Impact on Compaction of Virginia's Dense-Graded Asphalt Surface Mixtures From Recent Changes to Design and Construction Acceptance Criteria

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In 2016, the Virginia Department of Transportation implemented new design criteria for most dense-graded surface mixtures with the objective of improving material durability. The 2016 construction season was also significant for a series of pilot projects that were designed to explore how potential incentives for in-place density might affect constructed quality. These 2016 pilot projects included a special provision for incentivizing density that was notable in that it required direct measurement of in-place density instead of Virginia's traditional approach, which was to accept compaction using a thin-lift nuclear gauge (an indirect method). This report documents the in-place density and permeability characteristics of a series of projects that represented both the newly adopted design criteria and the density-based constructed quality incentive.

The new designs were analyzed and contrasted with earlier criteria using data from 2015 trials. This analysis determined that the new criteria likely explain as much as a 1.5% average improvement in achieved in-place density. The better density is accompanied by substantially improved (lower) in-place permeability. Selected data from the 2015 trials, as well as earlier research projects, also facilitated analysis to isolate any affect that could be attributed solely to the density acceptance method. The average improvement with the new acceptance method (but the same mix design) was non-statistically significant at approximately 0.5%, but the percentage of samples passing the minimum density increased by 12 to 13%.

Additional support from the Federal Highway Administration's In-Place Density Initiative (2016/2018) enabled the researchers to follow asphalt compaction trends forward for 3 years past the 2016 density pilot program. This allowed for a review of the densities from field cores from 2017 through 2019, which provided for a far more developed discussion of related implementation and benefit consequences than is usually possible. This follow-up review suggested that improved densities (overall averages and percentage of passing samples) have continued. A closing comparison to the previous-generation design criteria and the traditional density acceptance method suggested improvement in in-place quality that may offset $70M per year in maintenance costs through extended service lives.

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FINAL REPORT

IMPACT ON COMPACTION OF VIRGINIA'S DENSE-GRADED ASPHALT SURFACE MIXTURES FROM RECENT CHANGES TO DESIGN AND CONSTRUCTION ACCEPTANCE CRITERIA

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In Cooperation with the U.S. Department of Transportation
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(A partnership of the Virginia Department of Transportation
and the University of Virginia since 1948)

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DISCLAIMER

ABSTRACT

In 2016, the Virginia Department of Transportation implemented new design criteria for most dense-graded surface mixtures with the objective of improving material durability. The 2016 construction season was also significant for a series of pilot projects that were designed to explore how potential incentives for in-place density might affect constructed quality. These 2016 pilot projects included a special provision for incentivizing density that was notable in that it required direct measurement of in-place density instead of Virginia's traditional approach, which was to accept compaction using a thin-lift nuclear gauge (an indirect method). This report documents the in-place density and permeability characteristics of a series of projects that represented both the newly adopted design criteria and the density-based constructed quality incentive.

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INTRODUCTION

The in-place density of asphalt concrete is well known to be one of the more important determinants of long-term performance. The term that refers to the process of achieving that density, compaction, is often used interchangeably with density. The compaction process and the corresponding performance implications are described and referenced very well at a popular online resource (Pavement Interactive, 2009):

> Compaction is the greatest determining factor in dense graded pavement performance (Scherocman and Martenson, 1984; Scherocman, 1984; Geller, 1984; Brown, 1984; Bell et al., 1984; Hughes, 1984; Hughes, 1989). Inadequate compaction results in a pavement with decreased stiffness, reduced fatigue life, accelerated aging/decreased durability, rutting, raveling, and moisture susceptibility (Hughes, 1984; Hughes, 1989).

Compaction Requirements

The Virginia Department of Transportation (VDOT) requires asphalt paving to begin with the construction of a roller pattern and control strip to verify that the maximum practical density is achieved on each route and for each asphalt mixture. The roller pattern and control strip process is described in detail in Virginia Test Method (VTM) 76; the roller pattern identifies the optimum number of roller passes that results in the highest compaction as indicated by a thin-lift nuclear gauge. A control strip is compacted using the optimum roller pattern and density cores are taken to compare to the specification minimum (92.5% of maximum theoretical density for dense-graded surface mixtures). Prior to the 2016 construction season, the target compaction for acceptance of test section lots was required to be within 98% and 102% of the average of 10 nuclear readings from a passing control strip.

In 2017, VDOT established two density testing methods labeled Method A and Method B for production acceptance (VDOT, 2016a). Method B is the same procedure that had been used previously, which compares (as previously described) nuclear readings to a control strip target.

Method A adds on the requirement to take a direct measurement (using a core or saw-cut plug) of density for each sublot (1,000 linear feet) to the Method B procedure; the average density of the lot must meet the minimum specified density for full payment. Method A was applied to all interstate and limited access primary routes and primary and secondary routes more than 20 ft wide with at least 5,000 average daily traffic (ADT). Smaller, low-volume routes used density acceptance by nuclear gauge since these routes were likely to have less structure and therefore present more difficulty achieving acceptable compaction. As a part of the change to require density acceptance by direct measurement, the minimum acceptable density was adjusted to 92.5% for all dense-graded surface mixtures; prior to 2017, mixtures designed to meet PG 64H-16 (D mixtures) or PG 64E-22 (E mixtures) had a minimum density requirement of 92.2%.

Mix Design and Construction Acceptance

Design Criteria

In very late 2013, VDOT began working cooperatively with the Virginia asphalt industry to develop material design criteria that would improve the durability of dense-graded mixtures (Katicha and Flintsch, 2016). During the spring and summer of 2015, this partnership moved from the laboratory to field testing with some newly proposed criteria. The most prominent feature of the new criteria was a change in laboratory design compaction, a reduction to 50 gyrations from 65 gyrations in a Superpave gyratory compactor. There were also slight (but important) adjustments to gradation and volumetric requirements, shown in Table 1. The ultimate goal of these new criteria was improved durability, which was expected to be accompanied by better compactability and lower permeability.

Positive feedback from VDOT and contractors and encouraging preliminary results from the 2015 trials led to a statewide adoption of the lower-gyration design criteria starting with the 2016 construction season.

Table 1. 2016 Mix Design Changes With 50-Gyration Laboratory Design Compaction

	SM-9.5		SM-12.5	
Mix Property	**Previous Range**	**New 2016 Range**	**Previous Range**	**New 2016 Range**
% passing ½ in	100	100	95-100	95-100
% passing 3/8 in	90-100	90-100	90 max.	90 max.
% passing No. 4	80 max	58-80		58-80
% passing No. 8	38-67	38-67	34-50	34-50
% passing No. 30	-	23 max.	-	23 max.
% passing No. 200	2-10	2-10	2-10	2-10
VFA Design	73-79	75-80	70-78	73-89
VFA Production	68-84	70-85	65-83	68-84
Min. VMA	15	16	14	15
Fines/Asphalt Ratio	0.6-1.2	0.7-1.3	0.6-1.2	0.7-1.3
No. of Gyrations	65	50	65	50

VFA = voids filled with asphalt; VMA = voids in mineral aggregate; - = no requirement,

Quality Incentives

The 2016 season was also notable for a series of pilot projects to incentivize the quality of asphalt pavement construction (VDOT, 2016a). This pilot program was composed of select resurfacing contracts from around the state (a target of two per district) in which provisions were inserted that provided for the potential for incentives for production control and achieved in-place density. The density provisions also involved plug- or core-based measurement of voids in lieu of Virginia's traditional indirect testing (with the nuclear gauge). As mentioned earlier, this direct measurement approach would be designated "Method A acceptance" by the following year (2017). By use of this method, incentives could be obtained when both a minimum and consistent level of density was achieved. If the in-place density for a lot averaged between 92.5% and 96.5% of theoretical maximum density (TMD) and "a minimum of 80% of each lot's samples is no lower than 92.5% of TMD," then the work qualified for a 5% incentive (VDOT, 2016a).

For several decades, Virginia has relied on the thin-lift nuclear gauge for estimation of maximum achievable density for given conditions (i.e., to establish roller patterns); for quality control; and for general compaction acceptance. The nuclear density readings were not, however, considered accurate enough to serve as the basis for base pay adjustments, which explains the decision to use core-based testing. This concern was at least partially supported by earlier research by Apeagyei and Diefenderfer (2011), which found weak correlations to core-determined density for a series of nondestructive gauges (to include nuclear sourced).

FHWA In-place Density Initiative

VDOT's pilot program of 2016 coincided with an initiative by the Federal Highway Administration (FHWA) designed to enhance the durability of asphalt pavements through increased in-place density. The goal was to sponsor a nationwide initiative to encourage highway departments and contractors to try methods not presently used in their state; 10 states were chosen, including Virginia. FHWA ultimately awarded Virginia two grants, one to concentrate on improving general mat density and the other (2 years later) to focus on improving compaction at longitudinal joints. Demonstration projects relating to both grants were ultimately constructed and documented, and the results incorporated in a series of workshops that were held throughout the United States (FHWA, 2018). The grants provided important base funding. However, because of donated time and materials by the contractor, as well as the ability for VDOT to absorb the relatively minor coordination and monitoring costs, a good portion of the original grants remained unspent. FHWA's Virginia Division Office agreed to apply the unspent balance toward helping VDOT and the Virginia Transportation Research Council (VTRC) evaluate the effect of recent mix design changes and density acceptance methods on in-place density.

Problem Statement

The encouraging preliminary findings from the 2015 trials related primarily to in-place properties—i.e., better density and lower permeability—with the new designs. These improved properties (discussed in more detail later) were observed from cored samples from both trial (50 gyration) and control (65 gyration) sections. Although the trial mixtures appeared improved compared to the status quo, the then-current density acceptance criterion would not have rewarded or perhaps even adequately recognized the added quality. One danger in moving to more compactable mixtures without also reviewing the acceptance procedures is that the full potential of the improved designs may not be realized, much less appropriately compensated. Further, the long history of accepting for density using indirect "estimates" in lieu of actual measurements from samples of compacted materials means that there is little in the way of a documented baseline for actual field compaction levels.

PURPOSE AND SCOPE

The purpose of this study was to review the in-place density and permeability of Virginia's dense-graded asphalt surface mixtures as designed using the newly adopted (as of 2016) criteria and placed with a density-based constructed quality incentive. In addition to material collected by VTRC staff in direct support of this review, data from VDOT's quality incentive pilot from 2016 were compiled and summarized to help tie the research to actual production/acceptance results.

The review was limited to dense-graded surface mixtures as placed on Virginia roadways. All in-place property measurements were made from material samples that were extracted from the newly placed overlay, using either saw-cut plugs or wet-coring.

Additional support from the FHWA (as described previously) enabled the researchers to follow in-place compaction trends forward for 3 years past the 2016 pilot program. This permitted for a far more developed discussion of implementation and benefits than is usually possible.

METHODS

Historically Observed In-place Properties

The focus of this review was typical asphalt construction using dense-graded surface mixtures during VDOT's 2016 construction season. For comparison's sake, the review also took advantage of the results of previous research that documented in-place asphalt properties incidental to other objectives. The previous work included limited datasets from research in 2005 and 2006 and a far more involved (and more recent) series of trials conducted in 2015.

In-place Properties—2016 Construction Season

As noted previously, the new density acceptance program designated two types of density acceptance methods; although not formally established until the 2017 asphalt construction season, the program was active in pilot form in 2016. Since Method A requires plugs or cores (and commensurate pay adjustments) and Method B continues to allow for the nuclear gauge (with no prospect for pay adjustments), these two methods were relevant for the 2016 trial period and helpful for distinguishing the sample sets.

There were three relevant datasets from the 2016 construction season:

1. density checked by cores taken by VTRC for projects where acceptance determination was being made based on nuclear gauge results (i.e., traditional Method B construction)

2. density checked by additional cores taken by VTRC for projects where the acceptance determination was being based on cores taken by contractors (for Method A pilots)

3. density checked by cores taken by contractors for projects where the acceptance determination was being based on those cores (for Method A pilots).

Dataset 1: Traditional (Method B) Construction

The first dataset provides directly measured properties for asphalt placement activities for which density acceptance is based on VDOT's traditional procedure. That procedure, as discussed in the "Introduction," is largely reliant on indirect estimates of in-place density as determined using a thin-lift nuclear gauge—Method B. This approach applies a stratified random testing plan within which two readings are taken in every 1,000-ft sublot, providing 10 density estimates for every 5,000-ft lot.

Direct measurements were obtained using cored specimens from a series of typical resurfacing projects. These representative projects were selected by reviewing the 2016 maintenance resurfacing contracts (also called "schedules") from all nine VDOT construction districts and selecting candidate routes for which 1 day's visit by a research team would enable testing over a full lot's (5,000-ft) worth of paving. Testing was performed in the contractor's lane closure immediately behind the quality control technician. The sampling plan during those visits can best be described through the schematic in Figure 1. Sampling included one density core per sublot coincident with a nuclear gauge reading and 4-in-diameter cores taken randomly throughout the section to support an evaluation of bond strength. The bond strength cores were deep enough to extract the new 1.5 to 2-in surface and the next layer below, preferably as one still-bonded sample.

Datasets 2 and 3: 2016 Quality Incentive (Method A) Pilots

The second and third relevant datasets were both drawn from the pilot projects designed to determine whether potential incentives could affect the quality of produced and placed asphalt concrete. That is, the direct samples (cores or plugs) were the basis of the acceptance decision during production, not the nuclear readings.

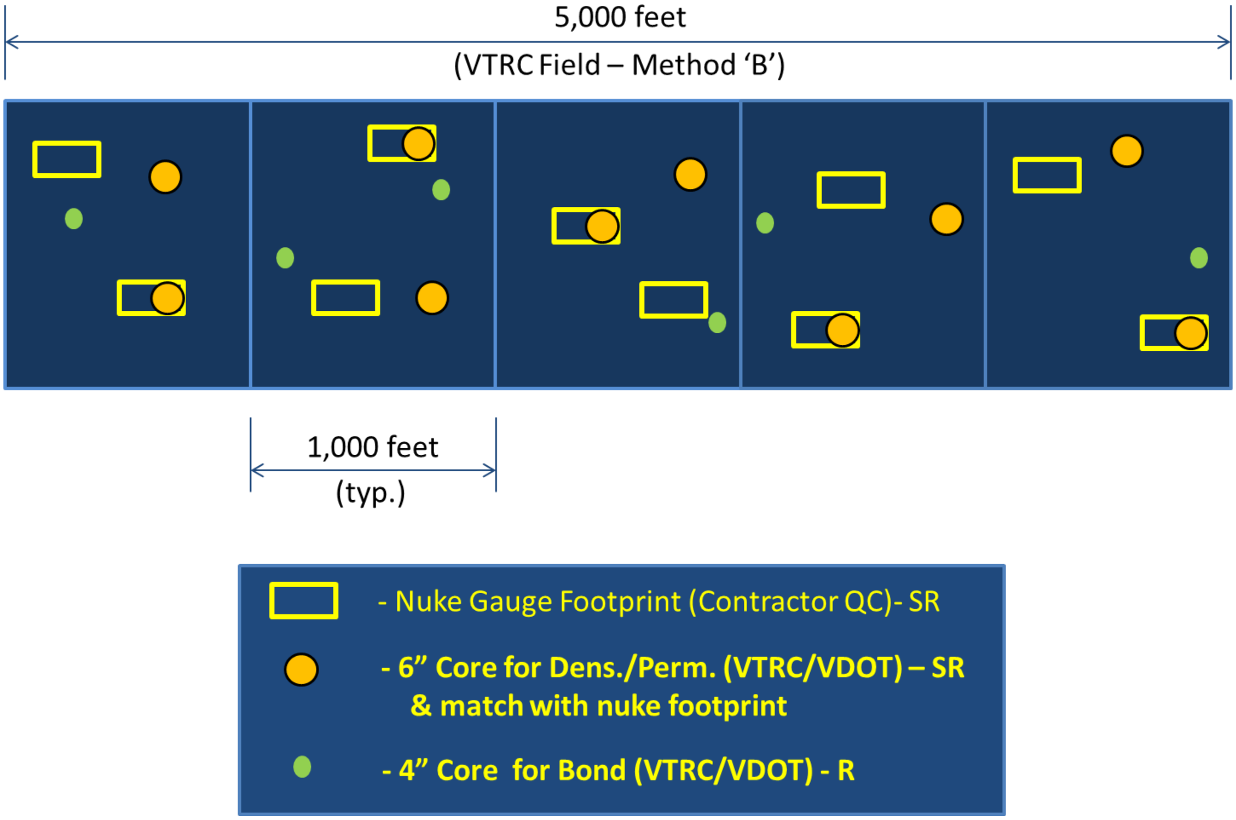

Figure 1. Sampling Plan for Method B Construction. SR = stratified random; R = random.

Dataset 2: VTRC Sampling/Testing

A VTRC field team conducted an independent series of site visits both to supplement the density information and gather snapshots of permeability and bond strength. The targeted routes were selected from the incentivized pilot projects using criteria similar to those employed to choose the traditional (i.e., Method B) pavement resurfacing activities, although the number of sites was more limited. The sampling plan was similar in nature (Figure 2); the most notable difference being that only one-half of the sampling for in-place density was considered necessary since the contractor would be performing direct measurements as part of the pilot program's acceptance criteria.

Dataset 3: Contractor/VDOT Compiled Data

The quality incentive pilot was effective for representing contractor, material, and geographic diversity, but the data were confined to in-place density. The data to support the 2016 quality incentive pilot originated from saw-cut plugs that were cut from the new mat at stratified random locations and bulked "in the presence of the engineer" by the contractor's quality control technician. The contractor and district quality assurance personnel worked together to compile the results and determine payment, including any eligible incentives. The statewide compilation was then obtained from the state materials office and incorporated for reference and comparison herein.

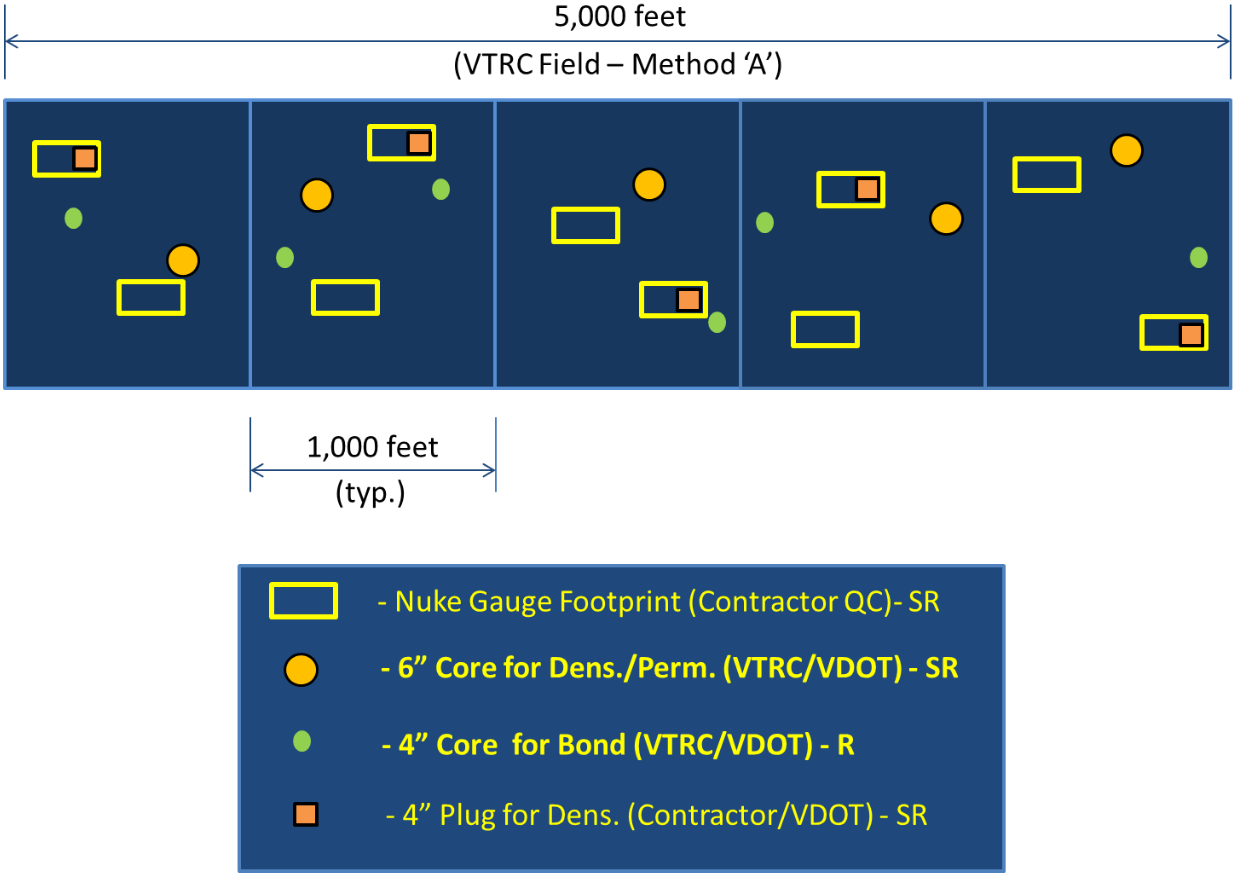

Figure 2. Sampling Plan for Quality Incentive Pilot (Method A) Projects. SR = stratified random; R = random.

Laboratory Test Methods

The specimens extracted by (or for) the VTRC team were transported to the VTRC laboratory where they were prepared and tested to determine density, permeability, and (when available) bond strength. The density tests were conducted in accordance with AASHTO T 166 (saturated surface dry) from 6-in-diameter cores using theoretical maximum density values as reported daily by the producer. The permeability was determined using a laboratory falling head permeameter in accordance with VTM 120 and ASTM D6752 (using CoreLok by Instrotek, Inc.). The bond of the new layer to the existing platform was characterized in accordance with VTM 128, which provides a test to determine both tensile and shear strength.

The density values as reported to VDOT by the contractor for the quality incentive projects were also calculated using a saturated surface dry method, but from 4-in saw-cut plugs (VTM 22).

RESULTS AND DISCUSSION

Historic Observations

Published VTRC Research

There have been occasions over the years where a study has required destructive sampling (usually wet-cut cores) to support related research, sampling that has provided for at least some anecdotal benchmarking of the level of compaction achieved for routine construction. One of those studies supported a review of VDOT's mix design requirement for permeability, which was established early in the adoption of Superpave to address durability concerns associated with coarser gradations. In that study, Maupin (2010) found the permeability requirement to have triggered the redesign of some mixtures, at least as reported by contractors and district staff. Limited sampling and testing confirmed that surface mix designs generally met requirements and the mixtures had sufficiently low permeability as long as they were adequately compacted. Field-compacted specimens (cores), however, demonstrated a high proportion of low-density in-place material (see Figure 3). Of 15 mixtures for which cores were taken as part of Maupin's review, 9 had in-place voids that were higher than 7.5%. Of the 9 mixtures for which the in-place voids were 7.5% or higher, 7 exhibited permeability that exceeded the design limit of 150 x 10^{-5} cm/s. The average in-place density for all 15 mixtures was 91.5% maximum theoretical density (MTD) with a standard deviation of 2.03. This is a full percentage point below VDOT's minimum density requirement of 92.5%.

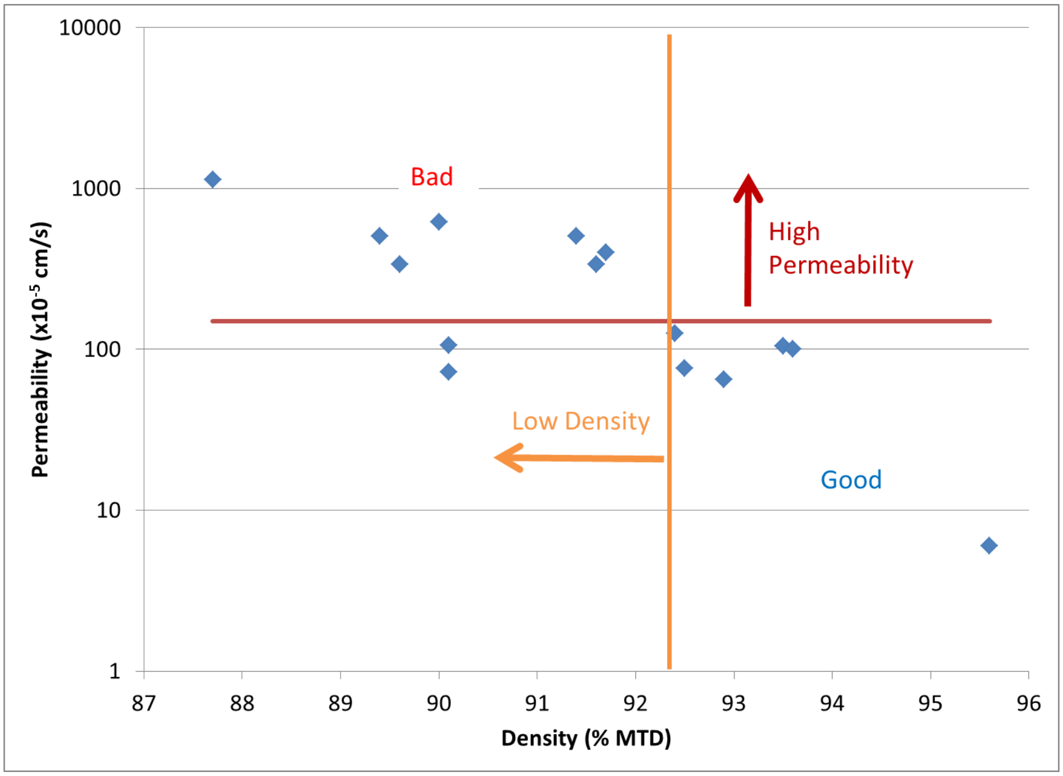

Figure 3. Density Versus Permeability. From Maupin (2010).

In 2006, another series of typical plant mixture projects were tested among other things to characterize in-place permeability and density (Hughes et al., 2007). For this work, seven projects that represented a range from county route to interstate caliber resurfacing work were tested. Of the seven projects, three were found to have average in-place void levels higher than 7.5% and two of them showed higher permeability than VDOT's design limit. The average in-place density for the seven projects was 92.6% MTD with a standard deviation of 1.69. If the density population for this series of projects is assumed to be normally distributed, an average that is essentially at the current minimum (~92.5%) suggests that nearly 50% of the in-place material would not meet the minimum requirement.

2015 Trials with 50-Gyration Mix Designs

The VTRC Asphalt Research Program supported trials with lower-design-compaction asphalt mixtures through a comprehensive laboratory performance evaluation and testing of field-compacted materials (Diefenderfer et al., 2018). In support of the trials, VTRC collected field-compacted specimens and measured basic properties for 11 complete sets of 50-gyration trial / 65-gyration control mixtures: a total of 330 cores. Figure 4 provides the cumulative frequency distributions for achieved density for the two categories of mixture.

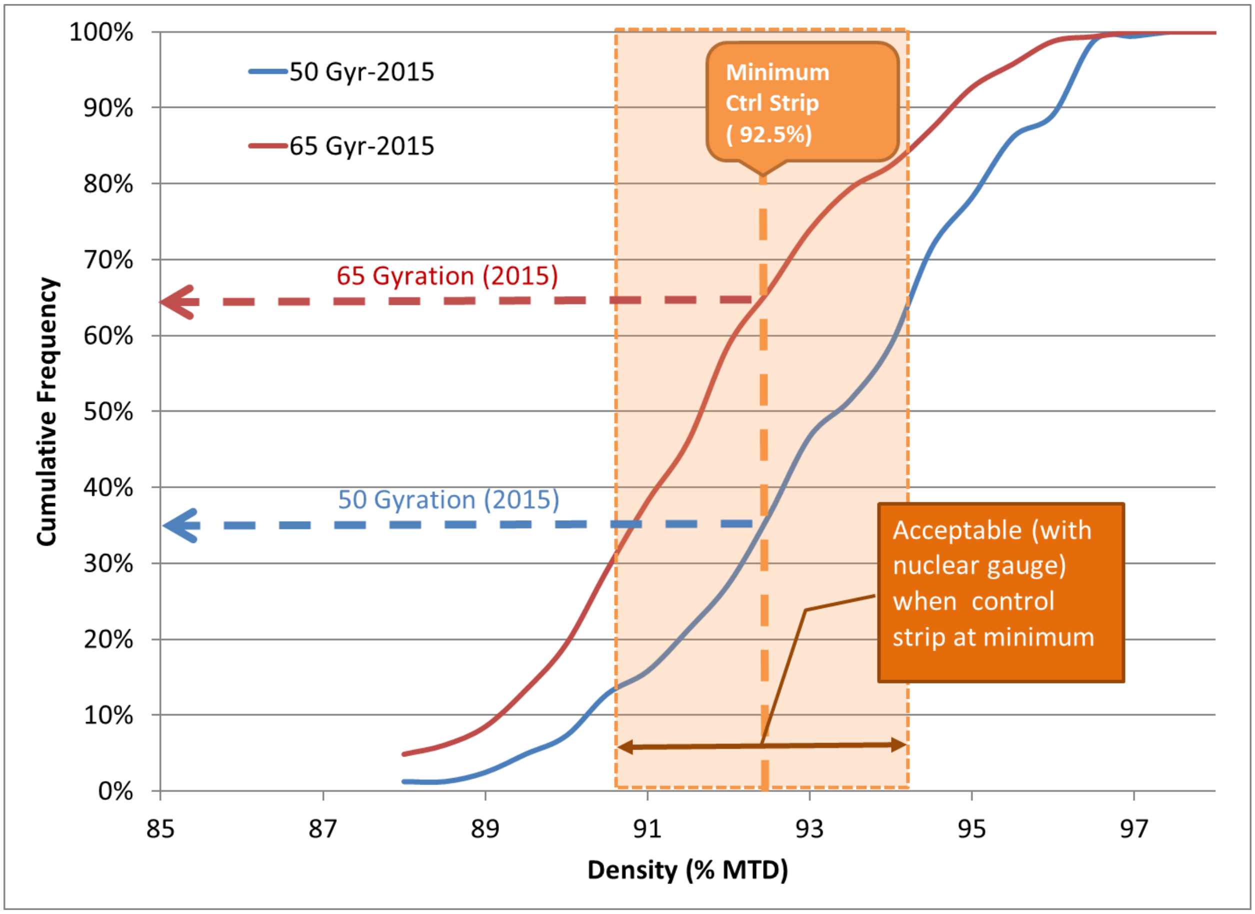

Figure 4. 2015 Trials—Cumulative Frequency Distribution for In-place Density

Figure 4 also shows one line depicting the average minimum required control-strip density (approximately 92.4% MTD) for all surface mixtures. It also includes a shaded box that represents the range of practical acceptable results according to VDOT's specification, which works from a target established with an indirect measurement (nuclear gauge). The specification then stipulates that acceptable in-place compaction need only achieve 98% of that target, even if that target is the absolute minimum.

The distribution from the 65-gryation (control) mixtures is consistent with results from the two previously referenced studies (Hughes et al., 2007; Maupin, 2010). Of the 165 cores taken from the control mixture sites, less than 40% met the minimum control-strip requirements. Conversely, of the 165 samples from the trial mixtures, approximately 65% were "passing" cores. The average in-place density for the eleven 65-gyration mixtures was 91.7% MTD with a standard deviation of 2.09. The 50-gyration trial projects averaged 93.2% MTD in-place with the same standard deviation of 2.09.

Results of the 2015 trials also indicated continued progress toward lower-permeability surface mixtures. Figure 5 compares density with permeability, much as Maupin did in 2010. It includes the 165 permeability/density pairings from the trial mixtures and the additional 165 from the standard designs (controls). Approximately 58% of the 65-gyration control mixture samples had acceptable permeability results, whereas more than 85% of the 50-gyration trial mixture cores passed the current threshold. A regression line of the datasets shows a slightly flatter slope for the trial mixtures, which suggests marginally lower permeability with in-place voids below 92.5%.

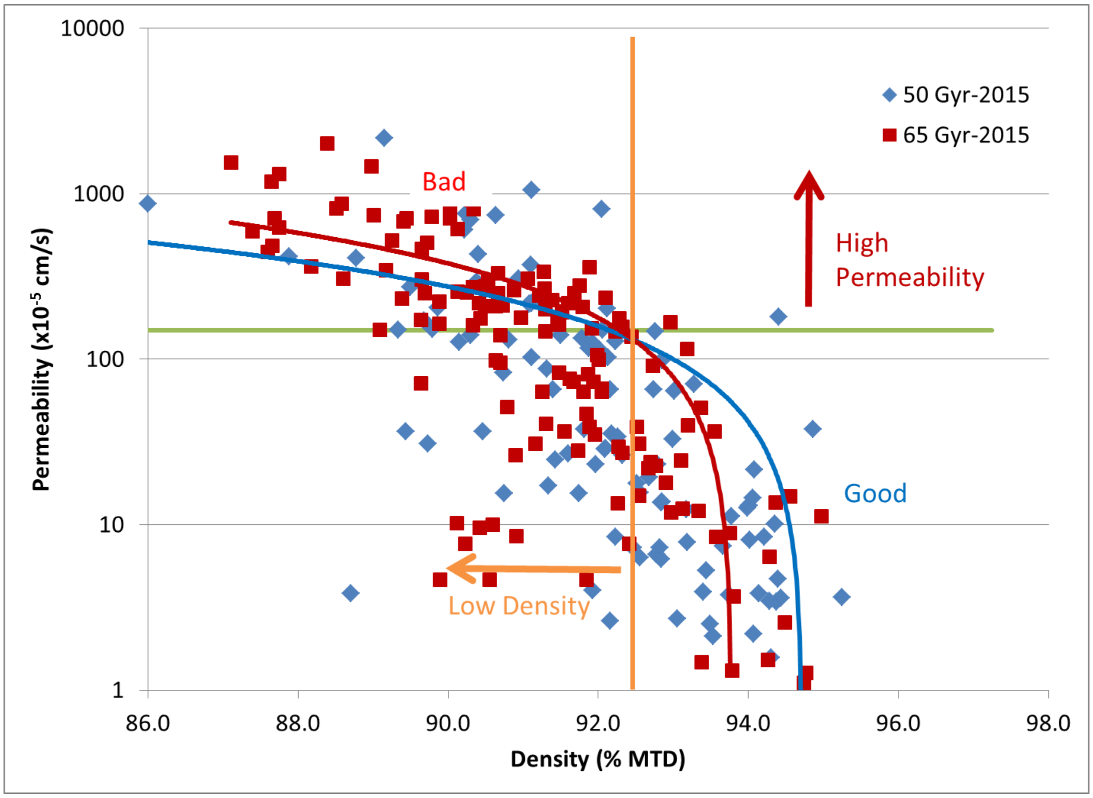

Figure 5. 2015 Trials—In-place Density Versus Permeability

2016 Construction Season

2016 VTRC Field Sampling and Testing of Both Acceptance Methods

The distribution of projects as sampled and tested by VTRC in 2016 is depicted through the map in Figure 6 and the "legend" from Table 2. The research team amassed data from 20 projects throughout the state representing every district. Thirteen of the projects were accepted using traditional methods (density by nuclear gauge, within 98% to 102% of control strip target), and seven were from projects that were part of the pilot program for quality-based incentives (density by cores or plugs, percentage of maximum theoretical density).

Mixture Properties—Design

Mix designs for the SM 9.5 and 12.5 mixtures used in this study are provided in Tables 3 and 4, which indicate that most of the mixtures designated A and D mixtures had a reclaimed asphalt pavement (RAP) content close to 30% and a virgin binder grade of PG 64-22 (PG 64S-22). In the mixture tested from Site H, the virgin binder grade was PG 70-22 (PG 64H-22) with only 15% RAP. All of the mixtures designated E mixtures had RAP contents of 15%, the maximum allowed per VDOT's specification when polymer-modified virgin binder is used (PG 76-22 / PG 64E-22).

Mixture Properties—Production

Production volumetrics were extracted from VDOT's Materials Information Tracking System / Producer Lab Analysis and Information Detail (MITS/PLAID) and are included in Tables 5 and 6. To match with the VTRC dataset, all data in MITS/PLAID from each relevant job-mix were downloaded and the reported results from the day of VTRC testing isolated to represent the material as tested in the field. When there was more than one set of results reported for a single day of testing, an average of the results was used to represent the sampled specimen. When no results were available for a specific day, the next closest day of reported results or an average of the two bracketing days was used.

All of the SM-9.5 mixtures met the volumetric requirements. The effective asphalt content of the SM-9.5 mixtures ranged from 5.25% to 5.96% (average of 5.49%). With the exception of the mixture from Site C, all SM-12.5 mixtures also met the volumetric requirements. The reported voids in mineral aggregate (VMA) from Site C averaged 14.4%, which is consistent with the lower effective asphalt binder (4.89%) as compared to other mixtures. The effective binder content of SM-12.5 mixtures ranged from 4.89% to 5.93% (average of 5.35%).

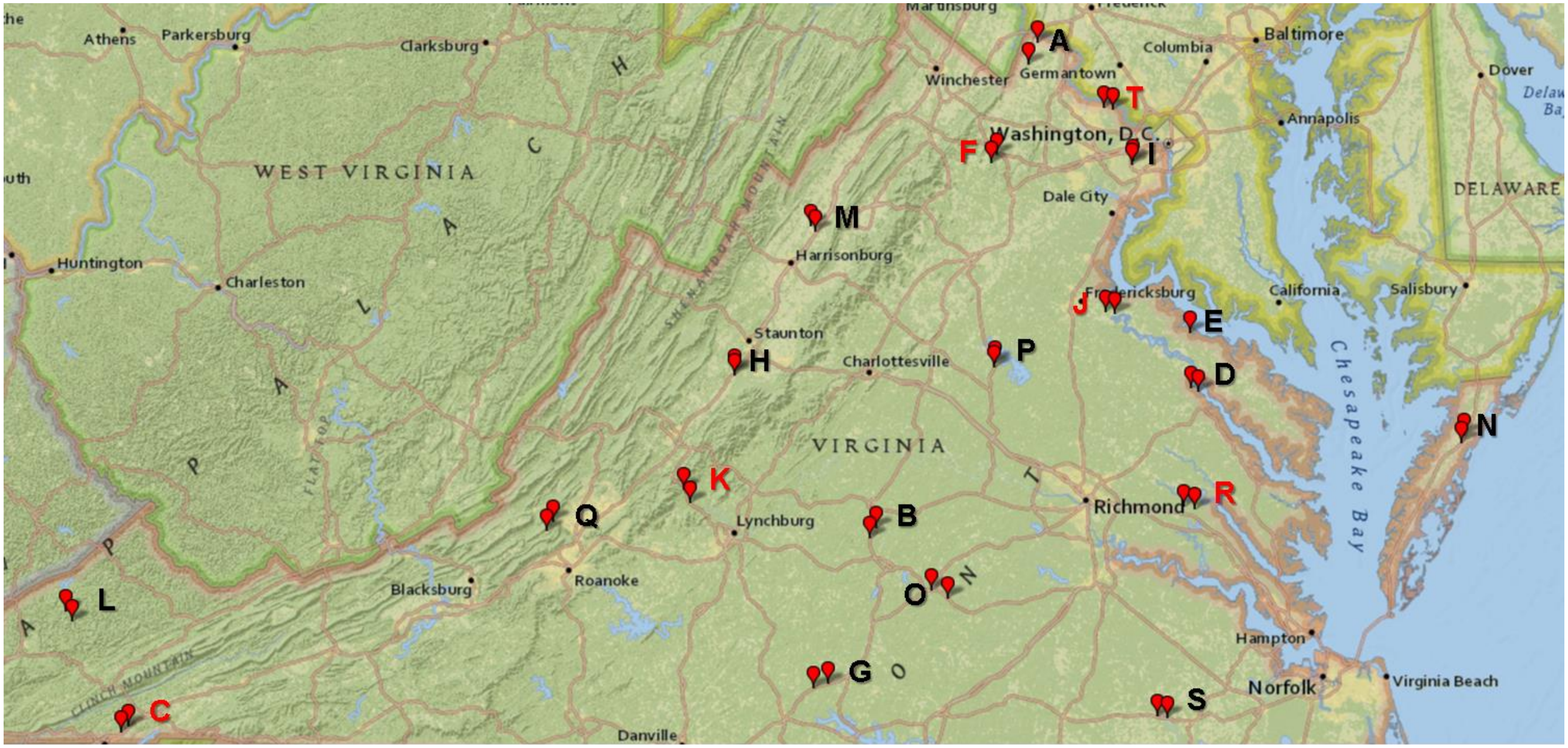

Figure 6. 2016 VTRC Density and Permeability Testing Locations. See Table 2 for Map Key. Red letters represent Method A projects. Black letters represent Method B projects.

Table 2. VTRC Testing From 2016 (and Legend for Figure 6)

Site[a]	Mix Type	Route	Operation	AADT[b]
A	SM-9.5A	CR 690	Mill/Fill	1,000
B	SM-12.5D	US 15	Mill/Fill	4,500
C	SM-12.5A	US 11	Mill/Fill	17,000
D	SM-12.5A	US 17	Mill/Fill	6,200
E	SM-12.5A	SR 204	Mill/Fill	210
F	SM-12.5A	CR 721	Str. Overlay	800
G	SM-9.5D	SR 360	Mill/Fill	5,000
H	SM-12.5D	US 11	Mill/Fill	7,500
I	SM-9.5A	Americana Dr.	Mill/Fill	2,200
J	SM-12.5D	SR 3	Mill/Fill	15,000
K	SM-9.5D	SR 501	Mill/Fill	1,800
L	SM-12.5E	SR 63	Str. Overlay	1,300
M	SM-12.5A	SR 259	Str. Overlay	8,100
N	SM-9.5D	US 13	Str. Overlay	18,000
O	SM-12.5E	SR 460	Mill/Fill	8,900
P	SM-12.5A	SR 522	Str. Overlay	3,900
Q	SM-9.5A	CR 600	Str. Overlay	350
R	SM-12.5E	SR 249	Mill/Fill	3,100
S	SM-12.5D	SR 58	Mill/Fill	16,000
T	SM-9.5A	CR 603	Mill/Fill	1,300

Red font = Method A (core/plug) acceptance; black font = Method B (nuclear gauge) acceptance; Str. Overlay = straight overlay.

[a] See Figure 6 for geographic location.

[b] Average annual daily traffic from Virginia Traffic Volume (VDOT, 2016b).

Table 3. Mix Designs for SM 9.5 Mixtures—VTRC Field Testing (2016)

Site	A	Q	I	T	K	N	G
	SM-9.5A	**SM-9.5A**	**SM-9.5A**	**SM-9.5A**	**SM-9.5D**	**SM-9.5D**	**SM-9.5D**
Asphalt Content (%)	5.5	5.60%	5.30%	5.40%	5.8%	6.1%	6.1%
RAP Content (%)	25%	26%	30%	30%	26%	30%	30%
Virgin Binder Grade	PG 64S-22 (PG 64-22)	PG 64S-22	PG 64S-22	PG 64S-22	PG 64S-22	PG 64S-22	PG 64S-22
Design VTM (%)	3.6%	3.9%	3.5%	4%	4%	3.9%	4%
Gradation							
Sieve Size (mm)	*% Passing*						
12.50	100.0	100	100.0	100.0	100.0	100.0	100.0
9.50	94.0	91.0	96.0	93.0	97.0	97.0	93.00
4.75	64.0	64.0	58.0	61.0	59.0	64.0	58.00
2.36	46.0	39.0	39.0	40.0	42.0	44.0	46.00
0.60	21.0	23.0	21.0	19.0	23.0	22.0	23.00
0.075	6.0	5.0	5.8	5.6	6.0	5.2	5.50

Red font = Method A; black font = Method B.

Table 4. Mix Designs for SM 12.5 Mixtures—VTRC Field Testing (2016)

	P	**M**	**F**	**C**	**D**	**E**	**H**	**S**	**B**	**J**	**L**	**O**	**R**
Site	**SM-12.5A**	**SM-12.5A**	**SM-12.5A**	**SM-12.5A**	**SM-12.5A**	**SM-12.5A**	**SM-12.5D**	**SM-12.5D**	**SM-12.5D**	**SM-12.5D**	**SM-12.5E**	**SM-12.5E**	**SM-12.5E**
Asphalt Content (%)	5.8%	5.80%	5.40%	5.3%	5.5%	5.60%	5.80%	5.3%	5.80%	5.20%	5.50%	6.0%	5.50%
RAP Content (%)	15%	25%	27%	30%	26%	30%	15%	30%	30%	30%	15%	15%	15%
Virgin Binder Grade	PG 64S-22 (PG 64-22)	PG 64S-22	PG 64S-22	PG 64S-22	PG 64S-22	PG 64S-22	PG 64H-22 (PG 70-22)	PG 64S-22	PG 64S-22	PG 64S-22	PG 64E-22	PG 64E-22	PG 64E-22
Design VTM (%)	4.5%	4.0%	4.0 %	3.9%	4%	3.9%	3.9%	3.8%	4%	4%	4%	3.6%	3.5%
Gradation													
Sieve Size (mm)	*% Passing*												
19.0	100.0	100.0	100	100	100	100	100	100	100	100	100	100	100
12.50	97.0	96.0	98	96	95	97	98	96	97	97	95	97	96
9.50	90.0	86.0	90	87	84	88	88	87	84	90	84	89	86
4.75	66.0	62.0	60	59	60	62	58	60	58	59	58	60	62
2.36	38.0	36.0	40	35	44	44.0	36	42	37	39	34	44	47
0.60	18.0	17.0	20	16	23.0	21	20	23	20	22	16	23	22
0.075	7.0	5.5	5.5	6.6	5.5	5.5	5.5	5.5	5.1	5.4	6.0	6.2	6.0

Red font = Method A; black font = Method B.

Table 5. Volumetric Properties for SM-9.5 Mixtures—VTRC Field Testing (2016)

	A	Q	I	T	K	N	G
Site	**SM-9.5A**	**SM-9.5A**	**SM-9.5A**	**SM-9.5A**	**SM-9.5D**	**SM-9.5D**	**SM-9.5D**
Asphalt Content	5.65%	5.60%	5.37%	5.45%	5.66%	5.78%	6.25%
Rice (Gmm)	2.655	2.55	2.577	2.691	2.483	2.5	2.511
Air Voids (VTM)	3.60%	3.30%	4.10%	2.60%	3.20%	3.60%	3.40%
VMA	17.20%	16.10%	16.67%	16.00%	16.10%	16.60%	17.40%
VFA	79.00%	80.00%	75.33%	84.00%	80.00%	78.00%	80.00%
Dust/AC	1.1	1	1	1.1	1.1	1	0.9
Bulk (Gmb)	2.56	2.467	2.471	2.62	2.404	2.411	2.426
Effective (Gse)	2.932	2.795	2.816	2.967	2.713	2.74	2.777
Aggregate (Gsb)	2.918	2.777	2.806	2.95	2.702	2.724	2.754
Binder Absorbed (Pba)	0.17%	0.24%	0.13%	0.20%	0.15%	0.22%	0.31%
Effective Binder (Pbe)	5.49%	5.37%	5.25%	5.26%	5.52%	5.57%	5.96%
Density @ Nini	88.30%	89.30%	89.57%	89.50%	89.20%	90.90%	89.90%

Source: VDOT Materials Information Tracking System/Producer Lab Analysis and Information Detail System. Red font = Method A; black font = Method B.

Table 6. Volumetric Properties for SM-12.5 Mixtures—VTRC Field Testing (2016)

	P	M	F	C	D	E	H	S	B	J	L	O	R
Site	**SM-12.5A**	**SM-12.5A**	**SM-12.5A**	**SM-12.5A**	**SM-12.5A**	**SM-12.5A**	**SM-12.5D**	**SM-12.5D**	**SM-12.5D**	**SM-12.5D**	**SM-12.5E**	**SM-12.5E**	**SM-12.5E**
Asphalt Content	5.51%	5.92%	5.29%	5.28%	5.31%	5.94%	5.99%	5.11%	5.79%	5.26%	5.49%	5.84%	5.58%
Rice (G_{mm})	2.543	2.515	2.726	2.545	2.498	2.477	2.4545	2.47	2.48	2.619	2.616	2.427	2.446
Air Voids (VTM)	3.65%	2.85%	2.90%	2.60%	3.15%	2.70%	4.45%	3.80%	3.05%	3.00%	3.80%	2.60%	3.60%
VMA	15.80%	16.60%	15.50%	14.40%	15.50%	16.60%	17.65%	15.40%	15.70%	15.65%	16.55%	15.40%	16.10%
VFA	77.00%	83.00%	81.00%	82.00%	80.00%	84.00%	75.00%	75.00%	81.00%	80.50%	77.00%	83.00%	77.50%
Dust/AC	0.95	1.05	1.1	1.2	0.95	0.9	1.05	1	1.1	1	1.2	0.95	1.1
Bulk (G_{mb})	2.4505	2.443	2.648	2.478	2.418	2.41	2.3455	2.375	2.403	2.541	2.517	2.364	2.357
Effective (G_{se})	2.7815	2.766	3.002	2.772	2.715	2.718	2.692	2.671	2.7145	2.8645	2.873	2.649	2.662
Aggregate (G_{sb})	2.7495	2.755	2.968	2.742	2.711	2.717	2.678	2.663	2.685	2.854	2.85	2.631	2.653
Binder Absorbed (P_{ba})	0.43%	0.15%	0.39%	0.41%	0.06%	0.01%	0.20%	0.12%	0.41%	0.13%	0.29%	0.27%	0.13%
Effective Binder (P_{be})	5.10%	5.78%	4.92%	4.89%	5.25%	5.93%	5.80%	5.00%	5.40%	5.15%	5.22%	5.59%	5.46%
Density @ N_{ini}	89.00%	87.70%	88.90%	88.70%	91.30%	90.90%	87.15%	90.30%	89.75%	90.10%	87.40%	91.50%	88.20%

Source: VDOT Materials Information Tracking System/Producer Lab Analysis and Information Detail System. Red font = Method A; black font = Method B.

In-place Density and Permeability

Table 7 provides basic descriptive statistics for the 13 Method B projects to include average in-place density and permeability. Passing rates are better for permeability with smaller nominal maximum aggregate size mixtures, which is consistent with results from others (Brown et al., 2004).

The researchers also noticed a slow improvement in achieved in-place density for the Method B projects as the season progressed. There was no obvious inflection point, but when projects were separated into those tested before and after August 1, the in-place density of the late season projects was nearly a full percentage point higher with slightly less variation (Table 8). An F and t-test demonstrated this difference to be significant at the 95% confidence level. The higher variability and percentage of passing permeability samples in the early season samples suggest that the lower average could be due to a handful of particularly low-density results. Table 9 provides the basic descriptive statistics for the seven Method A projects to include average in-place density and permeability.

Table 7. Method B Projects—In-place Density and Permeability

Mix Type	Routes	Cores	In-place Density		Permeability Tests Passing
			% MTD	Std. Dev.	
SM-9.5A	3	28	92.8	2.0	75%
SM-9.5D	2	20	94.2	1.4	85%
SM-12.5A	3	30	93.3	1.9	73%
SM-12.5D	3	20	92.3	2.1	63%
SM-12.5E	2	22	93.7	2.0	51%
Weighted[a] averages			93.2	1.9	70%

MTD = maximum theoretical density.

[a] Averages weighted by number of routes/projects.

Table 8. Method B Projects—Early Versus Late Season

Time Period	Mix Type		Routes	Cores	In-place Density		Permeability Tests Passing
	SM-9.5	SM-12.5			% MTD	Std. Dev.	
Before Aug. 1	2	4	6	54	92.8	2.2	75%
After Aug. 1	3	4	7	66	93.6	1.8	65%

MTD = maximum theoretical density.

Table 9. Method A Projects—In-place Density and Permeability

Mix Type	Routes	Cores	In-place Density		Permeability Tests Passing
			% MTD	Std. Dev.	
SM-9.5A	1	3	92.8	1.6	67%
SM-9.5D	2	10	95.2	1.1	100%
SM-12.5A	2	10	93.6	2.5	60%
SM-12.5D	1	5	93.0	0.7	60%
SM-12.5E	1	5	92.6	1.1	80%
Weighted[a] averages			93.7	1.5	75%

MTD = maximum theoretical density.

[a] Averages weighted by number of routes/projects.

Facilities that carry more traffic are likely to incorporate heavier pavement structures, whether that heavier structure evolved with increased use (and maintenance) or from original design. These heavier structures can also be expected generally to serve as a stiffer platform against which to compact a new overlay or inlay. In lieu of an objective measure of platform stiffness, the average achieved density is compared in Figure 7 to daily traffic for each type of project. Although it is possible that stiffer platforms (higher traffic volumes) made it easier to achieve good compaction, there does not appear to be a clear relationship between traffic volume and achieved density for either Method A or Method B projects. In a comparison of Method A and Method B projects below and above the median traffic levels, the contractor achieved 0.4% to 0.8% better densities on the higher trafficked sections, but the only two projects (both Method B) showing an average MTD noticeably below the 92.5% minimum had annual average daily traffic (AADT) of 4,500 to 6,200 that were at or above the median traffic level.

The general site characteristics provided in Table 2 also include whether the paving activity was a straight overlay (i.e., str. overlay) or part of a mill and inlay (i.e., Mill/Fill) operation. As is becoming more common, the mill/fill operations outnumbered the straight overlays, especially for the Method A projects. Nonetheless, Table 10 contrasts the mill/fill with the limited straight overlay projects. It is interesting to see that the in-place density results for straight overlays on Method B projects (eight of them) were similar to the mill/fill results for Method A projects.

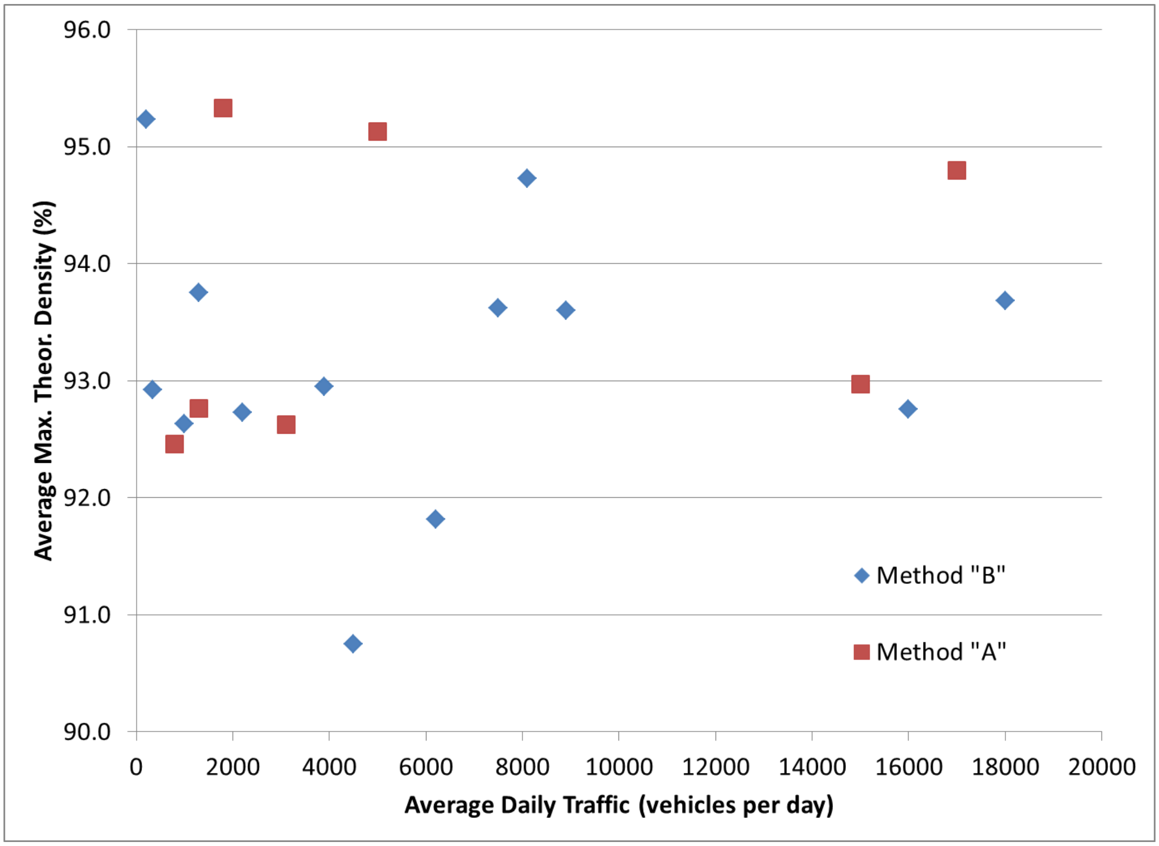

Figure 7. In-place Density Versus Traffic Volume

Table 10. Paving Operation—In-place Density and Permeability

Operation	Method A				Method B			
	No. of Projects	% MTD	Std. Dev.	Perm. Passing	No. of Projects	% MTD	Std. Dev.	Perm. Passing
Mill/Fill	6	93.9	1.45	81%	5	92.9	1.64	70%
Str. Overlay	1	92.5	1.44	40%	8	93.6	1.55	68%

MTD = maximum theoretical density; Perm. = permeability tests; Str. Overlay = straight overlay.

Tables 11 and provide a site-by-site summary of the in-place density and permeability results for each project/mixture, as well as key volumetric calculations and several finer sieve results. Table 11 pertains to the SM-12.5 mixtures and Table 12 the SM-9.5 mixtures. The sites for each mixture type are sorted by relative in-place quality, as represented by a single day of independent testing on 3 (short day) to 12 (longer day) cores per site. For density, "passing" indicates the proportion of cores with density equal to or greater than 92.5% MTD. For permeability, "passing" is the proportion of specimens with permeability less than 150 x 10^{-5} cm/s.

There do not appear to be any predominating mixture characteristics associated with the measured in-place density results. Most (but not all) of the top-performing SM-12.5 mixtures exhibited a higher effective volume of asphalt (calculated as proportion of VMA filled with asphalt). Those mixtures also had a moderate ratio of fines to asphalt (FA ratio). One exception was that for the mixture from Site C, it appears that fines were substituted for asphalt to achieve good apparent density and lower permeability. However, the mixture would not have met the minimum VMA requirement.

For the two top-listed mixtures among the SM-9.5 mixtures, it appears that elements of the two opposing strategies were incorporated. The first mixture had a higher effective asphalt volume and lower fines, and the second had an "optimized" fine aggregate content in lieu of asphalt cement with a VMA that was very close to the minimum requirement.

Bond Strength—VTRC Testing

Bond strength was tested for each VTRC field project and a cursory analysis conducted to see if there were differences relating to compaction acceptance method. Since there were no clear differences observed, a brief discussion of the results is provided in Appendix A.

2016 Quality Incentive Results on VDOT Method A Projects

VDOT's "quality incentive" pilots in 2016 called for Method A acceptance for 12 maintenance-resurfacing schedules from around the state (the VTRC team visited only 7 of them). Table 13 lists the specific schedules, their respective construction district, the quantity of surface mixtures involved, and the total value of each contract.

Table 11. Production and In-place Quality Characteristics—SM-12.5 Mixtures

Site[a]	Passing[b]		V_{be}	Production—Gradation and AC (Day of VTRC Sampling)[c]								
	Density	Perm.		AC%	No. 4	No. 8	No. 30	No. 200	VTM	VFA	VMA	FA Ratio
M	100%	90%	13.8%	5.92%	62.0%	37.0%	16.7%	5.9%	2.85%	83.0%	16.6%	1.05
E	90%	100%	13.9%	5.87%	59.0%	40.3%	22.3%	5.3%	2.70%	84.0%	16.6%	0.90
C	80%	80%	11.8%	5.32%	58.5%	38.0%	16.5%	6.5%	2.60%	82.0%	***14.4%***	1.20
H	75%	100%	13.2%	5.99%	58.0%	36.5%	19.0%	5.9%	4.45%	75.0%	17.7%	1.05
J	80%	60%	12.6%	5.21%	59.2%	40.0%	22.0%	5.2%	3.00%	80.5%	15.6%	1.00
L	75%	42%	12.7%	5.52%	***54.3%***	***33.7%***	15.0%	6.3%	3.80%	77.0%	16.6%	1.20
F	60%	40%	12.6%	5.24%	60.5%	40.5%	21.5%	5.3%	2.90%	81.0%	15.5%	1.10
O	60%	60%	12.8%	5.83%	60.6%	44.3%	23.0%	5.5%	2.60%	83.0%	15.4%	0.95
P	60%	40%	12.2%	5.59%	***55.0%***	35.0%	16.5%	4.8%	3.65%	77.0%	15.8%	0.95
R	50%	75%	12.5%	5.56%	62.0%	45.3%	***23.7%***	6.0%	3.60%	77.5%	16.1%	1.10
S	50%	50%	11.5%	5.11%	58.0%	43.0%	22.0%	5.2%	3.80%	75.0%	15.4%	1.00
D	30%	80%	12.4%	5.31%	59.5%	43.0%	22.5%	5.1%	3.15%	80.0%	15.5%	0.95
B	13%	38%	12.7%	5.80%	64.6%	44.3%	22.0%	5.8%	3.05%	81.0%	15.7%	1.10

[a] Red letter designation = Method A acceptance; black letter designation = Method B acceptance.

[b] Density = proportion of cores with voids less than 7.5%; Perm. = proportion of cores with permeability less than 150 x 10-5 cm/s.

[c] Red bold italicized font = does not meet VDOT specification requirement; V_{be} = volume of effective binder (VFA x VMA).

Table 12. Production and In-place Quality Characteristics—SM-9.5 Mixtures

Site[a]	Passing[b]		V_{be}	Production—Gradation and AC (Day of VTRC Sampling)[c]								
	Density	Perm.		AC%	No. 4	No. 8	No. 30	No. 200	VTM	VFA	VMA	FA-Ratio
G	100%	100%	13.9%	6.20%	61.5%	48.5%	***25.5%***	5.4%	3.40%	80.0%	17.4%	0.90
K	100%	100%	12.9%	5.66%	60.0%	43.0%	22.0%	6.1%	3.20%	80.0%	16.1%	1.10
Q	80%	90%	12.9%	5.64%	63.0%	38.5%	22.5%	5.4%	3.30%	80.0%	16.1%	1.00
N	80%	80%	12.9%	5.78%	65.0%	48.0%	***24.0%***	5.3%	3.60%	78.0%	16.6%	1.00
T	67%	67%	13.4%	5.45%	62.0%	40.0%	20.0%	5.9%	2.60%	84.0%	16.0%	1.10
I	63%	75%	12.6%	5.39%	58.9%	40.4%	22.0%	5.4%	4.10%	75.3%	16.7%	1.00
A	50%	60%	13.7%	5.63%	65.3%	45.0%	20.0%	6.1%	3.50%	79.5%	17.2%	1.05

[a] Red letter designation = Method A acceptance; black letter designation = Method B acceptance,

[b] Density = proportion of cores with voids less than 7.5%; Perm. = proportion of cores with permeability less than 150 x 10-5 cm/s.

[c] Red bold italicized font = does not meet VDOT specification requirement; V_{be} = volume of effective binder (VFA x VMA).

Table 13. Quality Incentive Pilot Projects—2016

Schedule	District	Quantity[a] (tons)	Contract Value ($)
PM1F	Bristol	74,468	4,614,151
PM2H	Salem	17,940	1,919,276
PM2L	Salem	14,553	1,651,595
PM3E	Lynchburg	35,928	3,846,140
PM3F	Lynchburg	48,494	3,852,821
PM4A	Richmond	30,596	3,550,777
PM4E	Richmond	22,964	2,615,706
PM5F	Hampton Roads	4,511	369,070
PM5H	Hampton Roads	15,602	3,268,899
PM6B	Fredericksburg	72,279	9,341,547
PM7E	Culpeper	27,099	3,197,485
PM9J	NOVA	27,707	3,904,663
Total		392,141	42,132,130

[a] Surface mixture (SM) only.

Incentive Summary

Tables 14 through 16 summarize in-place density results as reported by VDOT districts for Method A acceptance. Table 14 breaks down the results by mixture type. It includes the number of routes (projects) for which data were reported for each mixture type, the total number of plugs tested, the total days of paving, and the proportion of work determined eligible for a density incentive. The mixtures designated SM-12.5A mixtures were associated with consistent incentive-quality work whereas contractors appeared to struggle some with SM-9.5A mixtures. Interestingly, the SM-19.0A mixture was the most consistent at qualifying for an incentive, at least among the mixtures with more than one representative project. Use of the 19.0 surface mixtures was isolated to the Bristol District. It is also notable in this dataset as the only higher gyration (65 gyrations) material. Overall, the results fall between those observed through the VTRC-tested Method A and B projects, which showed an average overall in-place density of 93.7% and 93.2% MTD, respectively (see Tables 7 and 9).

Table 14. Mixture Type Breakdown—2016

Mixture	Routes	Plugs	Average Density (%)	Lots Paved		Bonus (%)
				Total	Bonus	
SM-9.5A	22	145	93.0	47	19	40.4%
SM-9.5D	43	963	93.4	242	165	68.2%
SM-9.5E	1	10	93.9	2	2	100.0%
SM-12.5A	22	520	93.7	123	102	82.9%
SM-12.5D	7	160	93.2	34	22	64.7%
SM-12.5E	6	159	92.8	31	16	51.6%
SM-19.0A	9	122	93.8	30	28	93.3%
Total	110	2079	93.4[a]	509	354	69.5%[b]

[a] Average weighted by number of routes.
[b] Average weighted by total days of paving.

Table 15 provides a breakdown by highway system. As interstate system paving is now predominantly gap-graded (i.e., stone matrix asphalt), there was a very small pool of dense-graded interstate projects to test. There was, however, good representation from primary and secondary system paving. The overall average in-place density was similar, regardless of system. Incentive-quality work was, however, more common on primary system projects, perhaps an indication of more uniform subgrade support.

Table 16 summarizes the results by the binder designation, in addition to any influence that might relate to "theoretical" binder stiffness. There appears to be very little (to no) practical difference between the predominant A- and D-type binders. Although difficult to confirm because of the small sample size, placement with the stiffest E-type binders achieved, on average, lower in-place density.

Table 15. System Breakdown—2016

Highway System	Projects	Plugs	Average	Lots Paved		Bonus (%)
				Total	Bonus	
Interstate	2	42	93.3	9	6	66.7%
Primary	39	1460	93.5	333	247	74.2%
Secondary	54	451	93.3	167	101	60.5%

Table 16. Binder Designation—2016

Highway System	Projects	Plugs	Average Density (%)	Lots Paved		Bonus (%)
				Total	Bonus	
A-Mixes[a]	43	656	93.5	170	121	71.2
D-Mixes	50	1123	93.4	276	187	67.8
E-Mixes	7	169	92.9	33	18	54.5

[a] Excludes SM-19.0A mixtures.

Impact of New Design Criteria

A primary motivation for this study was to explore the impact on in-place quality of the new (at the time) dense-grade mix design criteria. Absent general availability of historical core-based density records, the VTRC control sections from the 2015 trials provided the most extensive (and contemporary) baseline from which to judge the achieved in-place density of the previous-generation (i.e., 65-gyration) designs using traditional (i.e., Method B) acceptance for compaction. The 11 companion 50-gyration trial sections from 2015 (contrasted earlier in Figure 4) are relevant, but the 13 Method B projects from VTRC's 2016 field survey provide a better statewide sample of projects. To isolate any difference the changes in design criteria might have had, the cumulative frequency distributions for density of all the cores in each dataset were plotted (see Figure 8).

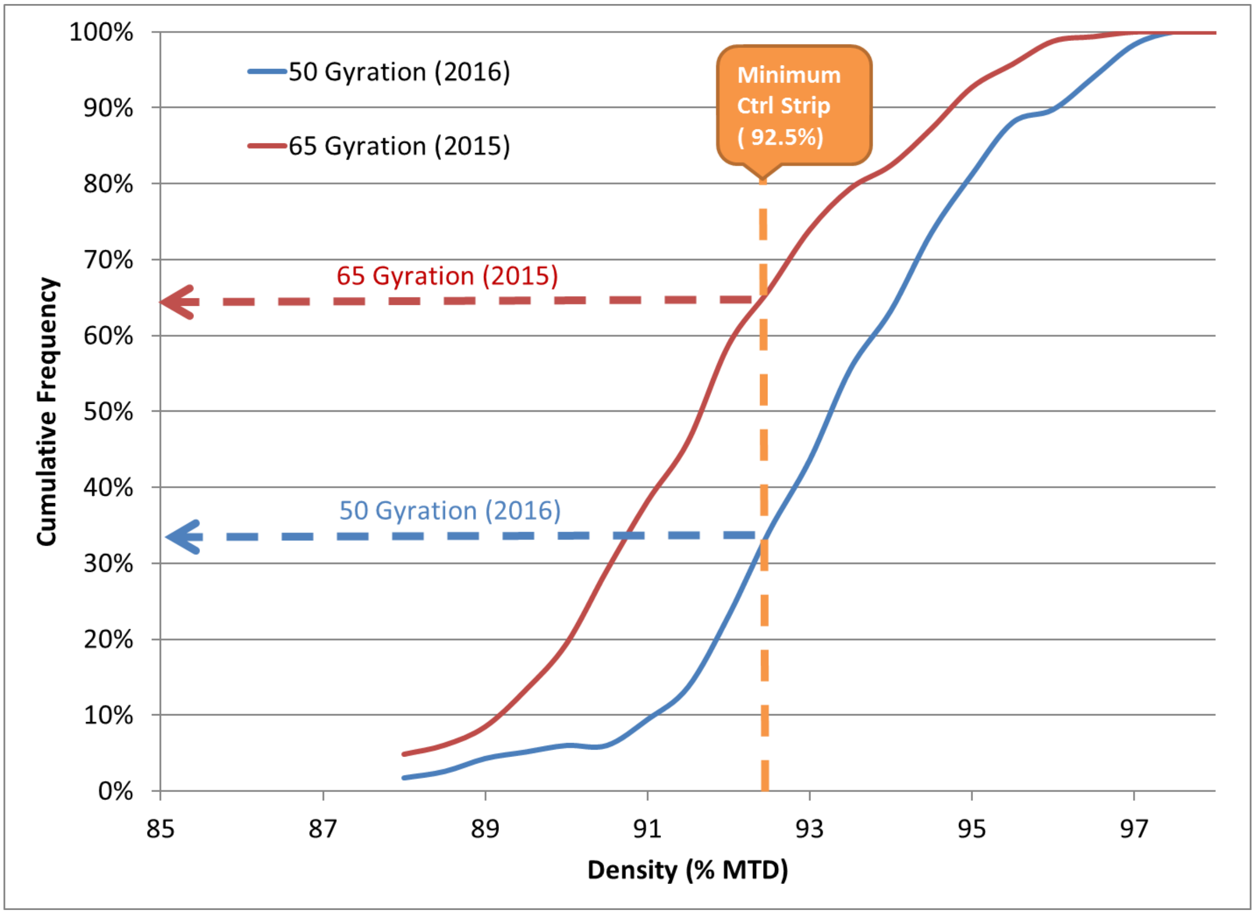

Figure 8. Impact of Design Criteria—Cumulative Frequency Distribution for In-place Density. All work accepted per VDOT Method B (nuclear gauge).

As noted earlier, in-place density measurements from the 2015 control sections indicated that approximately two-thirds (66%) of the mat was insufficiently compacted, i.e., the in-place voids exceeded VDOT's minimum control strip requirement. Also consistent with the 2015 trial results, the work that was accepted the next year using Method B but with the new standard design requirements, the 2016 data flipped almost exactly the out-of-compliance / in-compliance ratio with 66% of the mat testing as sufficiently compacted and the other one-third testing as something less than targeted.

Table 17 summarizes the data shown in the distributions from Figure 8 to include the overall average achieved density, actual distribution of specimens that met minimum requirements for each dataset, and arithmetic differences. Statistically speaking, F and t-tests found the variances to be similar but the average in-place densities to be significantly different at the 95% confidence level. The difference in average density results indicate that the new design criteria may be accounting for as much as a 1.6% improvement in average in-place density. The 32% improvement in the proportion of "passing" tests is also something to celebrate.

Table 17. Impact of Design Criteria on In-place Density

Measure		Design Criteria		
		65 Gyrations (2015)	50 Gyrations (2016)	Change
Density	Avg. (%)	91.7	93.3	1.6
	Std. Dev.	2.09	1.99	-0.1
	Distribution exceeding 92.5%	33.8%	65.8%	32%

Influence of a Quality Incentive

The 13 non-incentive (Method B) projects that were tested by the VTRC team in 2016 represent the most readily available baseline against which to assess the influence of the density-based quality incentives. To that end, Figure 9 contrasts the Method B baseline data against both the more limited VTRC testing of the 2016 Method A incentive pilots and all of the Method A contractor core data reported to VDOT from the 2016 season.

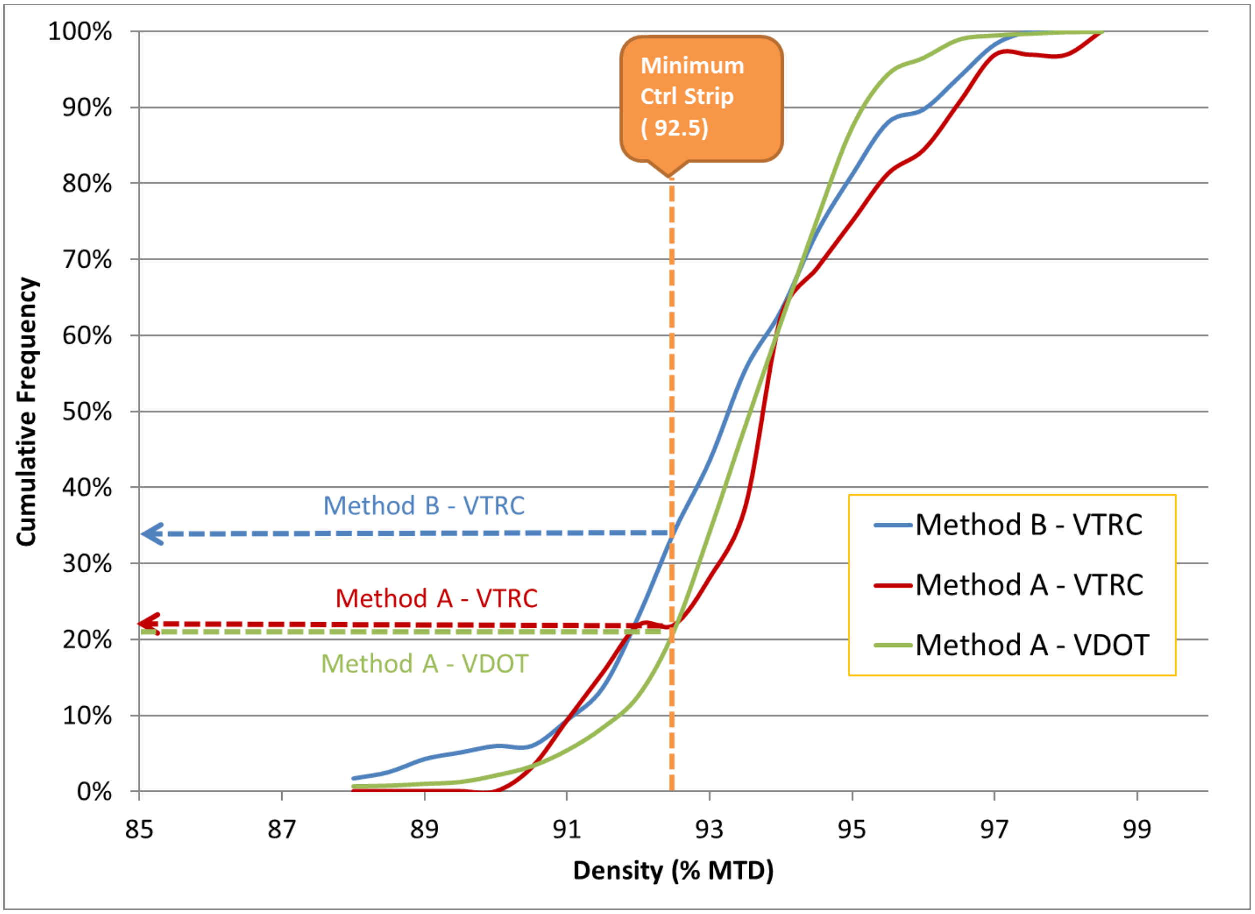

Figure 9. Impact of Incentive/Acceptance Method—Cumulative Frequency Distribution for In-place Density. Method A - VTRC = acceptance via Method A with sampling/testing by VTRC; Method B - VTRC = acceptance via Method B with sampling/testing by VTRC; Method A - VDOT = acceptance via Method A as reported to VDOT.

The distribution labeled “Method B - VTRC” is the same distribution as that labeled “50 Gyration (2016)” in Figure 8. The “Method A - VTRC” distribution suggests some overall improvement over Method B, and the season-wide Method A work (“Method A – VDOT”) was just slightly better yet. An observation regarding the “Method A - VTRC” data is that they are pretty flat, at just over 20% cumulative frequency approaching the minimum density line of 92.5%; this indicates that none of the VTRC density cores was just below the 92.5% density. This result is likely due to this dataset having fewer cores and projects than the other two datasets and having more cores that are just meeting the minimum density target.

Table 18 summarizes the data behind the distributions shown in Figure 9. Despite the modestly better overall distribution (78.8% vs. 78.1% exceeding 92.5%), the “Method A - VDOT” results averaged just slightly below the VTRC results. An F and t-test suggested that the two types of projects as tested by VTRC (Method A and B) varied similarly, and the means are not significantly different. A similar analysis of the “Method B - VTRC” results versus the “Method A - VDOT” results indicated that the variances may be different but also could not confirm a difference in the means (at a 95% confidence level).

Although the Method A results did not show a statistically significant difference in density from the Method B results, the average density of the Method A data shows an increase of 0.2% and 0.5% from the Method B dataset and an overall improvement of 1.8% and 2.1% from the 2015 baseline data. An analysis of that data could not confirm the difference to be attributable to the availability of incentives. However, frequency distributions suggesting that 12% to 13% more of the core samples met or exceeded VDOT’s 92.5% minimum requirement with Method A testing are encouraging and perhaps a sufficient reason to continue an incentive program for density.

Table 18. Impact of Acceptance Method on In-place Density

Measure		Acceptance Method				
		VDOT	VTRC		Difference	
		Method A	Method A	Method B	D - F	E - F
		D	E	F	G	H
Density	Avg. (%)	93.5	93.8	93.3	0.2	0.5
	Std. Dev.	1.54	1.93	1.99	-0.45	-0.06
	Distribution exceeding 92.5%	78.8	78.1	65.8	13	12.6

Summary of Results

In-place Density

- *Regarding the 2015 50-gyration design trials:*

  — The distribution from the in-place density from the 65-gryation (control) mixtures is consistent with results from the two previously referenced studies (Hughes et al., 2007; Maupin, 2010). Of the 165 cores taken from the control mixture sites, less than 40% met the minimum density requirement of 92.5%.

  - Conversely, of the 165 samples from the 50-gyration trial mixtures, approximately 65% met the minimum density requirement.

  - The average in-place density for the eleven 65-gyration mixtures was 91.7% of MTD with a standard deviation of 2.09.

  - The 50-gyration trial mixtures averaged 93.2% in-place with the same standard deviation of 2.09.

- *Regarding VTRC's field testing in 2016:*

  - There did not appear to be any predominate mixture characteristics associated with differences in the measured in-place results. Most (but not all) of the top-performing SM-12.5 mixtures exhibited a higher effective volume of asphalt (calculated as proportion of VMA filled with asphalt). Those mixtures also had moderate ratios of fines to asphalt (FA ratio).

  - The two top "achievers" among the SM-9.5 mixtures seemed to exemplify two opposing strategies to achieve excellent in-place properties. The first worked with a higher effective asphalt volume and lower fines, and the second "optimized" fine aggregate in lieu of asphalt cement with a VMA that was very close to the minimum requirement.

- *Regarding VDOT's Experience With 2016 Quality Incentive Pilots:*

  - The mixtures designated SM-12.5A mixtures were associated with consistent bonus-quality work, whereas contractors appeared to struggle some with SM-9.5A mixtures.

  - Interestingly, the SM-19.0A mixture was the most consistent at qualifying for the incentive, at least among the mixtures with more than one representative project.

  - Incentive-quality work was more common on primary system projects, perhaps an indication of more uniform subgrade support.

  - There appeared to be very little (to no) practical difference in the achieved in-place density of mixtures designated A and D mixtures.

- *A comparison of two datasets that represented the same density acceptance method (Method B/indirect) but different design criteria found a statistically significant improvement in density of as much as 1.6% with the new design criteria.*

- *A comparison of two datasets that represented different density acceptance methods (Method A vs. Method B) but the same mix design criteria found a modestly improved overall average in-place density with Method A, a difference that was not proven to be statistically significant. However, this comparison also found 12% to 13% more of the* *as-constructed mat to have met or exceeded VDOT's 92.5% minimum with Method A testing.*

Other Constructed Quality Characteristics

- Referring to the 2015 "50 gyration design" trials, approximately 58% of the control mixture samples had acceptable permeability results, whereas more than 85% of the trial-mixture cores passed the current threshold. A regression line of the data provides a slightly flatter slope for the trial mixtures, which suggests modestly lower permeability with similar in-place voids.

- There were no significant differences in bond strength between the two acceptance methods: Methods A and B.

CONCLUSIONS

- *Virginia's 2016 revisions for most asphalt concrete surface mix designs, which included reduced laboratory compaction and modest changes in gradation and volumetric criteria, are associated with reduced as-placed permeability, a change that should promote longer material service life.*

- *The 2016 mix design criteria combined with a change in density acceptance (direct measurement with incentives) resulted in an overall increase in in-place asphalt concrete density of 2%. In addition, the proportion of as-constructed mat that met or exceeded Virginia's minimum requirement for compaction increased by 44%.*

RECOMMENDATIONS

1. *VDOT should continue to apply the specification changes for design of dense-graded asphalt concrete as first published as a special provision (December 2015) and later reflected in the standard Road and Bridge Specifications for Section 211 (VDOT, 2020).* These criteria, which among other things reduce design compaction to 50 gyrations, promote improved in-place properties: better density and lower permeability.

2. *VDOT should continue to accept and pay for compaction of asphalt plant mixture in accordance with VDOT's Special Provision for Density Determination—S315HP1 (VDOT, 2018).* Key elements of this special provision include testing by direct measurement (core or plug) and an opportunity for payment incentives. For the 2016 construction season, Method A acceptance (from the special provision) was associated with an overall improved uniformity in achieved in-place density.

IMPLEMENTATION AND BENEFITS

Implementation

By the end of the 2016 construction season, positive results (or at least the lack of negative results) in the laboratory and during production with the 2015 cooperative trials (Diefenderfer et al., 2018) bolstered general acceptance of the newer mix design criteria. The in-place properties that are documented formally in this report, but were also available informally by early summer 2016, provided additional support for *Recommendation 1* to continue with the 50-gyration surface mix design criteria.

Regular and early feedback from the 2016 field density pilot projects testing (in support of this study) was also considered when VDOT officials decided to continue Method A density acceptance via cores or plugs with a potential for an incentive into the 2017 season and moving forward—*Recommendation 2*. Beginning in 2019, Method A density acceptance was expanded to include primary and secondary routes with at least 2,000 ADT (reduced from 5,000).

The revised specifications (regarding mix design) and special provision (regarding compaction acceptance) supported by this study have functioned in tandem to deliver 3 full years of Virginia's asphalt paving program since the first pilot studies in 2015 and 2016. The payment implications associated with Method A acceptance have compelled very close tracking of field density data over that timeframe. The records as received and maintained by the VDOT districts have also been shared centrally to permit a statewide assessment of how these fundamental changes are affecting as-placed quality. Tables that are modeled after Tables 14 through 16 are provided in Appendix B to summarize all 4 years of experience with Method A acceptance.

Benefits

A better visual comparison of how the design criteria and density incentives have affected in-place quality from 2015 to 2019 is shown in Figure 10. The "2015 (65-gyr)" distribution (also shown in Figures 4 and 8) represents the most comprehensive distribution of in-place density as determined with direct measurements (core-based) for the previous-generation surface mix design criteria. As stated previously, the baseline 2015 65-gyration dataset showed an overall average of approximately 91.7%, with 34% of the cores at or above VDOT's minimum of 92.5% TMD. The "2016" distribution in Figure 10 is the same distribution as that labeled "Method A - VDOT" in Figure 9. It represents individual test results from roughly 100 pilot-project routes. In contrast, the 2017 through 2019 distributions depict cumulative frequency of contractor sublot core (or plug) densities from approximately 400 to 450 routes each year. VDOT collected more than 5,000 results from contractor Method A density testing reports in 2017 and 2018; in 2019, the minimum traffic level for Method A on primary and secondary routes was reduced from 5,000 ADT to 2,000 ADT, resulting in more than 6,000 cores.

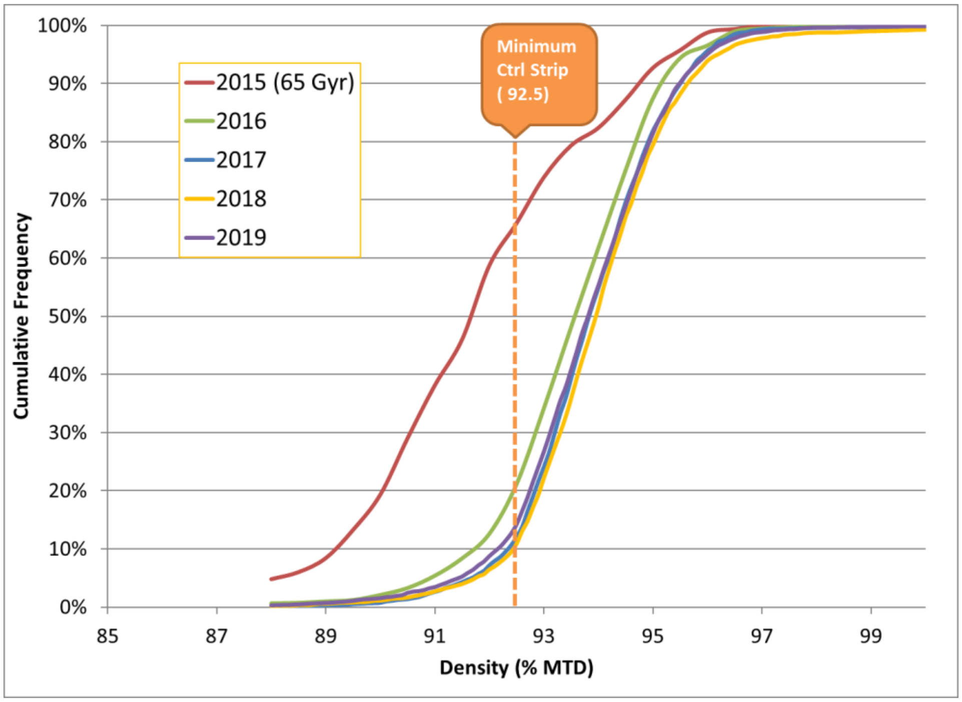

Figure 10. In-place Density of Surface Mixtures (2016-2019) as Accepted Using VDOT's Method A and Reported to the Central Office Materials Division by VDOT Districts

The distribution from 2016 indicates that approximately 80% of the in-place material was compacted to a degree that met or exceeded VDOT's 92.5% minimum requirement. Method A acceptance in the 3 subsequent years appears to be delivering even better in-place densities with average distributions of approximately 85% to 90% exceeding VDOT's minimum requirement. The frequency graphs for the 3 years are similar, which is credible given the large sample size and little change across the years. The 2019 data do show 86% of samples at or above the minimum density, 2% to 3% lower than the 2018 and 2017 datasets; this could be a result of expanding Method A in 2019 to include lower ADT routes.

It is difficult to separate the impact of the newest material design criteria from the method of density acceptance, but the combined positive effect is hard to deny. Results from the last three construction seasons suggest a slightly more than 2.0% increase in overall average in-place density. Perhaps more important, assuming the original target of 92.5% was indeed an adequate level of compaction, the contrast in distributions shown in Figure 10 indicates an approximate 50% improvement in the as-placed mat that now meets or exceeds VDOT's minimum density requirement.

Any quality-based cost avoidance analysis that starts with a 50% improvement would return gaudy and likely hard-to-believe economic benefits. A more practical, but nonetheless impressive economic analysis can be constructed around the 2.0% overall average improvement in in-place density (~93.8% today vs. 91.7% in 2015). The oft-referenced "1.0% increase in density leads to a 10% increase in fatigue life" (Tran et al., 2016), therefore, suggests the pavement life could see an improvement of up to 20% in this instance. Assuming resurfacing overlays have a 10-year average fatigue service life, extending this to 12 years and projecting this impact onto the approximately $350M annual program that stands to benefit, the annual economic return may be as much as $70M.

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APPENDIX A

BOND STRENGTH—2016 VTRC FIELD PROJECTS

A series of wet-cut 4-in cores were taken at every project with the goal of testing bond strength. As is typical with sampling designed to acquire multiple layers, the resulting specimen did not always survive intact. Testable specimens were available for most projects. The most common reason for non-testable specimens was a lack of sufficient integrity in the underlying layer.

The results are separated by project type and paving operation in Tables A1 and A2, respectively. There do not appear to be significant differences in average strength or variability between the two project types: Methods A and B. The average tensile and shear strength values are also consistent with the bond strength values measured during previous laboratory and field research (Clark et al., 2012; McGhee and Clark, 2009), which documented average tensile and shear strength values with idealized (laboratory prepared) specimens of approximately 80 psi and 260 psi, respectively.

There do appear to be more exaggerated differences between the two basic paving operations, although the stronger average bond observed at the milled interfaces is to be expected and has also been previously documented (Mohammad et al., 2012). The "Mill/Fill" results suggest a modest improvement over those observed by McGhee and Clark (2009) where the average milled surface (with tack) exhibited a tensile bond strength of 63 psi and a shear strength of 250 psi.

Table A1. Bond Strength Versus Acceptance Method

	Bond Strength					
	Tensile			Shear		
Project Type	**No. of Specimens**	**Avg. (psi)**	**Std. Dev.**	**No. of Specimens**	**Avg. (psi)**	**Std. Dev.**
Method B	23	88.5	30.9	25	265.4	65.4
Method A	10	87.3	39.3	13	309.9	47.2

Table A2. Bond Strength Versus Paving Operation

	Bond Strength					
	Tensile			Shear		
Operation	**No. of Specimens**	**Avg. (psi)**	**Std. Dev.**	**No. of Specimens**	**Avg. (psi)**	**Std. Dev.**
Str. Overlay	12	62.2	18.6	13	217.2	23.2
Mill/Fill	21	101.0	32.2	25	307.5	57.1

Str. Overlay = straight overlay.

APPENDIX B

2016-2019 TRENDS IN VIRGINIA COMPACTION

Table B1. In-Place Density Trends by Mixture Type—2016-2019

Mixture	Routes				Incentive Lots				Average Density			
	2016	2017	2018	2019	2016	2017	2018	2019	2016	2017	2018	2019
SM-9.5A	22	139	146	180	40%	68%	80%	65%	93.0%	93.5%	93.9%	93.3%
SM-9.5D	43	145	65	79	68%	70%	73%	69%	93.4%	93.7%	93.9%	93.7%
SM-9.5E	1	8	10	7	100%	65%	85%	100%	93.9%	93.0%	94.1%	95.0%
SM-12.5A	22	62	60	82	83%	91%	89%	89%	93.7%	94.0%	93.9%	94.1%
SM-12.5D	7	36	23	52	65%	88%	74%	81%	93.2%	94.0%	94.0%	94.0%
SM-12.5E	6	48	41	37	52%	92%	97%	90%	92.8%	94.0%	94.2%	94.2%
SM-19.0A	9	2	4	18	93%	0%	100%	67%	93.8%	92.9%	93.7%	93.5%
Overall	110	440	349	455	69.5%	76%	82%	74%	93.4%	93.7%	93.9%	93.7%

Table B2. In-Place Density Trends by System—2016-2019

Highway System	Routes				Incentive Lots				Average Density			
	2016	2017	2018	2019	2016	2017	2018	2019	2016	2017	2018	2019
Interstate	2	20	11	21	66.7%	90.0%	82.5%	78.6%	93.3%	94.0%	94.0%	94.1%
Primary	39	188	150	197	74.2%	84.6%	83.0%	78.6%	93.5%	93.9%	94.0%	93.9%
Secondary	54	245	235	268	60.5%	74.5%	78.1%	71.2%	93.3%	93.8%	93.9%	93.5%
Overall	95	453	396	486	66.3%	79.4%	80.1%	74.5%	93.4%	93.8%	93.9%	93.7%

Table B3. In-Place Density Trends by Binder Designation—2016-2019

Binder Design	Routes				Incentive Lots				Average Density			
	2016	2017	2018	2019	2016	2017	2018	2019	2016	2017	2018	2019
A-Mixes	43	203	217	284	71.2%	82.8%	83.3%	76.1%	93.5%	93.9%	93.9%	93.7%
D-Mixes	50	182	99	131	67.8%	74.4%	73.0%	72.1%	93.4%	93.8%	93.9%	93.8%
E-Mixes	7	57	57	47	54.5%	90.0%	94.2%	87.6%	92.9%	93.9%	94.2%	94.1%
Overall	100	442	373	462	68.3%	80.6%	81.5%	76.0%	93.4%	93.8%	93.9%	93.8%