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Importance of Fine Aggregates in Achieving Adequate Skid Resistance in TxDOT Hot Mix Asphalt Mixtures

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Abstract

Skid resistance is a critical roadway-safety characteristic, but it is not routinely evaluated during asphalt mixture design. TxDOT Project 0-7108 evaluated practical methods for improving the long-term frictional performance of hot-mix asphalt mixtures, particularly mixtures containing aggregates with relatively low polishing resistance. The experimental program examined material-related factors (binder grade and aggregate type), mixture-design factors (binder content, aggregate gradation, mixture type, and the distribution of aggregate types within individual gradation fractions), and a construction-related factor (air-void content). Laboratory specimens were polished with the Three-Wheel Polishing Device (TWPD), and friction was measured with the Dynamic Friction Tester (DFT). Field sections and producer mixture designs were also evaluated, and the modified mixtures were checked for rutting, cracking, and moisture-damage performance. Within the materials and ranges evaluated, aggregate type had the dominant effect on long-term friction, whereas binder grade, binder content, overall gradation, mixture type, and air-void content had comparatively small effects after the binder film was removed. Fraction-specific testing showed that the intermediate aggregate fraction—passing the No. 4 sieve and retained on the No. 30 sieve (4.75–0.60 mm)—was especially important. The No. 4-to-No. 16 subfraction (4.75–1.18 mm) provided the largest contribution, while replacing only the material passing the No. 30 sieve provided little benefit. Targeted replacement of low-friction aggregate in the critical fraction improved terminal DFT friction while limiting the quantity of premium aggregate required. Producer case studies increased terminal DFV from 0.21 to 0.28 for an SP-C mixture and from 0.25 to 0.32 for an SMA-D mixture without compromising the evaluated mechanical performance. The proposed laboratory friction levels and the approximately 0.30 terminal-DFV screening value should be considered provisional until they are correlated with field friction and validated through implementation projects.

Implementation Statement/

The project findings can be implemented as a staged friction-screening and mixture-optimization process. During mixture development, TxDOT and the producer should identify the Surface Aggregate Classification and polishing resistance of each aggregate source, determine which stockpiles contribute material to the critical No. 4-to-No. 16 fraction, and evaluate the approved BMD mixture using TWPD polishing and DFT measurements. When the terminal DFV is below the project-specific screening level, the first corrective action should be to replace or redistribute the aggregate source contributing to the critical intermediate fraction rather than replacing the entire aggregate blend.

Any modified mixture should then be rechecked for volumetrics and the applicable rutting, cracking, and moisture-damage requirements before field use. Because a direct laboratory-to-field acceptance relationship has not yet been established, the proposed terminal-DFV levels—particularly the approximate 0.30 screening value—should not be adopted as specification acceptance limits at this time. TxDOT should first construct and monitor pilot sections, collect laboratory and field friction data over time, evaluate laboratory repeatability and between-laboratory reproducibility, and adjust the criteria as warranted. The companion project guideline provides the recommended step-by-step process for this staged implementation.

Executive Summary

Roadway friction is a functional safety property that is not routinely included in conventional asphalt mixture design. Project 0-7108 investigated whether friction can be considered alongside rutting, cracking, and moisture-damage performance and whether mixtures containing low-polishing aggregates can be improved without replacing the complete aggregate blend.

The research combined a literature review, controlled laboratory testing, field trend verification, laboratory case studies, and optimization of producer mixture designs. Laboratory rings were polished with the TWPD and tested with the DFT. The program evaluated binder grade, binder content, aggregate type, aggregate gradation, mixture type, aggregate distribution among gradation fractions, and compacted air-void content.

Aggregate type was the dominant control on long-term friction. The intermediate fraction passing the No. 4 sieve and retained on the No. 30 sieve was more influential than the coarse fraction retained on the No. 4 sieve or the fines passing the No. 30 sieve. Within the intermediate fraction, the No. 4-to-No. 16 material produced the largest contribution. Binder grade, binder content, overall gradation, mixture type, and air-void content had comparatively small long-term effects within the ranges evaluated.

The case studies demonstrated that friction can often be improved economically by concentrating a polish-resistant aggregate in the source bin contributing most strongly to the critical fraction. The modified producer SP-C mixture increased terminal DFV from 0.21 to 0.28, while the modified SMA-D mixture increased from 0.25 to 0.32. The SP-C result also demonstrates that one optimization step may not be sufficient to meet a selected screening value.

The project recommends a staged implementation program rather than immediate specification adoption. TxDOT should conduct pilot projects, establish laboratory repeatability and between-laboratory reproducibility, and correlate terminal laboratory DFV with field friction and service conditions. Until that work is completed, the approximate 0.30 terminal-DFV value should be used only as a provisional screening indicator.

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CHAPTER 1

INTRODUCTION

Flexible and rigid pavements are the two principal pavement types used worldwide (Aziz et al., 2015). In the United States, flexible pavements account for more than 90% of the roadway network, with the remainder consisting primarily of rigid and composite pavements (Pavement Facts). Flexible pavements are widely used because they generally provide lower initial construction costs, good ride quality, relatively straightforward maintenance, and rapid opening to traffic after construction (Kipyator, 2013; Pranav et al., 2020).

A flexible pavement consists of multiple layers, including the subgrade, base, and asphalt binder and surface courses (Gottam et al., 2020). The asphalt surface course is particularly important because it is directly exposed to traffic loading and changing environmental conditions and therefore strongly influences both structural and functional pavement performance (Titus-Glover et al., 2019; Diefenderfer et al., 2023).

Recent advances in binder modification and asphalt mixture design have improved resistance to common pavement distresses (Yildirim, 2007; Kök et al., 2011; Costa et al., 2013; Liu et al., 2018b; Brown et al., 1997; Han et al., 2016; Lee et al., 2023). Collectively, these advances have supported the transition toward performance-based asphalt mixture design, including the Balanced Mix Design (BMD) process (West et al., 2018; Castillo, 2020; Li et al., 2023; Rocha et al., 2023).

The Federal Highway Administration (FHWA) Expert Task Group and AASHTO PP 105 define BMD as an asphalt mixture design process that uses performance tests on appropriately conditioned specimens to address multiple distress modes while considering mixture aging, traffic, climate, and the mixture's location within the pavement structure (AASHTO, 2022a).

BMD is intended to produce mixtures that provide an appropriate balance between rutting and cracking resistance; however, the functional performance of the pavement surface is also essential. User comfort is affected by pavement roughness and distress, while safety is influenced by roadway geometry, weather, vehicle and driver characteristics, and pavement-surface friction (Malone et al., 2017; Abrantes et al., 2023; Li et al., 2022; Chen et al., 2017; Fwa, 2021; Zhu et al., 2021). Skid resistance is particularly important under wet conditions. Musey et al. (2016), for example, reported an R^2 value of 0.62 between skid number and the percentage of crashes at the evaluated locations.

Transportation agencies have established programs to address wet-weather crash risk. TxDOT's Wet Weather Accident Reduction Program and a similar New Jersey Department of Transportation program use pavement-friction information to identify and treat locations with elevated risk (TxDOT, 2006; NJDOT, 2018). Despite these efforts, friction is not routinely considered during asphalt mixture design. Incorporating a friction evaluation into BMD would allow mixture designers to address functional safety and structural durability within a coordinated performance framework.

PURPOSE OF THE STUDY

The purpose of this research was to determine the importance of fine and intermediate aggregate fractions in achieving adequate skid resistance in TxDOT hot-mix asphalt mixtures and to develop a practical framework for considering friction together with conventional BMD performance. The study objectives were to:

- a. Conduct a comprehensive review of the BMD process and the mechanisms that govern pavement friction;
- b. Identify material-, mixture-design-, and construction-related parameters that may influence asphalt mixture friction;
- c. Quantify the effects of selected parameters through controlled laboratory testing;
- d. Verify the controlling parameters using field friction measurements;
- e. Conduct laboratory and producer case studies to improve the frictional performance of mixtures with inadequate friction; and
- f. Evaluate whether the friction-improvement strategies maintain acceptable rutting, cracking, and moisture-damage performance.

REPORT ORGANIZATION

This report is organized into eight chapters. Chapter 1 introduces the research need, purpose, and objectives. Chapter 2 reviews BMD and the parameters that influence asphalt mixture friction. Chapter 3 identifies the research gaps and presents the research methodology. Chapter 4 describes the materials, specimen preparation, and test methods. Chapter 5 presents the controlled laboratory evaluation of friction-controlling parameters. Chapter 6 verifies selected parameters using field measurements. Chapter 7 presents laboratory and producer case studies for improving mixture friction. Chapter 8 summarizes the conclusions, study limitations, and recommendations. Appendix A provides the Value of Research (VOR).

CHAPTER 2

LITERATURE REVIEW

This chapter reviews research relevant to incorporating frictional performance into the Balanced Mix Design (BMD) framework. The first part summarizes material- and mixture-related factors that influence rutting and cracking resistance. The second part reviews pavement-friction mechanisms, texture characteristics, and the parameters that influence asphalt mixture friction. Summary tables consolidate the principal findings and identify areas that were not adequately addressed in the available literature.

BALANCED MIX DESIGN PROCESS

In September 2015, the Federal Highway Administration (FHWA) Expert Task Group on Mixtures and Construction established a task force dedicated to Balanced Mix Design (BMD) (NAPA). The task force sought to improve mixture-performance reliability, encourage innovation for mixtures with inadequate field performance, and support cost-effective mixture optimization. AASHTO PP 105 defines BMD as an asphalt mixture design procedure that uses performance testing of conditioned specimens to evaluate multiple distress modes while accounting for aging, traffic, climate, and the mixture's location in the pavement structure (AASHTO, 2022a). Four primary BMD approaches are illustrated in Figure 1 and summarized below.

Approach A: Volumetric Design with Performance Verification at the Optimum Binder Content (OBC). Under this approach, the mixture is designed to satisfy all applicable volumetric requirements. Performance testing is then conducted at the selected OBC to verify that the mixture also meets the established performance criteria.

Approach B: Volumetric Design with Performance Optimization at the Preliminary OBC. The mixture must initially satisfy the volumetric requirements; however, moderate adjustments to the binder content are permitted to achieve the desired performance while maintaining acceptable volumetric properties.

Approach C: Performance-Modified Volumetric Design. An initial aggregate gradation and binder content are selected, and the mixture is evaluated using the specified performance tests. When the performance requirements are not satisfied, the aggregate gradation and binder content may be adjusted. Under this approach, certain volumetric requirements may be modified or eliminated to obtain an acceptable balance between mixture performance and volumetric properties.

Approach D: Performance Design. An initial aggregate gradation and binder content are selected and evaluated according to the required performance criteria. If the mixture does not meet these criteria, the mixture proportions are adjusted until satisfactory performance is achieved. This approach relies primarily on performance-test results and does not require the mixture to satisfy traditional volumetric criteria.

Effect of Asphalt Mixture Parameters on the BMD Process

Although four primary approaches are available for balancing the rutting and cracking resistance of asphalt mixtures, the effectiveness of each approach is strongly influenced by the characteristics

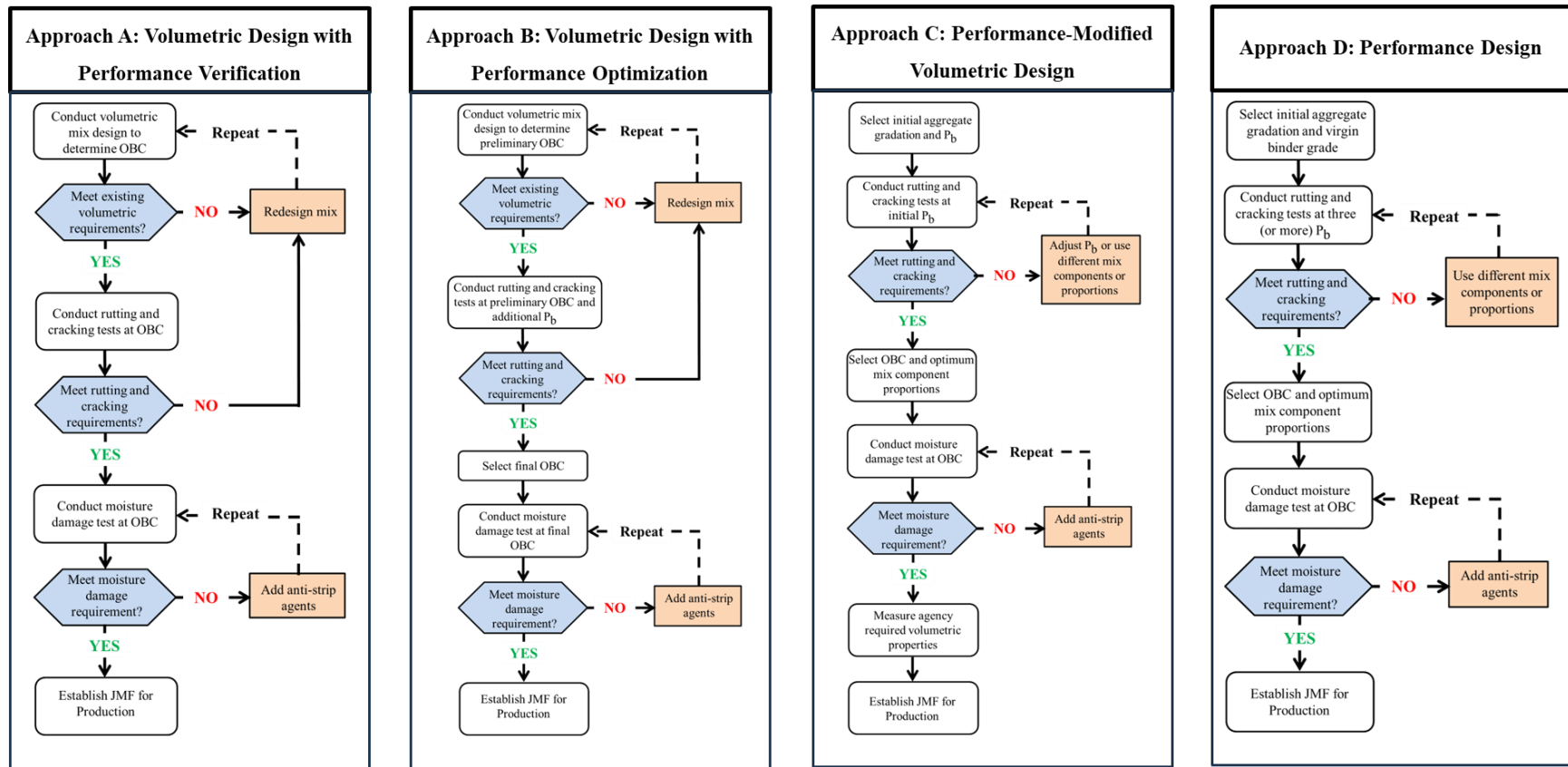


Figure 1: Four Approaches for BMD Process (NAPA).

of the mixture. Key parameters affecting the BMD process include binder content, binder grade, mixture volumetrics, aggregate gradation, mixture type, and aggregate properties. The following subsections discuss the influence of these parameters on mixture performance within the BMD framework. The studies reviewed in these subsections are limited specifically to research conducted in the context of Balanced Mix Design.

Effect of Binder Percentage

The asphalt binder coats and binds aggregate particles of different sizes, producing a cohesive asphalt mixture. The binder content selected through laboratory testing to satisfy the specified volumetric criteria is commonly referred to as the optimum binder content (OBC). Binder contents above the OBC generally improve cracking resistance but may increase the mixture's susceptibility to permanent deformation. Conversely, binder contents below the OBC may enhance rutting resistance while increasing the potential for cracking. Within the BMD framework, an acceptable binder-content range is therefore established by identifying the values that satisfy both the rutting and cracking performance criteria, as illustrated in Figure 2 (Zhou *et al.*, 2006).

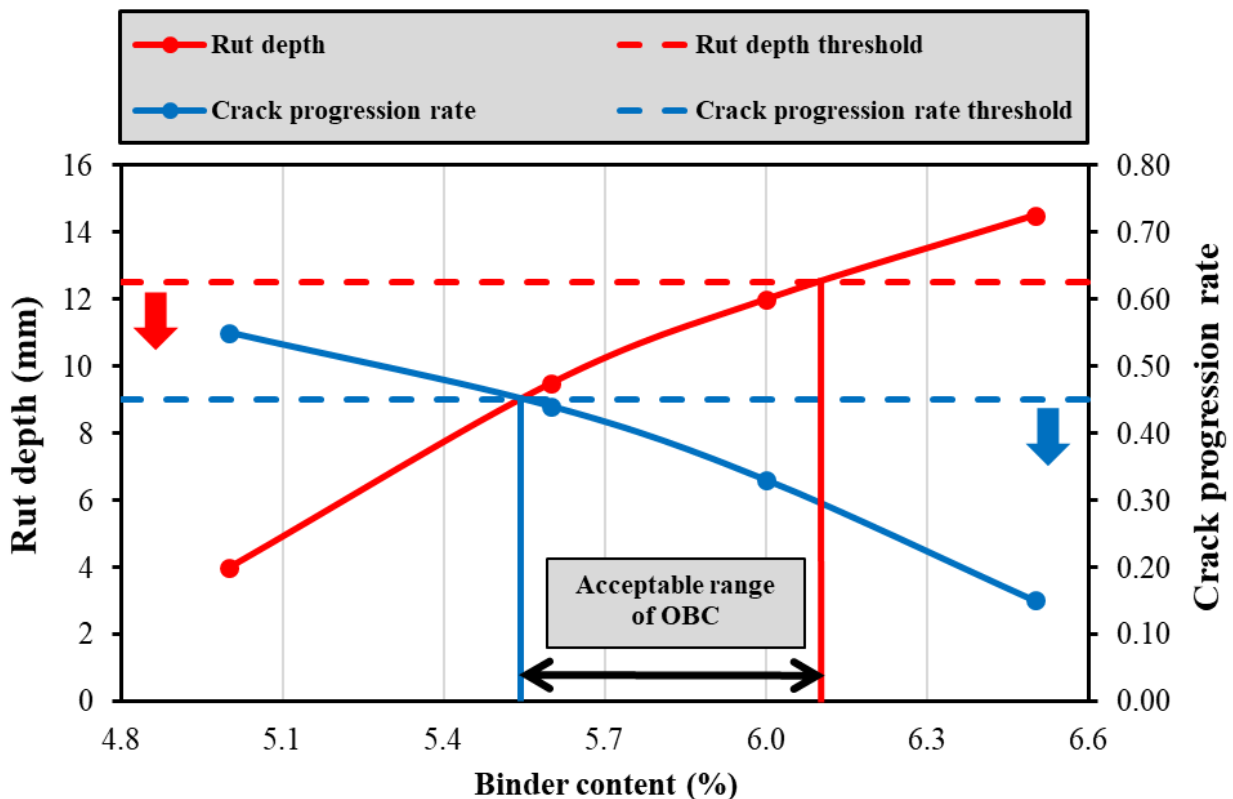


Figure 2: Effect of Binder Percentage on BMD Process (Zhou *et al.*, 2006).

Effect of Binder Grade

The performance grade of an asphalt binder identifies the pavement-temperature range over which the binder is expected to resist high-temperature rutting and low-temperature thermal cracking. For example, PG 70-22 is intended for pavement temperatures up to 70°C and down to -22°C (Elkashef *et al.*, 2018). Cooper *et al.* (2014) evaluated mixtures prepared with PG 64-22, PG 70-

22, and PG 76-22 binders and found that increasing the high-temperature grade improved the evaluated rutting and cracking measures. Veeraragavan et al. (2023) similarly reported that increasing the binder grade from PG 58-28 to PG 70-28 enabled 30 of 34 mixtures to satisfy the study's rut-depth and Flexibility Index criteria.

Effect of Mixture Volumetrics

Air-void content (Va) and voids in mineral aggregate (VMA) are two primary volumetric properties that influence asphalt mixture performance (Zhang et al., 2019b). Air-void content can be varied through compaction effort or binder content. VMA is the intergranular void space within a compacted aggregate structure, including the space occupied by air and effective binder, and therefore indicates the volume available to accommodate binder. As binder content increases, VMA generally decreases to a minimum and may subsequently increase as additional binder expands the aggregate structure.

Sreedhar et al. (2018) evaluated the influence of reducing the air-void content (Va) from 7% to 5% by increasing the compaction effort. Rutting resistance was assessed using the flow number, while cracking resistance was evaluated using the Flexibility Index (FI). The results indicated that lowering the air-void content from 7% to 5% improved both the rutting and cracking performance of the asphalt mixtures.

West et al. (2018b) reduced air-void content by increasing binder content approximately 0.3 to 0.4 percentage point above the optimum binder content. Reducing air voids from 4% to 3% substantially improved cracking performance and produced only a small reduction in rutting resistance; all mixtures continued to satisfy the specified rutting criterion.

Lee et al. (2023) evaluated target VMA levels of 13%, 14%, and 15% produced by modifying aggregate gradation. The results indicated that mixtures with higher VMA at 5% air voids and lower VMA at 3% air voids were more likely to satisfy the evaluated BMD criteria. Barros (2018) also reported improved performance at higher VMA for mixtures compacted to 7% air voids.

Effect of Aggregate Gradation

Aggregate gradation describes the distribution of particle sizes within an aggregate blend. A gradation curve located above the maximum density line is generally classified as fine-graded, whereas a curve below the line is considered coarse-graded. Changes in aggregate gradation and binder content influence the internal aggregate structure and volumetric properties of an asphalt mixture. These changes can subsequently affect the mixture's resistance to rutting and cracking.

Garcia (2021) evaluated the influence of coarse, intermediate, and fine aggregate gradations on the rutting and cracking performance of asphalt mixtures produced with dolomite, granite, gravel, and soft limestone aggregates. Rutting resistance was assessed using rut depth from the Hamburg Wheel-Tracking Test (HWTT), while cracking resistance was evaluated with the Overlay Tester (OT). The HWTT results did not indicate a consistent relationship between gradation type and rutting performance for any of the four aggregate sources. In contrast, aggregate gradation had a noticeable effect on cracking resistance. For all aggregate types, coarse-graded mixtures exhibited greater cracking resistance than the intermediate- and fine-graded mixtures. This improvement was attributed to the higher binder contents associated with the coarse-graded mixtures. In another

study, Sreedhar et al. (2018) investigated coarse- and fine-graded asphalt mixtures using the flow number to assess rutting resistance and the Flexibility Index (FI) to evaluate cracking resistance. Their findings showed that fine-graded mixtures provided greater rutting resistance, whereas coarse-graded mixtures demonstrated better cracking performance.

Effect of Asphalt Mixture Type and Aggregate Type

Asphalt mixture types are commonly differentiated by their nominal maximum aggregate size (NMAS) and aggregate-packing characteristics. In Texas, frequently used mixture types include Superpave Coarse (SP-C), Superpave Dense (SP-D), Dense-Graded Coarse (DG-C), Dense-Graded Dense (DG-D), Thin Overlay Mixture Coarse (TOM-C), Thin Overlay Mixture Fine (TOM-F), and Stone-Matrix Asphalt (SMA) (Hajj et al., 2021).

Jichkar (2021) evaluated the influence of mixture type using the Hamburg Wheel-Tracking Test (HWTT) and Overlay Tester (OT). Mixtures generally satisfied the evaluated TxDOT rutting and cracking criteria when aggregate-packing parameters were within the recommended ranges: a coarse-aggregate ratio of 0.50–0.65, fine-aggregate coarse and fine ratios of 0.35–0.50, and an appropriate Primary Control Sieve Index (PCSI). Aggregate type—gravel, igneous, or sandstone had no significant effect on rut depth or crack progression rate (CPR). Barros (2018) likewise reported negligible differences between mixtures prepared with dolomite and granite.

Summary Table

Table 1 summarizes the effects of key asphalt mixture parameters on rutting and cracking performance. As shown in the table, most mixture parameters influence either the rutting resistance, cracking resistance, or both, whereas aggregate type generally exhibits a negligible effect on these performance characteristics. The rutting-related measures included in the summary are rut depth and flow number, while the cracking-related measures include the critical J-integral value, Flexibility Index (FI), and crack progression rate (CPR).

Table 1: Summary of Effects of Asphalt Mixture Parameters on Rutting and Cracking Performances.

Mixture Parameter	Feature	Rutting Resistance	Cracking Resistance
Binder percentage (Zhou et al., 2006)	Above OBC	Decrease (↓)	Increase (↑)
Binder percentage (Zhou et al., 2006)	Below OBC	Increase (↑)	Decrease (↓)
Binder grade (Cooper et al., 2014)	PG 76-22	Increase (↑)	Increase (↑)
Binder grade (Cooper et al., 2014)	PG 64-22	Decrease (↓)	Decrease (↓)
Air voids percentage – Compaction effort	Increasing	Decrease (↓)	Decrease (↓)

Mixture Parameter	Feature	Rutting Resistance	Cracking Resistance
(Sreedhar et al., 2018)			
Air voids percentage – Compaction effort (Sreedhar et al., 2018)	Decreasing	Increase (↑)	Increase (↑)
Voids in mineral aggregates (Lee et al., 2023)	Increasing	Decrease (↓)	Increase (↑)
Voids in mineral aggregates (Lee et al., 2023)	Decreasing	Increase (↑)	Decrease (↓)
Aggregate gradation (Garcia, 2021; Sreedhar et al., 2018)	Coarse	No significant change (↔)	Increase (↑)
Aggregate gradation (Garcia, 2021; Sreedhar et al., 2018)	Fine	No significant change (↔)	Decrease (↓)
Aggregate gradation (Garcia, 2021; Sreedhar et al., 2018)	CA ratio less than 0.65	Increase (↑)	No significant change (↔)
Aggregate gradation (Garcia, 2021; Sreedhar et al., 2018)	FA _(C) within the range of 0.35–0.50	Increase (↑)	No significant change (↔)
Aggregate gradation (Garcia, 2021; Sreedhar et al., 2018)	FA _(f) within the range of 0.35–0.50	Increase (↑)	No significant change (↔)
Aggregate gradation (Garcia, 2021; Sreedhar et al., 2018)	PCSI: positive for fine gradation and negative for coarse gradation	Increase (↑)	No significant change (↔)

Mixture Parameter	Feature	Rutting Resistance	Cracking Resistance
Asphalt mixture type (Jichkar, 2021)	SP-C, SP-D, DG-C, DG-D, TOM, and SMA	Performance depends on aggregate gradation, CA ratio, FA_C , FA_f , and PCSI	Performance depends on aggregate gradation, CA ratio, FA_C , FA_f , and PCSI
Aggregate type (Barros, 2018)	Limestone	No significant change ($\leftrightarrow$)	No significant change ($\leftrightarrow$)
Aggregate type (Barros, 2018)	Sandstone	No significant change ($\leftrightarrow$)	No significant change ($\leftrightarrow$)
Aggregate type (Barros, 2018)	Gravel and granite	No significant change ($\leftrightarrow$)	No significant change ($\leftrightarrow$)

SKID RESISTANCE OF ASPHALT MIXTURES

Definition and Importance of Skid Resistance

Skid resistance is the resistance developed at the tire–pavement interface that opposes sliding or skidding. It is commonly expressed as a coefficient of friction (μ) or as Skid Number (SN), which is 100 times the coefficient of friction (Hall et al., 2009). Figure 3 illustrates the frictional and normal forces used in this relationship.

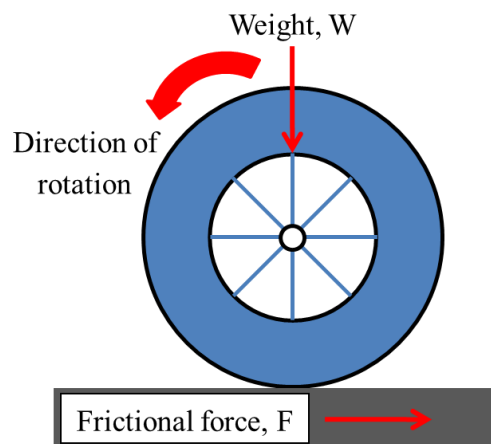


Figure 3: Frictional and Normal Forces Acting on a Tire (Fwa 2021).

Pavement friction is generally lower under wet conditions because water reduces the effective contact between the tire and the pavement surface (Figure 4) (Peng et al., 2021). When water cannot be removed rapidly from the contact area, hydroplaning may occur. Under full hydroplaning, the tire loses direct contact with the pavement, substantially reducing braking and directional control (Yu et al., 2020).

Skid Resistance Development Mechanism

Pavement skid resistance is governed primarily by macrotexture and microtexture at the tire–pavement interface. As illustrated in Figure 5, macrotexture has wavelengths of approximately 0.5 to 50 mm, whereas microtexture has wavelengths below approximately 0.5 mm (Hall et al., 2009). Megatexture (approximately 50 to 500 mm) and roughness (greater than approximately 500 mm) have comparatively little direct effect on skid resistance but strongly influence ride quality and user comfort (Praticò and Vaiana, 2015).

Macrotexture contributes primarily to hysteresis as the tire deforms over surface irregularities, whereas microtexture contributes primarily to adhesion at the tire–pavement contact (Figure 6) (Raymond, 2006; Kouchaki et al., 2017). Both mechanisms contribute to braking and vehicle control. Cohesive forces are generally considered negligible because the tire and pavement are dissimilar materials (Hall et al., 2009; Flintsch et al., 2012; Bazrafshan et al., 2019; Xiao et al., 2018).

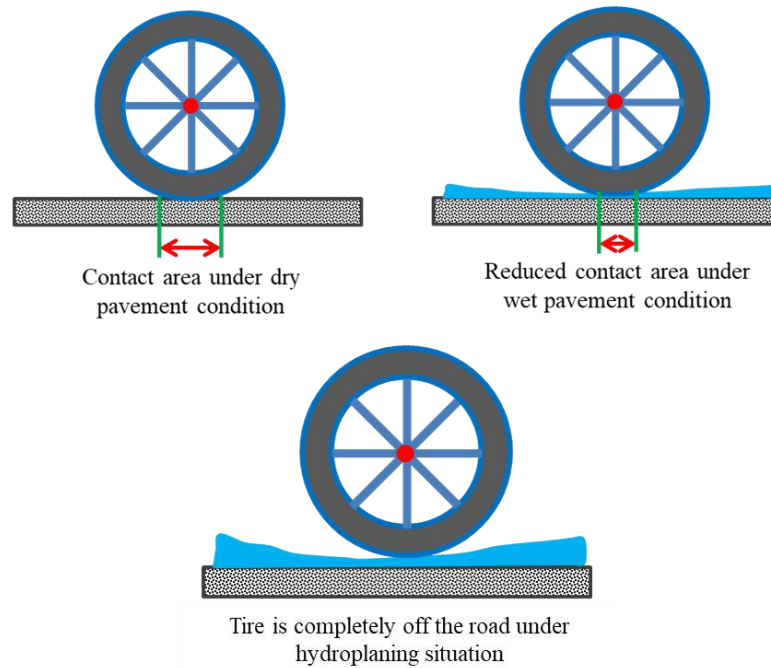


Figure 4: Contact Area between Pavement and Tire Under Dry, Wet, and Hydroplaning Conditions (Yu et al., 2020).

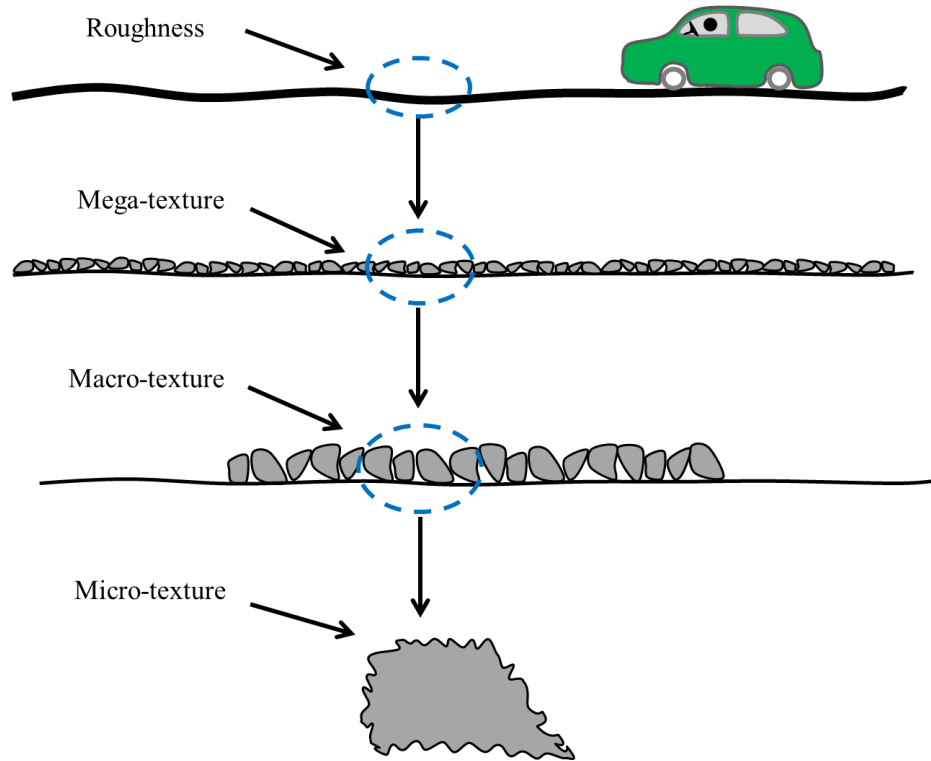


Figure 5: Illustration of Various Levels of Texture in Asphalt Pavement (*Hall et al., 2009*).

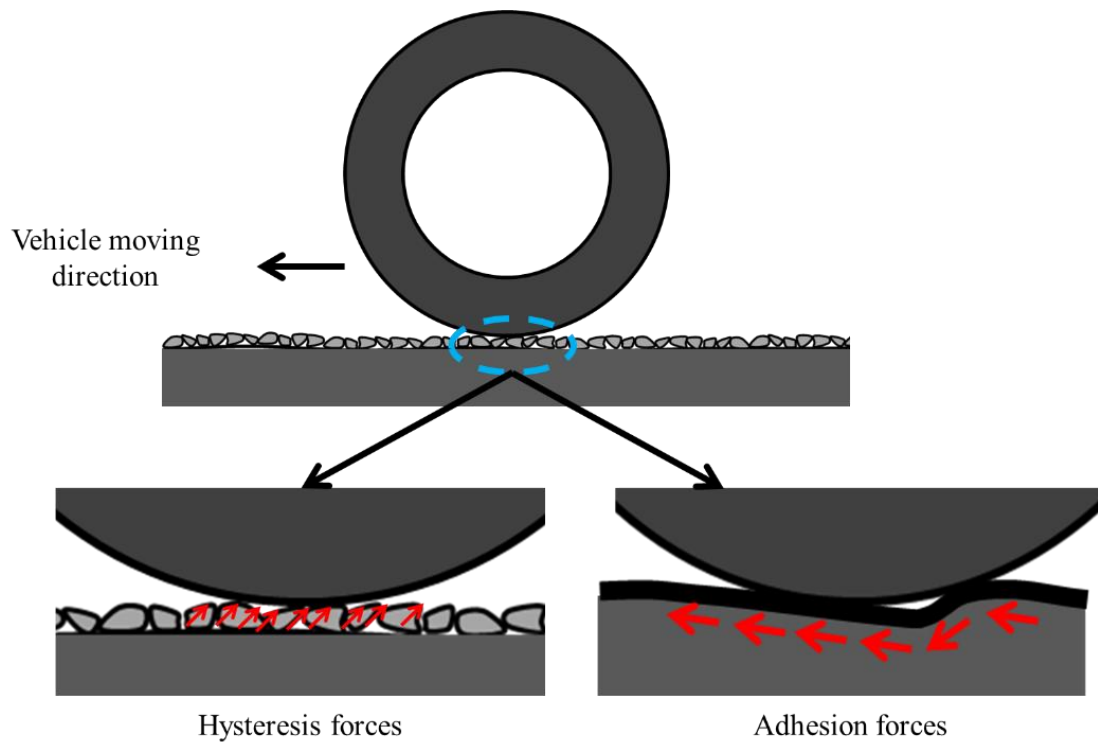


Figure 6: Illustration of Hysteresis and Adhesion Forces Developed between Tire and Pavement Interaction (*Hall et al., 2009*).

Asphalt mixture friction is therefore governed by the combined effects of macrotexture and aggregate microtexture. Macrotexture is influenced by aggregate size and gradation, mixture type, binder characteristics, and volumetric properties. Microtexture is controlled primarily by aggregate mineralogy, surface morphology, and resistance to polishing. During the early life of a pavement, binder film may temporarily mask aggregate microtexture until traffic removes the surface film.

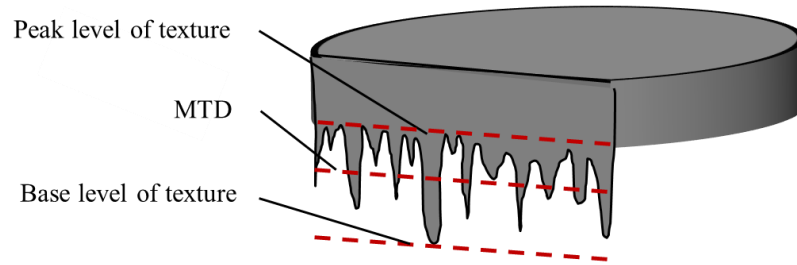
Asphalt Mixture Parameters Controlling Macrotexture

This section begins with a review of the test methods used to characterize the macrotexture of asphalt mixtures. It then examines the influence of binder characteristics, aggregate properties, and mixture volumetrics on macrotexture development. Finally, the section discusses the relationships reported between pavement macrotexture and the skid resistance of asphalt mixtures.

Test Methods for Assessing Asphalt Mixture Macrotexture

Mean Texture Depth (MTD) and Mean Profile Depth (MPD) are widely used indicators of pavement macrotexture (Figure 7) (Praticò and Vaiana, 2015; Li et al., 2016). MTD is a volumetric, three-dimensional measure commonly obtained with the sand-patch method, whereas MPD is a two-dimensional profile-based measure commonly obtained with laser or circular-track devices. Figure 8 summarizes representative methods used to obtain MTD and MPD.

(a) MTD



(b) MPD

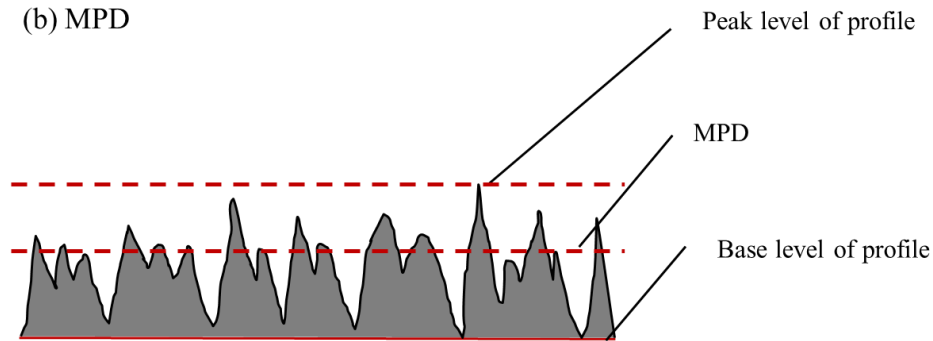


Figure 7: Illustration of MTD and MPD of Asphalt Surface (Kováč et al., 2015; Özcan et al., 2020).

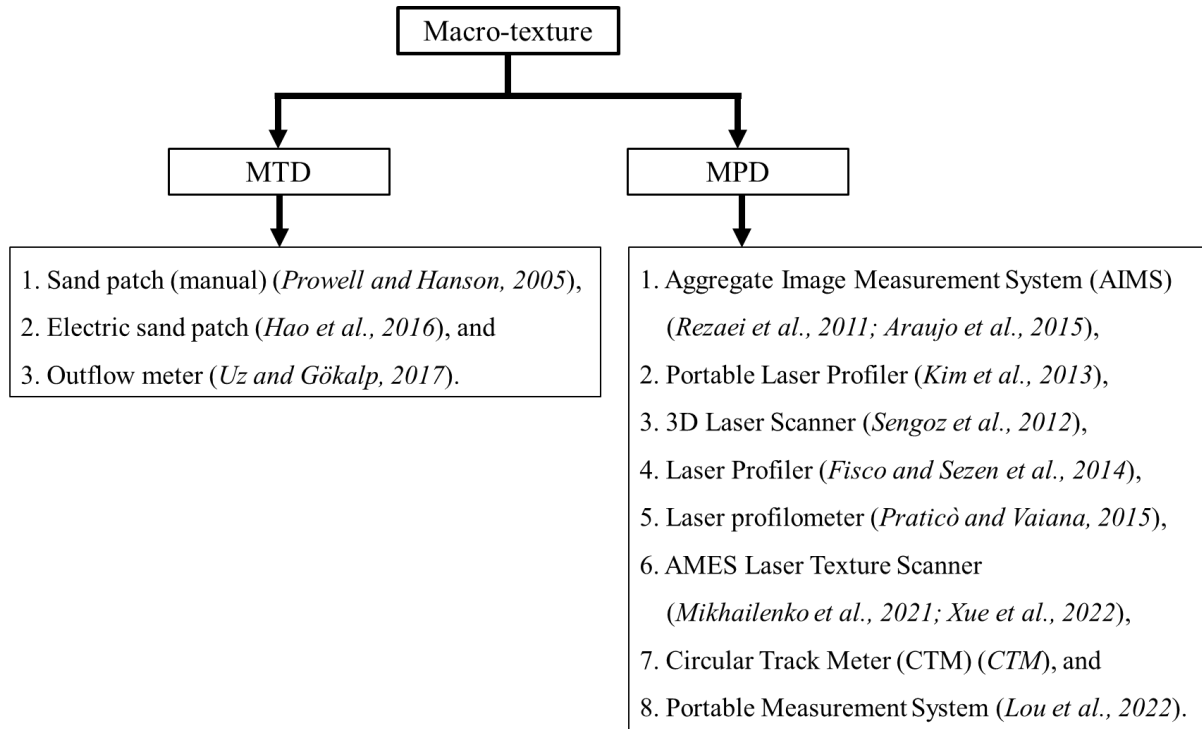


Figure 8: Various Test Methods for Capturing MTD and MPD.

Effect of Binder Parameters on Macrotexture

Praticò et al. (2015) reported that increasing binder content by 0.6 percentage point reduced MPD by approximately 0.17 mm (Figure 9). Zhu et al. (2022) reported a 0.26-mm decrease in MPD associated with a 1.0-percentage-point increase in binder content. These studies indicate that additional binder can reduce exposed macrotexture, although the magnitude of the effect depends on the mixture and the range of binder contents evaluated.

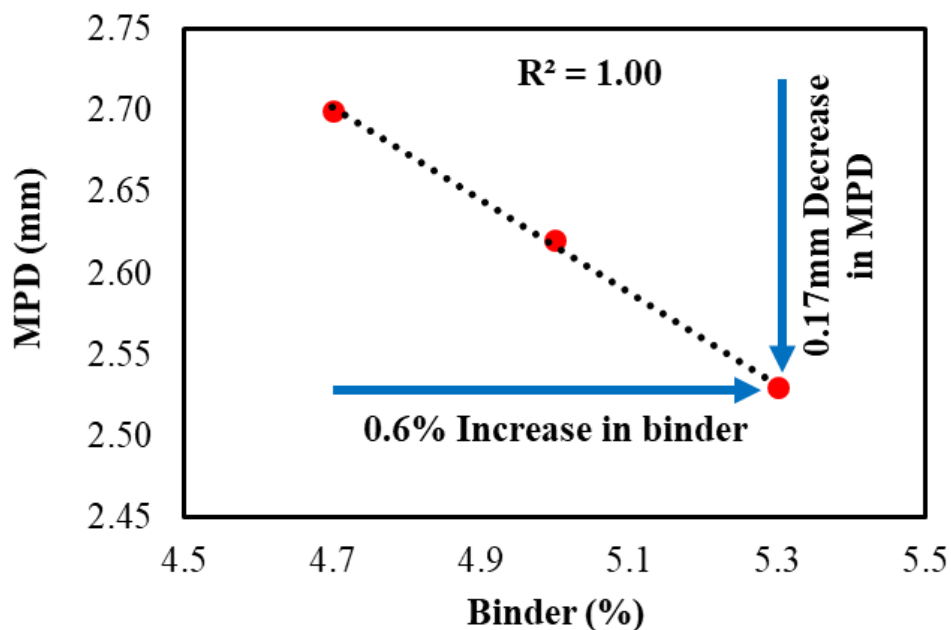


Figure 9: Effect of Binder Percentage on MPD of Asphalt Mixtures (*Praticò and Vaiana, 2015*).

Effect of Aggregate Parameters on Macrotexture

Cui et al. (2023) evaluated coarse-, medium-, and fine-graded SMA mixtures and reported MPD values of approximately 1.6, 1.4, and 1.3 mm, respectively. Nekkanti et al. (2019) similarly found that increasing the percentage passing the No. 4 sieve reduced MPD in open-graded friction-course mixtures. Williams (2008) reported a strong relationship between MPD and the percentage passing the No. 16 sieve for a fine mixture, and Ahammed et al. (2012) reported a strong relationship between MTD and the coarse-to-fine aggregate ratio. Collectively, these studies indicate that increasing the proportion of fine aggregate generally reduces macrotexture.

Mixture type and nominal maximum aggregate size (NMAS) also influence macrotexture. Ahammed et al. (2012) reported different MTD values for SMA, rubberized open-graded friction course, and Superpave mixtures. Other studies generally found greater MTD or MPD for larger NMAS and coarser gradations (Kowalski et al., 2010; Praticò et al., 2015; Khasawneh et al., 2020, 2023) (Figure 10). The wider particle-size range and greater exposure of coarse particles in these mixtures provide a plausible explanation for the observed increase in macrotexture.

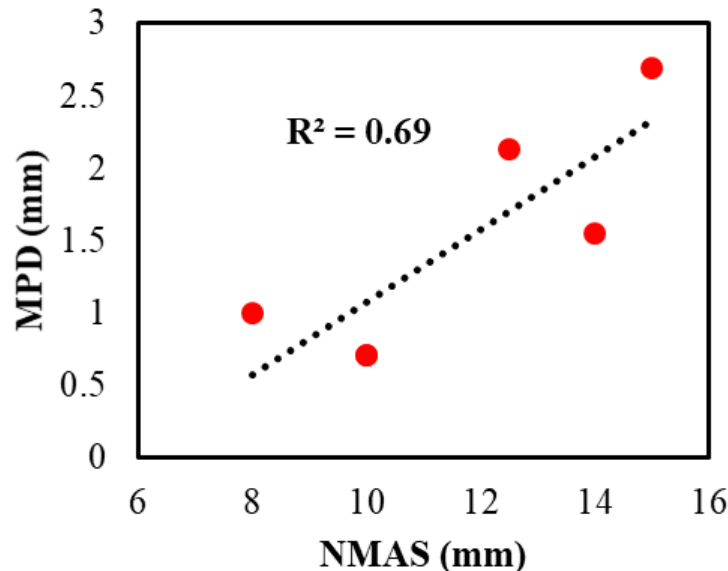


Figure 10: Correlation between NMAS and MPD (*Praticò and Vaiana, 2015*).

Aggregate shape can also affect macrotexture. The literature generally indicates that aggregate angularity influences asphalt mixture macrotexture, while both angularity and surface texture influence microtexture (Sengoz et al., 2014; Lin and Tongjing, 2018; Wang et al., 2020b; Zong et al., 2021; Cui et al., 2022, 2023; Kouchaki et al., 2017; Li et al., 2021a).

Angular aggregates promote particle interlock and tend to produce a rougher surface than rounded, flat, or elongated particles. Flaky and elongated aggregates may break or orient during compaction, producing a flatter surface and lower macrotexture. Studies using the British Pendulum Tester and image-based shape measures reported lower friction for mixtures containing flat and elongated particles and moderate-to-strong relationships between aggregate angularity and macrotexture (Oduroh et al., 2000; Shah et al., 2010; Shah and Abdullah, 2010; Lin and Tongjing,

2018; Gao et al., 2020; Wang et al., 2020b; Zong et al., 2021). Overall, aggregate proportioning, NMAS, and particle shape jointly influence the macrotexture developed at the compacted surface.

Effect of Volumetric Parameters on Macrotexture

The available literature has focused primarily on VMA and air-void content. Several studies reported increasing MPD or MTD as VMA and air voids increased, or decreasing texture as compaction effort and roller passes increased (Vaiana et al., 2013; Alsheyab et al., 2022; Kassem et al., 2016). Other studies found little relationship within more limited volumetric ranges (Ahammed et al., 2009, 2012). These findings suggest that volumetrics can influence macrotexture, but the response depends on the magnitude of the volumetric change, mixture type, and compaction process.

Correlation between Macrotexture and Asphalt Mixture Skid Resistance

Field studies generally report positive, but variable, relationships between texture depth and measured friction. Kouchaki et al. (2018) reported R^2 values of 0.77 and 0.69 between MPD and Grip Number at 70 and 50 km/h, respectively. Li et al. (2020) reported an R^2 value of 0.59 across several surface-treatment types, and Pranjić et al. (2018) reported a similar value for SMA sections. Afonso et al. (2019), however, reported a weaker relationship for porous asphalt.

The variability among these relationships is expected because friction depends on both macrotexture and microtexture, as well as test speed, tire characteristics, water-film conditions, and measurement method. Macrotexture alone therefore cannot fully characterize asphalt mixture friction.

Asphalt Mixture Parameters Controlling Aggregate Microtexture

This section reviews methods for measuring aggregate microtexture, the effects of binder and aggregate characteristics on microtexture, and the reported relationships between microtexture parameters and aggregate or asphalt mixture friction.

Test Methods for Assessing Aggregate Microtexture

Aggregate microtexture is often evaluated indirectly with friction devices, although imaging and laser-scanning systems can provide direct measures of small-scale surface morphology. Direct imaging requires specialized equipment and analysis software but can quantify parameters such as angularity, texture, root-mean-square roughness (R_q), and surface-smoothness depth (R_p). Figure 11 summarizes representative methods used to measure these characteristics.

Effect of Binder Parameters on Aggregate Microtexture

Florková et al. (2020) reported a linear relationship between binder-film thickness and the measured degradation or masking of aggregate microtexture (Figure 12). Zhu et al. (2022) likewise observed reduced exposed aggregate microtexture as binder content increased. These results indicate that a thicker binder film can temporarily reduce the microtexture available at the pavement surface, particularly during the initial polishing period.

Effect of Aggregate Parameters on Microtexture

Aggregate microtexture and its resistance to polishing are governed by mineralogical and morphological characteristics (Masad et al., 2009; Kamani and Ajalloeian, 2020; Diógenes et al., 2021). Mineral composition affects hardness and differential wear, while crushing and particle

formation affect angularity and surface texture. Consequently, aggregates of the same general rock type can exhibit different morphology when produced with different crushing processes.

Relevant mineralogical characteristics include mineral composition, grain size, grain shape, and hardness (Perry, 2014). Aggregates dominated by lower-hardness minerals, such as many limestones and dolomites, tend to polish more readily than aggregates containing harder minerals. Sandstone, gravel, granite, basalt, rhyolite, slag, and quartzite are among the materials commonly associated with greater polishing resistance, although performance remains source-specific (O'Brien et al., 2004; West et al., 2001; Kane and Edmondson, 2020; Roy et al., 2021).

Morphological characteristics include particle angularity and surface texture. Image-based parameters such as Rq and Rp have also been used to quantify small-scale roughness. The literature generally reports greater friction for aggregates with higher angularity, texture, Rq, and Rp, although the strength of the relationship depends on mineralogy, polishing method, and measurement scale (Masad et al., 2009; Kouchaki et al., 2017; Florková and Komačka, 2015; Lei et al., 2022).

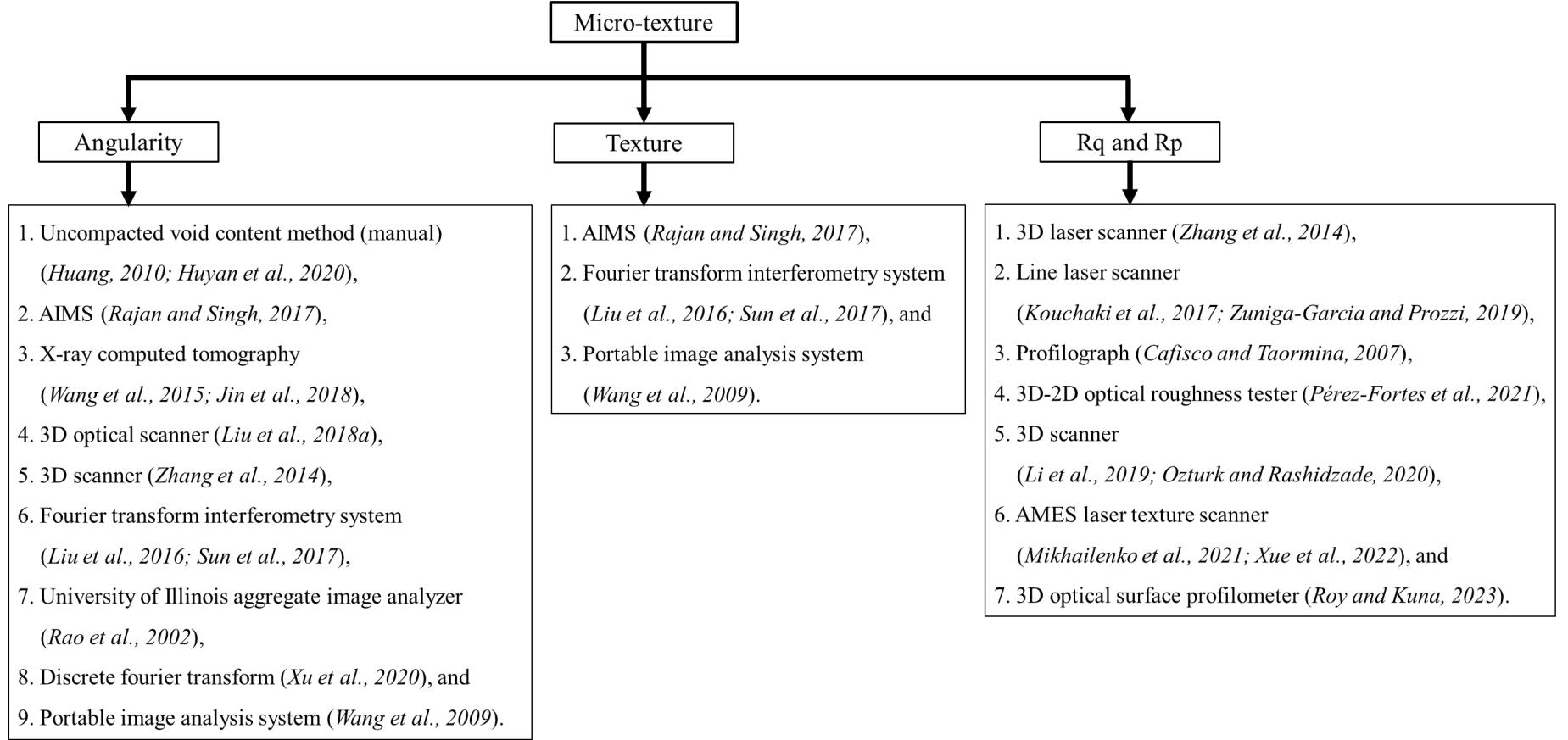


Figure 11: Various Test Methods for Capturing Micro-Texture Parameters of Aggregates.

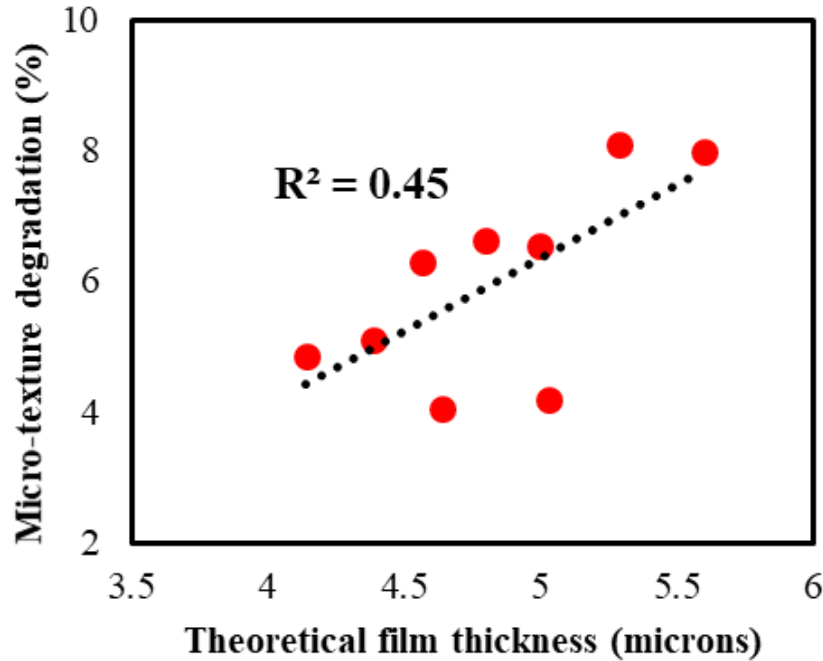


Figure 12: Correlation between Binder Film Thickness and Micro-Texture Degradation of Aggregates (Florkova et al., 2020).

Correlation between Microtexture Parameters and Aggregate or Asphalt Mixture Friction

Average Hardness Value (AHV) and Contrast of Hardness (COH) have been used to relate aggregate mineralogy to polishing resistance. AHV combines the percentage and Mohs hardness of the minerals present in an aggregate, while COH represents the contrast between harder and softer mineral phases. Higher mineral hardness and greater differential wear generally help preserve microtexture during polishing. Other potentially relevant characteristics include mineral bonding, grain shape, crystallization, alteration, and tectonization (Tourenq et al., 1971; Perry, 2014; Kane and Edmondson, 2020; Roy et al., 2021; Li et al., 2021a).

Masad et al. (2009) reported correlations between polishing resistance and changes in aggregate angularity and texture measured with the Aggregate Image Measurement System. Other studies using regression or correlation analyses also found angularity, texture, Rq, and Rp to be associated with friction or polishing resistance (Kangkhajitre et al., 2011; Cafiso et al., 2007; Kouchaki et al., 2017). In general, aggregates that retain higher small-scale roughness after polishing provide greater friction.

Asi (2007) evaluated Marshall mixtures at the optimum binder content and at 0.5 and 1.0 percentage point above the optimum. The reported British Pendulum Numbers decreased from 87 to 81 and 74, respectively, indicating that additional binder can reduce initial surface friction by masking aggregate microtexture.

Mineral hardness is therefore an important control on aggregate polishing resistance. Gu et al. (2022) reported progressively greater laboratory and field friction as low-polishing dolomite coarse aggregate was replaced with sandstone. Kowalski (2010) similarly observed improved

friction when carbonate aggregate was replaced with steel slag or quartzite. These findings support the use of source-specific, polish-resistant aggregate where long-term friction is critical.

The effect of binder content is most pronounced during the initial polishing period, before traffic removes the surface binder film. Long-term friction is then governed primarily by aggregate mineralogy, morphology, and the ability to retain microtexture. Binder grade, binder–aggregate compatibility, film thickness, temperature, and polishing history may affect the rate of binder-film removal. Aggregates containing harder mineral phases and durable angular or textured surfaces generally retain friction longer than aggregates that polish rapidly (Kowalski et al., 2010; Wang et al., 2015).

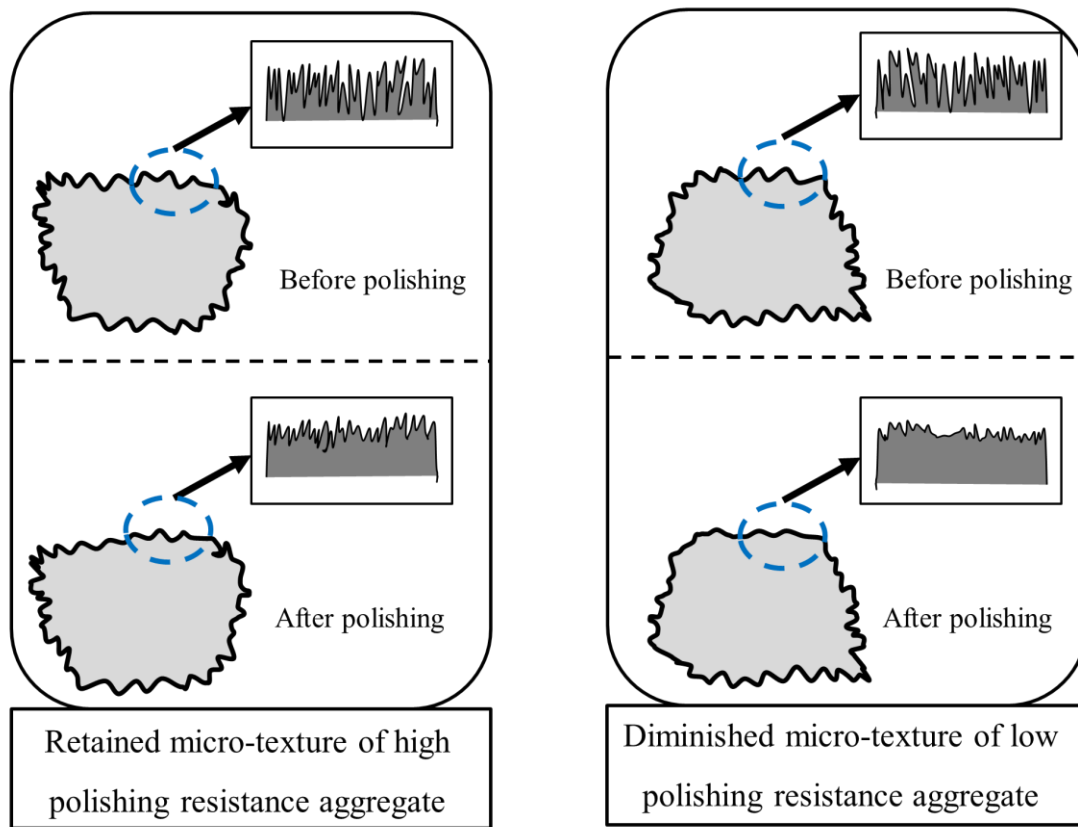


Figure 13: Micro-Texture of High and Low Polishing Resistance Aggregate Before and After Polishing (*Wang et al., 2015*).

Summary Table

Table 2 summarizes the reported effects of asphalt mixture parameters on macrotexture and aggregate microtexture. The table also identifies parameters for which the available literature was limited or inconclusive. These gaps informed the experimental program described in the following chapters.

Table 2: Summary of Effects of Asphalt Mixture Parameters on Macro-Texture and Micro-Texture Formation.

Mixture Parameter	Feature	Macrotecture	Microtexture
Binder percentage (Praticò and Vaiana, 2015; Florkova et al., 2020; Zhu et al., 2022)	Above OBC	Decrease	Decrease
Binder percentage (Praticò and Vaiana, 2015; Florkova et al., 2020; Zhu et al., 2022)	Below OBC	Increase	Decrease
Air voids percentage – Compaction effort (Vaiana et al., 2013; Alsheyab and Khasawneh, 2022)	Increasing	Increase	Not studied (NS)
Air voids percentage – Compaction effort (Vaiana et al., 2013; Alsheyab and Khasawneh, 2022)	Decreasing	Decrease	Not studied (NS)
Voids in mineral aggregates (Ahammed, 2009; Ahammed and Tighe, 2012; Vaiana et al., 2013)	Increasing	Increase	Not studied (NS)
Voids in mineral aggregates (Ahammed, 2009; Ahammed and Tighe, 2012; Vaiana et al., 2013)	Decreasing	Decrease	Not studied (NS)
Aggregate parameters (Williams, 2008; Masad et al., 2009; Kouchaki et al., 2017; Lin and Tongjing, 2018; Xu et al., 2020)	Angularity	Increase	Increase
Aggregate parameters (Williams, 2008; Masad et al., 2009; Kouchaki et al., 2017; Lin and Tongjing, 2018; Xu et al., 2020)	Texture	Not studied (NS)	Increase
Aggregate parameters (Williams, 2008; Masad et al., 2009; Kouchaki et al., 2017; Lin and Tongjing, 2018; Xu et al., 2020)	R _q	Not studied (NS)	Increase
Aggregate parameters (Williams, 2008; Masad et al., 2009; Kouchaki et al., 2017; Lin and Tongjing, 2018; Xu et al., 2020)	R _a	Not studied (NS)	Increase
Aggregate parameters (Williams, 2008; Masad et al., 2009; Kouchaki et al., 2017; Lin and Tongjing, 2018; Xu et al., 2020)	Mineral hardness	Not studied (NS)	Increase
Aggregate parameters (Williams, 2008; Masad et al., 2009; Kouchaki et al., 2017; Lin and Tongjing, 2018; Xu et al., 2020)	Contrast of hardness of minerals	Not studied (NS)	Increase
Aggregate gradation parameters (Ahammed and Tighe, 2012; Praticò and Vaiana, 2015; Cui et al., 2023)	Coarse gradation	Increase	Not studied (NS)
Aggregate gradation parameters (Ahammed and Tighe, 2012; Praticò and Vaiana, 2015; Cui et al., 2023)	Fine gradation	Decrease	Not studied (NS)

Mixture Parameter	Feature	Macrotexture	Microtexture
Aggregate gradation parameters (Ahammed and Tighe, 2012; Praticò and Vaiana, 2015; Cui et al., 2023)	Larger NMAS	Increase	Not studied (NS)

NS = not studied or not sufficiently documented in the literature.

CHAPTER 3

RESEARCH GAPS AND METHODOLOGY

RESEARCH GAPS

The literature review identified several parameters that can influence rutting, cracking, macrotexture, or microtexture, including binder content and grade, air-void content (Va), VMA, aggregate type and gradation, mixture type, and particle morphology. However, the relative contribution of these parameters to long-term mixture friction was not clearly established, and several effects were not sufficiently documented, as indicated by “NS” in Table 2. A key practical question therefore remained: which mixture components should be modified when an otherwise acceptable BMD mixture exhibits inadequate friction? The research methodology was designed to isolate the controlling parameters, verify the findings in the field, and demonstrate economical methods for improving friction without compromising conventional performance.

RESEARCH METHODOLOGY

Figure 14 summarizes the research methodology used to develop an approach for incorporating skid resistance into the asphalt BMD framework. The work progressed from material and method selection, through controlled laboratory evaluation and field verification, to mixture-optimization case studies and implementation recommendations.

Selection of Materials and Methods

- Binders, aggregates, laboratory-produced mixtures, plant-produced mixtures, and field sections were selected to provide a range of material and design characteristics.
- The selected materials were evaluated using friction, polishing, rutting, cracking, and moisture-damage test methods appropriate to each phase of the study.

Preliminary Study to Understand the Parameters Controlling the Frictional Performance of Asphalt Mixtures

- A controlled mixture was used to isolate the influence of individual parameters. Typical production mixtures may contain multiple aggregate sources, manufactured sand, natural sand, and reclaimed asphalt pavement (RAP), making it difficult to attribute changes in friction to a single factor.
- The controlled program evaluated the following material-, mixture-design-, and construction-related parameters:
 - Material-related parameters: binder grade and aggregate type.
 - Mixture-design-related parameters: binder content, aggregate gradation, mixture type, and the distribution of aggregate types among gradation fractions.
 - Construction-related parameter: compacted air-void content.

Verification of Controlling Parameters in the Field

- The parameters identified in the controlled laboratory program were evaluated using available field sections. Sections representing different binder grades, aggregate types, aggregate gradations, and mixture types were identified, and wheel-path friction was measured at multiple locations.

Case Studies to Improve Frictional Performance of Asphalt Mixtures Based on Controlled Study Findings

- Case studies were then conducted to determine whether mixtures with inadequate friction could be improved by targeting the aggregate fractions identified in the controlled study. The modified mixtures were also evaluated for rutting, cracking, and, where applicable, moisture-damage performance.

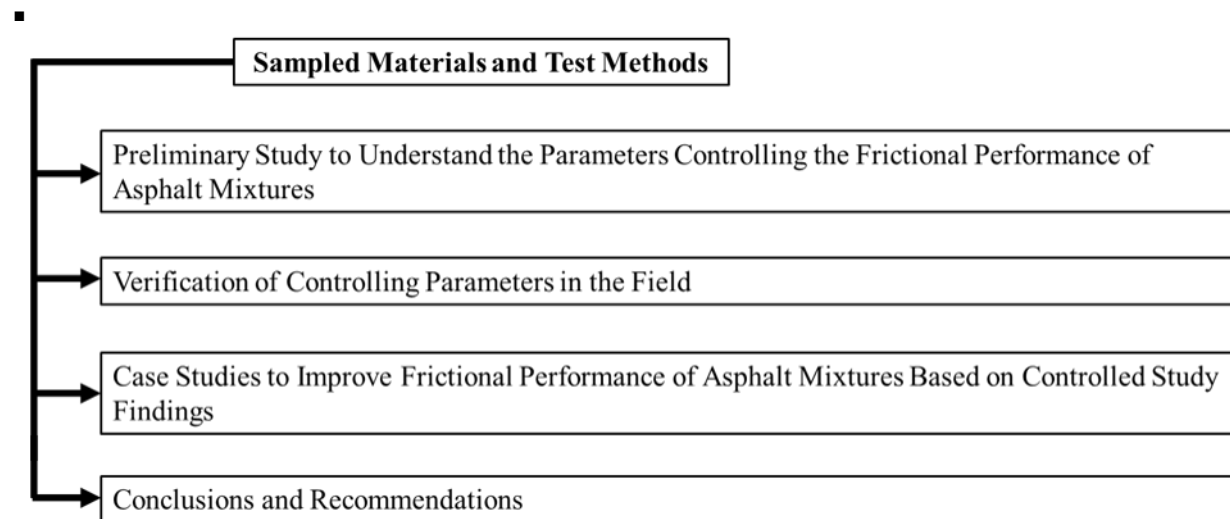


Figure 14: Research Methodology of the Study.

CHAPTER 4

EXPERIMENTAL MATERIALS AND METHODS

MATERIALS

Binder

Table 3 summarizes the three binders used in the study. A dynamic shear rheometer was used to determine complex shear modulus (G^*) and phase angle (δ), and a bending beam rheometer was used to determine flexural creep stiffness (S) and the slope of the creep-stiffness curve (m -value). Each binder satisfied the applicable performance-grade criteria.

Table 3: Test Results of Collected Binders.

Parameter	PG 64-22 Passing temperature (°C)	PG 70-22 Passing temperature (°C)	PG 76-22 Passing temperature (°C)	Limits	Test method
$G^*/\sin\delta$ Unaged	65	72	77	$\geq 1.00\text{kPa}$	AASHTO T 315 (AASHTO 2022c)
$G^*/\sin\delta$ RTFO aged	66	74	77	$\geq 2.20\text{kPa}$	AASHTO T 315 (AASHTO 2022c)
S and m -value	-25	-25	-23	$\leq 300\text{MPa}$ & ≥ 0.300	AASHTO T 313 (AASHTO 2022b)

RTFO – Rolling Thin Film Oven

Asphalt Mixtures

The experimental program included 24 laboratory-produced and 26 plant-produced asphalt mixtures. Laboratory-compacted specimens were prepared in general accordance with Tex-204-F (2016), using a target specimen height of 115 ± 5 mm and a target air-void content of $4.0 \pm 0.5\%$ where applicable. Table 4 summarizes the 50 mixtures, which included SP-C, SP-D, DG-C, DG-D, TOM-C, TOM-F, and SMA-C/SMA-D mixture types.

Table 4: Summary of Fifty Mixes Mix Design Details.

Name of the mixture	Binder grade	NMAS (mm)	Design gyrations	OBC (%)	Remarks
SP-C – 1	70-22	12.5	50	5.1	Lab produced, Coarse gradation with limestone – 1
SP-C – 2	70-22	12.5	50	5.1	Lab produced, Intermediate gradation with limestone – 1
SP-C – 3	70-22	12.5	50	5.1	Lab produced, Fine gradation with limestone – 1
SP-C – 4	70-22	12.5	50	5.1	Lab produced, Primary aggregate: Sandstone – 1

Name of the mixture	Binder grade	NMAS (mm)	Design gyrations	OBC (%)	Remarks
SP-C – 5	70-22	12.5	50	5.1	Lab produced, CA Limestone – 1: FA Sandstone – 1
SP-C – 6	70-22	12.5	50	5.1	Lab produced, CA Sandstone – 1: FA Limestone – 1
SP-C – 7	70-22	12.5	50	5.1	Lab produced, CA Limestone – 1: IA Limestone – 1: FS Sandstone – 1
SP-C – 8	70-22	12.5	50	5.1	Lab produced, CA Limestone – 1: IA Sandstone – 1: FS Limestone – 1
SP-C – 9	70-22	12.5	50	5.1	Lab produced, CA Limestone – 1: IA 26% Sandstone – 1, 10% Limestone – 1: FS Limestone – 1
SP-C – 10	70-22	12.5	50	5.1	Lab produced, CA Limestone – 1: IA 12% Sandstone – 1, 24% Limestone – 1: FS Limestone – 1
SP-C – 11	70-22	12.5	50	5.7	Plant produced, Primary aggregate: Trap rock
SP-C – 12	70-22	12.5	50	5.4	Plant produced, Primary aggregate: Trap rock
SP-C – 13	64-22	12.5	50	5.3	Plant produced, Primary aggregate: Sandstone – 1
SP-C – 14	64-22	12.5	50	5.9	Plant produced, Primary aggregate: Sandstone – 1
SP-C – 15	64-22	12.5	50	5.4	Plant produced, Primary aggregate: Sandstone – 1
SP-C – 16	70-22	9.5	50	5.4	Lab produced, Primary aggregate: Limestone – 1
SP-C – 17	70-22	9.5	50	5.4	Lab produced, Primary aggregate: Sandstone – 1
SP-C – 18	70-22	9.5	50	6.0	Lab produced, Primary aggregate: Gravel – 1
SP-C – 19	70-28	12.5	50	5.4	Plant produced, Primary aggregate: Limestone – 2
SP-C – 20	70-28	12.5	50	5.4	Plant produced, Primary aggregate: Limestone – 2
SP-C – 21	70-28	12.5	50	5.2	Plant produced, Primary aggregate: Granite – 1
SP-D – 1	70-22	9.5	50	5.4	Lab produced, Primary aggregate: Limestone – 1
SP-D – 2	70-22	9.5	35	5.3	Plant produced, Primary aggregate: Limestone – 3
SP-D – 3	70-22	9.5	35	6.0	Plant produced, Primary aggregate: Limestone – 3
SP-D – 4	64-22	9.5	35	6.1	Plant produced, Primary aggregate: Limestone – 3

Name of the mixture	Binder grade	NMAS (mm)	Design gyrations	OBC (%)	Remarks
SP-D – 5	64-22	9.5	50	5.9	Plant produced, Primary aggregate: Limestone – 4
DG-C – 1	70-22	9.5	50	5.0	Lab produced, Primary aggregate: Limestone – 1
DG-C – 2	70-22	9.5	35	5.2	Plant produced, Primary aggregate: Trap rock
DG-C – 3	64-22	9.5	50	4.7	Plant produced, Primary aggregate: Sandstone – 1
DG-D – 1	70-22	9.5	50	5.9	Lab produced, Primary aggregate: Limestone – 1
DG-D – 2	70-22	9.5	50	5.0	Plant produced, Primary aggregate: Limestone – 4
DG-D – 3	70-28	9.5	50	5.6	Plant produced, Primary aggregate: Granite – 1
DG-D – 4	70-22	9.5	50	5.4	Plant produced, Primary aggregate: Granite – 1
DG-D – 5	70-28	9.5	50	5.6	Plant produced, Primary aggregate: Granite – 1
TOM-C – 1	76-22	9.5	75	6.5	Plant produced, Primary aggregate: Gravel – 2
TOM-C – 2	76-22	9.5	35	6.8	Lab produced, Primary aggregate: Sandstone – 2
TOM-C – 3	76-22	9.5	35	6.4	Lab produced, Primary aggregate: Limestone – 5
TOM-C – 4	76-22	9.5	35	6.8	Lab produced, Primary aggregate: Limestone – 5
TOM-C – 5	76-22	9.5	35	6.8	Lab produced, Primary aggregate: Limestone – 5
TOM-C – 6	76-22	9.5	35	6.8	Lab produced, Primary aggregate: Limestone – 5
TOM-C – 7	76-22	9.5	35	6.8	Lab produced, Primary aggregate: Limestone – 5
TOM-C – 8	76-22	9.5	35	6.8	Lab produced, Primary aggregate: Limestone – 5
TOM-C – 9	76-22	9.5	35	6.8	Lab produced, Primary aggregate: Limestone – 5
TOM-C – 10	76-22	9.5	35	6.3	Plant produced, Primary aggregate: Sandstone – 2
TOM-C – 11	76-22	9.5	35	6.5	Plant produced, Primary aggregate: Limestone – 6
TOM-C – 12	76-22	9.5	35	6.5	Plant produced, Primary aggregate: Limestone – 7
TOM-F – 1	70-22	4.75	50	7.0	Lab produced, Primary aggregate: Limestone – 1

Name of the mixture	Binder grade	NMAS (mm)	Design gyrations	OBC (%)	Remarks
TOM-F – 2	76-22	4.75	35	7.0	Lab produced, Primary aggregate: Limestone – 5
SMAC	70-22	12.5	50	6.1	Lab produced, Primary aggregate: Limestone – 1

Note: Each mixture designation represents a separate mixture design or material combination. Gradation terminology used in the controlled study: CA = coarse aggregate retained on the No. 4 sieve (4.75 mm); IA = intermediate aggregate passing the No. 4 and retained on the No. 30 sieve (4.75–0.60 mm); FA = total fine aggregate passing the No. 4 sieve; and FS = fines passing the No. 30 sieve (0.60 mm). The critical subfraction identified later in the study is the material passing the No. 4 and retained on the No. 8 sieve (4.75–2.36 mm).

Asphalt Ring Preparation Method for Three-Wheel Polishing Test

AASHTO PP 104 describes preparation of asphalt-mixture slabs for TWPD polishing and permits alternative specimen configurations prepared from compacted briquettes. This study used the ring-specimen method described by McDaniel et al. (2018), which facilitates control of specimen air voids and avoids the need for a laboratory roller compactor. The method can also accommodate appropriately sized field cores.

Four 150-mm-diameter, 80-mm-thick briquettes were compacted with a Superpave Gyratory Compactor. Each briquette was cut vertically into two halves, and seven half-cylinders were trimmed and arranged in a custom ring mold, as shown in Figure 15. A binding material was placed around the specimens and cured before polishing. Asphalt rings were polished with the TWPD for as many as 300,000 cycles using centipede-tread solid-rubber tires under dry conditions at 60 revolutions per minute.

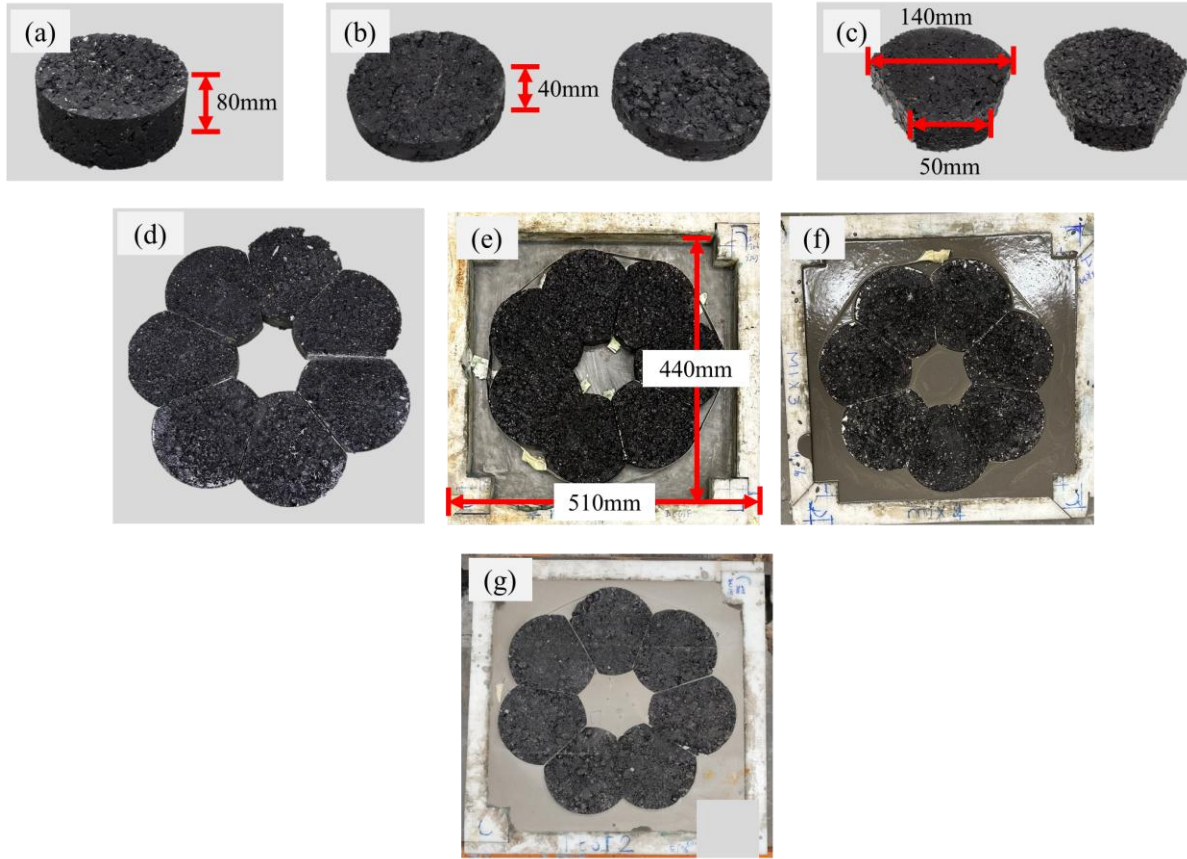


Figure 15: Preparation Process of Asphalt Rings: (a) Compacted 80mm Cylindrical Sample, (b) Two Halves of Cut Samples, (c) Trimmed Sides of Samples, (d) Combined Samples into a Ring, (e) Ring Placement, (f) Binding Agent Poured into the Mold, and (g) Final Asphalt Specimen.

Friction Test

Figure 16 shows the Dynamic Friction Tester (DFT) used in the study. The rotating disk contains three rubber sliders and is accelerated to approximately 80 km/h before being lowered onto the wetted specimen surface. Measurements were obtained in general accordance with ASTM E1911 at selected TWPD cycle intervals. For asphalt specimens, testing was conducted from the unpolished condition through as many as 300,000 polishing cycles. Three DFT runs were performed at each interval, and the average Dynamic Friction Value at 60 km/h (DFV60) was reported.

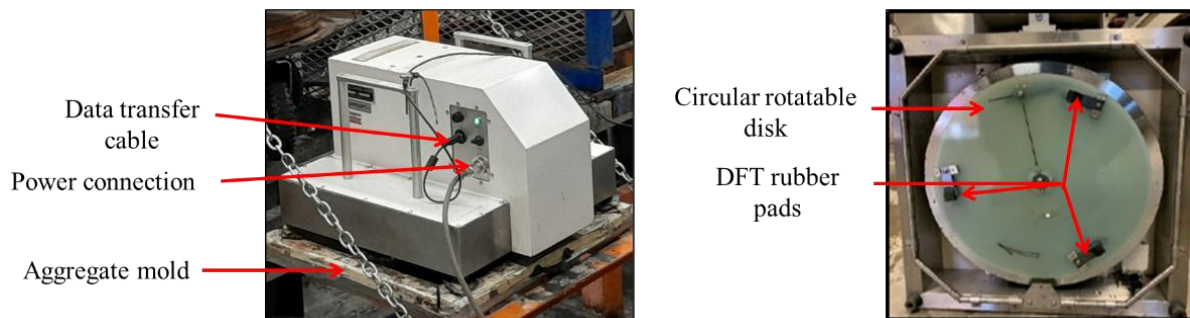


Figure 16: DFT Device Used in this Study.

Rutting Test

The Hamburg Wheel-Tracking Test (HWTT) was conducted in general accordance with AASHTO T 324 to evaluate rutting and moisture susceptibility (Figure 17). Paired 150-mm-diameter, 62-mm-thick specimens were compacted to $7.0 \pm 0.5\%$ air voids and tested in a 50°C water bath for as many as 20,000 wheel passes at approximately 50 passes per minute. Rut depth was measured with a linear variable differential transformer.

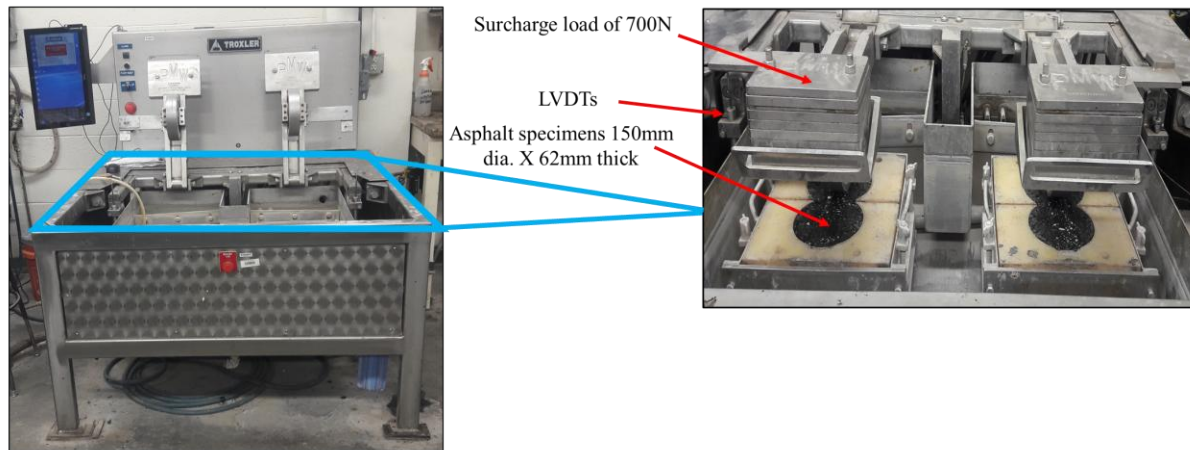


Figure 17: HWTT Device Utilized in this Study.

Cracking Test

The Overlay Test (OT) was used to evaluate cracking resistance (Figure 18) using the procedure described in ASTM WK26816. Specimens approximately 150 mm long, 76 mm wide, and 38 mm thick were trimmed from gyratory-compacted specimens, bonded to the OT plates, and cured for at least 24 hours. Testing was conducted at 25°C in displacement control until the load decreased to 7% of the first-cycle peak load. Crack Progression Rate (CPR) was calculated from the measured load–displacement response.

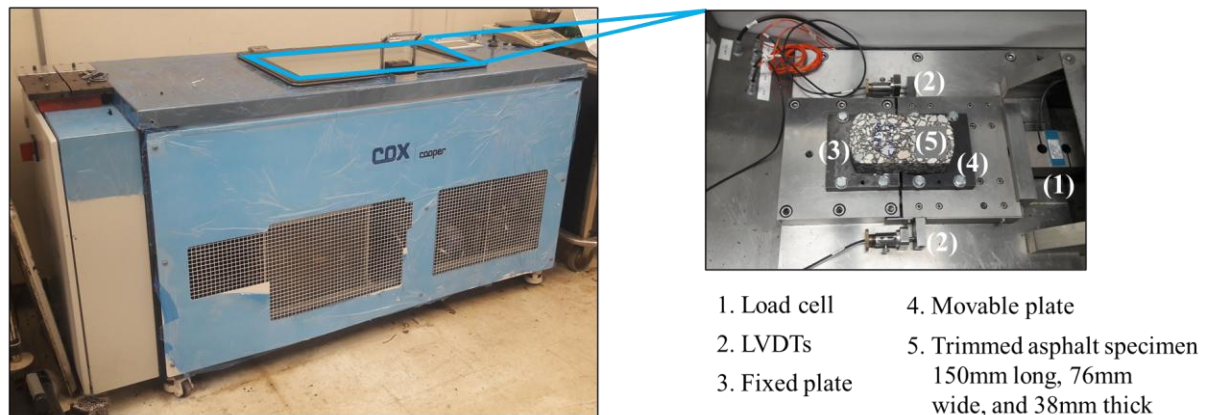


Figure 18: OT Device Utilized in this Study.

Moisture Damage Test

Moisture conditioning was conducted with the Moisture Induced Stress Tester (MIST), followed by indirect tensile strength testing (Figure 19). Three 150-mm-diameter, 62-mm-thick specimens were compacted to $7.0 \pm 0.5\%$ air voids. Dry and conditioned specimens were tested at 25°C and a loading rate of 50 mm/min in general accordance with ASTM D6931. For conditioning, specimens were subjected to 3,500 cycles at 276 kPa and 60°C in general accordance with ASTM D7870/D7870M, then held in a $25 \pm 2^\circ\text{C}$ water bath for 2 hours before testing. Indirect tensile strength was calculated using Equation 4.1.

$$\text{IDT strength (kPa)} = 2000P/(\pi td) \quad (4.1)$$

where P is the peak load (N), t is specimen thickness (mm), and d is specimen diameter (mm).

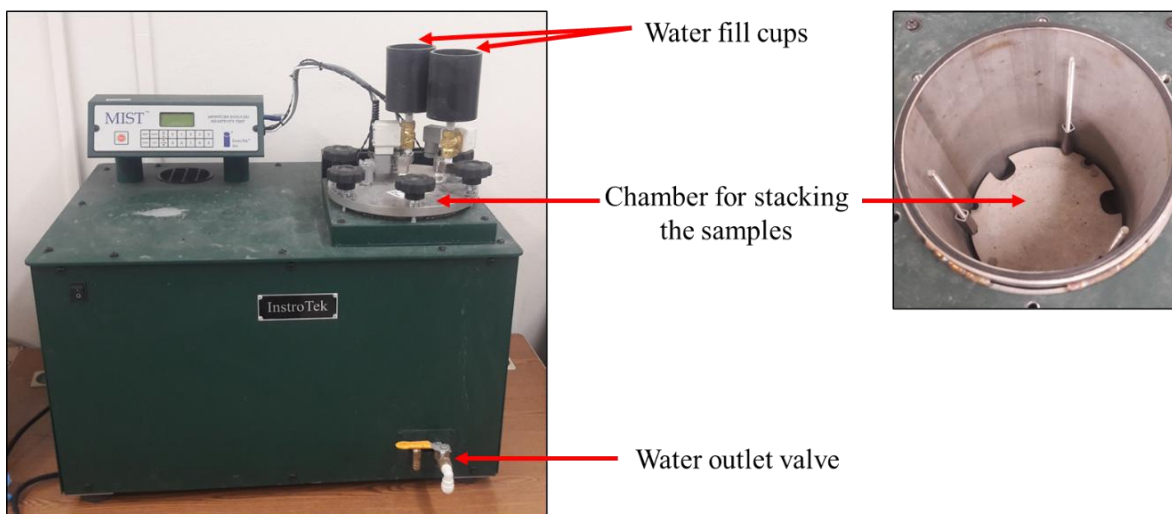


Figure 19: MIST Device Utilized in this Study.

TERMINOLOGY AND REPORTING CONVENTIONS

DFV60 is the Dynamic Friction Value measured by the DFT at 60 km/h. An FDC is the relationship between DFV60 and TWPD polishing cycles. The terminal friction value (TFV), also referred to as terminal DFV, is the stabilized DFV60 reported at the final polishing interval used for a test series.

For gradation reporting, U.S. sieve designations are presented first: coarse aggregate is retained on the No. 4 sieve (4.75 mm); the intermediate fraction passes the No. 4 and is retained on the No. 30 sieve (4.75–0.60 mm); and fines pass the No. 30 sieve. The critical subfraction identified by the controlled study passes the No. 4 and is retained on the No. 16 sieve (4.75–1.18 mm).

Unless stated otherwise, reported laboratory friction values are DFV60 measurements. The proposed terminal-DFV levels are research-based screening categories and are not TxDOT specification acceptance limits.

CHAPTER 5

PRELIMINARY EVALUATION OF PARAMETERS CONTROLLING ASPHALT MIXTURE FRICTION

A friction deterioration curve (FDC) was defined as DFV60 plotted against the number of TWPD polishing cycles, as illustrated in Figure 20. The stabilized value at the final polishing interval is referred to in this report as the terminal friction value (TFV), or terminal DFV. A pretest program indicated coefficients of variation of approximately 5% or less for repeated DFT measurements; consequently, one ring specimen was used for each controlled scenario and three DFT runs were obtained at each measurement interval.

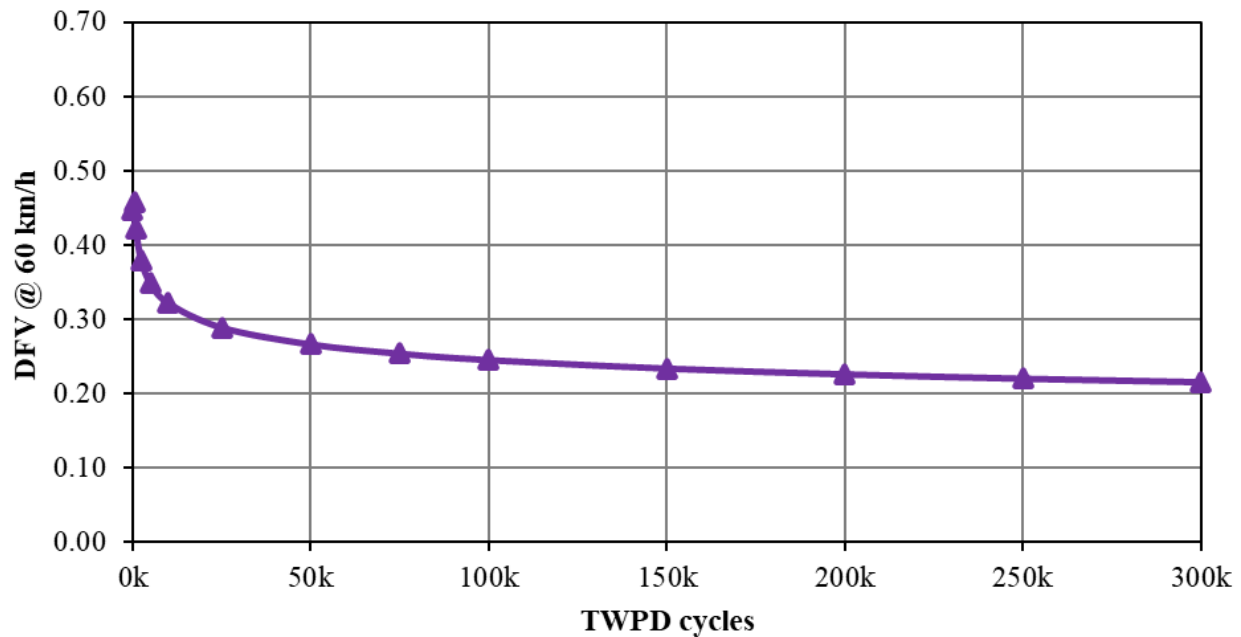


Figure 20: FDC of Asphalt Mixture.

Two-sample t-tests and one-way analyses of variance (ANOVA) were used as exploratory comparisons of the measured friction-deterioration curves. The null hypothesis was that the mean measured DFV did not differ among the compared curves at the selected 95% confidence level.

Statistical Interpretation and Replication

The inferential comparisons in this chapter are descriptive because one independent asphalt ring was tested per controlled scenario. Measurements collected at successive polishing cycles are repeated observations on the same specimen and are not independent replicates. Accordingly, the p-values are used to support comparison of curve trends and should not be interpreted as a substitute for an independently replicated experimental design.

MATERIAL-RELATED PARAMETERS

Effect of Binder Grade

Figure 21 presents FDCs for the limestone SP-C-1 mixture prepared with three binder grades. The curves were similar, and the one-way ANOVA produced a p-value of 0.533. Within the tested materials and grades, binder grade had little effect on long-term friction after the surface binder film was removed.

Effect of Aggregate Type

Figure 22 compares SP-C mixtures prepared with limestone and sandstone aggregate and PG 70-22 binder. Aggregate type produced a pronounced difference in friction (exploratory p-value = 0.001). The limestone mixture had a TFV of 0.25, compared with 0.40 for the sandstone mixture.

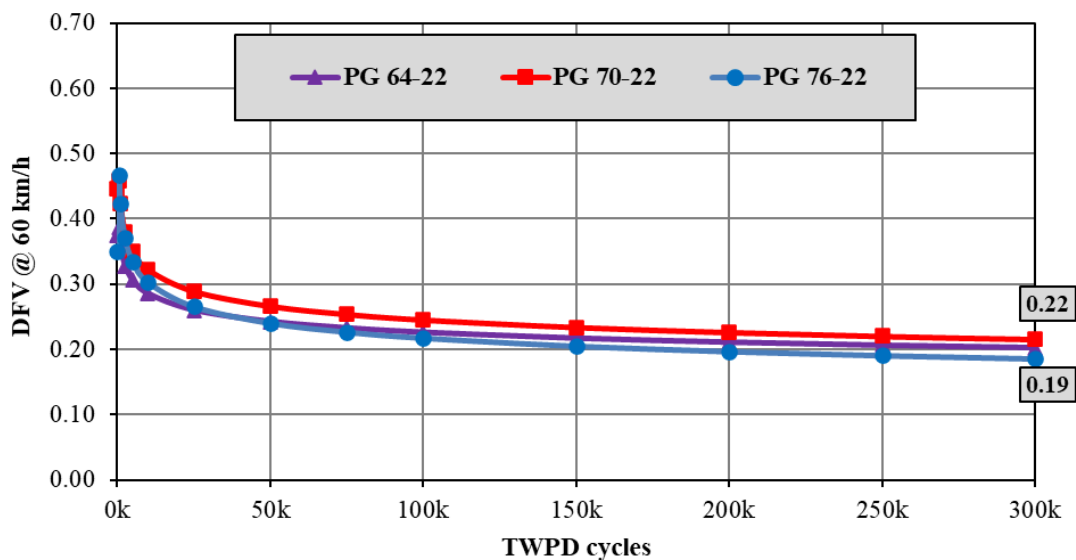


Figure 21: FDCs of Mixture with Three Binder Grades.

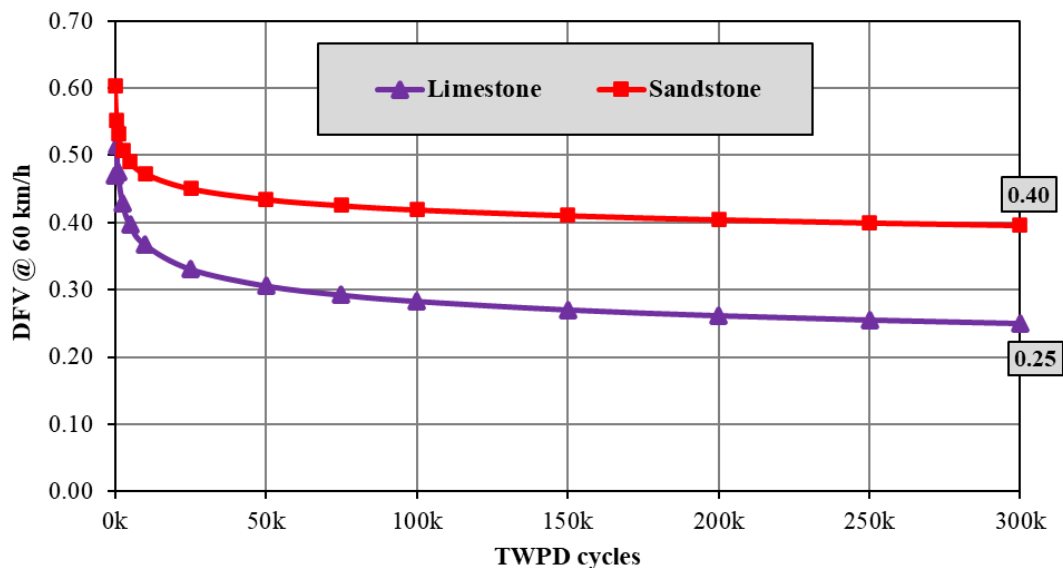


Figure 22: FDCs of Mixture with Two Aggregate Types Across All Sizes.

MIX DESIGN-RELATED PARAMETERS

Effect of Binder Content

Figure 23 compares the limestone SP-C-1 mixture at four binder contents. The curves differed during the initial polishing period while the binder film was being removed, but the long-term portions of the curves converged. The exploratory comparison produced a p-value of 0.60, indicating little long-term effect of binder content within the evaluated range.

Effect of Aggregate Gradation

Three SP-C gradations were evaluated at coarse-to-fine ratios of 60:40, 50:50, and 40:60. The coarse-graded mixture generally produced slightly lower DFV, but the differences were within the approximate precision of the DFT and the exploratory ANOVA produced a p-value of 0.468. Thus, overall gradation had little direct effect on long-term friction for the materials evaluated, although gradation can affect the surface texture and conventional BMD performance.

Effect of Asphalt Mixture Type

Figure 25 compares SP-C, SP-D, DG-C, and DG-D mixtures prepared with limestone aggregate and PG 70-22 binder. The SP-C mixture had a 12.5-mm NMAS, and the other mixtures had a 9.5-mm NMAS. The FDCs were similar, and the one-way ANOVA produced a p-value of 0.707. The small observed differences were attributed primarily to gradation and exposed surface structure rather than to mixture designation or NMAS alone.

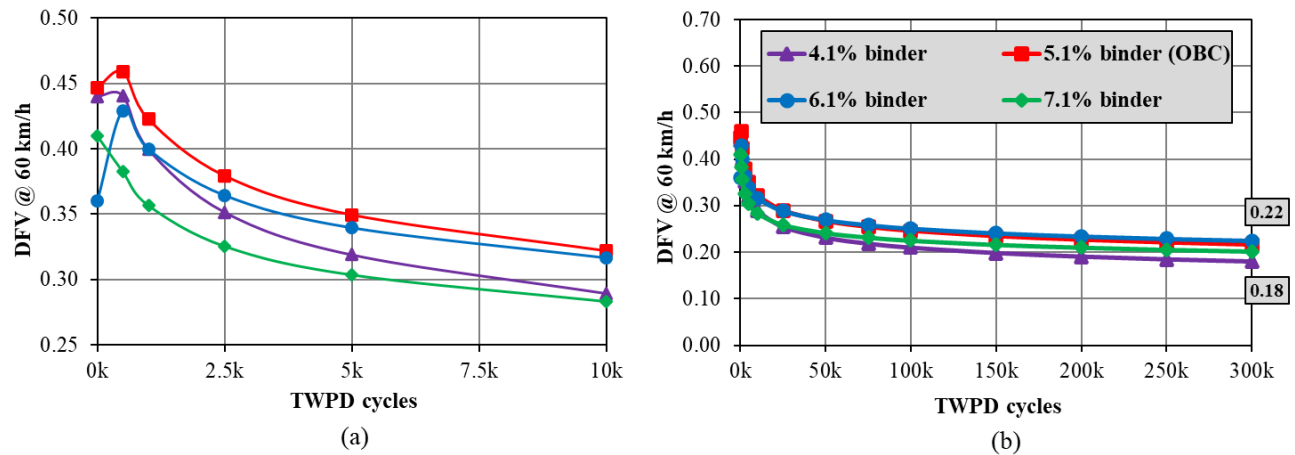


Figure 23: FDCs of Mixture with Varying Binder Content: (a) FDCs Up to 10k Polishing Cycles of Four Mixtures and (b) Entire FDCs of Four Mixtures.

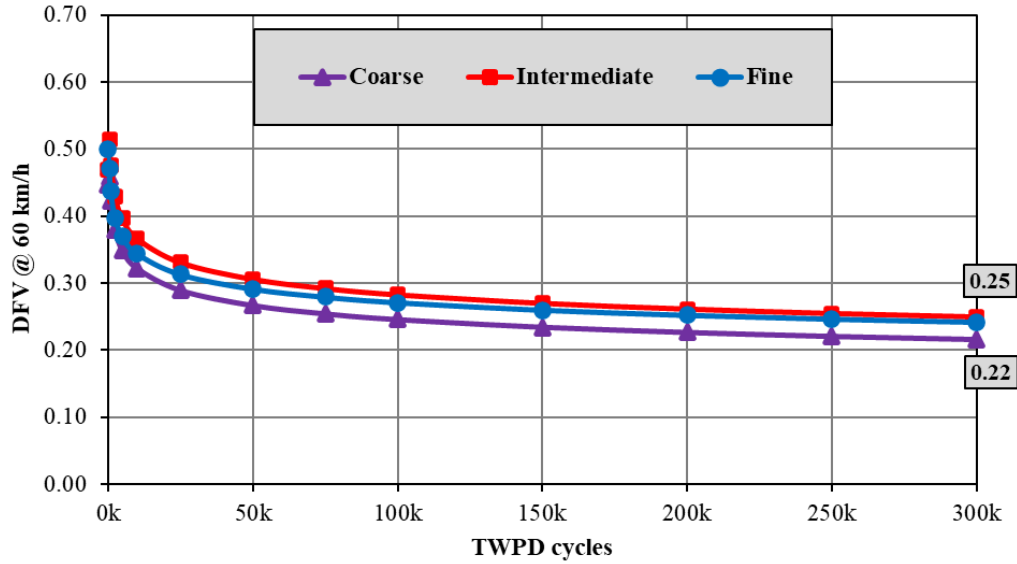


Figure 24: FDCs of Mixtures with Changes in Aggregate Gradation.

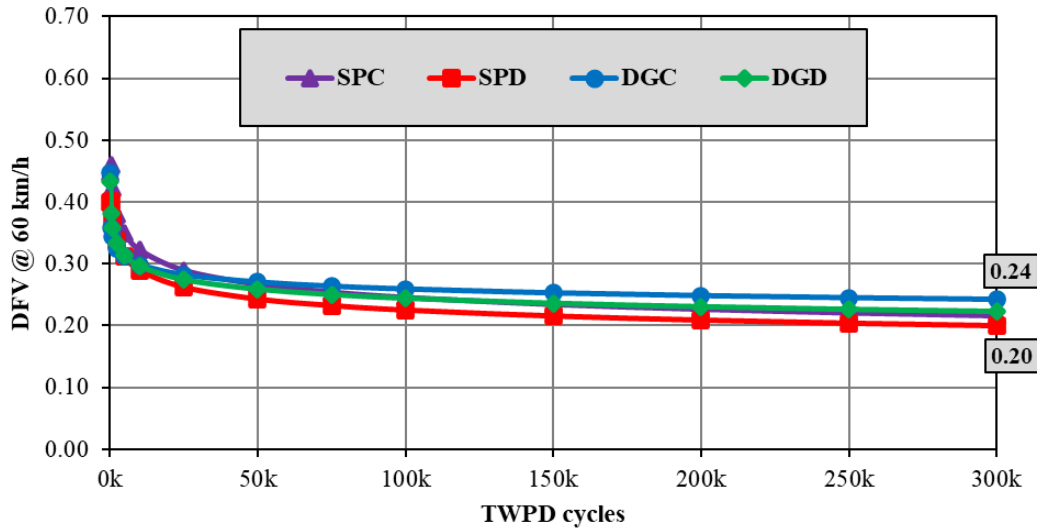


Figure 25: FDCs of Four Asphalt Mixtures.

Effect of Aggregate Type within Gradation Fractions

Six mixtures were prepared with limestone and sandstone distributed among the coarse, intermediate, and fines fractions shown in Table 5. All mixtures used the SP-C-2 gradation, a 50:50 coarse-to-fine ratio, PG 70-22 binder, and 5.1% binder content.

Figure 26 compares the six FDCs. The all-limestone and all-sandstone reference mixtures produced TFVs of 0.25 and 0.40, respectively. Replacing the intermediate and fines fractions of the limestone mixture with sandstone increased TFV to 0.37, whereas replacing those fractions of the sandstone mixture with limestone reduced TFV to 0.31. These results show that the material below the No. 4 sieve had substantially greater influence on friction than the coarse fraction retained on the No. 4 sieve.

Replacing only the fines passing the No. 30 sieve increased TFV from 0.25 to only 0.26. In contrast, replacing the complete intermediate fraction—passing the No. 4 and retained on the No. 30 sieve—with sandstone increased TFV to 0.36. The intermediate fraction therefore controlled most of the long-term friction response in this controlled mixture.

The importance of the intermediate fraction is attributed to its exposed surface area and its persistence at the polished surface. Intermediate particles provide more surface area than the coarse fraction, while the finest particles are present in smaller effective quantities, may be embedded in binder or mortar, and can be removed more readily during polishing. Consequently, the TWPD tires and DFT sliders interact prominently with the intermediate particles.

Table 5: Formulated Asphalt Mixtures for Understanding the Effect of Aggregate Type in Gradation Portions.

Sieve sizes (Passing – Retained)	Aggregate type in asphalt mixture					
	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6
1 in. to No. 4 (25.0–4.75 mm) (Coarse)	Limestone (100%)	Sandstone (100%)	Limestone (50%)	Sandstone (50%)	Limestone (50%)	Limestone (50%)
No. 4 to No. 30 (4.75–0.60 mm) (Intermediate)			Sandstone (50%)	Limestone (50%)	Limestone (36%)	Sandstone (36%)
Passing No. 30 (≤0.60 mm) (Fines)					Sandstone (14%)	Limestone (14%)

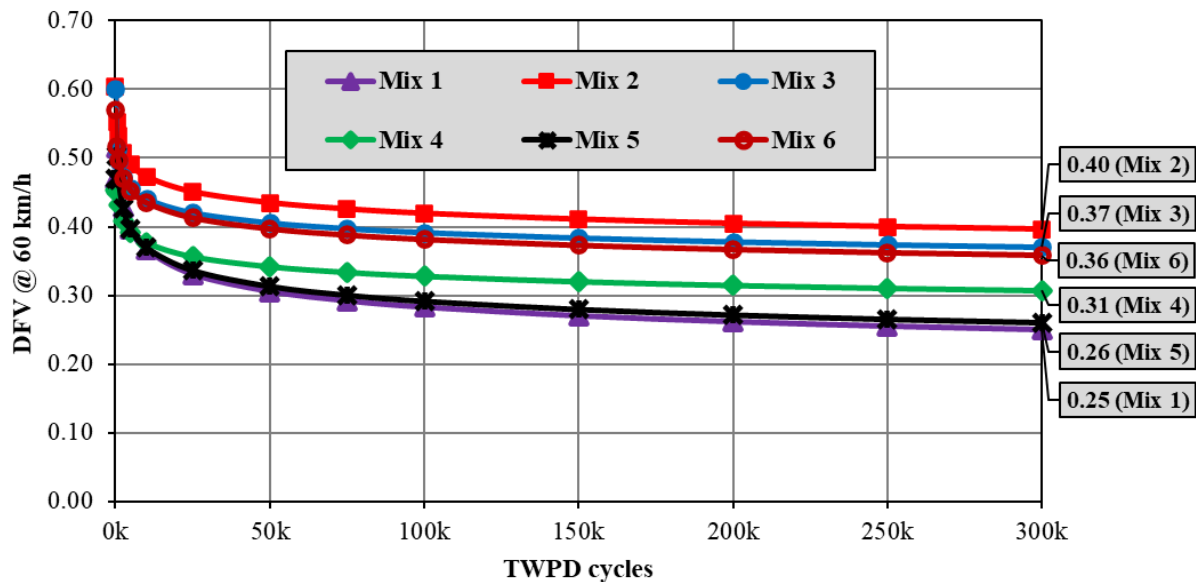


Figure 26: FDCs of Asphalt Mixtures with Varying Aggregate Types in Gradation Portions.

Table 6: Formulated Asphalt Mixtures for Final Verification.

Sieve sizes (Passing – Retained)	Aggregate type in asphalt mixture		
	Mix 6	Mix 7	Mix 8
1 in. to No. 4 (25.0–4.75 mm) (Coarse)	Limestone (50%)	Limestone (50%)	Limestone (50%)
No. 4 to No. 8 (4.75–2.36 mm)	Sandstone (12%)	Sandstone (12%)	Sandstone (12%)
No. 8 to No. 16 (2.36–1.18 mm)	Sandstone (14%)	Sandstone (14%)	Limestone (14%)
No. 16 to No. 30 (1.18–0.60 mm)	Sandstone (10%)	Limestone (10%)	Limestone (10%)
Passing No. 30 (≤ 0.60 mm) (Fines)	Limestone (14%)	Limestone (14%)	Limestone (14%)

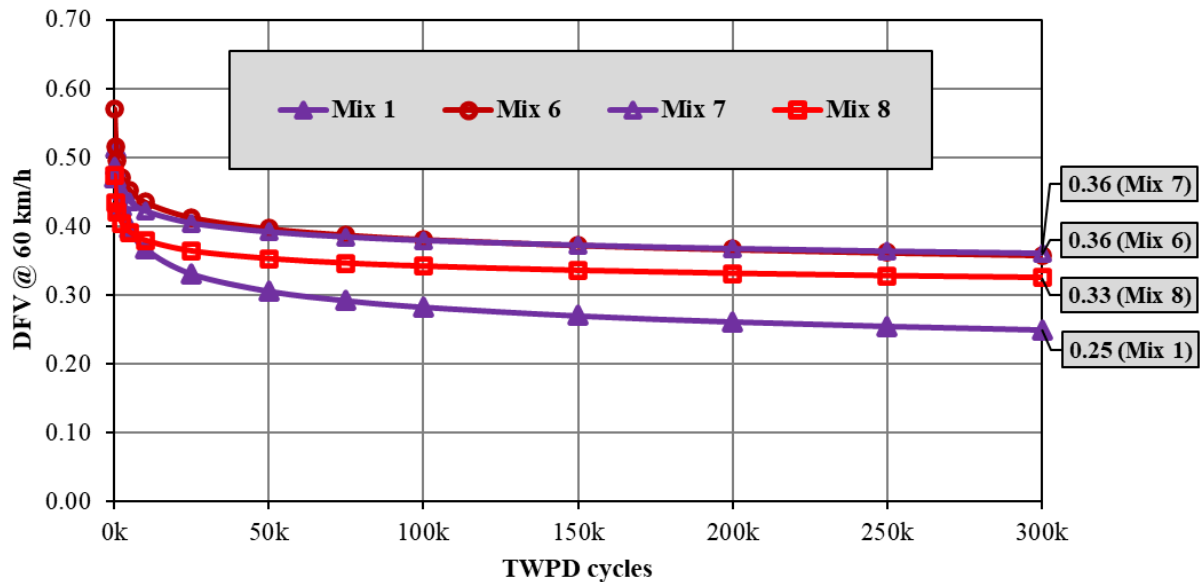


Figure 28: FDCs of Final Verification Asphalt Mixtures.

CONSTRUCTION-RELATED PARAMETER

Effect of Air-Void Content

Figure 29 compares the SP-C-1 mixture compacted to nominal air-void contents of 3% and 7%. The FDCs were similar, and the exploratory two-sample comparison produced a p-value of 0.910. Within this dense-graded mixture and the evaluated compaction range, air-void content had little effect on long-term friction. This conclusion should not be extended to open-graded or permeable friction-course mixtures without additional testing.

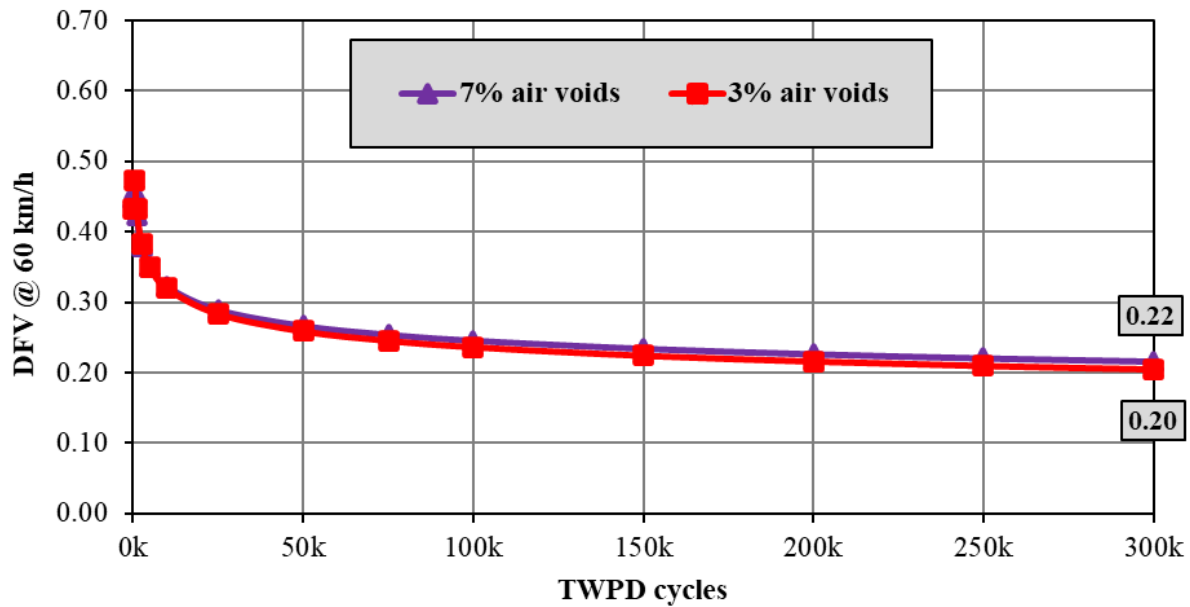


Figure 29: FDCs of Asphalt Mixtures with Varying Air Voids Percentage.

SUMMARY

The controlled study showed that aggregate polishing resistance was the primary determinant of long-term mixture friction. The intermediate fraction passing the No. 4 and retained on the No. 30 sieve was most influential, with the No. 4-to-No. 16 subfraction providing the largest individual contribution. Binder grade, binder content, overall gradation, mixture type, and air-void content had comparatively small long-term effects within the materials and ranges evaluated.

CHAPTER 6

VERIFICATION OF CONTROLLING PARAMETERS IN THE FIELD

This chapter evaluates whether the principal findings from the controlled laboratory program were also observed in the field. Available pavement sections were selected to represent differences in binder grade, aggregate type, gradation, and mixture type. Purposefully varying binder content or construction air voids in the field was not practical because such changes could compromise pavement performance; therefore, those parameters were not included in the field comparison.

MATERIAL-RELATED PARAMETERS

Effect of Binder Grade

Figure 30 presents wheel-path DFT measurements for sections representing two binder-grade comparisons. Measurements were obtained at three locations within each section. The measured friction values were similar within each comparison, and exploratory two-sample tests produced p-values of 0.779 and 0.152. These field observations were consistent with the controlled laboratory finding that binder grade had little effect on friction for the evaluated mixtures.

Effect of Aggregate Type

Figure 31 compares a TOM-C mixture containing gravel, trap rock, and limestone with an SP-D mixture containing limestone aggregate. The blended-aggregate section produced higher wheel-path friction, and the exploratory comparison produced a p-value of 0.026. Although the sections also differed in mixture type and binder grade, the result was consistent with the laboratory finding that aggregate source and polishing resistance strongly influence friction.

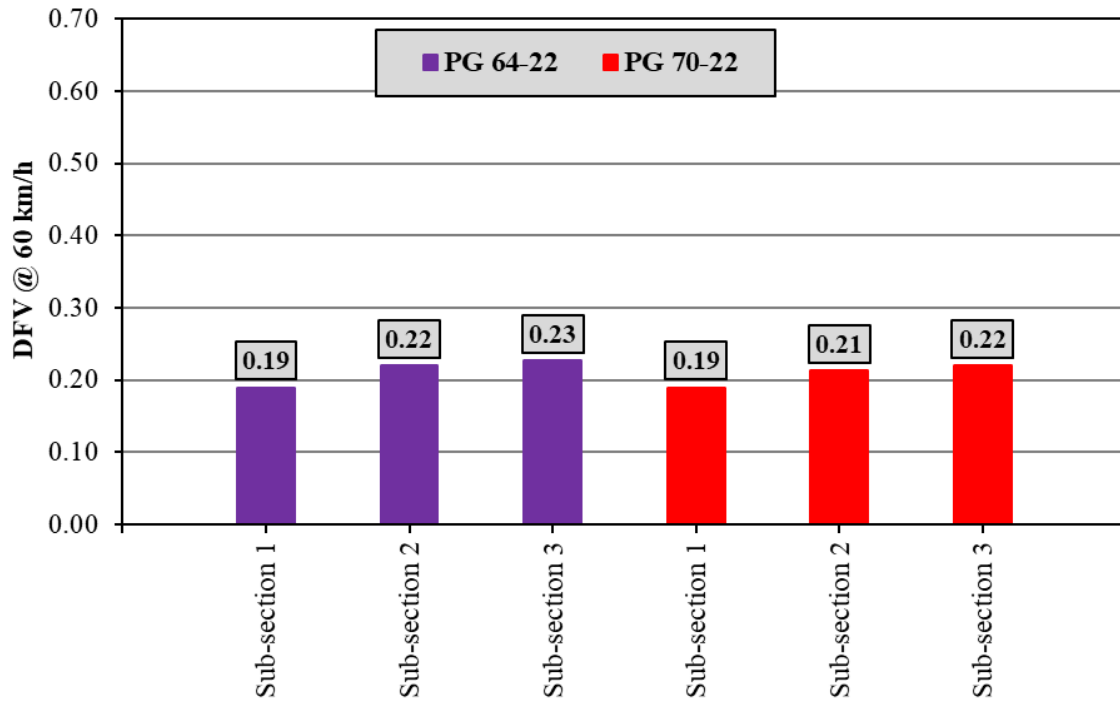
MIX DESIGN-RELATED PARAMETERS

Effect of Aggregate Gradation

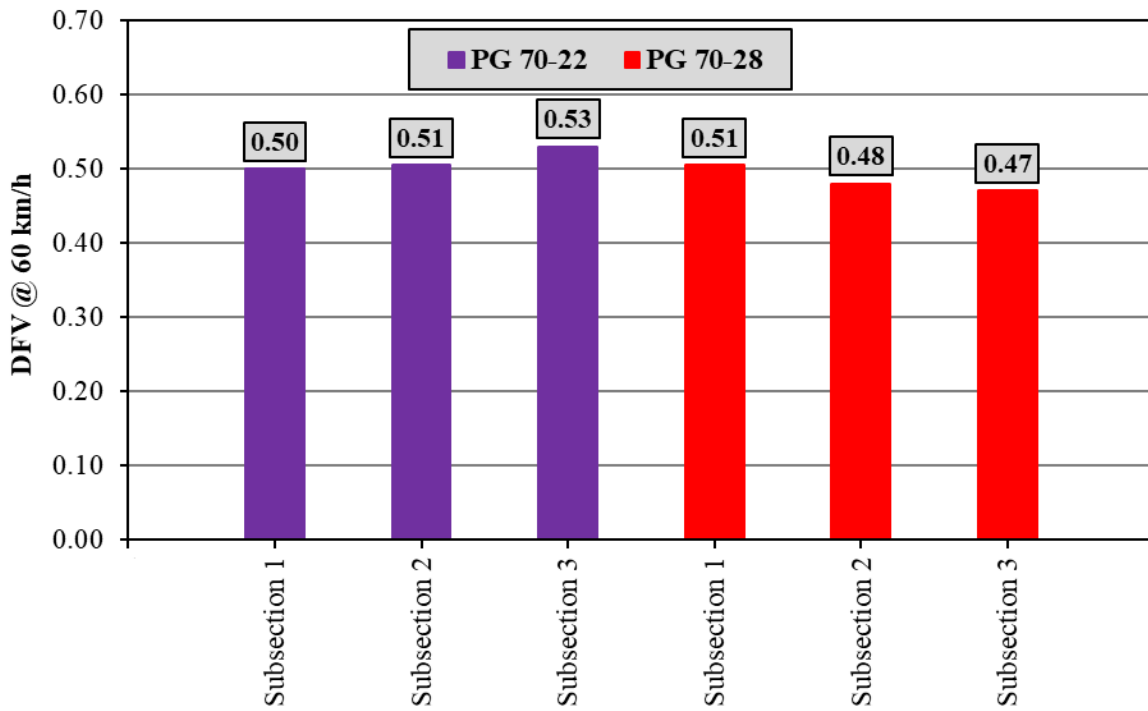
Figure 32 compares coarse- and fine-graded SP-C mixtures prepared with PG 64-22 binder. The wheel-path friction values were similar, and the exploratory comparison produced a p-value of 0.483. This result was consistent with the controlled laboratory finding that overall gradation had little direct influence on friction when aggregate type was similar.

Effect of Asphalt Mixture Type

Figure 33 compares SP-C with DG-C and SP-D with DG-D sections having generally comparable aggregate types. The measured friction values were similar within each pair. Exploratory two-sample comparisons produced p-values of 0.398 and 0.855, respectively, indicating no detectable mixture-type effect in these field comparisons.



(a)



(b)

Figure 30: Field Friction Values of Mixtures with Varying Binder Grade: (a) Friction Values of Mixtures with Limestone Aggregates and (b) Friction Values of Mixtures with Blend of Granite and Limestone Aggregates.

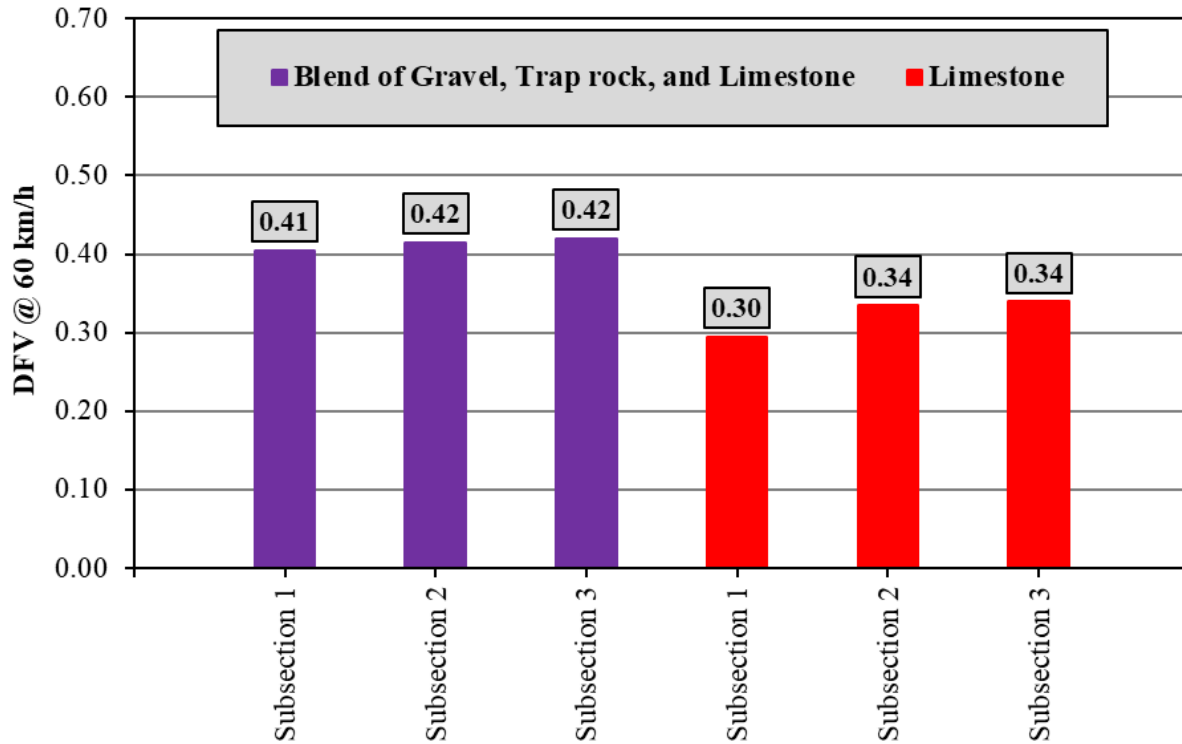


Figure 31: Field Friction Values of Mixtures with Different Aggregate Types.

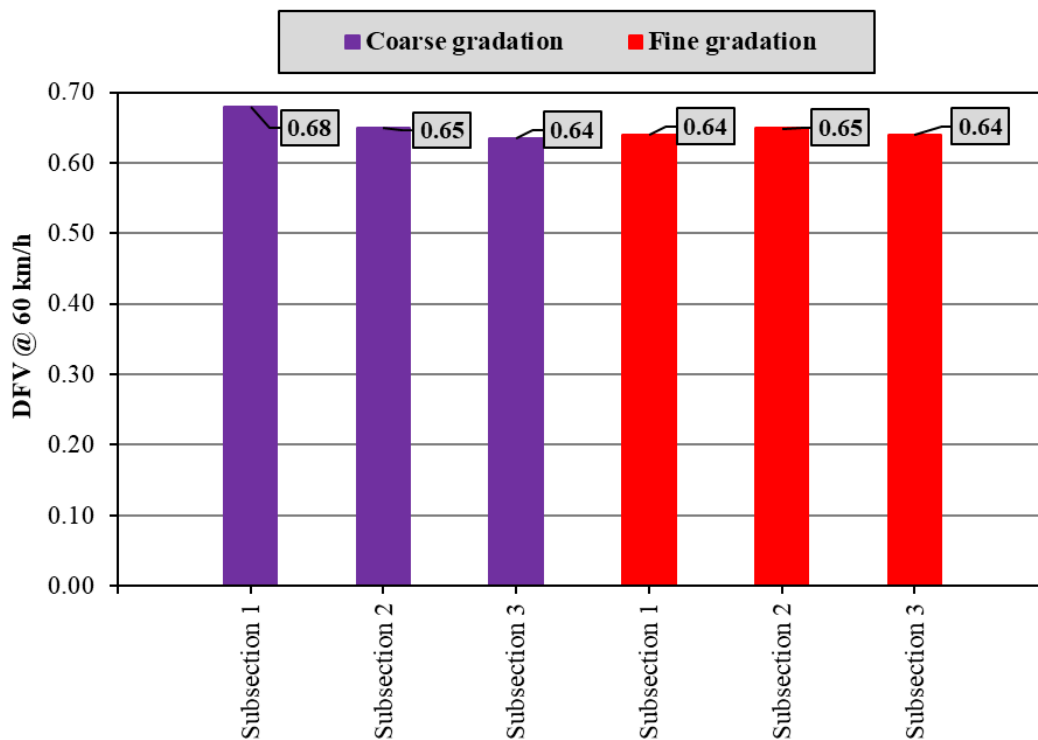


Figure 32: Field Friction Values of Mixtures with Changes in Aggregate Gradation.

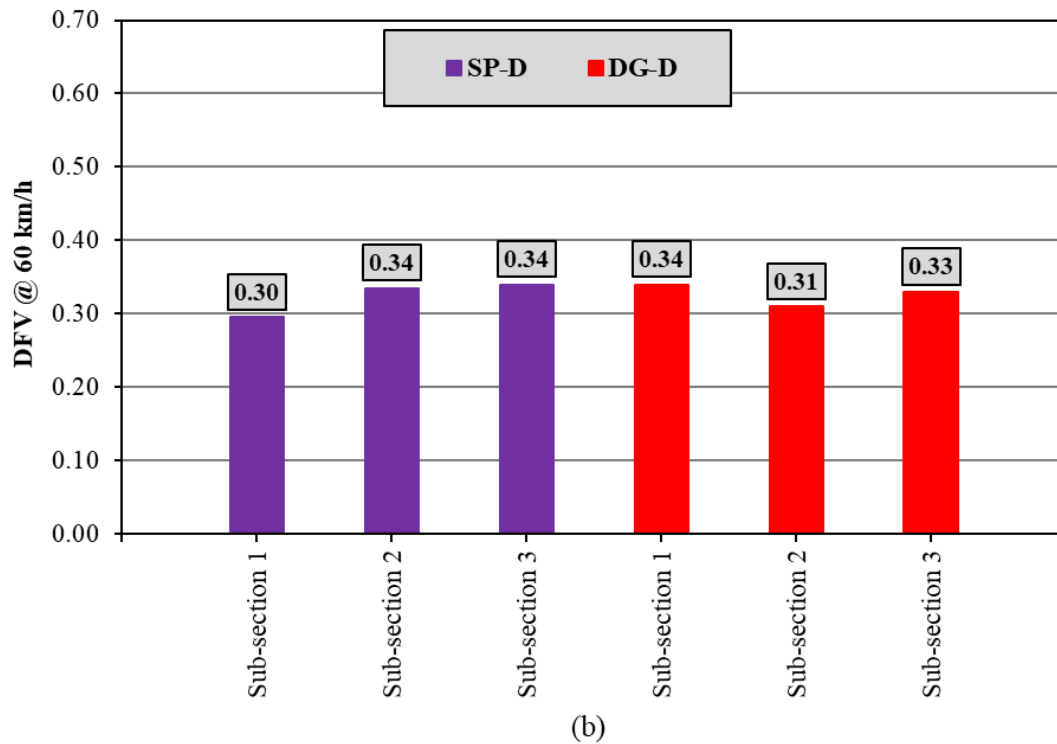
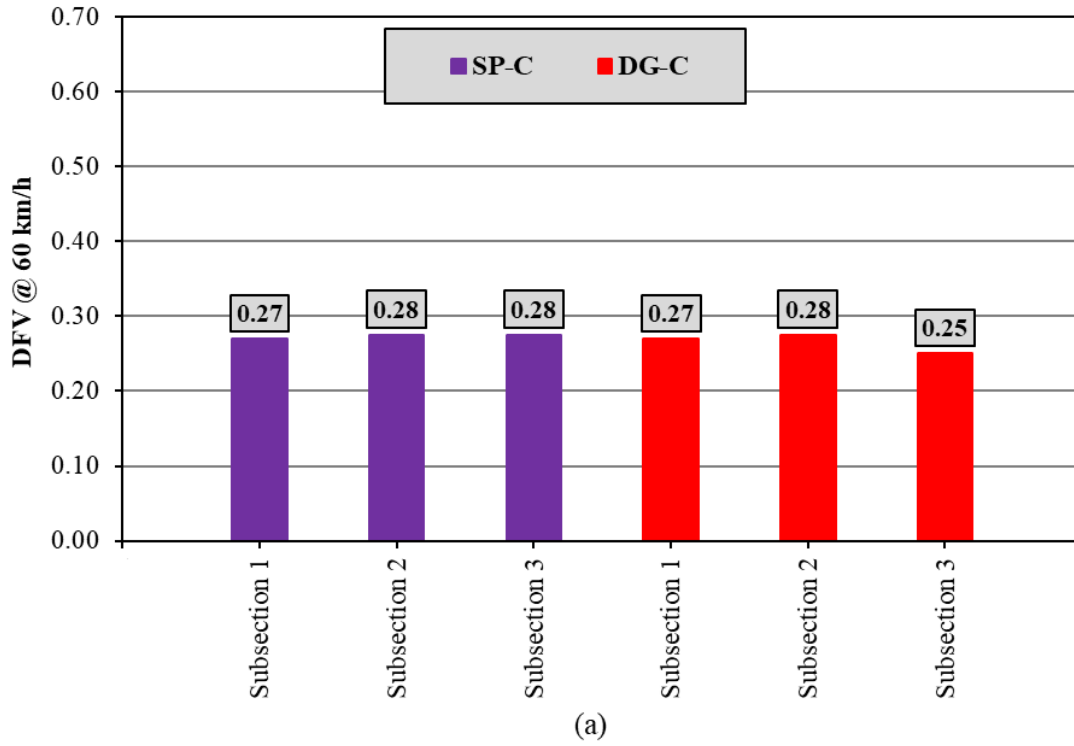


Figure 33: Field Friction Values of Mixtures with Varying Mixture Types: (a) Friction Values of Mixtures with SP-C and DG-C Gradations and (b) Friction Values of Mixtures with SP-D and DG-D Gradations.

SUMMARY

The field observations were generally consistent with the controlled laboratory results: binder grade, aggregate gradation, and mixture type produced comparatively small differences when aggregate type was similar, while the section containing more polish-resistant aggregate produced greater friction. Because the field sections were not a controlled factorial experiment and differed in more than one characteristic, these results should be interpreted as verification of trends rather than as isolated causal estimates.

CHAPTER 7

CASE STUDIES FOR IMPROVING THE FRICTIONAL PERFORMANCE OF TYPICAL HOT-MIX ASPHALT MIXTURES

This chapter presents a two-phase investigation of methods for improving mixtures with inadequate friction. The laboratory findings in Chapter 5 showed that friction was controlled primarily by aggregate quality within the intermediate gradation fraction, especially the No. 4-to-No. 16 subfraction. The case studies therefore concentrated higher-quality, friction-resistant aggregate in the stockpile or bin contributing most strongly to that critical fraction.

- **Phase 1 used three laboratory case studies to evaluate targeted replacement with sandstone or high-friction RAP and, where necessary, adjustment of the overall gradation.**
- **Phase 2 evaluated two producer mixture designs in their original condition and after targeted redistribution of aggregate quality.**

The modified mixtures retained the original design and proportions as closely as practical and were rechecked for relevant mechanical performance. The examples demonstrate both the potential and the limitations of fraction-specific friction optimization.

PHASE 1: LABORATORY-PRODUCED ASPHALT MIXTURES **CASE STUDY 1: SUPERPAVE MIXTURE**

The SP-C mixture summarized in Table 7 used the SP-C-16 gradation, five aggregate bins, and PG 70-22 binder. TWPD/DFT testing produced a TFV of 0.26 (Figure 34).

Analysis of the source contributions showed that Bin 2, which represented 40% of the blend, contributed a large portion of the critical intermediate fraction. Replacing the original Bin 2 material with sandstone increased TFV to 0.35.

For comparison, replacing all aggregate bins with sandstone produced a TFV of 0.40. Thus, concentrating sandstone in the 40% source bin achieved most of the friction benefit of an all-sandstone mixture while using substantially less premium aggregate.

Table 7: Details of Collected SP-C Mix Design.

Sieve size (Cumulative percent passing)	Bin 1 (14%) Limestone	Bin 2 (40%) Igneous	Bin 3 (26%) Limestone	Bin 4 (10%) Mortar sand	Bin 5 (10%) RAP
1"	100.0	100.0	100.0	100.0	100.0
3/4"	90.6	100.0	100.0	100.0	100.0
1/2"	57.6	100.0	100.0	100.0	100.0
3/8"	39.8	97.5	100.0	99.9	98.0
No. 4	7.5	29.5	93.6	99.7	65.7
No. 8	3.4	4.7	61.4	99.4	43.2
No. 16	2.3	3.1	38.7	98.4	30.7
No. 30	2.0	2.5	25.1	85.5	18.1
No. 50	1.7	2.2	13.1	44.2	9.0
No. 200	1.1	1.0	2.4	1.0	1.1
Design number of gyrations	50				
Binder grade	PG 70-22				
Optimum binder content	6% (0.4% from RAP)				

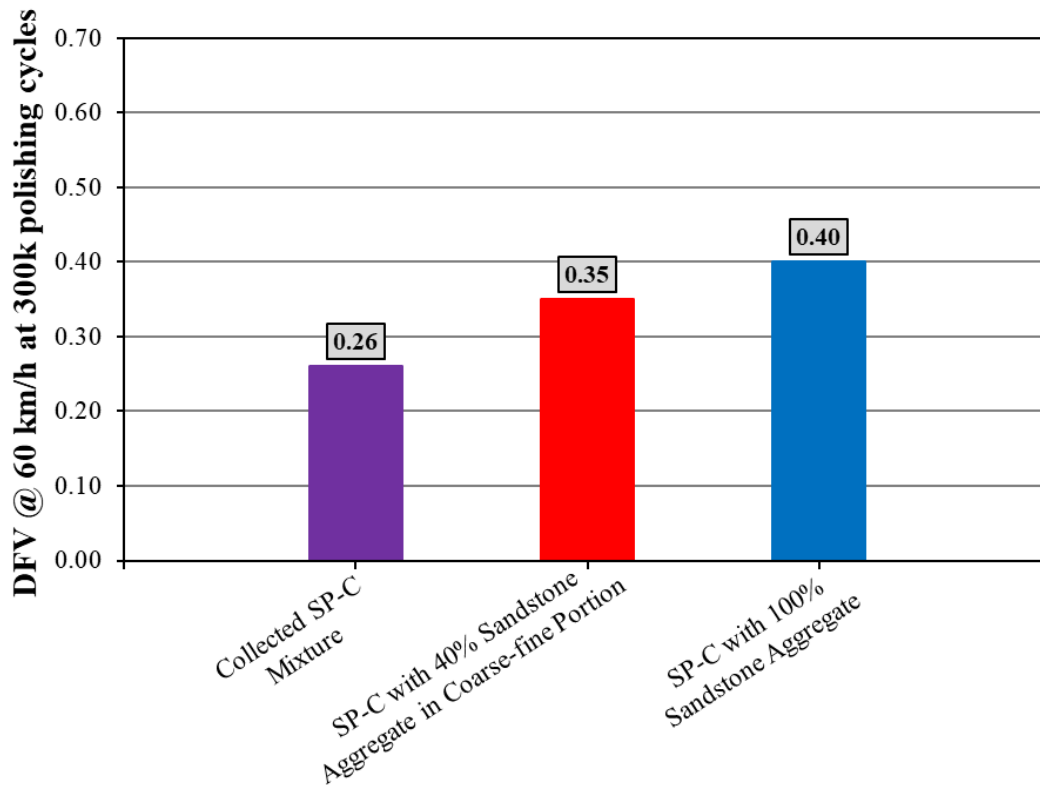


Figure 34: TFVs of Mixtures with Varying Aggregate Percentages in a SP-C Mix.

CASE STUDY 2: THIN-OVERLAY MIXTURE

The TOM-C mixture summarized in Table 8 used three aggregate bins and PG 76-22 binder. Its original TFV was 0.12 (Figure 35).

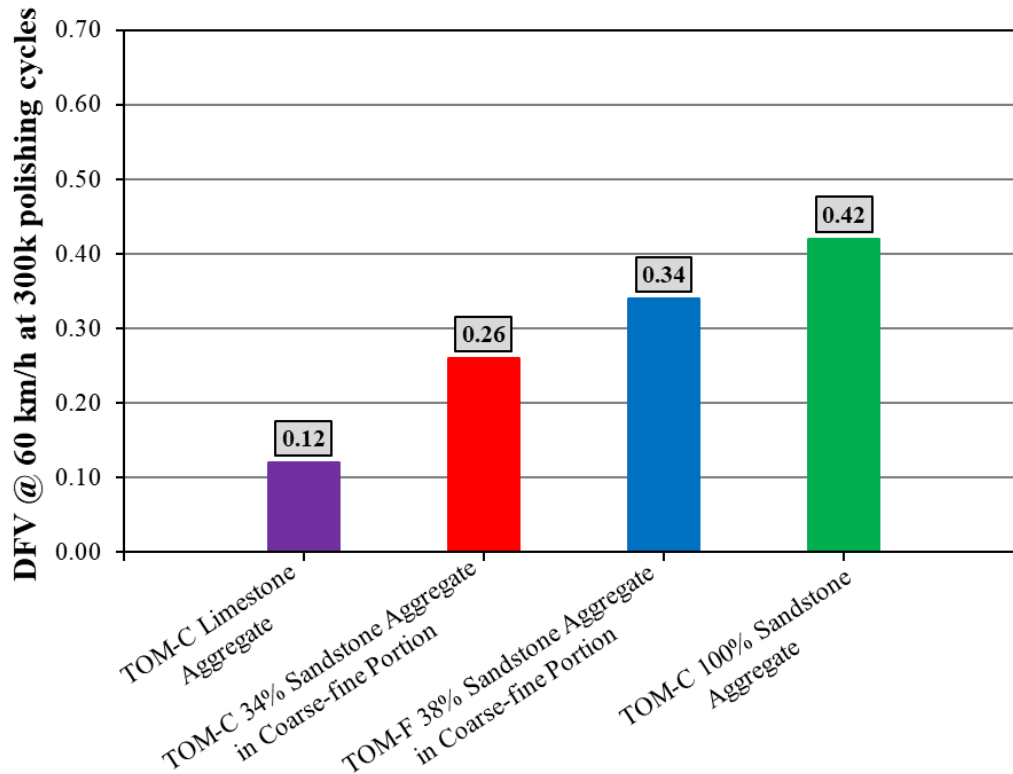


Figure 35: TFVs of Mixtures with Varying Aggregate Percentages in a TOM.

Replacing the 34% intermediate-aggregate source bin with locally available sandstone increased TFV to 0.26. An all-sandstone TOM-C mixture produced a TFV of 0.42, indicating that source replacement alone did not reproduce the friction of the all-sandstone mixture.

The limited improvement was attributed to the coarse TOM-C gradation, which exposed a relatively large proportion of coarse limestone aggregate. Aggregate quality in the intermediate source bin was therefore not the only factor controlling this case.

The mixture was subsequently changed to the finer TOM-F-2 gradation, with sandstone concentrated in the 38% intermediate source bin (Table 9). The modified mixture produced a TFV of 0.34, substantially greater than the original TOM-C mixture and closer to the all-sandstone result. This case shows that gradation adjustment may be necessary when a coarse surface structure limits the benefit of targeted source replacement.

Table 8: Details of Collected TOM-C Mix Design.

Sieve size (Cumulative percent passing)	Bin 1 (47%)	Bin 2 (34%)	Bin 3 (19%)
	Limestone	Limestone	Limestone
1/2"	100.0	100.0	100.0
3/8"	91.6	100.0	100.0
No. 4	22.1	70.7	100.0
No. 8	3.5	13.1	95.5
No. 16	2.6	4.2	76.5
No. 30	2.3	3.0	60.5
No. 50	2.1	2.6	48.3
No. 200	1.9	2.2	30.6
Design number of gyrations	35		
Binder grade	PG 76-22		
Optimum binder content	6.8%		

Table 9: Details of Produced TOM-F Mix Design.

Sieve size (Cumulative percent passing)	Bin 1 (30%)	Bin 2 (38%)	Bin 3 (32%)
	Limestone	Sandstone	Limestone
1/2"	100.0	100.0	100.0
3/8"	100.0	100.0	100.0
No. 4	70.0	100.0	100.0
No. 8	70.0	86.0	100.0
No. 16	70.0	71.0	100.0
No. 30	70.0	62.0	100.0
No. 50	70.0	62.0	86.0
No. 200	70.0	62.0	76.0
Design number of gyrations	35		
Binder grade	PG 76-22		
Optimum binder content	7.0%		

CASE STUDY 3: SUPERPAVE MIXTURE WITH RAP

The SP-C-16 mixture from Case Study 1, with an original TFV of 0.26, was used as the reference mixture for evaluating high-friction reclaimed asphalt pavement (RAP).

A new SP-C blend containing 40% high-friction RAP in Bin 5 produced a TFV of 0.32 (Table 10 and Figure 36). A comparison mixture prepared with 100% of the same RAP aggregate produced a TFV of 0.35. These results indicate that appropriately characterized RAP can contribute to improved friction and may reduce the need for virgin premium aggregate; however, RAP source consistency, recovered aggregate properties, and binder effects should be verified before routine implementation.

SUMMARY

The Phase 1 case studies confirmed that fraction-specific aggregate replacement can improve friction. Concentrating sandstone in the critical source bin captured most of the benefit of an all-sandstone SP-C mixture; the TOM case showed that overall surface gradation may also require adjustment; and high-friction RAP produced a substantial improvement when concentrated in the critical portion of the blend.

Table 10: Details of Produced SP-C RAP Mix Design.

Sieve size (Cumulative percent passing)	Bin 1 (20%) Limestone	Bin 2 (20%) Igneous	Bin 3 (10%) Limestone	Bin 4 (10%) Mortar sand	Bin 5 (40%) RAP (High-friction)
1"	100.0	100.0	100.0	100.00	100.0
3/4"	92.0	100.0	100.0	100.00	100.0
1/2"	33.0	100.0	100.0	100.00	96.8
3/8"	17.0	97.0	100.0	100.00	89.2
No. 4	2.0	37.0	100.0	100.00	57.9
No. 8	1.0	4.0	63.0	99.00	33.8
No. 16	1.0	2.0	37.0	98.00	20.3
No. 30	1.0	1.0	24.0	91.00	11.1
No. 50	1.0	1.0	17.0	42.00	3.9
No. 200	0.3	0.4	10.6	0.50	0.0
Design number of gyrations	50				
Binder grade	PG 70-22				
Optimum binder content	6% (0.4% from RAP)				

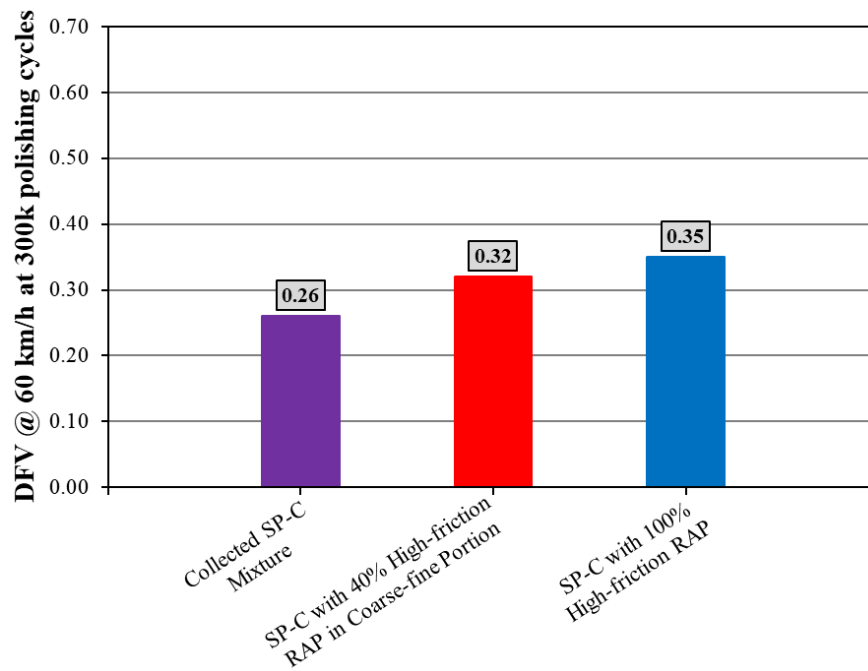


Figure 36: TFVs of Mixtures with Varying RAP Percentages in a SP-C Mix.

PHASE 2: ASPHALT MIXTURE DESIGNS OBTAINED FROM PRODUCERS

CASE STUDY 1: SUPERPAVE MIXTURE

Producer mixture designs were evaluated to determine whether the laboratory findings could be applied without substantially changing established designs. For the original SP-C mixture shown in Figure 37, Bin 2 was a limestone-dolomite source covering approximately the 3/8-in.-to-No. 16 range and contributed much of the critical No. 4-to-No. 16 material.

	Bin No.1	Bin No.2	Bin No.3	Bin No.4	Bin No.5	Bin No.6	Bin No.7	Bin No.8
Individual Bin (%):	Bin No.1 = 26 %	Bin No.2 = 32 %	Bin No.3 = 31 %		Bin No.5 = 1 %			Bin No.8 = 10 %
Aggregate Source:	Igneous	Limestone_Dolomite	Limestone_Dolomite	Limestone_Dolomite	Limestone_Dolomite			Fractionated RAP
Aggregate Number:	2411513	2407120	2407120	2407120				RAP 1/2"
Class (A) Rock (Y/N):	Yes	No	No	No	No			
Sieve Size:								
Passing	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %
-	1"	0.0	0.0	0.0	0.0			0.0
1"	3/4"	0.0	0.0	0.0	0.0			0.0
3/4"	1/2"	7.0	0.0	0.0	0.0			0.0
1/2"	3/8"	11.2	3.5	0.0	0.0			0.3
3/8"	No. 4	7.3	18.9	0.3	0.0			2.4
No. 4	No. 8	0.1	8.3	5.0	0.0			2.1
No. 8	No. 16	0.1	0.3	9.0	0.0			1.7
No. 16	No. 30	0.1	0.3	5.2	0.0			0.8
No. 30	No. 50	0.0	0.2	3.3	0.0			0.7
No. 50	No. 200	0.0	0.2	4.8	0.0			1.2
No. 200	Pan	0.1	0.3	3.4	1.0			0.8
Total:		26.0	32.0	31.0	1.0			10.0
Percent of plus No. 4		25.5	22.4	0.3	0.0			2.7

Figure 37: Original SP-C mix design

The original SP-C mixture satisfied the evaluated rutting and cracking criteria but produced a terminal DFV of 0.21, below the project's provisional screening value of approximately 0.30 (Figure 38). Aggregate quality was therefore redistributed within the blend to improve friction.

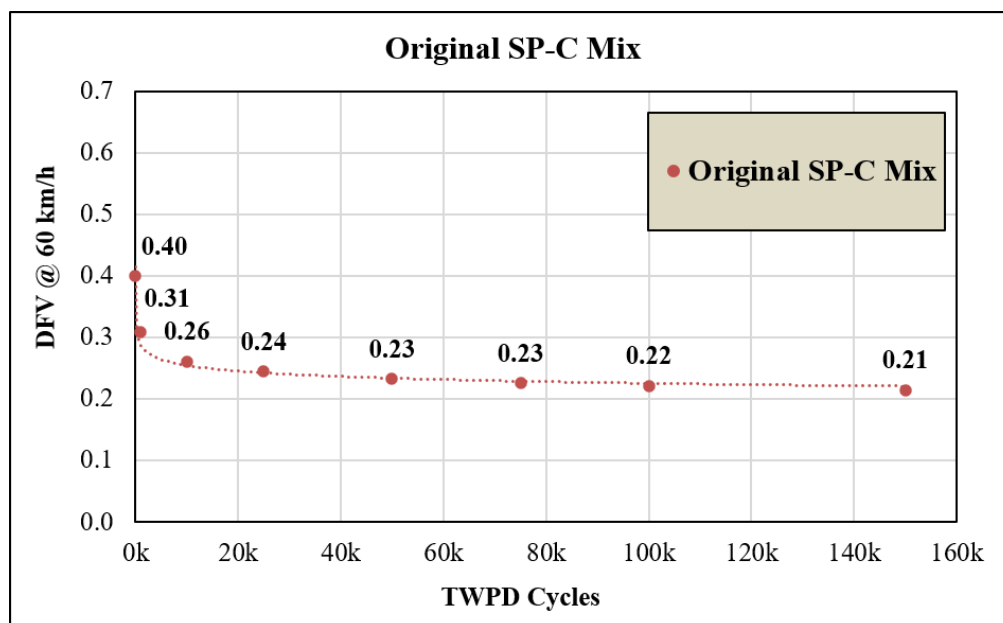


Figure 38: Friction Results of Original SP-C Mix

Modified SP-C Mixture

In the modified SP-C design (Figure 39), the 3/4-in. source bin was changed from SAC A igneous aggregate to SAC B limestone-dolomite, while the 3/8-in. source bin that contributed most strongly to the critical fraction was changed to SAC A aggregate. This redistribution concentrated the premium aggregate where it was expected to provide the greatest friction benefit while limiting the total quantity of SAC A material. The gradation remained within the applicable limits.

	Bin No.1	Bin No.2	Bin No.3	Bin No.4	Bin No.5	Bin No.6	Bin No.7	Bin No.8
Individual Bin (%):	Bin No.1 = 26 %	Bin No.2 = 32 %	Bin No.3 = 31 %		Bin No.5 = 1 %			Bin No.8 = 10 %
Aggregate Source:	Limestone_Dolomite	Igneous	Limestone_Dolomite	Limestone_Dolomite	Limestone_Dolomite			Fractionated RAP
Aggregate Number:	2407120	2411513	2407120	2407120				RAP 1/2"
Class (A) Rock (Y/N):	Yes	No	No	No	No			
Sieve Size:								
Passing	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %
Retained								
- 1"	0.0	0.0	0.0		0.0			0.0
1" 3/4"	0.0	0.0	0.0		0.0			0.0
3/4" 1/2"	7.0	0.0	0.0		0.0			0.0
1/2" 3/8"	11.2	3.5	0.0		0.0			0.3
3/8" No. 4	7.3	18.9	0.3		0.0			2.4
No. 4 No. 8	0.1	8.3	5.0		0.0			2.1
No. 8 No. 16	0.1	0.3	9.0		0.0			1.7
No. 16 No. 30	0.1	0.3	5.2		0.0			0.8
No. 30 No. 50	0.0	0.2	3.3		0.0			0.7
No. 50 No. 200	0.0	0.2	4.8		0.0			1.2
No. 200 Pan	0.1	0.3	3.4		1.0			0.8
Total:	26.0	32.0	31.0		1.0			10.0
Percent of plus No. 4	25.5	22.4	0.3		0.0			2.7

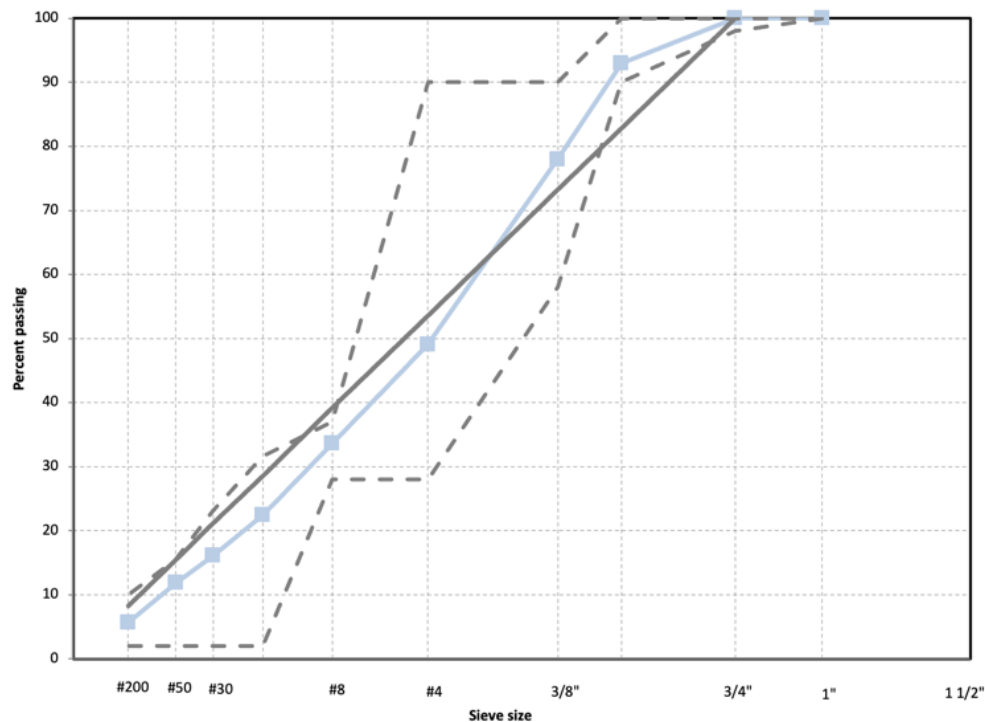


Figure 39: Modified SP-C Mix design & gradation (SP-C)

The modified SP-C mixture maintained acceptable mechanical performance (Figure 40). The HWTT rut depth was approximately 4.35 mm after 20,000 wheel passes. IDEAL-CT and OT

results also indicated acceptable cracking resistance, and the measured CFE and CPR values remained within the evaluated performance region.

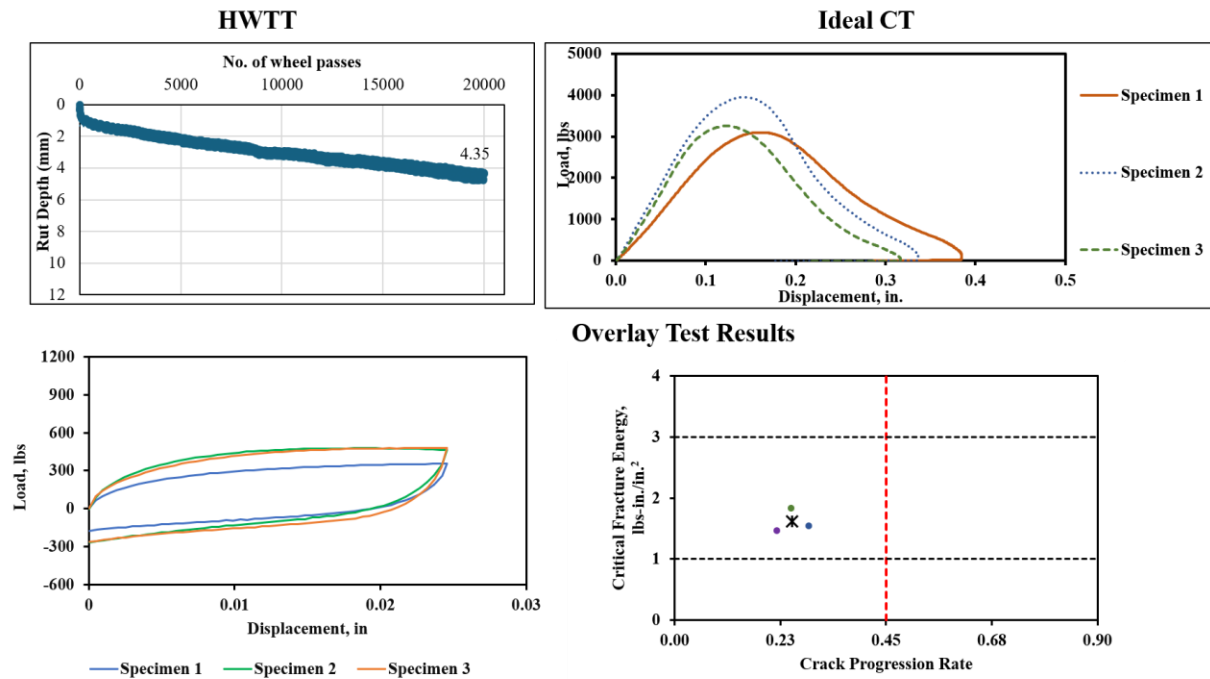


Figure 40: Modified SP-C Mix - Performance Test Results

As shown in Figure 41, targeted redistribution increased terminal DFV from 0.21 to 0.28. The improvement confirms the value of concentrating a polish-resistant aggregate in the critical fraction; however, the modified mixture remained below the provisional 0.30 screening value and would require additional optimization or project-specific evaluation before being considered to have met that screening level.

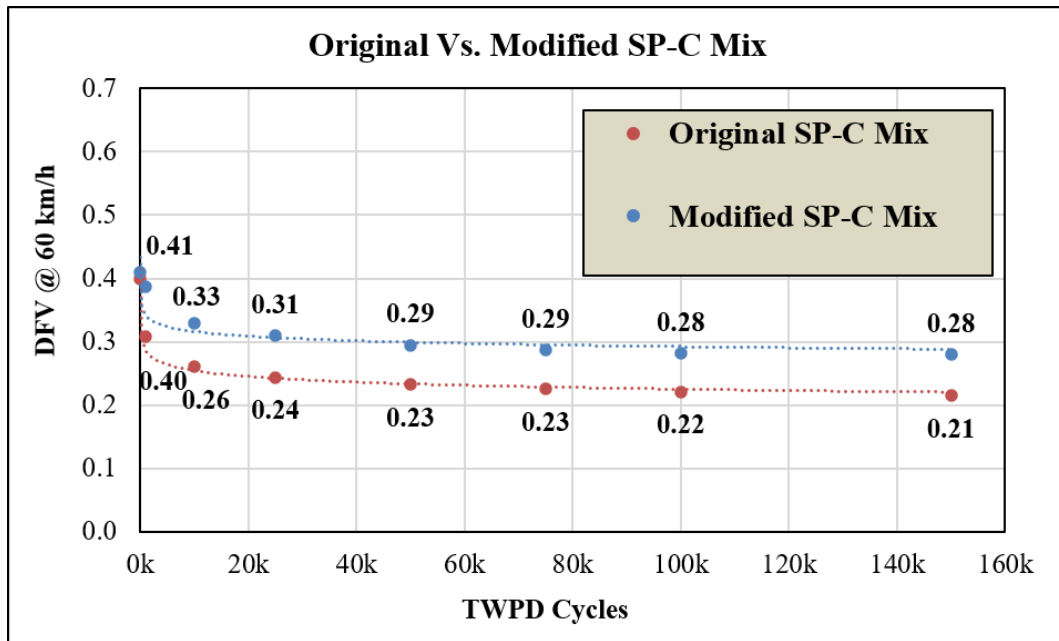


Figure 41: Modified SP-C Mix – Friction Results

CASE STUDY 2: STONE-MATRIX ASPHALT MIXTURE

The original SMA-D mixture shown in Figure 42 was evaluated using the same approach. Bin 2, a limestone-dolomite source covering approximately the 3/8-in.-to-No. 16 range, contributed a large portion of the critical No. 4-to-No. 16 fraction. The original mixture was first evaluated for mechanical and frictional performance.

		Bin No.1	Bin No.2	Bin No.3	Bin No.4	Bin No.5	Bin No.6	Bin No.7	Bin No.8
Individual Bin (%):		Bin No.1 = 40 %	Bin No.2 = 37 %	Bin No.3 = 9 %	Bin No.4 = 1 %	Bin No.5 = 3 %			Bin No.8 = 10 %
Aggregate Source:		Igneous	Limestone_Dolomite	Limestone_Dolomite					RAP
Aggregate Number:		2411513	2407120	2407120					RAP 1/2"
Class (A) Rock (Y/N):		Yes	No	No					
Sieve Size:									
Passing	Retained	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %
-	3/4"	0.0	0.0	0.0	0.0	0.0			0.0
3/4"	1/2"	14.0	0.0	0.0	0.0	0.0			0.0
1/2"	3/8"	14.0	4.1	0.0	0.0	0.0			0.0
3/8"	No. 4	10.0	22.9	0.0	0.0	0.0			3.0
No. 4	No. 8	0.7	8.9	0.1	0.0	0.3			0.5
No. 8	No. 16	0.6	0.3	1.6	0.0	0.2			2.2
No. 16	No. 30	0.1	0.3	2.7	0.0	0.2			0.8
No. 30	No. 50	0.0	0.3	1.7	0.0	0.1			0.7
No. 50	No. 200	0.0	0.0	0.9	0.0	0.7			0.7
No. 200	Pan	0.1	0.1	1.0	0.0	1.7			1.4
Total:		40.0	37.0	9.0	1.0	3.0			10.0
Percent of plus No. 4		38.0	27.0	0.0	0.0	0.0			3.0

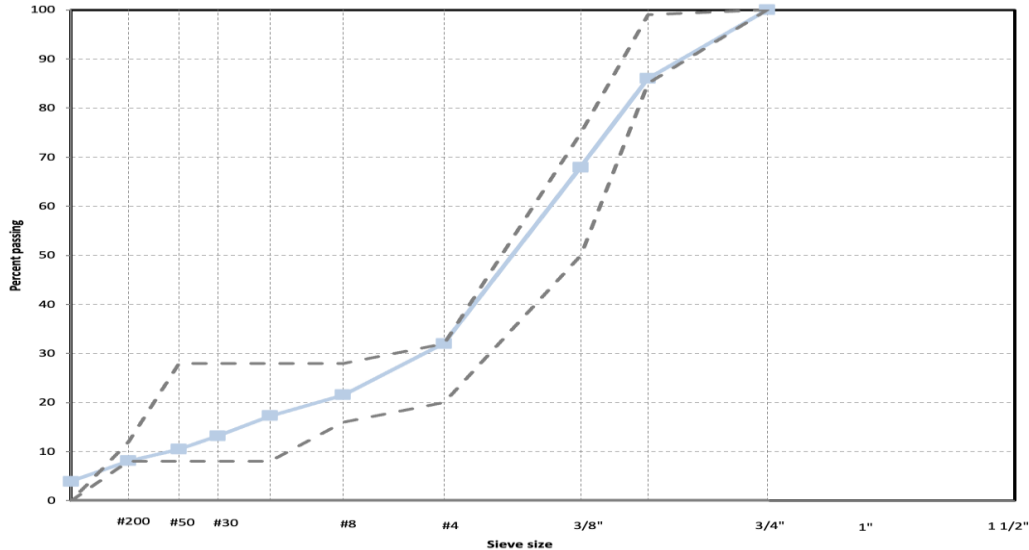


Figure 42: Original SMA-D Mix design & gradation

The original SMA-D mixture satisfied the evaluated rutting and cracking criteria but produced a terminal DFV of 0.25, below the provisional 0.30 screening value (Figure 43).

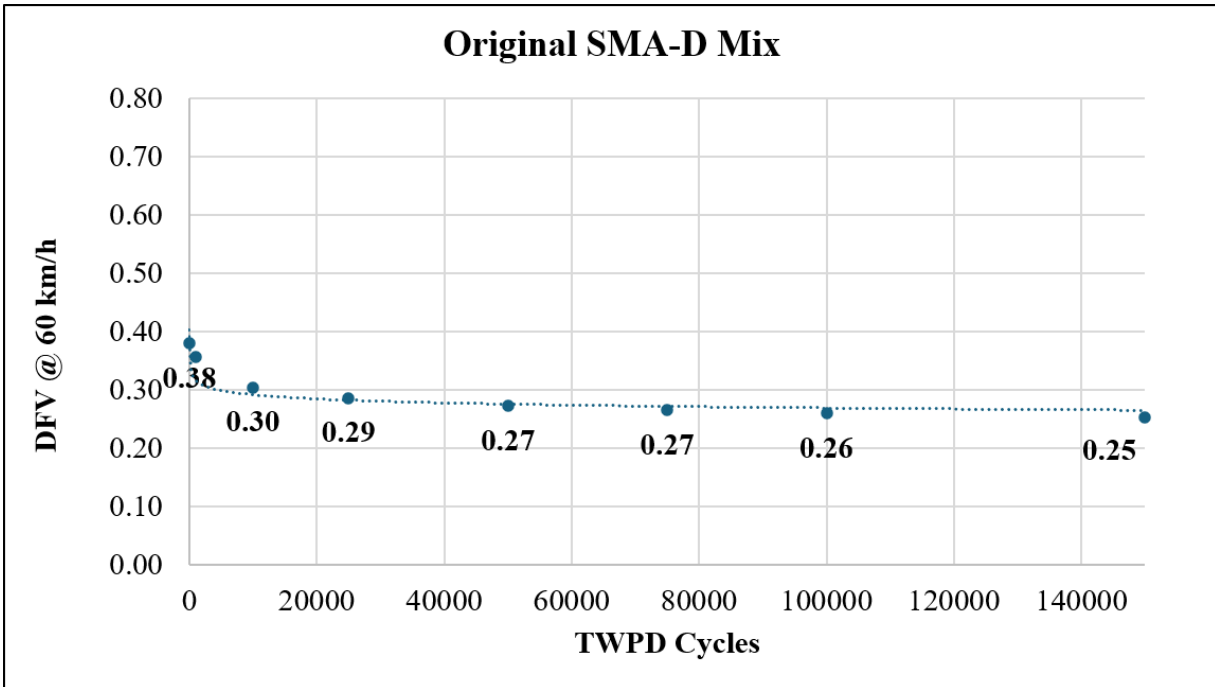


Figure 43: SMA-D Mix – Friction Results

Modified SMA-D Mixture

In the modified SMA-D design (Figure 44), Bin 2 was replaced with SAC A aggregate while the remaining blend was maintained as closely as practical. This change concentrated the premium aggregate in the source bin contributing most strongly to the critical fraction, and the gradation remained within the applicable limits.

		Bin No.1	Bin No.2	Bin No.3	Bin No.4	Bin No.5	Bin No.6	Bin No.7	Bin No.8
Individual Bin (%):		Bin No.1 = 40 %	Bin No.2 = 37 %	Bin No.3 = 9 %	Bin No.4 = 1 %	Bin No.5 = 3 %			Bin No.8 = 10 %
Aggregate Source:		Igneous	Igneous	Limestone_Dolomite					RAP
Aggregate Number:		2411513	2411513	2407120					RAP 1/2"
Class (A) Rock (Y/N):		Yes	No	No					
Sieve Size:									
Passing	Retained	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %	Individual Ret., %
-	3/4"	0.0	0.0	0.0	0.0	0.0			0.0
3/4"	1/2"	14.0	0.0	0.0	0.0	0.0			0.0
1/2"	3/8"	14.0	4.1	0.0	0.0	0.0			0.0
3/8"	No. 4	10.0	22.9	0.0	0.0	0.0			3.0
No. 4	No. 8	0.7	0.0	0.1	0.0	0.3			0.5
No. 8	No. 16	0.6	0.3	1.6	0.0	0.2			2.2
No. 16	No. 30	0.1	0.3	2.7	0.0	0.2			0.8
No. 30	No. 50	0.0	0.3	1.7	0.0	0.1			0.7
No. 50	No. 200	0.0	0.0	0.9	0.0	0.7			0.7
No. 200	Pan	0.1	0.1	1.0	0.0	1.7			1.4
Total:		40.0	37.0	9.0	1.0	3.0			10.0
Percent of plus No. 4		38.0	27.0	0.0	0.0	0.0			3.0

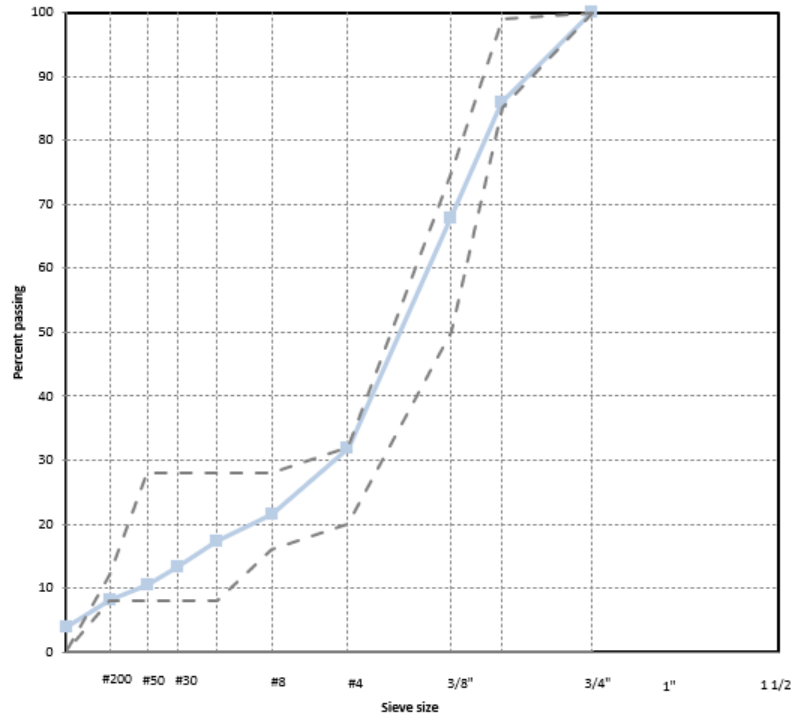


Figure 44: Modified SMA-D Mix design & gradation

The modified SMA-D mixture maintained acceptable mechanical performance (Figure 45). The final HWTT rut depth was approximately 3.46 mm after 20,000 wheel passes, and the IDEAL-CT, OT, CFE, and CPR results remained within the evaluated performance region.

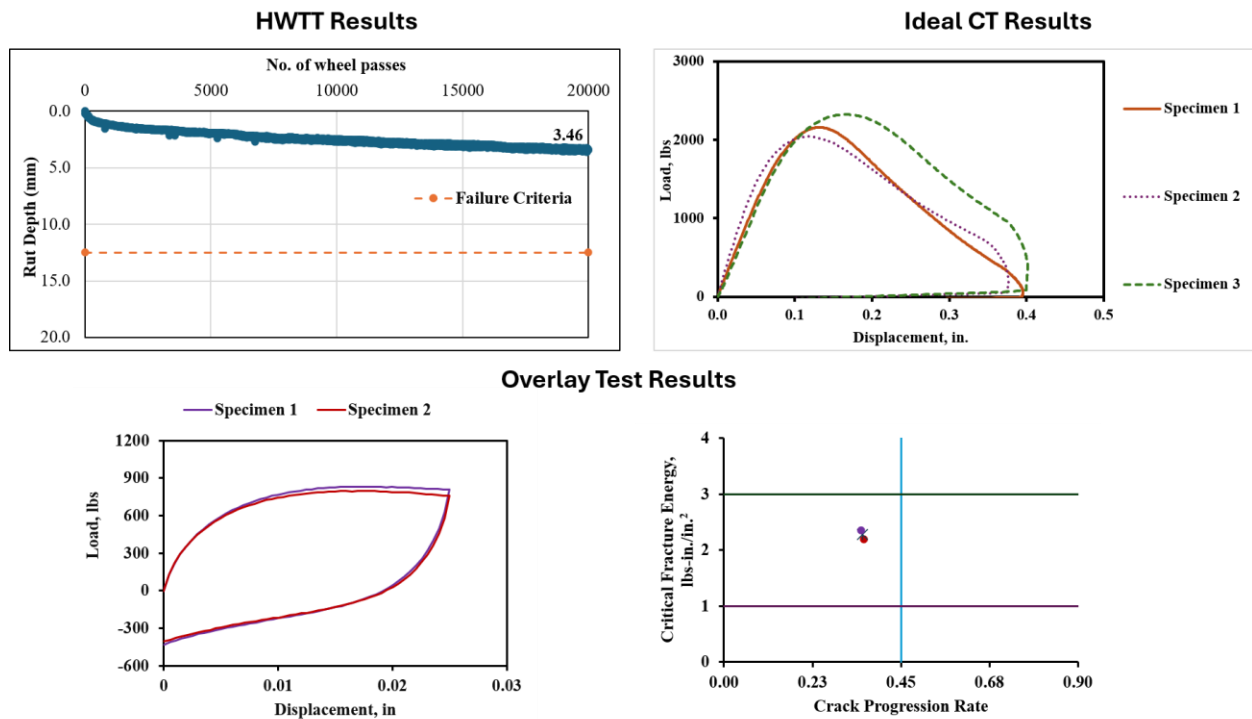


Figure 45: Modified SMA-D Mix - Performance Test Results

Figure 46 shows that the targeted aggregate replacement increased terminal DFV from 0.25 to 0.32, exceeding the project's provisional 0.30 screening value.

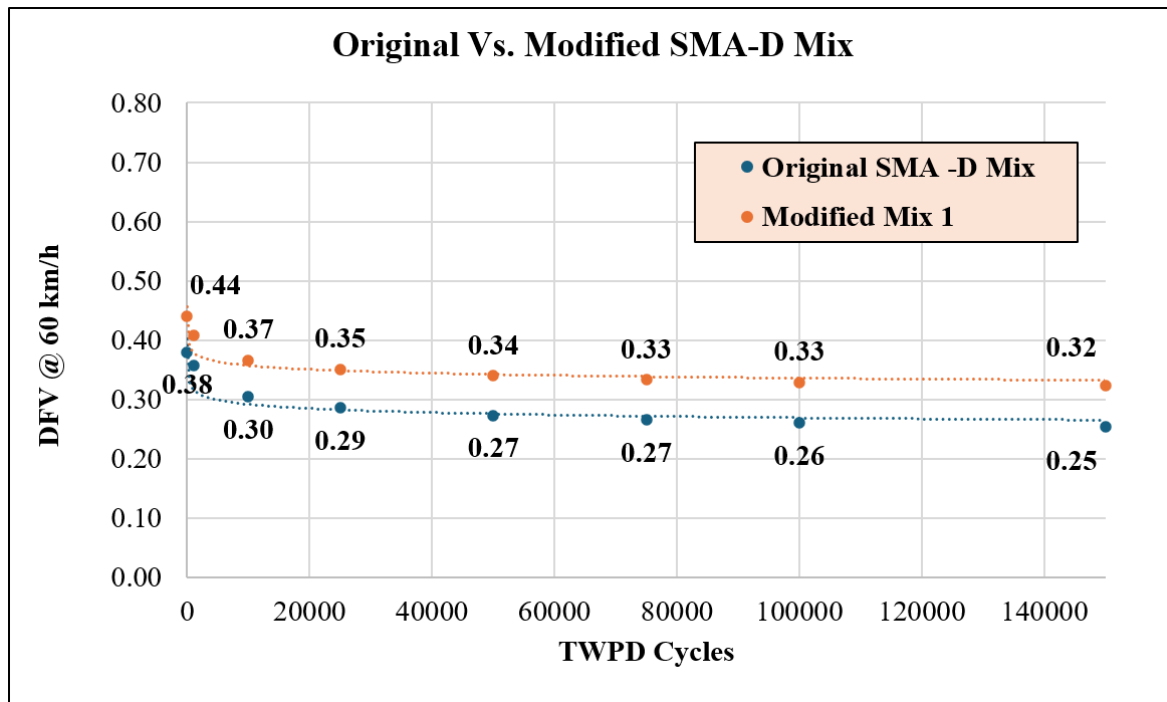


Figure 46: Original Vs. Modified SMA-D Mix – Friction Results

SUMMARY

Table 11 summarizes the two original and two modified producer mixtures. All four mixtures satisfied the evaluated mechanical-performance criteria. Final HWTT rut depths ranged from approximately 3.46 to 6.55 mm, and the cracking indicators remained within the evaluated

Table 11: Summary of mechanical performance and friction characteristics of the mixtures

Performance Tests	Original SP-C Mix	Modified SP-C Mix	Original SMA-D Mix	Modified SMA-D Mix
HWTT	6.55 mm @ 20K Cycles	4.35 mm @ 20K cycles	4.31 mm @ 20K Cycles	3.46 mm @ 20K cycles
RT	N/A	N/A	150	143
IDT (psi)	133	127	170	204
CT Index	87	68	447	464
CFE	2.9	1.8	2.39	2.27
CPR	0.30	0.30	0.26	0.35
Terminal DFV	0.21	0.28	0.25	0.32

acceptance regions. Terminal DFV ranged from 0.21 to 0.32. The SP-C modification provided a meaningful improvement but remained below the provisional 0.30 screening value, whereas the modified SMA-D mixture exceeded that value. The case studies demonstrate that aggregate-quality redistribution can improve friction without necessarily compromising conventional mixture performance, but the degree of improvement is mixture-specific.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The research evaluated how material-, mixture-design-, and construction-related parameters affect asphalt mixture friction and developed a practical method for improving mixtures with inadequate friction. Controlled laboratory testing was followed by field trend verification and laboratory and producer case studies. The principal conclusions are summarized below.

1. Aggregate type and polishing resistance were the dominant controls on long-term mixture friction. Within the controlled fraction study, the intermediate aggregate passing the No. 4 and retained on the No. 30 sieve had the greatest influence, and the No. 4-to-No. 8 subfraction provided the largest individual contribution.
2. Binder grade, binder content, overall aggregate gradation, mixture type, and compacted air-void content produced comparatively small long-term friction differences within the materials and ranges evaluated. These factors can still affect early-life friction, macrotexture, and conventional BMD performance and should not be considered universally insignificant.
3. The field comparisons generally supported the laboratory trends: sections with similar aggregate types showed little difference attributable to binder grade, gradation, or mixture type, while the section containing more polish-resistant aggregate produced greater friction.
4. Targeted replacement or redistribution of the aggregate source contributing to the critical fraction substantially improved friction while limiting the amount of premium aggregate. Replacing only the fines passing the No. 30 sieve provided little benefit.
5. The modified mixtures generally maintained acceptable rutting, cracking, and moisture-damage performance, demonstrating that friction can be incorporated as an additional BMD screening consideration. The producer SP-C example improved from 0.21 to 0.28 but remained below the provisional 0.30 screening value; the producer SMA-D example improved from 0.25 to 0.32.
6. High-friction RAP improved terminal DFV in the laboratory, but source consistency, recovered aggregate properties, and binder effects must be characterized before routine use as a friction-improvement material.
7. The project provides a practical friction-screening and aggregate-optimization framework, but a laboratory terminal-DFV criterion cannot yet be treated as a field acceptance requirement.

STUDY LIMITATIONS

1. The controlled laboratory program included a finite number of aggregate sources, binders, and dense-graded mixture types; the findings should be expanded before they are generalized to all Texas materials or to open-graded and permeable friction courses.
2. One asphalt ring specimen was used for each controlled scenario after a repeatability pretest. The multiple DFT measurements along each curve are repeated measurements on the same specimen; therefore, the reported p-values are exploratory and do not replace testing with independent replicate specimens.
3. The available field sections were not a controlled factorial experiment. Several comparisons involved differences in more than one material or design characteristic, so the field results verify general trends rather than isolate a single causal effect.

4. The TWPD/DFT terminal values have not yet been calibrated to TxDOT field skid-number requirements, traffic level, climate, or service age.
5. The producer case studies were limited in number. One modified SP-C mixture improved substantially but remained below the provisional 0.30 screening value, demonstrating that targeted replacement may require more than one optimization iteration.

RECOMMENDATIONS

1. Construct pilot field sections representing low-, moderate-, and high-terminal-DFV mixtures and monitor DFT/skid measurements, traffic, texture, and surface condition over time.
2. Establish a laboratory-to-field relationship before adopting terminal DFV as a specification acceptance criterion. The approximate 0.30 value used in this project should remain a provisional screening value until validated.
3. Evaluate within-laboratory repeatability and between-laboratory reproducibility of the ring-preparation, TWPD-polishing, and DFT-measurement procedures using independent replicate specimens and common proficiency samples.
4. During mixture design, identify the aggregate sources contributing to the No. 4-to-No. 16 fraction and prioritize source replacement or redistribution in that fraction before replacing the entire blend or only the fines.
5. Reverify all modified mixtures for the applicable volumetric, HWTT, cracking, and moisture-damage requirements; friction improvement should not be accepted at the expense of conventional mixture durability.
6. Develop project- and facility-level quality-control procedures for specimen air voids, ring fabrication, DFT slider conditioning, equipment calibration, polishing intervals, and reporting of terminal DFV.
7. Evaluate high-friction RAP separately by source and processing history before using it as a substitute for virgin polish-resistant aggregate.
8. Expand the database to include additional TxDOT districts, aggregate mineralogies, mixture types, traffic levels, climates, and construction conditions, including open-graded and permeable friction-course mixtures.
9. Use the companion guideline as an implementation aid and provide training and standardized reporting templates for TxDOT districts, laboratories, and producers participating in pilot implementation.

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APPENDIX A

Value of Research

IMPORTANCE OF FINE AGGREGATES IN ACHIEVING ADEQUATE SKID RESISTANCE IN TxDOT HOT MIX ASPHALT MIXTURES

PROJECT STATEMENT

Skid resistance is an essential pavement-surface characteristic that directly affects roadway safety, particularly under wet-weather conditions. The current Balanced Mix Design (BMD) framework emphasizes rutting, cracking, and moisture-damage resistance; however, friction is generally not evaluated as part of mixture design. Consequently, an asphalt mixture can satisfy structural and durability-related performance requirements while still providing inadequate friction after construction and subsequent traffic polishing.

The frictional performance of an asphalt mixture can be influenced by binder grade and content, aggregate type and gradation, mixture type, the distribution of aggregate sources among gradation fractions, and compacted air-void content. Project 0-7108 provides the relative influence of these factors to provide TxDOT and asphalt producers with a focused and economical procedure for improving friction without unnecessarily changing the entire mixture.

Project 0-7108 addressed this need through controlled laboratory testing, field trend verification, and practical mixture-optimization case studies. Accelerated polishing with the Three-Wheel Polishing Device (TWPD) and friction measurements with the Dynamic Friction Tester (DFT) demonstrated that aggregate type and polishing resistance exert the strongest influence on long-term friction. The intermediate aggregate fraction passing the No. 4 sieve and retained on the No. 30 sieve was particularly influential, with the No. 4-to-No. 16 subfraction providing the largest individual contribution to mixture friction.

Field observations generally supported the laboratory findings. The case studies further demonstrated that mixtures with inadequate friction can be improved by strategically replacing or redistributing the low-friction aggregate source that contributes most strongly to the critical fraction while maintaining the original gradation and mixture design as closely as practical. The modified mixtures were then reverified for rutting, cracking, moisture-damage, and friction performance.

The principal value of the research is therefore not simply the identification of a friction-sensitive aggregate size range. The project provides a practical decision framework that can be incorporated into mixture development and approval to identify friction deficiencies before construction, concentrate premium aggregate where it is most effective, reduce unnecessary use and hauling of high-quality aggregate, preserve acceptable BMD performance, and reduce the risk of premature friction-related maintenance or rehabilitation. The proposed laboratory terminal-DFV screening levels remain provisional and should be refined through field implementation and laboratory-to-field validation.

VALUE OF RESEARCH SUMMARY

The strongest directly quantifiable economic benefit identified by this project is the more efficient use of premium, polish-resistant aggregate. In the laboratory SP-C case study, replacing only the critical intermediate bin with sandstone resulted in a mixture containing 40% high-friction aggregate and increased the terminal friction value from 0.26 to 0.35. A companion mixture produced with 100% sandstone yielded a terminal friction value of 0.40. Thus, the targeted approach achieved a terminal friction value close to the all-sandstone mixture while using 60 percentage points less premium aggregate. This finding provides a defensible basis for estimating material-cost savings associated with implementation.

The economic analysis presented below is intentionally screening-level. It monetizes only the potential reduction in premium-aggregate use and does not assign monetary value to potential crash reduction, avoided premature friction-restoration treatments, avoided overlays, reduced traffic control, reduced field investigation and retesting, reduced user delay, or environmental benefits. Consequently, the calculated economic value should be viewed as a conservative estimate of the total potential value of implementation.

Table 12: Functional Areas for Project 0-7108

Benefit Area	Qualitative	Economic	Both	TxDOT	State	Both
Level of Knowledge	X			X		
Roadway Safety			X			X
Customer Satisfaction	X					X
Environmental Sustainability			X			X
Increased Functional Service Life			X	X		
Reduced Construction, Operations, and Maintenance Cost		X		X		
Materials and Pavements			X	X		
Infrastructure Condition			X			X
Engineering Design Improvement			X	X		

QUALITATIVE BENEFITS

Level of Knowledge and Engineering Design Improvement

This project provides TxDOT with an improved understanding of the material and mixture-design parameters that control asphalt-mixture friction. The research evaluated the mechanisms associated with macrotexture, microtexture, aggregate polishing, binder-film removal, and friction deterioration and separately examined binder grade, binder content, aggregate type, aggregate gradation, mixture type, aggregate distribution within the gradation, and air-void

content. The resulting framework adds a functional-performance consideration to the BMD process and gives designers a targeted response when a mixture exhibits inadequate friction.

The most important design finding is that friction improvement does not necessarily require replacing the entire aggregate blend. Aggregate polishing resistance is the dominant material control, and the intermediate fraction passing the No. 4 sieve and retained on the No. 30 sieve - particularly the No. 4-to-No. 16 subfraction - has the greatest influence on long-term friction. This provides TxDOT and producers with a more focused basis for source selection and blending than relying only on the overall aggregate quality of the complete mixture.

Safety

Inadequate pavement friction can increase stopping distance and reduce vehicle control, particularly on wet pavement. Incorporating friction evaluation during mixture design allows TxDOT to identify mixtures that may become excessively polished before those mixtures are placed in the field. Potential deficiencies can therefore be addressed during design and approval, when changes are generally less disruptive and less costly than corrective actions after construction.

Strategically using polish-resistant aggregate in the critical fraction can improve friction retention under traffic polishing. Implementation therefore supports TxDOT roadway-safety objectives by reducing the likelihood that a structurally acceptable mixture develops inadequate surface friction. Because Project 0-7108 did not establish a project-specific crash-modification factor, crash-reduction benefits are not monetized in the economic analysis below.

Customer Satisfaction and Infrastructure Condition

Pavement surfaces with inadequate friction may require additional monitoring, corrective surface treatments, or early rehabilitation. These activities may produce lane closures, traffic interruptions, construction delays, and public concern regarding roadway safety and pavement quality. Evaluating friction during mixture development can reduce the likelihood of these unplanned interventions and help preserve the intended functional condition of the pavement surface.

Environmental Sustainability

High-quality, friction-resistant aggregates may not be locally available in all parts of Texas and may require longer haul distances. Replacing the complete aggregate blend with premium aggregate can therefore increase material consumption, hauling, fuel use, emissions, and cost. The optimization approach developed in this project concentrates premium aggregate in the fraction that most strongly controls friction while retaining locally available aggregate in the remainder of the mixture. This targeted strategy improves material efficiency and can reduce both hauling-related environmental impacts and project cost.

ECONOMIC BENEFITS

Direct Material-Cost Savings from Targeted Premium Aggregate Use

A screening-level economic analysis was developed to quantify the potential direct material savings from the targeted aggregate-blending strategy. The calculation uses the laboratory case study in which 40% high-friction sandstone in the critical intermediate bin produced a terminal friction value of 0.35, compared with 0.40 for a mixture containing 100% sandstone. For economic screening, this represents a 60% reduction in the quantity of premium aggregate relative to full replacement.

The estimated annual direct material saving is calculated as:

$$\text{Annual Savings} = Q_{HMA} \times f_{agg} \times (1 - f_{target}) \times \Delta C_{premium}$$

where Q_{HMA} is the annual quantity of HMA to which the approach is applied; f_{agg} is the aggregate fraction of the mixture by mass; f_{target} is the fraction of premium aggregate used in the targeted design; and $\Delta C_{premium}$ is the delivered-cost difference between premium and locally available aggregate.

Screening assumptions:

- The HMA mixture is assumed to contain approximately 95% aggregate by mass, consistent with typical binder contents evaluated in this project.
- The targeted strategy uses 40% premium aggregate rather than 100% premium aggregate, consistent with the laboratory case study; therefore, the premium-aggregate reduction is 60% of the aggregate mass.
- An illustrative implementation quantity of 50,000 tons of HMA per year is used. The results scale linearly and can be replaced with the quantity actually implemented by TxDOT.
- Because delivered aggregate prices vary substantially by source and haul distance, premium-aggregate cost differentials can vary from \$15 to \$35 per ton. These are sensitivity values, not measured project costs, and should be replaced with district-specific supplier or bid information during implementation. For the remaining portion of the analysis assume an average of \$25 per ton.
- Benefits are evaluated over 10 years using a 4% discount rate for screening purposes.
- The current public project record lists total Project 0-7108 funding of \$860K. This value is treated conservatively as an initial investment in the benefit-cost calculation and should be confirmed against final TxDOT project financial records before submission.

Table 13: Screening-Level Economic Value of Targeted Aggregate Optimization Assuming \$25 per Ton

Economic Metric	\$25/ton Premium
Premium aggregate avoided per 1,000 tons of HMA	570 tons
Potential savings per 1,000 tons of HMA	\$14,250
Annual direct material savings at 50,000 tons HMA/year	\$712,500
Present value of 10 years of benefits at 4%	\$5.78 million
Net present value after \$863,000 research investment	\$4.92 million
Benefit-cost ratio	6.7 : 1
Simple payback period	1.2 years

Interpretation of Economic Value

Under the middle sensitivity case, applying the targeted aggregate strategy to 50,000 tons of HMA per year and assuming a \$25-per-ton delivered-cost premium for high-friction aggregate produces an estimated direct material saving of approximately \$712,500 per year. Over a 10-year implementation period, the present value of these direct benefits is approximately \$5.78 million. After subtracting the \$863,000 research investment, the estimated net present value is approximately \$4.92 million, corresponding to a benefit-cost ratio of approximately 6.7 to 1 and a simple payback period of about 1.2 years.

These estimates should not be interpreted as guaranteed bid-price savings. The actual economic value to TxDOT will depend on aggregate source, haul distance, mixture proportions, contractor pricing, and the number and size of projects on which the framework is implemented. The analysis is nevertheless useful because it identifies the magnitude of potential direct savings and provides a transparent calculation that can be updated with actual TxDOT project data.

Increased Functional Service Life and Avoided Corrective Work

A pavement may remain structurally serviceable after its surface friction has declined to an undesirable level. When this occurs, a surface treatment, overlay, or other friction-restoration action may be required before the structural capacity of the pavement has been fully utilized. Improving friction retention at the mixture-design stage can extend functional surface life and delay or avoid friction-driven corrective work.

The economic values in Table 13 do not include avoided costs for premature surface treatments or overlays, mixture redesign after construction, additional friction investigations, traffic control and lane closures, user delay, or wet-weather crashes. Any one of these benefit categories could materially increase the total value of implementation. During field implementation, TxDOT can quantify these additional benefits using actual treatment costs, quantities, friction histories, and crash data.

Recommended Value for TxDOT VoR Documentation

For a screening-level TxDOT Value of Research calculation, the middle sensitivity case provides a reasonable illustrative value while remaining limited to direct material savings: expected value of approximately \$712,500 per year for 10 years; 4% screening discount rate; present value of benefits of approximately \$5.78 million; net present value of approximately \$4.92 million after an \$863,000 project investment; benefit-cost ratio of approximately 6.7:1; and simple payback of approximately 1.2 years. If TxDOT prefers a more conservative value for final documentation, the \$15-per-ton sensitivity case yields approximately \$427,500 per year and a benefit-cost ratio of approximately 4.0:1. The final VoR spreadsheet should replace the assumed cost differential and implementation quantity with TxDOT-verified values.

Additional Potential Economic Benefits Not Monetized

- Avoided or delayed friction-restoration surface treatments and overlays.
- Reduced costs for redesigning, investigating, or replacing mixtures after inadequate friction is identified.
- Reduced traffic-control and lane-closure costs associated with corrective work.
- Reduced hauling and production costs through more efficient use of premium aggregate.
- Extended functional service life of pavement surfaces while maintaining structural performance.
- Potential reductions in agency and road-user costs associated with wet-weather crashes on low-friction surfaces.
- Potential use of suitable high-friction RAP as an alternative source of premium friction-resistant aggregate, where mixture performance requirements are satisfied.

OVERALL VALUE OF RESEARCH

Project 0-7108 provides TxDOT with a practical method for adding frictional performance to the asphalt mixture-design decision process without requiring wholesale replacement of locally available aggregates. The research shows that premium aggregate can be strategically concentrated in the gradation fraction that controls friction, thereby improving long-term friction while preserving satisfactory rutting, cracking, and moisture-damage performance. The direct material-savings analysis indicates that broader implementation has the potential to recover the research investment relatively quickly and to generate several million dollars in net economic value over a 10-year period, even before safety, service-life, corrective-maintenance, traffic-control, user-cost, and environmental benefits are monetized. Field implementation and validation should be used to refine the laboratory screening levels and replace the economic assumptions with actual TxDOT costs and project quantities.