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Virginia's 2024 Implementation of Balanced Mix Design

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The BMD implementation was reviewed through data from contract locations, bid prices, performance test results, field density, mixture comparison to previous years, and a survey of stakeholders involved with BMD mixtures.

Collection of project information was challenging because the information was kept in disparate locations in different divisions within the agency. Given the concern for cracking performance, it was encouraging to see that BMD mixtures had slightly higher asphalt content than previous Superpave designs. BMD type D mixtures showed lower production air voids. Voids filled with asphalt values, especially for 12.5 mm mixtures, were found to be increasing toward the upper production limit as mixtures evolve to meet BMD cracking requirements. VDOT and producer performance results distributions aligned well for Cantabro and indirect tensile cracking tests, with indirect tensile cracking test results largely greater than the threshold limits, indicating improvements in cracking resistance. VDOT showed better results overall for indirect tensile at high temperature testing, and more producer labs indicated an issue with the indirect tensile at high temperature testing. BMD production samples consistently met all performance testing thresholds. In addition, BMD mixtures showed no overall change in field density. Finally, the survey provided a range of positive and negative feedback regarding the testing in 2024.

Based on the information collected, it is recommended that increasing the indirect tensile cracking test production threshold, allowing reduced frequency of production performance testing, and adjusting voids filled with asphalt requirements for BMD should be considered. Training on the indirect tensile at high temperature test should be continued because the test is still relatively new, and some technicians have experienced issues running the test. Finally, based on data collection challenges during the study, it is recommended that improved alignment of data sources and systems be pursued such that data can be easily accessed and compiled to allow for continued performance monitoring and fully informed maintenance decisions.

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FINAL REPORT

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ABSTRACT

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INTRODUCTION

The Virginia Department of Transportation (VDOT) started efforts to implement balanced mix design (BMD) in 2017. The first effort selected performance-related tests to use within the BMD framework and developed initial criteria for those tests that could be used to identify what should be well-performing mixtures. The Cantabro mass loss test, asphalt pavement analyzer (APA) rut test, and indirect tensile cracking test (IDT-CT) at intermediate temperature were selected for use in developing VDOT's initial BMD special provisions (Bowers et al., 2022; Diefenderfer and Bowers, 2019). Statistical methods were used to establish initial test criteria from benchmarked mixtures, based on the assumption that cracking resistance was a priority and that the criteria should result in the design of mixtures that were equal to or improved in performance than the benchmarked mixtures.

Following this activity, the special provisions were applied to trial projects in 2019 and 2020 (Diefenderfer et al., 2021b; Diefenderfer et al., 2023b), with modifications made as experience warranted. As understanding of the materials and testing required increased, the special provision was gradually implemented into maintenance resurfacing contracts. In 2021 and 2022, the special provisions were applied to selected routes (Diefenderfer et al., 2023a), before being applied to all applicable mixtures in specific contracts by each District in 2023 during the initial implementation effort.

The phased implementation effort culminated in 2024, as the specification was applied to all surface mixture (SM)-9.5 and SM-12.5 A and D mixtures in maintenance resurfacing contracts. This was the first statewide application of the specifications and provided an opportunity to document the lessons learned during the implementation experience and determine the need for additional adjustments or improvements to the specification and practices.

PURPOSE AND SCOPE

The purpose of this project was to document and assess the first year of full BMD implementation for SM-9.5 and SM-12.5 A and D surface mixtures and provide recommendations for changes to specifications and practices. The effort compiled all available information related to BMD surface mixtures constructed for the 2024 maintenance resurfacing contracts, conducted a survey of Department and industry personnel, and developed a white paper on the history of BMD implementation in Virginia to provide a resource for future reference.

METHODOLOGY

The effort compiled all information related to BMD surface mixtures constructed for the 2024 maintenance resurfacing contracts, such as schedule documents, mixture design submissions, producer quality control data, Department quality assurance data, and field density data to a central location. The experiences of the Department and producers during the first year of full implementation were documented using surveys, interviews, and observations gathered from other meetings. In addition, a white paper on the history of BMD was developed with the information and analysis to provide a baseline for future reference and comparison of mixtures and performance. Finally, recommendations and supporting evidence for changes to specifications and practices were made based on the results of this work and other ongoing projects.

White Paper

A white paper was developed to summarize the history of BMD in Virginia. This paper provides a concise review of the initiative from research through implementation for future reference. Information in the white paper was obtained through Virginia Transportation Research Council (VTRC) reports, published articles, internal emails and files, and discussions with relevant stakeholders.

2024 Balanced Mix Design Specification

The special provision for the 2024 implementation is provided in Appendix A. This special provision was included in annual maintenance resurfacing contracts statewide for 9.5 and 12.5 nominal maximum aggregate size surface mixtures designated as type A (performance grade [PG] 64S-16, routes less than 2,000 average daily traffic) and type D (PG 64H-16, routes greater than 2,000 average daily traffic). These are the typical surface mixtures used on VDOT resurfacing contracts. The BMD mixtures were labeled as BMD P+VO (balanced mix design performance and volumetric optimized). The BMD mixtures required Cantabro, IDT-CT, indirect tensile high temperature (IDT-HT) testing, and APA testing as part of the mixture design. The design air void target and gradation bands were widened, as previous VDOT design requirements had added additional restrictions to the #4, #8, and #30 sieves. Type D mixtures were tested in production for Cantabro, IDT-CT, and IDT-HT (report only) by both the producer and VDOT laboratories. Based on previous research, different production requirements were set for IDT-CT depending on whether the sample was cooled and then reheated prior to specimen fabrication or was maintained at production temperatures without reheating for specimen fabrication.

Data Collection

All available information related to schedules, mixture design, production, and construction was requested and compiled through the Materials Division. This data included the following:

- Schedule information, including pavement maintenance scheduling system locations.
- Mixture design submittals and TL-127 information.
- Quality assurance test data, such as TL-50 and BMD production test results.
- Field density test data.

The collection of information was a challenge because information was kept in disparate locations in different agency divisions and required cooperative efforts to access.

In addition, BMD paving locations from the 2024 paving season with a range of performance test results were identified for future performance assessment.

Survey

A survey of 55 questions was sent to Districts with schedules having BMD mixtures using the online platform SurveyMonkey. Districts were requested to share the survey with agency staff and industry partners working on the resurfacing schedules with BMD mixtures. The intent of the survey was to collect information about experiences during the design, production, and construction of BMD mixtures. Appendix B presents the survey questions.

Additional Information

Information was also collected during discussions at various meetings, including Asphalt Technical Committee, District Asphalt Co-op, and VDOT/Virginia Asphalt Association Statewide Asphalt Co-op meetings.

Analyses

Data were reviewed and analyzed to assess any trends in design, production, construction, and acceptance data. Data were assessed for anomalies that may indicate a need for further examination. Feedback from laboratories and producers was used to assist in this process as well as to identify specific mixtures for additional focus that may provide useful information. The data were also used for comparison with information from prior years. Survey and discussion data were analyzed to identify any trends in response and determine potential knowledge or process gaps or improvements.

RESULTS AND DISCUSSION

White Paper

VDOT engineers identified that mixture durability was an issue for Superpave-designed asphalt mixtures, especially as reclaimed asphalt pavement (RAP) contents increased in the late 2000s. To increase asphalt content, VDOT moved to 50-gyration mixtures and adjusted gradation requirements to have restrictions on the #30, #8, and #4 sieves in 2016. While this action led to a slightly increased asphalt content, a BMD approach relying on performance testing was planned to achieve durable, crack-resistant, and rut-resistant mixtures. Following more than 5 years of research studies and BMD field trials, VDOT fully implemented BMD performance test requirements on SM-9.5 and SM-12.5 mixtures in its 2024 resurfacing contracts. This experience is summarized in a white paper, found in Appendix C.

2024 Balanced Mix Design Contract Review

VDOT let 105 contracts ahead of the 2024 paving season with BMD mixtures across eight districts. The Bristol district commonly uses SM-19.0 surface mixtures and did not have any SM-9.5 or SM-12.5 mixtures for 2024. Twenty-two different contractors submitted bids, and 17 different contractors were awarded contracts. The list of bidders on these BMD contracts was in line with the bidders on previous annual maintenance resurfacing contracts; only two asphalt mixture producers that bid on 2023 contracts did not submit a bid on any 2024 BMD contracts.

The statewide planned tonnage of BMD was 1.70 million tons of type D mixture and 0.66 million tons of type A mixture. Contracts specified the type D mixture for routes with at least 2,000 average daily traffic, corresponding to routes requiring cores for field density acceptance. While the total 2.36 million tons was designed using BMD performance testing, only the type D mixture required production testing of the performance properties. Figure 1 maps the locations of resurfacing routes, and Figure 2 shows the quantities.

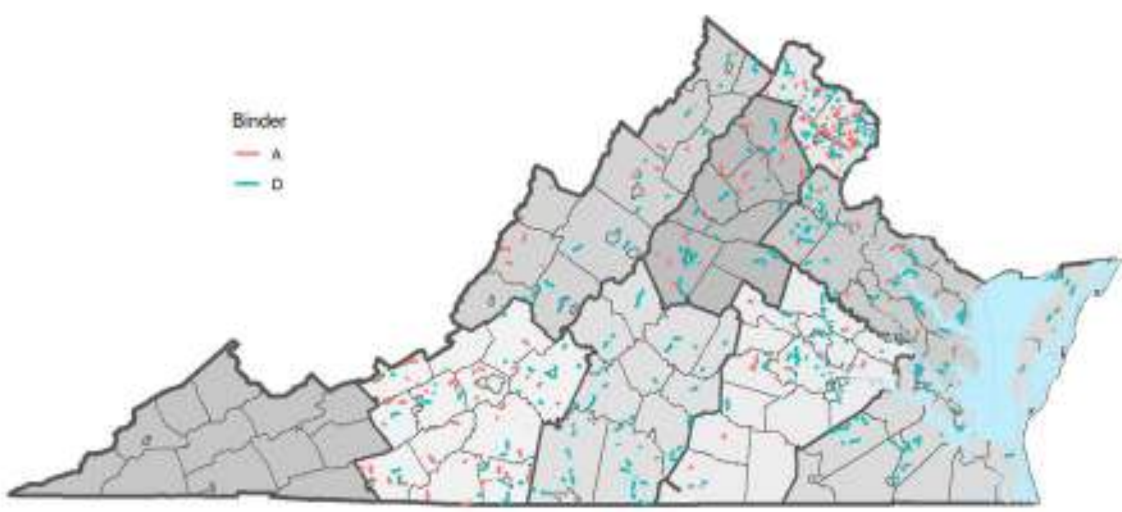


Figure 1. Map of 2024 Balanced Mix Design Paving by Binder Type

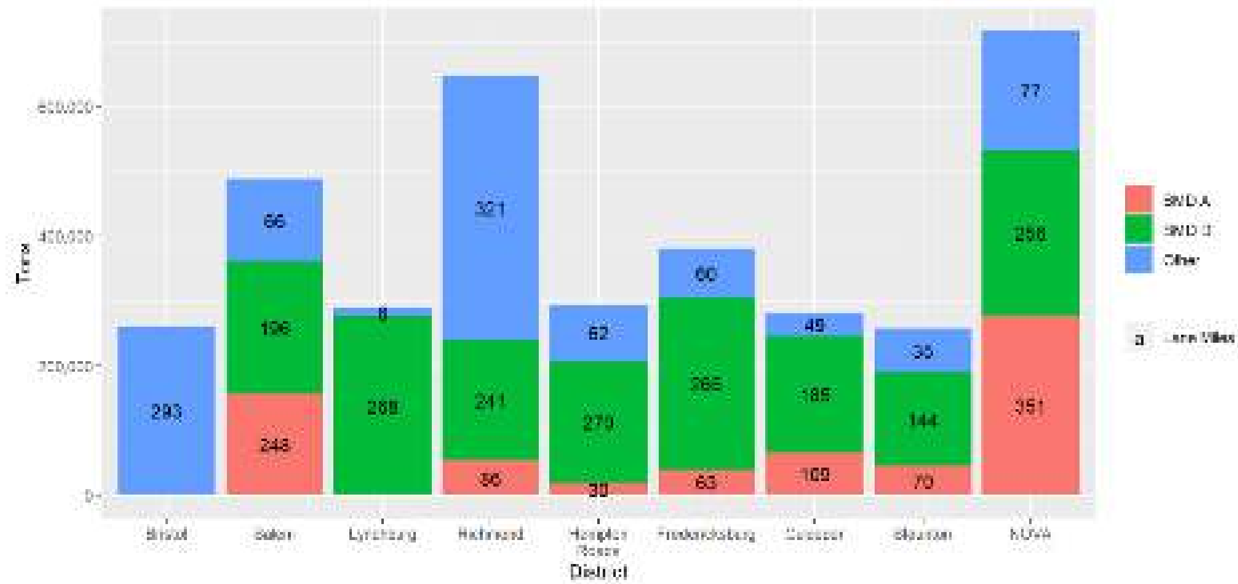


Figure 2. 2024 Annual Paving Contracts Planned Asphalt Quantity by Tonnage and Lane Miles. BMD A = balanced mix design, type A binder; BMD D = balanced mix design, type D binder.

The weighted average bid price for the A and D mixtures is plotted in Figure 3. The average bid price is calculated from the low bidder unit price per ton for the asphalt mixture, weighted by the contract quantity. The averages include the annual maintenance resurfacing contracts for 2021 through 2024. The type A and D surface mixtures combine SM-9.5 and SM-12.5 mixtures with the different binder type. The standard mixture refers to the Superpave dense-graded mixture standard prior to BMD implementation. The intermediate mixture (IM-19.0) includes both type A and D mixtures and is presented as a baseline comparison of change in asphalt prices during the period.

Figure 3 shows that asphalt mixture prices have increased significantly in the years prior to BMD implementation, from about $75/ton in 2021 to nearly $100/ton in 2023. The overall price for 2023 BMD trials (15 contracts statewide) was similar overall to the standard mixture price that year, although the type D BMD mixture saw a lower price and the BMD A mixture saw a higher price. This change in prices is likely due to factors besides the BMD design, such as field conditions and location, which affect bid prices. The BMD type A mixture price stayed steady in 2024, which suggests mixture design adjustments to meet the BMD requirements did not greatly increase cost; however, the type D BMD mixture showed an increase in 2024 bid prices.

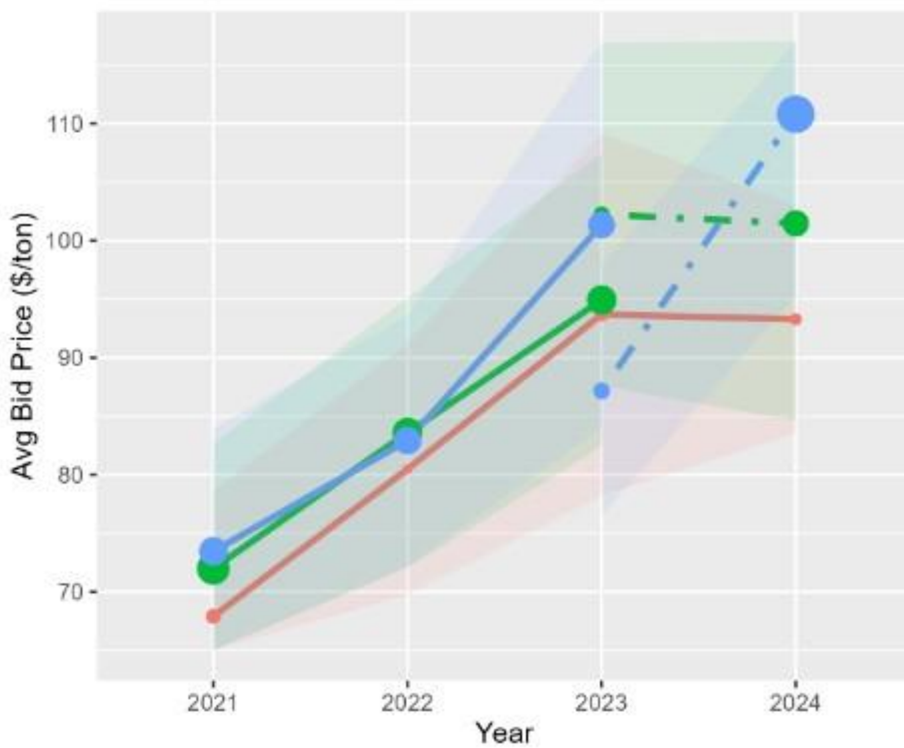


Figure 3. Asphalt Weighted Average Bid Price for Annual Maintenance Resurfacing Contracts. Shaded area indicates range of individual bid prices. BMD = balanced mix design; IM = intermediate mixture; SM A = surface mixture, type A binder; SM D = surface mixture, type D binder.

Balanced Mix Design Mixture Design Analysis

For the 2024 production year, 313 BMD job mix formulas (JMFs) were submitted; however, only 109 of the JMFs produced at least one lot of material (4,000 tons). This difference between submitted and produced JMFs is common for VDOT in other mixture types. Of the 109 produced BMD JMFs, 32 are listed as being rolled over from previous years. This includes JMFs for BMD trials in previous paving seasons and, potentially, existing Superpave mixture designs that met the performance BMD requirements.

Table 1 shows that of the 110 production JMFs, 78 (71%) of mixtures had 30% RAP in the mixture design, the upper limit allowed for surface mixtures. Of these mixtures, 71 used PG 64S-22 binder and seven used PG 58S-28 binder to meet the PG 64H-16 type D mixture requirement. Additionally, 18 other mixtures have between 26% and 29% RAP, meeting the requirement to bump the PG 64S-22 binder to meet the type D mixture requirement. Three mixture designs showed RAP content of 15% to 16% and the remaining 11 mixtures contained 23% to 25% RAP.

Table 1. RAP Contents and Binder Grades Used in 2024 Balanced Mix Design Job Mix Formulas with at Least One Production Lot

RAP Content	Binder Grade	Type A Mixture Count	Type D Mixture Count	Percent of Total
Less than 20	PG 64S-22	2	1	3%
> 20 and <= 25	PG 64S-22	4	7	9%
> 25 and < 30	PG 64S-22	5	13	17%
30%	PG 64S-22	29	42	65%
	PG 58S-28	3	4	6%
	Total	43	67	100.0%

PG = performance grade; RAP = reclaimed asphalt pavement.

BMD Mixture Comparison to Previous Superpave Mixtures

BMD JMFs were analyzed by comparing the JMFs with a corresponding Superpave surface mixture design of the same nominal maximum aggregate size, binder type, and asphalt plant produced in 2023. This analysis matched 68 BMD JMFs to a comparison mixture from the previous year. Table 2 shows the changes in production asphalt content percent binder, laboratory air voids in total mixture (VTM), voids in mineral aggregate (VMA) and voids filled with asphalt (VFA). The asphalt content, VTM, VMA, and VFA are calculated as the average producer production results across the year.

The comparison results in Table 2 show a slight overall increase in asphalt content of about 0.1%. About one-third of mixtures showed a 0.1% higher asphalt content in production, whereas only three JMFs had a noticeable decrease in production asphalt content. The production air void comparisons show a mix of increasing and decreasing air voids. Interestingly, both the 12.5 and 9.5 A mixtures show an average increase in VTM when moving to BMD, whereas type D mixtures show an average decrease in VTM. This observation could stem from the type D mixtures requiring performance testing in production and necessitating maintaining lower air voids to meet the IDT-CT requirements. All mixtures except the 12.5 D mixtures showed an increase in VMA when moving to BMD. Both 12.5 and 9.5 A mixtures show an average decrease in VFA, although the 9.5 and 12.5 D mixtures show an average increase likely related to the decrease in VTM. Figure 4 shows the individual mixture comparisons for asphalt content and VTM.

Table 2. Comparison of 2024 Balanced Mix Design JMFs to Corresponding 2023 Superpave Production Results

Mixture Type	Number of JMFs	Avg Pb Increase, %	% JMFs with > 0.1% Pb Increase	% JMFs with > 0.1% Pb Decrease	Avg VTM Change, %	% JMFs with > 0.25% VTM Decrease	% JMFs with > 0.25% VTM Increase	Avg VMA Change, %	Avg VMA, %	Avg VFA Change, %	Avg VFA, %
SM-12.5 A	5	0.03	40.0	0.0	0.25	20.0	60.0	0.4	16.9	-0.9	78.7
SM-12.5 D	21	0.11	38.1	14.3	-0.22	38.1	14.3	0.0	16.6	1.4	79.8
SM-9.5 A	26	0.08	30.8	0.0	0.07	26.9	34.6	0.2	17.2	-0.1	78.9
SM-9.5 D	16	0.05	43.8	0.0	-0.06	31.3	12.5	0.1	16.9	0.5	80.6
All	68	0.08	36.8	4.4	-0.04	30.9	25.0	0.2	16.9	0.4	79.6

A = type A mixture; Avg = average; D = type D mixture; JMFs = job mix formulas; Pb = percent binder (asphalt content); SM = surface mixture; VFA = voids filled with asphalt; VMA = voids in mineral aggregate; VTM = voids in total mixture.

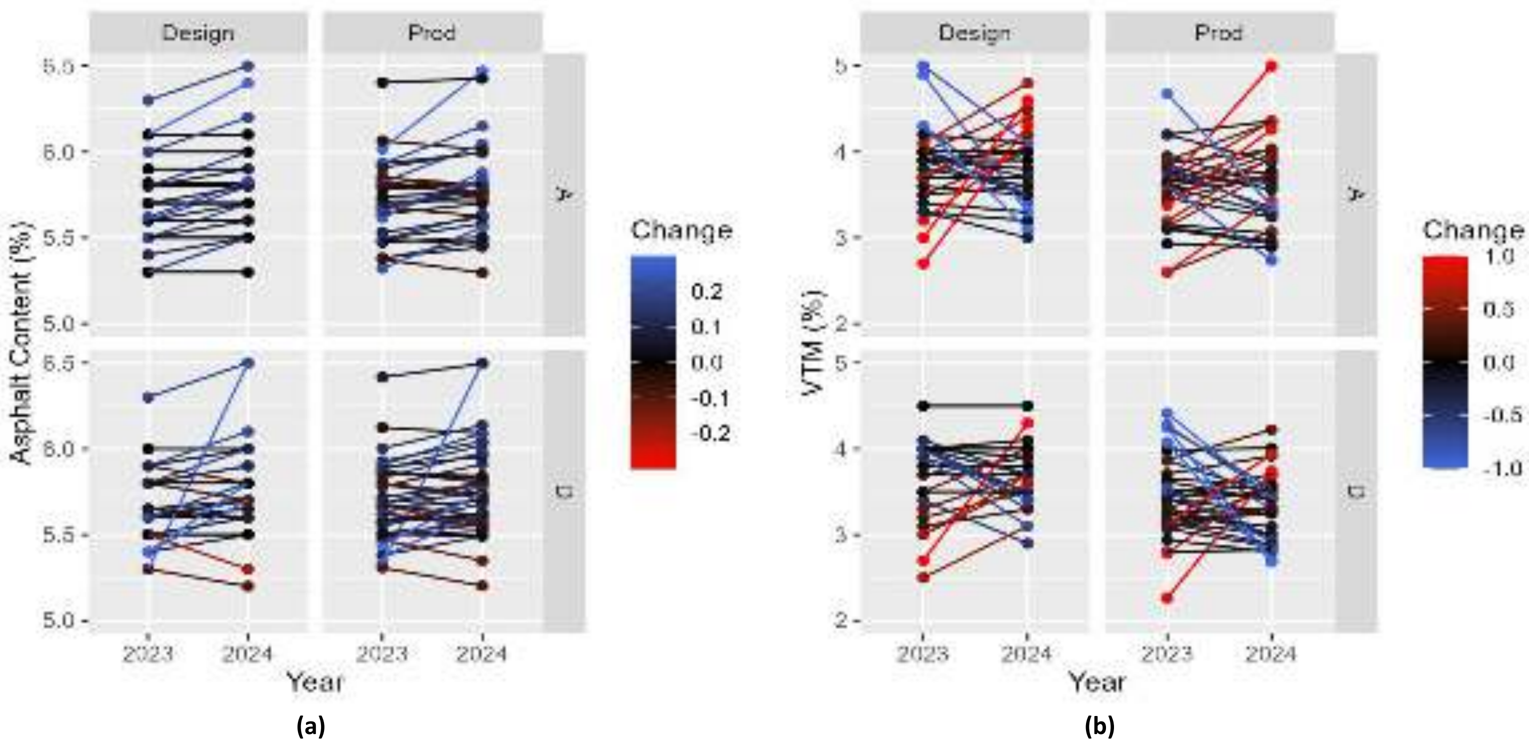


Figure 4. Comparison of 2023 and 2024 (a) Asphalt Content and (b) Voids in Total Mixture for Matched Job Mix Formulas.

Figure 5 shows boxplots of the average values from the 2023 and 2024 production results. These boxplots have outliers removed to better focus on the majority values, and the data combine both A and D mixture types. This illustration shows that VFA is increasing, especially for the SM-12.5 mixtures. The values are much closer to the upper end of the specification (production limits of 68% to 84% for 12.5 mixtures), and the 75th percentile value is approaching the production limit.

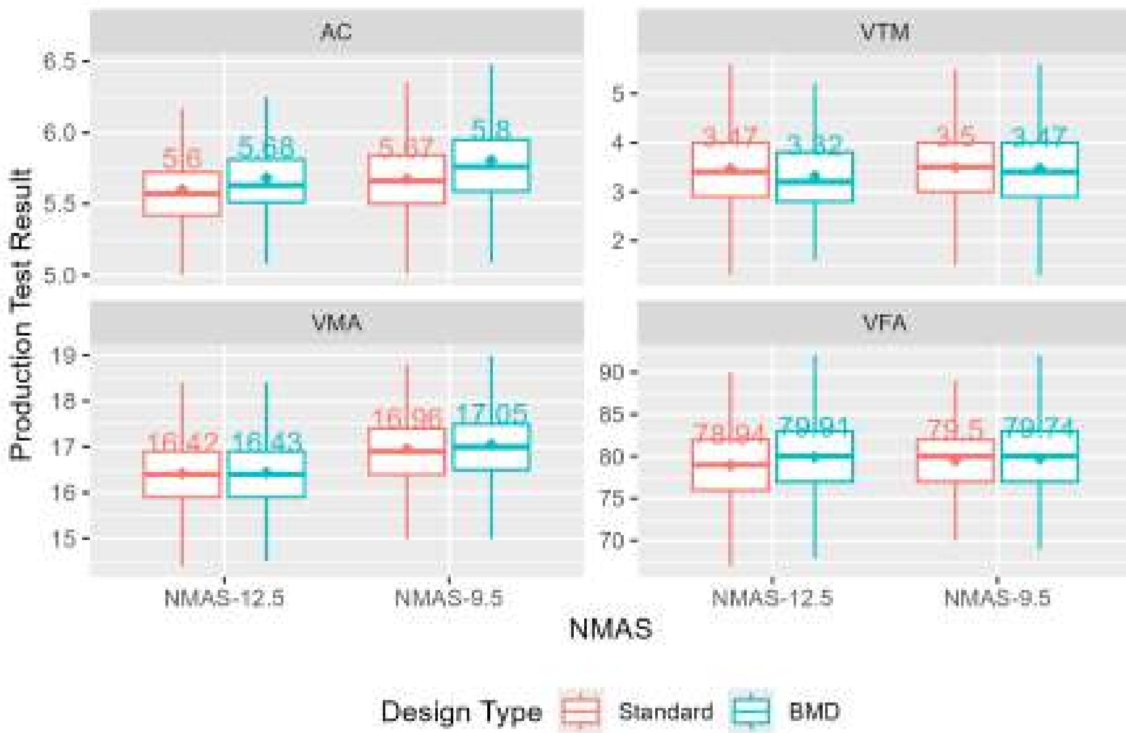


Figure 5. Comparison of 2023 and 2024 Average Production Values. AC = asphalt content; BMD = balanced mix design; NMAS = nominal maximum aggregate size; VFA = voids filled with asphalt; VMA = voids in mineral aggregate; VTM = voids in total mixture.

The average production asphalt content is plotted across all production sample producer results for the past 10 years in Figure 6. The lines represent the progression from 65-gyration design to 50-gyration design to implementation of BMD design. The ribbon bars show the 25th and 75th percentile values. The nominal maximum aggregate size 12.5 and 9.5 plots combine both A and D mixture types. The figure indicates that the 50-gyration mixtures showed about a 0.1% higher asphalt content than the previous 65-gyration Superpave mixtures. The BMD mixture design shows about a 0.1% increase from the 50-gyration design. This increase is more notable for the SM-12.5 mixtures because the SM-9.5 mixtures show similar asphalt contents in 2024. Reviewing the asphalt content of BMD mixtures in the future may be helpful as more experience is gained and producers continue to adjust mixtures.

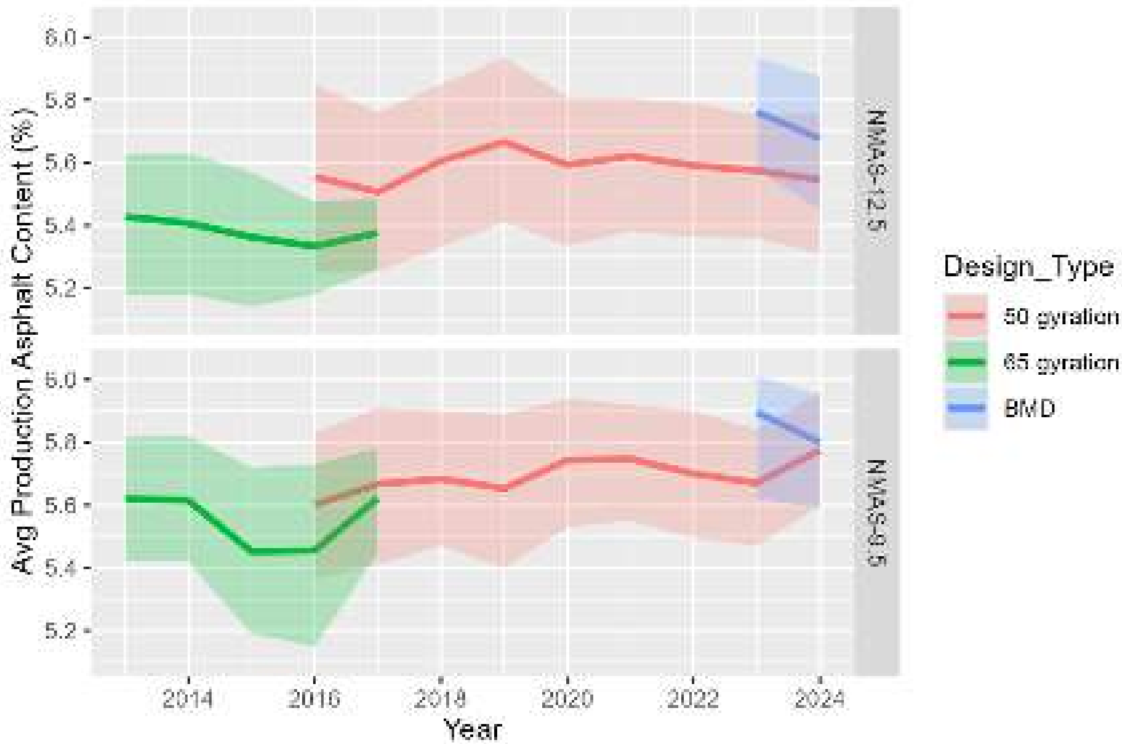


Figure 6. Average Production Asphalt Content by NMAS and Mixture Design Method. Shaded area indicates 25th and 75th percentile values. BMD = balanced mix design; NMAS = nominal maximum aggregate size.

Balanced Mix Design Performance Testing Results

The BMD production performance tests results by both producers and VDOT in production for the type D mixtures were compiled by the VDOT Materials Division. Producers and districts submitted performance test results in Excel workbooks for much of the paving season. In August 2024, the VDOT data entry system for laboratory results, Materials Information Tracking System and Producer Laboratory Analysis and Information Details (MITS/PLAID), was updated to include performance testing. The production results for the three production performance tests—Cantabro, IDT-CT, and IDT-HT—are summarized in cumulative frequency plots in Figures 7–9, respectively. Table 3 presents a summary of the quantity of samples represented by Figures 7–9. More specific comparisons between VDOT and producer results are being included in other research studies.

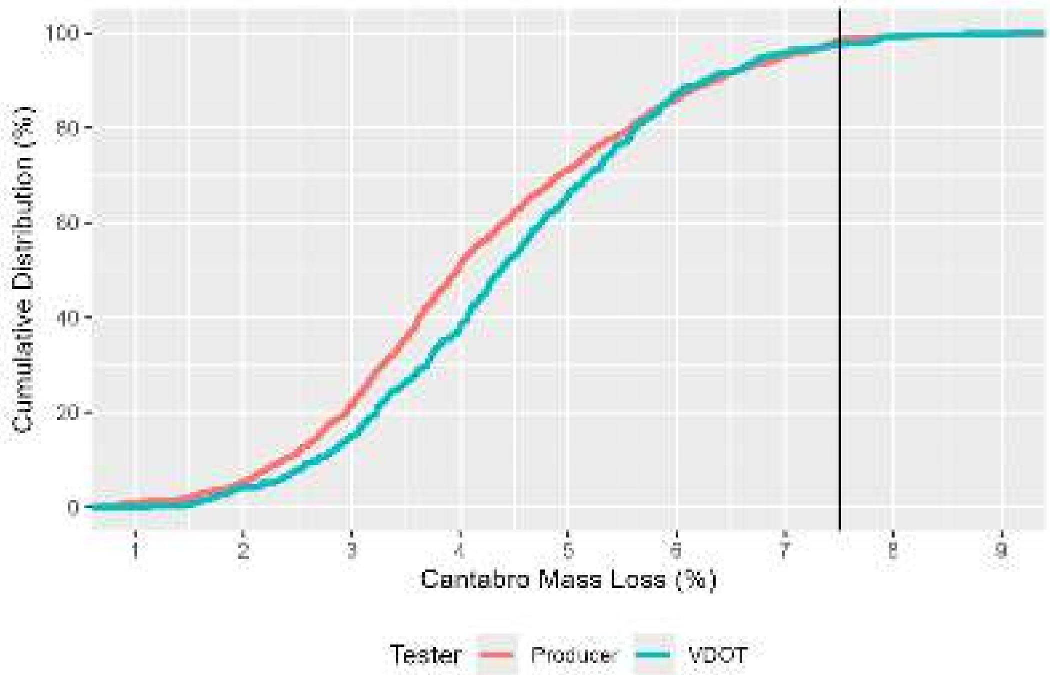


Figure 7. Cantabro Mass Loss Production Results (Maximum Passing Threshold of 7.5% Mass Loss)

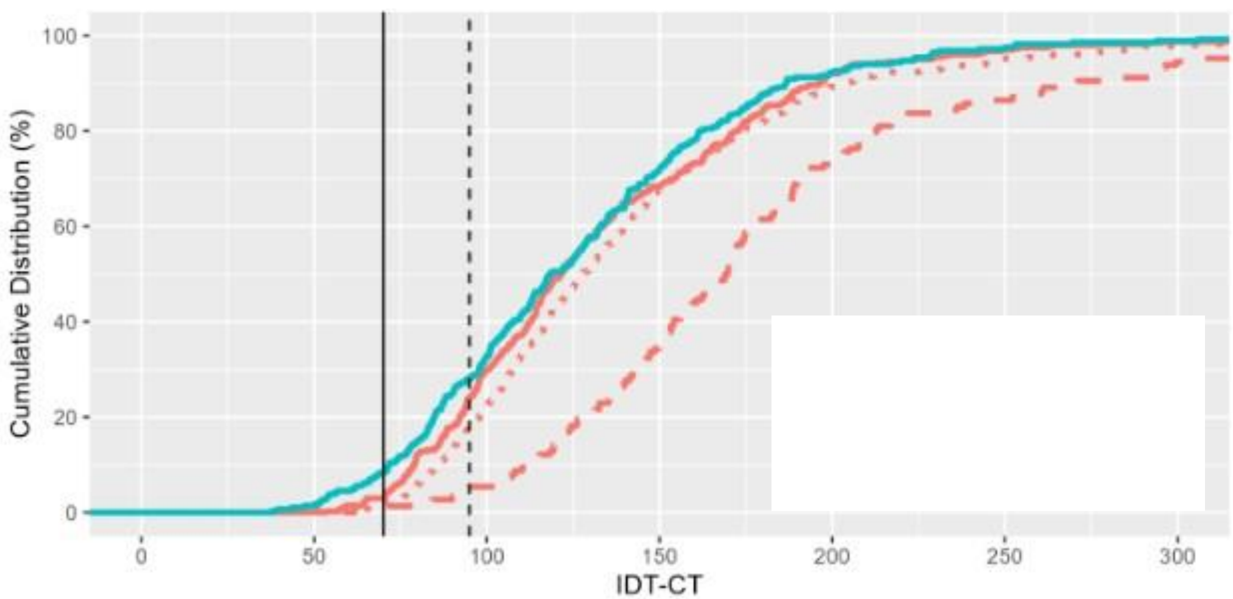


Figure 8. Indirect Tensile Cracking Test Production Results (Minimum Passing CT Index Threshold of 70 for Reheat and 95 for Non-reheat). CT = cracking tolerance.

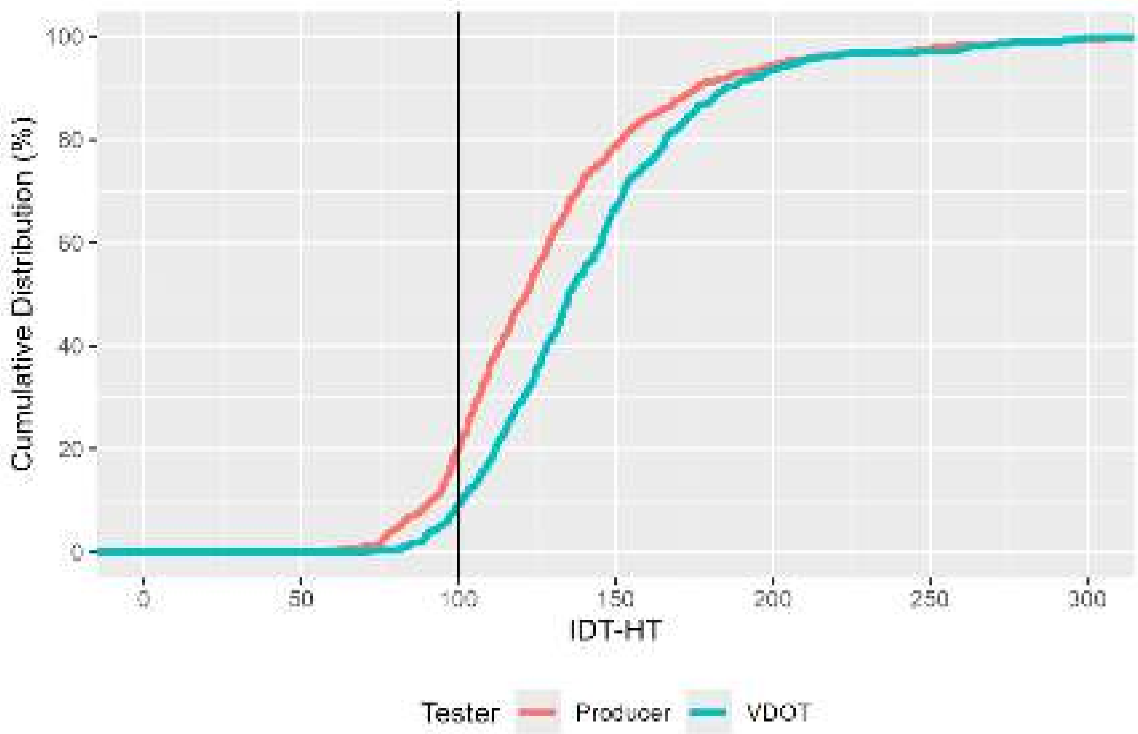


Figure 9. IDT-HT Production Results (100 kPa Minimum Strength Limit; Report Only in 2024 Production). IDT-HT = indirect tensile at high temperature.

Table 3. Number of Producer and VDOT Sample Test Results Shown in Figures 7 through 9

Test Type	Producer	VDOT
Cantabro	1,121	527
IDT-CT Reheat	405	287
IDT-CT Non-reheat	148	0
IDT-CT Not Specified	572	0
IDT-HT	655	522

IDT-CT = indirect tensile cracking test; IDT-HT = indirect tensile at high temperature test.

The Cantabro mass loss showed that nearly all samples passed the 7.5% specification criterion. The couple of samples that failed the criterion were identified as having testing equipment issues with improper revolutions per minute. The producer results showed slightly lower values by about 0.5% overall, but results correspond more closely for values at 6% mass loss and higher.

The IDT-CT was expected to be a more critical test that may require adjustment to mixtures to meet the performance criteria. Again, relatively few samples show results below the production thresholds. Less than 5% of producer results did not meet the reheat criteria of 70 or the nonreheat criteria of 95. The producer IDT-CT results were slightly higher, by about five CT index units, than the VDOT values. The 2024 BMD production results show the mixtures consistently outperformed the threshold, which was selected from the average CT index from trial 50-gyration mixtures (Bowers and Diefenderfer, 2018). The 2024 production median reheat values are closer to 125, showing significant improvement after the performance tests are included in mixture design and production. IDT-CT values greater than 100 have also been shown to relate to better performance from asphalt overlays (Habbouche et al., 2025a; Zhou et al., 2017).

The data submitted from Excel reports show that two-thirds of producer samples were designated as reheat samples. Although the results submitted through MITS/PLAID did not indicate whether they were conducted as reheat or nonreheat, they did match the reheat results line fairly closely and are presumably majority reheat samples. Adding a check box or other data entry indicator to VDOT's TL-127 and TL-50 P forms to indicate if submitted test results are reheat or nonreheat would clarify this issue.

The IDT-HT results showed a higher percentage of samples not meeting the production minimum strength threshold of 100 kPa. Approximately 20% of producer samples and 10% of VDOT samples were below the 100 kPa threshold. Because this test is still reported only in production, mixture adjustments are not required to ensure the mixture meets the minimum strength, as required for Cantabro and IDT-CT failures. Four mixtures showed average strength values between 88 kPa and 93 kPa below the threshold, with average IDT-HT strength values around 90 kPa. Notably, two of these four mixtures used a PG 58S-28 binder with 30% RAP.

In contrast to the IDT-CT and Cantabro results, VDOT showed overall better values on the IDT-HT result by about 10 kPa. These observations could be due to the IDT-HT test being a relatively newly implemented test, with laboratories having less experience with the test than with Cantabro and IDT-CT, which have been used more in previous years. Additional training with this relatively new test could be helpful to get the VDOT and producer distributions better aligned.

Field Density Comparison

Boxplots in Figure 10 show the average lot density from acceptance cores from 2023 and 2024. The density is from producer quality control testing on cores for Method A density lots, as submitted from district materials staff. The plot considers acceptance cores only for SM-9.5 and SM-12.5 D mixtures. The distributions for the 2023 Superpave data and 2024 BMD data show no difference in density. The average lot density in 2024 and 2023 are both 94%. The density analysis shows no change in field density overall with the switch to BMD mixture designs. The roller pattern information was not captured to evaluate if BMD mixtures reached their maximum density with fewer roller passes.

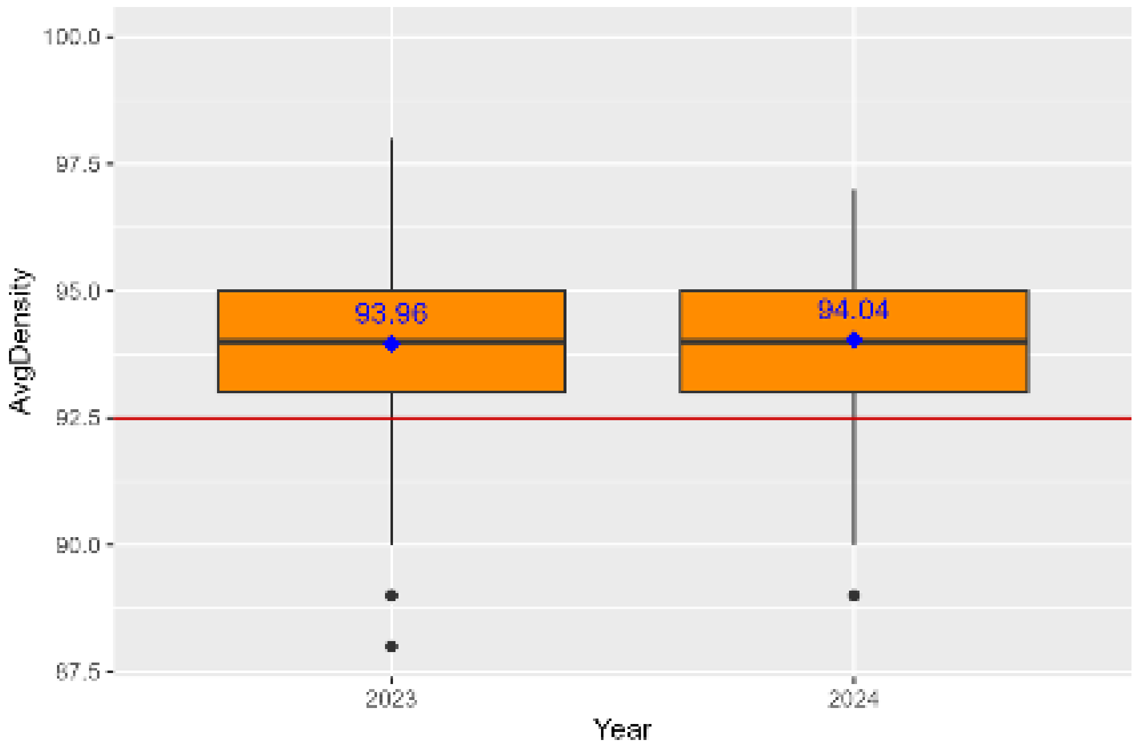


Figure 10. Balanced Mix Design Field Density Box Plot Comparison. Average density is shown in blue. Red line indicates VDOT specification.

Selected 2024 Balanced Mix Design Paving Locations

VDOT's pavement management system's records of completed paving with the identified mixture were reviewed to identify specific segments paved with BMD mixtures and associated mixture performance results. Table 4 shows the selected segments. The segments were selected from the eight districts with BMD paving which show a range of performance characteristics. Table 4 presents the segments with the VDOT average performance test results for the paving mixture.

Table 4. Selected 2024 Balanced Mix Design Paving Segments with Production Results

District	County	Route	Direction	MP From	MP To	Mixture Type	Avg VTM	Avg Mass Loss	Avg IDT-CT	Avg IDT-HT	Avg Lot Density
Salem	Botetourt	US 11	NB	163.3	164.6	SM-9.5D*	2.5%	2.4%	213	136	94.6%
Salem	Carroll	US 58	WB	201.6	205.8	SM-9.5D	3.2%	4.3%	121	123	93.1%
Lynchburg	Halifax	US 501	NB	28.3	29.6	SM-12.5D	2.9%	3.0%	118	111	NA
Richmond	Hanover	SR 657	Both	12.1	14.4	SM-12.5D	3.0%	6.4%	146	113	94.0%
Richmond	Chesterfield	SR 656	Both	0.0	1.6	SM-12.5D	3.5%	4.4%	84	111	94.3%
Richmond	Prince George	SR 630	Both	10.6	12.0	SM-9.5D	5.0%	5.7%	129	101	93.8%
Hampton Roads	Southampton	US 460	EB	355.2	358.8	SM-12.5D	2.6%	3.4%	107	165	94.7%
Hampton Roads	Northampton	US 13	NB	91.7	93.5	SM-12.5D	3.4%	3.9%	76	192	95.0%
Fredericksburg	Westmoreland	SR 3	Both	84.5	87.2	SM-12.5D	3.2%	4.9%	133	134	94.2%
Fredericksburg	Spotsylvania	SR 208	SB	39.9	42.7	SM-12.5D	3.4%	6.9%	65	167	94.1%
Culpeper	Greene	SR 230	Both	0.0	3.4	SM-12.5D	3.8%	4.6%	176	133	94.8%
Culpeper	Rappahannock	US 211	WB	43.9	46.4	SM-12.5D	4.0%	6.0%	127	167	92.9%
Staunton	Rockbridge	I-64	EB	43.9	46.6	SM-12.5D	2.4%	2.2%	294	100	94.1%
Staunton	Augusta	SR 42	Both	187.1	189.5	SM-12.5D	4.5%	1.8%	192	122	93.3%
Staunton	Alleghany	I-64	EB	35.9	38.5	SM-12.5D	3.4%	1.9%	255	86	93.8%
Northern VA	Prince William	SR 784	EB	0.0	4.1	SM-9.5D	3.3%	4.5%	181	145	NA
Northern VA	Fairfax	US 1	NB	187.5	191.5	SM-9.5D	3.9%	5.0%	93	196	93.4%

* SM-9.5D mix with fibers; Avg laboratory properties from VDOT results. D = type D mixture; EB = eastbound; I = Interstate; IDT-CT = indirect tensile cracking test; IDT-HT = indirect tensile at high temperature; MP = milepost; NA = not applicable; NB = northbound; SB = southbound; SM = surface mixture; SR = state route; VTM = voids in total mixture; WB = westbound.

Survey

The 2024 BMD survey collected 50 responses and is summarized herein. Refer to the supplemental materials available at [https://library.vdot.virginia.gov/vtrc/supplements] for detailed results.

Fourteen of the respondents were identified as VDOT employees, and 36 respondents were identified as industry employees. Figure 11 shows that respondents reported working in all nine VDOT districts.

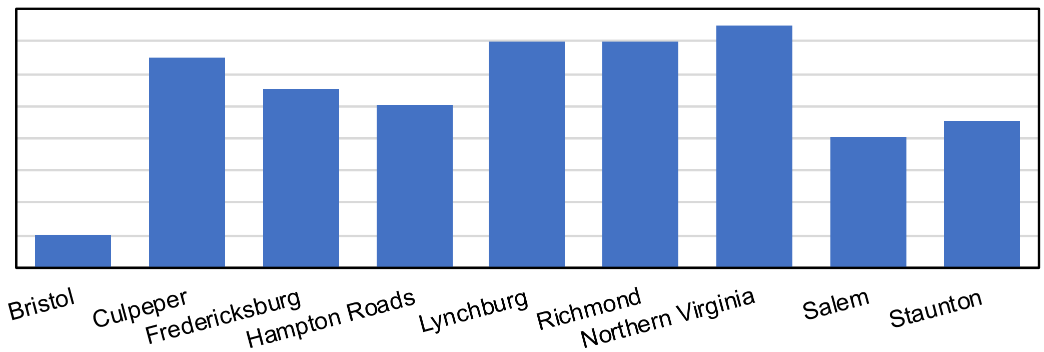


Figure 11. Work Locations for Respondents. Individuals may work in more than one location.

General Experience with Balanced Mix Design

When asked if BMD helps to improve mixtures during design, 53% of respondents indicated that it does, 41% of respondents indicated that it does not, and 8% of respondents were unsure. Figure 12 shows a summary of responses by agency and industry. In addition, respondents were asked to explain their responses.

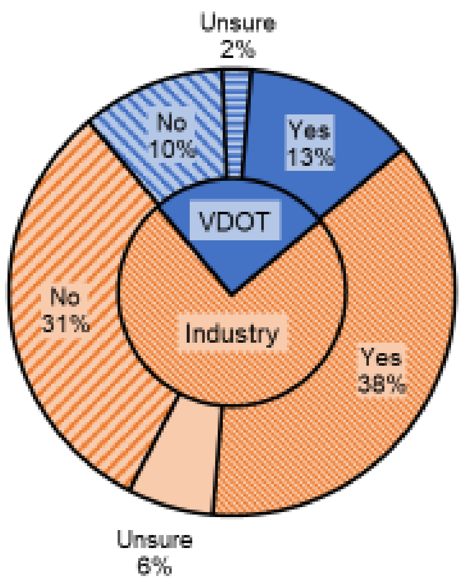


Figure 12. Responses Addressing Whether Balanced Mix Design is Helping to Improve Mixtures During Design (48 Responses).

Agency responses indicated that BMD is improving mixtures by increasing asphalt content and producing more consistent test results with fewer failures. However, those respondents answering maybe or no to the question observed that some mixtures have not needed to change to meet BMD requirements, or have changed only in small ways, and additional time is necessary to assess the mixtures and determine if there has been improvement.

Industry responses from those who believed that BMD is improving mixtures indicated that by measuring mixture performance indicators, BMD is increasing asphalt content and resulting in a more balanced mixture. BMD is also encouraging assessment of binder and RAP binder quality, allowing more flexibility for material use and mixture properties within the specification, and promoting evaluating properties more related to performance, such as film thickness. Respondents who were unsure or believed that BMD is not improving mixtures noted that the method still relies on Superpave but also requires more testing, is time consuming, and costly for mixtures that may not have changed or have changed only a small amount. Other concerns raised included the additional cost and effort required to import materials when needed to meet specifications, issues with the difference between laboratory-produced design results and plant production results, and that the process addresses the laboratory only, while more focus is needed on plant and paving operations to achieve performance improvements.

Figure 13 shows the percentage of respondents reporting that changes were made to existing mixture designs to meet the 2024 BMD requirements. It also shows the percentage of respondents who indicated that they anticipate making changes to designs for the 2025 paving season. The differences between VDOT and industry responses about changes to mixture designs in 2024 are likely due to the respondents' varying positions and their locations within the state.

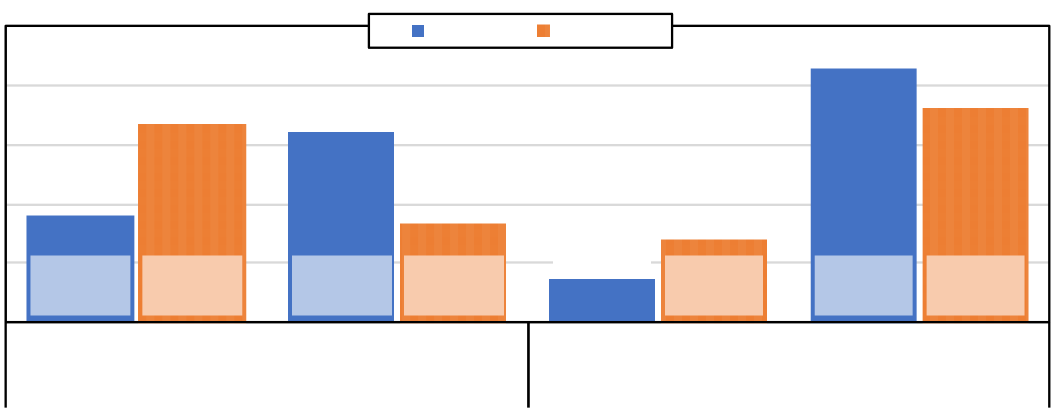


Figure 13. Changes Made to Existing Superpave Mixture Designs to Meet 2024 Balanced Mix Design Requirements and Distribution of Changes Made. Multiple changes could be applied.

Figure 14 shows the distribution of reported changes from 2024 and expected changes for 2025; multiple changes could be selected for each response. In 2024, the most widely applied design change was to increase the asphalt content and decrease the design voids; using a softer binder or finer gradation were the next most popular choices, with equal responses. Those respondents who chose "other" indicated that they used a warm mix additive, imported an aggregate, changed materials, and adjusted a gradation to be slightly gap-graded. For 2025, increasing asphalt content remained the most popular change, followed by gradation adjustments to either the finer or coarser side, respectively. The 2025 response for "other" indicated the addition of natural sand to the design.

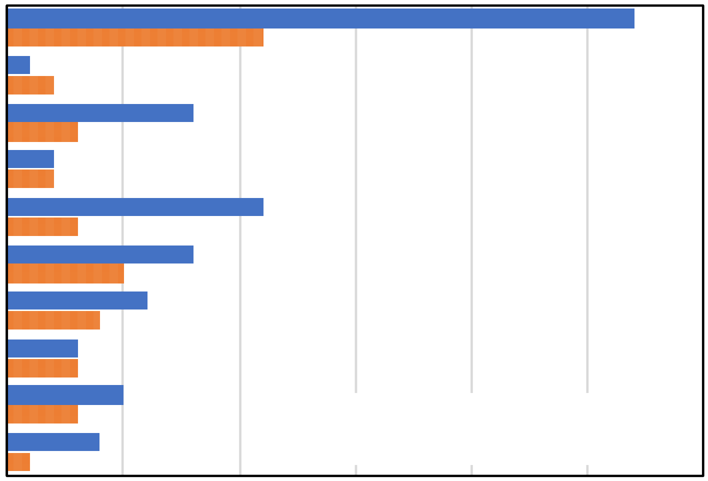


Figure 14. Distribution of Changes to Mixture Designs for the 2024 Paving Season and Anticipated Changes for 2025. Multiple changes could be applied. AC = asphalt content; VMA = voids in mineral aggregate.

One concern voiced by various agencies across the country about BMD implementation has been the cost (Gopisetti et al., 2023; Hajj et al., 2025; Sufian et al., 2024; Yin et al., 2025). Specific concerns have included increased material, equipment, and personnel costs. Figure 15 illustrates agency and industry responses about BMD driving changes to mixture designs that otherwise might not be economically feasible. Figure 15a indicates that 43% of VDOT and 56% of industry respondents believe that BMD is driving design changes that are not economically favorable. Respondents provided numerous comments when asked why, and these comments are summarized in Figure 15b. The primary response was the increased binder content that many BMD mixtures require over their volumetrically designed counterparts. Although the question was intended to address material changes, it is clear that the costs incurred by manpower, time, and additional equipment factor heavily into concerns.

Those who responded that BMD is not driving otherwise economically infeasible changes indicated that the mixtures have not changed enough to introduce significant cost increases or that mixtures could be modified in ways that do not increase costs, such as changing the mixture structure using available aggregates. It was also observed that economic feasibility is interrelated with specification requirements, such that what is economically feasible will adjust to meet what is required in the specification.

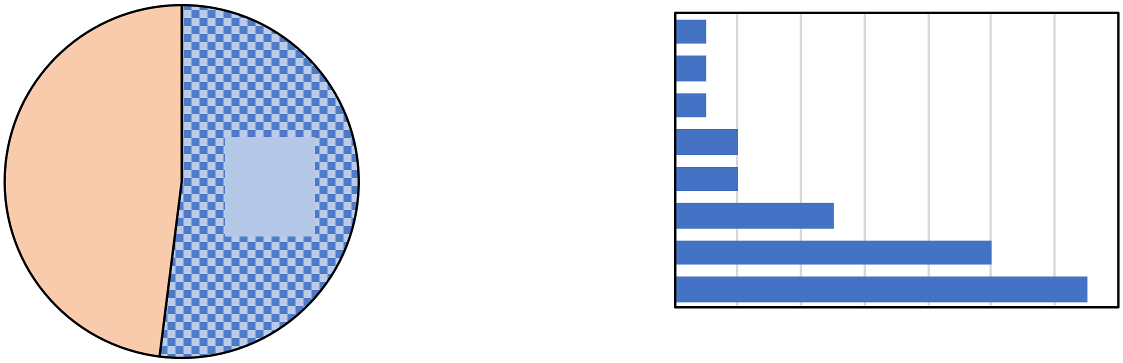


Figure 15. Responses (a) Addressing Whether Balanced Mix Design Drives Design Changes that Are Otherwise Not Economically Feasible and (b) Explanations of Why. Explanation categories were summarized from responses to an open-ended question. AC = asphalt content; RAP = reclaimed asphalt pavement.

The survey also asked respondents for their preferred method of adjustment to mixtures to meet BMD requirements. Figure 16 illustrates that although a binder content change is most frequently used, making a structure or gradation change is the second most preferred option. Respondents also noted that production mixture temperatures may be adjusted. It was noted that mixture adjustments may be limited due to the availability of materials. One comment noted that mixture quality would be enhanced by improved binder quality.

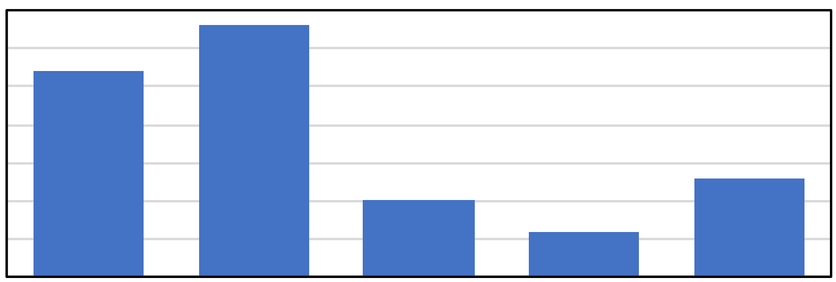


Figure 16. Preferred Method of Adjustment to Meet Balanced Mix Design Requirements. Multiple adjustments could be selected. RAP = reclaimed asphalt pavement.

Figure 17a shows the overall percentages of responses of employees who think BMD is or is not improving mixtures during production, and Figure 17b shows how agency and industry personnel responded. Responses are similar between the agency and industry, and overall, slightly more than one-half of respondents do not think BMD improved mixtures during production.

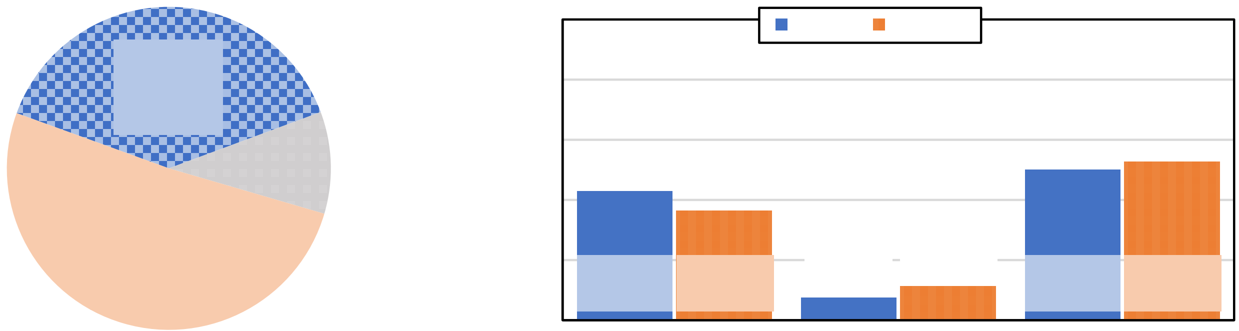


Figure 17. (a) Overall and (b) Agency and Industry Responses Concerning Whether Balanced Mix Design is Helping to Improve Mixtures During Production.

Those respondents who think BMD is improving mixtures during production cite more consistent test results, improved field density, easier to achieve density, and the additional binder content of BMD mixtures as reasons why. Other responses indicated that BMD mixtures have increased quality, and that attention during production has increased, resulting in mixtures that are produced as designed.

Responses indicating that BMD is not improving mixtures during production noted that there have been minimal changes to previous mixtures, gradation band changes have allowed worse mixtures, that the design may not match production due to material variability, especially RAP variability, and that there have been no changes in enforcement of failing volumetric properties or BMD test results. In addition, it was observed that BMD slows down production and requires time-consuming testing. One respondent pointed out that although mixtures can be enhanced, cracking and other issues will continue for all mixtures until VDOT and the industry start placing these mixtures on suitable prepared surfaces. Both groups of respondents think that BMD performance over the long term must still be proven.

Responses varied widely when asked what factors other than asphalt content and gradation change impact test results during production. Figure 18 shows responses for four alternatives: no other factors found, plant temperature, silo dwell time, and changes in RAP source; an open-ended option was also available. These responses included binder quality, RAP binder quality, binder film thickness, aggregate quality inconsistencies, and laboratory material handling practices such as time in the oven before specimen fabrication.

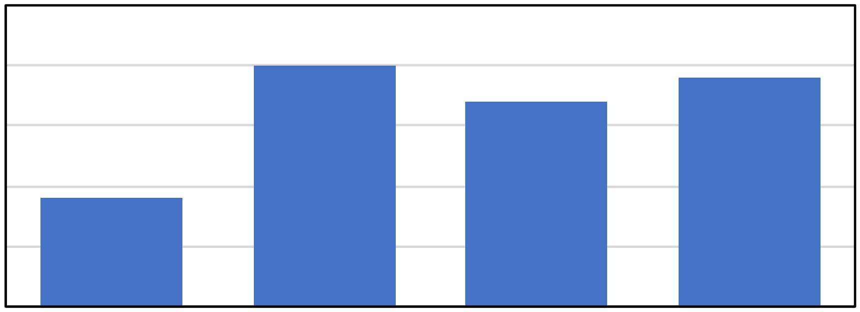


Figure 18. Factors Other than Asphalt Content and Gradation Change that Impact Results During Production. Multiple factors could be selected. RAP = reclaimed asphalt pavement.

The survey also asked respondents if changes in laboratory operations were made to keep up with BMD testing. Figure 19 shows that 80% of respondents indicated that additional test equipment had been acquired. One-half of the respondents added additional ovens to their lab, and approximately 40% of respondents increased laboratory staffing.

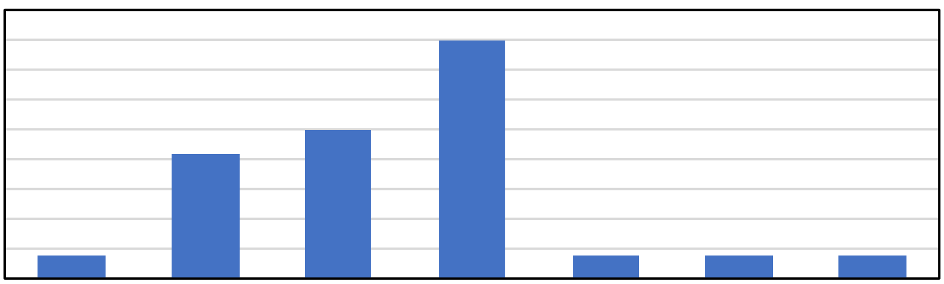


Figure 19. Changes in Operations Made by Laboratories to Keep Up with Balanced Mix Design Testing. Multiple changes could be selected. IDT-CT = indirect tensile cracking test.

Figure 20 summarizes responses regarding production testing frequency. Overall, most respondents believe that production testing occurs too frequently (Figure 20a), although Figure 20b shows this belief is primarily driven by industry responses. Agency responses are nearly split between testing frequency being "just right" and "too frequent." Interestingly, the one response that production testing is not occurring frequently enough is from industry, and because at the current test frequency, entire tanker loads of substandard binder could be missed between tests, resulting in an underperforming mixture with no indications of issues.

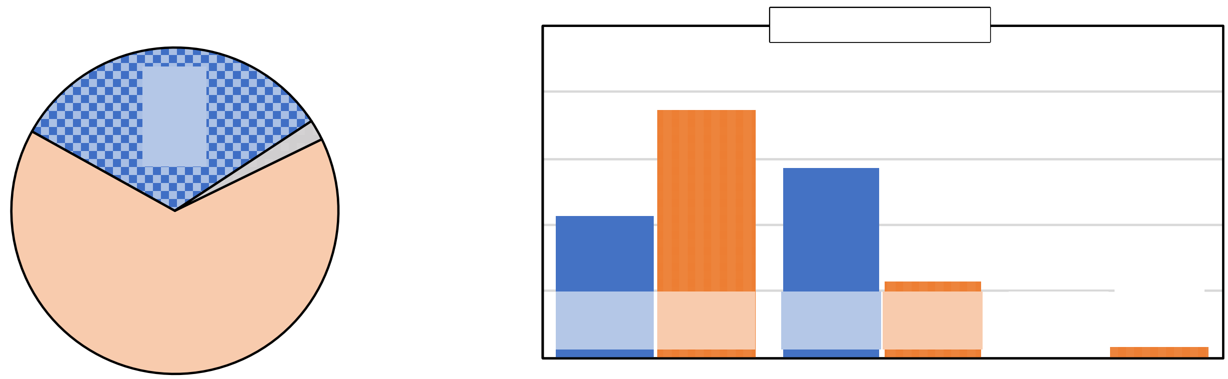


Figure 20. (a) Overall and (b) Agency and Industry Responses Regarding Balanced Mix Design Production Frequency.

Responses to why the current production testing frequency is "just right" provided the following reasons:

- The current frequency seems to be efficient because results are more consistent.
- There has not been much of a difference between samples once processes are dialed in.
- The testing frequency needs to be compared along with the volumetric testing to determine if it represents the finished product.
- The current frequency allows technicians to keep up with demand.
- This is the right frequency given the amount of additional work needed.
- Additional testing would be a burden to staff.
- The frequency should depend on the day's production, so for the most part, it is good; however, it may be too much for plants producing a large tonnage per day.

A summary of reasons why the current testing frequency is too high includes the following:

- Once a consistent passing product is established, testing frequency should be reduced as long as the mixture does not change.
- The current frequency involves too much testing, requires too much work by technicians, is too time-consuming, and technicians cannot keep up.
- The current testing frequency is a burden for those respondents who have test equipment at a central location rather than in every laboratory.
- The current frequency is detrimental to hiring and maintaining staffing.
- The only test that fails is IDT-CT, so it should be run less frequently. Cantabro and IDT-HT testing could be eliminated.
- Testing is not causing mixture adjustments that would not otherwise be addressed through volumetric testing.
- The design already meets BMD criteria, and significant coring validates quality post-paving.

Respondents were asked about observed changes in field density that may be occurring with BMD mixtures compared with prior mixtures. Figure 21 summarizes the responses. In most cases, no changes were observed; however, several responses indicated positive changes such as less variability in density, less compactive effort required to meet density, and increased density. Five responses indicated that BMD mixtures required more compactive effort to reach the target density.

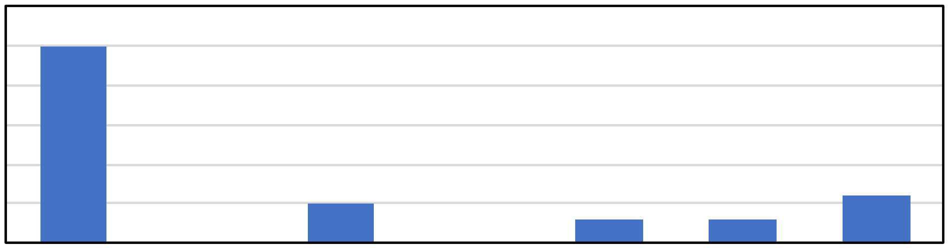


Figure 21. Field Density Changes Seen for Balanced Mix Design Mixtures versus Superpave Mixtures. Multiple changes could be selected.

One of the challenges for BMD design and production is the adjustment of mixture properties to meet both volumetric and BMD test requirements (Gopisetti et al., 2023). The question of the existence of relationships between volumetric properties and BMD test results is ongoing and important for the continued success of BMD. In the survey, respondents were asked if volumetric properties relate to BMD test results; Figure 22 shows a summary of responses. Overall, Figure 22a indicates that more respondents believe that relationships do exist. Looking more closely at the responses from VDOT and the industry in Figure 22b, the responses from industry are evenly split, and VDOT responses indicate that a majority think volumetric properties and BMD results are related.

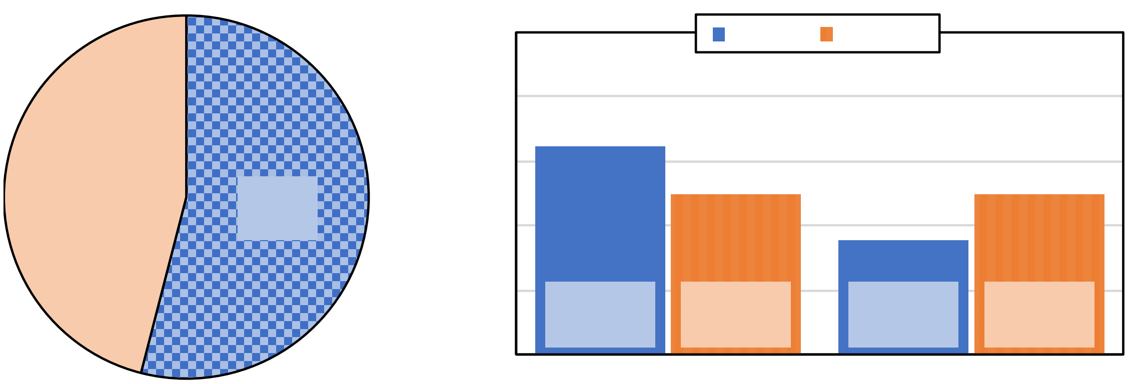
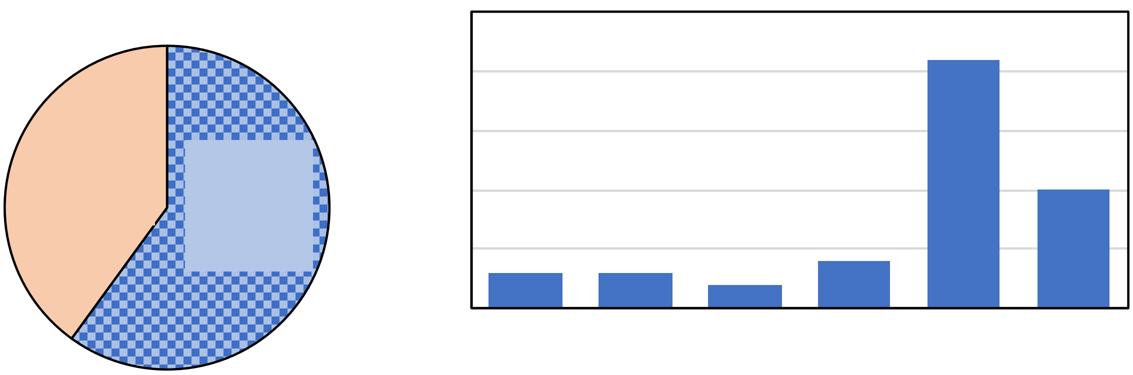


Figure 22. (a) Overall and (b) Agency and Industry Responses Concerning Whether Balanced Mix Design Results Relate to Volumetric Properties.

Respondents who believe in the presence of relationships provided numerous examples of relationships between specific properties and test results. Some point out that asphalt content and gradation affect BMD results more than specific volumetric properties. Responses indicating that volumetrics and BMD test results do not relate primarily report experiences with mixtures having consistent volumetric properties but variability in BMD results. To date, some respondents have not seen any evidence of relationships. Both groups report that in some cases, volumetrics and BMD results appear to relate, but in other cases, they do not. That lack of consistency across mixtures tended to limit confidence in relationships.

Respondents were further asked if some volumetric properties should be eliminated from requirements for acceptance, or if all volumetric properties should be kept for acceptance. Figure 23a shows the overall results, indicating that 60% of responses favor eliminating some volumetric properties, and 40% prefer to keep all volumetrics. Comments in favor of eliminating some properties noted that some volumetric properties seem to have little effect on BMD results, and that if the emphasis is on BMD testing because it indicates performance, that the volumetrics then seem redundant. Arguments to keep volumetrics suggest that they are needed to ensure that mixtures are produced according to the JMF, that BMD results are too variable, and that volumetrics are closely related to controlling field density. One observation was that volumetric property requirements should be removed from design, which would be done to meet BMD requirements but would be used during production to verify mixture properties. Another observation suggested that acceptance could be done based on BMD tests, but producers would still be evaluating volumetrics to control mixture production.

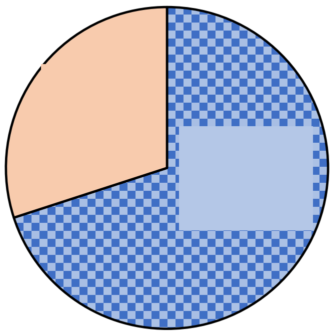


(b)

Figure 23. Responses Indicating that (a) Volumetric Properties Should Be Removed from Acceptance or Not and (b) Which Properties Should Be Removed. Multiple properties could be selected. AC = asphalt cement; FA = fines to asphalt; VFA = voids filled with asphalt; VMA = voids in mineral aggregate.

The following question asked what properties should be dropped, and Figure 23b shows the responses. VFA and fines to asphalt ratio both received higher responses in favor of eliminating them from acceptance, with asphalt content, gradation, air voids, and VMA drawing much fewer responses. Reasons for the selection of each property varied widely.

Respondents were also asked if the current BMD test frequency is acceptable if some volumetric properties are dropped. Figure 24a indicates that most respondents agree that the current BMD test frequency is acceptable. Figure 24b shows that VDOT and the industry give approximately equal percentages of responses.



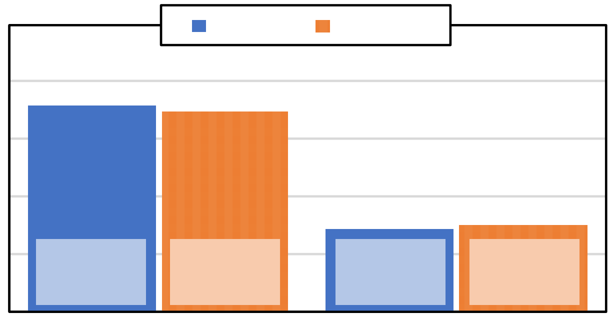
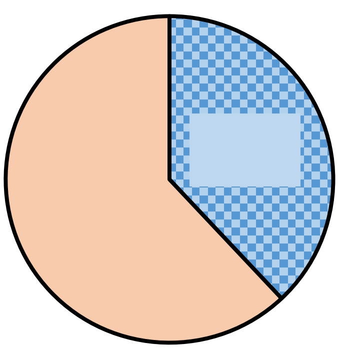


Figure 24. (a) Overall and (b) Agency Versus Industry Responses Concerning Whether the Current Test Frequency is Acceptable or Not if Some Volumetric Properties are Dropped.

Those respondents who believed that the current frequency is not acceptable thought that the current test frequency is already too high, and that BMD testing overall takes too much time. Other respondents thought that too much material is being paved before results are available, and that the testing frequency is not sufficient to identify short-lived changes that impact performance and not frequent enough to catch binder source issues. One comment indicated that increasing BMD test frequency because volumetric properties were removed was not a suitable trade-off. A common observation from those who responded that the current frequency is acceptable is that producers will still need to test for volumetric properties to control production.

Cantabro Test

Respondents were asked how effective the Cantabro test has been as a BMD test. Figure 25 shows that responses were similar from VDOT and industry respondents, with slightly less than 40% of each indicating that the Cantabro has been an effective test; slightly more than 60% of respondents indicated that the Cantabro test has been ineffective.



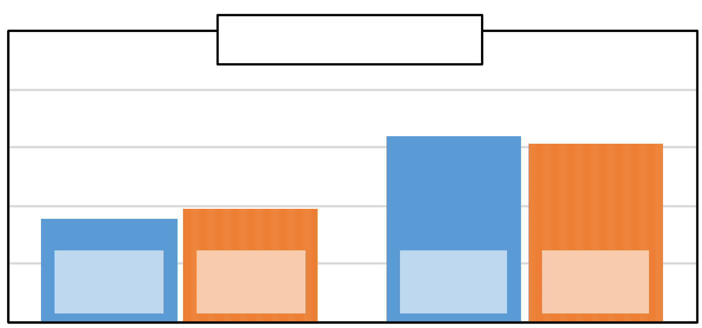


Figure 25. (a) Overall and (b) Agency Versus Industry Responses Regarding the Effectiveness of the Cantabro Test as a Balanced Mix Design Test.

When asked what they liked about the Cantabro test, respondents generally liked that the test is simple and quick and uses specimens that are already fabricated for volumetric testing. Other respondents liked that the test indicates durability, high void contents, and low asphalt content. Additionally, it was noted that the test can identify if the mixture has structural issues and can catch problems with both binder and aggregate.

Respondents disliked the fact that the Cantabro test rarely provides a failing test result. They do not think that the test translates to practical conditions, are not sure what it represents in terms of traffic conditions, or believe that it is a waste of time. Some respondents did not like the time required to dry, condition, and test specimens. Others disliked the noise, the cost of the equipment, and the space required for the equipment.

Figure 26 shows that when respondents were asked if they had issues with the Cantabro test, only 8% of respondents answered in the affirmative. The issues reported included the machine not meeting specifications, problems related to temperature, and difficulties matching results from equipment produced by different manufacturers.

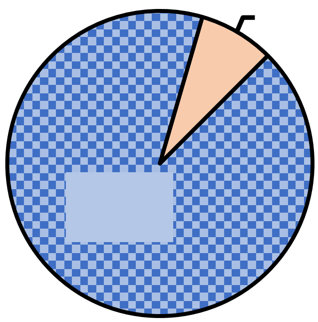


Figure 26. Issues with the Cantabro Test

Figure 27 shows that only 2% of respondents generated unusual or unexpected data from the Cantabro test. When asked to explain the cause of the unusual data, respondents identified specimen temperature as the cause.

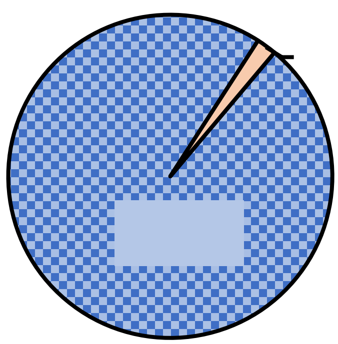


Figure 27. Unusual or Unexpected Data from the Cantabro Test

Respondents were asked for tips on running the Cantabro test. Responses were varied and are summarized as follows:

- Have a good mixture to begin with, not too coarse, and have plenty of AC.
- Be consistent with how you obtain each sample. Collect sufficient material to prevent segregation.
- Remember to put in the bottom plate when compacting specimens. Be careful not to segregate the mixture while charging the mold.
- Be sure to have a proper place in the lab to dry your pills quickly. Make sure the pills are dried back in accordance with specifications.
- Make sure to follow the temperature requirements.
- Clean the pills after pulling them out of the machine. Also, clean the dustpan underneath the drum.

Indirect Tensile Cracking Test

Figure 28 shows that more than three-fourths of respondents think the IDT-CT has been an effective BMD test. VDOT and the industry displayed nearly identical percentages of responses indicating the test was effective and not effective.

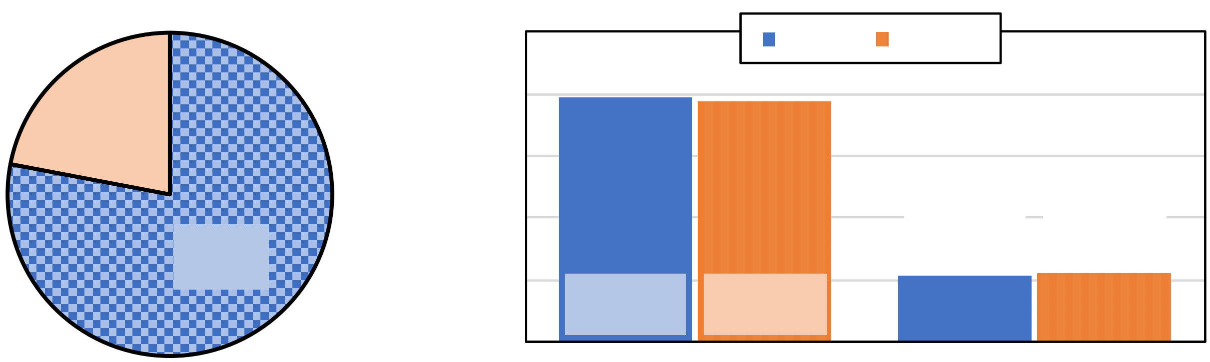


Figure 28. (a) Overall and (b) Agency and Industry Responses Regarding Whether the Indirect Tensile Cracking Test Has Been Effective as a Balanced Mix Design Test.

Respondents were asked what they like about the IDT-CT. Generally, they like that the test is relatively simple, easy to understand, uses smaller specimens, and seems to be related to cracking and mixture performance on the road. Some respondents like that the test helps to ensure adequate binder content, and others appreciate that the coefficient of variance indicates consistency.

Respondents dislike making the required number of pills, have difficulty making specimens with consistent air voids, dislike inconsistent test results, and dislike the amount of time it takes to make and test specimens.

When asked about issues with the IDT-CT, 30% of respondents indicated that they have experienced issues, with VDOT respondents having a slightly higher percentage of issues than industry (Figure 29). Issues reported include equipment not working properly, obtaining variable coefficient of variance values for results, and the test sensitivity to specimen fabrication. Another reported issue was managing the time requirements to make and test specimens.

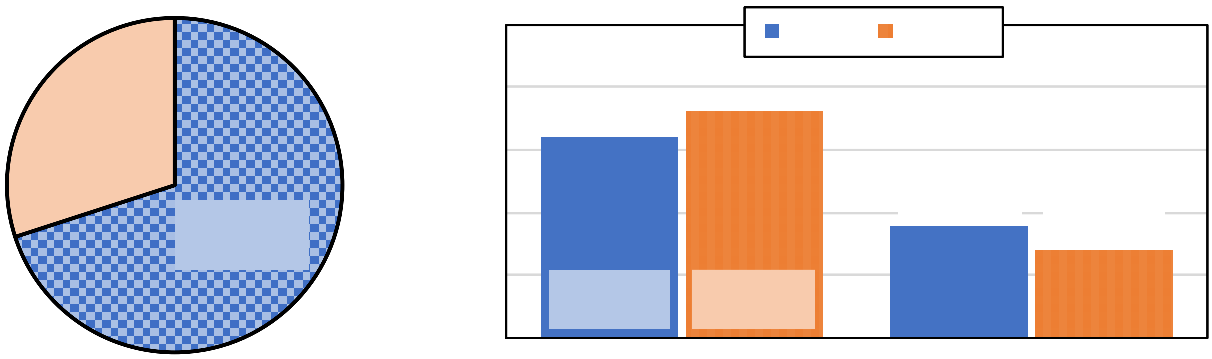


Figure 29. (a) Overall and (b) Agency and Industry Issues with Indirect Tensile Cracking Test.

Figure 30 illustrates that 20% of respondents have seen unusual or unexpected data from the IDT-CT, with both the agency and industry experiencing similar percentages. Reports of unusual or unexpected data included identical specimens with varied results, unexpected random outliers, and increased variability.

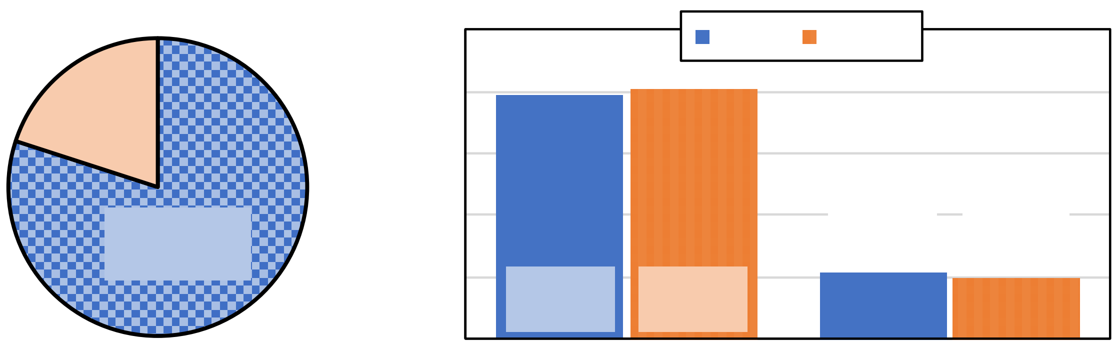


Figure 30. (a) Overall and (b) Agency and Industry Unusual or Unexpected Data from the Indirect Tensile Cracking Test.

Respondents offered the following tips on running the test:

- Be consistent in sampling, splitting, fabricating specimens, and conditioning specimens.
- Run Rice values from the sample to improve accuracy and hit air void targets.
- Do not allow material to remain in the oven for too long.
- Temperature at all stages is critical.

Indirect Tensile at High Temperature Test

When asked about the effectiveness of the IDT-HT, the rutting test specified for the first time in 2024, only 34% of respondents indicated that it was effective. Figure 31 shows that when comparing agency and industry responses, a slightly higher percentage of industry responses indicated a belief in the effectiveness of the test, and a slightly higher percentage of VDOT responses indicated that it was not effective.

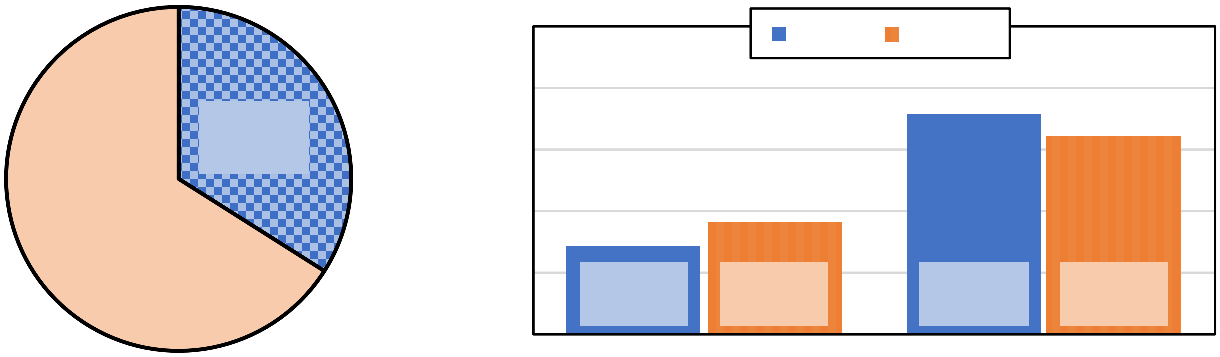


Figure 31. (a) Overall and (b) Agency and Industry Responses Regarding Whether Indirect Tensile at High Temperature has been Effective as a Balanced Mix Design Test.

When asked what they like about the test, respondents indicated that the test is simple and straightforward to perform, that specimens are the same size as those for the IDT-CT, and that it is similar to the IDT-CT. Respondents also appreciate the consistency of test results.

Respondents do not like fabricating additional test specimens or the need for an additional water bath. In addition, many respondents do not see a correlation or relationship between the IDT-HT and APA results. They are not clear on how the test is meaningful or how it relates to field conditions.

Figure 32 shows that VDOT respondents indicated that they had no issues in running the IDT-HT test; however, 31% of industry respondents reported issues. The issues reported included highly variable results, difficulties meeting the criterion, and inconsistent failures that made no sense.

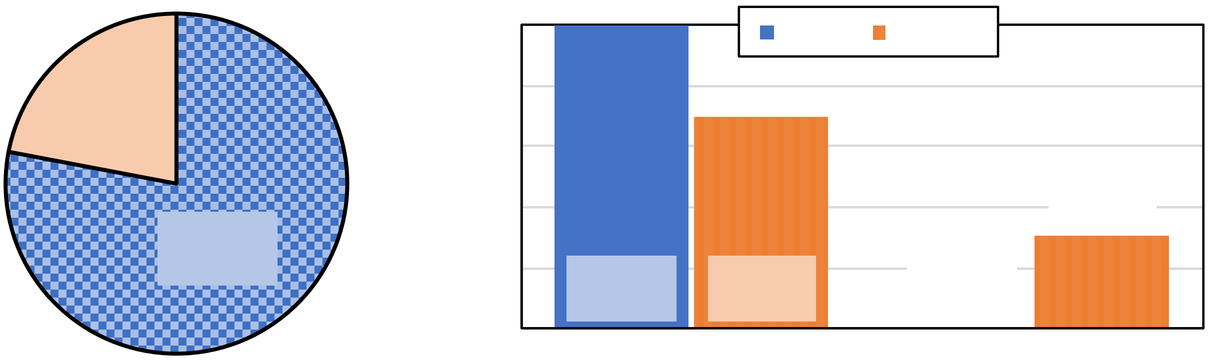


Figure 32. (a) Overall and (b) Agency and Industry Issues with Indirect Tensile at High Temperature Test.

Figure 33 shows that equal percentages of VDOT and the industry reported collecting unusual or unexpected data from the IDT-HT test. The unusual or unexpected data included inconsistent or variable results, an unusually large range of results, and a lack of correlation with APA results.

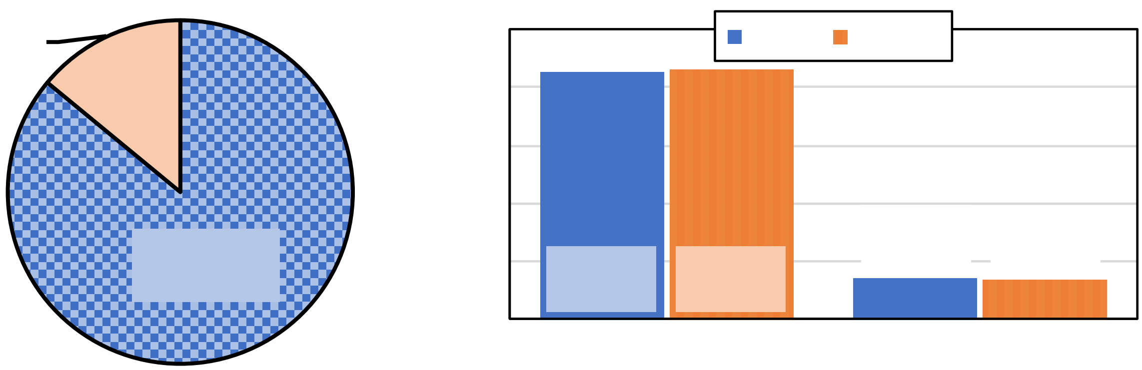


Figure 33. (a) Overall and (b) Agency and Industry Unusual or Unexpected Data from the Indirect Tensile at High Temperature Test.

Respondents were asked for tips on running the IDT-HT test. These tips were varied and are summarized as follows:

- Just as for ICT-CT specimen fabrication, be consistent in sampling, splitting, fabricating specimens, and conditioning specimens.
- Temperature is critical.

Final Thoughts

When asked what went well with BMD during the 2024 paving season, VDOT respondents believed that the paving season had been fairly smooth and that most labs had adapted and figured out how to handle the testing workload. They believed that communication between VDOT and the industry was a key factor and had been very good. The VDOT respondents also thought that producer test submissions had been entered in a timely manner, which was helpful.

Industry respondents also believed that the paving season went well, with good communication and improved consistency in test results. Respondents were happy that VDOT fabricated their own specimens for testing (a change from BMD trials in previous years), which reduced the industry workload. A positive sense regarding being able to pass tests and gaining a greater understanding of mixtures existed. Several industry respondents reported getting improved density results. One respondent noted that the testing allowed them to catch more than one instance of subpar binder or RAP that otherwise would have been missed.

Respondents were also asked what did not go well. VDOT responses included difficulty with the administration of nonmaintenance contracts and necessary work orders for plants producing only BMD mixtures to be able to sell mixtures for other uses. In some cases, getting results back on time was difficult. Some respondents reported difficulty with the consistency of results. In addition, some VDOT respondents were concerned that the relationship between the IDT-HT test and APA is not understood.

Industry responses included that the testing required a lot of additional work and time, and that too much additional testing is performed. Respondents believed that designs took an excessive amount of time. Reporting results presented some challenges. Respondents were frustrated with some of the sample quantities requested by VDOT and with VDOT or consultant personnel being unable to lift samples and requiring assistance. One respondent pointed out that the limitations on additives and continued volumetric restrictions hinder the producer's ability to provide optimally performing and truly balanced mixtures.

When asked about what is missing from BMD, VDOT respondents indicated that an understanding of how the results impact roadway performance is missing, and an understanding of the binder source impact on performance test results is also missing. Respondents would like to see a reduced testing frequency and are concerned with the time required for testing relative to the production quantities of material being paved.

The industry responded that correlations between BMD and volumetrics are missing. Additionally, respondents are concerned that sufficient movement toward end-result type specifications is lacking, and that continued restrictions on volumetrics and additives are stifling innovation.

Summary of Findings

- Collecting information was a challenge because information is kept in disparate locations in different agency divisions and requires cooperative efforts to access.

2024 Balanced Mix Design Contract Review

- The BMD type A mixture price stayed steady from 2023 to 2024, suggesting that mixture design adjustments to meet the BMD requirements did not greatly increase cost. Type D BMD mixtures showed an increase in 2024 bid prices compared with 2023 type D BMD prices.

BMD Mixture Comparison to Previous Superpave Mixtures

- Comparison of 68 BMD JMFs to corresponding 2023 Superpave mixtures indicated that about one-third of mixtures showed a 0.1% higher asphalt content in production. In contrast, only three JMFs had a noticeable decrease in production asphalt content.

- Both 12.5 and 9.5 type A mixtures show an average increase in VTM when moving to BMD, whereas type D mixtures show an average decrease in VTM. This activity could stem from the type D mixtures requiring performance testing in production and the need to maintain lower air voids to meet IDT-CT requirements.

- Average VFA values from the 2023 and 2024 production data indicated that VFA is increasing, especially for the 12.5 mixtures, where the values are closer to the upper end of the specification, and the 75th percentile is approaching the production limit.

- Production asphalt contents showed a general increase across the progression from 65-gyration design to 50-gyration design to implementation of BMD design. The 50-gyration mixtures had approximately a 0.1% higher asphalt content than the previous 65-gyration Superpave mixtures. The BMD mixture designs have about a 0.1% increase from the 50-gyration designs. The increase is more notable for the SM-12.5 mixtures, as the 50-gyration and BMD SM-9.5 mixtures showed similar asphalt contents in 2024.

Balanced Mix Design Performance Testing Results

- Cantabro mass loss showed nearly all samples passed the 7.5% specification criterion. A couple of samples that failed that criterion were identified as having testing equipment issues with improper revolutions per minute. The producer results showed slightly lower values by about 0.5% overall, but the results correspond more closely for values at 6% mass loss and higher.

- Relatively few IDT-CT samples had results below the production thresholds. Less than 5% of producer results did not meet the reheat criteria of 70 or the nonreheat criteria of 95. Producer IDT-CT results were slightly higher, by about five units, than the VDOT results.

- The 2024 IDT-CT reheat results show that mixtures consistently outperform the test threshold of 70, which was selected from the average IDT-CT results of 50-gyration trial mixtures (Bowers and Diefenderfer, 2018).

- The 2024 production median nonreheat values are closer to 125, showing significant improvement after the performance tests are included in mixture design and production.

- Excel-submitted data showed that two-thirds of producer samples were designated as reheat samples. Although results submitted through MITS/PLAID did not indicate whether testing was conducted as reheat or nonreheat, they did match the reheat results line fairly closely and are presumably a majority of reheat samples.

- IDT-HT results indicated that approximately 20% of producer samples and 10% of VDOT samples were below the minimum 100 kPa threshold. The test information was reported but not enforced for 2024.

- VDOT results showed better values overall on the IDT-HT result by about 10 kPa than the producer results showed. These observations could be due to the IDT-HT test being relatively new, with laboratories having less experience with the test.

Field Density Comparison

- The distributions for the 2023 Superpave data and 2024 BMD data show no difference in density, with the average lot density for both years being 94%.

Survey

General Experience with Balanced Mix Design

- A majority of industry and agency respondents believed that BMD is improving mixtures. The most common reason was an increase in binder content.

- In 2024, the most popular design changes included increasing binder and decreasing voids. Increasing binder remains the most popular change to designs anticipated for 2025.

- Approximately one-half of respondents believe that BMD drives changes that are not economically feasible, with the primary concerns being additional asphalt content and costs incurred by manpower and hours required for further testing.

- Those respondents who did not think that BMD changes were economically impractical note that mixtures have not changed enough to introduce significant costs. It was pointed out that economic feasibility is interrelated with specification requirements, such that what is economically feasible will adjust to meet what is required by the specification.

- Some respondents were concerned that BMD is not improving mixtures during production, due to minimal changes in mixtures and material variability; however, more consistent test results, improved field density and ease in achieving density, and increased binder contents were cited as improvements.

- Numerous factors exist, aside from binder content and gradation, which may impact test results during production. These factors include plant temperature, silo dwell time, changes in RAP source, binder quality, RAP binder quality, aggregate quality, and laboratory material handling practices.

- The most common changes to laboratory operations to keep up with BMD testing were the purchase of additional test equipment and ovens, and increased staffing.

- A majority of respondents believed that the 2024 testing frequency was too high.

- Approximately one-half of respondents believe that volumetric properties and BMD results are related. Although numerous examples of relationships exist, a lack of consistency has limited confidence in relationships.

- A majority of respondents favored eliminating some volumetric properties, with VFA and fines to asphalt ratio being the most popularly cited.

- Seventy percent of respondents indicated that the 2024 test frequency was acceptable if some volumetric properties were dropped.

Cantabro Test

- A majority of respondents indicated that the Cantabro test is not an effective test, because it rarely has failing results, does not translate to practical conditions, and is not clear on what is represented in terms of traffic conditions.

- Cantabro testing presented few issues. These issues included the test machine not meeting specifications, temperature-related problems, and difficulties matching test results from equipment produced by different manufacturers.

- Tips on successfully running the Cantabro test included using proper and consistent sampling practices, drying back pills in accordance with the specification, and following temperature requirements.

Indirect Tensile Cracking Test

- More than three-quarters of respondents believed that the IDT-CT has been an effective BMD test.

- The IDT-CT is liked because of its simplicity and relationship with cracking and mixture performance. The test is disliked because of the required number of test specimens, difficulties in fabricating specimens, and inconsistent test results.

- One-third of respondents have had issues with the IDT-CT due to equipment issues, variability in results, and the test's sensitivity to inconsistent specimen fabrication practices.

Twenty percent of respondents saw unusual or unexpected data, such as identical specimens with varied results, unexpected random outliers, and increased variability.

- Tips on successfully running the IDT-CT included being consistent in sampling, splitting, fabricating specimens, and conditioning specimens; using Gmm values from the sample to improve accuracy in hitting air void targets; not allowing material to remain in the oven for too long, and understanding that temperature at all stages is critical.

Indirect Tensile at High Temperature

- More than 60% of respondents do not believe that the IDT-HT test has been effective as a BMD test. This response appears to be due to not seeing a correlation or relationship between the IDT-HT and APA tests and not being clear on how the test is meaningful or relates to the field.

- Twenty percent of respondents had issues running the test, such as highly variable results, difficulties meeting the criteria, and inconsistent failures that made no sense.

- Tips on successfully running the IDT-HT test included being consistent in sampling, splitting, fabricating specimens, and conditioning specimens, and being aware that temperature is critical.

Final Thoughts

- Overall, both industry and VDOT respondents believed that the 2024 paving season went well. It was agreed that communication was key and had been very good overall. A positive sense regarding being able to pass tests and gaining a greater understanding of mixtures was present.

- VDOT responses indicated that a few aspects had been challenging, such as the administration of nonmaintenance contracts and necessary work orders, such that plants producing only BMD mixtures could be able to sell mixtures for other uses, getting results back on time, and difficulty with consistency of results.

- Challenges for industry respondents included the time and work required for testing, the time required for designs, difficulties in reporting results, and frustration with large sample quantities.

- BMD still lacks an understanding of how test results impact road performance and how binder source impacts test results. In addition, correlations between BMD tests and volumetric properties are needed. Concerns exist with the time required for testing relative to production quantities of material being paved. There are also concerns that movement toward an end-result type specification has stalled, and that continued restriction on volumetrics and additives is stifling innovation.

CONCLUSIONS

- *Collecting project information was challenging because it was kept in disparate locations within different divisions.* Matching the specific job mix, plant lot, and field lot with the paving location was not possible across all 2024 resurfacing schedules.

- *BMD mixtures showed slightly higher asphalt content than previous Superpave designs.*

- *BMD type D mixtures showed lower production air voids.* The production performance tests of type D mixtures may have encouraged producers to tighten mixtures to meet BMD requirements.

- *VFA values, especially for SM-12.5 mixtures, have been increasing toward the upper production limit as mixture designs evolve to meet BMD cracking requirements.* The increase has not been accompanied by any increase in rutting susceptibility as measured by BMD test results, indicating that it should be reviewed further for possible adjustment.

- *VDOT and producer performance results distribution align well for Cantabro and IDT-CT. VDOT showed better results overall for IDT-HT testing, and more producer labs indicated an issue with the IDT-HT test. Survey results supported the performance data, with agency and industry respondents indicating that Cantabro and IDT-CT testing went well, and the IDT-HT test was more challenging to achieve passing test results and agreement between VDOT and producer results.* 2024 was the first year of reporting IDT-HT results during production.

- *Few samples failed the Cantabro mass loss test. Accordingly, survey responses indicated that respondents thought the Cantabro may be an ineffective test and it should be reviewed in relation to other performance and volumetric properties.*

- *IDT-CT results were largely higher than the threshold limits, indicating that mixtures have improved in crack resistance compared with initial benchmarking from 50-gyration mixtures and can achieve the 100+ values suggested in other research for good performance. The survey results support that the IDT-CT performance test effectively drives mixture adjustments due to its simplicity and relationship with cracking and mixture performance.*

- *Continued training and sharing of information about IDT-HT testing are needed to counteract perceptions that the test is not effective.* Survey results indicate that the perception is due to not seeing the correlation or relationship between the IDT-HT and APA tests, and not being clear on how the IDT-HT test is meaningful or how it relates to field conditions and performance. As noted above, 2024 was the first year reporting IDT-HT results during production.

- *BMD mixtures showed no overall change in field density based on statewide averages; however, survey responses indicated that some respondents experienced improvements in density or required less compactive effort to reach density.* The difference in these results may be due to the reported field density data evaluated in this report being expressed as averages.

- *The 2024 paving season successfully implemented BMD into VDOT specifications.* Both agency and industry expressed positive impressions of the experience. Communication was a key aspect of success.

- *Based on survey results, BMD still faces challenges such as the time and effort required for testing and the processes required for consistent test results. Concerns with testing frequency, time required for testing relative to production quantities, and acceptance still need to be addressed.*

- *The survey results show continuing needs for understanding how BMD test results relate to roadway performance, how binder source impacts test results, and the correlations between BMD tests and volumetric properties.*

RECOMMENDATIONS

1. *Materials Division should consider increasing the IDT-CT production threshold, allowing reduced frequency of production performance testing, and adjusting VFA requirements for BMD.*

2. *Materials Division should continue to support IDT-HT BMD testing through training and additional evaluation to better align VDOT and producer results because it is a relatively new test.* Performance data and survey responses indicated that there have been challenges in meeting the IDT-HT criterion by producers and in agreement between VDOT and producer labs.

3. *VDOT should pursue better alignment of data sources and systems to compile data more easily.* Data related to asphalt pavement materials are found in a number of disparate locations, making it challenging to collect and compile data on field locations, materials, and performance to make fully informed maintenance decisions, provide continued monitoring, and perform future evaluations.

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 process 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

Regarding Recommendation 1, the Materials Division has already implemented the recommended changes of CT index production value, alternate production test frequency, and reports only the VFA value in the BMD special provision dated April 21, 2025. This special provision will be included in the 2026 maintenance resurfacing contracts.

Regarding Recommendation 2, the Materials Division will encourage the Virginia Asphalt Association and the Virginia Education Center for Asphalt Technologies to continue providing information and training for the IDT-HT test into future Asphalt Plant and Mix Design certification courses by updating the certification exams and proficiency evaluations to incorporate this information. This effort will be verified when exam questions are updated by November 1, 2026. VTRC will continue ongoing research into verifying the IDT-HT performance criterion through UPC 127210, which is expected to be complete in September 2026.

Regarding Recommendation 3, within one year of publication of this report, the Materials Division will develop a need or business case to link specific data systems to effectively analyze the health of the program.

Benefits

The primary benefits of this study were to document the implementation of BMD, summarize the lessons learned, and identify needs for future changes. This activity provides the Materials Division with baseline information regarding BMD that will be useful for future comparisons to assess the success of the initiative and provide supporting data for ongoing changes to specifications and procedures.

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APPENDIX A: 2024 SPECIFICATION

SQ315-000200-24

VIRGINIA DEPARTMENT OF TRANSPORTATION
SPECIAL PROVISION FOR
BALANCED MIX DESIGN (BMD) SURFACE MIXTURES DESIGNED USING PERFORMANCE CRITERIA

April 24, 2023

I. Description

This Specification covers the requirements and materials used to produce surface mixtures designed using performance criteria. Balanced Mix Design (BMD) surface mixtures shall be designed, produced, and placed as required by this Special Provision and Sections 211 and 315 of the Specifications.

II. Materials

All materials shall conform to Section 211.02 of the Specifications with the exception that recycled asphalt shingles (RAS) will not be allowed in these mixes.

III. Job-Mix Formula (JMF)

Mix Types SM-9.5A, SM-9.5D, SM-12.5A, and SM-12.5D shall be designed to meet the performance + volumetric optimized (BMD P+VO) criteria included in this section. Each mix type used shall conform to Section 211 of the Specifications. The Contractor shall submit the mix design at least two weeks before the mix is produced. Approval from the Engineer is required if the Contractor uses a binder with a PG grade not recommended by Table II-14A of Section 211 of the Specifications.

Type Performance + Volumetric Optimized (BMD P+VO) asphalt mixtures shall be designed to conform to Section 211.03 of the Specifications as well as Table 1 herein, except that the following table shall replace Table II-13 in Section 211.03 of the Specifications:

Asphalt Concrete Mixtures: Design Range

Mix Type	Percentage by Weight Passing Square Mesh Sieves							
	3/4 in	1/2 in	3/8 in	No. 4	No. 8	No. 30	No. 50	No. 200
SM-9.5 A,D		100[1]	90-100	90 max.	32-67			2-10
SM-12.5 A,D	100	90-100	90 max.		28-58			2-10

The design binder content shall be selected within a range of 3.0% --4.5% air voids.

This mix shall conform to Table 1 at the design binder content.

The results of supplementary performance testing at different binder contents (informational purposes) in addition to the design binder content shall be reported as follows:

1. Asphalt pavement analyzer (APA) rut testing (VTM-142): at design binder content and at 0.5% above the design binder content
2. Indirect tensile test at high temperature (IDT-HT)(VTM-145): at design binder content and at 0.5% above the design binder content
3. Cantabro testing (VTM-144): at design binder content and at 0.5% below the design binder content
4. Indirect tensile cracking test at intermediate temperature (IDT-CT) (VTM-143): at design binder content, at 0.5% above, and at 0.5% below the design binder content

The minimum design asphalt binder contents shall be based on the following unless otherwise approved by the Engineer:

Bulk Specific Gravity of the Total Aggregate	**Minimum Design Binder Content Mix Type (%)**	
	SM-9.5	**SM-12.5**
Less Than 2.65	5.5	5.3
2.65 - 2.74	5.4	5.2
2.74 - 2.85	5.3	5.1
Greater Than 2.85	5.2	5.0

For the BMD P+VO mixtures, a set of five IDT-CT pills with the final design JMF (only at the design binder content) shall be fabricated from long-term aged loose mix and tested in accordance with ASTM D8225. Test results shall be submitted with the JMF for the mix design review. Long-term aging shall be performed by aging loose laboratory produced mix for 8 hours at 135ºC, after short term oven aging is performed as required by Table 1. During long-term aging, the mix shall be uniformly placed in a pan such that the height of the loose mix shall not exceed the mixture nominal max aggregate size. Opening of the oven door shall be minimized during long-term aging. Specimens shall be heated to compaction temperature following aging and then compacted. The heating to compaction temperature shall not exceed 75 minutes.

The JMF shall meet the nominal max aggregate size of the designated mix type. The JMF shall establish a single percentage of aggregate passing each required sieve, a single percentage of binder to be added to the mix, the Superpave volumetric properties defined by AASHTO R 35 and a temperature range at which the mixture is to be produced.

The Contractor shall have a Department-certified Asphalt Mix Design Technician with the BMD training certification approved by the Department for designing and adjusting mixes. The Asphalt Mix Design Technician or an Asphalt Plant Level II Technician with the BMD training certification approved by the Department shall be capable of conducting necessary performance tests. The Asphalt Mix Design Technician shall be responsible for producing a mixture that complies with the requirements of this Specification.

Table 1. Performance Testing Requirements for Mix Design

Performance Property	Performance Test	Test Method	Criteria
Rutting	APA Rut depth	VTM-142	≤ 8.0mm
	IDT-HT	VTM-145	Strength ≥ 100 kPa
Durability	Cantabro Mass Loss	VTM-144	Mass loss ≤ 7.5%
Cracking	IDT-CT	VTM-143	$CT_{index} \geq 70$ COV ≤ 18.3%[1]

[1] Single operator testing tolerance: Coefficient of Variance (COV) shall be applied for the mix design IDT-CT test for all short-term aged specimens. For the long-term aged specimen test during design the COV shall be reported only for informational purposes.

The JMF shall indicate which type of specimen preparation will be used during production for Indirect Tensile Cracking Test at intermediate temperature (IDT-CT) testing for the mix: non-reheat or reheated mixture. Throughout the production of the approved JMF, the indicated method shall be followed for every IDT-CT sample, unless otherwise approved by the Engineer.

IV. Production Testing

Lot sizes defined by Sections 211 and 315 of the Specifications shall be followed for all production testing.

The Contractor shall conduct testing as required by Sections 211.05 and 211.06 of the Specifications for both A and D designated mixes. If less than 300 tons of asphalt mixture is produced under a single JMF in a day, Superpave testing will not be required on that day. That day's tonnage shall be added to subsequent production. When the accumulated tonnage exceeds 300 tons, minimum testing frequency for Superpave testing shall apply and results shall be reported.

In addition to all of the testing requirements for Superpave mixes, performance testing shall also be conducted on D designated mixes by the Contractor, in accordance with Table 2 and at the frequency shown in Table 3. The Contractor shall report BMD performance test results within 48 hrs of sampling to the Department unless otherwise approved by the appropriate District Materials Engineer.

The approved asphalt concrete mixture shall also produce a tensile strength ratio (TSR) of not less than 0.80 in accordance with Section 211 of the Specification and as verified by the Contractor during the first lot of production.

Table 2. Performance Testing Requirements for Production

Performance Property	Performance Test	Test Method	Criteria
Rutting	APA Rut depth[1]	VTM-142	≤ 8.0mm
	IDT-HT	VTM-145	Report only COV report only
Durability	Cantabro Mass Loss	VTM-144	Mass loss ≤ 7.5%
Cracking	IDT-CT	VTM-143	CT_{index}[2] ≥ 70, reheated CT_{index}[2] ≥ 95, non-reheated COV report only

APA Rut will be performed during production by VDOT with specimens made by the Contractor at the request of the Engineer.
IDT-CT specimens shall be prepared (reheat or non-reheat) in accordance with the method indicated on the JMF and VTM-143.

Table 3. Performance Testing Frequency

Property/Test	Frequency (tons)
IDT-CT	2,000
Cantabro Mass Loss	2,000
IDT-HT[1]	4,000
APA Rut depth	As requested by Engineer[2]

IDT-HT shall be performed on the same sample as IDT-CT.
APA test will be performed by VDOT, however, specimens shall be made by the Contractor at the request of the Engineer.

V. Acceptance

Lot acceptance for BMD P+VO shall be as required by Section 211.08 of the Specifications.

Although acceptance will be based on Section 211, should any performance test results (based on the average of required number of specimens tested) fail to meet the criteria as specified in Table 2, the Department may require that production be stopped until corrective actions are taken by the Contractor. The Engineer will investigate and determine the acceptability of material placed and represented by failing performance test results.

Field density shall be determined in accordance with Section 315 of the Specifications.

VI. Adjustment System

The Department will determine adjustment points in accordance with Section 211.09 of the Specifications except for the following:

1. If the total adjustment is 25 points or less and the Contractor does not elect to remove and replace the material, the unit price for the material will be reduced 3% of the unit price bid for each adjustment point the material is outside of the process tolerance.
2. The Engineer will reduce the unit bid price by 1.0 % for each adjustment point applied for standard deviation.

3. The Engineer will increase the unit bid price by 5% if the following criteria are met: 1) the standard deviation of the binder content is within the ranges of 0.0 – 0.15; 2) there are no adjustment points assigned for any sieve sizes as noted in Table II-16; and 3) the average binder content is no less than 0.10% below and no more than 0.20% above the approved mix design binder content.

VII. Initial Production

Mix type BMD P+VO shall be subject to Section 211.15 of the Specifications at the Engineer's discretion.

VIII. Measurement and Payment

Asphalt Concrete BMD P+VO will be measured in tons and will be paid for at the Contract ton price. Net weight information shall be furnished with each load of material delivered in accordance with Section 211 of the Specifications. Batch weights will not be permitted as a method of measurement unless the Contractor's plant is equipped in accordance with Section 211 of the Specifications, in which case the cumulative weight of the batches will be used for payment. This price shall include all labor, equipment, and materials necessary to furnish, install, and finish the work described herein.

Payment will be made under:

Pay Item	Pay Unit
Asphalt Concrete BMD P+VO (mix type)	Ton

APPENDIX B: 2024 BALANCED MIX DESIGN (BMD) SURVEY

Section 1—Respondent Information

1. Do you work for:
   a. VDOT
   b. Industry

2. What District(s) do you work in?
   a. Bristol
   b. Culpeper
   c. Fredericksburg
   d. Hampton Roads
   e. Lynchburg
   f. Northern Virginia
   g. Richmond
   h. Salem
   i. Staunton

Section 2—General BMD Questions

3. Do you think BMD is helping to improve mixes during design?
   1. Yes
   2. No
      i. Why or why not?
      ii. If yes—What improvements have you seen?

4. Were any changes made to existing Superpave mix designs to meet 2024 BMD requirements?
   a. Yes
   b. No
      i. If yes—What changes were made?
         - Gradation finer
         - Gradation coarser
         - Increase AC
         - Decrease AC
         - Increase VMA
         - Decrease VMA
         - Decrease voids
         - Increase voids
         - Softer binder, e.g. 58-28
         - Other

5. Do you anticipate making changes to your BMD mix designs for the 2025 paving season?
   - o Yes
   - o No

i. If yes—What changes do you anticipate?
   - Gradation finer
   - Gradation coarser
   - Increase AC
   - Decrease AC
   - Increase VMA
   - Decrease VMA
   - Increase voids
   - Decrease voids
   - Increase RAP content
   - Decrease RAP content
   - Use softer binder (e.g. PG 58-28)

ii. Other

6. Is BMD driving changes to mix designs that would otherwise not be economically feasible?
   - o Yes
   - o No

7. What is your preferred method of adjustment to a mix to meet BMD criteria:
   - o Structure/gradation change
   - o Binder grade change
   - o Binder content change
   - o Additive use
   - o RAP content change
   - o Other

8. Do you think BMD is helping to improve mixes during production?
   - o Yes
   - o No
   - o Why or why not?

   i. If yes—What improvements have you seen?

9. Are you finding factors other than asphalt content and gradation changes that are impacting your BMD results during production?
   a. Plant temperatures
   b. Silo dwell time
   c. Changes in RAP source, primary versus secondary versus interstate milling
   d. Other

10. What changes in operations has your lab made to keep up with BMD testing?
    a. Increased staffing
    b. Additional ovens
    c. Additional test equipment
    d. Reheating IDT-CT instead of making specimens at sampling
    e. Slower production rates
    f. Other

11. Do you think the BMD production test frequency is:
    a. Too frequent
    b. Just right
    c. Not frequent enough
    d. Why?

12. How did you see the field density change with the BMD mix compared with a Superpave mix in previous paving seasons?
    a. Decreased density
    b. More compactive effort required to reach maximum density
    c. More variability in density
    d. No change
    e. Less variability in density
    f. Less compactive effort required to reach maximum density
    g. Increased density
    h. Other

13. Do you think that BMD test results are relating to volumetric properties?
    a. Yes
    b. No
    c. Why or why not?

14. Should some volumetric properties be dropped from acceptance testing?
    a. Yes
    b. No
        i. If yes—Which properties should be dropped?
            - AC content
            - Gradation
            - Air voids
            - VMA
            - VFA
            - FA Ratio
        ii. Why or why not?

15. If some volumetric properties are dropped from acceptance testing, is the current frequency of BMD testing enough to identify issues in a timely manner?
    a. Yes
    b. No
    c. Why or why not?

16. What do you think has gone well with BMD during the 2024 paving season?

17. What do you think has not gone well with BMD during the 2024 paving season?

18. What is missing from BMD?

Section 3—Cantabro Test

19. Do you think the Cantabro test has been effective as a BMD test?
    - Yes
    - No

20. What do you like about the Cantabro test?

21. What do you dislike about the Cantabro test?

22. Have you had any issues with Cantabro testing?
    - Yes
    - No
        i. Please explain.

23. What are your most helpful tips about Cantabro specimen fabrication and testing?

24. Have you seen anything unusual or unexpected with Cantabro data?
    - Yes
    - No
        i. Please explain.

Section 4—IDT-CT

25. Do you think the IDT-CT has been effective as a BMD test?
    - Yes
    - No

26. What do you like about the IDT-CT?

27. What do you dislike about the IDT-CT?

28. Have you had any issues with IDT-CT testing?
    - Yes

- No
    i. Please explain.

29. What are your most helpful tips about IDT-CT specimen fabrication and testing?

30. Have you seen anything unusual or unexpected with IDT-CT data?
    - Yes
    - No
        i. Please explain.

Section 5—IDT-HT

31. Do you think the IDT-HT has been effective as a BMD test?
    - Yes
    - No

32. What do you like about the IDT-HT?

33. What do you dislike about the IDT-HT?

34. Have you had any issues with IDT-HT testing?
    - Yes
    - No
        i. Please explain.

35. What are your most helpful tips about IDT-HT specimen fabrication and testing?

36. Have you seen anything unusual or unexpected with IDT-HT data?
    - Yes
    - No
        i. Please explain.

Section 6—Final Thoughts

37. Please share any other thoughts about BMD and the 2024 paving season.

38. Would you be willing to talk further with us about your experiences with BMD in 2024? If so, please enter your name and contact info below. All responses are confidential and will not be associated with any identifying information when survey results are shared.

APPENDIX C: BALANCED MIX DESIGN DEVELOPMENT IN VIRGINIA

Marshall and Superpave Design

Asphalt researchers have worked for decades to improve the durability of asphalt mixtures. In the past, asphalt mixtures have alternated between cycles of being rut-prone and crack-prone. In the 1980s, surface and intermediate layer traditional 50-blow Marshall mixtures experienced premature rutting and flushing. The Virginia Department of Transportation (VDOT) began designing 75-blow Marshall mixtures to address this condition for moderate to heavy traffic routes. These mixtures were highly rut-resistant and did not flush; however, the increased compaction effort reduced the asphalt content and caused durability issues, primarily cracking and raveling (Maupin, Jr., 1991). Efforts continued throughout the 1990s to address durability issues through mixture design changes.

In 1997, VDOT adopted performance grade (PG) binders (Prowell, 1999) and consideration of Superpave mixtures began, with VDOT adopting Superpave in 2000. Within a couple of years, VDOT had begun to look at reducing design gyrations to try to incorporate more asphalt into mixtures, already recognizing that, although the Superpave mixtures were highly rut-resistant, durability continued to be an issue. Maupin, Jr. (2003) evaluated several surface mixtures and the changes in properties when 0.5% and 1.0% additional binder was added. The asphalt content of most of the mixtures could be increased by 0.5% with no detrimental effects. This scenario supported the Department's reduction in design gyrations from 75 to 65 for all dense-graded surface mixtures in 2002.

In the mid-2000s, material cost escalation resulted in a significant increase in the cost of asphalt mixtures. This increase resulted in greater interest in the use of reclaimed asphalt pavement (RAP) in mixtures. At that time, VDOT allowed up to 20% RAP in nonpolymer-modified dense-graded surface mixtures before virgin binder grades had to be adjusted. This percentage had been adopted as a compromise between the 15% RAP limit in the national Superpave specifications (McDaniel et al., 2000) and previous VDOT specifications allowing up to 25% RAP (VDOT, 1996). To address the cost issues, a joint committee of asphalt industry representatives and staff from VDOT's Asset Management Division decided to increase the allowable percentage of RAP for mixtures on specific maintenance overlay schedules from 20% to 30%. Initial laboratory evaluation indicated that these mixtures had no significant differences from 20% RAP control mixtures for fatigue, rutting, and moisture susceptibility, and no issues were seen during construction (Maupin, Jr. et al., 2008). The increase in allowable RAP content was incorporated in the specifications the following year.

Unfortunately, reports of durability issues with Superpave mixtures continued. Additional work conducted by Maupin, Jr. (2010) sought to compare 9.5 mm Superpave mixtures and mixtures produced prior to the adoption of Superpave to determine if asphalt contents had significantly reduced. No significant differences were found, although gradation differences may have affected results. To further look at asphalt content, several mixtures were evaluated in the laboratory to see if additional asphalt could be incorporated without detrimental results; the results from this effort were mixed, with some mixtures being improved, while the performance of others worsened. The report recommended further evaluation of 12.5 mm Superpave mixtures to allow for the evaluation of the differences in production gradations seen in the pre-Superpave mixtures.

Around this time, an industry-VDOT collaborative group called the Asphalt Quality Task Force was assembled. The group's purpose was to consider ongoing concerns about mixture durability and quality that could be addressed relatively quickly and easily. Durability was a priority, and several efforts originated from the group.

Moving to 50-Gyrations

Additional work related to incorporating RAP contents higher than 30% contributed valuable information to the efforts to improve durability. Boriack et al. (2014) investigated the effect of added binder content on plant mixtures containing 0%, 20%, 40%, and 100% RAP on stiffness, fatigue resistance, and rutting resistance. The results indicated that 0.5% binder could be added to the 0% and 20% RAP mixtures, improving the laboratory fatigue and rutting resistance; however, the mixture did not meet VDOT volumetric requirements, and effects on compaction in the field could not be determined.

Continued work with RAP mixtures resulted in a change to section 6C of Virgina Test Method (VTM) 102 *Determination of Asphalt Content from Asphalt Paving Mixtures by the Ignition Method* (VDOT, 2025). The change consisted of adding a default RAP correction factor to be used during ignition furnace testing of RAP asphalt content.

Additional efforts commenced to address durability through collaborative work with VDOT and the industry in 2014 (unpublished data). The first phase of the work sampled production mixtures and evaluated the differences in volumetric results for 50- and 65-gyration pills and 50- and 75-blow Marshall pills. Results indicated that the gyratory compactor produced pills with approximately 2% lower air voids and 1–2% lower voids in mineral aggregate than those of Marshall hammer-produced pills.

The next phase of the work focused on plant-produced 9.5 mm surface mixtures with gradations having ≤ 23% passing the #30 sieve and ≥ 58% passing the #4 sieve (Katicha and Flintsch, 2016). The asphalt content, gradation, and volumetric properties of the mixtures were determined; a second set of the mixtures was developed to determine optimum asphalt content for 3.5% air voids at 50 gyrations. Additional binder contents (+0.2% and +0.4% higher than optimum) along with the initial mixture and optimized mixture were assessed for performance. The laboratory results led to the proposal of a field study to evaluate specification changes that would reduce design gyrations from 65 to 50 and change requirements on the #4, #8, and #30 sieves.

Demonstration projects to evaluate the proposed specification were paved during 2015 (Diefenderfer et al., 2018). Eleven contractors with plant mixture maintenance schedules paved control and experimental sections consisting of a typical 65-gyration mixture and a 50-gyration experimental mixture, respectively. The mixtures consisted of 9.5 mm and 12.5 mm surface mixtures with PG 64-22 binders, with one mixture containing a PG 76-22 binder. Loose mixture samples were collected along with road cores and density data during production. Mixture volumetric properties, gradation, and permeability were measured. The changes in mixture design requirements were found to have little impact on volumetric properties or gradation, except for a general reduction in core air voids. Permeability impacts were mixed, because 9.5 mm mixtures required greater compaction to meet permeability requirements, and 12.5 mm mixtures showed less permeability even at high air void contents. These results encouraged VDOT to adopt the proposed specification change, which began in 2016.

Asphalt Mixture Design Task Force

In March of 2016, the Materials Division initiated the Asphalt Mixture Design Task Force with support from the Virginia Transportation Research Council (VTRC) (Bowers and Kim, 2017). The task force was formed to evaluate VDOT asphalt mixture design procedures and identify means to enhance and improve mixture designs in the future. Two primary tasks were set for the group:

- Benchmark current key asphalt mixture attributes by collecting data relevant to the mixture modifications made in response to the 50-gyration and volumetric specification design changes during 2016.
- Collect information about national efforts to improve mixture design procedures to result in better field performance; recommend changes to VDOT design procedures, specifications, and field quality assurance methods; and pilot the proposed changes strategically to determine benefits before widespread application.

The task force was comprised of 13 members from VDOT, VTRC, Federal Highway Administration, and industry and met five times between May 2016 and June 2017. The group invited guest speakers to present on balanced mix design (BMD), Superpave 5 design, Michigan Regression Method design, and information from the ongoing National Center for Asphalt Technology (NCAT) cracking study (West et al., 2019). In addition, VTRC research data on the 2015 50-gyration mixtures were considered along with 2016 production data. The group concluded that changing the current mixture specifications for SM-9.5 and SM-12.5 mixtures was not needed, although additional work may need to be pursued in the future. The group also decided that the balanced mixture design method may be a good candidate for consideration in future mixture design procedures. Consequently, work was planned to begin benchmarking current mixtures within the BMD framework.

Initial Specification Development

In October 2017, VTRC began the evaluation of various test methods for inclusion in a BMD specification (Bowers and Diefenderfer, 2018). The effort intended to select performance-related tests to support BMD, select initial design criteria, and develop a draft specification that could be applied to mixtures having RAP contents greater than 30% such that their performance was expected to be equal to or greater than comparable mixtures being produced at the time. The draft specification was intended for application to high RAP (HRAP) pilot projects expected to occur during the 2018 and 2019 paving seasons. The study used 11 plant mixture samples collected in 2015 from evaluating the 50-gyration design change due to time constraints. The study considered a durability test, a rut susceptibility test, and four cracking tests.

Durability

The Cantabro test (AASHTO TP 108) was proposed as a simple test for durability. The test received attention due to work by Cox et al. (2017) and was included in testing for the NCAT cracking group experiment (West et al., 2019).

Rutting Susceptibility

VDOT had already implemented rut testing in the early 2000s in accordance with Virginia Test Method 110 (VDOT, 2025). However, it did not follow AASHTO T 340 for hose pressure and wheel load and gave a tighter tolerance for rutting (2016 Road and Bridge book, section 211.03). The evaluation of the asphalt pavement analyzer (APA) test was based on the same adjusted wheel load and hose pressure (120 pound-force and 120 psi), but increased the test temperature from 49 to 64 ºC to correspond to Virginia's base binder grade temperature to incorporate more sensitivity to the test. VDOT's BMD APA requirement was later adjusted to apply a hose pressure of 100 psi and wheel load of 100 pound-force, in accordance with AASHTO T 340.

Cracking Susceptibility

Four cracking tests were considered—the indirect tensile asphalt cracking test (or IDEAL-CT and referred to as IDT-CT in Virginia) (Zhou et al., 2017), the I-FIT test (Ozer et al., 2016), the Texas Overlay test (Texas DOT, n.d.), and the Nflex test (West et al., 2017).

Initial Specification

The final recommended tests were the Cantabro durability test, APA rut test, and IDT-CT. Table C1 presents the recommended test procedures, specimen requirements, and criteria. Unfortunately, due to a wet summer in 2018, the HRAP pilots were not placed.

Table C1. Recommended Test Procedures, Specimen Requirements, and Threshold Values for the Higher RAP Balanced Mix Design Specification (Bowers and Diefenderfer, 2018)

Test	Procedure	Specimens	Criteria
APA rutting (in accordance with AASHTO T340, except hose pressure and wheel load)	8,000 passes 64ºC 120 pounds, 120 psi	2 replicates of 2 pills (APA Jr) Gyratory pill: 150 mm dia., 75±2 mm height Compact to 7±0.5% air voids Lab-produced mix—subject loose mix to 2 hours STOA at the design compaction temperature prior to compacting [Note: Plant-mix shall not be reheated when producing APA specimens]	Rutting ≤ 8.0 mm
Cantabro	300 rotations 30–33 rotations/min	3 replicates Gyratory pill: 150 mm dia., 115±5 mm height Compact to Ndesign, report air voids	Mass loss ≤ 7.5%

Test	Procedure	Specimens	Criteria
		Lab-produced mix—subject loose mix to 2 hours STOA at the design compaction temperature prior to compacting	
CT index	• Condition specimens 25±1 °C for 2±0.5 hour • Apply contact load of 0.1±0.02 kN with loading rate of 0.05 kN/s • After contact reached, load using load-line displacement control at rate of 50 mm/min, record load to peak and through failure; analyze.	3 replicates Gyratory pill- 150 mm dia., 62±2 mm height Compact to 7±0.5% air voids Lab-produced mix—subject loose mix to 4 hours STOA at the design compaction temperature prior to compacting	CT index ≥ 70

AASHTO = American Association of State Highway and Transportation Officials; APA = asphalt pavement analyzer; CT = cracking tolerance; RAP = reclaimed asphalt pavement; STOA = short-term oven aging.

Balanced Mix Design Implementation

Implementation Timeline

In late 2017, as the initial work for a performance-related specification was in progress, the VDOT Materials Division determined that the potential benefits of implementing BMD were compelling and developed a general roadmap delineating the general strategy and timeline to achieve initial BMD implementation. Figure C1 shows this timeline, which guided the initial efforts and progress toward BMD implementation.

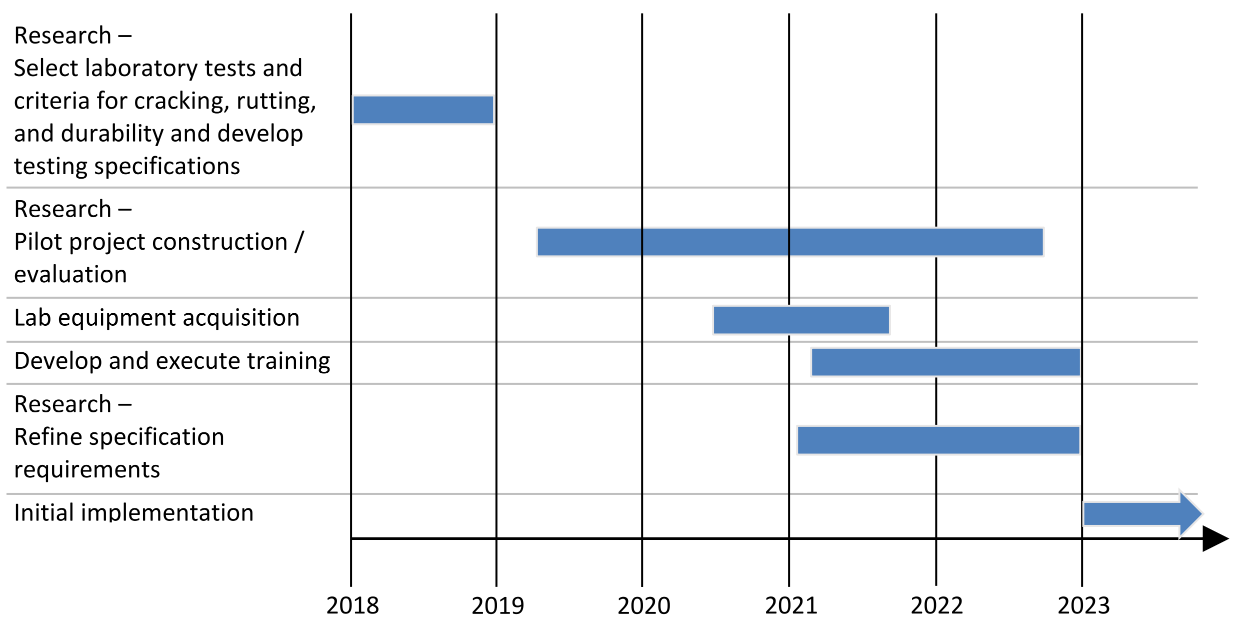

Figure C1. Timeline for Initial Implementation

Balanced Mix Design Technical and Advisory Committees

In December 2018, the BMD Technical Committee held its first meeting. The committee was created to provide a forum for VDOT and the industry to collaborate on BMD implementation. Table C2 shows the initial committee membership, which was comprised of 21 members from VDOT, VTRC, industry, Federal Highway Administration, and NCAT. An Executive Advisory Committee was created at the executive level to provide agency-wide guidance and oversight. Table C3 lists the initial committee members.

Table C2. Initial Membership of the Balanced Mix Design Technical Committee, December 2018

VDOT	VTRC	Industry
Sungho Kim (co-chair)	Kevin McGhee (co-chair)	David Bradeson
Angela Beyke	Iker Boz	Travis Cable
Rob Crandol	Stacey Diefenderfer	Mike Dudley
Doug McAvoy		David Lee
Todd Rorrer	**FHWA**	Derek Patterson
Tommy Schinkel	Vanna Lewis	Danny Poole
Sameer Shetty		Kevin Vaughn
	NCAT	Marty Wallace
	Nathan Moore	Dave Wyant

FHWA = Federal Highway Administration; NCAT = National Center for Asphalt Technology.

Table C3. Initial Membership of the Balanced Mix Design Executive Committee

VDOT	Industry
Rob Crandol, chair, Assistant State Materials Engineer Andy Babish, State Materials Engineer Kerry Bates, State Construction Engineer Sungho Kim, Asphalt Program Manager Randy Kiser, Staunton District Engineer Cathy McGhee, Director, VTRC Kevin McGhee, Assoc. Director, Pavements Team, VTRC Branco Vlacich, State Maintenance Engineer	Trenton Clark, Virginia Asphalt Association Ed Dalrymple, Old Dominion Highway Contractors Association Tom Witt, Virginia Transportation Construction Alliance

The first meeting outlined the expectations of the committee. The group would address not only BMD but also HRAP pilots. Data from the 2018 shadow testing were presented and discussed. The group discussed the recommended test methods and approaches to BMD design:

- Volumetric design with performance verification.
- Performance-modified volumetric design.
- Performance design.

It was decided to develop separate HRAP and BMD special provisions, although the pilots for BMD and HRAP BMD mixtures would be combined. The committee discussed guidance for the 2019 pilots—that they should be at least 4,000 tons, placed on routes with similar surfaces and traffic loads, and located such that the pilots could be monitored by VDOT's pavement management system.

The BMD technical committee continued to meet periodically to discuss ongoing research results, specification developments, training needs, and other topics. Table C4 provides the dates of each subsequent meeting and summarizes the meeting discussions and outcomes.

Table C4. Balanced Mix Design Technical Committee Meeting Dates and Outcomes

Meeting Date	Discussion and Outcomes
1st meeting 12/18/2018	a. Initial meeting b. Outline of committee expectations c. Review of 2018 shadow project data d. Decision to develop separate BMD and HRAP BMD special provisions e. Discussion of guidance for 2019 pilots
2nd meeting 1/29/2019	f. General requirements for 2019 pilots were developed g. Special provision and work order language were discussed
3rd meeting 3/11/2019	h. Special provision language further discussed i. Special provision updated after meeting and sent out for review, then finalized
4th meeting 1/8/2020	j. Review of 2019 pilot projects o Noted that specimen preparation adds variability k. Update on IDT-CT round robin testing l. Discussion of needed training and the need for affordable equipment m. Reporting aged (8 hours @ 135ºC) CT index during design requirement added to special provision
5th meeting 3/9/2020	n. Update on IDT-CT round robin testing o. Update on plans for BMD HVS experiment—construction summer 2020 p. VDOT is developing an equipment purchase plan q. Industry requested a common form to report BMD design information r. Request to draft RNS for wet versus dry IDT-CT testing s. Discussion and agreement to add BMD on 2021 pavement maintenance contracts o Discussion of pay items, whole projects, or selected routes. o Suggested to add one performance test to the specification each year leading up to full implementation. o Industry requested eliminating or widening gradation band requirements.
6th meeting 6/11/2020	1. Need recommendations on equipment and on training 2. Further review of 2018 shadow project and 2019 pilot projects a. Noted inconsistent CT index values between design and production 3. Discussion of 2021 pavement maintenance contracts a. Suggested two projects per district b. Separate pay item number for Superpave and BMD mixtures
7th meeting 12/4/2020	4. Review of 2020 pilots 5. Discussion of 2021 pilot project special provision and plan a. Testing frequency reduced to two tests per 4,000T lot because of increased production b. LTOA included in special provision c. 5 districts with pilots (Salem has two separate contracts, other districts have BMD on existing contracts) 6. Discussion of 2022 pilot project special provision a. Anticipate every district has at least one full contract with BMD mixtures b. Only BMD special provision, no HRAP special provision c. Suggested to relax gradation or volumetrics 7. Training task group initiated
8th meeting 4/29/2021	8. Discussion of workload and workforce 9. VDOT BMD equipment will be in place by end of May 2021 10. Research—BMD Phase I and 2019 Field Trials reports in edit 11. Training presented by VAA and VTRC—2-hour live webinar and Q&A, recorded for availability 12. 2022 pilot project special provision—BMD P+VO mixtures a. Reduced testing frequency from 2021—4,000T lot b. Wider design range for air voids, gradation changes with same tolerances

Meeting Date	Discussion and Outcomes
	c. Allow softer binder with Engineer approval, no recycling agents d. Asphalt standard deviation and density bonuses apply 13. No RAP > 30%, more quality control and control on stockpiles needed before consistently allowed
9th meeting 12/8/2021	14. Updates on IDT-CT round robin a. Need to calibrate equipment, will provide quality checks for equipment in test procedure 15. Update on monotonic loading rutting test a. IDT-HT recommended for initial implementation 16. Training and certification—2 half-day training classes, certification tied to plant certification 17. 2023 pilot project special provision—BMD P+VO mixtures a. Require design IDT-CT meet single operator tolerance, 5 replicates with COV < 18.3% b. TSR on same specimen size as IDT-CT c. IDT-HT design data for report only d. BMD certification required e. Mixture lift thickness on long-term oven-aging added f. Scope of implementation still under discussion
10th meeting 4/19/2022	18. Each District to have at least one contract for 2023 pilots 19. Training continuing, will be incorporated into plant and mixture design for 2023 20. CT index of 70 compares with lab aging for design and reheats, not plant production 21. APA testing once per project for 2022 22. Rollover designs—run performance testing at design AC only 23. Contractor continuing to make test pills for VDOT
11th meeting 9/29/2022	24. CT index ≥ 95 recommended for nonreheat specimens a. Producer will need to specify if testing reheat or nonreheat with design 25. IDT-HT recommended ≥ 133 kPa at 54.4 °C, condition for 3 hours, wet testing 26. BMD incorporated into 2023 plant and mixture design classes, including proficiency 27. 2023—APA testing at request of Engineer 28. 2024 specification discussion a. SM 9.5 and 12.5 A/D will be BMD P+VO b. VDOT will make their own specimens c. IDT-CT—loading range rate 50±3 mm, design IDT-CT COV requirement, aging and production COV report only, allow wet or dry testing d. Nonreheat CT ≥ 95, reheat ≥ 70; must be selected on JMF e. IDT-HT—loading range rate 50±3 mm, wet testing, test every other lot f. Quality control results required within 48 hours
12th meeting 2/2/2023	29. 2024 special provision a. All SM 9.5 and 12.5 A/D will be BMD designs; only D mixtures tested during production b. D mixtures on traffic group X and higher routes, Method A density routes c. VDOT will make their own specimens d. CT index requires meeting COV during design e. Producer must specify on JMF if will be using reheat or nonreheat for CT index f. IDT-HT run at design and +0.5% AC, threshold >100 kPa g. If IDT-HT not comparing, APA pills will be requested by Engineer, tested by VDOT 30. Concerns about tonnage, workload, turnaround time affecting production, failing results 31. Test requirements in specification replaced with Virginia Test Methods
13th meeting 7/17/2023	32. Review of 2022 data, 2023 midyear update 33. BMD Guidance document being drafted—lists sample sizes, frequencies, test methods, JMF submittal and rollover procedures. a. Discussion on sampling, splitting b. Need to define reheat and nonreheat 34. Trying hard to have MITS/PLAID BMD available by March, otherwise will have standardized form

APA = asphalt pavement analyzer; BMD = balanced mix design; COV = coefficient of variance; CT = cracking tolerance; HRAP = high RAP; HVS = heavy vehicle simulator; IDT-CT = indirect tensile cracking test; IDT-HT = indirect tensile at high temperature; JMF = job mix formula; LTOA = long-term oven aging; MITS/PLAID = Materials Information Tracking System and Producer Lab Analysis and Information Details; P+VO = performance and volumetric optimized; RAP = reclaimed asphalt pavement; RNS = research needs statement; SM = surface mixture; TSR = tensile strength ratio; VAA = Virginia Asphalt Association.

Research Reports

During this same time period, VTRC's BMD research was ongoing to keep pace with the implementation timeline. The following outlines a summary of the findings and recommendations from each report.

- Diefenderfer, S.D., Boz, I., and Habbouche, J. (2021a) *Balanced Mix Design for Surface Asphalt Mixes: Phase I, Initial Roadmap Development and Specification Verification*. VTRC 21-R15.
  - Other states were reviewed to compare types of performance testing and performance criteria.
  - An initial roadmap for research and implementation activities was developed.
  - It was verified that the IDT-CT aligned with the seven desirable factors for a cracking test for VA, and the results were compared with those of other tests that did not meet those factors.
  - The testing procedures for the APA, IDT-CT, and Cantabro tests were validated.
  - A major difference was observed between reheated and nonreheated CT samples. The best performing mixtures had CT index values greater than 100.
  - The nonreheat APA specimens were compared with reheat APA specimens, and widening the already existing state criteria from 6 to 8 mm was recommended because rutting showed no issues.

- Diefenderfer, S.D., Boz, I., and Habbouche, J. (2021b) *Balanced Mix Design for Surface Asphalt Mixes: 2019 Field Trials.* VTRC 21-R21.
  - A large difference was seen in the CT index reheat specimens compared with the nonreheat specimens. A performance criterion for reheated samples should be developed if this test is to be used in a quality assurance program.
  - It was shown that 40% RAP mixtures could perform the same as 30% RAP mixtures if a softer binder or recycling agent (RA) were used.

- Habbouche, J., Boz, I., Diefenderfer, S.D., and Bilgiç, Y.K. (2021) *Round Robin Testing Program for the Indirect Tensile Cracking Test at Intermediate Temperature: Phase I.* VTRC 22-R3.
  - No significant impact of 1 year of climate-controlled storage of compacted specimens on the calculated IDT-CT index existed.
  - Various test equipment was compared and found not to be statistically different.
  - No statistical difference was found between 52 mm/min and 53 mm/min loading rates.
  - Minimal differences occurred between dry and wet cores; however, more data are needed.
  - The single operator coefficient of variance (COV) of 18.3% compares to NCAT and Rutgers University.
  - Specimen preparation is a large factor in variability.

- Habbouche, J., Boz, I., and Diefenderfer, S.D. (2022) *Interlaboratory Study for the Indirect Tensile Cracking Test at Intermediate Temperature: Phase II*. VTRC 23-R3.
    - Hands-on training between phases I and II increased the amount of usable data.
    - It was decided to use five specimens and a higher acceptable single operator COV of 18.3% instead of using three trimmed specimens and a lower acceptable COV.
    - No difference in CT-index for wet or dry specimen conditioning existed. Wet specimen testing should be allowed for the IDT-CT.
    - The acceptable loading rate range was increased to 50±3 mm/min.
    - No difference was found between hydraulic or screw type equipment.
    - It was recommended to establish an annual proficiency testing program for the IDT-CT and routinely offer hands-on training and demonstrations of the laboratory tests considered by VDOT as part of the BMD initiative.

- Boz, I., Habbouche, J., Diefenderfer, S.D., Coffey, G.P., Ozbulut, O.E., and Seitllari, A. (2023) *Simple and Practical Tests for Rutting Evaluation of Asphalt Mixtures in the Balanced Mix Design Process.* VTRC 23-R11.
    - The temperature of 54.2ºC was chosen for the indirect tensile at high temperature (IDT-HT) test because it resulted in a lower COV and higher performance discrimination.
    - The APA and IDT-HT showed six distinct statistical groups indicating performance discrimination.
    - Most tests identified bulk specific gravity and nonrecoverable creep compliance as significant factors influencing mixture rutting potential.
    - The correlation of APA to IDT-HT had an $R^2 = 60\%$.
    - The IDT-HT test was recommended with a minimum strength of 133 kPa based on the testing conditions used in this study.

- Diefenderfer, S.D., Habbouche, J., and Boz, I. (2023b) *Balanced Mix Design for Surface Mixtures: 2020 Field Trials.* VTRC 23-R13.
    - Based on the test results, mixtures containing 35% or greater RAP contents, softer binders, RAs, and fiber may be designed and produced to meet current BMD performance thresholds and current volumetric properties, gradation, and asphalt content requirements.
    - Some mixtures that were volumetrically designed under current VDOT specifications met BMD requirements.
    - Modest relationships between nonreheated and reheated specimen results for the Cantabro test and IDT-CT were present.
    - Comparisons of extracted and recovered binders from control and BMD mixtures were found to depend on the binder test under consideration, with different tests indicating differences in expected performance.
    - A testing protocol capable of evaluating the performance of RAs used in BMD mixtures is needed to provide a means for VDOT to evaluate and accept these materials.

- Diefenderfer, S.D., Boz, I., and Habbouche, J. (2023a) *Balanced Mix Design for Surface Mixtures: 2021 and 2022 Plant Mix Schedule Pilots*. VTRC 23-R19.
    - The variability in test results from 2021 to 2022 decreased, showing the benefits derived from training and experience in BMD testing performance.

- The source and formulation of the virgin binder used, along with the properties of the aged binder in the RAP stockpile, contributed to substantial variations in binder properties and affected the expected performance of the produced mixtures.
    - 2022 binder extraction testing showed slightly softer behavior and lower PG high temperatures observed compared with 2021.
    - Binder extraction testing found that nothing graded out to be higher than V or H.
    - Not enough data points were available to show that a correlation between mixture and binder properties existed.
    - A precision statement for the Cantabro and APA is needed.
    - A ruggedness study to refine specimen preparation and test methods for the IDT-CT and IDT-HT, and to provide guidance, is needed.
    - A study to assess the relationships between the properties of virgin and RAP asphalt binders and the properties of the corresponding asphalt mixtures is needed.

- Bowers, B.F., Lynn, T., Yin, F., Moore, N., Diefenderfer, S.D., and Boz, I. (2023) *Impact of Production Variability on Balanced Mix Designs in Virginia.* VTRC 23-R20.
    - It was found that mixtures that were originally balanced could become unbalanced due to production variability.
    - Mixtures showed excellent rutting resistance but could be susceptible to durability and cracking issues as the gradation and binder content change.
    - Cantabro, APA, and IDT-CT were sensitive to changes in binder content.
    - When evaluating the interaction between changes in gradation and binder content, performance test results were sometimes negatively influenced.
    - Further refinement of the BMD specifications is needed to ensure mixtures stay balanced through production despite variability.

- Habbouche, J., Boz, I., Underwood, B.S., Castorena, C., Preciado, J., Gulzar, S., and Fried, A. (2023) *Engineered Frameworks for Evaluating the Use of Recycling Agents in Surface Asphalt Mixtures for Virginia.* VTRC 24-R3.
    - The effectiveness of RAs in improving the properties of asphalt binder blends is specific to the product being used and the targeted temperatures or conditions.
    - RAs can enhance the performance and increase the use of recycled materials in asphalt mixtures, provided that the correct and suitable dosage of RA product is determined through a performance-based testing framework.
    - Adoption of the streamlined frameworks presented in this study to determine the acceptability of a given RA is recommended.
    - Further validation of framework using different component materials is needed
    - Investigating the availability and activity of binders, especially with RAs, in RAP materials is needed.
    - A protocol to assess the consistency of RAP materials is needed.

- Diefenderfer, S.D., Boz, I., Bowers, B.F., Lynn, T., Yin, F., and Moore, N. (2024) *Asphalt Mixture Variability and Its Effect on BMD Testing from Design to Production.* VTRC 25-R1.
    - Test variability was similar to or wider than the variation induced from the production tolerance limits on coarse and fine aggregates, suggesting that the current material tolerance limits on aggregates are appropriate based on the IDT-CT.

    - The variations induced due to the production tolerance limits on asphalt content, in this case ±0.3%, were significantly wider than the test variability.
    - Asphalt mixtures designed with an average performance result within the single-operator precision estimates of CT index performance thresholds may risk failures during production due to the inherent material and test variability.

- Boz, I., Diefenderfer, S.D., Habbouche, J., and Seitllari, A. (2025a) *Interlaboratory Study for the Indirect Tensile at High Temperature Test and IDEAL Rutting Test*. VTRC 25-R14.
    - Confirmed that specimen reaches temperature using water bath conditioning at 54.4 °C 1 hour sooner than environmental chamber. One hundred kPa IDT-HT is suitable minimum for wet conditioned specimens.
    - Significant differences in specimen conditioning time between water bath and environmental chamber conditioning existed, and water bath-conditioned specimens consistently showed lower parameter and index values.
    - The repeatability of both tests was not significantly affected by conditioning environment, loading rate, loading frame, or storage.
    - Loading rate, loading frame, and storage did not significantly affect IDT-HT and Ideal RT test results, especially in the context of single-operator precision estimates.
    - For specimens conditioned in a water bath at 54.4 °C, minimum strength values of 100 kPa for IDT-HT and rutting test index of 62 for Ideal RT test were recommended.
    - A Virginia Test Method was developed for the IDT-HT test.
    - The precision estimates and statements for both tests were developed.
    - Proficiency testing was conducted for the IDT-HT test only, involving 31 VDOT and contractor laboratories in Virginia, and employed compacted specimens from a single mixture. The results revealed that 93.5% of the laboratories performed satisfactorily, indicating proficiency in the IDT-HT test.

- Habbouche, J., Diefenderfer, S.D., Diefenderfer, B.K., Flintsch, G., Tong, B., and Urbaez Perez, E. (2025b) *Evaluation of BMD Surface Mixtures with Conventional and High RAP Contents Under Laboratory-Scale and Full-Scale Accelerated Testing.* VTRC 25-R16.
    - Designing dense-graded, unmodified surface mixtures with higher RAP contents is possible using the current BMD special provision.
    - Those mixtures can be produced with no significant differences in aggregate gradations and asphalt binder content from the design.
    - When designing conventional and HRAP surface mixtures to meet BMD requirements, using RAs, a softer binder, or both may be necessary.
    - BMD tests characterized the laboratory performance of the mixtures similarly to the performance observed under accelerated pavement testing.
    - It was recommended to consider allowing the use of other tools in addition to increasing binder content, such as RA or softer binder or both, for the design and production of BMD surface mixtures, even at allowable RAP contents.
    - It was recommended to consider allowing mixtures with RAP contents of up to 45%, when properly controlled and where desired by the district, designed using current BMD specifications modified to allow additional tools like RA and softer binder.

- Boz, I., Hajj, E.Y., Habbouche, J., Diefenderfer, S.D., Alam, I., and El Hajj, H. (2025b) *A Practical Oven-Aging Method for Evaluating Long-Term Cracking Performance of Asphalt Mixtures in Virginia*. VTRC 26-R04.
    - The CT index effectively captured the anticipated behavior of asphalt mixtures undergoing laboratory oven aging.
    - The research suggests that laboratory oven aging at 95 °C can be used for shorter durations to assess long-term performance effectively. Furthermore, aging at the compaction temperature provides results equivalent to 95 °C, supported by consistent binder characteristics.
    - For VDOT's BMD mixtures, a 6-hour oven-aging duration at compaction temperature is recommended for the design phase, with a preliminary CT index threshold of 55.
    - An oven-aging duration of 2 hours at compaction temperature following reheating during production and 4 hours at compaction temperature for nonreheat conditions (i.e., hot compacted) is deemed suitable for evaluating the long-term performance of asphalt mixtures during production, with a preliminary CT index threshold of 55 for both cases.

- Diefenderfer, S.D. and Nair, H. (2025) *Evaluation of Fiber-Modified Asphalt Mixtures Using BMD Tests*. VTRC 26-R05.
    - For most of the mixtures evaluated, the addition of fibers did not improve performance test results compared with test results from the control mixtures because of reductions in production binder content from the design binder content.
    - Effective binder content and film thickness appeared to most influence mass loss, CT index, and indirect tensile strength.
    - Volumetric and BMD test results indicated that fiber-modified mixtures should be designed and optimized based on performance criteria.
    - It is recommended that fiber-modified mixtures be designed using BMD.

- Habbouche, J., Boz, I., Diefenderfer, S.D., Underwood, B.S., and Othman, O. (2025a) *Mechanistic-Based Evaluation of Performance Thresholds for Balanced Mix Design Asphalt Surface Mixtures*. VTRC 26-R08.
    - VDOT's BMD tests effectively assess durability, rutting, and cracking performance, aligning with advanced tests measuring fundamental properties.
    - Current BMD thresholds can be revised and refined, incorporating traffic-based rutting and cracking thresholds.
    - Mechanistic-based evaluation simulations indicated that mixtures intended for moderate to heavy traffic pavement structures (D) should be designed to meet a maximum mass loss of 6.3% (instead of 7.5%), a minimum cracking tolerance index of 110 (instead of 70), while maintaining the same APA rut depth threshold of 8.0 mm.
    - Mixtures intended for low-volume traffic pavement structures (A) should meet a maximum mass loss of 5.9% (instead of 7.5%), a minimum cracking tolerance index of 124, and a maximum APA rut depth of 10 mm.

- Kuchiishi, K., Habbouche, J., Boz, I., Castorena, C., Underwood, B.S., Turbay, E., and Preciado, J. (2025) *Verification of Engineered Frameworks for Evaluating the Use of Recycling Agents in Surface Asphalt Mixtures*. VTRC 26-R09.

- The proposed framework yielded an optimized RA dosage consistently less than the supplier-recommended dosage to restore the low-temperature PG of the recycled binder blend.
- The rejuvenation path index was confirmed to be independent of the RA dosage and could be used to accept other RAs into VDOT's Approved Product List.
- Lower asphalt content showed lower cracking tolerance index and higher Cantabro mass loss values, with some mixtures failing the BMD thresholds.
- The APA rutting test could not discriminate between the mixtures' rutting susceptibility.
- The new binder blends and mixtures confirmed the negative relationship between cracking tolerance index and Glover-Rowe parameter, highlighting the importance of binder properties on the mixtures' cracking performance.
- A preliminary cracking tolerance index aging sensitivity of 45% was verified and proposed.

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