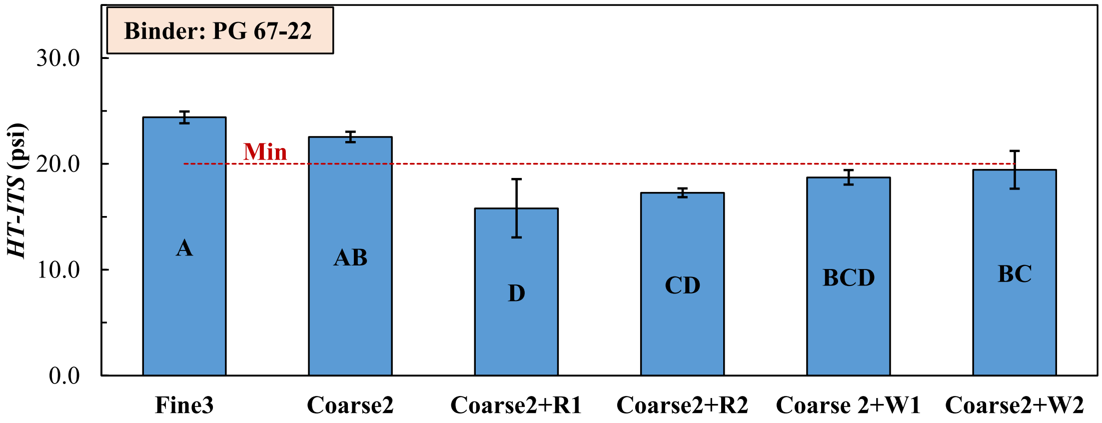


Figure 29. Effects of Additives on *HT-ITS* Results for PG 67-22 Coarse2 Mixtures

6.1.3. HWTT Results for PG 67-22 Coarse2 Mixtures

Despite the *HT-ITS* reductions, HWTT results (Figure 30) showed that all mixtures with additives maintained acceptable rutting performance. Rut depths after 10,000 passes remained below ALDOT's 10 mm criterion for all mixtures, with values ranging from 6.6 mm to 8.6 mm. Recycling agents showed higher rut depths compared to WMA additives, consistent with their greater binder softening effect. Among all additives, W1 demonstrated the lowest susceptibility to rutting.

The difference between HT-IDT and HWTT results emphasizes key distinctions between the two test methods. HT-IDT measures material strength at a single temperature and loading rate, which may be overly sensitive to the effects of binder softening. HWTT evaluates cumulative deformation under repeated loading with moisture exposure, potentially better capturing the benefits of aggregate interlock and structural support that remain intact despite binder softening. These results suggest that HWTT may provide a more balanced assessment of field rutting performance for mixtures with additives.

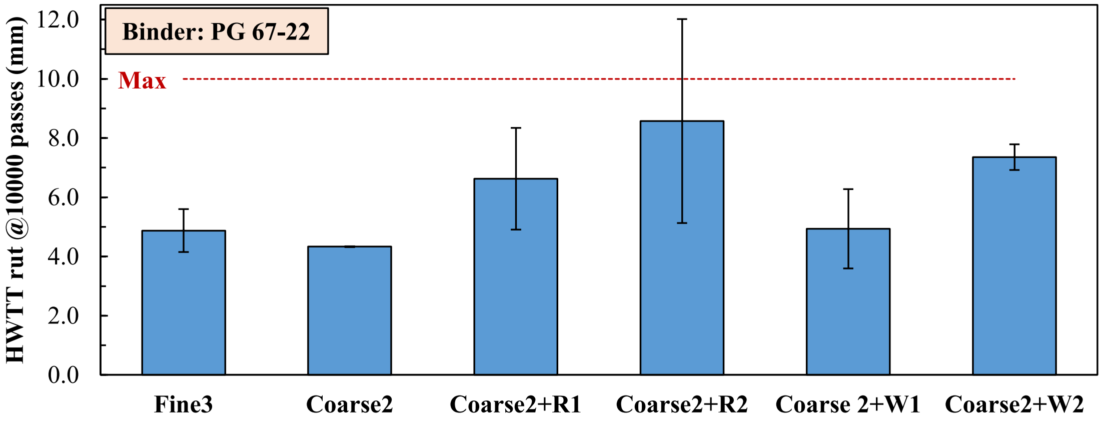


Figure 30. Effects of Additives on HWTT Results for PG 67-22 Coarse2 Mixtures

6.1.3. Balance of Cracking and Rutting Resistance for PG 67-22 Coarse2 Mixtures

Figure 31 illustrates a cracking and rutting performance diagram for the PG 67-22 Coarse2 mixtures by plotting CT_{Index} against *HT-ITS*. Mixtures with additives shifted toward the lower-right portion of the performance space, indicating improved cracking resistance accompanied by reduced high-temperature strength.

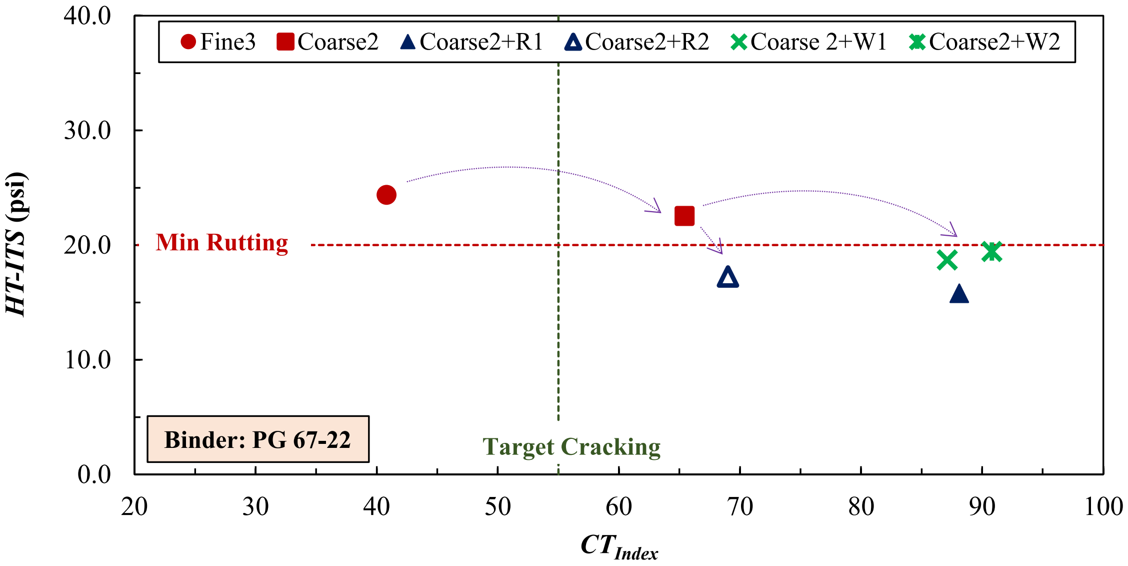


Figure 31. Effects of Additives on Balance of Cracking and Rutting Resistance for PG 67-22 Coarse2 Mixtures

The results indicate that chemical additives can significantly enhance CT_{Index}, with improvements of 30-40% over the Coarse2 baseline mixture. However, this improvement is accompanied by a decrease in HT-ITS. It is important to note that the HWTT results showed that all mixtures with additives maintained acceptable performance against rutting. This highlights the necessity of validating laboratory thresholds with field performance data to ensure that specification criteria are appropriate.

6.2. Effects of Additives on PG 76-22 Fine3 Mixtures

This section examines the effect of the four additives on the performance of the PG 76-22 Fine3 baseline mixture, which exhibits balanced performance due to polymer modification. The research question was whether the high-temperature properties of the polymer-modified binder could counteract the softening effects of the additives. The goal was to determine if this combination could lead to improvements in cracking resistance while still maintaining sufficient rutting resistance.

Table 12 summarizes performance test results for the control (PG 67-22 Fine3), the baseline mixture (PG 76-22 Fine3), and the four mixtures with additives. A discussion of individual test results follows in the subsequent subsections.

Table 12. Effects of Additives on BMD Test Results for PG 76-22 Fine3 Mixtures

Test Method	**Property**	**Experimental Mixtures (All using Fine3 Aggregate Gradation)**					
		67-22	**76-22**	**76-22+R1**	**76-22+R2**	**76-22+W1**	**76-22+W2**
IDEAL-CT (STA)	CT_{Index}	40.8	59.6	89.0	71.1	90.6	72.8
	G_f (J/m^2)	6368.7	8859.8	7289.7	6815.2	8174.8	8068.9
	L_{75}/m_{75} (mm^2/kN)	0.960	1.008	1.831	1.565	1.662	1.350
IDEAL-CT (LTA)	CT_{Index}	12.0	19.0	24.3	26.3	21.2	19.5
	G_f (J/m^2)	5834.0	8028.0	7651.3	7259.0	8015.1	7610.4
	L_{75}/m_{75} (mm^2/kN)	0.308	0.353	0.474	0.542	0.396	0.377
HT-IDT (STA)	*HT-ITS* (psi)	24.4	29.4	23.3	27.8	24.8	24.2
HWTT (STA)	Rutting at 10,000 passes (mm)	4.874	1.868	4.564	4.662	2.445	2.485
	Passes to 12.5 mm	15850	> 2000	15350	14350	> 2000	> 2000

6.2.1. IDEAL-CT Results for PG 76-22 Fine3 Mixtures

Figure 32 presents CT_{Index} values for the PG 76-22 Fine3 mixtures under STA and LTA conditioning. The average COV was 13.0%, slightly higher than the PG 67-22 Coarse2 mixtures but still indicating reasonable repeatability. Statistical groupings follow the same convention as the previous section.

Similar to the PG 67-22 Coarse2 mixtures, all PG 76-22 Fine3 mixtures with additives increased CT_{Index} relative to the PG 76-22 Fine3 baseline mixture under STA. Recycling agent R1 and WMA additive W1 achieved the highest values (89.0 and 90.6, respectively), representing improvements of approximately 50% over the baseline mixture. All additives except R2 produced statistically significant CT_{Index} gains.

Under LTA, CT_{Index} values for all mixtures with additives remained higher than those of the 76-22 Fine3 baseline mixture, although the differences were not statistically significant due to the increased variability under extended aging. Recycling agents were less affected by long-term aging compared to WMA additives. This was likely due to the lower STA conditioning temperature used for WMA mixtures (240°F), which resulted in less aging during STA conditioning and, consequently, more aging over the long term.

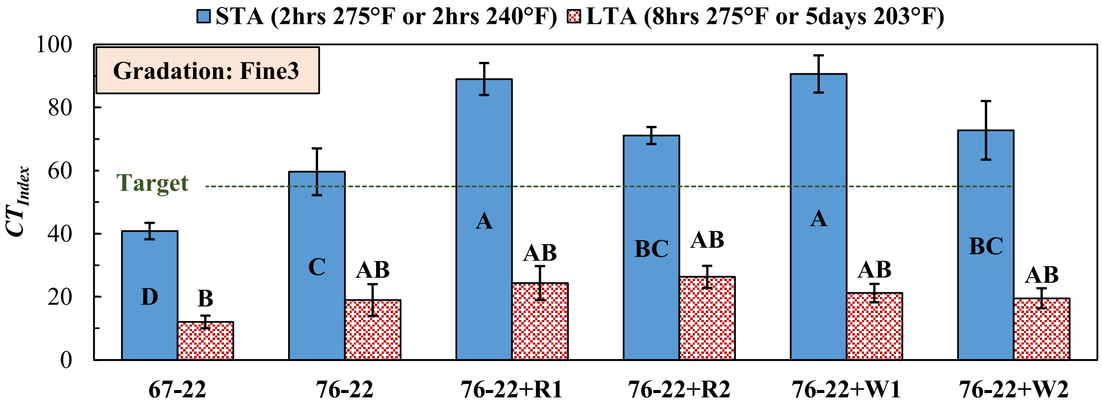


Figure 32. Effects of Additives on $\mathrm{CT}_{\mathrm{Index}}$ Results for PG 76-22 Fine3 Mixtures

***CT_{Index}* Component Analysis.** Figure 33 shows G_f trends similar to those observed in the PG 67-22 Coarse2 mixtures. Under STA, all additives reduced G_f relative to the 76-22 Fine3 baseline mixture, with recycling agents producing the most reductions. Statistical groupings confirmed that mixtures with WMA additives maintained significantly higher G_f than mixtures with recycling agents. Under LTA, differences among mixtures narrowed substantially, with mixtures with recycling agents exhibiting increased G_f after extended aging.

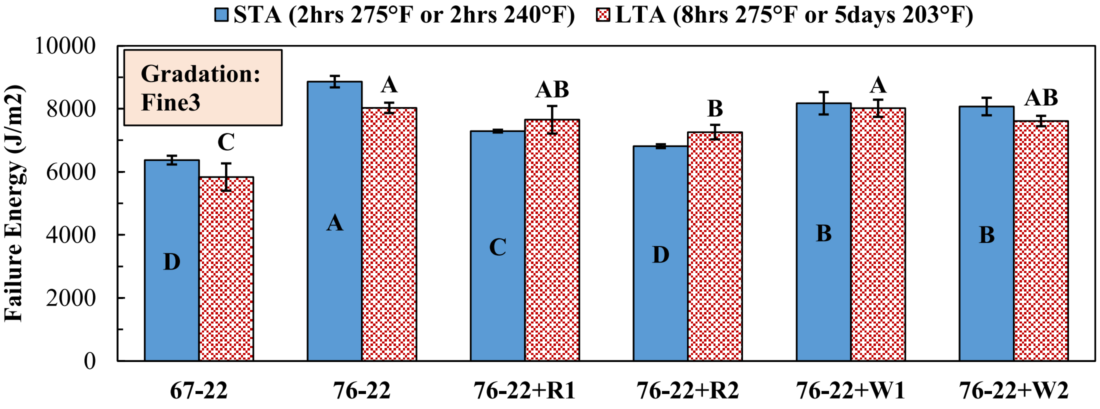


Figure 33. Effects of Additives on G_f Results for PG 76-22 Fine3 Mixtures

Figure 34 demonstrates that, as with the PG 67-22 Coarse2 mixtures, CT_{Index} improvements stemmed primarily from increased $l_{75}/|m_{75}|$ rather than enhanced toughness. Additives, particularly W1 and R1, significantly elevated this ductility parameter compared to the PG 76-22

Fine3 baseline mixture, confirming that the ductility enhancement mechanism operates consistently across both binder grades.

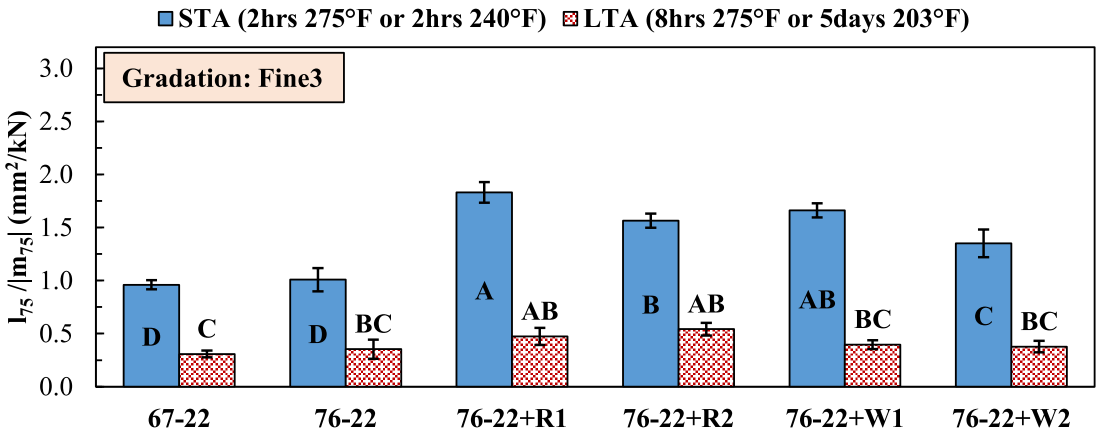


Figure 34. Effects of Additives on $I_{75}/|m_{75}|$ Results for PG 76-22 Fine3 Mixtures

6.2.2. HT-IDT Results for PG 76-22 Fine3 Mixtures

Figure 35 shows the results of the HT-ITS tests under STA conditioning. Unlike the PG 67-22 Coarse2 mixtures, all PG 76-22 Fine3 mixtures with additives maintained *HT-ITS* values above the minimum threshold of 20 psi. This indicates that the excellent high-temperature properties of the polymer-modified binder effectively counteract the softening effects of the additives.

Reductions in HT-ITS relative to the PG 76-22 Fine3 baseline mixture were observed for all additives except R2, though all values remained acceptable. The smallest reduction occurred for R2 (27.8 psi versus 29.4 psi baseline), while the largest occurred for R1 (23.3 psi). Despite these differences, overall high-temperature strength remained satisfactory for all mixtures, confirming that additive incorporation into polymer-modified binder systems does not compromise minimum rutting resistance requirements when measured by HT-IDT.

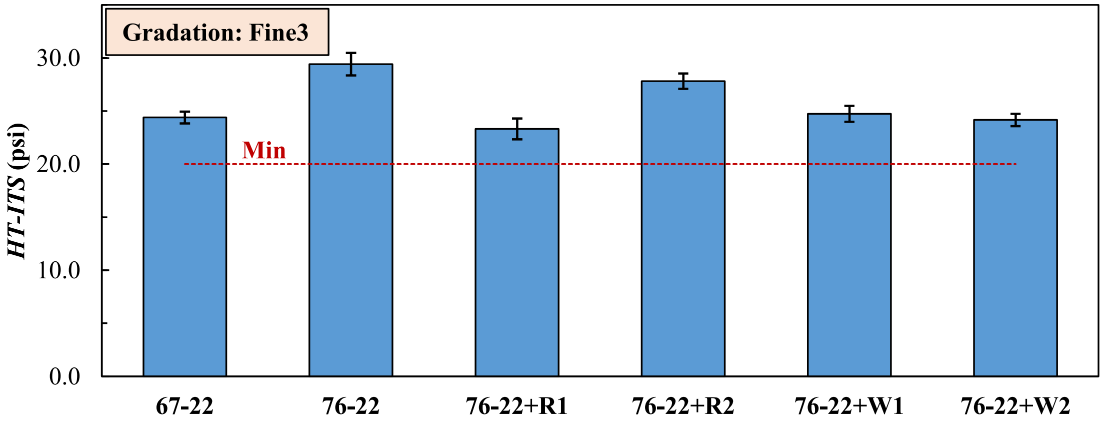


Figure 35. Effects of Additives on HT-ITS Results for PG 76-22 Fine3 Mixtures

6.2.3. HWTT Results for PG 76-22 Fine3 Mixtures

Figure 36 shows HWTT rut depths after 10,000 passes. Additives slightly increased rutting compared to the PG 76-22 Fine3 baseline mixture, with the largest increases observed for mixtures with recycling agents (R1: 4.6 mm, R2: 4.7 mm). WMA additives produced smaller rutting increases (W1: 2.4 mm, W2: 2.5 mm), maintaining rutting performance closer to the PG 76-22 Fine3 baseline mixture (1.9 mm).

All mixtures with additives remained well below ALDOT's 10 mm criterion and exhibited better rutting resistance than the unmodified control (PG 67-22 Fine3) with a rut depth of 4.9 mm. These results indicate that polymer modification provides sufficient rutting resistance margin to accommodate the softening effects of additives.

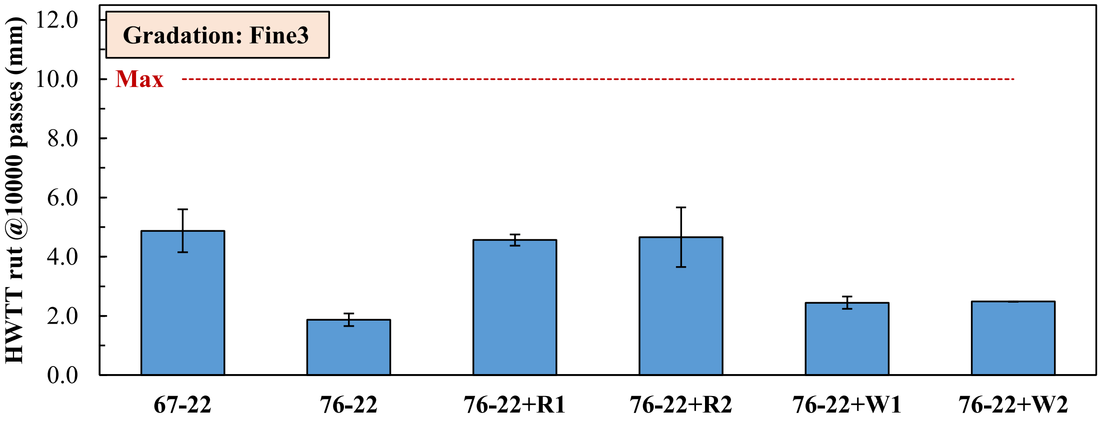


Figure 36. Effects of Additives on HWTT results for PG 76-22 Fine3 Mixtures

6.2.4. Balance of Cracking and Rutting Performance for PG 76-22 Fine3 Mixtures

Figure 37 illustrates a performance diagram for the PG 76-22 Fine3 mixtures. The PG 76-22 Fine3 mixtures with additives shifted toward the upper-right region of the performance space, representing simultaneous achievement of CT_{Index} improvements and maintenance of *HT-ITS* above the minimum criterion.

This outcome demonstrates that two-step modification—combining polymer-modified binder with selected additives—can substantially enhance cracking resistance while maintaining rutting performance. The increased rutting resistance provided by polymer modification appears to offset the softening introduced by recycling agents or WMA additives, resulting in balanced overall performance that meets both cracking and rutting criteria. This represents an important practical pathway for agencies seeking maximum cracking improvement without compromising rutting resistance.

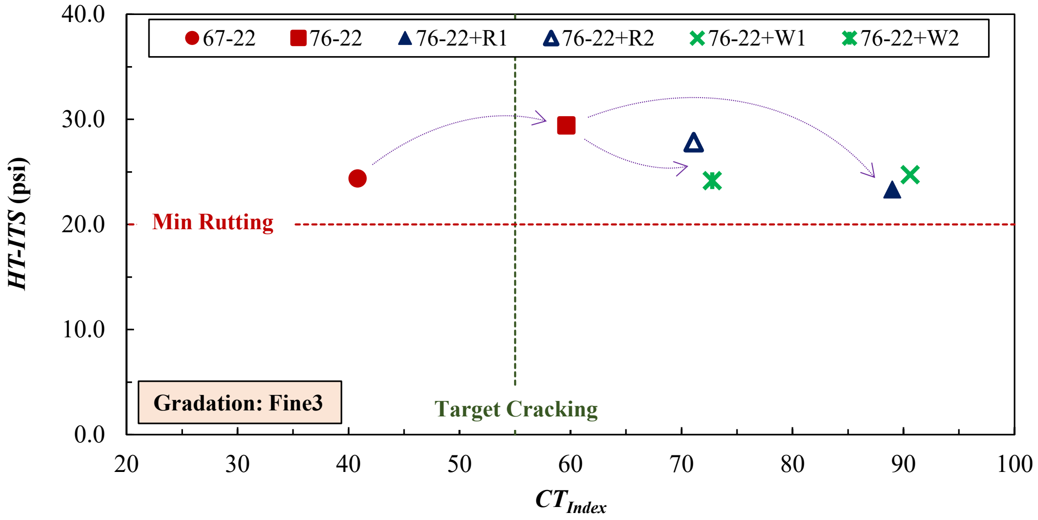


Figure 37. Effects of Additives on Balance of Cracking and Rutting Resistance for PG 76-22 Fine3 Mixtures

6.3. Summary of Additive Effects

The findings demonstrate that chemical additives can substantially improve cracking performance when applied to optimized baseline mixtures, though the rutting implications differ depending on the baseline mixture's initial rutting resistance margin. Below are specific observations.

- **Cracking Improvement.** All additives increased CT_{Index} under both STA and LTA conditioning, with improvements ranging from 30-50% over the baseline mixtures. R1 and W1 consistently provided the largest gains. Also, additives improve CT_{Index} primarily through enhanced ductility ($l_{75}/|m_{75}|$) rather than increased toughness (G_f), similar to the mechanism observed for softer binders.
- **Rutting Resistance.** Use of additives reduces *HT-ITS* across all mixtures, with recycling agents producing larger reductions than WMA additives. However, the practical significance depends on the rutting resistance of the baseline mixtures.

In summary, the findings suggest that effectively applying additives to enhance cracking performance requires a careful selection of the baseline mixture. Polymer-modified binders provide a good foundation for additive application, enabling significant improvements in cracking resistance while maintaining rutting resistance. In the case of unmodified binders, optimizing the gradation can enhance rutting resistance and support the use of additives.

7. CONCLUSIONS AND RECOMMENDATIONS

This study evaluated practical strategies to enhance the cracking resistance of ALDOT surface mixtures while ensuring acceptable rutting performance within a balanced mix design framework. For analysis, this study used a target CT_{Index} of 55.0, a minimum *HT-ITS* value of 20.0, and a maximum allowable HWTT rut depth of 10.0 mm (ALDOT, 2022c). Based on these criteria, the control mixture meets the requirements for rutting resistance but does not meet the threshold for cracking resistance. This outcome underscores the need for enhanced cracking resistance as the primary focus of the BMD framework evaluated in this study. The study evaluated three types of adjustments:

- Binder-related adjustments, which included increasing binder content by regressing air voids, as well as using a softer binder and a modified binder.
- Aggregate-related adjustments, focusing on gradation and nominal maximum aggregate size.
- Chemical additives, which involve the use of recycling agents and warm mix additives.

The findings help provide guidance for ALDOT and contractors on optimizing asphalt mixture performance by adjusting the mixture components.

7.1. Binder-Related Strategies

The regressed air voids approach, which reduces design air voids from 4.0 to 3.0 percent, increased the binder content by 0.3 to 0.4 percent. This change resulted in a modest improvement in the CT_{Index}, primarily due to enhanced ductility, with minimal impact on toughness or rutting resistance. This approach represents a refinement suitable for incremental improvements. Its ease of implementation makes it a viable strategy.

The use of a softer binder (PG 58-22) significantly increased the CT_{Index} and successfully met the cracking target. However, it resulted in a reduction of *HT-ITS* to below 20 psi and caused the HWTT rut depth to exceed 10 mm. For this mixture composition, solely using a softer binder grade to enhance cracking resistance may not provide adequate rutting resistance. When considering this method, additional adjustments, such as optimizing gradation, may be needed to achieve acceptable rutting performance.

Using a polymer-modified binder (PG 76-22) enhances resistance to both cracking and rutting. This binder enhances the CT_{Index} and G_f values for cracking resistance while improving *HT-ITS* and HWTT results for rutting resistance. The advantages of this polymer modification are its ability to enhance both toughness and high-temperature stiffness without compromising overall performance, providing the best balance among all binder-related strategies.

7.2 Gradation-Based Strategies

Coarser mid-range gradations, characterized by a lower percentage of material passing through the #8 sieve, significantly increased the CT_{Index} while still maintaining acceptable rutting performance. Specifically, coarser blends—Fine5 and Coarse2—achieved CT_{Index} values exceeding 55. These blends also maintained an *HT-ITS* above 20 psi and HWTT rut depths below 10 mm, demonstrating that optimizing gradation can lead to substantial improvements in cracking resistance without altering the binder grade or content.

Increasing the nominal maximum aggregate size (NMAS) from 9.5 mm to 12.5 mm had little effect on both cracking and rutting resistance. This indicates that simply changing the NMAS is not an effective strategy for adjustments within standard mix design limits.

7.3 Additive Strategies

Chemical additives, such as recycling agents and WMA additives, can improve the CT_{Index} of asphalt mixtures. When these additives were incorporated into a mixture with an unmodified binder (PG 67-22 Coarse2), the CT_{Index} increased by 30-39%. However, the *HT-ITS* dropped below 20 psi. Despite this, the HWTT rut depths remained below the 10 mm threshold. This discrepancy suggests that *HT-ITS* may be overly sensitive to binder softening, whereas the HWTT results may better reflect the rutting resistance provided by aggregate interlock and pavement confinement.

When the additives were used in a polymer-modified mixture (PG 76-22 Fine3), the CT_{Index} increased by approximately 50%. Additionally, both the *HT-ITS* remained above 20 psi, and the HWTT remained below 10 mm. This approach demonstrates that using a polymer-modified binder offers a sufficient performance margin to counteract the softening effects of additives while maximizing resistance to cracking.

7.4 Recommendations

Based on the findings of this study, the following recommendations provide practical guidance for ALDOT and contractors seeking to improve cracking resistance while maintaining balanced performance.

- Gradation optimization can be a cost-effective approach for improving cracking resistance. This approach requires no premium materials and can achieve higher CT_{Index} values exceeding 55 while maintaining acceptable rutting resistance. Specifically, coarser mid-range gradations, characterized by P_8 values of 41-47%, demonstrated substantial improvements in cracking. However, the effectiveness of this strategy depends on the availability and characteristics of local aggregate materials, requiring validation through mixture testing.
- The regressed air voids approach, which reduces design air voids from 4.0% to 3.0%, can provide incremental improvements with minimal impact on rutting. This strategy is suitable as a refinement when additional cracking resistance is required without altering the binder grade or gradation. The simplicity and ease of implementation make this a viable complementary adjustment to gradation optimization.
- Using a softer binder (PG 58-22 instead of PG 67-22) can significantly increase CT_{Index} and meet cracking targets. However, this study demonstrated that such binder softening reduced *HT-ITS* below 20 psi and increased HWTT rut depth beyond 10 mm for the evaluated mixture. Therefore, this approach may be combined with other adjustments to enhance rutting resistance.
- For high-traffic applications or pavements requiring enhanced performance, upgrading from PG 67-22 to polymer-modified PG 76-22 binder provides improvements in both cracking and rutting resistance. This approach increased CT_{Index} to approximately 60 while improving *HT-ITS* to 29.4 psi and reducing HWTT rut depth to less than 2 mm. This method offers the most balanced performance among single-component adjustments, but it results in higher material costs. Prioritization for implementation may be given to interstate highways and primary routes where the performance justifies the additional expense.

- Chemical additives, such as rejuvenators and WMA additives, can significantly improve CT_{Index} values, although the extent of improvement varies depending on the asphalt mixture. Their dosages can be optimized through performance testing.

7.5 Recommendations for Implementation

These strategies for improving cracking resistance can be implemented through an iterative process, first in the laboratory, then with field trials, finally with broad implementation.

First, a representative sample of existing approved mix designs should be altered using one or more of the cracking resistance improvement strategies recommended. The original designs and altered designs can be tested using IDEAL-CT, HT-IDT, and HWTT. Analysis of test results can be performed to evaluate the effect of each strategy or combination of strategies on each mix design regarding cracking and rutting test performance.

After one or more of the strategies have proven effective for a representative sample of approved mix designs field trials can begin. Field trials can be located in several different regions of the state to test mixture performance using different aggregates, in different field conditions, and with varying traffic levels. During the field trial process, it is important to keep communication open with all stakeholders including but not limited to: ALDOT central office personnel, industry partners, Area ALDOT personnel, and academic partners.

Recommendations for Field Trials:

- The control mix can be designed and approved by the current ALDOT process, then tested using IDEAL-CT, HT-IDT, and HWTT.
- Mix designs for each trial section can be designed by altering the control design using one or more of the mitigation strategies. Each trial mix design can be tested using IDEAL-CT, HT-IDT, and HWTT. Mix designs that perform poorly during one or more of the performance tests may be reconsidered.
- If multiple cracking mitigation strategies are to be used together for a single mix design, it would also be beneficial to place trial sections with each mitigation strategy applied separately to isolate variables.
- During production and construction of each mixture, samples can be collected and compacted in both plant mixed laboratory compacted – hot compacted (PMLC-HC) and plant mixed laboratory compacted – reheated (PMLC-RH) conditions. These specimens can be tested using IDEAL-CT, HT-IDT, and HWTT to better understand how mixture performance changes between design, production, and after reheating.
- Trial sections can be at least 1000 feet in length while longer sections are preferable.
- Each field trial section can be clearly marked and geo located for ease of monitoring using ALDOT's pavement management system, or by NCAT.
- A portion of the project paved with the control mix can also be clearly marked and located to be used as the control section.
- Personnel can be present during construction to note any challenges during the production and construction process.

Following successful placement of field trials varied in location, aggregate sources, and traffic levels to ALDOT's satisfaction, ALDOT can elect to continue monitoring field trials for a time deemed sufficient or begin a broader implementation effort. During this phase of implementation, it is once again important to communicate with all stakeholders. Mechanical test data along with volumetric data and any noted production and construction challenges can be analyzed and considered when drafting specifications for implementation.

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