



Improving Mixture Durability Through Design Gyration, Air Voids, and Binder Content

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Final Report VTRC 16-R17

Standard Title Page—Report on State Project

Report No.: VTRC 16-R17	Report Date: April 2016	No. Pages: 46	Type Report: Final Contract	Project No.: 105448
			Period Covered: Dec. 2013 – Dec. 2015	Contract No.:
Title: Improving Mixture Durability Through Design Gyration, Air Voids, and Binder Content				Key Words: Laboratory compaction, asphalt content, cracking resistance, rutting resistance, flow number, fracture energy
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Supplementary Notes:				
<p>Abstract:</p> <p>This report describes a laboratory study that supports a larger and continuing effort to improve durability of Virginia's dense-graded asphalt mixtures. This component of that larger effort explores the rutting and cracking resistance for a series of dense graded mixtures that represent different design gradation levels and binder contents. The rutting resistance was evaluated using the unconfined Flow Number test (also called unconfined Repeated Load Permanent Deformation test). The cracking resistance was evaluated using the indirect tension strength test. The matrix of trial mixtures were generated from four different Virginia "source" mixtures, all of which conformed to a Virginia Department of Transportation (VDOT) SM-9.5D designation.</p> <p>The study found that additional binder affects the rutting resistance of the tested mixtures but that change can be toward both the better and worse. The response appears to be related to VMA and gradation of the mixture. The cracking resistance was nearly universally improved with the addition of binder, although test results were highly variable for the improvement to be deemed statistically significant and results with the coarsest mixture demonstrated that it was possible to weaken a mixture with too much additional binder.</p> <p>The study developed a series of recommended design criteria and recommends field trials to explore the response from multiple producers. These trials should be well documented and include a similar regimen of laboratory performance tests. As warranted by preliminary results from field trials, additional trials may be tested using the VDOT accelerated loading facility.</p>				

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AND BINDER CONTENT**

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and the University of Virginia since 1948)

Charlottesville, Virginia

April 2016
VTRC 16-R17

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ABSTRACT

This report describes a laboratory study that supports a larger and continuing effort to improve durability of Virginia's dense-graded asphalt mixtures. This component of that larger effort explores the rutting and cracking resistance for a series of dense graded mixtures that represent different design gyrations levels and binder contents. The rutting resistance was evaluated using the unconfined Flow Number test (also called unconfined Repeated Load Permanent Deformation test). The cracking resistance was evaluated using the indirect tension strength test. The matrix of trial mixtures were generated from four different Virginia "source" mixtures, all of which conformed to a Virginia Department of Transportation (VDOT) SM-9.5D designation.

The study found that additional binder affects the rutting resistance of the tested mixtures but that change can be toward both the better and worse. The response appears to be related to VMA and gradation of the mixture. The cracking resistance was nearly universally improved with the addition of binder, although test results were highly variable for the improvement to be deemed statistically significant and results with the coarsest mixture demonstrated that it was possible to weaken a mixture with too much additional binder.

The study developed a series of recommended design criteria and recommends field trials to explore the response from multiple producers. These trials should be well documented and include a similar regimen of laboratory performance tests. As warranted by preliminary results from field trials, additional trials may be tested using the VDOT accelerated loading facility.

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INTRODUCTION

The Superpave volumetric mixture design procedures were established to assure sufficient space for binder to provide long-term durability while maintaining adequate aggregate structure to resist densification and rutting (Federal Highway Administration [FHWA], 2010). The number of compacting gyrations set by the Superpave design procedure has however been criticized as based on a very limited number of evaluated samples (Maupin, 2003; Prowell and Brown, 2006). The main critique of the Superpave methodology is that the number of specified gyrations is too high and results in low added binder to the mixture. While a high gyration design is beneficial for rutting resistance, it may inadvertently cause durability issues such as mixture cracking and raveling.

As a result of these concerns, some agencies have already modified the Superpave design criteria and the National Cooperative Highway Research Program (NCHRP) has funded a project to verify the original gyration levels. The results of this project were published in NCHRP Report 573, which recommended lowering the compaction effort (Prowell and Brown, 2006). Virginia was among the states to modify the number of gyrations, moving to 65 gyrations (75 for Stone Matrix Asphalt mixtures) for all traffic levels. Maupin (2003) evaluated a sample of VDOT-produced mixtures (at the 65 gyration levels) and concluded, based on rutting and fatigue testing, that as much as 0.5% binder could be added to the evaluated mixtures with beneficial results. The benefits of additional binder to VDOT-produced mixtures, based on rutting and cracking tests, were also reported by Maupin and Diefenderfer (2007) and Boriack et al. (2015). The results of these projects suggest that mixtures meeting VDOT criteria may be further optimized in terms of additional binder content to better resist cracking without detrimental effects on mixture rutting, an observation that has also been made by some field personnel. However, the three VDOT research projects (Maupin, 2003; Maupin and Diefenderfer, 2007;

Boriack et al., 2015) did not address the issue of how the mixture design specifications should be changed to allow this additional binder without adversely affecting other mixture properties.

The FHWA recognized the concerns expressed by many states that the Superpave mixture design system was producing asphalt concrete mixtures that were too low in asphalt binder. However, they did not fully endorse the reduced gyration levels proposed in NCHRP Report 573 (FHWA, 2010) based on the observation that the statistical results were weak. The main concern of the FHWA was that reduced gyration levels will generally result in higher binder contents, which could cause rutting problems. Furthermore, it is also still possible, by changing the aggregate gradation, to achieve the same air voids content at a reduced gyration level without increasing the binder content. For these reasons, the FHWA suggests that if it is desired to increase the asphalt binder content, either the minimum VMA requirement should be increased or the air void requirement should be reduced accompanied by mixture performance testing. Its final recommendation was that the issues of gyration levels should be addressed by individual agencies and if a reduction in gyration levels is proposed, it should at a minimum be accompanied with rutting performance tests.

PURPOSE AND SCOPE

The purpose of this study was to evaluate the rutting and cracking resistance of a series of dense graded mixtures that represent different design gyration levels and binder contents. The rutting resistance was evaluated using the unconfined Flow Number (FN) test (also called unconfined Repeated Load Permanent Deformation [RLPD] test). The cracking resistance was evaluated using the indirect tension (IDT) strength test. The matrix of trial mixtures were generated from four different Virginia “source” mixtures, all of which conforming to a Virginia Department of Transportation (VDOT) SM-9.5D designation. These mixtures and producers were solicited cooperatively by VDOT and industry representatives.

METHODS

As recommended by the FHWA, efforts to increase the mixtures’ binder content to improve mixture durability should be accompanied by mixture performance testing. Furthermore, the framework by which increasing binder content is achieved should be properly set so that it achieves its desired outcome (of increasing the binder content) while improving overall mixture performance. For this purpose, laboratory performance testing of the selected and modified mixtures was performed using the flow number test (for mixture rutting potential), and the indirect tension strength test (for mixture cracking potential).

Material Collection and Preparation

The selection criteria for the four original source mixtures targeted an aggregate gradation consisting of at least 58% passing the 4.75 mm (No. 4) sieve and a maximum of 23% passing the 600 mm (No. 30) sieve. All four of the collected mixtures satisfied the 4.75 mm (No.

4) sieve requirement while only three of the mixtures satisfied the 600 mm (No. 30) sieve criterion. One mixture was much coarser than the other three mixtures with a gradation of 18.5% passing the 600 mm (No. 30) sieve.

All four plant produced mixtures were prepared according to VDOT specifications, sampled loose at the plant and transported to the Virginia Tech Transportation Institute (VTTI). For the purpose of this research, the main specification of interest is design gyration level and the air void content, which are 65 gyrations and 4%, respectively. These four source mixtures were further modified to obtain nine additional mixtures (three per original mixture/producer) that contained additional liquid asphalt. For the first modified mixture, the additional binder content was determined as that content needed to obtain 3.5% air voids at 50 gyrations (using the SGC). To determine this binder content, trial mixtures with no additional binder, with 0.5% additional binder, and with 1% additional binder were compacted to 50 gyrations to determine the effect of added binder on the air void content. Interpolation was then used to determine the amount of binder that needs to be added to the collected mixtures to obtain the desired 3.5% air voids at 50 gyrations. This procedure was repeated for each of the four original mixtures. The remaining two modified mixtures (per source) were obtained by adding 0.2% and 0.4% binder to the first modified mixture. The resulting matrix of mixtures is summarized in Table 1. For all mixtures, the volumetric properties of VTM, VFA and, VMA were determined along with asphalt content and gradation.

Table 1. Design Matrix of Tested Mixtures

Mixture Source	Original	Modified 1	Modified 2	Modified 3
A	4.0% VTM at 65 Gyration	3.5% VTM at 50 Gyration	Modified 1 + 0.2%	Modified 1 + 0.4%
B	4.0% VTM at 65 Gyration	3.5% VTM at 50 Gyration	Modified 1 + 0.2%	Modified 1 + 0.4%
C	4.0% VTM at 65 Gyration	3.5% VTM at 50 Gyration	Modified 1 + 0.2%	Modified 1 + 0.4%
D	4.0% VTM at 65 Gyration	3.5% VTM at 50 Gyration	Modified 1 + 0.2%	Modified 1 + 0.4%

Mixture Analysis

The gradation, asphalt content, maximum specific gravity, VTM, and VMA were measured at the VTTI asphalt laboratory. Some constituent properties (i.e., aggregate specific gravities) were obtained from the producer design sheets.

Mixture Performance Testing and Data Analysis

For performance testing, samples were compacted to a target VTM of 7% using the Superpave gyratory compactor. The performance tests include the flow number test (for rutting potential), and the IDT strength test (for cracking performance). For all mixtures and each test, 6 samples were prepared.

The specimens were compacted at a temperature of 143°C (290°F) to a height 178 mm (7 inches) in a 152 mm (6 inch) diameter mold. Since the goal was to achieve a target air void level of 7.0% ± 0.5%, the number of gyrations necessary to compact each mixture varied based on the air void target of 7%. Once sufficiently cooled, the specimens were then cut and cored to a length of 152 mm (6 inches) and a diameter of 102 mm (4 inches). The bulk specific gravity (G_{mb}) of the cut and cored specimens was then determined using AASHTO T 166-10 (AASHTO, 2010). For the IDT test, each cut and cored specimen was used to obtain two specimens that are 51 mm (2 inches) thick.

Flow Number Test

The unconfined repeated load permanent deformation (RLPD) test was used to determine permanent deformation characteristics of the mixtures in this study (Witczak et al., 2002). The flow number (FN) for each of the specimens is obtained using the results of the RLPD and is defined as the loading cycle under which tertiary flow commences (Biligiri et al., 2007). The procedures specified in AASHTO TP 79 (AASHTO, 2009) and the NCHRP Project 9-19 (Witczak, 2005) were followed in the execution of the unconfined RLPD test. The specimens were subjected to a repeated haversine compressive loading pulse of 600 kPa (89 psi) for 0.1 seconds followed by 0.9 seconds of rest using a Material Testing Systems (MTS) servohydraulic machine.

The axial deformation and cycle data from the RLPD test is then fitted to a mathematical model in order to calculate the cycle in which tertiary flow begins or the FN. The Francken model was used as it was determined to be the best model to describe all three phases of permanent deformation and calculate the FN by Biligiri et al. (2007). The Francken model is given in Equation 1.

$$\varepsilon_p(N) = AN^B + C[\exp(DN) - 1] \quad (1)$$

where

ε_p = Permanent strain
 N = Number of cycles
 $A, B, C,$ and D = Regression coefficients

To determine the FN, the model is fit to the RLPD test data using numerical optimization. Then, after the regression coefficients are determined, the second derivative of the Francken model, also known as the gradient of the strain slope, is calculated as follows (Biligiri et al., 2007).

$$\frac{\partial^2 \varepsilon_p(N)}{\partial N^2} = A \times B(B-1)N^{B-2} + C \times D^2 \exp(DN) \quad (2)$$

The gradient of the strain slope starts as a negative number that decreases with increasing cycles. The point at which the strain slope goes from negative to positive indicates where the

secondary phase of permanent deformation ends and the tertiary flow begins and is defined as the FN. The recommended test temperature for the values reported in Table 4 is the 50% reliability high temperature 20 mm below the surface. However, the test was performed at a constant 54°C in this study. The temperature of 54°C was used because it has traditionally been used for flow number testing in Virginia (Apeageyi and Diefenderfer, 2012; Diefenderfer and Apeageyi, 2015; Boriack et al., 2015).

Fracture Energy (FE) Index with Indirect Tension Strength Test

The indirect tension (IDT) strength to evaluate the mixture's resistance to cracking was proposed by Walubita et al. (2013) as a faster alternative to the Texas Overlay Tester (OT). The IDT test is conducted by applying a constant displacement rate of 25 mm/minute (1 inch/minute) along the vertical diameter of a cylindrical specimen. This loading configuration develops tensile stresses and strains perpendicular to the direction of the applied load. As the loading approaches failure of the specimen, tensile cracks develop at the center of the specimen and propagate vertically causing the specimen to fail. During testing, the load, actuator displacement, and horizontal deformation at the middle of the specimen are recorded and used to calculate cracking parameters. The specimen used consists of a 100 mm (4 inches) diameter 50 mm (2 inches) thick cylinder and the testing temperature used was 25°C. The horizontal tensile stress at the middle of the specimen can be calculated from the measured load during the test using Equation 3

$$\sigma = \frac{2P}{\pi ad} \quad (3)$$

where

σ	=	stress along the vertical or horizontal diameter
P	=	applied load
a	=	loading strip width
d	=	specimen thickness

To determine a mixture's potential to resist cracking, Walubita et al. (2013) proposed the fracture energy (FE) Index, which can be used for both the IDT or OT. The original motivation for developing the FE Index was to 1) reduce the variability in the Texas Overlay Tester (OT) test results and 2) reduce the testing time of the OT test. It was however also found that the FE Index can be effectively used with the IDT test (Walubita et al. 2013). The FE index for the IDT specimen can be calculated using Equation 4

$$FE\ Index = \left(\frac{G_f}{l_{cr} \sigma_t} \varepsilon_t \right) \times 10^5 \quad (4)$$

where

G_f	=	fracture energy defined as work per area of cracked section
σ_t	=	tensile strength (maximum tensile stress)
ε_t	=	tensile strain corresponding to maximum tensile stress

l_{cr} = length traversed by crack (specimen thickness)

RESULTS

Mixture Volumetric Analysis

The gradation, asphalt content, maximum specific gravity, VTM, VMA, and aggregate specific gravity, G_{sb} , of the collected mixtures are shown in Table 2. All properties were measured at the VTTI asphalt laboratory except for G_{sb} which was obtained from the four producers (note that G_{sb} is used to calculate VMA). Although not presented here, the producer volumetric results were similar to the ones presented in Table 2. Mixtures A, C, and D had similar results for the percent passing the number 600 sieve (23.17% to 23.50%) while mixture B had a lower percent of 18.51%.

Table 2. Mixture Lab Results

U.S. Standard Sieve No.	Percent Passing			
	A	B	C	D
12.5 mm (1/2 in)	100.00	99.71	99.59	99.80
9.5 mm (3/8 in)	94.83	94.18	95.02	95.18
4.75 mm (No. 4)	64.92	59.72	63.30	65.77
2.36 mm (No. 8)	45.43	37.72	40.97	45.82
1.18 mm (No. 16)	32.82	25.96	30.54	32.27
600 mm (No. 30)	23.17	18.51	23.50	23.35
300 mm (No. 50)	15.42	12.77	16.27	16.02
150 mm (No. 100)	10.47	8.74	9.63	9.71
75 mm (No. 200)	7.35	6.09	6.18	5.69
Pan + Washed	0.00	0.00	0.00	0.00
AC (%)	5.22	5.22	5.36	5.91
G_{mm}	2.627	2.722	2.523	2.454
VTM (%)	4.27	4.35	4.00	4.14
VMA (%)	15.99	17.93	17.69	16.46
G_{sb}	2.837	3.007	2.785	2.649

Figure 1 shows the VTM of the trial mixtures used to determine the asphalt content needed to achieve 3.5% VTM at 50 gyrations. These trial mixtures consist of the collected loose mixtures (whose asphalt content at 65 gyrations is presented in Table 2) and mixtures consisting of the collected loose mixtures with added extra binder in the laboratory in the amount of 0.50 and 1.0%. For mixtures A, C, and D, the needed additional binder content to achieve 3.5% VTM at 50 gyrations ranged from 0.35 to 0.65%. For mixture B, the needed additional asphalt content was 1.0%. Figure 2 shows the VMA of the trial mixtures with mixture B having the highest measured VMA, close to 20%. Note also that for mixtures A, C, and D, there was a significant initial drop in VMA with the addition of 0.5% asphalt binder while for mixture B the initial drop in VMA is comparatively small. These observations are pointed out because, as will be presented later, mixture B was found to have the lowest FN among all tested mixtures. This could be suspected based on the relatively high VMA values reported in Figure 2. The final designed mixtures' asphalt contents and asphalt binder film thickness are listed in Table 3.

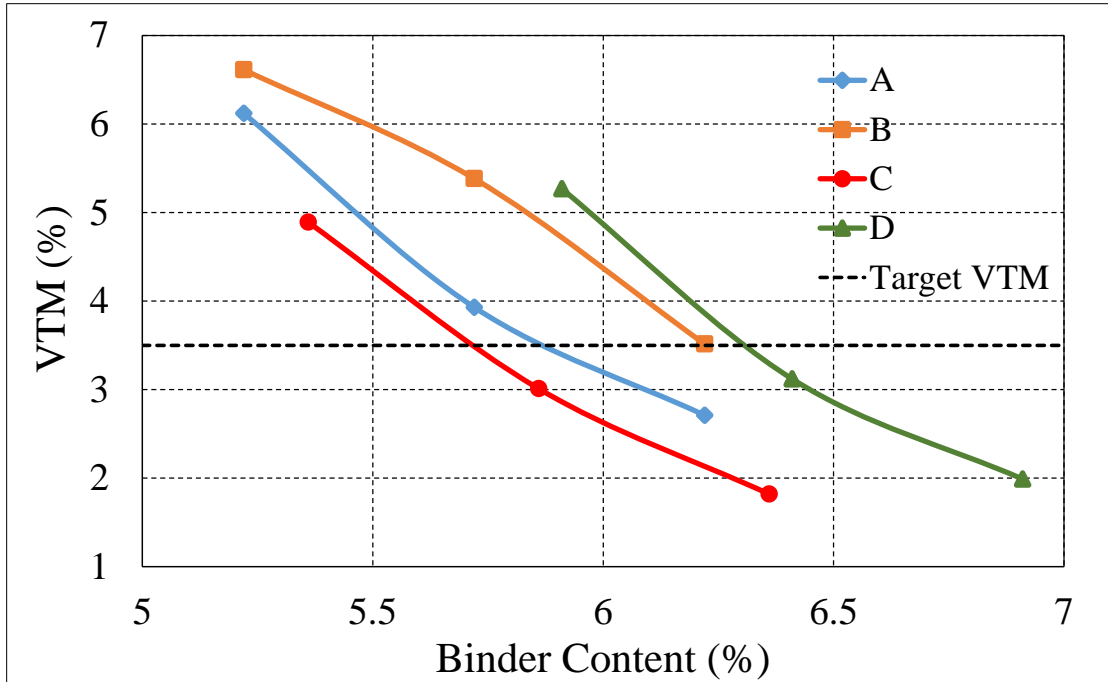


Figure 1. VTM as a Function of Binder Content at 50 Gyration

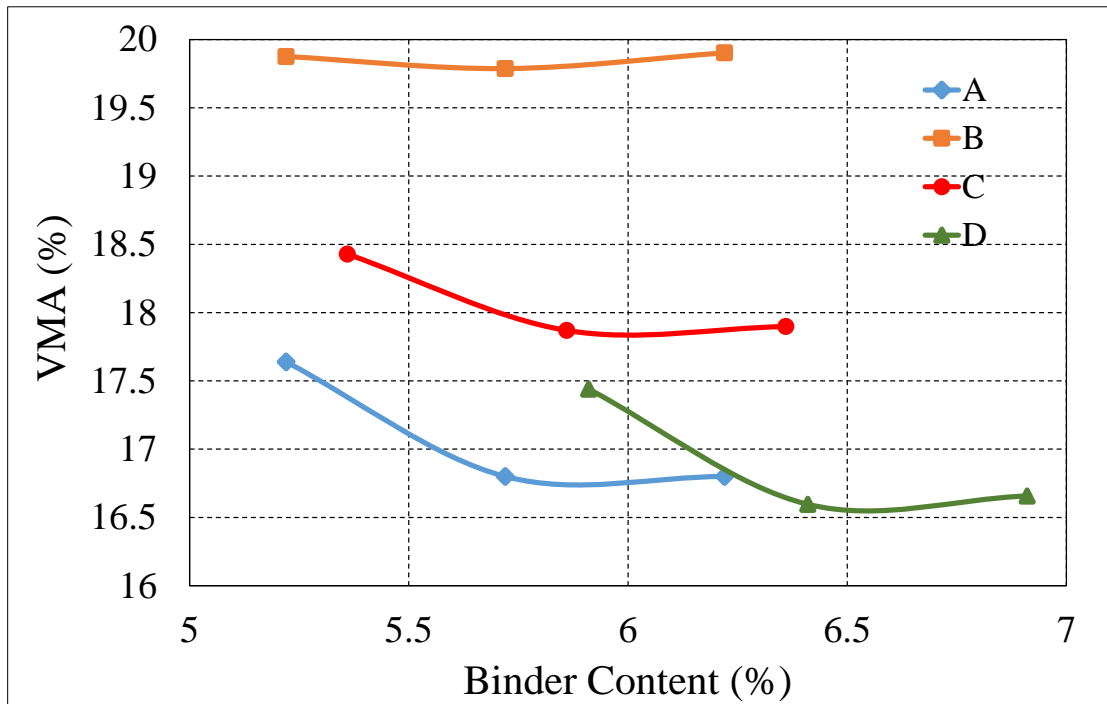


Figure 2. VMA as a Function of Binder Content at 50 Gyration

Table 3. Asphalt Content of Mixtures (%) (Total and in Parenthesis Amount Added With Respect to the Plant Produced Mixture) and Binder Film Thickness (Microns)

Mix Source	Original		Modified 1		Modified 2		Modified 3	
	AC	Film Thickness	AC	Film Thickness	AC	Film Thickness	AC	Film Thickness
A	5.22	7.7	5.87 (0.65)	8.7	6.027 (0.85)	9.1	6.27 (1.05)	9.4
B	5.22	8.7	6.22 (1.00)	11.1	6.42 (1.20)	11.5	6.62 (1.40)	11.9
C	5.36	8.6	5.725 (0.365)	9.2	5.925 (0.565)	9.6	6.125 (0.765)	9.9
D	5.91	8.8	6.31 (0.40)	9.5	6.51 (0.60)	9.8	6.71 (0.80)	10.2

Performance Testing

Flow Number Test

The average flow number test results of six tested samples for each mixture are presented in Figure 3. Of the as-produced mixtures (Optimal Binder at 65), mixture A, the best performing mixture, had a flow number more than three times the flow number of mixture B, the worst performing mixture. Referencing Table 2, the flow number results seem to be most affected by a combination of mixture VMA and, to a lesser extent, gradation. Mixtures B and C had similar and comparatively lower FN values and high VMA values. However, once the mixtures were modified, the rutting resistance of mixture B significantly decreased while that of mixture C initially increased slightly. An important difference among the mixtures is noted in the gradation. Mixtures A and D, the mixtures that exhibit the highest FN values, are very similarly graded. Mixture C has a slightly coarser grading (less material passing the No. 8 and No. 16 sieves) and lower FN values. Mixture B is the coarsest of the mixtures and exhibits the lowest FN values in all comparisons. While coarse mixtures are commonly thought to be more rut-resistant, the findings in this context indicate that a finer gradation is preferred. Calculation of binder film thickness presented in Table 3 did not reveal it has a clear effect of rutting resistance.

Of the mixtures with the most similar gradations (and best flow performance), the binder content for mixture A appeared to be near optimum (for rutting resistance) as originally designed while performance for mixtures D improved initially with the 50 gyration/3.5% VTM design criterion. Overall, the results shown in Figure 3 are inconclusive as to how the added binder content caused by the reduction in the number of gyrations affected the flow number. For mixture A and mixture B, this resulted in a decrease in the flow number while for mixture C and mixture D, an initial slight increase in flow number was observed followed by a slight decrease. The results for mixture C and mixture D suggest that there is an optimal binder content for flow number performance at a point close to that determined with the 50 gyration procedure. The statistical analysis presented in Appendix A suggests that changes in performance as a function of asphalt binder is in general statistically significant.

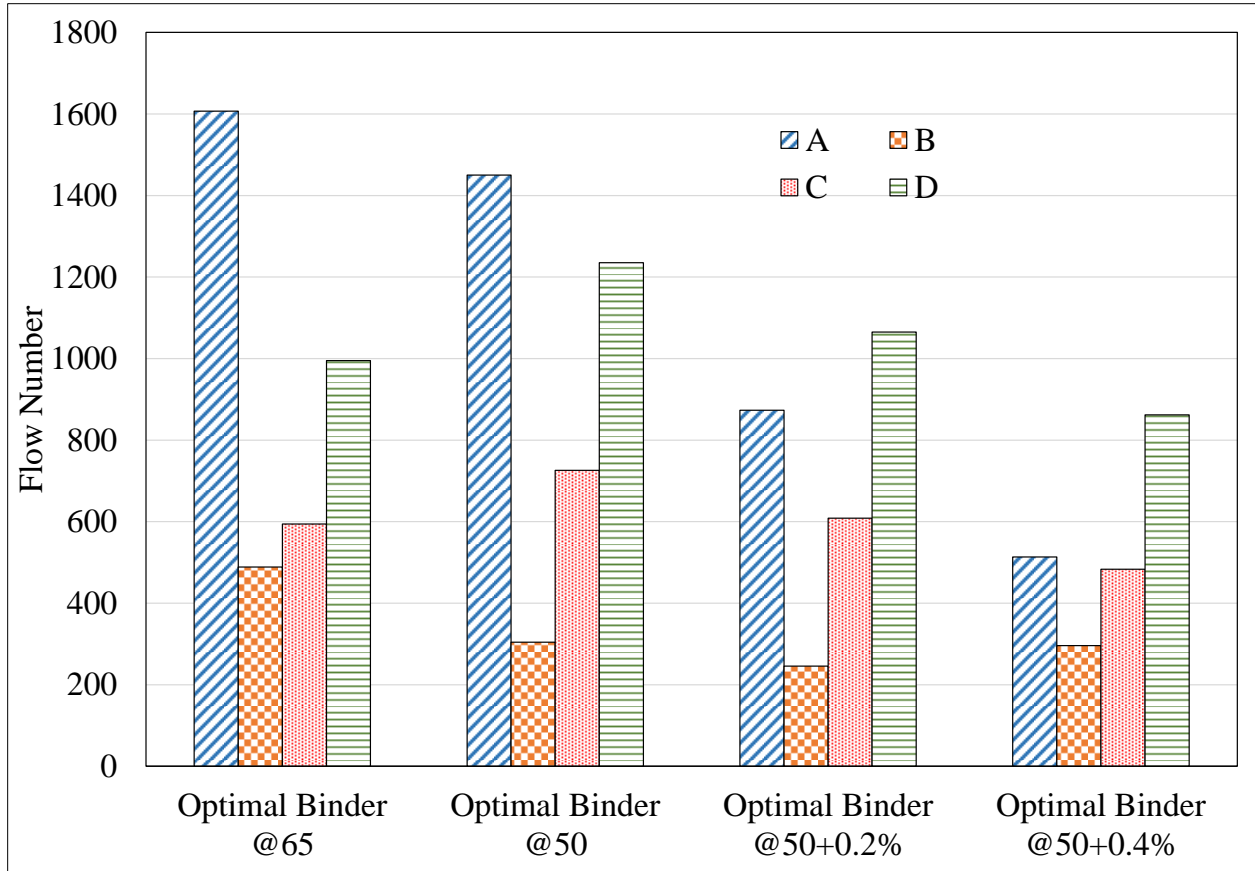


Figure 3. Flow Number Test Results

Table 4 shows the minimum recommended unconfined flow number at 600 kPa (87 psi) depending on traffic level. All tested mixtures passed the recommended minimum for ESAL levels below 30 million. Note that the recommended test temperature for the values reported in Table 4 is the 50% reliability high temperature 20 mm below the surface. However, the test was performed at a constant 54°C in this study. The temperature of 54°C was used because it has traditionally been used for flow number testing in Virginia (Apeageyi and Diefenderfer, 2012; Diefenderfer and Apeageyi, 2015; Boriack et al., 2015).

Table 4. Recommended Minimum Flow Number Requirements

Traffic Level (Million ESALs)	Minimum Flow Number (Cycles)
<3	---
3 to <10	53
10 to <30	190
≥30	740

Data from Advanced Asphalt Technologies (2011).

IDT Strength Test

The average FE Index test results of six tested samples for each mixture are presented in Figure 4. The results for the originally produced mixtures show different trend than those for the flow number with mixture B having a higher FE Index than mixture A (mixture B had the lowest FN while mixture A had the highest FN). In general, adding binder to the mixture resulted in an

increase of the FE Index. This increase is however initially small for mixture C and eventually decreased for mixture B and mixture D once too much binder was added to the mixture. This points to the fact that while additional binder results in a more flexible mixture that is beneficial to cracking resistance, it also results in reducing the mixture strength which is a detriment to cracking resistance. At some point, the strength reduction outweighs the benefits of improved flexibility. The statistical analysis of the IDT strength test presented in Appendix A did not show a significant effect of binder content on the FE Index.

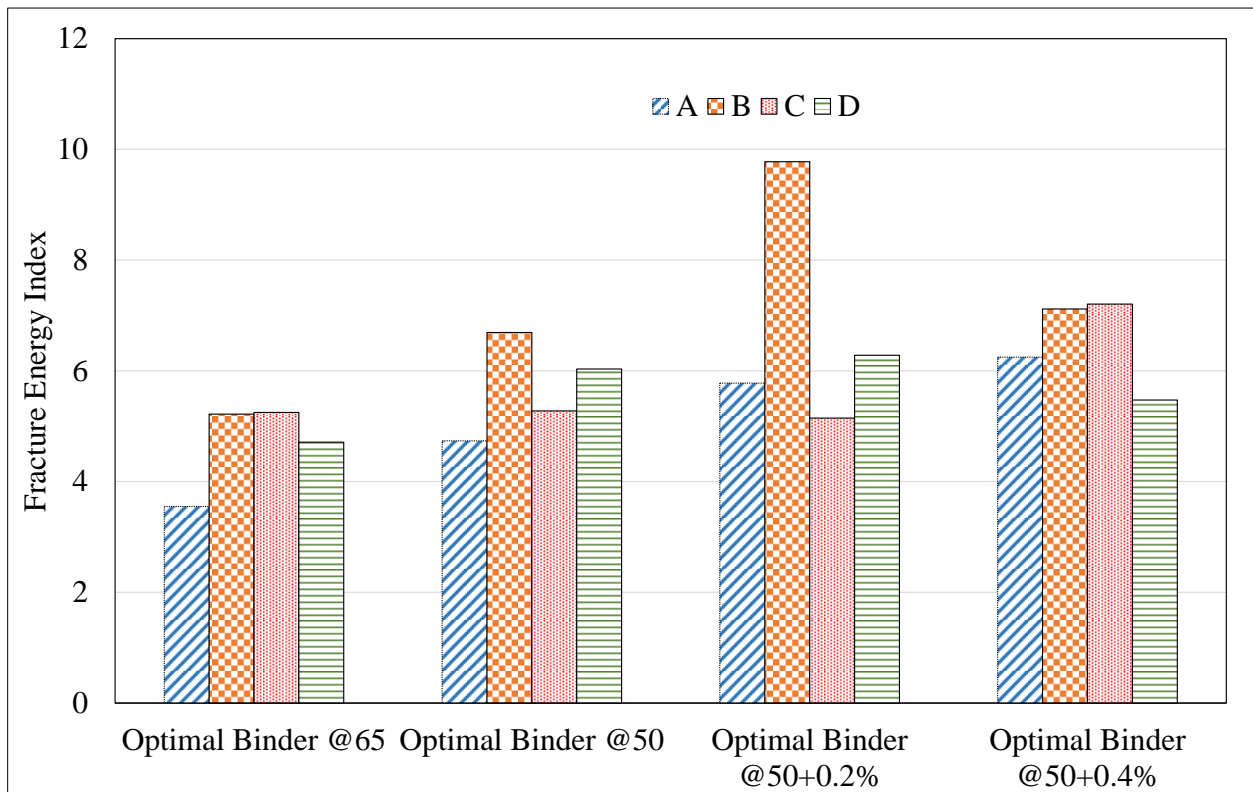


Figure 4. FE Index Test Results

DISCUSSION

The flow number and IDT strength tests were used as indicators of rutting and cracking performance of the tested mixtures. The data from the flow number testing suggests an effect of different amounts of added binder on rutting performance. For two mixtures the FN decreased with increasing binder. For two others, the FN initially increased with added binder. From a practical perspective it would be expected that too much binder will result in aggregate slippage which will lead to lower FN values while too little binder will result in a mixture that barely holds together and therefore does not perform well in the FN test. Therefore, there is an optimal amount of binder that will result in the highest FN. Depending on where the original mixtures are located with regards to this optimal binder content, evidence from this research shows that adding binder can result in decrease in the flow number, or increase followed by a decrease in the flow number.

The data for the IDT test show a general increase in the FE Index with added binder content. The increase is however small compared to the test variability and the FDR analysis presented in Appendix A could not confirm the effect of binder content on the FE Index. Note that the FE Index depends on both the tensile strength and flexibility of the mixture. A high FE Index results from a high tensile strength and high flexibility. In general, when binder is added, the tensile strength of the mixture decreases and the flexibility increases. This results in a competing effect on the FE Index, although the overall effect in the range tested seems to be to slightly increase the FE Index.

Testing of the mixtures was performed to support the decision on whether changes in the design method of mixtures (number of gyrations, gradation specification) could result in improved mixture performance in the field. The test results of flow number and IDT-based FE Index suggest that laboratory performance in some cases can be improved with added binder. However, in other cases, the performance can be adversely affected. This shows that any changes in the mixture design methodology should not solely be based on revised design gyrations and air voids content, but also on possible modification to additional properties such as VMA, and gradation requirements that collectively promote improved cracking resistance without jeopardizing rutting resistance. Although the flow number and FE Index correlate well with loading related field performance, they do not take into account other important factors to the performance of mixtures. Added binder should also improve resistance to environmental degradation (e.g., block cracking and raveling).

The VMA and aggregate gradation seem to be important parameters that affect the rutting resistance as measured in the FN test although the exact effect of these parameters could not be quantified due to the limited scope of this study. However, this observation suggests that reducing gyration levels without changing air void, aggregate gradation, and VMA requirements (and possibly other parameters) can potentially lead to a weaker aggregate structure with no increase in mixture binder content as initially intended. Therefore, any effort to introduce more binder into the mixtures by changing gyration levels should be accompanied with modified air voids, VMA, and aggregate gradation requirements to ensure the intended purpose of increasing the binder content.

CONCLUSIONS

- *The effect of reducing the number of gyrations from 65 to 50 and reducing the design VTM from 4.0% to 3.5% was to require additional binder to be added to the plant-produced mixtures. The added binder ranged from 0.365% to 1.000%.*
- *The amount of binder in the mixture had a significant effect on the flow number test results. The effects were however mixed. For some mixtures the flow number increased initially while for other mixtures the flow number decreased. All tested mixtures passed the recommended minimum requirement for traffic levels less than 30 million ESALs recommended in NCHRP Report 673 (Advanced Asphalt Technologies, Inc., 2011).*

- *Additional binder could be incorporated in the tested mixtures to increase the FE Index and possibly improve cracking resistance.*
- *For some mixtures, it was possible to improve both rutting resistance and cracking resistance as measured by laboratory testing by reducing the number of gyrations and therefore increasing the mixture binder content.*

RECOMMENDATIONS

1. *VDOT's Materials Division and the Virginia Transportation Research Council (VTRC) should continue research that facilitates a better understanding of design criteria for dense-graded asphalt mixtures that promote the best compromise between rutting and cracking resistance. The proposed next step is a statewide pilot that involves a spectrum of raw materials and contractors from around Virginia. Specific design criteria for those trials are included in Appendix B, which is a revised Section 211 of VDOT's *Road and Bridge Specifications*.*
2. *VTRC should evaluate the design criteria included in the revised Section 211 (Appendix B) using accelerated pavement testing. As timing permits, the accelerated testing should incorporate preliminary findings from the statewide pilot proposed in Recommendation 1.*

BENEFITS AND IMPLEMENTATION

A “better understanding” of what contributes to good rutting and cracking resistance enables researchers and practitioners to establish criteria that will lead to better overall performance of asphalt mixtures. Continued development of laboratory performance tests (for rutting and cracking) may also enable innovation toward more sustainable materials that use a higher amount of recycled product and advanced modifiers. Full-scale accelerated loading lets researchers safely push the limits of design concepts without concern for failure under “live” traffic.

This study precipitated a VDOT Special Provision for Section 211 of VDOT's *Road and Bridge Specifications*, which introduced specifications for the design of dense-graded asphalt mixtures at 50 gyrations (see Appendix B). The special provision guided an extensive series of trial mixtures that were placed, sampled, and tested during VDOT's 2015 construction season. The results of the 2015 work supported additional revisions that will see further trial in 2016.

ACKNOWLEDGMENTS

The authors thank the technical review panel for this study: Robert Crandol, Stacey Diefenderfer, Sungho Kim, David Lee, and Todd Rorrer from VDOT and Trenton Clark from the Virginia Asphalt Association. The research team also thanks William Hobbs and Kenny

Smith from VTTI for preparing the samples and the four asphalt producers that provided the tested mixtures.

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APPENDIX A

STATISTICAL ANALYSIS OF TEST RESULTS

A statistical analysis of cracking and rutting test results was performed to evaluate whether the observed performance differences when binder was added to the mixtures are statistically significant. Because the variability in the test results is not normally distributed, traditional tests such as the t-test or the Analysis of Variance (ANOVA) cannot be used. For this reason, the Wilcoxon rank sum test (or Mann-Whitney U-test) was used to evaluate the difference in performance between pairwise test results as a substitute for the t-test, while the Kruskal-Wallis one-way ANOVA was used as a substitute for the traditional ANOVA. Both these tests are non-parametric and can be used when the distribution of the variables is not known. Given g groups (here a group is identified as a set of specimens from one of the producers at a specific asphalt content) with n_i measurements per group, the Kruskal-Wallis test calculates the statistic K as follows:

$$K = (N - 1) \frac{\sum_{i=1}^g n_i \left(\bar{r}_i - \frac{N+1}{2} \right)^2}{\sum_{i=1}^g \sum_{j=1}^{n_i} \left(r_{ij} - \frac{N+1}{2} \right)^2} \quad (5)$$

where

$$\begin{aligned} N &= \text{total number of observations;} \\ n_i &= \text{number of observations in group } i; \\ r_{ij} &= \text{rank among all observations of observation } j \text{ from group } i; \\ \bar{r}_i &= \frac{\sum_{j=1}^{n_i} r_{ij}}{n_i} \text{ is the average rank of all observations in group } i; \end{aligned}$$

The distribution of the test statistic K is well approximated by a chi-squared distribution (for $n_i > 4$) which can be used to determine the significance of the calculated K . For the Wilcoxon rank sum test (which is used to compare pairwise group), the test statistic U is determined as the smallest U_i ($i = 1, 2$ representing each of the two groups) where U_i is calculated as follows

$$U_i = n_i \times \bar{r}_i - \frac{n_i(n_i + 1)}{2} \quad (6)$$

The test statistic U is converted to a p-value using significance tables (in this study, the software Matlab was used to calculate the p-values).

For the Wilcoxon rank sum test, with four mixtures and four asphalt content levels per mixture, the resulting number of pairwise comparisons is 24 leading to 24 calculated p-values. This large number of p-values is problematic if statistical hypothesis testing is used without modification. The problem that arises is illustrated in Figure 5 which shows the actual p-value

control versus the desired p-value control. The case of a single p-value being evaluated is represented by the line of equality which shows that the desired and actual p-value control are the same. However, when 24 p-values are tested, the actual p-value control is much higher than the desired p-value control. For the case of the widely used significance level of 0.05, the actual achieved significance level is 0.71. This could be interpreted that, using a significance level of 0.05, there is a 71% of wrongly observing a significant difference (making a type I error) when in reality there is none.

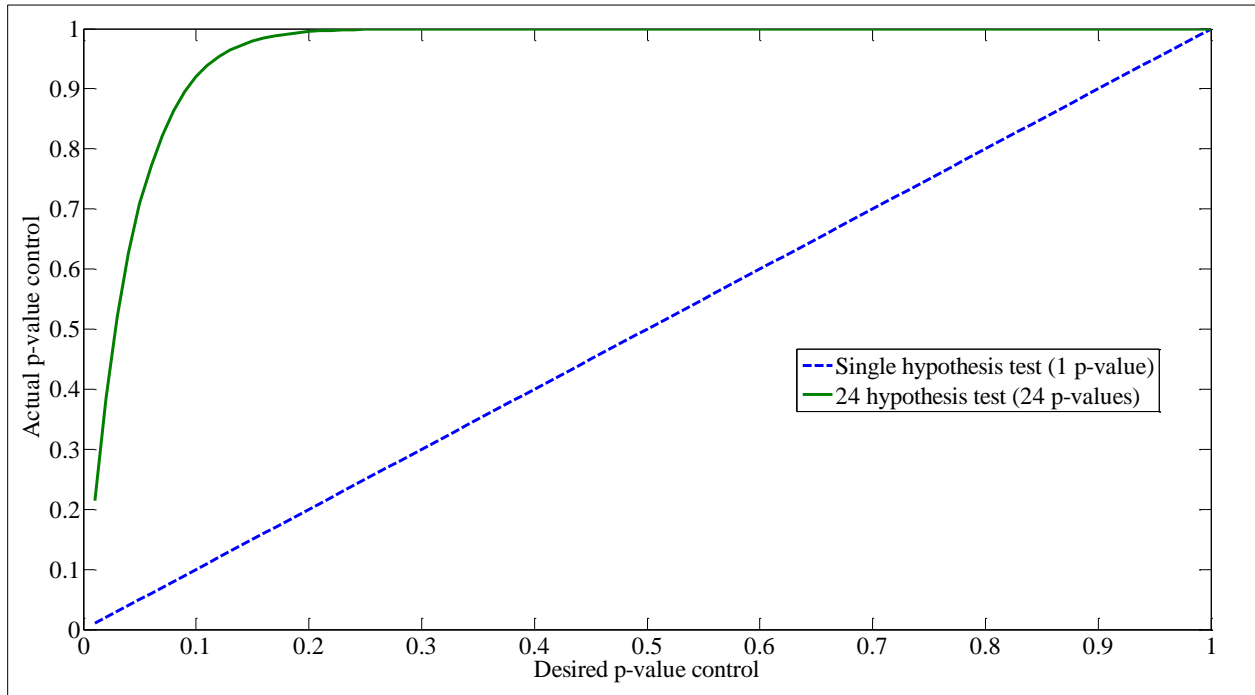


Figure 5. Type I Error Rate With Unadjusted Hypothesis Testing

Therefore, the False Discovery Rate (FDR), first proposed by Benjamini and Hochber (1995), was used to take into account the multiplicity of the p-values. The FDR is a slightly different concept that controls the expected proportion of false discoveries among all discoveries. The main advantage of the FDR is that it automatically takes into account the number of p-values being evaluated. In FDR terminology, a discovery is an observation for which the null hypothesis (of no difference) is rejected. To determine which observations are discoveries, a q value is selected as the FDR control level. For example, a selected q value of 0.1 means that the expected proportion of wrongly identified discoveries is 0.1 (or 10%). Once the q value is selected, discoveries can be identified using a linear step up procedure. The original procedure for m p-values given by Benjamini and Hochberg (1995) proceeds as follows:

1. Order the m p-values in increasing order ($p_{(1)} \leq p_{(2)} \leq \dots \leq p_{(i)} \leq \dots \leq p_{(m)}$)
2. Calculate $\frac{i}{m}q$ for $i = 1, \dots, m$
3. Determine k as the largest i for which $p_{(i)} \leq \frac{i}{m}q$

4. Reject the null hypothesis for all $p_{(i)} \leq p_{(k)}$ resulting in k rejections which are the discoveries

Benjamini and Hochberg (1995) proved that this procedure, which has now become known as the BH procedure, guarantees that the FDR is controlled at a level equal to $a \times q$, where $0 \leq a \leq 1$ is the true (unknown) proportion of the observations that follow the null hypothesis (i.e. that should not be labeled as discoveries). This shows that BH is conservative and could be improved if a is known. Gavrilov et al. (2009) proposed an adaptive procedure that estimates a and still controls the FDR. Their approach consists of replacing

$$\frac{i}{m}q$$

in step 3 of BH with

$$\frac{i}{m+1-i(1-q)}q.$$

Control of the FDR either with BH or with the method of Gavrilov et al. (2009) has a graphical interpretation which will be presented in the results section.

Statistical Analysis of Test Results

Flow Number

The statistical analysis for significance of the effect of binder content was performed with two nonparametric tests, the Kruskal-Wallis one-way ANOVA and the Wilcoxon rank sum test. These tests were selected because they can be used with non-normally distributed data which is the case for both the flow number and IDT test results.

The Kruskal-Wallis one-way ANOVA for mixtures obtained from each producer shows a significant change in performance at the 0.05 level for both mix A and mix B (adjusting for multiplicity, only mix A is found to be significant). Note that the p-values for mix C and mix D are less than 0.10 which suggests moderate significance. This can be justified by FDR control analysis at a level $q = 0.10$. In this case, the sorted p-values are 0.0033, 0.0448, 0.0874, and 0.0933. These would be tested against 0.025, 0.05, 0.075, and 0.1 (iq/m with $m = 4$, $q = 0.1$ and $i = 1, 2, 3, 4$ is the ranking). The FDR approach determines the largest p-value less than or equal to its corresponding test statistic (iq/m). In this case, the largest p-value satisfying this criterion is 0.0933 (≤ 0.10) and all p-values are deemed significant with a FDR equal to 0.10 (i.e. one would expect $4 \times 0.10 = 0.4$ of the rejected hypothesis to be wrong).

Table 5. Kruskal -Wallis One-Way ANOVA with Resulting p-value for Flow Number Performance

	A	B	C	D
p-value (KW)	0.0033	0.0448	0.0933	0.0874

The Kruskal-Wallis with FDR control at a level of 0.10 suggests that for each mixture, the binder content had an effect on the flow number. The Wilcoxon rank sum test can be used to further investigate pairwise differences within the same mix. There are 4 different binder content levels, which results in 6 possible pairwise comparison for each mixture for a total of 24 comparison for the 4 mixtures (24 p-values). Figure 6 shows a graphical interpretation of the FDR approach. The x-axis represents the theoretical p-value if there is no difference (i.e. p-value for the null). For example, if there was no difference, the p-value of the mid observation should be 0.5. The y-axis represents the observed (calculated) p-value. The line of equality represents the ideal case for the null (i.e. the theoretical and observed are equal). The observed data for the flow number significantly deviates from this ideal line of equality. The remaining curves show the line used in the testing FDR procedure which are

$$\frac{i}{m}q$$

for the non-adaptive approach and

$$\frac{i}{m+1-i(1-q)}q$$

for the adaptive approach. The last point where the FDR line crosses the observed data is taken as the cut-off of what is deemed significant. For the observed data, both $q = 0.10$ and $q = 0.20$ result in rejecting 20 of the 24 p-values using the adaptive FDR approach suggesting a difference in performance. What FDR does is provide an upper bound on the expected proportion of false discoveries (wrong rejections); it however does not give the proportion of false discoveries in the observed data. As such, it cannot be ascertained that $20 \times 0.1 = 2$ of the discoveries are wrong. It could be that 1, 2, 5, or none are wrong but on average, 2 or less will be wrong when following the FDR controlling approach.

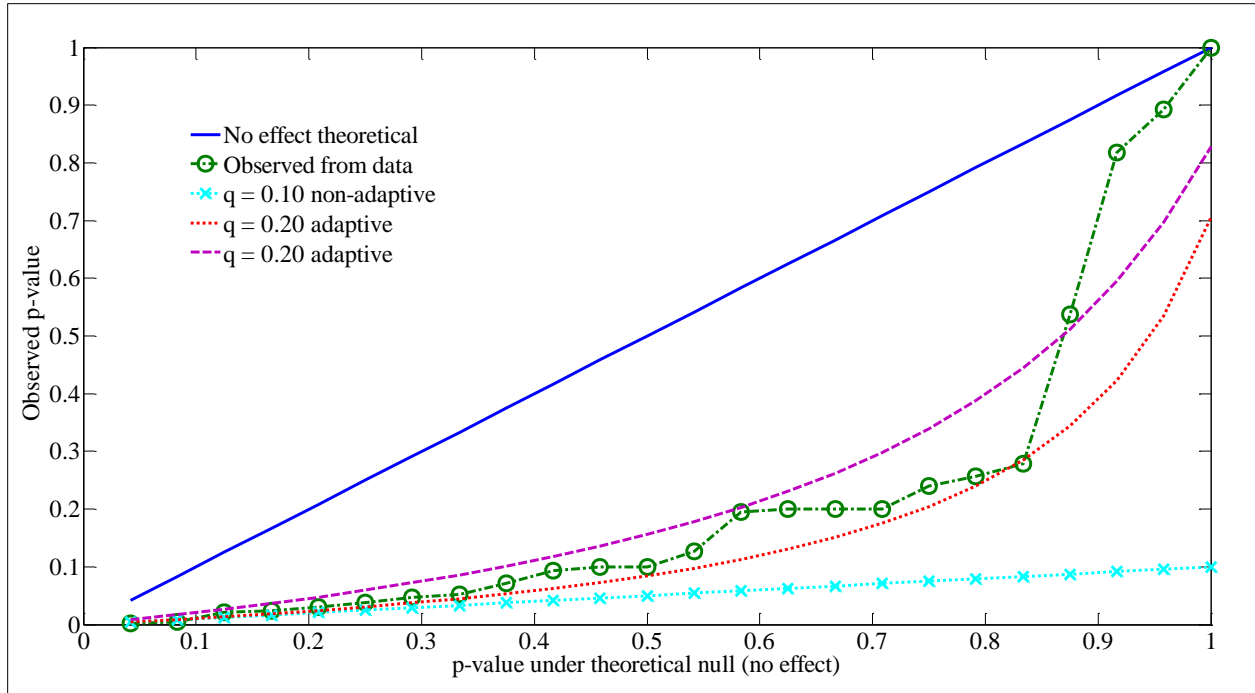


Figure 6. Graphical Representation of FDR Control for Flow Number Test Results

IDT FE Index

The Wilcoxon rank sum test for the IDT FE Index is shown in Figure 7. Both $q = 0.10$ and $q = 0.20$ result in no rejections of the null hypothesis. Most observations lying below the line of equality suggests possible effect however no strong evidence is provided by the data. Using $q = 0.50$ results in all of the smallest 17 p-values lying below the FDR line. Using FDR control at a level of 0.50 can result in rejecting the null hypothesis for some observed p-values can occur 50% of the time. However, a simulation (1 million simulated cases) was done to see the probability of rejecting 17 p-values out of a total of 24 and the results showed that this occurred in only 0.88% of the cases.

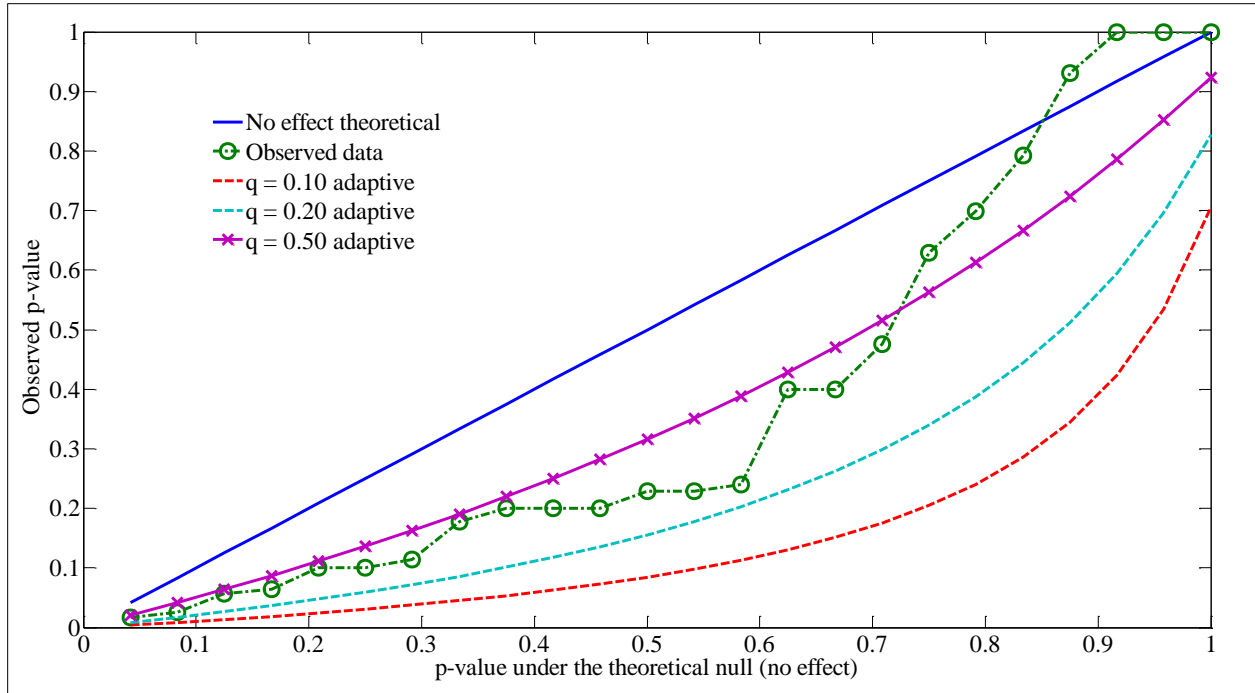


Figure 7. Graphical Representation of FDR Control for FE Index Test Results

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APPENDIX B

SECTION 211—ASPHALT CONCRETE

Section 211.01—Description

Asphalt concrete shall consist of a combination of mineral aggregate and asphalt material mixed mechanically in a plant specifically designed for such purpose.

An equivalent single-axle load (ESAL) will be established by the Engineer, and SUPERPAVE mix types may be specified as one of the types listed as follows:

Mix Type	Equivalent Single-Axle Load (ESAL) Range (millions)	Minimum Asphalt Performance Grade (PG) ²	Aggregate Nominal Maximum Size ¹
SM-9.0A	0 to 3	64S-16	3/8 in
SM-9.0D	3 to 10	64H-16	3/8 in
SM-9.0E	Above 10	64E-22	3/8 in
SM-9.5A	0 to 3	64S-16	3/8 in
SM-9.5D	3 to 10	64H-16	3/8 in
SM-9.5E	Above 10	64E-22	3/8 in
SM-12.5A	0 to 3	64S-16	1/2 in
SM-12.5D	3 to 10	64H-16	1/2 in
SM-12.5E	Above 10	64E-22	1/2 in
IM-19.0A	Less than 10	64S-16	3/4 in
IM-19.0D	10 to 20	64H-16	3/4 in
IM-19.0E	20 and above	64E-22	3/4 in
BM-25.0A	All ranges	64S-16	1 in
BM-25.0D	Above 10	64H-16	1 in

¹**Nominal Maximum Size** is defined as one sieve size larger than the first sieve to retain more than 10 percent aggregate.

²**Minimum Asphalt Performance Grade (PG)** is defined as the minimum binder performance grade for the job mixtures as determined by AASHTO T170 or AASHTOM332.

Asphalt concrete shall conform to the requirements for the mix type designated on the plans or elsewhere in the contract for use

At the Contractor's option, an approved Warm Mix Asphalt (WMA) additive or process may be used to produce the asphalt concrete (AC) mix type designated.

211.02—Materials

- (a) **Asphalt materials** shall conform to the requirements of Section 210 except asphalt cement materials shall be performance graded (PG) in accordance with the requirements of AASHTO M332. In addition, asphalt mixtures with the E designation shall meet the asphalt cement requirements in Section 211.04(e)1.
- (b) **Coarse aggregate** shall be Grade A or B conforming to the requirements, except for grading, of Section 203 for quality. In addition, the coarse aggregate sizes retained on and above the No. 4 sieve shall comply with the coarse aggregate requirements in Table II-12A. Flat and elongated (F&E) particles shall be tested in accordance with the requirements of ASTM D 4791, and coarse aggregate angularity (CAA) shall only be tested on crushed gravel in accordance with the requirements of ASTM D 5821.
- (c) **Fine aggregate** shall conform to the requirements, except for grading, of Section 202 for quality and the fine aggregate requirements in Table II-12A. Fine aggregate angularity (FAA) shall be tested in accordance with the requirements of AASHTO T 304 (Method A) and the sand equivalent (SE) shall be tested in accordance with the requirements of AASHTO T 176.
- (d) After a gradation test is performed:
 - 1. If 10 percent or more of the material is retained on the No. 4 sieve, that portion shall be tested in accordance with the requirements for coarse aggregate.
 - 2. If 10 percent or more of the material passes the No. 4 sieve, that portion shall be tested for SE.
 - 3. If 10 percent or more of the material passes the No. 8 sieve, that portion shall be tested for FAA.
- (e) Fine or coarse aggregates that tend to polish under traffic will not be permitted in any final surface exposed to traffic except in areas where the two-way average daily traffic is less than 750 vehicles per day and as permitted elsewhere in these Specifications.

TABLE II-12A
Aggregate Properties

Mix Type	Coarse Aggregate Properties				
	CAA		ASTM D4791	Fine Aggregate Properties	
	1 fractured face	2 fractured faces	F & E “(5:1) % by weight	SE	FAA
SM-9.0 A	85% min.	80% min.	10% max. ¹	40% min.	40% min.
SM-9.0 D	85% min.	80% min.	10% max. ¹	45% min.	45% min.
SM-9.0 E	95% min.	90% min.	10% max. ¹	45% min.	45% min.
SM-9.5 A	85% min.	80% min.	10% max. ¹	45% min.	45% min.
SM-9.5 D	85% min.	80% min.	10% max. ¹	45% min.	45% min.
SM-9.5 E	95% min.	90% min.	10% max. ¹	45% min.	45% min.
SM-12.5 A	85% min.	80% min.	10% max. ¹	45% min.	45% min.
SM-12.5 D	85% min.	80% min.	10% max. ¹	45% min.	45% min.
SM-12.5 E	95% min.	90% min.	10% max. ¹	45% min.	45% min.
IM-19.0 A	85% min.	80% min.	10% max. ¹	45% min.	45% min.
IM-19.0 D	95% min.	90% min.	10% max. ¹	45% min.	45% min.
IM-19.0 E	95% min.	90% min.	10% max. ¹	45% min.	45% min.
BM-25.0 A	80% min.	75% min.	10% max. ¹	45% min.	45% min.
BM-25.0 D	80% min.	75% min.	10% max. ¹	45% min.	45% min.

¹10 percent measured at 5:1 on maximum to minimum dimensions

- (f) **Mineral filler** shall conform to the requirements of Section 201.
- (g) **Aggregate for asphalt concrete** shall be provided in sufficient sizes and amounts to produce a uniform mixture. The Contractor shall indicate on the proposed job-mix formula the separate approximate sizes of aggregate to be used.

Where segregation or nonuniformity is evident in the finished pavement, the Engineer reserves the right to require the Contractor to discontinue the use of crusher run or aggregate blends and to furnish separate sizes of open-graded aggregate material.

- (h) An antistripping additive shall be used in all asphalt mixtures. It may be hydrated lime or a chemical additive from the VDOT Materials Division Approved Products List No. 7 or a combination of both. The approved chemical additive shall be added at a rate of not less than 0.30 percent by weight of the total asphalt content of the mixture.

The mixture shall produce a tensile strength ratio (TSR) of not less than 0.80 for the design and production tests. The TSR shall be determined in accordance with AASHTO T283, including a freeze-thaw cycle (4-inch specimens compacted with a Marshall Hammer or 3.5 by 6-inch specimens when compacted with a gyratory compactor); except that the 16-hour curing time requirement and the 72 to 96-hour storage period will not be enforced by the Department. Design tests shall use the same materials that are to be used in the production mix and shall be conducted in a laboratory approved by the Department.

When a chemical additive is used, it shall be added to the asphalt cement prior to the introduction of the cement into the mix. Any chemical additive or particular concentration of chemical additive found to be harmful to the asphalt material or that changes the original asphalt binder performance grade (PG) shall not be used.

- (i) **Hydrated lime** shall conform to the requirements of ASTM C977. Hydrated lime shall be added at a rate of not less than 1 percent by weight of the total dry aggregate.

A separate bin or tank and feeder system shall be provided to store and accurately proportion the dry or slurried lime into the aggregate... The lime and aggregate shall be mixed by pugmill or other Department approved means to achieve a uniform lime coating of the aggregate prior to entering the drier. If lime is added in dry form, the aggregate shall contain at least 3 percent free moisture. The Department will not permit the stockpiling of lime treated aggregate.

The feeder system shall be controlled by a proportioning device, which shall be accurate to within ± 10 percent of the specified amount. The proportioning device shall have a convenient and accurate means of calibration. A flow indicator or sensor shall be provided with the proportioning device and interlocked with the plant controls, aggregate feed or weigh system, such that production of the mixture shall be consistently maintained and, if there is a stoppage of the lime feed, interrupted.

The method of introducing and mixing the lime and aggregate shall be subject to approval by the Engineer prior to beginning production.

- (j) **Reclaimed Asphalt Pavement (RAP)** material may be used as a component material of asphalt mixtures in conformance with the following:

1. Asphalt surface, intermediate and base mixtures containing RAP (but without RAS) should use the performance grade (PG) of asphalt cement as indicated in Table II-I4A, however, the choice of PG to use in the mix shall be the responsibility of the Contractor in order to meet the requirements of Section 211.01.
2. The final asphalt mixture shall conform to the requirements for the type specified.
3. During the production process, RAP material shall not be allowed to contact open flame.

4. RAP material shall be handled, hauled, and stored in a manner that will minimize contamination. Further, the material shall be stockpiled and used in such manner that variable asphalt contents and asphalt penetration values will not adversely affect the consistency of the mixture.
5. RAP shall be processed in such a manner as to ensure that the maximum top size particle of material introduced into the mix shall be 2 inches. The Engineer may require smaller sized particles to be introduced into the mix if the reclaimed particles are not broken down or uniformly distributed throughout the mixture during heating and mixing.

(k) **Reclaimed Asphalt Shingles (RAS) – Tear-off RAS Materials** in Asphalt Concrete

1. Asphalt surface, intermediate, and base mixtures containing **Tear-off RAS Materials** shall meet the requirements of Section 211.01 and 211.03 of the Specifications.
2. Tear-off RAS Materials shall be discarded shingle scrap from the re-roofing of domestic buildings. These tear-offs shall have been produced by the manufacturing process for roofing shingles.
Tear-off RAS materials shall contain less than 3.0 percent foreign materials such as paper, roofing nails, wood, or metal flashing. Materials shall be shredded prior to being incorporated in the AC mixture so that at least 99 percent of the shredded pieces passes the ½ inch (12.5 mm) sieve and at least 80 percent passed the #4 (4.75 mm) sieve.

Tear-off RAS materials shall not have asbestos containing material (ACM) as defined by the National Emission Standards for Hazardous Air Pollutants (NESHAP), which is less than 1 percent asbestos. The Contractor shall furnish a certification obtained from the recycler that Polarized Light Microscopy (PLM) tests were performed on random samples of RAS at the rate of 1 test per 100 tons or if operating under a Virginia DEQ permit the rate will be the 1 test per 750 tons. The test results shall reveal no detectable level of ACM. Copies of the test results from the recycler shall be available upon request.

3. Asphalt Binder of the asphalt concrete mixture shall be Performance Grade (PG) of asphalt conforming to the requirements specified in Section 211 of the Specifications.
4. RAS tear-offs in asphalt concrete shall be mixed mechanically in a plant specifically designed for asphalt concrete production.
5. Contractors shall store tear-off RAS materials by stockpiling either whole or as partial shingles which have not been shredded or shredded shingles that meet the maximum size requirements. Stockpiled RAS shall not be contaminated by dirt or other objectionable foreign materials. Blending of the shingles with fine aggregate may be necessary to prevent conglomeration of shingle particles. When fine aggregate is used for this purpose, this material shall be accounted for in the mix design.

(l) **Reclaimed Asphalt Shingles (RAS) – Tabs RAS Materials** in Asphalt Concrete

1. Asphalt surface, intermediate, and base mixtures containing **Tabs RAS Materials** shall meet the requirements of Section 211.01 and 211.03 of the Specifications.

2. Tabs RAS Materials shall be produced by the manufacturing process for domestic roofing shingles. Blending or mixing of Tabs and Tear-offs shall not be permitted. RAS Materials shall be shredded prior to being incorporated into the asphalt concrete mixture so that one hundred percent of the shredded pieces are less than ½ inches (12.5 mm) in any dimension.

RAS Materials shall not contain asbestos fibers. The Contractor shall furnish the Department a certification from the manufacturer of the shingles stating that the shingles are free of asbestos. If a certification cannot be obtained then the contractor shall furnish test results of RAS sample analysis for Polarized Light Microscopy (PLM) on the shingles which certify the material to be used is free of asbestos. Testing is required at the specified rate of 1 per manufacturer per type of RAS prior to processing and results shall be submitted prior to or during the stockpile approval process.

3. Asphalt Binder of the asphalt concrete mixture shall be Performance Grade (PG) of asphalt conforming to the requirements specified in Section 211 of the Specifications.
4. Tabs RAS Materials in asphalt concrete shall be mixed mechanically in a plant specifically designed for asphalt concrete production.
5. Contractors shall store Tabs RAS materials by stockpiling either whole or as partial shingles which have not been shredded or shredded shingles that meet the maximum size requirements. Stockpiled RAS shall not be contaminated by dirt or other objectionable foreign materials. Blending of the shingles with fine aggregate may be necessary to prevent conglomeration of shingle particles. When fine aggregate is used for this purpose, this material shall be accounted for in the mix design.

- (k) **Warm Mix Asphalt (WMA)** additives or processes shall be approved by the Department prior to use and shall be obtained from the Department’s approved list which is included in the Materials Division’s Manual of Instructions.

211.03—Job-Mix Formula

The Contractor shall submit a job-mix formula for each mixture planned for use on the project for the Department’s evaluation and approval through the “Producer Lab Analysis and Information Details” (PLAID) website. Paper copies of the job mix formula along with supporting documentation shall also be submitted to the Department. The job-mix formula shall be within the design range specified. The job-mix formula shall establish a single percentage of aggregate passing each required sieve, a single percentage of asphalt material to be added to the aggregate, a temperature at which the mixture is to be produced, and a temperature at which the mixture is to be compacted for SUPERPAVE testing in accordance with the requirements of AASHTO R35. Each approved job-mix formula shall remain in effect provided the results of tests performed on material currently being produced consistently comply with the requirements of the job-mix formula for grading, asphalt content, temperature, and SUPERPAVE compaction results and the requirements of Section 315.

- (a) SUPERPAVE mixtures shall be designed and controlled in accordance with the requirements of AASHTO R35 and as specified herein. The Contractor shall have available all of the equipment outlined in AASHTO T312 (Section 4-6) and a Department-certified Asphalt Mix Design Technician. The SUPERPAVE mixture shall be compacted in a gyratory compactor with an internal angle of 1.16 ± 0.02 degrees. **The internal angle shall be measured and calibrated using a cold (non-mix) device.** The SUPERPAVE Gyratory Compactor (SGC) shall be one from the Department’s approved list of devices found in the VDOT Materials

Division's Manual of Instructions. The SUPERPAVE mixtures shall conform to the requirements of Table II-13 and Table II-14. Section 7.1.2 of AASHTO R30 shall be modified such that the compaction temperature is as specified in (d) 6 herein.

- (b) In conjunction with the submittal of a job-mix formula, the Contractor shall submit complete SUPERPAVE design test data, ignition furnace calibration data in accordance with VTM-102 prepared by an approved testing laboratory, and viscosity data or supplier temperature recommendations for the asphalt cement if different from (d) 6 herein.
- (c) Three trial blends for gradation shall be run at one asphalt content

TABLE II-13
Asphalt Concrete Mixtures: Design Range¹

Mix Type	Percentage by Weight Passing Square Mesh Sieves										
	2 in	1 1/2 in	1 in	3/4 in	1/2 in	3/8 in	No. 4	No. 8	No. 30	No. 50	No. 200
SM-9.0 A,D,E					100 ²	90-100	90 max.	47-67			2-10
SM-9.5 A,D,E					100 ²	90-100	58-80	38-67	23 max		2-10
SM-12.5 A,D,E				100	95-100	90 max.	58-80	34-50	23 max		2-10
IM-19.0 A,D,E			100	90-100	90 max.	--	--	28-49			2-8
BM-25.0 A,D		100	90-100	90 max.	--	--	--	19-38			1-7
C (Curb Mix)					100	92-100	70-75	50-60	28-36	15-20	7-9

¹SM = Surface Mixture; IM = Intermediate Mixture; BM = Base Mixture; C = Curb Mixture.

²A production tolerance of 1% will be applied to this sieve regardless of the number of tests in the lot.

TABLE II-14
Mix Design Criteria

Mix Type	VTM (%) Production (Note 1)	VFA (%) Design	VFA (%) (Note 2)	Min. VMA (%)	Fines/Asphalt Ratio (Note 3)	No. of Gyrations N Design
SM-9.0A ^{Notes 1,2,3}	2.0-5.0	75-80	70-85	16	0.6-1.3	65
SM-9.0D ^{Notes 1,2,3}	2.0-5.0	75-80	70-85	16	0.6-1.3	65
SM-9.0E ^{Notes 1,2,3}	2.0-5.0	75-80	70-85	16	0.6-1.3	65
SM-9.5A ^{Notes 1,2,3}	3.0-6.0		- 65-80	16	0.7-1.3	50
SM-9.5D ^{Notes 1,2,3}	2.0-5.0 3.0-6.0		65-80	16	0.7-1.3	50
SM-9.5E ^{Notes 1,2,3}	2.0-5.0		70-85	16	0.7-1.3	50
SM-12.5A ^{Notes 1,2,3}	3.0-6.0		65-80	16	0.7-1.3	50
SM-12.5D ^{Notes 1,2,3}	3.0-6.0		65-80	16	0.7-1.3	50
SM-12.5E ^{Notes 1,2,3}	2.0-5.0		70-85	16	0.7-1.3	50
IM-19.0A ^{Notes 1,2,3}	2.0-5.0	69-76	64-81	13	0.6-1.2	65
IM-19.0D ^{Notes 1,2,3}	2.0-5.0	69-76	64-81	13	0.6-1.2	65
IM-19.0E ^{Notes 1,2,3}	2.0-5.0	69-76	64-81	13	0.6-1.2	65
BM-25.0A ^{Notes 2,3,4}	1.0-4.0	67-87	67-92	12	0.6-1.3	65
BM-25.0D ^{Notes 2,3,4}	1.0-4.0	67-87	67-92	12	0.6-1.3	65

¹SM = Surface Mixture; IM = Intermediate Mixture; BM = Base Mixture.

Note 1: Asphalt content should be selected at 4.0 % Air Voids for A & D mixtures, 3.5% air voids for E mixtures,

Note 3: Fines-asphalt ratio is based on effective asphalt content.

Note 4: Base mix shall be designed at 2.5% air voids. BM-25.0A shall have a minimum asphalt content of 4.4% unless otherwise approved by the Engineer. BM-25.0D shall have a minimum asphalt content of 4.6% unless otherwise approved by the Engineer.

- (d) The SUPERPAVE design test data shall include, but not be limited to, the following information:
1. Grading data for each aggregate component of three trial blends shall be submitted to the Department. The data for the mixture shall show percent passing for the following sieves: 2 inch, 1 1/2 inch, 1 inch, 3/4 inch, 1/2 inch, 3/8 inch, No. 4, No. 8, No. 16, No. 30, No. 50, No. 100, and No. 200. The grading shall be reported to the nearest 1.0 percent except the No. 200 sieve shall be reported to the nearest 0.1 percent.
 2. The test data shall include, but not be limited to, the percentage of each aggregate component as compared to the total aggregate in the asphalt mixture. The specific gravity and aggregate properties for coarse and fine aggregates defined in Section 211.02 (b) and (c), including flat and elongated properties, for each aggregate component or for the total aggregates used in the mixture shall be reported. Aggregate properties, except sand equivalent, shall be reported for RAP portions of a mixture. The aggregate specific gravity of RAP shall be the effective aggregate specific gravity calculated from the results of tests conducted in accordance with AASHTO T 209 and VTM-102.
 3. The aggregate grading in the asphalt mixture shall be determined by igniting or extracting the asphalt from a laboratory-prepared sample. The laboratory sample shall be batched on the basis of component percentages as indicated in (d) 2. herein and at the proposed job-mix asphalt content. The aggregate shall be obtained in accordance with the requirements of VTM-102 or VTM-36, when approved. Sieves specified in (d) 1. herein shall be reported, beginning with the top size for the mix.
 4. The following volumetric properties of the compacted mixture, calculated on the basis of the mixture's maximum specific gravity determined in accordance with AASHTO T-209, shall be reported to the Engineer. The mixture shall be aged in accordance with AASHTO R30 and the bulk specific gravity of the specimens determined in accordance with AASHTO T-166, Method A, for each asphalt content tested. Properties shall be determined and reported in accordance with the requirements of AASHTO R35.
 - a. Voids in total mix (VTM)
 - b. Voids in mineral aggregate (VMA)
 - c. Voids filled with Asphalt (VFA)
 - d. Fines/Asphalt ratio (F/A)
 5. The value of the maximum specific gravity of the asphalt mixture used in (c) 4. herein shall be reported to three decimal places.
 6. The mixing and compaction temperature for testing shall be as follows:
 - a. For mixtures designation A, the mix temperature shall be 300 degrees F to 310 degrees F and the compaction temperature shall be 285 degrees F to 290 degrees F.
 - b. For mixtures designation D, the mix temperature shall be 310 degrees F to 320 degrees F and the compaction temperature shall be 295 degrees F to 300 degrees F.
 - c. In cases involving PG 64E-22 or modified binders, the temperatures shall be based on documented supplier's recommendations.

7. The field correction factor as determined by subtracting the bulk specific gravity of the aggregate from the effective specific gravity of the aggregate at the design asphalt content.
 8. For surface mixtures, permeability test data shall be submitted in accordance with VTM 120 using either single point verification or the regression method for each surface mix having a different gradation. If the average of the permeability results from the single point verification method exceeds 150×10^{-5} cm/sec, or if the regression method predicts a permeability exceeding 150×10^{-5} cm/sec at 7.5% voids, the Contractor shall redesign the mixture to produce a permeability number less than 150×10^{-5} cm/sec.
- (e) The SUPERPAVE design binder content test data shall be plotted on graphs as described in AASHTO R 35 and shall show that the proposed job-mix formula conforms to the requirements of the designated mix type.
- (f) A determination will be made to verify if any asphalt concrete mixture being produced conforms to the job-mix formula approved by the Department. The Department and Contractor will test the mixture using samples removed from production. The following tests will be conducted to determine the properties listed:

Property	Test
Asphalt content	VTM-102, (VTM-36 when approved)
Gradation	AASHTO T-30
SUPERPAVE properties	AASHTO R35
Asphalt cement material	AASHTO T316 or T-201

For Warm Mix Asphalt (WMA), SUPERPAVE properties for mixing and compaction temperatures will be determined by the Department and Contractor based on the mix designations in Section 211.03(d)6.

The Department will perform rut testing in accordance with the procedures detailed in VTM-110. If the results of the rut testing do not conform to the following requirements, the Engineer reserves the right to require adjustments to the job-mix formula:

Mix Designation	Maximum Rut Depth, mm
A	7.0
D	5.5
E, (S)	3.5

After calibration of the gyratory compactor is completed, the Engineer may require the Contractor to make adjustments to the job-mix formula.

If the Department determines that the mixture being produced does not conform to the approved job-mix formula and volumetric properties specified in Table II-14 based on the Department's or

Contractor's test results, the Contractor shall immediately make corrections to bring the mixture into conformance with the approved job-mix formula or cease paving with that mixture.

Subsequent paving operations using either a revised or another job-mix formula that has not been verified as described herein shall be limited to a test run of 100 to 300 tons of mixture if such material is to be placed in Department project work. No further paving for the Department using that specific mixture shall occur until the acceptability of the mixture being produced has been verified using the 100 to 300 ton constraint.

TABLE II-14A

Recommended Performance Grade of Asphalt Cement

Mix Type	Percentage of Reclaimed Asphalt Pavement (RAP) in Mix		
	%RAP ≤ 25.0%	25.0% < %RAP ≤ 30%	25.0% < %RAP ≤ 35%
SM-4.75A, SM-9.0A, SM-9.5A, SM-12.5A	PG 64S-22	PG 64S-22	
SM-4.75D, SM-9.0D, SM-9.5D, SM-12.5D	PG 64H-22	PG 64S-22	
IM-19.0A	PG 64S-22	PG 64S-22	
IM-19.0D	PG 64H-22	PG 64S-22	
BM-25.0A	PG 64S-22		PG 64S-22
BM-25.0D	PG 64H-22		PG 64S-22

Based on rut testing performed by the Department and/or field performance of the job mix, the Engineer reserves the right to require the Contractor to make adjustments to the job-mix formula.

- (g) When utilizing **RAS Materials (Tear-off or Tabs)**, the Contractor shall submit material samples to include the RAS stockpiled tear-off shingles, reclaimed asphalt pavement (RAP) and PG Binder.

The amount of RAS material used in the recycled mixture shall be no more than five percent of the total mixture weight. However, the combined percentages of RAS and RAP shall not contribute more than 30 percent (by weight) of the total asphalt content of the mixture, according to the following equation:

$$\frac{\left(\%RAS_{mix} \times \%AC_{RAS} / 100 \right) + \left(\%RAP_{mix} \times \%AC_{RAP} / 100 \right)}{\%AC_{JMF}} \leq 30.0\%$$

Where:

$\% \text{RAS}_{mix} =$ Percent RAS in the Job Mix Formula

$\% \text{AC}_{RAS} =$ Average Percent AC in the RAS

$\% \text{RAP}_{mix} =$ Percent RAP in the Job Mix Formula

$\% \text{AC}_{RAP} =$ Average Percent AC in the RAP

$\% \text{AC}_{JMF} =$ Design AC content of the JMF

The Contractor shall determine the asphalt content of the RAS using AASHTO T-164, Method B, or VTM-102 and report the average results to the nearest 0.1 percent. When the ignition furnace is used, a correction factor shall be applied for the non-asphalt combustible materials in the RAS. Unless the actual correction factor is determined by comparing the test results on paired samples from AASHTO T-164 Method B and VTM-102, the estimated correction factor for the RAS shall be 5 percent.

Used separately or with RAP, RAS can be used to stiffen the asphalt concrete mixture binder to meet the requirements in Section 211.01 of Specifications. Asphalt surface, intermediate, and base mixtures containing RAS in order to meet the asphalt concrete mixture stiffness of PG 70-16 should use PG 64-22 asphalt cement. Further, mixtures using RAS shall not exceed the 30% (by weight) and are required to use the maximum binder replacement criteria noted here:

5% RAS and 0% RAP

4% RAS and 5% RAP minimum

3% RAS and 10% RAP minimum
2% RAS and 20% RAP minimum

Interpolation shall be used to determine combinations between the whole number RAS/RAP usage figures shown herein, subject to review and approval by the Engineer.

211.04—Asphalt Concrete Mixtures

Asphalt concrete mixtures shall conform to the requirements of Table II-14 and the following:

- (a) **Types SM-9.0A, SM-9.0D, SM-9.0E, SM-9.5A, SM-9.5D, SM-9.5E, SM-12.5A, SM-12.5D, and SM-12.5E asphalt concrete** shall consist of crushed stone, crushed slag, or crushed gravel and fine aggregate, slag or stone screenings, or a combination thereof combined with asphalt cement.

NOTE: For all surface mixtures, except where otherwise noted, no more than 5 percent of the aggregate retained on the No. 4 sieve and no more than 20 percent of the total aggregate may be polish susceptible. At the discretion of the Engineer, SM-9.5AL or SM-12.5AL may be specified and polish susceptible aggregates may be used (without percentage limits).

NOTE: Unless Type C (curb mix) is specified by the Engineer in the contract plans and specifications, SM9.0, SM-9.5, and SM-12.5 mix types are acceptable for use in the construction of asphalt curbing.

- (b) **Types IM-19.0A, IM-19.0D, and IM-19.0E asphalt concrete** shall consist of crushed stone, crushed slag, or crushed gravel and fine aggregate, slag or stone screenings, or a combination thereof combined with asphalt cement.

NOTE: At the discretion of the Engineer, an intermediate mix may be designated as either SM-19.0A, SM-19.0D or SM-19.0E. When designated as such, no more than 5 percent of the aggregate retained on the No. 4 sieve may be polish susceptible. All material passing the No. 4 sieve may be polish susceptible.

- (c) **Types BM-25.0A and BM-25.0D asphalt concrete** shall consist of crushed stone, crushed slag, or crushed gravel and fine aggregate, slag or stone screenings, or a combination thereof combined with asphalt cement.
- (d) **Type C (curb mix) asphalt concrete** shall consist of a blend of No. 78 or No. 8 crushed aggregate, No. 10 crushed aggregate, fine aggregate, mineral filler, and a stabilizing additive from the Department's approved list found in the Materials Division's Manual of Instructions combined with 6.0 to 9.0 percent of PG 64S-22. This mix does not require a volumetric mix design or volumetric testing under the SUPERPAVE system.
- (e) **Type SM-9.5, SM-12.5, IM-19.0 and BM-25.0 asphalt concrete** may be designated E (polymer modified), or stabilized (S). Asphalt concrete mixtures with the E designation may not be stabilized.
1. **Type E designated mixtures** shall consist of mixtures incorporating a neat asphalt material with polymer modification complying with the requirements of PG 76-22 and have a rolling thin film oven test residue elastic recovery at 77 degrees F of a minimum of 70 percent when tested in accordance with ASTM D 6084 procedure A... E designated mixtures shall not contain more than 15 percent reclaimed asphalt pavement (RAP) material (by weight) or 3% recycled asphalt shingles (RAS) (by weight).
 2. **Type (S) asphalt mixtures** shall consist of mixtures incorporating a stabilizing additive from the Department's approved list found in the Materials Division's Manual of Instructions. These mixtures shall be designated with an (S) following the standard mix designation. The minimum required additive shall be as specified on the Department's approved list found in the Materials Division's Manual of Instructions.
 3. **Type L asphalt mixtures** will be allowed to contain a 100 percent polishing coarse and fine aggregate. These mixtures shall be designated with a L following the standard mix designation.

211.05—Testing

The Contractor shall provide the quality control and quality assurance necessary for the Department to determine conformance with the required grading, asphalt content, and temperature properties for asphalt concrete.

The Contractor shall have a Department-certified Asphalt Mix Design Technician for designing and adjusting mixtures as necessary. The Asphalt Mix Design Technician or Asphalt Plant Level II Technician may perform testing of asphalt mixtures. The Asphalt Mix Design Technician shall be responsible for reviewing and approving the results of all testing. The Asphalt Mix Design Technician shall be available and have direct communication with the plant for making necessary adjustments in the asphalt concrete mixtures at the mixing plant. The Asphalt Mix Design Technician and Asphalt Plant Level II Technician shall each be capable of conducting any tests necessary to put the plant into

operation; however, the Asphalt Mix Design Technician shall be responsible for producing a mixture that complies with the requirements of these Specifications. The Department will award certification.

The Contractor shall maintain all records and test results associated with the material production and shall maintain appropriate current quality control charts. Test results and control charts shall be available for review by the Engineer.

The Contractor shall execute a quality control plan of process inspections and tests, including the determination of SUPERPAVE properties. The results of the SUPERPAVE tests shall be used, along with the results of other quality control efforts, to achieve and maintain the quality of the mixture being produced.

The Contractor shall perform at least one field SUPERPAVE test per day per mix or per 1,000 tons per mix if more than 1,000 tons of a mix is produced per day. Aging as described in AASHTO R30 shall not be performed. If less than 300 tons of asphalt mixture is produced under a single job-mix formula in a day, field 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 shall apply. Field SUPERPAVE test results shall be plotted and displayed in control chart form in the plant immediately following the completion of each individual test. The tests shall determine asphalt content in percentages to the nearest 0.01. The tests shall determine VTM, VMA, VFA, and F/A in percentages to the nearest 0.1 percent. The Department will conduct on-site inspections so the Contractor's Asphalt Mix Design Technician can demonstrate knowledge of the SUPERPAVE mix design and production requirements on Department-supplied mixtures.

Aggregate specific gravity and aggregate property tests shall be conducted by a Department-certified Aggregate Properties Technician or Asphalt Mix Design Technician on each aggregate component (including RAP) or total aggregate mixture once at mix design stage and once prior to beginning production in each calendar year. Sand equivalent shall not be determined on RAP. In addition, for each 50,000 tons of each aggregate size used at each plant, aggregate specific gravity and the results of aggregate property tests shall be reported for each aggregate component or the total aggregate mixture. Otherwise, if the total blend (cold feed) is used to determine aggregate specific gravity and aggregate properties, these tests shall be run for each 50,000 tons of the total blend.

Field SUPERPAVE tests shall be performed to N_{design} gyrations as specified in Table II-14.

For surface mixtures, permeability test data shall be submitted in accordance with VTM 120 using either single point verification or the regression method for each surface mix having a different gradation.

211.06—Tests

The Department may sample materials entering into the composition of the asphalt concrete, the mixture, or the completed pavement. The Contractor shall cooperate with the Engineer in obtaining these samples. When samples are obtained from the pavement by coring, the resulting voids shall be filled and refinished by the Contractor without additional compensation.

Abson recovery samples shall be PG graded according to the requirements of AASHTO M 322-14. Samples meeting the required grades specified in Section 211.01 shall be acceptable.

When the Department performs PG grading on the asphalt in a Contractor's liquid asphalt storage tank, the Engineer will notify the asphalt concrete producer and binder supplier if tests indicate that the binder properties of the asphalt material differ from those of the approved job-mix. The asphalt concrete producer and binder supplier shall determine what corrective action must be taken with the approval of the Engineer.

211.07—Plant Inspection

The Department will accept the preparation of asphalt concrete mixtures under a quality assurance plan. The Contractor shall provide a laboratory as specified in Section 106.07.

In addition, the Contractor shall have all laboratory scales and gyratory compactors calibrated once a year by an independent source. The Contractor shall maintain the calibration records for 3 years from the date of the last calibration.

211.08—Acceptance

Acceptance will be made under the Department's quality assurance program, which includes the testing of production samples by the Contractor and of monitor samples by the Department. Sampling and testing for the determination of grading, asphalt cement content, and temperature shall be performed by the Contractor, and the Department will perform independent monitor checks at a laboratory of its choosing. The Contractor shall input such test results within 24 hours of sampling to the Department through the "Producer Lab Analysis and Information Details" (PLAID) website <https://plaid.vdot.virginia.gov>, unless otherwise approved by the appropriate District Materials Engineer.

Where the Contractor's test results indicate that the mixture conforms to the gradation, asphalt cement content, and mix temperature requirements of the Specifications, the mixture will be acceptable for these properties; however, nothing herein shall be construed as waiving the requirements of Section 106.06, Section 200.02, Section 200.03, and Section 315 of the Specifications or relieving the Contractor of the contractual obligation to furnish and install a finished functional product that conforms to the requirements of the Contract.

If a statistical comparative analysis of the Contractor's test results and the Department's monitor tests indicate a statistically significant difference in the results and either of the results indicates that the material does not conform to the grading and asphalt cement content requirements of the Specifications, the Department and the Contractor will make an investigation to determine the reason for the difference. If it is determined from the investigation that the material does not conform to the requirements of the Contract, price adjustments will be made in accordance with the requirements of Section 211.09.

Acceptance for gradation and asphalt cement content will be based on the mean of results of eight tests performed on samples taken in a stratified random manner from each 4,000-ton lot (8,000-ton lots may be used when the normal daily production of the source from which the material is being obtained is in excess of 4,000 tons). The Contractor shall take samples from the approximate center of the truckload of material unless otherwise approved by the Engineer. Any statistically acceptable method of randomization may be used to determine when to take the stratified random sample; however, the Department shall be advised of the method to be used prior to the beginning of production.

A lot will be considered to be acceptable for gradation and asphalt content if the mean of the test results obtained is within the tolerance allowed for the job-mix formula as specified in Table II-15.

The temperature of the mixture at the plant shall be controlled to provide load-to-load uniformity during changing weather conditions and surface temperatures. The maximum temperature of mix designations A and D and base mixtures shall not exceed 350 degrees F unless otherwise directed by the Engineer. The maximum temperature as recommended by the supplier shall not be exceeded for a mix designated E or (S).

If the job-mix formula is modified within a lot, the mean test results of the samples taken will be compared to the applicable process tolerance shown in Table II-15.

Asphalt content will be measured as extractable asphalt or weight after ignition.

Field SUPERPAVE tests will be performed by the Department in accordance with the requirements of AASHTO R35 during the production of the approved job mixtures designed by the SUPERPAVE method. Aging, as described in AASHTO R30, will not be performed. Should any field SUPERPAVE test fail with regard to the limits specified in Table II-14, the Department may require that production be stopped until necessary corrective action is taken by the Contractor. The Engineer will investigate and determine the acceptability of material placed and represented by failing field SUPERPAVE test results.

Should visual examination by the Engineer reveal that the material in any load or portion of the paved roadway is obviously contaminated or segregated, that load or portion of the paved roadway will be rejected without additional sampling or testing of the lot. If it is necessary to determine the gradation or asphalt content of the material in any load or portion of the paved roadway, samples will be taken and tested and the results will be compared to the requirements of the approved job-mix formula. The results obtained in the testing will apply only to the material in question.

TABLE II-15
Process Tolerance

Tolerance on Each Laboratory Sieve and Asphalt Content: Percent Plus and Minus												
No. Tests	Top Size¹	1 ½"	1"	¾"	½"	3/8"	No. 4	No. 8	No. 30	No. 50	No. 200	AC
1	0.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	6.0	5.0	2.0	.60
2	0.0	5.7	5.7	5.7	5.7	5.7	5.7	5.7	4.3	3.6	1.4	0.43
3	0.0	4.4	4.4	4.4	4.4	4.4	4.4	4.4	3.3	2.8	1.1	0.33
4	0.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	3.0	2.5	1.0	0.30
5	0.0	3.6	3.6	3.6	3.6	3.6	3.6	3.6	2.7	2.2	0.9	0.27
6	0.0	3.3	3.3	3.3	3.3	3.3	3.3	3.3	2.4	2.0	0.8	0.24
7	0.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	2.3	1.9	0.8	0.23
8	0.0	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.1	1.8	0.7	0.21
12	0.0	2.3	2.3	2.3	2.3	2.3	2.3	2.3	1.7	1.4	0.6	0.17

¹Defined as the sieve that has 100% passing as defined in Table II-13.

211.09—Adjustment System

If a lot of material does not conform to the acceptance requirements of Section 211.08, the Department will determine adjustment points as follows:

Adjustment Points for Each 1% the Gradation Is Outside the Process Tolerance Permitted In Table II-15

Sieve Size	(Applied in 0.1% increments)
1 1/2 in	1
1 in	1
3/4 in	1
1/2 in	1
3/8 in	1
No. 4	1
No. 8	1
No. 30	2
No. 50	2
No. 200	3

One adjustment point will be applied for each 0.1 percent that the material is out of the process tolerance for asphalt content.

If the total adjustment for a lot is greater than 25 points, the Contractor shall remove the failing material from the road. 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 1 percent of the unit price bid for each adjustment point the material is outside of the process tolerance. The Engineer will apply this adjustment to the tonnage represented by the sample(s). If the Engineer applies adjustment points against two successive lots, the Contractor shall ensure plant adjustment is made prior to continuing production.

The Contractor shall control the variability of the Contractor’s product in order to furnish a consistently uniform mix. When the quantity of any one type of material furnished to a project exceeds 4,000 tons, the variability of the total quantity furnished will be determined on the basis of the standard deviation for each sieve size and the asphalt content. If the standard deviation is within the ranges specified in Table II-16, the Engineer will adjust the unit bid price for the material as indicated herein. The Engineer will not make adjustments for standard deviation computations on more than two job mixtures for the same type of material.

TABLE II-16
Standard Deviation

Sieve Size and A.C.	Standard Deviation 1 Adjustment Point for Each Sieve Size and A.C.	2 Adjustment Points for Each Sieve Size and A. C.	3 Adjustment Points for Each Sieve Size and A.C.
1/2 in.	3.8-4.7	4.8-5.7	5.8-6.7
3/8 in	3.8-4.7	4.8-5.7	5.8-6.7
No. 4	3.8-4.7	4.8-5.7	5.8-6.7
No. 8	3.0-3.9	4.0-4.9	5.0-5.9
No. 30	2.2-3.1	3.2-4.1	4.2-5.1
No. 50	1.5-2.4	2.5-3.4	3.5-4.4
No. 200	1.1-2.0	2.1-3.0	3.1-4.0
A.C.	0.27-0.36	0.37-0.46	0.47-0.56

The Engineer will reduce the unit bid price by 0.5 percent for each adjustment point applied for standard deviation.

211.10—Referee System

- (a) If the test results obtained from one of the eight samples taken to evaluate a particular lot appear to be questionable, the Contractor may request in writing that the results of the questionable sample be disregarded, whereupon the Contractor shall have either an AASHTO-accredited lab or a Department lab perform tests on five additional samples taken from randomly selected locations in the roadway where the lot was placed.

If the Engineer determines that one of the 8 test results appears to be questionable, the Department will perform tests on five additional samples taken from the randomly selected locations in the roadway where the lot was placed. The test results of the seven original, i.e. unquestioned, samples will be averaged with the test results of the five road samples, and the mean of the test values obtained for the twelve samples will be compared to the requirements for the mean of twelve tests as specified in Table II-15.

- (b) If the Contractor questions the mean of the eight original test results obtained for a particular lot, the Contractor may request in writing approval to have either an AASHTO-accredited lab or a Department lab perform additional testing of that lot.

If the Engineer determines that the mean of the eight original test results are questionable, the Department will perform additional testing of that lot. The test results of the eight samples will

be averaged with the test results of four additional samples taken from randomly selected locations in the roadway where the lot was placed, and the mean of the test values obtained from the twelve samples will be compare to the requirements for the mean of twelve tests as specified in Table II-15.

If the Contractor requests additional tests, as described in (a) or (b) herein, the Contractor shall sample the material and have either an AASHTO-accredited lab or Department lab test the material in accordance with Department-approved procedures. The Engineer may observe the sampling and testing.

If the mean of the test values obtained for the twelve samples conforms to the requirements for the mean of twelve tests, the material will be considered acceptable. If the mean of the test values obtained for the twelve samples does not conform to the requirements for the mean result of twelve tests, the lot will be adjusted in accordance with the adjustment rate specified in Section 211.09.

Samples of the size shown herein shall be saw cut by the Contractor for testing without the use of liquids:

Application Rate	Minimum Sample Size
125 lb/yd ²	8 by 8 in
150 lb/yd ²	7 by 7 in
200 lb/yd ²	6 by 6 in
300 lb/yd ²	5 by 5 in

211.11—Handling and Storing Aggregates

Aggregates shall be handled, hauled, and stored in a manner that will minimize segregation and avoid contamination. Aggregates shall be stockpiled in the vicinity of the plant and on ground that is denuded of vegetation, hard, well drained, or otherwise prepared to protect the aggregate from contamination. Placing aggregate directly from the crusher bins into the cold feed may be permitted provided the material is consistent in gradation. When different size aggregates are stockpiled, the stockpiles shall be separated to prevent commingling of the aggregates.

211.12—Asphalt Concrete Mixing Plant

Plants used for the preparation of asphalt concrete mixtures shall conform to the following requirements:

- (a) **Certification for Plant Operation and Sampling:** A Certified Asphalt Plant Level I Technician or a Certified Asphalt Plant Level II Technician shall sample material at the plant.
- (b) **Plant Scales:** Scales shall be approved in accordance with the requirements of Section 109.01.
- (c) **Drier:** The plant shall include a drier(s) that continuously agitates the aggregate during the heating and drying process. The aggregate shall be dried to a point at which the moisture content of the completed mixture does not exceed 1 percent as determined from samples taken at the point of discharge from the mixing operation.

- (d) **Feeder for Drier:** The plant shall be equipped with accurate mechanical means for uniformly feeding the aggregate into the drier so that a consistent production and temperature are reached and maintained. Where different size aggregates are required to comply with grading specifications, they shall be proportioned by feeding into the cold elevator through a multiple compartment feeder bin, one bin for each size used, equipped with positive action gates that can be securely locked to maintain desired proportioning.
- (e) **Bins:** When bins are used, adequate and convenient facilities shall be provided to make possible the sampling of representative aggregate material from each bin. Each compartment shall be provided with an overflow pipe of such size and location to prevent contamination of the aggregate in adjacent compartments. Bins shall be provided with individual outlet gates that, when closed, will allow no leakage.
- (f) **Thermometric Equipment:** The plant shall be equipped with a thermometric instrument so placed at the discharge chute of the drier as to register automatically or indicate the temperature of the heated aggregate or the completed mix if a drier drum mixing plant is used.

A thermometric device shall be fixed in the asphalt feed line at a suitable location near the charging valve at the mixer unit.

Thermometric devices shall be maintained in good working condition and shall be subject to checking against the laboratory thermometer. Any thermometric devices that do not operate or accurately register temperatures shall be removed and repaired or replaced.

- (g) **Pollution Control:** Pollution control shall conform to the requirements of Section 107.16.
- (h) **Equipment for Preparation of Asphalt Material:** Tanks for the storage of asphalt material shall be equipped with a heating system capable of heating and holding the material at the required temperatures. A separate storage tank or a storage tank having separate compartments shall be available for each grade of asphalt cement being used on the project. The heating system shall be designed to heat the contents of the tank by means of steam, electricity, or other approved means so that no flame is in direct contact with the heating surface of the tank. The circulating system for the asphalt material shall be designed to assure proper and continuous circulation during the operating period and to minimize oxidation. Pipelines shall be steam jacketed or insulated to prevent undue loss of heat. Storage facilities for asphalt material shall be sufficient capacity for at least one day's operation or an equivalent means of supply shall be provided that will ensure continuous operation. Provisions shall be made for measuring and sampling asphalt within storage tanks. When asphalt material is proportioned by volume, the temperature of the asphalt material in storage shall be uniformly maintained at ± 20 degrees F during operation of the plant by means of an automatic temperature control device. A sampling valve shall be provided for sampling of each asphalt storage tank used in production of the mix. If there are multiple storage tanks, a dedicated valve for each tank shall be provided.
- (i) **Asphalt Control:** Asphalt material shall be accurately proportioned by volume or weight. When volumetric methods are used, measurements shall be made by means of meters or pumps, calibrated for accuracy. The section of the asphalt line between the charging valve and the spray bar shall be provided with an outlet valve for checking the meter.

When proportioned by weight, the asphalt material shall be weighed on approved scales. Dial scales shall have a capacity of not more than 15 percent of the capacity of the mixer. The value of the minimum graduation shall not be greater than 2 pounds.

Except when a drier-drum mixing plant is used, the asphalt material bucket and its valves and spray bar shall be steam jacketed or heated by other Department approved means. The bucket shall have a capacity of at least 115 percent of the weight of the asphalt material required in any mixture and shall be supported by fulcrums.

The asphalt shall be delivered to the mixer in multiple uniform streams for the full width of the mixer.

- (j) **Proportioning Aggregates:** Mineral filler and any bag house fines the Contractor uses shall be metered or introduced by means of an approved device for uniform proportioning by weight or by volume.

The weigh hopper shall be of sufficient size to hold the maximum required weight of aggregate for one batch without hand raking or running over. Sufficient clearance between the weigh hopper and supporting devices shall be provided to prevent accumulation of foreign materials.

The discharge gate of the weigh hopper shall be situated in such a manner that the aggregates will not segregate when dumped into the mixer. Gates on the bins and weigh hopper shall be constructed to prevent leakage when closed.

- (k) **Drum Mixer:** The aggregate shall be proportioned by a positive weight control at the cold aggregate feed by use of a belt scale that will automatically regulate the supply of material being fed and permit instant correction of variations in load. The cold feed flow shall be automatically coupled with the asphalt flow to maintain the required proportions.

- (l) **Batch Mixer:** The batch mixer shall be of a twin pugmill or other approved type, steam jacketed or heated by other approved means, and capable of producing uniform mixtures within the specified tolerances. It shall be equipped with a sufficient number of paddles or blades operating at such speeds as to produce a properly and uniformly mixed batch. The number and arrangement of the mixer paddles shall be subject to the Engineer's approval. Worn or defective blades shall not be used in mixing operations.

The mixer shall be provided with an approved time lock that will lock the discharge gate after the aggregates and asphalt have been placed in the mixer and will not release the gate until the specified time for mixing has elapsed.

Batch-type mixing plants used to produce asphalt concrete shall be equipped with approved automatic proportioning devices. Such devices shall include equipment for accurately proportioning batches of the various components of the mixture by weight or volume in the proper sequence and for controlling the sequence and timing of mixing operations. The automated system shall be designed to interrupt and stop the batching operation at any time batch quantities are not satisfied for each of the materials going into the mix. A means shall be provided for observing the weight of each material during the batching operation.

The aggregate may be proportioned by cold feed controls in lieu of plant screens provided the cold aggregate feed conforms to the requirements specified in (j) herein.

Should the automatic proportioning devices become inoperative, the plant may be allowed to batch and mix asphalt materials for a period of not more than 48 hours from the time the breakdown occurs provided alternate proportioning facilities are verbally approved by the Engineer. Written permission of the Engineer will be required for operation without automatic proportioning facilities for periods longer than 48 hours.

(m) **Continuous Mixing Plant:** A continuous mixing plant shall include a means for accurately proportioning each size of aggregate either by weighing or volumetric measurement. When gradation control is by volume, the unit shall include a feeder mounted under the compartment bins. Each bin shall have an accurately controlled individual gate to form an orifice for volumetrically measuring the material drawn from each respective bin compartment. The orifice shall be rectangular, with one dimension adjustable by positive mechanical means, and shall be provided with a lock. Indicators shall be provided to show the individual gate opening in inches. The plant shall be equipped with a satisfactory revolution counter.

The plant shall include a means for calibrating gate openings by weight. The materials fed out of the bins through individual orifices shall be bypassed to a suitable test box, with each component material confined in a separate section. The plant shall be equipped to conveniently handle test samples weighing up to 200 pounds per bin with accurate platform scales provided for this purpose.

Positive interlocking control shall be provided between the flow of aggregate from the bins and the flow of asphalt material from the meter or other proportioning device. This shall be accomplished by approved interlocking devices or other approved positive means.

Accurate control of the asphalt material shall be obtained by weighing, metering, or volumetric measurement.

The aggregate may be proportioned by cold feed controls in lieu of plant screens provided the cold aggregate feed conforms to the requirements specified in (j) herein.

The plant shall include a continuous mixer of an approved type that is steam jacketed or heated by other approved means. The paddles shall be of any adjustable type for angular position on the shafts and reversible to retard the flow of the mixture.

Interlock cutoff circuits shall be included to interrupt and to stop the proportioning and mixing operations when the aggregate level in the plant or the asphalt material in storage falls below that necessary to produce the specified mixture.

(n) **Trucks, Truck Scales, and Automatic Printer System:** These shall conform to the requirements of Section 109.01.

211.13—Preparation of Mixture

The asphalt and aggregate shall be introduced into the mixer at a temperature that will produce a mixture that conforms to the requirements of the job-mix formula.

After the required amounts of aggregate and asphalt material have been introduced into the mixer, the materials shall be mixed until a uniform coating of asphalt and a thorough distribution of the aggregate throughout the mixture are secured that comply with the requirements of the Ross count procedure in AASHTO T195.

The wet mixing time, based on the procedures in AASHTO T195, shall be determined by the Contractor at the beginning of production and will be approved by the Engineer for each individual plant or mixer and for each type of aggregate used; however, in no case shall the wet mixing time be less than 20 seconds. The *wet mixing time* is the interval of time between the start of introduction of the asphalt material into the mixer and the opening of the discharge gate. A wet mixing time that results in fully coating a minimum of 95 percent of the coarse particles, based on the average of the three samples is

acceptable, provided that none of the three sample results has a coating less than 92 percent of the coarse particles shall be the minimum wet mixing time requirement.

A dry mixing time of up to 15 seconds may be required by the Engineer to accomplish the degree of aggregate distribution necessary to obtain complete and uniform coating of the aggregate with asphalt.

211.14—Storage System

If the Contractor elects to use a storage system, the system shall be capable of conveying the mix from the plant to the storage bins and storing the mix without a loss in temperature or segregation or oxidation of the mix. Storage time shall be limited by the ability of the bins to maintain the mix within the quality requirements specified herein with a maximum time limit not to exceed 10 days. Material may be stored in bins for no more than 24 hours without a Department approved heating system.

The conveyor system may be a continuous or skip bucket type. Continuous type conveyors shall be enclosed so that the mix temperature is maintained.

The storage bins shall be designed in a manner to prevent segregation of the mix during discharge from the conveyor into the bins and shall be equipped with discharge gates that will not cause segregation of the mix while the mix is being loaded into the trucks.

Approval for the use of storage bins may be withdrawn by the Engineer if the amount of heat loss, segregation, or oxidation of the mix is excessive.

211.15—Initial Production

- (a) **Warm Mix Asphalt (WMA):** At the start of production, the Contractor shall place no more than 500 tons or up to one day's production as directed by the Engineer at an approved site, which may be the project site, so the Engineer can examine the process control of the mixing plant, the Contractor's placement procedures, surface appearance of the mix, compaction patterns of the Contractor's roller(s), and correlation of the nuclear density device.
- (b) **Hot Mix Asphalt (HMA):** At the start of production of a mix not previously used on a state roadway, the Contractor shall place 100 to 300 tons or up to one day's production as directed by the Engineer at an approved site, which may be the project site, so the Engineer can examine the process control of the mixing plant, the Contractor's placement procedures, surface appearance of the mix, compaction patterns of the Contractor's roller(s), and correlation of the nuclear density device.

The material shall be placed at the specified application rate. The Engineer will determine the disposition of material that was not successfully produced and/or placed due to negligence in planning, production, or placement by the Contractor.