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Functional Characteristics of Dense-Graded Asphalt Surface Mixtures

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16. Abstract:

As asphalt mix design criteria evolve beyond prescriptive to performance-based specifications, traditional limits may be challenged in the pursuit of material durability. As designers explore these limits, it is important to understand how basic design criteria ultimately affect the comfort and safety of the public who travels over these mixtures.

This study assessed the short-term functional (surface) characteristics of pavements constructed using dense-graded asphalt surface mixtures designed with the balanced mix design (BMD) methodology as compared to counterpart mixtures designed using the existing design methodology (Superpave). Another objective of this study was to establish a functional performance baseline for the Virginia Department of Transportation's (VDOT) BMD trial mixtures constructed in the 2019 through 2021 construction seasons in terms of friction and macrotexture. This study also sought to define a potential empirical relationship to link mixture volumetric properties to the surface characteristics of asphalt mixtures in terms of macrotexture. In this effort, 52 different field projects encompassing pairs of BMD and control mixtures with service lives ranging from 0.1 to 2.8 years were surveyed for friction, macrotexture, and pavement roughness. Descriptive statistics and parametric statistical techniques were used to identify systematic trends or differences in the functional characteristics of the pavements.

The results showed that application of the BMD methodology resulted in slight changes in volumetric properties and gradations of asphalt mixtures, but these changes mostly fell within the production variability limits of conventionally designed mixtures. The results also showed that BMD mixtures, on average, provided similar or better friction, macrotexture, and smoothness characteristics. In addition, similar or more uniform texture characteristics were, on average, obtained for the surfaces receiving BMD mixtures, potentially indicating better construction uniformity. Further, an empirical model incorporating production volumetric and gradation properties was developed to predict macrotexture.

The study concludes that based on the results from the sites evaluated, use of the BMD methodology yields similar or better functional surface characteristics when compared to those of conventionally designed mixtures.

The study recommends the continuation of BMD implementation, as the functional characteristics are either preserved or enhanced with the use of the BMD methodology. Further, the study recommends the assessment of existing and future BMD projects and continued collaboration among VDOT's Maintenance Division, Materials Division, and Traffic Operations Division on developing a friction and texture management framework

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FINAL REPORT

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ABSTRACT

As asphalt mix design criteria evolve beyond prescriptive to performance-based specifications, traditional limits may be challenged in the pursuit of material durability. As designers explore these limits, it is important to understand how basic design criteria ultimately affect the comfort and safety of the public who travels over these mixtures.

This study assessed the short-term functional (surface) characteristics of pavements constructed using dense-graded asphalt surface mixtures designed with the balanced mix design (BMD) methodology as compared to counterpart mixtures designed using the existing design methodology (Superpave). Another objective of this study was to establish a functional performance baseline for the Virginia Department of Transportation's (VDOT) BMD trial mixtures constructed in the 2019 through 2021 construction seasons in terms of friction and macrotexture. This study also sought to define a potential empirical relationship to link mixture volumetric properties to the surface characteristics of asphalt mixtures in terms of macrotexture. In this effort, 52 different field projects encompassing pairs of BMD and control mixtures with service lives ranging from 0.1 to 2.8 years were surveyed for friction, macrotexture, and pavement roughness. Descriptive statistics and parametric statistical techniques were used to identify systematic trends or differences in the functional characteristics of the pavements.

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FINAL REPORT

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INTRODUCTION

Many agencies are moving toward implementing the balanced mix design (BMD) methodology for design and acceptance of asphalt mixtures (West et al., 2018). The popularity of this design concept stems from the prospect of increasing durability and performance of asphalt mixtures and responsibly permitting for material and design innovations that would be very challenging with traditional recipe-type designs. In line with national trends, the Virginia Department of Transportation (VDOT) is currently in the process of implementing the BMD methodology for dense-graded asphalt surface mixtures with A and D designations.

Unlike the existing asphalt mix design methodology (Superpave), the BMD methodology requires a series of laboratory performance tests to be conducted on an asphalt mixture. The test results are then used to check the performance of a mixture with respect to performance-based specifications considering several modes of distress (i.e., cracking, rutting, and moisture susceptibility) and long-term durability (Boz et al., 2022). Several local and national research efforts have evaluated and are currently evaluating the impact of the BMD methodology on the durability of the mixtures, supporting the movement toward full implementation (Boz et al., 2023; Diefenderfer et al., 2021a, 2021b, 2023a, 2023b; Habbouche et al., 2021, 2022; West et al., 2018; Yin and West, 2021). However, little to no research has been aimed at understanding how the latitude in design options that BMD enables (theoretically) might affect the functional properties of those mixtures when placed in the field. Although rarely the expressed intent, traditional design criteria for dense- and gap-graded mixtures provide important guardrails on as-placed surface characteristics, e.g., surface drainability, skid resistance, tire-pavement noise, etc.

As BMD evolves and begins to challenge some of those guardrails, it becomes more important to understand just how basic mix design criteria ultimately affect the comfort and safety of the traveling public. Absent this understanding, engineers will have trouble knowing where exceptions to traditional criteria in pursuit of better durability (for instance) might jeopardize safe function.

Pavement surface frictional characteristics provide the needed grip at the tire-pavement interface that keeps vehicles safely connected to the road while undergoing maneuvers. They are considered among the important factors contributing to the safety of the traveling public, as the frictional characteristics have been linked to crashes (Flintsch et al., 2012; Hall et al., 2009; Najafi et al., 2017; Underwood et al., 2022). Pavement surface texture is considered the most important component for the friction developed at the tire-pavement interface (Underwood et al., 2022) and is defined as the deviations of the pavement surface from a true planar surface (Flintsch et al., 2012). Pavement surface texture as relates to friction is typically assessed based on two levels of texture: microtexture and macrotexture. Microtexture, describing pavement texture with wavelengths less than 0.5 mm, is the most significant contributor to skid resistance at lower speeds for dry surfaces (McGhee and Flintsch, 2003; de León Izeppi et al., 2019). Macrotexture, describing pavement texture with wavelengths in the range of approximately 0.5 mm to 50.0 mm, is considered the primary component related to high-speed skid resistance for dry and wet surfaces (de León Izeppi et al., 2019; McGhee and Flintsch, 2003). In general, higher levels of friction and macrotexture are indicative of good characteristics for pavement surfaces. There are various methodologies and technologies for measuring friction and macrotexture, and further details on these can be found in other documentation (Flintsch et al., 2012; Hall et al., 2009; Underwood et al., 2022).

Pavement roughness (or smoothness) is another important functional characteristic of pavement surfaces that affects vehicle dynamics, ride quality, dynamic loads, and drainage, thereby also affecting the comfort of the traveling public. Pavement roughness is also used to quantify pavement condition by many state agencies including VDOT (Nair et al., 2015; Zhou et al., 2021). This surface characteristic is quantified by the international roughness index (IRI) and is often expressed in terms of inches per mile. Smaller IRIs indicate a smoother ride, and higher IRIs indicate a rougher ride. Pavement roughness is typically measured by vehicle-based profiling devices (e.g., inertial profiler) in accordance with ASTM E950, Standard Test Method for Measuring the Longitudinal Profile of Traveled Surfaces, and the IRI is calculated in accordance with ASTM E1926, Standard Practice for Computing International Roughness Index of Roads from Longitudinal Profile Measurements.

PURPOSE AND SCOPE

The purpose of this study was to compare the short-term functional (surface) characteristics (i.e., skid resistance, macrotexture, and smoothness) of pavements constructed using dense-graded asphalt surface mixtures designed with the BMD methodology to those of the counterpart control mixtures designed using the existing design methodology (Superpave). In addition, an objective of this study was to establish a functional performance baseline for the BMD mixtures constructed during VDOT’s 2019, 2020, and 2021 construction seasons in terms of friction and macrotexture. A further objective was to define a potential empirical relationship to link mixture volumetric properties to the surface characteristics of asphalt mixtures in terms of macrotexture.

The scope of the study included identifying the BMD and control projects in the field; surveying the field projects for skid resistance (friction), macrotexture, and roughness; processing the data; compiling volumetric properties of the mixtures; and performing various statistical analyses to fulfill the study objectives.

METHODS

Field Sites

BMD field trials were planned and executed in six VDOT districts during the 2019, 2020, and 2021 construction seasons. The trial BMD mixtures were designed using VDOT's BMD special provisions developed for dense-graded surface mixtures or dense-graded surface mixtures with a high reclaimed asphalt pavement (RAP) content. The contents for both special provisions were the same with the exception of the requirement regarding RAP contents, which varied by the construction season. Trials also included control mixtures designed in accordance with Section 211 of VDOT's *Road and Bridge Specifications* (VDOT, 2016, 2020). Standard equipment and practices were used during production and paving of these mixtures with no reports of operations-related issues. Further details on the mixtures and the special provisions for each construction season are provided in other documents (Diefenderfer et al., 2021a, 2023a, 2023b). Table 1 shows the number of field projects selected from each district for evaluation. In addition, the research team in collaboration with the technical review panel for the study included additional testing sites from 2022 BMD projects selected from the Salem and Richmond districts, as also shown in Table 1. No control sites were available for the 2022 BMD projects. Overall, 52 field projects or mixtures were included in this study.

Table 1. Selected Field Projects for Surveying

District	Paving Year	BMD	Control
Northern Virginia	2019	2	1
	2020	1	1
	2021	2	2
Lynchburg	2019	1	1
	2021	2	2
Fredericksburg	2020	2	1
Hampton Roads	2021	3	2
Salem	2019	1	1
	2021	2	2
	2022	4	-
Richmond	2020	3	2
	2021	2	2
	2022	10	-

BMD = balanced mix design.

Mixture Volumetric Properties and Gradations

As-produced volumetric and gradation information for the BMD and control mixtures from the 2019, 2020, and 2021 construction seasons was compiled from other Virginia Transportation Research Council (VTRC) studies (Diefenderfer et al., 2021b, 2023a, 2023b). Although the mixtures were fully characterized in accordance with the Superpave mix design requirements, the complied data included only percent RAP content, nominal maximum aggregate size (NMAS), percent asphalt content (P_b), percent passing the No. 4 and No. 200 sieves, air voids (voids in total mixture [VTM]); voids in mineral aggregate [VMA]; and voids filled with asphalt [VFA]). In addition, several gradation-related parameters were calculated, namely, the coefficient of curvature (Cc), coefficient of uniformity (Cu), and primary control sieve index (PCSI). The review of the literature indicated these parameters as statistically significant factors influencing the macrotexture properties of asphalt mixtures (D'Apuzzo et al., 2012; Davis, 2001; Flintsch et al., 2003; Leiva and West, 2021; Stroup-Gardiner and Brown, 2000; Sullivan, 2005; Underwood et al., 2022). Therefore, they were included in this study for analysis.

Cc and Cu are parameters used to define gradation shape and aggregate size distribution and can be calculated using Equations 1 and 2, respectively.

$$C_C = \frac{D_{30}^2}{D_{10} * D_{60}} \quad \text{[Eq. 1]}$$

$$C_u = \frac{D_{60}}{D_{10}} \quad \text{[Eq. 2]}$$

where

D_{60}= sieve size associated with 60% passing, mm
D_{30}= sieve size associated with 30% passing, mm
D_{10}= sieve size associated with 10% passing, mm.

The PCSI is calculated as the difference in percent passing between the given gradation and the point on the maximum density line at the primary control sieve (i.e., Percent passing – Percent passing at the primary control sieve) (Leiva and West, 2021). The primary control sieve is the No. 8 sieve for 9.5 and 12.5 NMAS gradations, as defined in AASHTO M 323, Standard Specification for Superpave Volumetric Mix Design. The percent passing the primary control sieve (No. 8) at the maximum density line for 9.5 and 12.5 NMAS gradations is 47 and 39, respectively.

Field Data Collection

Friction, macrotexture, and roughness data were collected from the field projects. Friction and macrotexture surveys were conducted twice during the course of the study, covering one warm and one cool temperature cycle to capture seasonal fluctuations and their effect on the surface properties. On average, the first survey was conducted at 2.3, 1.1, and 0.3 years after the paving of the 2019, 2020, and 2021 projects, respectively. The second survey was conducted approximately 0.5 year later than the first survey. The exceptions to the testing program were that the 2020 sites in the Hampton Roads District and the 2022 sites in the Salem and Richmond districts were surveyed only once. A Sideway-force Coefficient Routine Investigation Machine (SCRIM) was used to collect the friction and macrotexture data. The friction in terms of the sideway-force reading at 40 mph (SR40) and the macrotexture in terms of mean profile depth (MPD) from the left wheel path for every 0.1 m, using a single spot laser system, were generated from the SCRIM data. These parameters were measured from a single pass of the SCRIM over the entire length of a given project. It must be noted that the pairs of BMD and control mixtures had comparable lengths. The SCRIM can also measure other relevant information such as GPS coordinates, road geometry, and temperature (air, pavement surface, and tire) of surveyed projects during the data collection process. Further details related to the SCRIM are provided in other documentation (de León Izeppi et al., 2019).

The GPS coordinates and distance measured by the SCRIM for each project were referenced with the milepost information derived from VDOT's iVision software, a web-based application used for pavement management purposes. This exercise was carried out to examine the data for "abnormalities" that cause significant fluctuations in the response (often as increases) resulting from, for instance, bridges and railroads. When located, such data were filtered out to provide a better representation of the project surface characteristics. Figure 1 presents the variation of friction and macrotexture data along the longitudinal length of a project as an example.

Roughness surveys were conducted on a limited number of projects due to equipment issues encountered during the course of the study. Eight field projects encompassing pairs of BMD and control mixtures were surveyed once. The sections included were the 2021 projects from the Salem, Richmond, and Lynchburg districts, which were surveyed approximately 1.7 years after paving, and the 2020 projects from the Fredericksburg District, which were surveyed 2.4 years after paving.

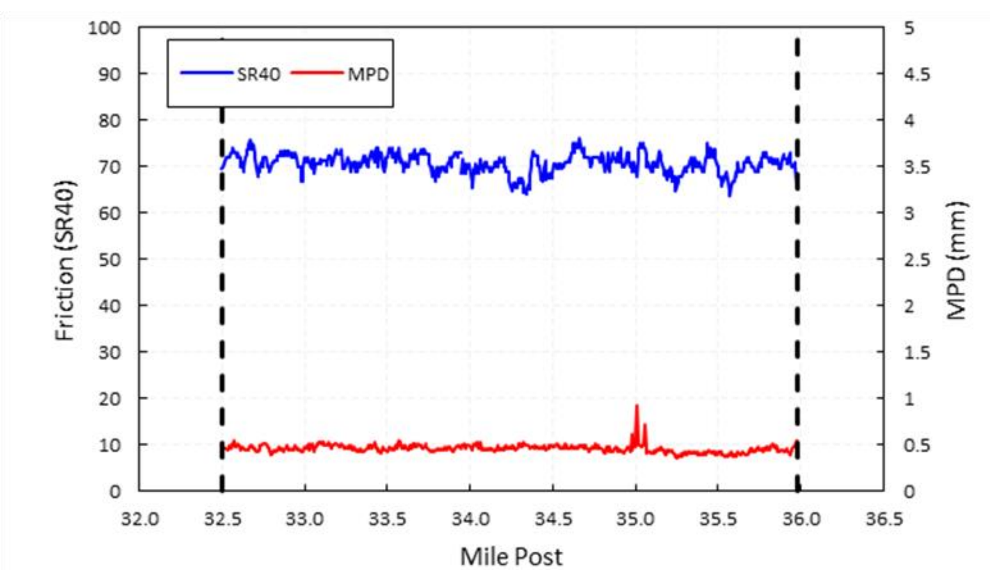

Figure 1. Example Friction and Texture Data. SR40 = friction index; MPD = mean profile depth.

The roughness surveys were performed in a manner consistent with VDOT's standard procedure (Virginia Test Method 106) using VDOT's high-speed inertial profiler equipped with a single spot laser system. The left and right wheel path elevation profiles were quantified at 16-m (0.01-mi) intervals in terms of IRI in accordance with ASTM E1926, Standard Practice for Computing International Roughness Index of Roads from Longitudinal Profile Measurements. Figure 2 presents an example of the IRI variation along the longitudinal length for a given project.

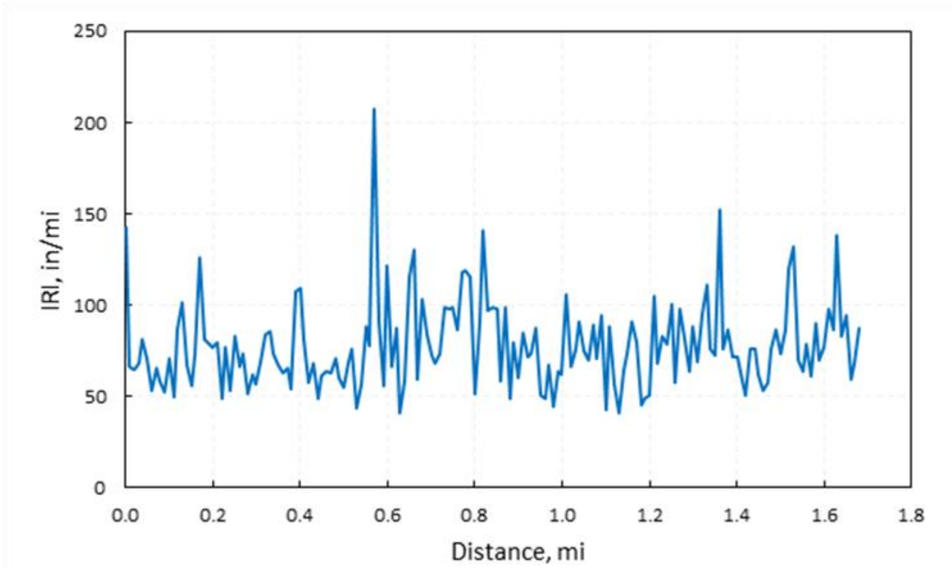

Figure 2. Example Roughness Data. IRI = international roughness index.

Data Analysis

Basic descriptive statistics were used to compare the trends in volumetric properties and gradations of the BMD and control mixtures. For each of pavement surface characteristics included in the study, project and network level comparisons between the BMD and control mixtures were performed using descriptive statistics and parametric statistical techniques (e.g., t-test and analysis of variance) to identify any systematic trends or differences in the collected data. In addition, macrotexture and its variability were used to perform an assessment of the level of variability between the BMD and control mixtures, as these parameters are associated with construction uniformity. The variability assessments were performed by testing the equality of variances between the groups. Moreover, the functional characteristics of the 2022 BMD mixtures were compared to the functional characteristics of the 2019-2021 BMD and control mixtures at a network level. This was performed to evaluate how functional characteristics of new mixtures compare to the baseline functional characteristics established from the 2019-2021 mixtures. Further, an analysis of covariance was used to investigate the effect of volumetric properties and gradation parameters on macrotexture, and a regression analysis was performed to develop an empirical equation to predict macrotexture. All statistical analyses were performed at a 95% confidence interval.

RESULTS AND DISCUSSION

Mixture Volumetric Properties and Gradations

Table 2 shows the production volumetric properties and gradation parameters for the 2019 BMD and control mixtures as an example. The information for the mixtures from the other construction seasons is presented in Appendix A. In this study, there were 21 pairs of comparison mixtures (BMD vs. control) from the 2019, 2020, and 2021 construction seasons. For some of the projects, there were two BMD mixtures paired with a given control mixture. Thus, the control mixture was included twice for those projects. In addition, there were 14 BMD mixtures from the 2022 construction season with no control mixtures. The following observations were made from the comparison of the mixture pairs:

- Although 10 pairs of mixtures incorporated the same amount of RAP, nine BMD mixtures had higher RAP contents as compared to their control mixtures. The remaining two control mixtures had 4% higher RAP contents as compared to their test (BMD) mixtures. The overall average RAP contents were 32.7% and 29.3% for the BMD and control mixtures, respectively.

- No change was observed in the NMAS of the mixtures with the application of BMD. There were 10 pairs of 9.5 mm NMAS mixtures and 11 pairs of 12.5 mm NMAS mixtures.

- Eleven BMD mixtures had an average 0.2% higher total asphalt content than the corresponding control mixtures, whereas six control mixtures had an average 0.3% higher total asphalt content than the corresponding BMD mixtures. The remaining four pairs of mixtures had equivalent asphalt binder contents. The overall average total asphalt binder content was 5.8% for both mixture types.

- Thirteen BMD mixtures had an average 0.6% higher VTM than the corresponding control mixtures, and VTM was, on average, 0.7% higher for eight control mixtures. The overall average VTM was 3.1% and 3.0% for the BMD and control mixtures, respectively.

- Thirteen BMD mixtures had an average 0.6% higher VMA than the corresponding control mixtures, and VMA was, on average, 1.1% higher for seven control mixtures. One pair had an equal VMA. The overall average VMA was 16.4% and 16.5% for the BMD and control mixtures, respectively.

- Nine BMD mixtures had an average 3.1% higher VFA than the corresponding control mixtures, and VFA was, on average, 2.9% higher for 13 control mixtures. The overall average VFA was 81.6% and 82% for the BMD and control mixtures, respectively.

Table 2. Volumetric Properties and Gradation Parameters for the 2019 Mixtures

District	Mix ID	Mix Type	RAP, %	NMAS, mm	P_b, %	Sieve, % Passing No. 4	Sieve, % Passing No. 200	VTM, %	VMA, %	VFA, %	Cu	Cc	PCSI
Salem	S-19-I	Control	26	9.5	5.9	64.6	6.3	2.5	16.6	84.8	23.8	1.62	-2.7
	S-19-II	BMD	26	9.5	5.9	65.8	6.3	2.8	16.9	83.5	23.1	1.67	-2.5
Lynchburg	L-19-I	Control	26	9.5	5.9	61.6	6.2	2.1	16.0	86.8	23.2	1.89	-5.5
	L-19-II	BMD	26	9.5	5.3	63.9	6.2	3.9	16.2	76.2	22.7	1.69	-3.9
Northern Virginia	N-19-I	Control	30	9.5	5.5	63.5	6.7	3.4	17.0	80.1	28.2	2.37	-6.0
	N-19-II	BMD	30	9.5	5.6	61.8	8.0	3.6	17.4	79.5	36.4	1.99	-6.7
	N-19-III	BMD	40	9.5	5.6	64.1	6.3	2.5	16.6	84.8	27.4	1.93	-4.4

RAP = reclaimed asphalt pavement; NMAS = nominal maximum aggregate size; P_b = percent asphalt content; VTM = voids in total mixture; VMA = voids in mineral aggregate; VFA = voids filled with asphalt; Cu = coefficient of uniformity; Cc = coefficient of curvature; PCSI = primary control sieve index; BMD = balanced mix design.

- Twelve BMD mixtures had an average 2% higher passing the No. 4 sieve than the corresponding control mixtures, and the percent passing was, on average, 3.1% higher for nine control mixtures. The overall average percent passing the No. 4 sieve was 59.4 and 59.6 for the BMD and control mixtures, respectively.

- Seven BMD mixtures had an average 0.6% higher passing of the No. 200 sieve than the corresponding control mixtures, and the percent passing was, on average, 0.6 % higher for nine control mixtures. The remaining six pairs had the same percent passing the No. 200 sieve. The overall average percent passing the No. 200 sieve was 5.9% for both mixture types.

- Nine BMD mixtures had an average 2.2 unit higher Cu than the corresponding control mixtures, and Cu was, on average, 3.8 units higher for 13 control mixtures. The overall average Cu was 27.8 and 27.4 for the BMD and control mixtures, respectively.

- Thirteen BMD mixtures had an average 0.39 unit higher Cc than the corresponding control mixtures, and Cc was, on average, 0.25 units higher for eight control mixtures. The overall average Cc was 2.12 and 1.98 for the BMD and control mixtures, respectively.

- Eleven BMD mixtures had an average 3.1 unit higher PCSI than the corresponding control mixtures, and PCSI was, on average, 3.4 units higher for 10 control mixtures. The overall average PCSI was −3.4 and −2.5 for the BMD and control mixtures, respectively.

These observations indicate that the BMD mixtures were, overall, produced within the production variability limits of volumetric properties and gradations for the control mixtures when the process tolerance for four tests (representing the average number of sample testing for volumetric properties in this study) from Table II-15 of the VDOT specifications (VDOT, 2020) is considered. The volumetric properties and gradations for the 2022 mixtures were not available to the research team at the time of the completion of this study.

Macrotexture

Table 3 shows the average MPD and its variability for the 2019 mixtures as an example. These descriptive statistics were calculated for the length of each project from a single pass of the SCRIM for each survey. The table also shows the results of pairwise comparisons made between the BMD and control mixtures at a 95% confidence interval. The observations having the same letter are not statistically different. The statistical comparisons were performed for each pair and parameter (mean and variance) independently. Thus, the letters are applicable only to evaluation of the mixtures within the same pair (i.e., there was no comparison of mixtures across different districts). The data for the mixtures from other construction seasons are provided in Appendix B.

Table 3. Descriptive Statistics and Pairwise Comparison of Macrotexture for the 2019 Mixtures

District	Mix ID	Mix Type	Survey Time, year	MPD, mm	STDEV, mm	Pairwise Comparison	
						Mean	Variance
Salem	S-19-I	Control	2.3	0.44	0.034	a	a/c
			2.8	0.43	0.026	a	b
	S-19-II	BMD	2.3	0.42	0.039	b	c
			2.8	0.42	0.030	b	a/b
Lynchburg	L-19-I	Control	2.3	0.44	0.053	a	a/b
			2.8	0.45	0.043	a	a
	L-19-II	BMD	2.3	0.47	0.061	b	a/b
			2.8	0.49	0.070	b	b
Northern Virginia	N-19-I	Control	2.3	0.41	0.058	a	a/c
			2.8	0.41	0.061	a	a
	N-19-II	BMD	2.3	0.40	0.052	b	a/b
			2.8	0.40	0.048	b	b/c
	N-19-III	BMD	2.3	0.39	0.035	c	d
			2.8	0.40	0.035	b	d

The mean values or variance values for mixtures sharing the same letter in the table for a given pair were statistically similar.
MPD = mean profile depth; STDEV = standard deviation; BMD = balanced mix design.

Figure 3 compares the MPD values between the BMD and control mixtures, combining the data from both surveys. For 19 of the 40 observations (47.5%), the BMD mixtures had higher MPD values than the control mixtures. On the other hand, the control mixtures had higher MPD values for 18 of the 40 observations (45%). For 3 of the 40 observations (7.5%), the mixtures had equal MPD values. The pairwise statistical comparison indicated that the average MPD values between the two mixture types were significantly different for 28 observations, corresponding to 70% of the data.

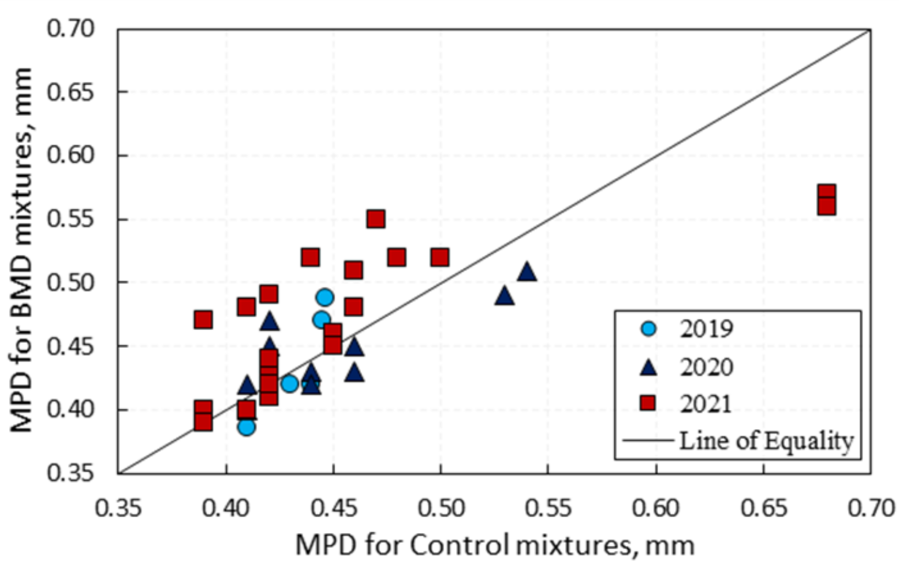

Figure 3. Comparison of MPD Between the BMD and Control Mixtures. BMD = balanced mix design; MPD = mean profile depth.

Table 4 lists the descriptive statistics of the MPD values for the BMD and control mixtures. They document the overall magnitude and spread of the distribution of macrotexture data as a performance baseline for the BMD mixtures for future evaluation. The data for the control mixtures were included for comparison and reference purposes. As shown in the table, the average and spread of the BMD mixture macrotexture distribution were, overall, higher and wider (based on the interquartile range [IQR]) than those of the control mixtures. This network level observation agrees with the trend observed in the project level comparison. The network level comparison indicated no statistical differences in MPD values between the BMD and control mixtures.

The average macrotexture and its variability (quantified in terms of standard deviation) have been used as parameters to identify areas of excessive variability that can be linked to construction non-uniformity, or segregation, of the surface, and the presence of pavement distresses (McGhee et al., 2003; Stroup-Gardner and Brown, 2000). There are different approaches to investigating construction non-uniformity (McGhee et al., 2003). In this study, the surface macrotexture variability was used as a parameter to assess relative construction uniformity levels between the BMD and control mixtures. In this standard deviation–based approach, if the variability of texture increases, it is assumed that the mixture and/or placement process was at least temporarily under less control and that the pavement surface is, as a consequence, exhibiting at least some level of segregation (McGhee et al., 2003).

Figure 4 compares the surface MPD variability between the BMD and control mixtures, using the data from both surveys. The control mixtures had a higher variability for 20 of the 40 observations (50%). For the BMD mixtures, the surface MPD variability was higher for the remaining 20 observations (50%). The pairwise statistical comparison indicated that the surface MPD variability between the two mixture types was significantly different for 14 observations, corresponding to 35% of the data.

Table 5 presents the descriptive statistics of the surface MPD variability for the BMD and control mixtures. As seen, at a network level, the average and spread of the surface MPD variability distribution for the BMD mixtures were, overall, slightly higher and narrower (based on the IQR range) than those for the control mixtures. The network level comparison indicated no statistical differences in the surface MPD variability between the BMD and control mixtures.

The macrotexture and associated variability for the 2022 BMD mixtures were compared to the overall macrotexture and associated variability for the 2019-2021 BMD and control mixtures. This network level analysis was performed for two reasons: (1) the 2022 BMD mixtures did not have any control mixtures, and (2) it was desired to evaluate how baseline parameters (macrotexture and variability) compared to the results of a new set of mixtures constructed later.

Table 4. Descriptive Statistics of MPD for the BMD and Control Mixtures

Mix Type	Mean	Minimum	Quartile 1	Quartile 3	Maximum	IQR
BMD	0.46	0.39	0.41	0.49	0.57	0.08
Control	0.45	0.39	0.41	0.46	0.68	0.05

MPD = mean profile depth; BMD = balanced mix design; IQR = interquartile range.

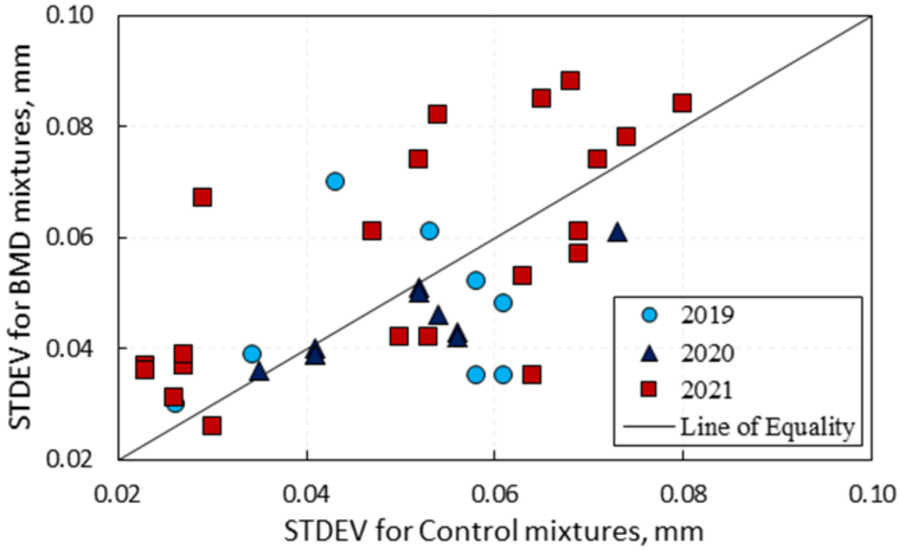

Figure 4. Comparison of Surface MPD Variability Between the BMD and Control Mixtures. BMD = balanced mix design; MPD = mean profile depth; STDEV = standard deviation.

Table 5. Descriptive Statistics of Surface MPD Variability for the BMD and Control Mixtures

Mix Type	Mean	Minimum	Quartile 1	Quartile 3	Maximum	IQR
BMD	0.051	0.026	0.037	0.061	0.088	0.024
Control	0.050	0.023	0.034	0.063	0.080	0.028

MPD = mean profile depth; BMD = balanced mix design; IQR = interquartile range.

The boxplots of MPD are presented in Figure 5 and the boxplots of surface MPD variability are presented in Figure 6 for the 2022 BMD mixtures and the baseline BMD and control mixtures. The circle and line in the boxes symbolize the mean and median values of the data, respectively, and the IQR represents the middle 50% of the data. In addition, the whisker bars spreading out from either side of the box indicate the ranges for the bottom 25% and the top 25% of the data, not including outliers, which are represented by asterisks (*). As seen in Figure 5, the 2022 BMD mixtures had an average MPD value that was (statistically) similar to that of the baseline mixtures. However, the 2022 BMD mixtures had a wider range of MPD values than the baseline mixtures and constituted several mixtures (four) that had MPD values lower than the minimum MPD value of 0.39 mm for the baseline mixtures.

As seen from Figure 6, the 2022 BMD mixtures had a higher level of average macrotexture variability compared to the baseline mixtures, and this difference was statistically significant. The results indicate that either the baseline values do not capture well the macrotexture ranges in Virginia or some of the 2022 BMD mixtures had unusual macrotexture characteristics. If it is the former, more work is needed to establish a more robust macrotexture baseline for these mixtures. If it is the latter, more work is also needed to establish accepted performance values for macrotexture and its variability to ensure safe and uniform pavement surfaces.

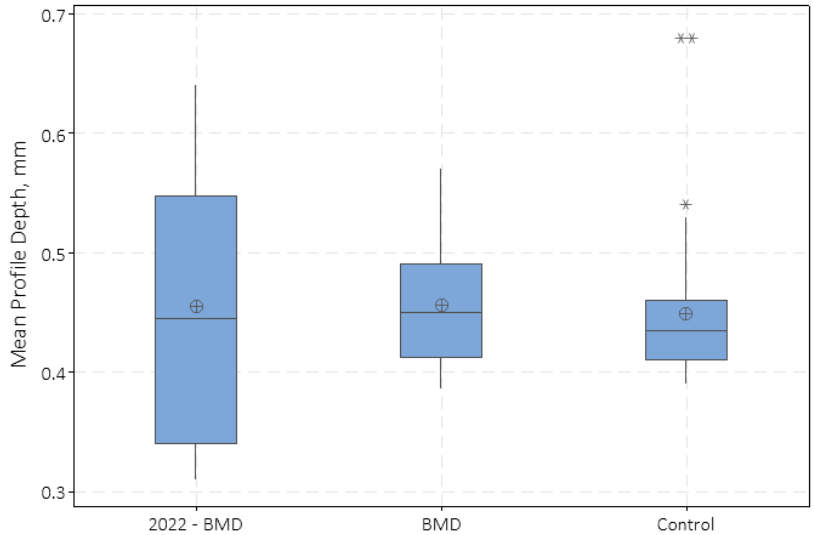

Figure 5. Boxplots of MPD for the BMD and Control Mixtures. BMD = balanced mix design; MPD = mean profile depth. The circle and line in the boxes symbolize the mean and median values of the data, respectively, and the IQR represents the middle 50% of the data. The whisker bars spreading out from either side of the box indicate the ranges for the bottom 25% and the top 25% of the data, not including outliers, which are represented by asterisks (*).

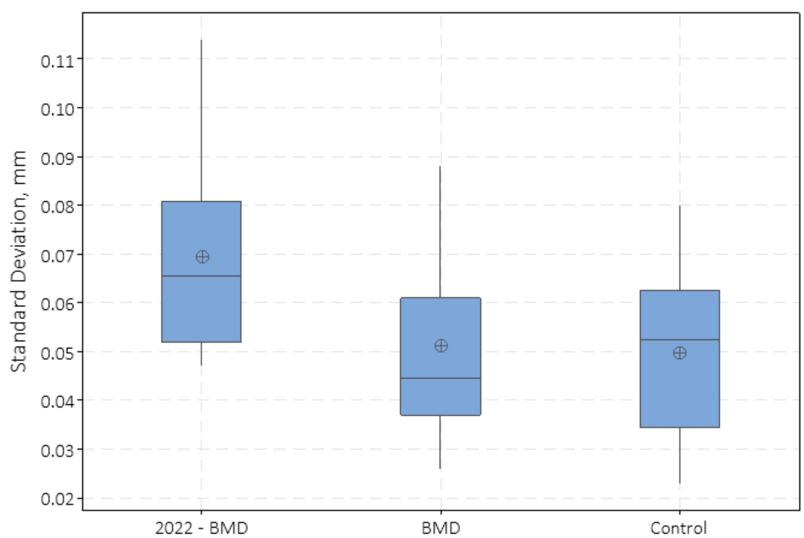

Figure 6. Boxplots of MPD Variability for the BMD and Control Mixtures. BMD = balanced mix design; MPD = mean profile depth. The circle and line in the boxes symbolize the mean and median values of the data, respectively, and the IQR represents the middle 50% of the data. The whisker bars spreading out from either side of the box indicate the ranges for the bottom 25% and the top 25% of the data, not including outliers, which are represented by asterisks (*).

A statistical analysis was also performed to investigate the effects of mixture volumetric properties and gradation parameters on macrotexture and to determine an empirical relationship to link those characteristics to macrotexture. The stepwise regression analysis was performed at a 95% confidence level. The following were included in the analysis as factors: NMAS, P_b, VTM, VMA, VFA, percent passing the No. 4 and No. 200 sieves, Cc, Cu, PCSI, and numerous interaction factors. These as-produced factors were compiled from the BMD and control mixtures from the 2019, 2020, and 2021 construction seasons.

The statistically significant factors influencing macrotexture were identified, and a model was developed to predict macrotexture. This model, shown in Equation 3, resulted in a coefficient of determination of 77.4% and an adjusted coefficient of determination of 72.8%.

$$MPD\ (mm) = -2.10 - 0.0947*(PCSI) + 0.0674*(P_{No.4}) - 0.1483\ (NMAS) + 0.4170\ (P_b) + 0.0015\ (PCSI)*(P_{No.4}) - 0.0118\ (P_{No.4})*(P_b) + 0.0281\ (NMAS)*(P_b) \quad \text{[Eq. 3]}$$

where

NMAS = nominal maximum aggregate size, mm
PCSI = primary control sieve index
$P_{No.4}$ = percent passing No. 4 sieve, %
P_b = asphalt content, %.

This model can be used by VDOT to screen projects with potentially low field-macrotexture values for further field investigations during and/or after placement of dense-graded asphalt surface mixtures with A and D designations. The model can also be used as a means to investigate the possibility of detecting and quantifying segregation of field projects based on one of the approaches discussed by McGhee et al. (2003). For such uses, the accuracy and reliability of the model must be improved and verified with additional data sets, which will require additional data collection efforts. In addition, the validity of the approaches discussed by McGhee et al. (2003) for confirming uniformity of construction must be further demonstrated, especially with the current available technological capabilities, prior to implementation of such a model. Most important, a macrotexture management process, including identification of performance threshold limits, must be established.

Friction

Table 6 presents the friction values in terms of SR40 and associated variability for the 2019 mixtures as an example. Similar to the macrotexture, these descriptive statistics were calculated for the length of each project from a single pass of the SCRIM for each survey. The table also shows the results of pairwise comparisons of the BMD and control mixtures at a 95% confidence interval. Further, the table shows the average temperatures for air, pavement surface, and test tire collected at the time of each survey. The data for the mixtures from other construction seasons are presented in Appendix C.

Figure 7 compares the average SR40 values of the BMD and control mixtures, combining the data from both surveys. For 23 of the 40 observations (57.5%), the BMD mixtures had higher friction values than the control mixtures. On the other hand, the control mixtures had higher friction values for the remaining observations (42.5%). The pairwise statistical comparison indicated that the average friction values of the two mixture types were significantly different for 31 observations, corresponding to 77.5% of the data.

Table 6. Descriptive Statistics and Pairwise Comparison of Friction for the 2019 Mixtures

District	Mix ID	Mix Type	Survey Time, years	SR40	STDEV	Pairwise Comparison		Temperature, °C		
						Mean	Variance	Air	Surface	Tire
Salem	S-19-I	Control	2.3	61.6	3.0	a	a	8	17	16
			2.8	57.3	3.1	b	a	30	45	34
	S-19-II	BMD	2.3	67.0	3.8	c	b	8	17	16
			2.8	60.9	3.6	a	a/b	30	45	34
Lynchburg	L-19-I	Control	2.3	70.4	2.7	a/b	a	16	17	20
			2.8	70.7	2.7	a	a	23	38	29
	L-19-II	BMD	2.3	69.4	4.3	b	b	16	17	20
			2.8	69.9	3.9	a/b	b	23	38	29
Northern Virginia	N-19-I	Control	2.3	57.1	4.3	a	a/b	19	28	26
			2.8	59.0	4.5	b	a/b	19	36	30
	N-19-II	BMD	2.3	57.2	4.0	a	a	19	27	27
			2.8	60.5	5.0	c	b	19	37	32
	N-19-III	BMD	2.3	65.6	2.5	d	c	19	25	22
			2.8	71.5	3.1	e	c	17	31	28

The mean values or variance values for mixtures sharing the same letter in the table for a given pair were statistically similar. SR40 = friction index; STDEV = standard deviation; BMD = balanced mix design.

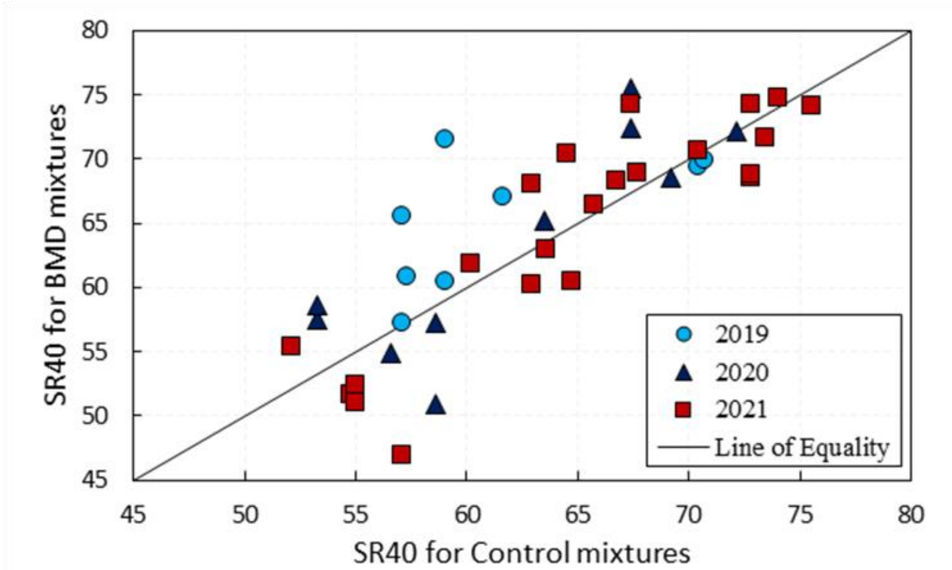

Figure 7. Comparison of Friction Between the BMD and Control Mixtures. BMD = balanced mix design; SR40 = friction index.

Table 7 presents the descriptive statistics of the friction values for the BMD and control mixtures. As seen, at a network level, the average and spread of distribution of friction for the BMD mixtures were, overall, slightly higher and lower (based on the IQR), respectively, than those of the control mixtures. The network level comparison indicated no statistical differences in the friction numbers between the BMD and control mixtures. The baseline values in Table 7 were obtained at a temperature range shown in Figure 8. Temperature has a significant impact on friction resistance (Underwood et al., 2022).

To the best of the knowledge of the research team, no information exists on relating the amount of friction variability to any performance metrics. The researchers investigated a potential relationship between the variability of macrotexture and friction and found no meaningful correlation between the two. However, the levels of friction variability observed in this study are presented for consistency and documentation of the "typical" amount of variability of this parameter for potential future investigations.

Figure 9 compares the friction variability between the BMD and control mixtures, using the data from both surveys. The BMD mixtures had a higher variability for 25 of the 40 observations (62.5%), whereas the surface friction variability was higher for the remaining 15 observations (37.5%) for the control mixtures. The pairwise statistical comparison indicated that the friction variability between the two mixture types was significantly different for 18 observations, corresponding to 45% of the data.

Table 7. Descriptive Statistics of SR40 for the BMD and Control Mixtures

Mix Type	**Mean**	**Minimum**	**Quartile 1**	**Quartile 3**	**Maximum**	**IQR**
BMD	64.4	47.0	57.8	70.6	75.5	12.8
Control	63.6	52.1	57.2	70.1	75.5	12.9

SR40 = friction index; BMD = balanced mix design; IQR = interquartile range.

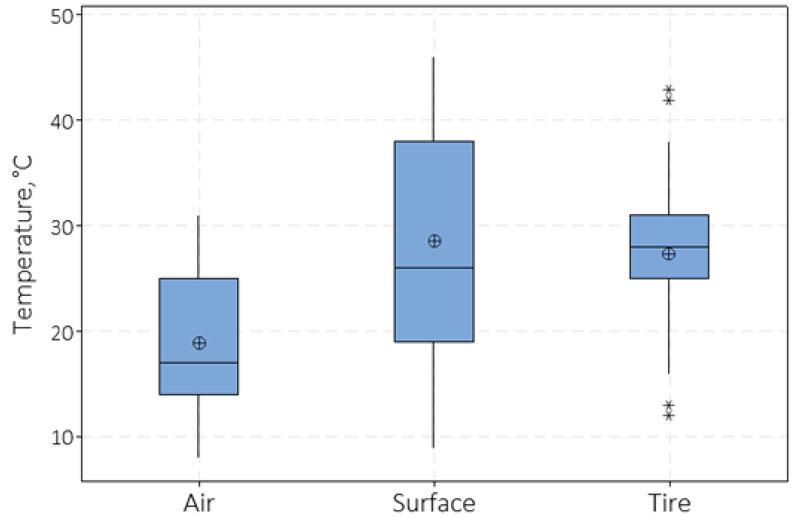

Figure 8. Temperature Distribution During Friction Surveys. The circle and line in the boxes symbolize the mean and median values of the data, respectively, and the IQR represents the middle 50% of the data. The whisker bars spreading out from either side of the box indicate the ranges for the bottom 25% and the top 25% of the data, not including outliers, which are represented by asterisks (*).

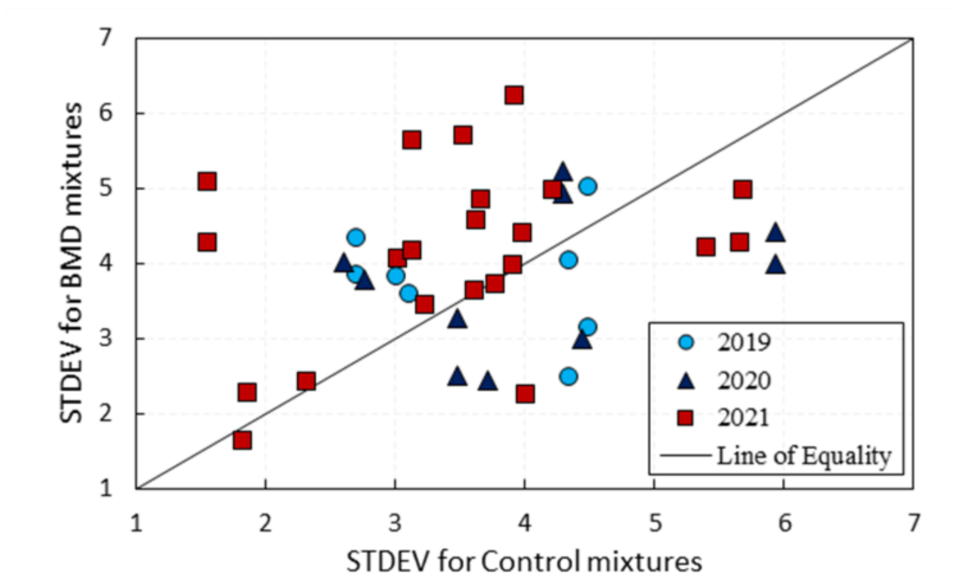

Figure 9. Comparison of SR40 Variability Between the BMD and Control Mixtures. BMD = balanced mix design; SR40 = friction number; STDEV = standard deviation.

Table 8 shows the descriptive statistics of the friction variability for the BMD and control mixtures. As seen, at a network level, the average and spread of distribution of surface friction variability of the BMD mixtures were, overall, slightly higher and wider than those of the control mixtures. The network level comparison indicated no statistical difference in the friction variability between the BMD and control mixtures.

Table 8. Descriptive Statistics of Friction (SR40) Variability for the BMD and Control Mixtures

Mix Type	Mean	Minimum	Quartile 1	Quartile 3	Maximum	IQR
BMD	4.0	1.6	3.3	4.8	6.2	1.5
Control	3.7	1.6	3.0	4.3	5.9	1.3

BMD = balanced mix design; SR40 = friction index; IQR = interquartile range.

Similar to the macrotexture analysis, the friction and associated variability for the 2022 BMD mixtures were compared to the overall friction and variability for the 2019-2021 BMD and control mixtures. Figure 10 presents the boxplots of friction values for the 2022 BMD mixtures and the baseline BMD and control mixtures. As seen, the 2022 BMD mixtures had a higher average friction value and narrower friction range compared to the baseline mixtures. However, the higher average friction value can be attributed to the differences in temperatures. As shown in Figure 11, the survey for the 2022 BMD mixtures was performed at lower temperatures than the baseline mixtures. A decrease in temperature had a positive effect on friction. The researchers were not able to isolate the effect of temperature on friction values for network analysis as no temperature correction factor yet exists for Virginia mixtures.

Figure 12 presents the boxplots of friction variability for the 2022 BMD mixtures and the baseline mixtures. The friction variability between the groups was statistically insignificant, indicating that the mixtures overall provided similar levels of friction variability at the network level, suggesting that the differences in temperature may not have an effect on surface friction variability measurements.

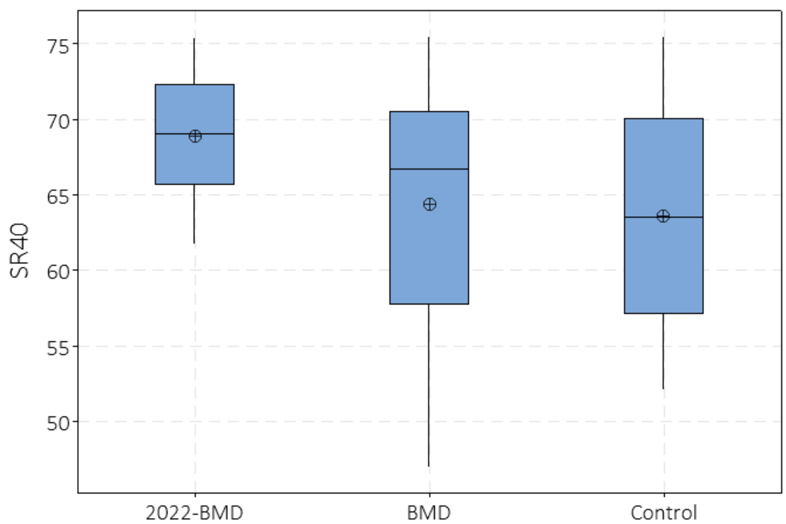

Figure 10. Boxplots of SR40 for the BMD and Control Mixtures. SR40 = friction index; BMD = balanced mix design. The circle and line in the boxes symbolize the mean and median values of the data, respectively, and the interquartile range (IQR) represents the middle 50% of the data. The whisker bars spreading out from either side of the box indicate the ranges for the bottom 25% and the top 25% of the data, not including outliers, which are represented by asterisks (*).

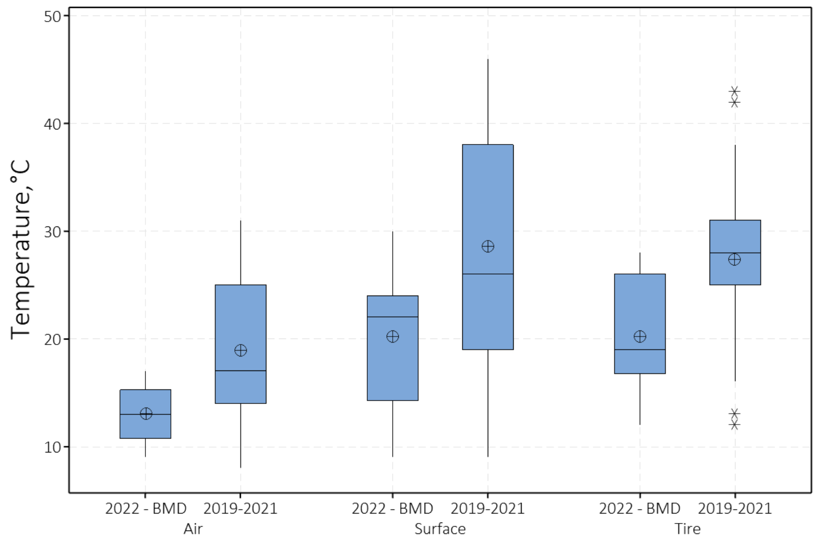

Figure 11. Comparison of Temperature Distributions Between the 2022 BMD and Baseline Mixtures. BMD = balanced mix design. The circle and line in the boxes symbolize the mean and median values of the data, respectively, and the interquartile range (IQR) represents the middle 50% of the data. The whisker bars spreading out from either side of the box indicate the ranges for the bottom 25% and the top 25% of the data, not including outliers, which are represented by asterisks (*).

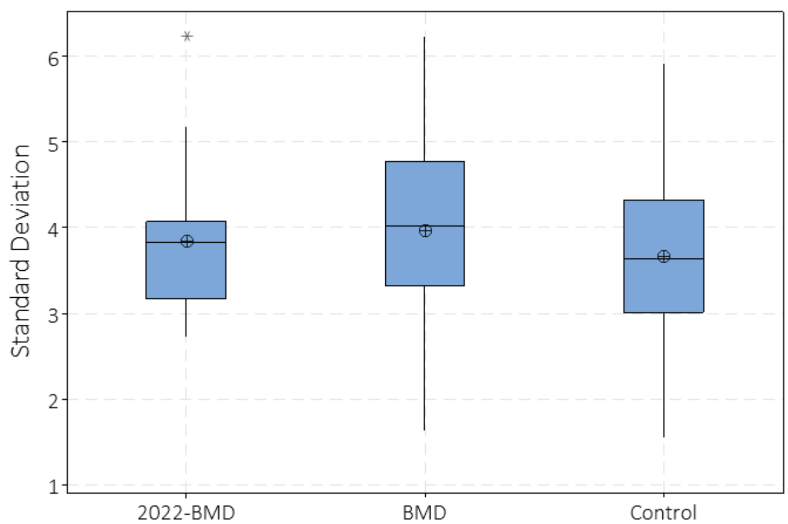

Figure 12. Boxplots of SR40 Variability for the BMD and Control Mixtures. SR40 = friction index; BMD = balanced mix design. The circle and line in the boxes symbolize the mean and median values of the data, respectively, and the interquartile range (IQR) represents the middle 50% of the data. The whisker bars spreading out from either side of the box indicate the ranges for the bottom 25% and the top 25% of the data, not including outliers, which are represented by asterisks (*).

This study did not attempt to define an empirical relationship or model between friction (skid resistance) and mixture volumetric and gradation properties. This was because the mineralogical and morphological properties of aggregates have a greater effect on skid resistance and they were not available or characterized in this study due to time and budget limitations.

Roughness

Table 9 presents the results of roughness surveys for 15 mixtures. The IRI values represent average values calculated for the length of each project based on two passes by VDOT's inertial profiler. The table also presents the results of pairwise comparisons at a 95% confidence interval. As seen, three of the eight observations (37.5%) indicated statistically significant differences in surface roughness between the BMD and control mixtures. As seen in Figure 13, the BMD mixtures overall provided a smoother ride.

Table 9. Results of IRI and Statistical Analysis

District	Mix ID	Mix Type	Survey Time, year	IRI, in/mi	Statistically Similar
Salem	S-21-I	Control	1.7	84.1	No
	S-21-II	BMD	1.7	71.6	
Salem	S-21-III	Control	1.7	79.2	Yes
	S-21-IV	BMD	1.7	79.6	
Fredericksburg	F-20-I	Control	2.4	110.6	Yes
	F-20-II	BMD	2.4	100.6	
	F-20-III	BMD	2.4	104.2	
Richmond	R-21-I	Control	1.5	122.7	Yes
	R-21-III	BMD	1.5	117.2	
Richmond	R-21-III	Control	1.5	121.7	Yes
	R-21-IV	BMD	1.5	132.0	
Lynchburg	L-21-I	Control	1.5	57.6	No
	L-21-II	BMD	1.5	46.7	
Lynchburg	L-21-III	Control	1.7	53.3	No
	L-21-IV	BMD	1.7	58.8	

IRI = international roughness index; BMD = balanced mix design.

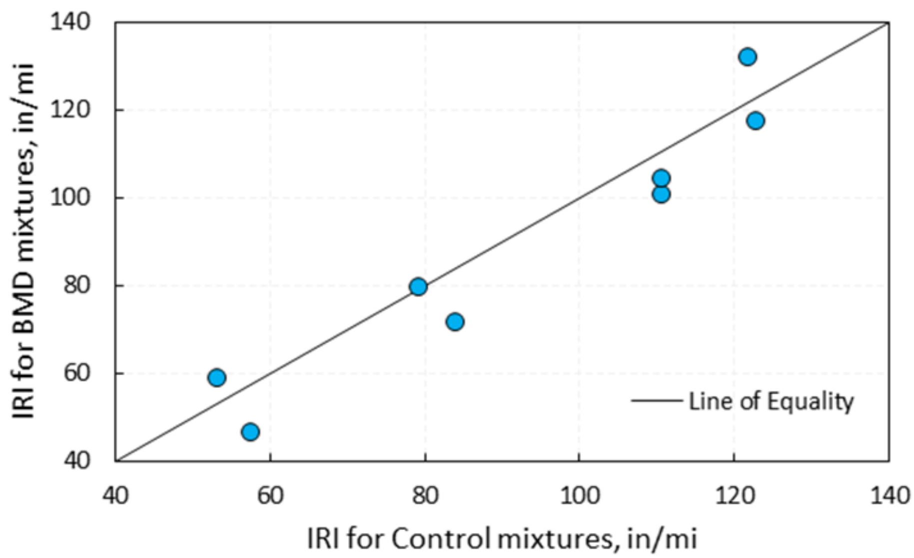

Figure 13. Comparison of Roughness Between the BMD and Control Mixtures. BMD = balanced mix design; IRI = international roughness index.

Summary of Findings

- Use of the BMD concept resulted in slight changes in mixture volumetric and gradation properties. These changes were mostly within the production variability limits of conventionally designed mixtures.

- In the field sections evaluated in this study, the BMD mixtures, on average, tended to have higher macrotexture values than the control mixtures.

- In the field sections evaluated in this study, the BMD mixtures, on average, tended to have a more uniform surface texture than the control mixtures.

- An empirical model incorporating volumetric and gradation properties was developed for potential use in identifying potential projects with low macrotexture levels and subsequent investigation.

- In the field sections evaluated in this study, the BMD mixtures, on average, tended to have higher skid resistance values than the control mixtures.

- In the field sections evaluated in this study, the BMD mixtures, on average, tended to have a better ride quality (smoothness) than the control mixtures.

CONCLUSIONS

- *Based on the results from the sites evaluated in this study, use of the BMD methodology provides similar or better functional surface characteristics when compared to conventionally designed mixtures.*

- *VDOT has no accepted or established thresholds for friction and macrotexture performance.* The functional properties of the BMD mixtures were compared to those of the control mixtures.

RECOMMENDATIONS

1. *VDOT's Materials Division should continue with the implementation of BMD.* The results of this study did not indicate any adverse effects on the functional characteristics of pavements due to the application of the BMD concept.

2. *VDOT's Maintenance Division and Materials Division should consider assessing existing and future BMD projects in terms of functional characteristics to confirm further the findings of this study.* The BMD mixtures surveyed in this study were limited to the trial mixtures. It is expected that the full implementation of the BMD concept will result in changes in mixture composition in upcoming years.

3. *VDOT's Maintenance Division, Materials Division, and Traffic Operations Division should continue to collaborate on developing a friction and texture management framework.*

IMPLEMENTATION AND BENEFITS

Researchers and the technical review panel (listed in the Acknowledgments) for the project collaborate to craft a plan to implement the study recommendations and to determine the benefits of doing so. This is to ensure that the implementation plan is developed and approved with the participation and support of those involved with VDOT operations. The implementation plan and the accompanying benefits are provided here.

Implementation

With regard to Recommendation 1, no further implementation is necessary at this time. VDOT's Materials Division is continuing the process of BMD implementation.

With regard to Recommendation 2, a research needs statement will be drafted and submitted to the VTRC Pavement Research Advisory Subcommittee A by no later than Fiscal Year 2025.

With regard to Recommendation 3, VTRC Project No. 118900, Pavement Friction Management Program Implementation for the Virginia Commonwealth Department of Transportation—Phase 3 (a collaboration among the three VDOT divisions), is ongoing. The objective of that project is to continue the development and implementation of a continuous data-based pavement friction management program. The outcomes of this effort are expected to be available in January 2024.

Benefits

Although the BMD approach is expected to improve the durability of asphalt mixtures and reduce the life cycle cost of the VDOT pavement network, it is important that this be achieved without compromising the safety and comfort of the traveling public. This study showed that the functional characteristics of asphalt mixtures/pavements are either preserved or enhanced with the implementation of the BMD methodology, allowing VDOT to gain confidence in its new mixture design and acceptance practice and provide safer pavements to the traveling public.

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APPENDIX A

VOLUMETRIC PROPERTIES AND GRADATION PARAMETERS

Table A1. Volumetric Properties and Gradation Parameters for the 2020 Mixtures

District	Mix ID	Mix Type	RAP, %	NMAS, mm	P_b, %	Sieve, % Passing		VTM, %	VMA, %	VFA, %	Cu	Cc	PCSI
						No. 4	No. 200						
Richmond	R-20-I	Control	30	12.5	5.9	60.6	5.9	2.1	15.7	86.5	31.4	1.55	4.00
	R-20-II	BMD	35	12.5	5.8	58.5	6.0	1.8	14.7	87.6	36.2	1.57	2.25
	R-20-III	BMD	35	12.5	6.0	57.8	5.9	1.7	15.0	88.8	35.3	1.68	1.25
Richmond	R-20-IV	Control	30	12.5	5.8	53.0	6.8	2.5	15.6	84.0	35.9	2.97	-3.33
	R-20-V	BMD	40	12.5	5.7	53.7	5.9	2.7	15.9	83.0	29.9	2.43	-3.00
Northern Virginia	N-20-I	Control	30	9.5	5.4	59.3	6.0	2.8	16.3	83.0	27.2	2.08	-7.00
	N-20-II	BMD	40	9.5	5.5	63.3	6.0	3.2	16.7	81.0	25.3	1.93	-4.80
Fredericksburg	F-20-I	Control	30	12.5	5.4	59.5	5.4	3.4	16.1	79.0	28.8	2.24	0.50
	F-20-II	BMD	40	12.5	5.4	57.0	6.1	2.2	15.4	86.0	34.0	2.40	-0.50
	F-20-III	BMD	40	12.5	5.2	62.5	6.4	3.5	16.1	78.5	31.4	2.13	3.25

RAP = reclaimed asphalt pavement; NMAS = nominal maximum aggregate size; P_b = percent asphalt content; VTM = voids in total mixture; VMA = voids in mineral aggregate; VFA = voids filled with asphalt; Cu = coefficient of uniformity; Cc = coefficient of curvature; PCSI = primary control sieve index; BMD = balanced mix design.

Table A2. Volumetric Properties and Gradation Parameters for the 2021 Mixtures

District	Mix ID	Mix Type	RAP, %	NMAS	P_b, %	Sieve, % Passing		VTM, %	VMA, %	VFA, %	Cu	Cc	PCSI
						No. 4	No. 200						
Lynchburg	L-21-I	Control	30	12.5	6.5	63.6	5.1	2.6	16.7	84.7	22.5	1.15	4.1
	L-21-II	BMD	30	12.5	6.6	64.6	5.0	2.7	17.1	84.0	20.4	1.08	5.2
Lynchburg	L-21-III	Control	27	12.5	6.0	65.1	5.9	3.4	16.2	79.3	22.1	1.41	3.0
	L-21-IV	BMD	27	12.5	6.3	62.3	4.6	4.1	17.8	76.9	16.6	2.99	-6.0
Salem	S-21-I	Control	26	9.5	5.7	61.8	5.8	4.7	17.9	73.8	20.6	1.75	-6.1
	S-21-II	BMD	26	9.5	5.9	65.4	5.8	5.1	18.8	72.8	19.1	1.68	-3.8
Salem	S-21-III	Control	30	9.5	5.9	49.5	6.0	2.3	16.0	85.6	29.2	1.02	-10.3
	S-21-IV	BMD	30	9.5	6.2	53.4	6.6	2.2	16.6	86.7	31.0	1.21	-8.9
Northern Virginia	N-21-I	Control	30	9.5	6.1	59.8	6.8	2.1	17.1	87.9	32.3	3.72	-9.6
	N-21-II	BMD	40	9.5	5.6	57.8	6.6	2.9	15.8	81.9	31.7	3.79	-11.3
Northern Virginia	N-21-III	Control	30	9.5	6.1	59.8	6.8	2.1	17.1	87.9	32.3	3.72	-9.6
	N-21-IV	BMD	40	9.5	6.2	56.5	6.6	2.8	17.9	84.6	31.8	4.38	-13.2
Richmond	R-21-I	Control	30	12.5	5.6	57.2	6.6	3.1	16.1	80.8	27.9	1.55	0.9
	R-21-II	BMD	30	12.5	5.7	57.9	5.5	4.5	16.8	73.7	23.2	1.99	-0.5
Richmond	R-21-III	Control	30	9.5	5.9	56.8	6.6	4.4	17.7	75.5	28.7	2.98	-10.7
	R-21-IV	BMD	30	9.5	6.1	57.8	6.9	3.8	17.8	78.7	30.6	3.22	-10.4
Hampton Roads	H-21-I	Control	30	12.5	5.5	53.4	3.8	3.9	16.5	76.3	22.9	1.23	-1.2
	H-21-II	BMD	30	12.5	5.6	55.1	3.8	4.2	17.0	75.4	21.2	1.30	-0.7
Hampton Roads	H-21-III	Control	30	12.5	5.6	59.3	4.7	3.2	16.3	80.0	24.8	1.03	4.2
	H-21-IV	BMD	26	12.5	5.6	58.7	4.7	1.9	14.7	87.1	25.4	1.63	0.4
	H-21-V	BMD	26	12.5	5.1	49.1	4.3	2.5	14.1	82.5	29.8	1.89	-3.9

RAP = reclaimed asphalt pavement; NMAS = nominal maximum aggregate size; P_b = percent asphalt content; VTM = voids in total mixture; VMA = voids in mineral aggregate; VFA = voids filled with asphalt; Cu = coefficient of uniformity; Cc = coefficient of curvature; PCSI = primary control sieve index; BMD = balanced mix design.

APPENDIX B

STATISTICAL COMPARISON TABLES FOR MACROTEXTURE

Table B1. Descriptive Statistics and Pairwise Comparison of Macrotexture for the 2020 Mixtures

District	Mix ID	Mix Type	Survey Time, year	MPD, mm	STDEV, mm	Pairwise Comparison	
						Mean	Variance
Richmond	R-20-I	Control	1.1	0.46	0.056	a/b	a
			1.7	0.42	0.052	c	a
	R-20-II	BMD	1.1	0.43	0.043	c	a
			1.7	0.47	0.051	a	a
	R-20-III	BMD	1.1	0.45	0.042	b	a
			1.7	0.45	0.050	b	a
Richmond	R-20-IV	Control	0.9	0.53	0.054	a	a/b
			1.5	0.54	0.073	a	a
	R-20-V	BMD	0.9	0.49	0.046	b	b
			1.5	0.51	0.061	c	a
Northern Virginia	N-20-I	Control	1.3	0.44	0.041	a	a
			1.8	0.44	0.035	a	a
	N-20-II	BMD	1.3	0.43	0.040	a/b	a
			1.8	0.42	0.036	b	a
Fredericksburg	F-20-I	Control	1.1	0.41	0.041	a	a
	F-20-II	BMD	1.1	0.40	0.039	a	a
	F-20-III	BMD	1.1	0.42	0.039	b	a

The mean values or variance values for mixtures sharing the same letter in the table for a given pair were statistically similar.
MPD = mean profile depth; STDEV = standard deviation; BMD = balanced mix design.

Table B2. Descriptive Statistics and Pairwise Comparison of Macrotexture for the 2021 Mixtures—Part I

District	Mix ID	Mix Type	Survey Time, year	MPD, mm	STDEV, mm	Pairwise Comparison	
						Mean	Variance
Lynchburg	L-21-I	Control	0.2	0.45	0.026	a/b	a
			0.8	0.45	0.030	a	a
	L-21-II	BMD	0.2	0.46	0.031	b	a
			0.8	0.45	0.026	a	a
Lynchburg	L-21-III	Control	0.5	0.42	0.050	a	a
			1	0.41	0.027	b	b
	L-21-IV	BMD	0.5	0.49	0.042	c	c
			1	0.48	0.037	c	c
Salem	S-21-I	Control	0.4	0.42	0.053	a	a
			1	0.41	0.064	a	a
	S-21-II	BMD	0.4	0.41	0.042	a	a
			1	0.40	0.035	a	a
Salem	S-21-III	Control	1	0.68	0.063	a	a
			1.5	0.68	0.068	a	a
	S-21-IV	BMD	1	0.57	0.053	b	a
			1.5	0.56	0.088	b	a
Northern Virginia	N-21-I	Control	0.2	0.50	0.069	a	a
			0.7	0.46	0.069	b	a
	N-21-II	BMD	0.2	0.52	0.061	c	a/b
			0.7	0.48	0.057	d	b
Northern Virginia	N-21-III	Control	0.2	0.47	0.074	a	a
			0.7	0.44	0.071	b	a
	N-21-IV	BMD	0.2	0.55	0.078	c	a
			0.7	0.52	0.074	d	a

The mean values or variance values for mixtures sharing the same letter in the table for a given pair were statistically similar.
MPD = mean profile depth; STDEV = standard deviation; BMD = balanced mix design.

Table B3. Descriptive Statistics and Pairwise Comparison of Macrotexture for the 2021 Mixtures—Part II

District	Mix ID	Mix Type	Survey Time, year	MPD, mm	STDEV, mm	Pairwise Comparison	
						Mean	Variance
Richmond	R-21-I	Control	0.2	0.44	0.080	a	a/c
			0.8	0.39	0.047	b	b
	R-21-II	BMD	0.2	0.52	0.084	c	c
			0.8	0.47	0.061	d	a
Richmond	R-21-III	Control	0.2	0.46	0.054	a	a
			0.8	0.48	0.065	b	a
	R-21-IV	BMD	0.2	0.51	0.082	b/c	c
			0.8	0.52	0.085	c	c
Hampton Roads	H-21-I	Control	0.1	0.42	0.029	a	a
			0.7	0.42	0.052	a	b
	H-21-II	BMD	0.1	0.41	0.067	a	b
			0.7	0.43	0.074	a	b
Hampton Roads	H-21-III	Control	0.1	0.42	0.027	a	a
			0.7	0.39	0.023	b	a
	H-21-IV	BMD	0.1	0.44	0.037	c	b
			0.7	0.40	0.037	d	b
	H-21-V	BMD	0.1	0.42	0.039	a	b
			0.7	0.39	0.036	b	b

The mean values or variance values for mixtures sharing the same letter in the table for a given pair were statistically similar.
MPD = mean profile depth; STDEV = standard deviation; BMD = balanced mix design.

Table B4. Descriptive Statistics of Macrotexture for the 2022 Mixtures

District	Mix ID	Mix Type	Survey Time, years	MPD, mm	STDEV, mm
Richmond	R-22-I	BMD	0.2	0.52	0.052
	R-22-II	BMD	0.2	0.35	0.095
	R-22-III	BMD	0.1	0.39	0.076
	R-22-IV	BMD	0.1	0.34	0.061
	R-22-V	BMD	0.2	0.31	0.067
	R-22-VI	BMD	0.3	0.34	0.054
	R-22-VII	BMD	0.3	0.62	0.071
	R-22-VIII	BMD	0.2	0.64	0.114
	R-22-IX	BMD	0.2	0.6	0.052
	R-22-X	BMD	0.2	0.53	0.096
Salem	S-22-I	BMD	0.4	0.42	0.072
	S-22-II	BMD	0.2	0.50	0.051
	S-22-III	BMD	0.2	0.47	0.047
	S-22-IV	BMD	0.5	0.34	0.064

MPD = mean profile depth; STDEV = standard deviation; BMD = balanced mix design.

APPENDIX C

STATISTICAL COMPARISON TABLES FOR FRICTION

Table C1. Descriptive Statistics and Pairwise Comparison of Friction for the 2020 Mixtures

District	Mix ID	Mix Type	Survey Time, years	SR40	STDEV	Pairwise Comparison		Temperature, °C		
						Mean	Variance	Air	Surface	Tire
Richmond	R-20-I	Control	1.1	58.6	4.3	a	a/b	28	44	30
			1.7	67.4	3.5	b	a/d	14	31	26
	R-20-II	BMD	1.1	50.9	5.2	c	b	29	43	30
			1.7	75.5	2.5	d	c/d	13	33	26
	R-20-III	BMD	1.1	57.2	4.9	a	b	29	43	34
			1.7	72.4	3.3	e	a/c	13	30	28
Richmond	R-20-IV	Control	0.9	56.6	2.8	a	a	31	43	43
			1.5	69.2	2.6	c	a	14	22	26
	R-20-V	BMD	0.9	54.8	3.8	b	b	31	43	42
			1.5	68.6	4.0	c	b	14	19	26
Northern Virginia	N-20-I	Control	1.3	63.5	4.4	a	a	16	24	24
			1.8	72.1	3.7	b	b	14	20	27
	N-20-II	BMD	1.3	65.2	3.0	c	c	16	19	25
			1.8	72.2	2.4	b	c	14	19	29
Fredericksburg	F-20-I	Control	1.1	53.3	5.9	a	a	24	26	36
	F-20-II	BMD	1.1	58.6	4.0	b	b	24	30	35
	F-20-III	BMD	1.1	57.5	4.4	b	b	24	28	36

The mean values or variance values for mixtures sharing the same letter in the table for a given pair were statistically similar.
SR40 = friction index; STDEV = standard deviation; BMD = balanced mix design.

Table C2. Descriptive Statistics and Pairwise Comparison of Friction for the 2021 Mixtures—Part I

District	Mix ID	Mix Type	Survey Time, year	SR40	STDEV	Pairwise Comparison		Temperature, °C		
						Mean	Variance	Air	Surface	Tire
Lynchburg	L-21-I	Control	0.2	72.8	2.3	a	a	22	25	29
			0.8	74.0	1.8	b	b	19	40	27
	L-21-II	BMD	0.2	74.3	2.4	b/c	a	22	25	29
			0.8	74.8	1.6	c	b	19	40	27
Lynchburg	L-21-III	Control	0.5	73.4	3.2	a	a	21	23	27
			1	75.5	1.9	b	b	19	38	26
	L-21-IV	BMD	0.5	71.6	3.4	c	a	21	25	30
			1	74.2	2.3	d	b	19	38	28
Salem	S-21-I	Control	0.4	70.4	5.4	a	a	16	19	19
			1	65.7	5.7	b	a	25	42	32
	S-21-II	BMD	0.4	70.6	4.2	a	b	16	19	23
			1	66.5	4.3	b	b	25	42	32
Salem	S-21-III	Control	1	62.9	4.0	a	a	26	35	30
			1.5	67.4	3.6	b	a	15	18	28
	S-21-IV	BMD	1	68.0	2.3	b	b	26	35	30
			1.5	74.3	3.6	c	a	15	18	28
Northern Virginia	N-21-I	Control	0.2	62.9	3.9	a	a	15	18	22
			0.7	64.5	3.6	b	a	14	21	28
	N-21-II	BMD	0.2	60.2	4.0	c	a/b	15	17	25
			0.7	70.4	4.6	d	b	14	21	28
Northern Virginia	N-21-III	Control	0.2	63.6	3.0	a	a	14	17	21
			0.7	66.7	3.8	b	a/b	14	21	30
	N-21-IV	BMD	0.2	63.0	4.1	a	b/c	14	14	25
			0.7	68.3	3.7	c	a/c	14	21	30

The mean values or variance values for mixtures sharing the same letter in the table for a given pair were statistically similar.
SR40 = friction index; STDEV = standard deviation; BMD = balanced mix design.

Table C3. Descriptive Statistics and Pairwise Comparison of Friction for the 2021 Mixtures—Part II

District	Mix ID	Mix Type	Survey Time, year	SR40	STDEV	Statistical Comparison		Temperature, °C		
						Mean	Variance	Air	Surface	Tire
Richmond	R-21-I	Control	0.2	52.1	5.7	a	a	28	38	38
			0.8	60.2	3.7	b	b	26	43	31
	R-21-II	BMD	0.2	55.4	5.0	c	a	28	38	38
			0.8	61.8	4.8	d	a	26	44	34
Richmond	R-21-III	Control	0.2	54.8	4.0	a	a	31	45	32
			0.8	67.7	4.2	b	a	12	16	25
	R-21-IV	BMD	0.2	51.7	4.4	c	a	31	39	35
			0.8	68.9	5.0	d	a	12	16	28
Hampton Roads	H-21-I	Control	0.1	57.1	3.5	a	a	29	42	35
			0.7	64.7	3.9	b	a	17	34	25
	H-21-II	BMD	0.1	47.0	5.7	c	b	29	42	35
			0.7	60.5	6.2	d	b	17	34	25
Hampton Roads	H-21-III	Control	0.1	55.0	3.1	a	a	31	46	34
			0.7	72.8	1.6	b	b	10	22	25
	H-21-IV	BMD	0.1	52.4	4.2	c	c	31	46	34
			0.7	68.6	4.3	d	c	10	22	25
	H-21-V	BMD	0.1	51.0	5.6	e	d	31	46	34
			0.7	68.8	5.1	d	d/c	10	22	25

The mean values or variance values for mixtures sharing the same letter in the table for a given pair were statistically similar.
SR40 = friction index; STDEV = standard deviation; BMD = balanced mix design.

Table C4. Descriptive Statistics of Friction for the 2022 Mixtures

District	Mix ID	Mix Type	Survey Time, year	SR40	STDEV	Temperature, °C		
						Air	Surface	Tire
Richmond	R-22-I	BMD	0.2	63.6	2.8	12	19	19
	R-22-II	BMD	0.2	71.1	3.8	11	15	19
	R-22-III	BMD	0.1	66.1	3.2	9	9	12
	R-22-IV	BMD	0.1	75.4	6.2	10	11	13
	R-22-V	BMD	0.2	71.4	5.2	12	22	17
	R-22-VI	BMD	0.3	67.4	3.9	10	12	18
	R-22-VII	BMD	0.3	72.1	3.5	14	23	20
	R-22-VIII	BMD	0.2	61.8	3.2	17	27	19
	R-22-IX	BMD	0.2	67.0	3.2	16	30	16
	R-22-X	BMD	0.2	64.6	2.7	16	27	22
Salem	S-22-I	BMD	0.4	73.2	4.4	14	22	26
	S-22-II	BMD	0.2	73.4	4.0	13	22	28
	S-22-III	BMD	0.2	70.4	3.8	13	22	28
	S-22-IV	BMD	0.5	67.8	3.8	15	22	26

SR40 = friction index; STDEV = standard deviation; BMD = balanced mix design.