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Development of a Catalog of Resilient Modulus Values for Aggregate Base for Use With the Mechanistic-Empirical Pavement Design Guide (MEPDG)

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Base aggregate is one of the intermediate layers in a pavement system for both flexible and rigid surfaces. Characterization of base aggregate is necessary for pavement thickness design. Many transportation agencies, including the Virginia Department of Transportation, assign a layer coefficient for pavement design where consideration for gradation or rock type is not obvious. The mechanistic-empirical pavement design requires base aggregate to be characterized using a resilient modulus value. Therefore, 16 aggregates from different geophysical regions of Virginia were collected and tested for resilient modulus in order to develop a catalog for the implementation of the Mechanistic-Empirical Pavement Design Guide (MEPDG).

A wide range of resilient modulus values for base aggregate was found for different sources with different rock types. A catalog was developed with resilient modulus values for 16 aggregates from Virginia. The resilient modulus values ranged from approximately 10,000 to 30,000 psi. In general, limestone showed the higher modulus as compared to granite. An increase in compaction moisture content, even within allowable limits, adversely affected the resilient modulus value for many aggregates. This moisture sensitivity is related to both the percent of material passing the No. 200 sieve and the plastic nature of these fines. These values are recommended to be used as reference values for the MEPDG, but engineering judgment should be applied to account for moisture sensitivity.

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FINAL REPORT

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ABSTRACT

Base aggregate is one of the intermediate layers in a pavement system for both flexible and rigid surfaces. Characterization of base aggregate is necessary for pavement thickness design. Many transportation agencies, including the Virginia Department of Transportation, assign a layer coefficient for pavement design where consideration for gradation or rock type is not obvious. The mechanistic-empirical pavement design requires base aggregate to be characterized using a resilient modulus value. Therefore, 16 aggregates from different geophysical regions of Virginia were collected and tested for resilient modulus in order to develop a catalog for the implementation of the *Mechanistic-Empirical Pavement Design Guide* (MEPDG).

A wide range of resilient modulus values for base aggregate was found for different sources with different rock types. A catalog was developed with resilient modulus values for 16 aggregates from Virginia. The resilient modulus values ranged from approximately 10,000 to 30,000 psi. In general, limestone showed the higher modulus as compared to granite. An increase in compaction moisture content, even within allowable limits, adversely affected the resilient modulus value for many aggregates. This moisture sensitivity is related to both the percent of material passing the No. 200 sieve and the plastic nature of these fines. These values are recommended to be used as reference values for the MEPDG, but engineering judgment should be applied to account for moisture sensitivity.

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INTRODUCTION

Base aggregate is one of the intermediate layers in a pavement system for both flexible and rigid surfaces. The Virginia Department of Transportation (VDOT) currently uses the *Guide for Design of Pavement Structures* with supplements (American Association of State Highway and Transportation Officials [AASHTO], 1993), hereinafter referred to as the 1993 AASHTO design guide, which specifies that a structural layer coefficient be used to characterize the base course material. However, VDOT is in the process of implementing the *Mechanistic-Empirical Pavement Design Guide* (MEPDG) (AASHTO, 2008), which recommends use of the resilient modulus value to characterize base course materials for pavement design and analysis. VDOT mainly uses two grades of materials for its base course, designated No. 21A and No. 21B, based on gradation (VDOT, 2007). No. 21A material has a higher allowable fines content than No. 21B material; the percent of material passing the No. 200 sieve is 6% to12% and 4% to 7% for No. 21A and 21B, respectively. Therefore, an overlap exists between the grading requirements for the two, so that a single gradation can be produced to meet either grade. A study to obtain resilient modulus values for these base aggregates is warranted to facilitate the implementation of the MEPDG.

In Phase I of this study (Hossain, 2010), six aggregate sources were tested and resilient modulus values were measured. In order to have a broader coverage of different geophysical areas in Virginia, with consideration of rock types and aggregate particle shape and texture, the current Phase II study was performed. In this study, aggregates from 10 additional sources in Virginia were tested.

PURPOSE AND SCOPE

The purpose of this Phase II study was to conduct resilient modulus tests on aggregate sources typically used by VDOT for base course construction in pavement structures and to catalog respective regression coefficients (k-values) and resilient modulus values at a reference state of stress. The intent for developing such a catalog of values was for their use as input in MEPDG Level I and/or II analysis. Two aggregate gradations, VDOT No. 21A and VDOT No. 21B were tested. Sources of aggregate were selected to include most rock types available in all geophysical areas of Virginia.

METHODS

Three tasks were conducted to achieve the study objectives.

1. *A literature search of studies about base aggregate was conducted using resources from the VDOT Research Library and the Transportation Research Board's online database TRID.*

2. *Aggregate samples were collected from 10 sources in Virginia by VDOT's Materials Division.* The 10 sources were selected for aggregate testing for this Phase II study (2012-13) to supplement the 6 sources tested in Phase I (2008-09). All 16 sources are shown in Figure 1 with their respective location on a geophysical map of Virginia. A source from VDOT's Northern Virginia District (NOVA) was tested in both phases of the study; it is identified as Source 9 (P2AGG-9) in Phase II and AGG-5 in Phase I. Aggregate sources were selected to include both VDOT gradations (No. 21A and No. 21B) and a cross-section of predominant rock types available in Virginia. Each source provided one gradation, except for one source in NOVA from which separate No. 21A and No. 21B samples were collected. Samples were typically identified as either No. 21A or No. 21B, but some were labeled as No. 21A/B to indicate that the sample met the requirements of both gradations.

3. *Aggregates underwent multiple tests in accordance with the respective AASHTO standards (AASHTO, 2013).* About 200 lb of aggregate was collected from each source, and splitting was used in the laboratory to prepare samples for testing. All sources were tested for gradation (AASHTO T 27, Standard Method of Test for Sieve Analysis of Fine and Coarse Aggregates); specific gravity (AASHTO T 84, Standard Method of Test for Specific Gravity and Absorption of Fine Aggregate, and AASHTO T 85, Standard Method of Test for Specific Gravity and Absorption of Coarse Aggregate); moisture-density relationship (AASHTO T 99, Standard Method of Test for Moisture-Density Relations of Soils Using a 2.5-kg [5.5-lb] Rammer and a 305-mm [12-in] Drop); and uncompacted void content (AASHTO T 326, Standard Method of Test for Uncompacted Void Content of Coarse Aggregate (As Influenced by Particle Shape, Surface Texture, and Grading), and AASHTO T 304, Standard Method of Test for Uncompacted Void Content of Fine Aggregate). The samples were also examined for petrographic classification and particle shape. All tests were performed at VDOT laboratories. Table 1 summarizes the test matrix for Phases I and II.

Table 1. Aggregate Test Matrix

Test	AASHTO Standard	No. Samples per Source	
		Phase I	Phase II
Mineralogy and particle shape	Visual examination	1	1
Uncompacted voids	T 326 and T 304	-	1
Specific gravity	T 84 and T 85	-	2
Gradation	T 27	1	2
Moisture-density relation (standard Proctor)	T 99	1	1
Resilient modulus and quick shear test	T 307	3	2

The standards may be found in AASHTO (2013).

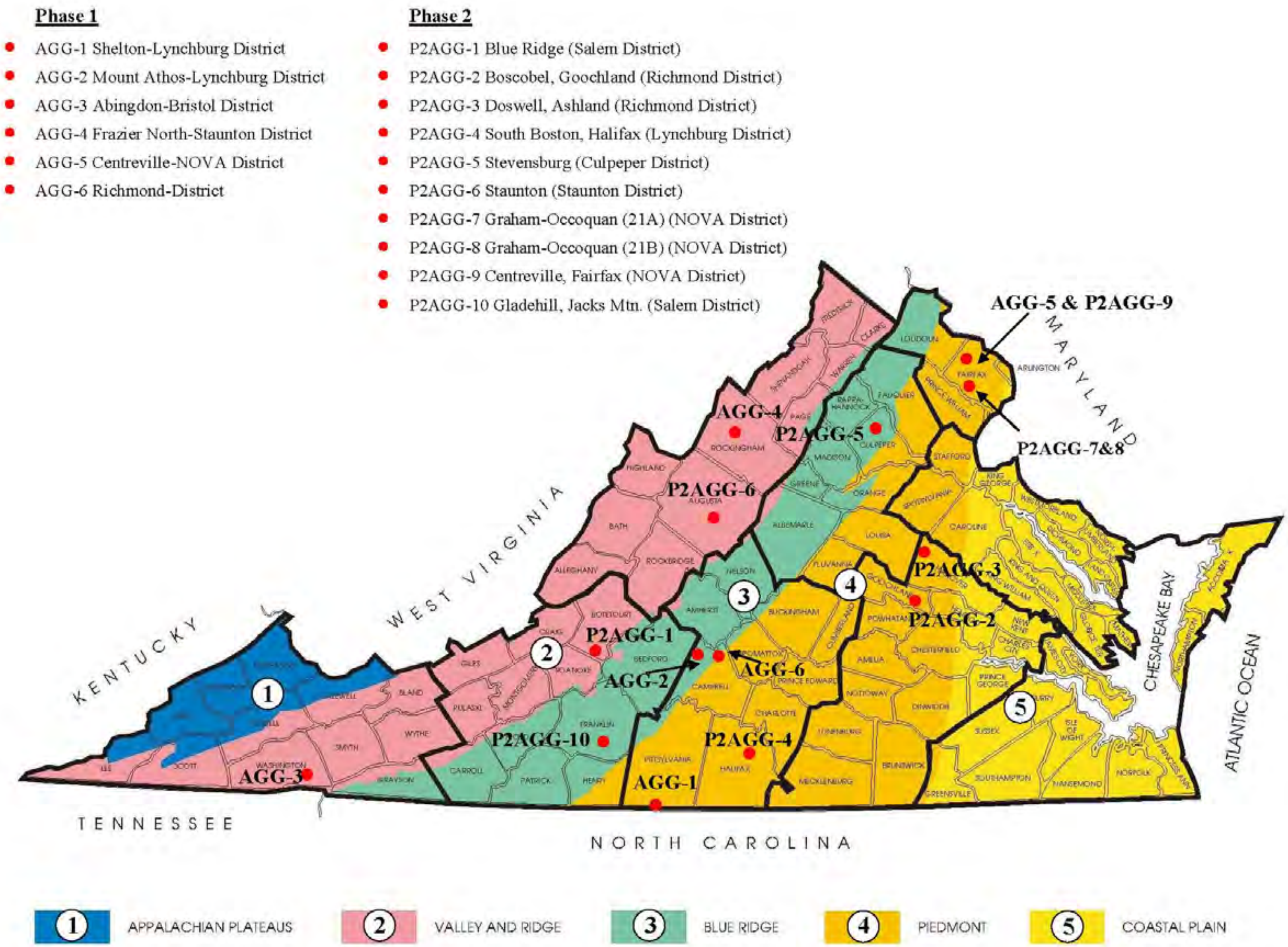

Figure 1. Aggregate Source Locations

The moisture-density relationship was determined in accordance with AASHTO T 99, Method D, which uses a standard Proctor hammer. A 5.5-lb automatic hammer with a 12-in drop was used to compact the samples in a 6-in mold. Samples were compacted in three layers with 56 drops per layer. The particles retained on the ¾-in sieve were not scalped when they comprised less than 6% of the total, but for the sources with higher percentages, they were scalped and correction was applied for comparison.

The presence of plastic fines was investigated for a few sources; plastic and liquid limit tests were conducted on materials passing the No. 200 sieve in accordance with AASHTO T 89, Standard Method of Test for Determining the Liquid Limit of Soils, and AASHTO T 90, Standard Method of Test for Determining the Plastic Limit and Plasticity Index of Soils. The standards call for testing on materials passing the No. 40 sieve, and only one aggregate showed any plasticity when tested. Therefore, it was decided to test materials passing the No. 200 sieve to verify any presence of plastic fines.

Resilient modulus tests were conducted by an outside vendor in accordance with AASHTO T 307, Standard Method of Test for Determining the Resilient Modulus of Soils and Aggregate Materials. The VDOT aggregate gradations No. 21A and No. 21B were categorized as Type I material in accordance with AASHTO T 307; thus 6-in by 12-in samples were used. Although samples were prepared at 100% maximum dry density (MMD) of the standard Proctor result, a moisture variation was tried. Each sample was compacted using a modified Proctor hammer in six layers of equal mass to achieve desired density by controlling the compacted height. Samples were prepared at optimum moisture content (OMC) and 1% below OMC during Phase II and at OMC and 2% below OMC during Phase I of the study. A sample above OMC was tried during Phase I of the study (Hossain, 2010), but it was not successful because of constructability and stability issues. The sample was loaded in accordance with AASHTO T 307 with 15 combinations of various confining and axial (vertical) stresses after 1000 repetition of a conditioning load combination. The confining stresses were applied using a triaxial pressure chamber in static mode. On the other hand, axial loads were dynamic (cyclic) using a haversine-shaped load pulse with 0.1-sec loading and a 0.9-sec rest period. Each of the 15 test loads was repeated 100 times, and the recoverable strains were measured using two external linear variable differential transformers. Resilient modulus values were calculated as the ratio of the measured axial (deviator) stress to the average recoverable axial strain values for the last five cycles of each load combination. The stress dependent constitutive model (see Eq. 1) recommended in the MEPDG has been used to fit the laboratory tested resilient modulus values for each test and respective k-values were calculated through regression analysis; the coefficient of determination, R^2, was above 0.9 for all the tests.

$$M_r = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a} + 1\right)^{k_3} \quad \text{[Eq. 1]}$$

where

M_r = resilient modulus value
k_1, k_2, and k_3 = regression coefficients
P_a = normalizing stress (atmospheric pressure, e.g., 14.7 psi)

θ = bulk stress = $(\sigma_1 + \sigma_2 + \sigma_3) = (3\sigma_3 + \sigma_d)$ where σ_1, σ_2, and σ_3 = principal stresses where $\sigma_2 = \sigma_3$ and σ_d = deviator (cyclic) stress = $\sigma_1 - \sigma_3$

τ_{oct} = octahedral shear stress = $\frac{1}{3}\sqrt{(\sigma_1-\sigma_2)^2+(\sigma_1-\sigma_3)^2+(\sigma_2-\sigma_3)^2} = \frac{\sqrt{2}}{3}\sigma_d$.

At the end of the resilient modulus test, all samples were subjected to a static triaxial loading with 5 psi confining pressure until failure. This portion of the test is referred to as the "quick shear test" in AASHTO T 307.

RESULTS

Literature Review

Gandara et al. (2005) investigated the effect of gradation and fines content (percent passing the No. 200 sieve) on the engineering properties of two unbound granular materials. The optimum amount of fines was found to be 5% to 10%. When fines were within that range, the base aggregate showed less moisture susceptibility, higher compressive strength, and a higher resilient modulus. In general, an increase in fines resulted in a decrease in resilient modulus.

Bennert and Maher (2005) studied the effect of gradation on permeability, shear strength, California bearing ratio, and resilient modulus for three base aggregates and three subbase aggregates. The allowable limits for percentage of passing the No. 200 sieve were 3% to 12% and 0% to 8% for base and subbase aggregates, respectively. They reported a decrease in resilient modulus as gradation became finer but within the specification limits. This effect was suggested to be a result of the excessive fines in the sample.

In an NCHRP Synthesis of Practice for unbound aggregate in pavement layers, Tutumluer (2013) reported 7% to 8% passing the No. 200 sieve to be the optimum for aggregate strength, resilient modulus, and permanent deformation based on past research. The researcher suggested that the resilient modulus is usually higher for a well-graded aggregate, but an excess amount of fines (passing the No. 200 sieve) would displace the coarse aggregate and the properties of fines would dominate the performance. A 60% reduction in the resilient modulus was reported when fines (passing the No. 200 sieve) were increased from 0% to 10%.

Tutumluer et al. (2009) investigated the effect of particle shape and the presence of particles passing the No. 200 sieve on the strength, stiffness, and deformation behavior of three aggregate materials, i.e., limestone, dolomite, and uncrushed gravel, commonly used in Illinois for subgrade replacement and subbase. When the fines contents (passing the No. 200 sieve) were less than 8%, the properties that influenced the aggregate behavior the most were the particle shape/angularity, i.e., crushed versus uncrushed, and the amount of voids in the aggregate matrix as governed by materials passing the No. 200 sieve. Fines with a plasticity index (PI) of 10 or higher had a drastic effect on aggregate permanent deformation performance. Crushed aggregate with a high (more than 8%) amount of fines, both plastic and non-plastic, showed high moisture sensitivity and a design aggregate layer thickness increase of as much as

40% was suggested. With even a low amount of plastic fines, the aggregate showed moisture sensitivity at moisture contents exceeding OMC.

Aggregate Test Results

Rock Type and Particle Shape

Particles were visually examined for rock type/mineralogy and general particle shape characteristics. Rock type/mineralogy was consistent through different size fractions for all sources. Table 2 summarizes the results of the visual examination of rock type and particle shape. To provide a general idea about the impact and abrasion resistance of each rock type, Los Angeles abrasion loss values (determined in accordance with AASHTO T 96-02, Standard Method of Test for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine) from the VDOT materials approved list (VDOT, 2014a) were also included in Table 2.

For each source, uncompacted void content tests were conducted separately on the coarse and fine fractions: (1) particles retained on the No. 4 sieve, and (2) particles passing the No. 4 sieve. The tests were conducted on two gradations: Standard Grade (Method A), and As-Received Grade (Method C). Table 3 summarizes the results of the uncompacted void content tests for both coarse and fine fractions using Methods A and C.

Index Properties

Separate specific gravity tests were conducted on the coarse and fine fractions. Table 4 summarizes the specific gravity and absorption results for each aggregate source. Specific gravity values varied from 2.6 to 3.0.

Washed gradations were performed on two split samples from each source in accordance with AASHTO T 27, and the results were compared to the VDOT specifications (VDOT, 2007) for No. 21A and No. 21B. A summary of the gradations is shown in Table 5. Detailed results along with plots are provided in the Appendix. Although in many cases the gradation of the tested sample did not fall within the VDOT gradation range for all sizes, this does not mean the gradation was out of compliance. The applicable VDOT specification (VDOT, 2007) states:

> Grading shall conform to the requirements of the job-mix formula selected from within the design range specified in Table II-9, subject to the applicable tolerances specified in Table II-10 when tested in accordance with the requirements of VTM-25.

If the percent passing for a particular size is selected in the job-mix formula at the upper or lower limits of the design range, it can easily fall outside the range with the allowable tolerances. For example, the design range for percent passing the No. 200 sieve for VDOT No. 21A is 6% to 12% with a tolerance of ±4% when one QC/QA sample is used, so for a job-mix formula selected at 12%, the specification would allow up to 16% as acceptable. Because of the observed high sensitivity of the resilient modulus to moisture, the presence of plastic fines was investigated for a few sources. Liquid and plastic limit tests were conducted on materials passing the No. 200 sieve as opposed to the standard practice of using the No. 40 sieve, and the results are included in Table 5. When tested on materials passing the No. 40 sieve, the presence of plastic fines was not evident in most cases. The Atterberg limit test results could easily be influenced by the experience of the operator, so other alternate testing methods should be explored.

Table 2. Rock Type/Mineralogy and Particle Shape From Visual Examination

Aggregate Source	VDOT District	LA Abrasion Loss (%) (Grade B)[a]	Rock Type/ Mineralogy	Particle Shape and Comments
Phase I				
AGG–1 (Shelton)	Lynchburg	27.0	Granite gneiss	
AGG–2 (Mt. Athos)	Lynchburg	19.0	Schist/Greenstone	
AGG–3 (Abingdon)	Bristol	16.4	Dolomitic limestone	
AGG–4 (Frazier North)	Staunton	22.0	Limestone	
AGG–5 (Centreville)	NOVA	13.4	Diabase	
AGG–6 (Richmond)	Richmond	28.6	Marble	
Phase II				
P2AGG–1 (Blue Ridge)	Salem	15.8	Dolomitic limestone	10% shaley; 10% slightly weathered
P2AGG–2 (Boscobel)	Richmond	23.9	Granite	Fine-medium grained; 15% thin & flat particles
P2AGG–3 (Doswell)	Richmond	17.8	Granitic gneiss	Coarse-medium grained; 20% thin & flat particles
P2AGG–4 (South Boston)	Lynchburg	22.0	Granite	Fine-medium grained
P2AGG–5 (Stevensburg)	Culpeper	11.9	90% Siltstone, 10% Shale	15% particles flat & thin (7:5:1); 20% elongate (3.5:1)
P2AGG–6 (Staunton)	Staunton	21.0	Limestone	Micritic; 20% thin & flat particles
P2AGG–7 (Graham-Occoquan)	NOVA	28.4	Granite	Some gneissic foliation; fairly equant particles
P2AGG–8 (Graham-Occoquan)	NOVA	28.4	Granite	
P2AGG–9 (Centreville)	NOVA	13.4	65% Diabase, 35% Siltstone	Siltstone particles tended to be flat & thin
P2AGG–10 (Gladehill, Jacks Mtn.)	Salem	31.8	Amphibolite gneiss	45% fairly hard and equant particles; 25% fairly hard, thin & tablet-shaped particles (10:6:1); 30% rounded particles with weathered feldspar

Rock type/mineralogy was consistent through different size fractions for all sources.
VDOT = Virginia Department of Transportation; NOVA = Northern Virginia.
[a] LA abrasion values were taken from the VDOT materials approved list (VDOT, 2014a); no testing was done in this study.

Table 3. Uncompacted Void Content of Coarse and Fine Fractions of Each Aggregate Source

Aggregate Source	VDOT District	Uncompacted Void Content (%)			
		Standard Grade		As-received Grade	
		Coarse (>No. 4)	Fine (≤No. 4)	Coarse (>No. 4)	Fine (≤No. 4)
Phase I					
AGG–1 (Shelton)	Lynchburg	No testing during Phase I			
AGG–2 (Mt. Athos)	Lynchburg				
AGG–3 (Abingdon)	Bristol				
AGG–4 (Frazier North)	Staunton				
AGG–5 (Centreville)	NOVA				
AGG–6 (Richmond)	Richmond				
Phase II					
P2AGG–1 (Blue Ridge)	Salem	51.9	47.2	52.1	40.6
P2AGG–2 (Boscobel)	Richmond	49.5	47.6	47.3	43.5
P2AGG–3 (Doswell)	Richmond	50.9	45.0	51.0	40.6
P2AGG–4 (South Boston)	Lynchburg	47.6	48.5	49.2	39.8
P2AGG–5 (Stevensburg)	Culpeper	48.7	45.5	48.0	39.4
P2AGG–6 (Staunton)	Staunton	49.8	46.2	49.3	40.8
P2AGG–7 (Graham-Occoquan) (21A)	NOVA	49.0	46.7	47.5	38.4
P2AGG–8 (Graham-Occoquan) (21B)	NOVA	47.4	47.0	46.6	38.2
P2AGG–9 (Centreville)	NOVA	51.9	46.3	51.4	38.7
P2AGG–10 (Gladehill, Jacks Mtn.)	Salem	51.2	48.8	51.2	40.1

VDOT = Virginia Department of Transportation; No. 4 = No. 4 sieve; NOVA = Northern Virginia.

Table 4. Specific Gravity of Coarse and Fine Fractions of Each Aggregate Source

Aggregate	Source Location	Specific Gravity (AASHTO T 84 and T 85) (AASHTO, 2013)							
		Dry Bulk		SSD Bulk		Apparent		Absorption (%)	
		>No. 4	≤No. 4	>No. 4	≤No. 4	>No. 4	≤No. 4	>No. 4	≤No. 4
Phase I									
AGG-1	Shelton	No testing during Phase I							
AGG-2	Mt. Athos								
AGG-3	Abingdon								
AGG-4	Frazier North								
AGG-5	Centreville								
AGG-6	Richmond								
Phase II									
P2AGG-1	Blue Ridge	2.706	2.752	2.729	2.794	2.772	2.873	0.885	1.528
P2AGG-2	Boscobel	2.574	2.627	2.599	2.670	2.639	2.744	0.952	1.613
P2AGG-3	Doswell	2.711	2.698	2.727	2.722	2.755	2.765	0.591	0.902
P2AGG-4	South Boston	2.737	2.788	2.758	2.811	2.794	2.856	0.740	0.855
P2AGG-5	Stevensburg	2.699	2.652	2.728	2.702	2.780	2.790	1.068	1.856
P2AGG-6	Staunton	2.668	2.687	2.692	2.723	2.734	2.788	0.908	1.362
P2AGG-7	Graham-Occoquan (21A)	2.640	2.683	2.656	2.700	2.682	2.731	0.588	0.662
P2AGG-8	Graham-Occoquan (21B)	2.653	2.680	2.667	2.700	2.691	2.735	0.535	0.753
P2AGG-9	Centreville	2.832	2.803	2.856	2.848	2.902	2.936	0.847	1.619
P2AGG-10	Gladehill, Jacks Mtn.	3.016	2.974	3.043	3.013	3.102	3.095	0.916	1.306

SSD = Saturated Surface Dry; No. 4 = No. 4 sieve.

Table 5. Aggregate Gradations and VDOT Specification Limits

Aggregate Source	VDOT Grade 21__	Maximum Particle Size (in)	% Retained on ¾-in Sieve	% Passing by Sieve Size				Atterberg Limits (-No. 200 Sieve)	
				1 in	$^3/_8$ in	No. 4	No. 200	LL	PI
VDOT Spec 21A	*A*	*2 or 1*	*-*	*94-100*	*63-72*	*-*	*6-12*	*25.0*[a]	*6.0*[a]
VDOT Spec 21B	*B*	*2*	*-*	*85-95*	*50-69*	*-*	*4-7*	*25.0*[a]	*3.0*[a]
Phase I									
AGG–1 (Shelton)	A	1	8.7	97	68	51	12	29.0	5.0
AGG–2 (Mt. Athos)	A	¾	0.5	100	77	54	12	NP	NP
AGG–3 (Abingdon)	B	¾	2.3	100	72	48	9	19.0	2.0
AGG–4 (Frazier North)	B	¾	2.6	100	73	55	8	24.0	6.0
AGG–5 (Centreville)	B	¾	5.7	100	68	45	9	29.0	8.0
AGG–6 (Richmond)	B	¾	1.1	100	72	50	7	-	-
Phase II									
P2AGG–1 (Blue Ridge)	B	¾	2.4	100	66	42	10	-	-
P2AGG–2 (Boscobel)	A/B	¾	8.4	100	65	48	9	37.0	12.0
P2AGG–3 (Doswell)	A/B	¾	3.7	100	76	62	10	-	-
P2AGG–4 (South Boston)	A	¾	18.5	100	58	45	10	NP	NP
P2AGG–5 (Stevensburg)	B	¾	4.0	100	73	55	8	-	-
P2AGG–6 (Staunton)	A/B	¾	5.8	100	71	52	8	26.0	5.0
P2AGG–7 (Graham-Occoquan)	A	¾	12.9	100	71	57	14	33.0	9.0
P2AGG–8 (Graham-Occoquan)	B	¾	20.1	100	50	37	8	33.0	9.0
P2AGG–9 (Centreville)	A/B	¾	5.5	100	67	47	9	29.0	8.0
P2AGG–10 (Gladehill, Jacks Mtn.)	B	¾	4.8	100	71	52	19	NP	NP

VDOT = Virginia Department of Transportation; NP = non-plastic; LL= liquid limit; PI = plasticity index.
[a] Maximum allowed in VDOT specification when tested on materials passing the No. 40 sieve.

Moisture-Density Relationship

Moisture-density relationships were determined with the standard Proctor test in accordance with AASHTO T 99, Method D, without any scalping or correction applied for oversize particles. The OMCs and MDDs from the standard Proctor tests are summarized in Table 6.

Table 6. Moisture-Density Relationship (Standard Proctor)

Aggregate Source	VDOT Grade 21__	Approximate Specific Gravity[a]		Optimum Moisture Content (OMC), %	Maximum Dry Density (MDD), pcf
		≥No. 4 Sieve	<No. 4 Sieve		
Phase I					
AGG–1 (Shelton)	A	2.75	-	8.00	134.2
AGG–2 (Mt. Athos)	A	3.01	-	7.25	154.0
AGG–3 (Abingdon)	B	2.82	-	5.60	144.3
AGG–4 (Frazier North)	B	2.71	-	7.10	139.4
AGG–5 (Centreville)	B	2.82	-	7.65	142.5
AGG–6 (Richmond)	B	2.75	-	8.16	133.4
Phase II					
P2AGG–1 (Blue Ridge)	B	2.729	2.794	6.75	137.4
P2AGG–2 (Boscobel)	A/B	2.599	2.670	8.50	131.8
P2AGG–3 (Doswell)	A/B	2.727	2.722	7.50	141.2
P2AGG–4 (South Boston)	A	2.758	2.811	7.50	144.5
P2AGG–5 (Stevensburg)	B	2.728	2.702	7.80	138.3
P2AGG–6 (Staunton)	A/B	2.692	2.723	7.75	136.6
P2AGG–7 (Graham-Occoquan)	A	2.656	2.700	6.75	141.2
P2AGG–8 (Graham-Occoquan)	B	2.667	2.700	6.75	140.5
P2AGG–9 (Centreville)	A/B	2.856	2.848	7.50	146.3
P2AGG–10 (Gladehill, Jacks Mtn.)	B	3.043	3.013	7.60	155.8

Standard Proctor = AASHTO T 99, Method D; VDOT = Virginia Department of Transportation.
[a] Specific gravity values for Phase I were taken from the VDOT materials approved list (VDOT, 2014a); no testing was done in this study.

VDOT's usual practice is to conduct moisture-density relationship tests in accordance with Virginia Test Method-1 (VTM-1), Laboratory Determination of Theoretical Maximum Density Optimum Moisture Content of Soils, Granular Subbase, and Base Materials – (Soils Lab) (VDOT, 2014b). This method is similar to AASHTO T 99, Method A, which tests only on materials passing the No. 4 sieve. But VTM-1 applies a correction for oversize particles irrespective of the percent retained on the No. 4 sieve unlike the AASHTO method, which allows up to 40% oversize particles. VTM-1 may generate some unrealistic values when the percent retained on the No. 4 sieve is too high. Moreover, the AASHTO or ASTM standard (ASTM, 2014) allows tests to be run on particles as large as materials passing the ¾-in sieve as an option. Table 7 includes values of OMC and MDD for a few sources tested in accordance with VTM-1 and AASHTO T 99, Method D, with or without correction.

For comparison purposes, corrections were applied only for oversize particles when more than 6% was retained on the ¾-in sieve, but these values were not used in any subsequent testing. No scalping was done when corrections were not applied. The five sources presented in Table 7 had more than 6% retained on the ¾-in sieve. There are some differences in the values obtained in accordance with VTM-1 and AASHTO T 99, Method D; further investigation may be needed to verify actual field values and their implications with regard to resilient modulus values.

Table 7. Moisture-Density Relationship (Standard Proctor) According to Different Standards

Aggregate Source	VDOT Grade	% Retained on ¾-in Sieve	Optimum Moisture Content (OMC), %			Maximum Dry Density (MDD), pcf		
			AASHTO T 99[a]	No Scalping[b]	VTM-1[c]	AASHTO T 99[a]	No Scalping[b]	VTM-1[c]
AGG–1 (Shelton)	21A	11.4	6.5	8.0	5.2	138.6	134.2	144.4
P2AGG–2 (Boscobel)	21 A/B	8.4	7.0	8.5	5.4	133.2	131.8	138.8
P2AGG–4 (South Boston)	21A	18.5	6.4	7.5	4.8	146.9	144.5	152.5
P2AGG–7 (Graham-Occoquan)	21A	12.9	6.1	6.75	4.5	140.6	141.2	144.7
P2AGG–8 (Graham-Occoquan)	21B	20.1	5.7	6.75	3.9	143.3	140.5	144.9

Standard Proctor = AASHTO T 99, Method D; VDOT = Virginia Department of Transportation.
[a] AASHTO T 99, Method D (AASHTO, 2013), with scalping of particles >¾ in and correction applied in accordance with AASHTO T 224 (AASHTO, 2013).
[b] Tested in a manner similar to AASHTO T 99, Method D, but no oversize was scalped so no correction was applied.
[c] Data provided by VDOT's Materials Division; tested in accordance with VTM-1 (VDOT, 2014b) on materials passing the No. 4 sieve with correction applied for oversize.

Resilient Modulus

Resilient modulus testing was conducted in accordance with AASHTO T 307. All aggregates satisfied the gradation requirements of Type I material in AASHTO T 307; hence, a sample 6 in by 12 in was used for resilient modulus testing. In Phase I of the study, two sources were classified as VDOT No. 21A and the other four as No. 21B. In the current study (Phase II), two were classified as No. 21A, four as No. 21B, and four as combined No. 21 A/B. Those were the classifications provided by the producer, but some of the sources had different sizes outside the VDOT specification limits of No. 21A and No. 21B. As mentioned earlier, all samples were tested at OMC and to the dry side of OMC. Different constitutive models were fitted to the data using regression analysis, and the results for the MEPDG-recommended model are presented in Table 8 for the Phase I study and in Table 9 for the Phase II study. The regression coefficients, or k-values, presented in Tables 8 and 9 could be used to calculate the resilient modulus at actual stress conditions in the pavement. The stresses at the base aggregate layer could be calculated using layered elastic analysis of the designed pavement section. Rada and Witczak (1981) recommended a typical bulk stress of 20 to 40 psi at the base layer for resilient modulus calculation. For this study, resilient modulus values were calculated using a 5-psi confinement and a 15-psi deviator stress as suggested in NCHRP Research Results Digest 285 (TRB, 2004) and included in Tables 8 and 9; the calculated bulk stress would be 30 psi.

Table 8. Resilient Modulus Test Results for Phase I Aggregates

Soil Source	VDOT Grade and Rock Type	SSD Bulk Specific Gravity	Standard Proctor OMC (%)	Standard Proctor MDD (pcf)	Compaction M.C. (%) (target)[a]	End of the Test[b] M.C. (%)	End of the Test[b] S (%)	Failure Stress (psi)[c]	Resilient Modulus Test (MEPDG Model) k_1	k_2	k_3	M_r (psi)[d]
AGG-1 Lynchburg Shelton	21A Granite Gneiss	2.75	8.00	134.2	6	5.9	58.0	95	796.5	0.529	0.207	18,520
					8–OMC	7.7	76.5	105	441.0	0.656	0.372	11,981
AGG-2 Lynchburg Mt. Athos	21A Schist Greenstone	3.01	7.25	154.0	5.3	5.2	71.3	71	976.7	0.558	0.072	21,982
					7.3–OMC	5.8	79.5	69	920.5	0.637	-0.066	20,761
AGG-3 Bristol Abington	21B Dolomite Dolomitic LS	2.82	5.60	144.3	3.6	3.3	42.4	84	1325.2	0.567	0.109	30,465
					5.6–OMC	5.1	65.5	67	986.3	0.567	0.073	22,365
AGG-4 Staunton Frazier-North	21B Limestone	2.71	7.10	139.4	5.1	5	63.6	83	1369.2	0.481	0.262	31,452
					7.1–OMC	6.7	85.2	75	1241.6	0.492	0.329	29,514
AGG-5 NOVA Centreville	21B Diabase	2.82	7.65	142.5	5.7	5.6	67.2	107	836.6	0.581	0.399	21,760
					7.7–OMC	6.9	82.8	93	729.4	0.695	0.043	17,903
AGG-6 Richmond Appomattox	21B Marble	2.75	8.16	133.4	6.2	5.9	56.7	67	918.2	0.541	0.263	22,016
					8.2–OMC	7.5	72.0	59	849.7	0.665	0.091	20,809

All samples achieved 100% of maximum dry density (MDD) (pcf) after compaction.
VDOT = Virginia Department of Transportation; SSD = saturated surface dry; Standard Proctor = AASHTO T 99, Method D; OMC = optimum moisture content (%); MEPDG = *Mechanistic-Empirical Pavement Design Guide.*
[a] M.C. = moisture content during sample preparation.
[b] M.C. = moisture content and S = degree of saturation (%) at end of resilient modulus test.
[c] Stress from quick shear test performed at end of resilient modulus test.
[d] M_r = resilient modulus at a confining pressure of 5 psi and a cyclic deviator stress of 15 psi.

Table 9. Resilient Modulus Test Results for Phase II

Soil Source	VDOT Grade and Rock Type	SSD Bulk Specific Gravity (Avg.)	Standard Proctor		Compaction M.C. (%) (target)[a]	End of the Test[b]		Failure Stress (psi)[c]	Resilient Modulus Test (MEPDG Model)			
			OMC (%)	MDD (pcf)		M.C. (%)	S (%)		k_1	k_2	k_3	M_r (psi)[d]
P2AGG-1 Blue Ridge Salem	21B Dolomitic limestone	2.762	6.75	137.4	5.8	5.6	60.9	76	1338.4	0.53	0.074	29,481
					6.8–OMC	6.6	71.7	68	1152.0	0.57	-0.004	25,336
P2AGG-2 Boscobel Richmond	21 A/B Granite	2.635	8.50	131.8	7.5	7.5	79.9	76	639.9	0.58	0.317	16,130
					8.5–OMC	8.3	88.4	86	358.8	0.34	1.156	10,611
P2AGG-3 Doswell Richmond	21A/B Granite gneiss	2.725	7.50	141.2	6.5	6.3	84.1	105	1063.9	0.55	0.157	24,620
					7.5–OMC	7.1	94.8	126	795.6	0.63	0.120	19,213
P2AGG-4 South Boston Lynchburg	21A Granite	2.785	7.50	144.5	6.5	6.2	85.3	112	585.1	0.52	0.658	16,100
					7.5–OMC	7.1	97.7	127	549.8	0.46	0.843	15,571
P2AGG-5 Stevensburg Culpeper	21B 90% Siltstone 10% Shale	2.715	7.80	138.3	7.3	7.1	84.7	86	1085.9	0.52	0.248	25,509
					8.3–OMC	8.0	95.4	71	933.1	0.60	0.181	22,566
P2AGG-6 Staunton Staunton	21A/B Limestone	2.708	7.75	136.6	6.8	6.7	76.6	72	1403.0	0.43	0.229	30,732
					7.8–OMC	7.5	85.7	78	1369.3	0.54	0.038	30,034
P2AGG-7 Graham-Occ NOVA	21A Granite	2.678	6.75	141.2	5.8	5.6	81.7	80	979.6	0.63	0.062	23,133
					6.8–OMC	6.4	93.4	81	474.6	0.27	1.137	13,265
P2AGG-8 Graham-Occ NOVA	21B Granite	2.684	6.75	140.5	5.8	5.7	79.7	84	808.5	0.59	0.169	19,356
					6.8–OMC	6.6	92.3	106	628.5	0.49	0.434	15,527
P2AGG-9 Centreville NOVA	21A/B 65% Diabase 35% Siltstone	2.852	7.50	146.3	6.5	6.2	81.7	116	837.2	0.55	0.273	20,229
					7.5–OMC	7.1	93.6	99	645.4	0.42	0.659	16,557
P2AGG-10 Gladehill Salem	21B Amphibolite gneiss	3.028	7.60	155.8	6.6	6.3	89.7	107	780.4	0.71	0.186	20,413
					7.6–OMC	7.2	102.5	92	536.2	0.40	1.156	16,552

All samples achieved 100% of maximum dry density (MDD) (pcf) after compaction.

VDOT = Virginia Department of Transportation; SSD = saturated surface dry; Standard Proctor = AASHTO T 99, Method D; OMC = optimum moisture content (%); MEPDG = *Mechanistic-Empirical Pavement Design Guide.*

[a] M.C. = moisture content during sample preparation.

[b] M.C. = moisture content and S = degree of saturation (%) at end of resilient modulus test.

[c] Stress from quick shear test performed at end of resilient modulus test.

[d] M_r = resilient modulus at a confining pressure of 5 psi and a cyclic deviator stress of 15 psi.

The regression parameters for a simple bulk stress model (see Eq. 2) are also presented in Table 10 as a reference.

$$M_r = k_1(\theta)^{k_2} \qquad \text{[Eq. 2]}$$

where

M_r = resilient modulus value
k_1 and k_2 = regression coefficients
θ = bulk stress = {3 × confining stress + deviator (cyclic) stress}.

Table 10. Resilient Modulus Parameters for Bulk Stress Model at Optimum Moisture Content

Aggregate	Location	VDOT Grade	MEPDG Model				Bulk Stress Model		
			k_1	k_2	k_3	M_r (psi)	k_1	k_2	M_r (psi)
Phase I									
AGG–1	Shelton	A	441.0	0.656	0.372	11,981	919.1	0.745	11,590
AGG–-2	Mt. Athos	A	920.5	0.637	- 0.066	20,761	2530.1	0.621	20,883
AGG–-3	Abingdon	B	986.3	0.567	0.073	22,365	3039.0	0.585	22,221
AGG–4	Frazier North	B	1241.6	0.492	0.329	29,514	4103.7	0.571	28,664
AGG–-5	Centreville	B	729.4	0.695	0.043	17,903	1620.1	0.705	17,835
AGG–6	Richmond	B	849.7	0.665	0.091	20,809	1994.7	0.687	20,639
Phase II									
P2AGG–1	Blue Ridge	B	1152.0	0.57	-0.004	25,336	3695.4	0.566	25,346
P2AGG–-2	Boscobel	A/B	358.8	0.34	1.156	10,611	1144.8	0.624	9564
P2AGG–-3	Doswell	A/B	795.6	0.63	0.120	19,213	2022.9	0.659	19,009
P2AGG–4	South Boston	A	549.8	0.46	0.843	15,571	1541.9	0.658	14,464
P2AGG–5	Stevensburg	B	933.1	0.60	0.181	22,566	2496.5	0.643	22,224
P2AGG–6	Staunton	A/B	1369.3	0.54	0.038	30,034	4625.0	0.549	29,931
P2AGG–-7	Graham-Occoquan (21A)	A	474.6	0.27	1.137	13,265	1830.5	0.552	12,001
P2AGG–8	Graham-Occoquan (21B)	B	628.5	0.49	0.434	15,527	1982.2	0.594	14,946
P2AGG–9	Centreville	A/B	645.4	0.42	0.659	16,557	2201.1	0.576	15,626
P2AGG–10	Gladehill, Jacks Mtn.	B	536.2	0.40	1.156	16,552	1477.3	0.680	14,930

VDOT = Virginia Department of Transportation; MEPDG = *Mechanistic-Empirical Pavement Design Guide.*

DISCUSSION

Although VDOT's current pavement design procedure (AASHTO, 1993) assigns a single layer coefficient for all base aggregate, a wide variation of resilient moduli has been found among different sources of base aggregate while tested for MEPDG implementation. Many factors such as gradation, rock type, and particle shape might contribute to such variation, as discussed here.

Gradation Effect

All aggregate sources were supposed to comply with VDOT No. 21A or No. 21B gradation. Although most were close to or within the gradation band, as shown in Table 5, the quantities passing a few sieve sizes were above the limit. As discussed previously, in Phase I of the study, two sources were classified as VDOT No. 21A and four as No. 21B. In Phase II, two were classified as No. 21A, four as No. 21B, and four as combined No. 21A/B. Those were the classifications provided by the producer, but some of the sources had different sizes outside the VDOT specification limits of No. 21A and No. 21B. In most cases, quantities passing the No. 200 sieve were above the specification limits (design-range) for both grade designations. In some cases, material passing the $^3/_8$-in sieve was also above the limit (design-range). Resilient modulus values are grouped according to VDOT gradation in Figure 2 and Table 11 for comparison.

Although there was no consistent pattern in the values for No. 21A or No. 21B aggregates, in general, the resilient modulus values for the No. 21B aggregates were higher (15,520 to 29,510 psi) than those for the No. 21A aggregates (11,980 to 20,760 psi). The values for the combined No. 21A/B aggregates varied from 10,610 to 30,034 psi. It is important to note that No. 21B gradation is coarser than No. 21A and has a higher percent of material passing the No. 200 sieve than is the case with No. 21B, as allowed in the VDOT specification.

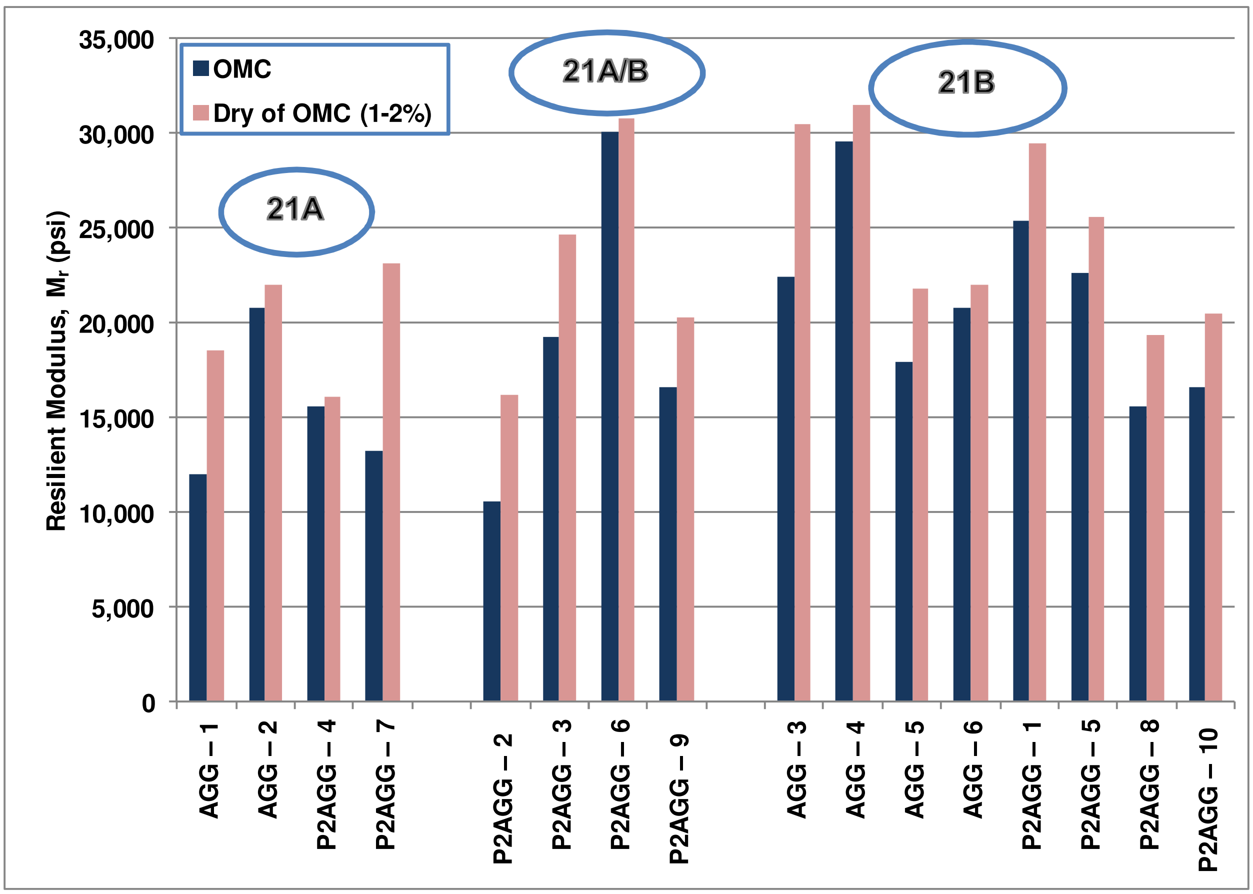

Figure 2. Effect of Moisture on Resilient Modulus Measurements. OMC = optimum moisture content.

Table 11. Resilient Modulus Values Using MEPDG Model

Aggregate Source	VDOT District	% Passing No. 200 Sieve	Resilient Modulus at 5 psi Confining and 15 psi Deviator Stresses (psi)		
			At OMC[a]	1% Below OMC	2% Below OMC
VDOT Grade 21A (Limit for No. 200: 6%-12%)					
AGG–1 (Shelton)	Lynchburg	12	11,981	-	18,520
AGG–2 (Mt. Athos)	Lynchburg	12	20,761	-	21,982
P2AGG–4 (South Boston)	Lynchburg	10	15,571	16,100	-
P2AGG–7 (Graham-Occoquan)	NOVA	10	13,265	23,133	-
VDOT Grade 21A/B					
P2AGG–2 (Boscobel)	Richmond	9	10,611	16,130	-
P2AGG–3 (Doswell)	Richmond	10	19,213	24,620	-
P2AGG–6 (Staunton)	Staunton	8	30,034	30,732	-
P2AGG–9 (Centreville)	NOVA	9	16,557	20,229	-
VDOT Grade 21B (Limit for No. 200: 4%-7%)					
AGG–3 (Abingdon)	Bristol	9	22,365	-	30,465
AGG–4 (Frazier North)	Staunton	8	29,514	-	31,452
AGG–5 (Centreville)	NOVA	9	17,903	-	21,760
AGG–6 (Richmond)	Richmond	7	20,809	-	22,016
P2AGG–1 (Blue Ridge)	Salem	10	25,336	29,481	-
P2AGG–5 (Stevensburg)	Culpeper	8	22,566	25,509	-
P2AGG–8 (Graham-Occoquan)	NOVA	8	15,527	19,356	-
P2AGG–10 (Gladehill, Jacks Mtn.)	Salem	19	16,552	20,413	-

MEPDG = *Mechanistic-Empirical Pavement Design Guide;* VDOT = Virginia Department of Transportation; NOVA = Northern Virginia.
[a] OMC = optimum moisture content. All samples were compacted to 100% maximum dry density.

Influence of Moisture Content

Some aggregate sources showed a significant influence of moisture content on the resilient modulus value. Each aggregate source was tested at two different moisture contents but compacted at the same MDD. Target moisture contents and compaction densities are not comparable among the sources. Therefore, degrees of saturation were calculated for each sample after the test and plotted against resilient modulus values in Figure 3. There are only two points per source in Figure 3; a third point would have characterized the influence of moisture better. As mentioned earlier, it was not possible to run a test at a moisture content higher than optimum because of excessive drainage during sample preparation and the sample was unstable under the compaction effort, but the expected trend of a decrease in resilient modulus with an increase in moisture content is obvious. Moisture has a greater influence on some aggregate than others, as shown by their respective slopes in Figure 3. Additional testing of Atterberg limits (liquid limit and plastic limit) were conducted on some of the aggregate sources with steeper slopes. Results showed the presence of plastic fines in the fraction passing the No. 200 sieve. Although standard practice for the Atterberg limit test is to conduct the test on the fraction passing the No. 40 sieve, all tests in this study were on the fraction passing the No. 200 sieve. The source (P2AGG–7) with the steepest slope had 14% passing the No. 200 sieve with a PI of 9. The aggregate from this same source (P2AGG-8) with coarser gradation (No. 21B) and only 8% passing the No. 200 sieve showed less sensitivity to moisture than the No. 21A gradation, as evident from the flatter slope in Figure 3. The source P2AGG–10 had the highest percent passing the No. 200 sieve

(19%) and showed significant moisture sensitivity despite being non-plastic. The aggregate P2AGG–2 had the second steepest slope; the corresponding PI was very high, but with only 9% passing the No. 200 sieve. Therefore, the results in Figure 3 suggest moisture sensitivity in the resilient modulus value when the percent passing the No. 200 sieve is high or fines are plastic in nature.

A significant change in resilient modulus was noticed when the moisture was only 1% or 2% below the OMC, which is the usual allowable tolerance in most specifications for base aggregate compaction. It will be difficult to recommend a value of resilient modulus for these aggregates since the allowable field moisture content can result in a large variation in modulus values.

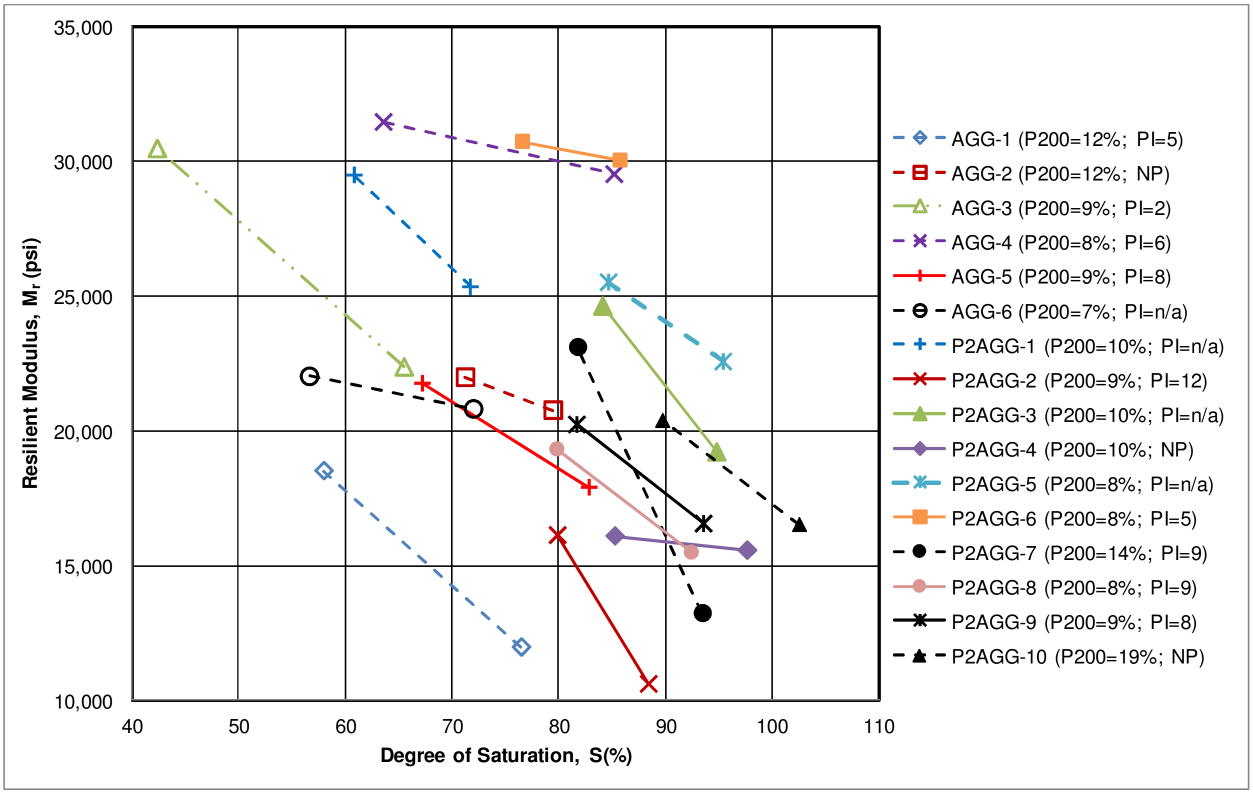

Figure 3. Influence of Moisture Content on Resilient Modulus Values. PI = plasticity index.

Effect of Rock Type

Different rock types were considered in selecting the aggregate sources for testing. The presence of plastic fines made it difficult to separate the effect of rock type on the resilient modulus value. The LA abrasion loss values presented in Table 2 showed that granite, marble, and amphibolite were more susceptible to impact and abrasion than were diabase, siltstone, dolomitic limestone, and limestone. Resilient modulus values are grouped according to their lithology in Figure 4. Limestone aggregates (AGG–4 and P2AGG–6) had the highest resilient modulus values, and granite (P2AGG–2, P2AGG–4, P2AGG-7, and P2AGG–8) had the lowest. Limestone sources were less sensitive to moisture than some of the granite sources. Although diabase (AGG–5 and P2AGG–-9) is usually the hardest rock and a high modulus is expected; the presence of plastic fines might have influenced the modulus values to be on the lower end of the spectrum in Figure 4.

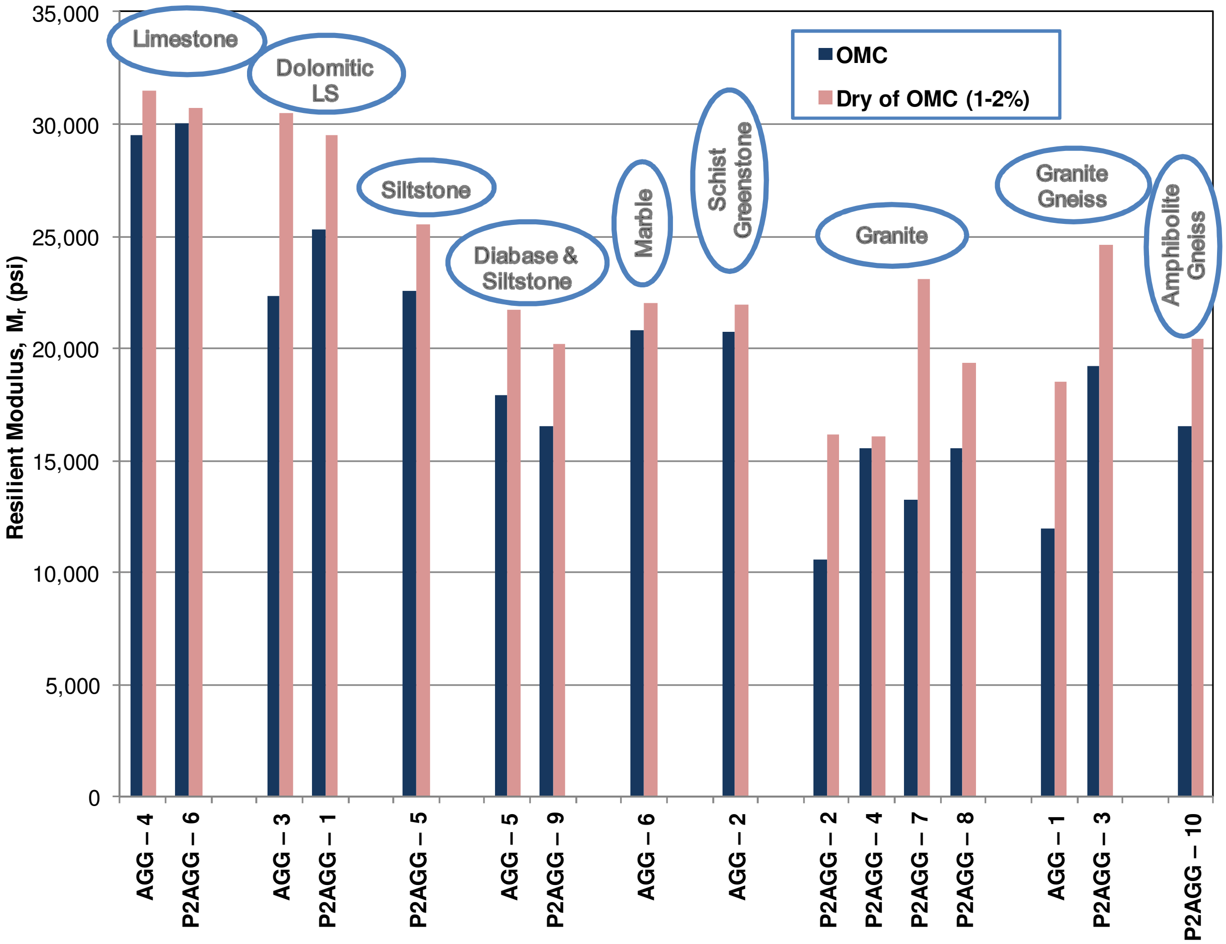

Figure 4. Effect of Mineralogy on Resilient Modulus Values. OMC = optimum moisture content.

Influence of Particle Shape

In general, uncompacted void content provides an indication of particle shape and texture where higher values would indicate more angular particles and a rougher texture. Table 3 summarizes the uncompacted void content results. It is important to note that the presence of flat and elongated particles may also yield higher voids and that sample grading also affects the results. These tests were conducted on two gradations: Standard Grade (Method A) and As-Received Grade (Method C). Because the grading of the test sample also affects the void content, results from Method A are preferable for comparing particle shape and texture among samples. Because of the gradation and moisture effect, no consistent influence of particle shape was observed in this study.

SUMMARY OF FINDINGS

- *There was a wide variation in resilient modulus values for base aggregate among the different sources*. The values ranged from approximately 10,000 to 30,000 psi.

- *VDOT No. 21B aggregate is somewhat stiffer than No. 21A aggregate, as No. 21B aggregate has a coarser gradation with less material passing the No. 200 sieve.* The resilient modulus values were 15,520 to 29,510 psi for No. 21B; 11,980 to 20,760 psi for No. 21A; and 10,610 to 30,034 psi for the combined No. 21A/B.

- *Of the 16 sources of aggregate tested in the Phase I and II studies, the resilient modulus values of 11showed a significant sensitivity to moisture content, but this effect seemed related to the amount of material passing the No. 200 sieve and/or the plastic nature of the fines.*

- *There was a wide variation in resilient modulus values among different rock types; limestone had the highest modulus and granite had the lowest modulus value.* This effect was also significantly influenced by whether the mixture was No. 21A or No. 21B, the percent passing the No. 200 sieve, and the presence of plastic fines.

- *No clear effect of particle shape was evident from this study*. The effects of gradation, lithology, and moisture content, along with the narrow range of uncompacted void contents, made it difficult to separate out the effect of particle shape.

- *Some aggregate gradations were outside VDOT specification limits (design-range), but most were within QC/QA acceptance tolerances.* The noted discrepancies usually occurred with the percent passing the $^{3}/_{8}$-in sieve and the No. 200 sieve. In both cases, values were higher than specified, meaning the aggregates were finer than the specification limits (design-range).

CONCLUSIONS

- *There are large variations in resilient modulus values among different sources of aggregate in Virginia.*

- *Moisture variation within allowable construction specifications can result in substantial change in resilient modulus values for many sources of aggregate in Virginia.*

- *Resilient modulus values of aggregate depend on gradation, rock type, and moisture content.*

- *The amount and nature (plastic versus non-plastic) of fines affect the moisture sensitivity of resilient modulus.*

RECOMMENDATIONS

1. *VDOT's Materials Division should implement the catalog of resilient modulus values from this study, based on the information presented in Tables 8 and 9 and Figures 2 and 4, for use with the MEPDG.*

2. *VDOT's Materials Division and the Virginia Center for Transportation Innovation and Research (VCTIR) should investigate the adjustment of modulus values in the MEPDG software based on moisture content, as moisture had a substantial impact on the value of the resilient modulus.*

3. *VCTIR and VDOT's Materials Division should further investigate the causes of variations in resilient modulus values despite similar gradations or rock types. The moisture sensitivity and the presence of plastic fines need to be investigated further.*

4. *VCTIR and VDOT's Materials Division should further investigate the differences among different Proctor standards and actual field-achieved values.*

BENEFITS AND IMPLEMENTATION

This study was conducted to develop a catalog of resilient modulus values for commonly used base aggregate in VDOT construction projects. The catalog is readily available for implementation. VDOT's State Materials Engineer will implement this catalog by modifying the VDOT Materials Division *Manual of Instructions,* Chapter VI: Pavement Design and Evaluation, to include a procedure for selection of appropriate aggregate modulus values based on the anticipated material to be used and moisture conditions. The values presented in the catalog can be referenced for pavement designs that follow the new MEPDG methodology and can be incorporated with the MEPDG protocol as it is adopted by VDOT.

ACKNOWLEDGMENTS

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APPENDIX

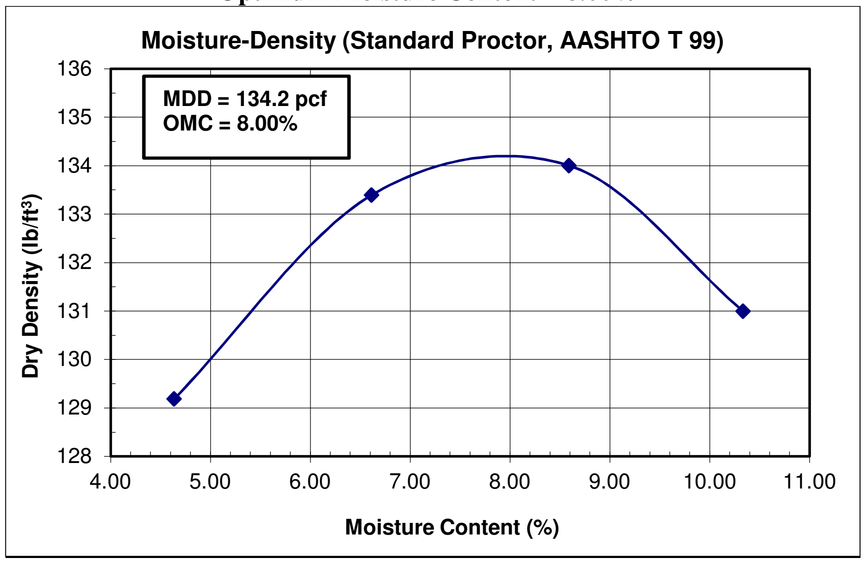
SUMMARY OF TEST RESULTS

SUMMARY SHEET: SHELTON-LYNCHBURG DISTRICT

Rock type: Granite gneiss
Comments: N/A

Gradation (AASHTO T 27)		
Sieve Size	Percent Retained	Percent Passing
2.00"	0.00	100.00
1.50"	0.00	100.00
1.00"	2.69	97.31
0.75"	8.74	88.58
0.50"	11.83	76.75
0.375"	8.98	67.77
No. 4	16.88	50.89
No. 8	11.73	39.15
No. 16	7.29	31.87
No. 30	5.11	26.76
No. 50	4.28	22.47
No. 100	4.68	17.79
No. 200	5.44	12.35
Pan	12.35	---

Proctor Results:
Maximum Dry Density = 134.2 pcf
Optimum Moisture Content = 8.00%

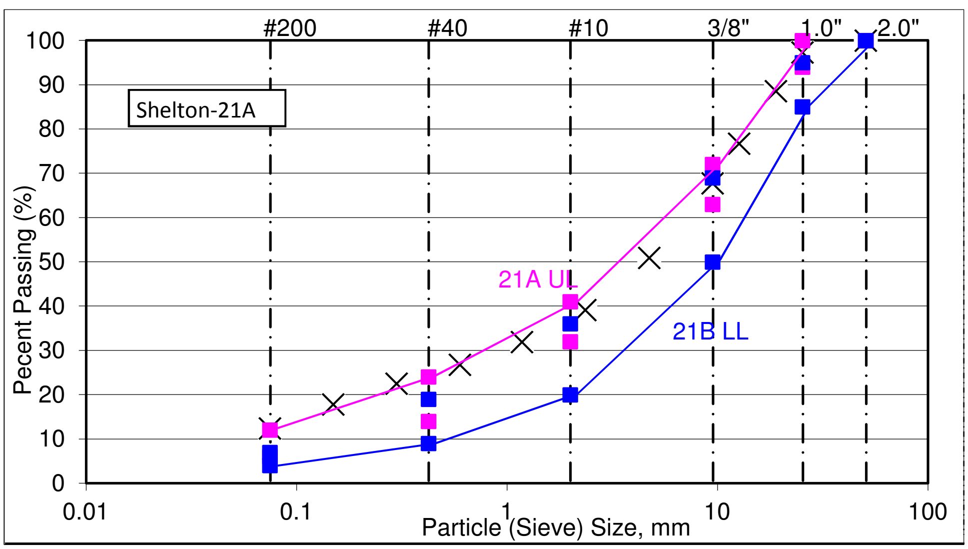


Specific Gravity (AASHTO T 84 and T 85)							
Dry Bulk		SSD		Apparent		Absorption (%)	
+4	-4	+4	-4	+4	-4	+4	-4
N/A	N/A	2.62*	N/A	N/A	N/A	N/A	N/A

*VDOT approved list 2012

Un-compacted Void Content (%)			
+4 (AASHTO T 326)		-4 (AASHTO T 304)	
Method A[1]	Method C[2]	Method A[1]	Method C[2]
N/A	N/A	N/A	N/A

[1]Standard Grade, [2]As-received Grade



Resilient Modulus Test Results (AASHTO T 307):

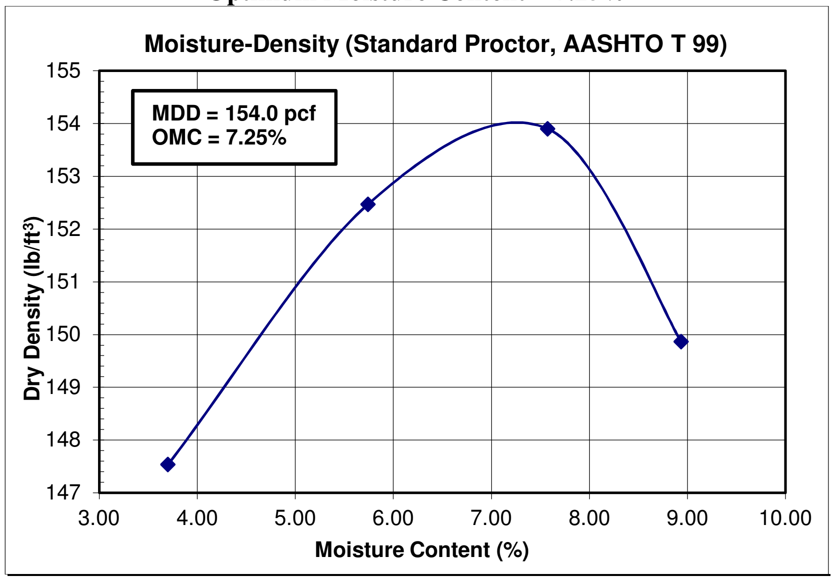
Test Moisture	MEPDG Model: $M_r = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2}\left(\frac{\tau_{oct}}{P_a}+1\right)^{k_3}$			Model Parameters	Confining (σ_3) : 5 psi Deviator (σ_d): 15 psi
	K_1	K_2	K_3	P_a = 14.7 psi	M_r
OMC	441.0	0.66	0.372	$\theta = (3\sigma_3 + \sigma_d)$	11981
OMC -2%	796.5	0.53	0.207	$\tau_{oct} = (\sqrt{2}/3)\sigma_d$	18520

SUMMARY SHEET: MOUNT ATHOS-LYNCHBURG DISTRICT

Rock type: Schist/ Greenstone
Comments: N/A

Gradation (AASHTO T 27)		
Sieve Size	Percent Retained	Percent Passing
2.00”	0.00	100.00
1.50”	0.00	100.00
1.00”	0.00	100.00
0.75”	0.51	99.49
0.50”	10.19	89.29
0.375”	12.27	77.02
No. 4	22.71	54.31
No. 8	14.81	39.50
No. 16	8.88	30.62
No. 30	6.15	24.47
No. 50	4.60	19.87
No. 100	4.17	15.70
No. 200	3.81	11.89
Pan	11.89	---

Proctor Results:
Maximum Dry Density = 154.0 pcf
Optimum Moisture Content = 7.25%

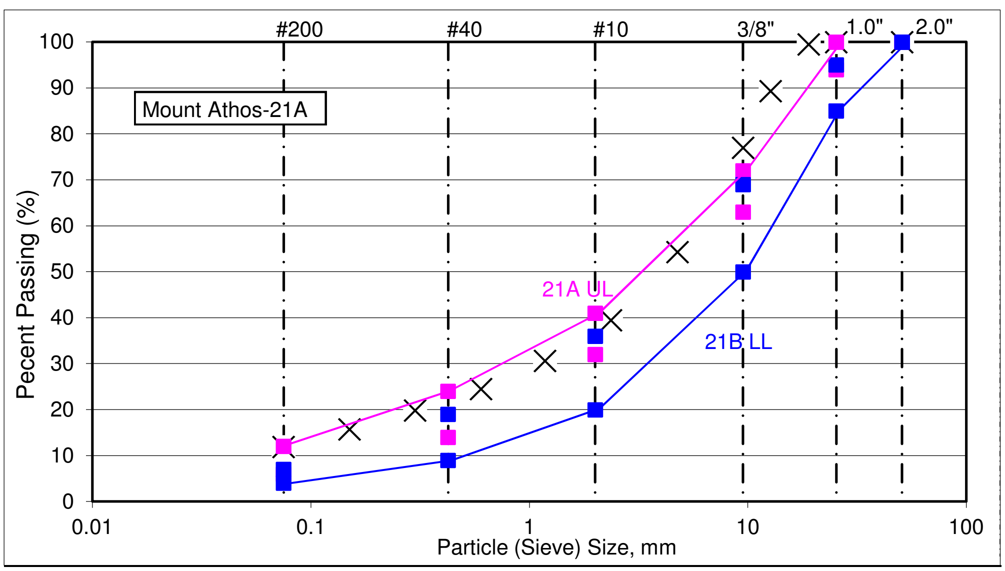


Specific Gravity (AASHTO T 84 and T 85)							
Dry Bulk		SSD		Apparent		Absorption (%)	
+4	-4	+4	-4	+4	-4	+4	-4
N/A	N/A	3.01*	N/A	N/A	N/A	N/A	N/A

*VDOT approved list 2012

Un-compacted Void Content (%)			
+4 (AASHTO T 326)		-4 (AASHTO T 304)	
Method A[1]	Method C[2]	Method A[1]	Method C[2]
N/A	N/A	N/A	N/A

[1]Standard Grade, [2]As-received Grade



Resilient Modulus Test Results (AASHTO T 307):

Test Moisture	MEPDG Model: $M_r = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2}\left(\frac{\tau_{oct}}{P_a}+1\right)^{k_3}$			Model Parameters	Confining (σ_3) : 5 psi Deviator (σ_d): 15 psi
	K_1	K_2	K_3	P_a = 14.7 psi	M_r
OMC	920.5	0.64	-0.066	$\theta = (3\sigma_3 + \sigma_d)$	20761
OMC -2%	976.7	0.56	0.072	$\tau_{oct} = (\sqrt{2/3})\sigma_d$	21982

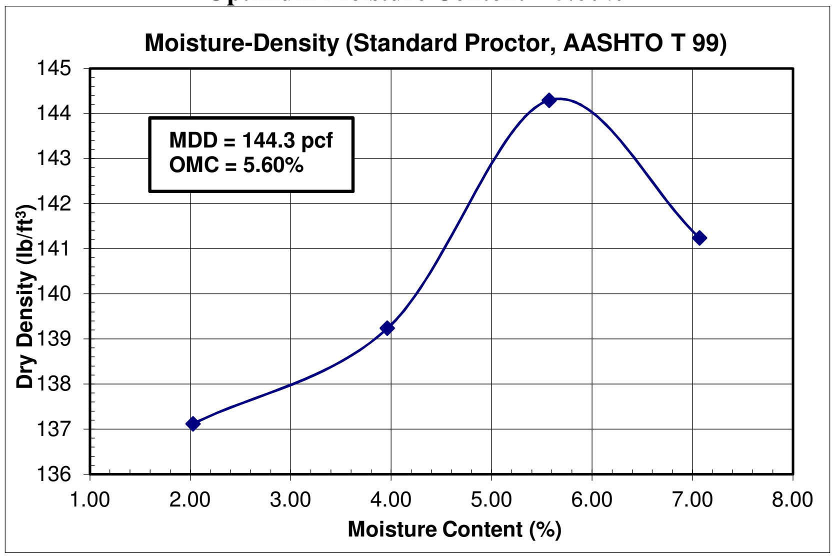
SUMMARY SHEET: ABINGDON-BRISTOL DISTRICT

Rock type: Dolomitic limestone

Comments: N/A

Gradation (AASHTO T 27)		
Sieve Size	Percent Retained	Percent Passing
2.00”	0.00	100.00%
1.50”	0.00	100.00%
1.00”	0.00	100.00
0.75”	2.32	97.68
0.50”	14.50	83.18
0.375”	10.93	72.24
No. 4	23.87	48.37
No. 8	16.28	32.09
No. 16	9.31	22.79
No. 30	5.64	17.15
No. 50	3.31	13.84
No. 100	2.24	11.60
No. 200	2.16	9.44
Pan	9.44	---

Proctor Results:
Maximum Dry Density = 144.3 pcf
Optimum Moisture Content = 5.60%

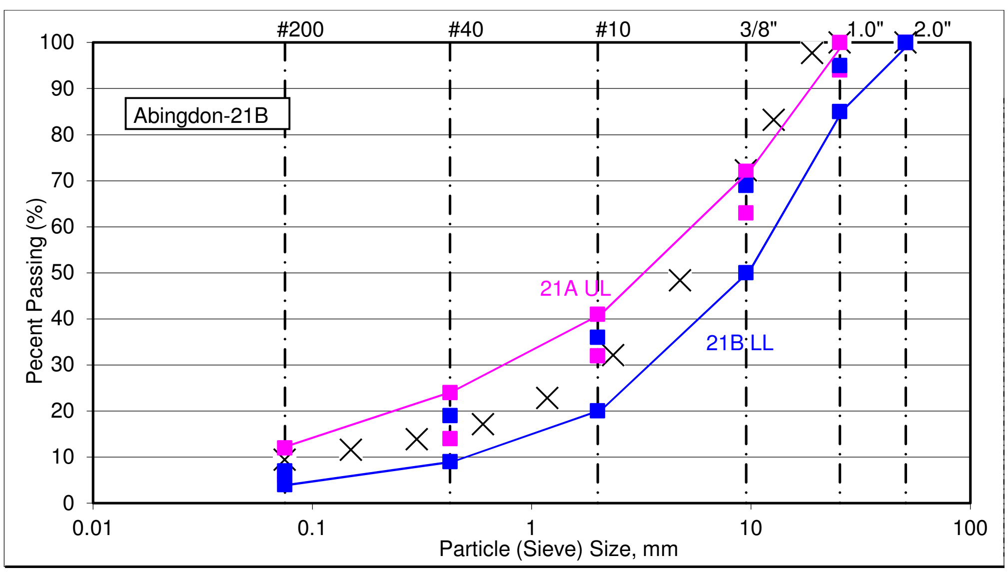


Specific Gravity (AASHTO T 84 and T 85)							
Dry Bulk		SSD		Apparent		Absorption (%)	
+4	-4	+4	-4	+4	-4	+4	-4
N/A	N/A	2.82*	N/A	N/A	N/A	N/A	N/A

*VDOT approved list 2012

Un-compacted Void Content (%)			
+4 (AASHTO T 326)		-4 (AASHTO T 304)	
Method A[1]	Method C[2]	Method A[1]	Method C[2]
N/A	N/A	N/A	N/A

[1]Standard Grade, [2]As-received Grade



Resilient Modulus Test Results (AASHTO T 307):

Test Moisture	MEPDG Model: $M_r = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2}\left(\frac{\tau_{oct}}{P_a}+1\right)^{k_3}$			Model Parameters	Confining (σ_3) : 5 psi Deviator (σ_d): 15 psi
	K_1	K_2	K_3	P_a = 14.7 psi	M_r
OMC	986.3	0.57	0.073	$\theta = (3\sigma_3 + \sigma_d)$	22365
OMC -2%	1325.2	0.57	0.109	$\tau_{oct} = (\sqrt{2/3})\sigma_d$	30465

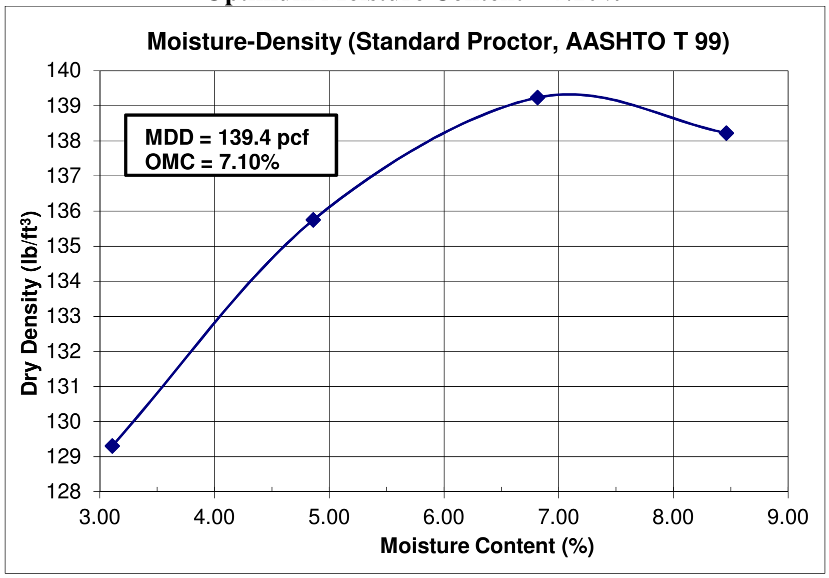
SUMMARY SHEET: FRAZIER NORTH-STAUNTON DISTRICT

Rock type: Limestone
Comments: N/A

Gradation (AASHTO T 27)

Sieve Size	Percent Retained	Percent Passing
2.00"	0.00	100.00%
1.50"	0.00	100.00%
1.00"	0.00	100.00
0.75"	2.64	97.36
0.50"	15.33	82.02
0.375"	9.24	72.79
No. 4	17.41	55.38
No. 8	19.71	35.67
No. 16	11.73	23.94
No. 30	7.18	16.76
No. 50	4.35	12.41
No. 100	2.69	9.72
No. 200	1.66	8.06
Pan	8.06	---

Proctor Results:
Maximum Dry Density = 139.4 pcf
Optimum Moisture Content = 7.10%



Specific Gravity (AASHTO T 84 and T 85)

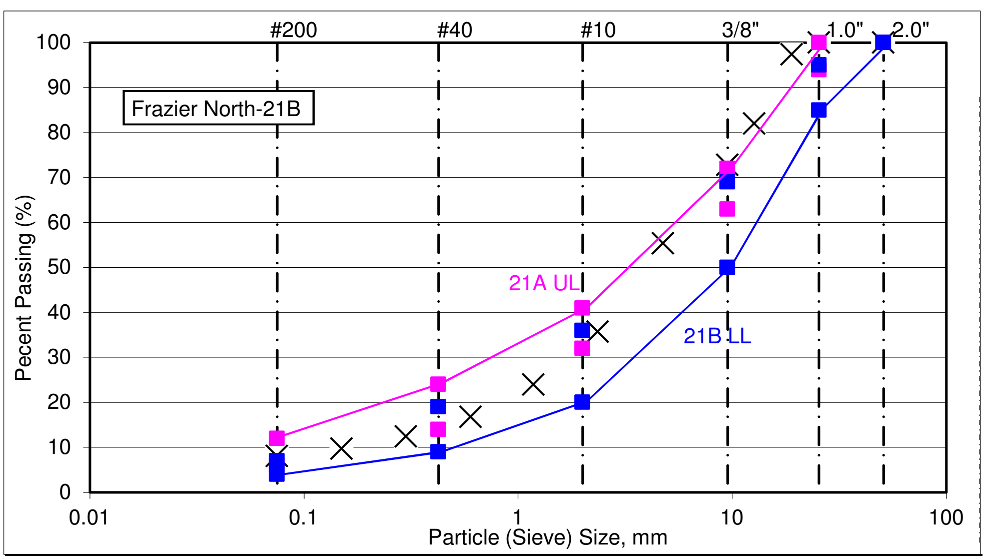
Dry Bulk		SSD		Apparent		Absorption (%)	
+4	-4	+4	-4	+4	-4	+4	-4
N/A	N/A	2.71*	N/A	N/A	N/A	N/A	N/A

*VDOT approved list 2012

Un-compacted Void Content (%)

+4 (AASHTO T 326)		-4 (AASHTO T 304)	
Method A[1]	Method C[2]	Method A[1]	Method C[2]
N/A	N/A	N/A	N/A

[1]Standard Grade, [2]As-received Grade



Resilient Modulus Test Results (AASHTO T 307):

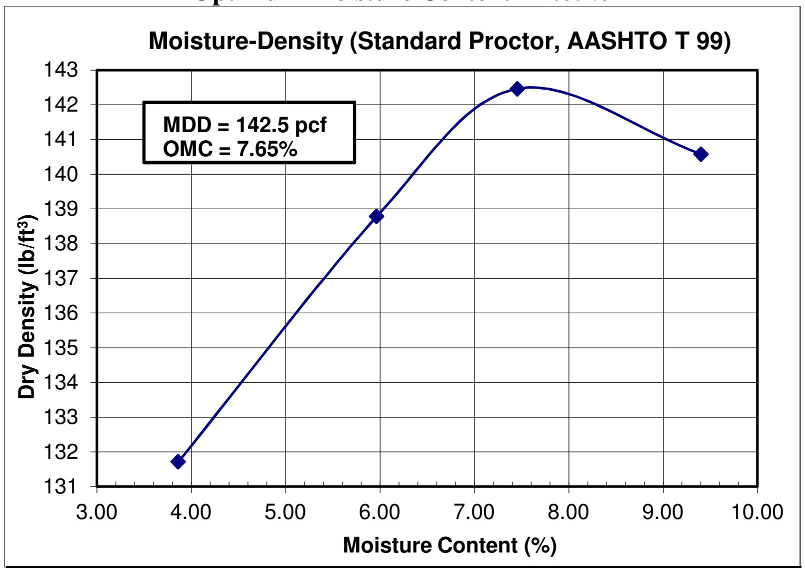
Test Moisture	MEPDG Model: $M_r = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a}+1\right)^{k_3}$			Model Parameters	Confining (σ_3) : 5 psi Deviator (σ_d): 15 psi
	K_1	K_2	K_3	P_a = 14.7 psi	M_r
OMC	1241.6	0.49	0.330	$\theta = (3\sigma_3 + \sigma_d)$	29514
OMC -2%	1369.2	0.48	0.262	$\tau_{oct} = (\sqrt{2}/3)\sigma_d$	31452

SUMMARY SHEET: CENTREVILLE-NOVA DISTRICT

Rock type: Diabase
Comments: N/A

Gradation (AASHTO T 27)		
Sieve Size	Percent Retained	Percent Passing
2.00”	0.00	100.00
1.50”	0.00	100.00
1.00”	0.00	100.00
0.75”	5.69	94.31
0.50”	13.35	80.96
0.375”	12.60	68.36
No. 4	23.33	45.02
No. 8	14.61	30.41
No. 16	7.98	22.43
No. 30	4.52	17.91
No. 50	3.32	14.59
No. 100	2.87	11.72
No. 200	2.65	9.08
Pan	9.08	---

Proctor Results:
Maximum Dry Density = 142.5 pcf
Optimum Moisture Content = 7.65%

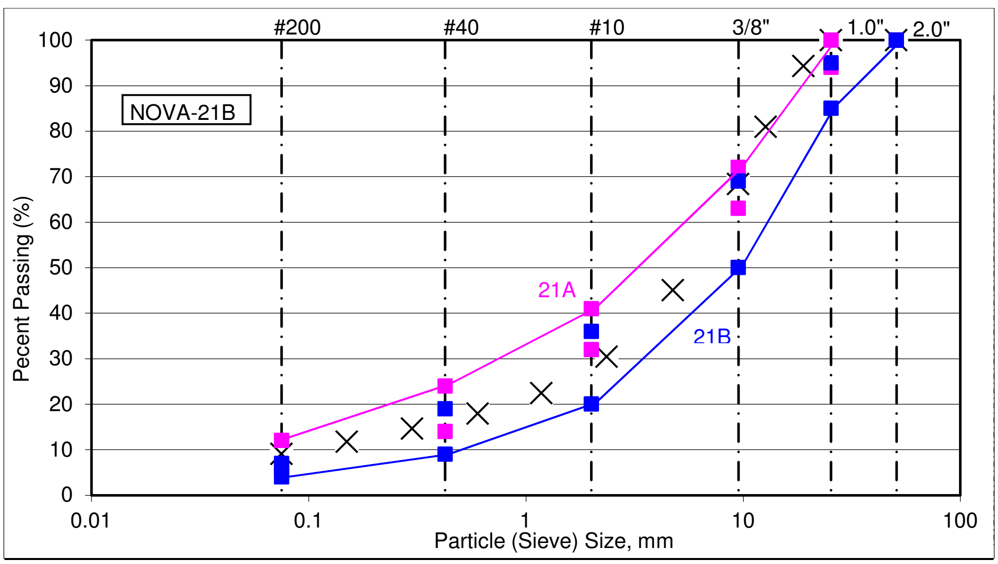


Specific Gravity (AASHTO T 84 and T 85)							
Dry Bulk		SSD		Apparent		Absorption (%)	
+4	-4	+4	-4	+4	-4	+4	-4
N/A	N/A	2.82*	N/A	N/A	N/A	N/A	N/A

*VDOT approved list 2012

Un-compacted Void Content (%)			
+4 (AASHTO T 326)		-4 (AASHTO T 304)	
Method A[1]	Method C[2]	Method A[1]	Method C[2]
N/A	N/A	N/A	N/A

[1]Standard Grade, [2]As-received Grade



Resilient Modulus Test Results (AASHTO T 307):

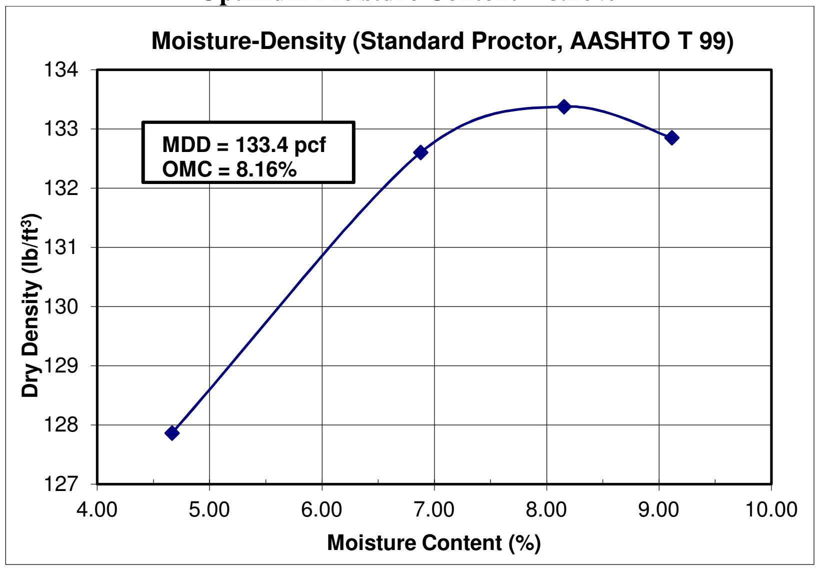
Test Moisture	MEPDG Model: $M_r = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a} + 1\right)^{k_3}$			Model Parameters	Confining (σ_3) : 5 psi Deviator (σ_d): 15 psi
	K_1	K_2	K_3	P_a = 14.7 psi	M_r
OMC	729.4	0.69	0.043	$\theta = (3\sigma_3 + \sigma_d)$	17903
OMC -2%	836.6	0.58	0.399	$\tau_{oct} = (\sqrt{2/3})\sigma_d$	21760

SUMMARY SHEET: RICHMOND DISTRICT

Rock type: Marble
Comments: N/A

Gradation (AASHTO T 27)		
Sieve Size	Percent Retained	Percent Passing
2.00”	0.00	100.00%
1.50”	0.00	100.00%
1.00”	0.00	100.00
0.75”	1.14	98.86
0.50”	16.11	82.74
0.375”	11.21	71.53
No. 4	21.51	50.02
No. 8	17.56	32.46
No. 16	10.41	22.05
No. 30	6.51	15.55
No. 50	4.09	11.45
No. 100	2.67	8.78
No. 200	1.88	6.90
Pan	6.90	---

Proctor Results:
Maximum Dry Density = 133.4 pcf
Optimum Moisture Content = 8.16%

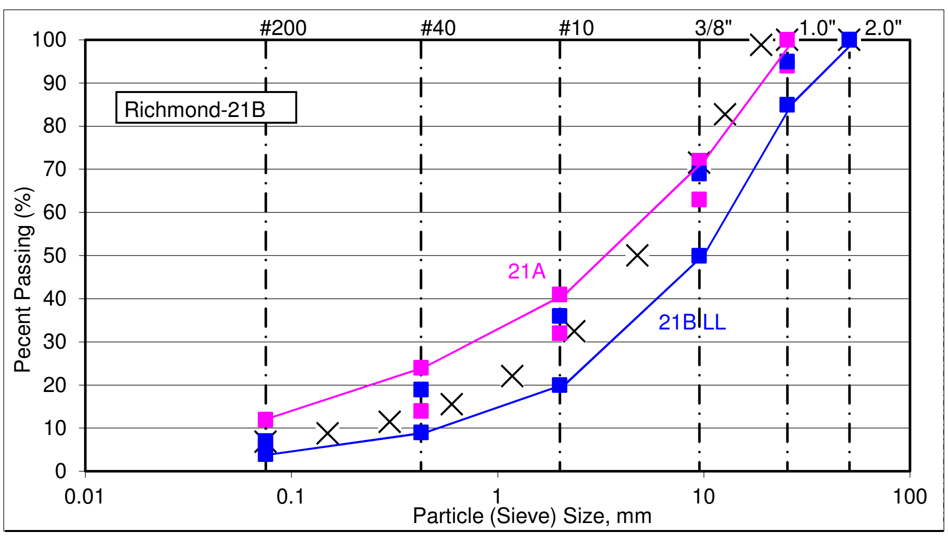


Specific Gravity (AASHTO T 84 and T 85)							
Dry Bulk		SSD		Apparent		Absorption (%)	
+4	-4	+4	-4	+4	-4	+4	-4
N/A	N/A	2.75*	N/A	N/A	N/A	N/A	N/A

*VDOT approved list 2012

Un-compacted Void Content (%)			
+4 (AASHTO T 326)		-4 (AASHTO T 304)	
Method A[1]	Method C[2]	Method A[1]	Method C[2]
N/A	N/A	N/A	N/A

[1]Standard Grade, [2]As-received Grade



Resilient Modulus Test Results (AASHTO T 307):

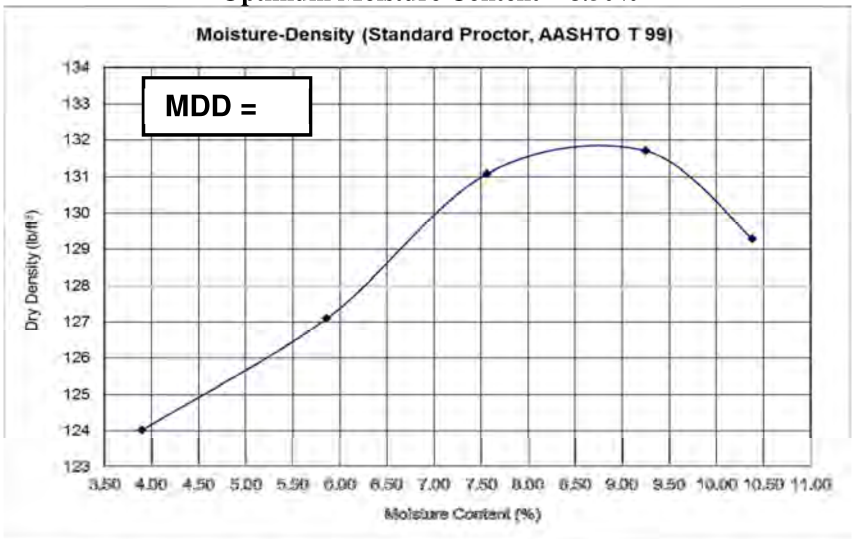
Test Moisture	MEPDG Model: $M_r = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a}+1\right)^{k_3}$			Model Parameters	Confining (σ_3) : 5 psi Deviator (σ_d): 15 psi
	K_1	K_2	K_3	P_a = 14.7 psi	M_r
OMC	849.7	0.67	0.091	$\theta = (3\sigma_3 + \sigma_d)$	20809
OMC -2%	918.2	0.54	0.263	$\tau_{oct} = (\sqrt{2/3})\sigma_d$	22016

SUMMARY SHEET: BOSCOBEL, GOOCHLAND (RICHMOND DISTRICT)

Rock type: Granite
Comments: Fine-medium grained, 15% thin, flat particles

Gradation (AASHTO T 27)		
Sieve Size	Percent Retained	Percent Passing
2.00”	0.00	100.00
1.50”	0.00	100.00
1.00”	0.00	100.00
0.75”	8.38	91.62
0.50”	17.47	74.14
0.375”	9.41	64.73
No. 4	17.11	47.62
No. 8	13.77	33.85
No. 16	8.80	25.04
No. 30	5.85	19.19
No. 50	4.19	15.00
No. 100	3.34	11.66
No. 200	2.72	8.94
Pan	8.86	---

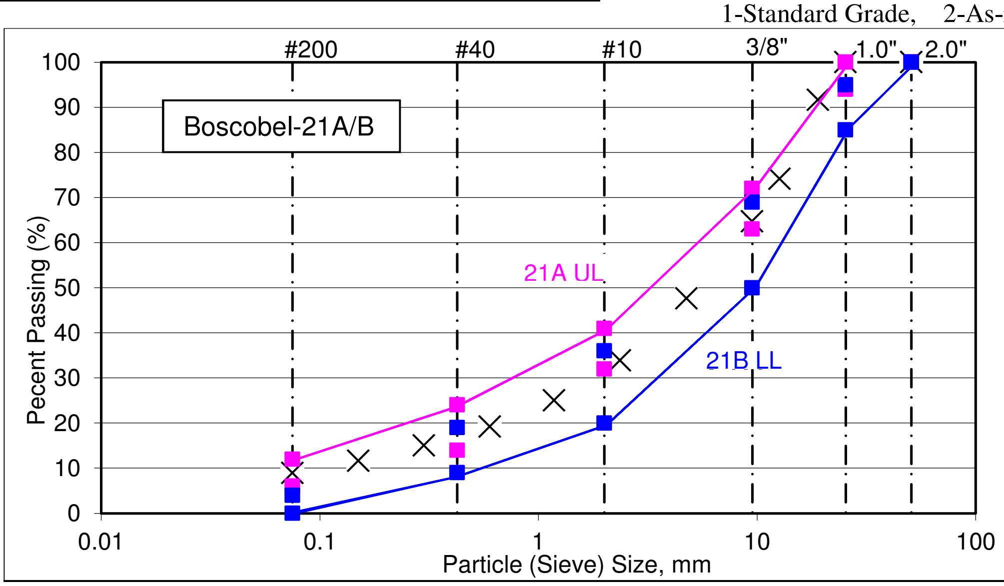
Proctor Results:
Maximum Dry Density = 131.8 pcf
Optimum Moisture Content = 8.50%



Specific Gravity (AASHTO T 84 and T 85)							
Dry Bulk		SSD		Apparent		Absorption (%)	
+4	-4	+4	-4	+4	-4	+4	-4
2.574	2.627	2.599	2.670	2.639	2.744	0.952	1.613

Un-compacted Void Content (%)			
+4 (AASHTO T 326)		-4 (AASHTO T 304)	
Method A[1]	Method C[2]	Method A[1]	Method C[2]
49.5	47.3	47.6	43.5

1-Standard Grade, 2-As-received Grade



Resilient Modulus Test Results (AASHTO T 307):

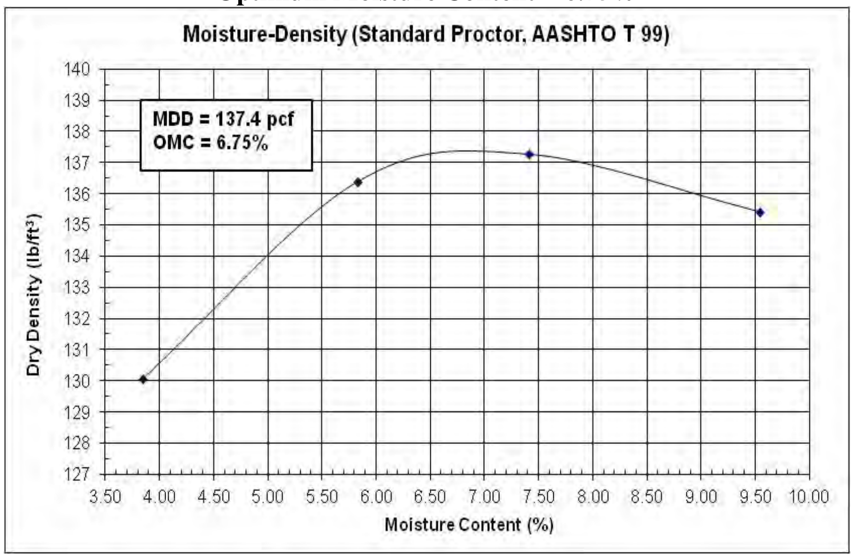
Test Moisture	MEPDG Model: $M_r = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a}+1\right)^{k_3}$			Model Parameters	Confining (σ_3) : 5 psi Deviator (σ_d): 15 psi
	K_1	K_2	K_3	P_a = 14.7 psi	M_r
OMC	358.8	0.34	1.156	$\theta = (3\sigma_3 + \sigma_d)$	10611
OMC -1%	639.9	0.58	0.317	$\tau_{oct} = (\sqrt{2}/3)\sigma_d$	16130

SUMMARY SHEET: BLUE RIDGE (SALEM DISTRICT)

Rock type: Dolomitic limestone
Comments: 10% shaley, 10% slightly weathered

Gradation (AASHTO T 27)		
Sieve Size	Percent Retained	Percent Passing
2.00”	0.00	100.00
1.50”	0.00	100.00
1.00”	0.00	100.00
0.75”	2.43	97.57
0.50”	17.95	79.62
0.375”	13.52	66.10
No. 4	24.43	41.67
No. 8	13.94	27.72
No. 16	7.48	20.25
No. 30	4.26	15.99
No. 50	2.60	13.38
No. 100	1.91	11.47
No. 200	1.48	9.99
Pan	9.99	---

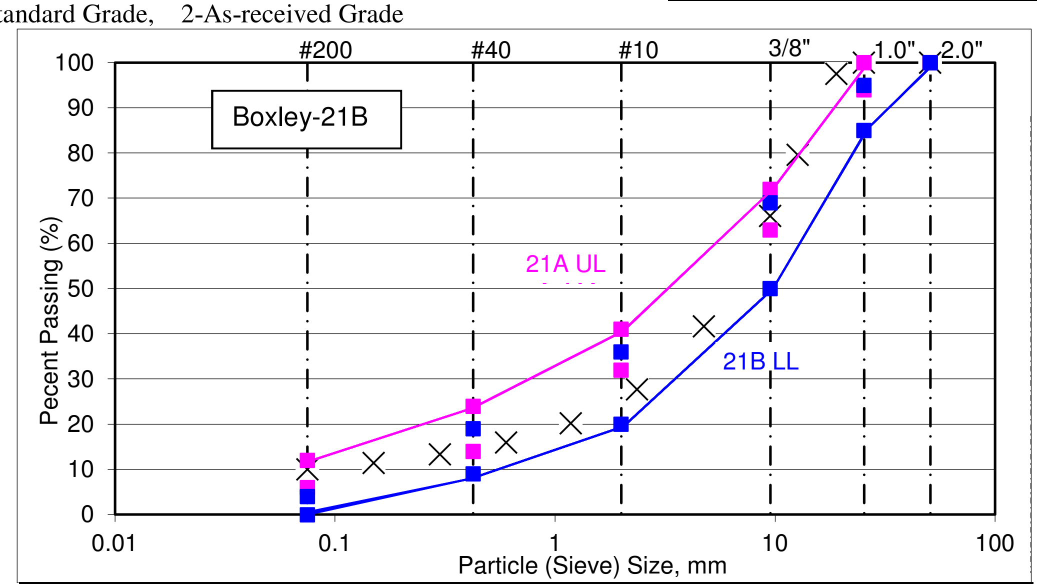
Proctor Results:
Maximum Dry Density = 137.4 pcf
Optimum Moisture Content = 6.75%



Specific Gravity (AASHTO T 84 and T 85)							
Dry Bulk		SSD		Apparent		Absorption (%)	
+4	-4	+4	-4	+4	-4	+4	-4
2.706	2.752	2.729	2.794	2.772	2.873	0.885	1.528

Un-compacted Void Content (%)			
+4 (AASHTO T 326)		-4 (AASHTO T 304)	
Method A[1]	Method C[2]	Method A[1]	Method C[2]
51.9	52.1	47.2	40.6

1-Standard Grade, 2-As-received Grade



Resilient Modulus Test Results (AASHTO T 307):

Test Moisture	MEPDG Model: $M_r = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a}+1\right)^{k_3}$			Model Parameters	Confining (σ_3) : 5 psi Deviator (σ_d): 15 psi
	K_1	K_2	K_3	P_a = 14.7 psi	M_r
OMC	1152.0	0.57	-0.004	$\theta = (3\sigma_3 + \sigma_d)$	25336
OMC -1%	1338.4	0.53	0.074	$\tau_{oct} = (\sqrt{2}/3)\sigma_d$	29481

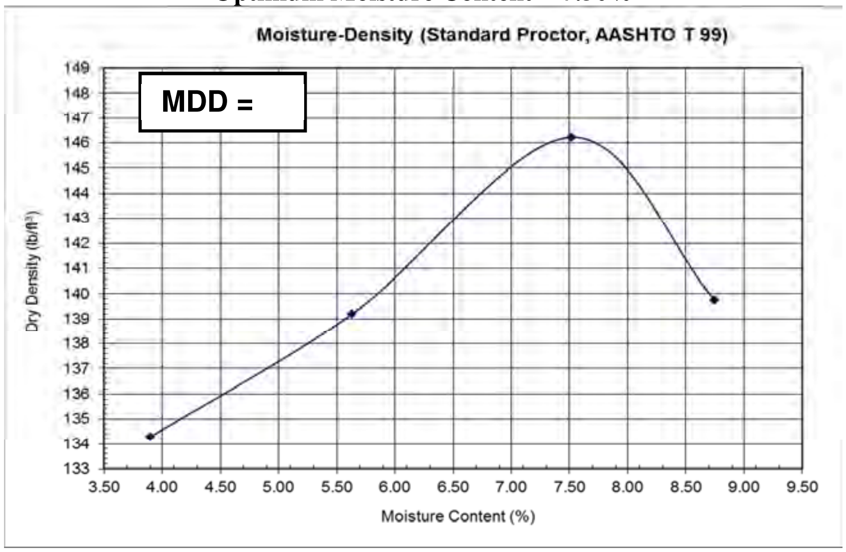
SUMMARY SHEET: CENTREVILLE, FAIRFAX (NOVA DISTRICT)

Rock type: 65% Diabase, 35% siltstone

Comments: Siltstone particles tend to be flat, thin

Gradation (AASHTO T 27)		
Sieve Size	Percent Retained	Percent Passing
2.00”	0.00	100.00%
1.50”	0.00	100.00%
1.00”	0.00	100.00%
0.75”	5.49	94.51%
0.50”	17.84	76.67%
0.375”	9.76	66.91%
No. 4	19.80	47.11%
No. 8	15.23	31.88%
No. 16	8.62	23.26%
No. 30	5.36	17.90%
No. 50	3.70	14.20%
No. 100	3.01	11.20%
No. 200	2.58	8.62%
Pan	8.63	---

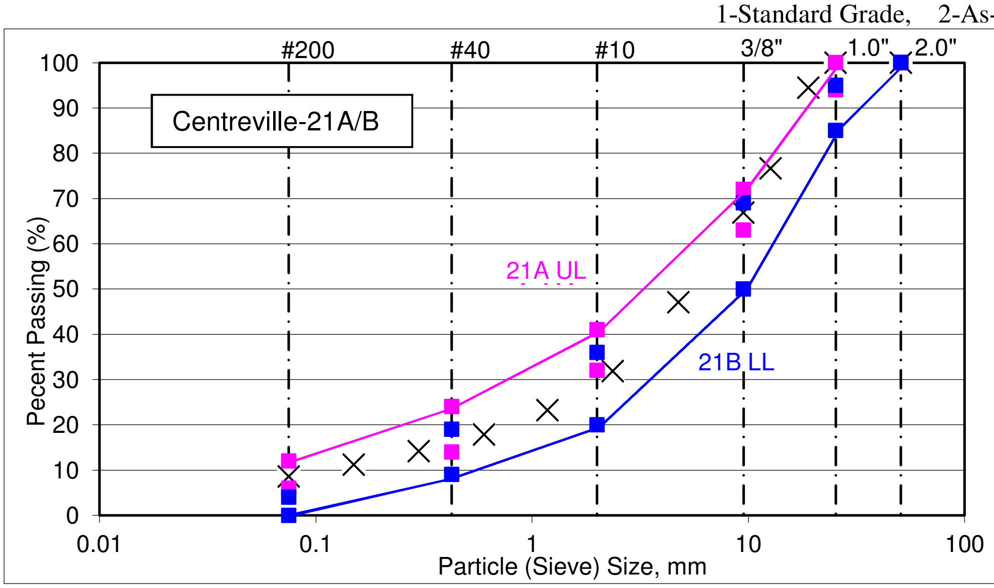
Proctor Results:
Maximum Dry Density = 146.3 pcf
Optimum Moisture Content = 7.50%



Specific Gravity (AASHTO T 84 and T 85)							
Dry Bulk		SSD		Apparent		Absorption (%)	
+4	-4	+4	-4	+4	-4	+4	-4
2.832	2.803	2.856	2.848	2.902	2.936	0.847	1.619

Un-compacted Void Content (%)			
+4 (AASHTO T 326)		-4 (AASHTO T 304)	
Method A[1]	Method C[2]	Method A[1]	Method C[2]
51.9	51.4	46.3	38.7

1-Standard Grade, 2-As-received Grade



Resilient Modulus Test Results (AASHTO T 307):

Test Moisture	MEPDG Model: $M_r = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a}+1\right)^{k_3}$			Model Parameters	Confining (σ_3) : 5 psi Deviator (σ_d): 15 psi
	K_1	K_2	K_3	P_a = 14.7 psi	M_r
OMC	645.4	0.42	0.658	$\theta = (3\sigma_3 + \sigma_d)$	16557
OMC -1%	837.2	0.55	0.273	$\tau_{oct} = (\sqrt{2}/3)\sigma_d$	20229

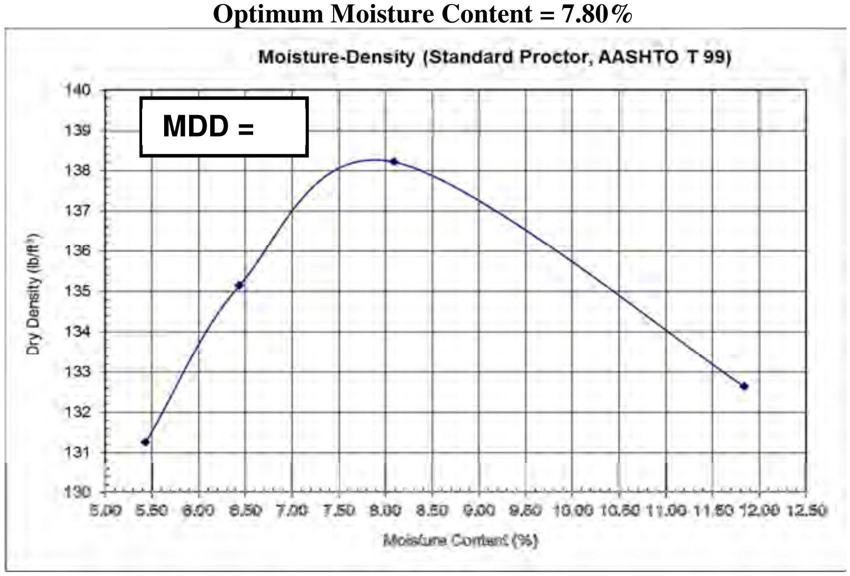
SUMMARY SHEET: STEVENSBURG (CULPEPER DISTRICT)

Rock type: 90% siltstone, 10% shale

Comments: 15% particles flat, thin (7:5:1); 20% elongate (3.5:1)

Gradation (AASHTO T 27)		
Sieve Size	Percent Retained	Percent Passing
2.00"	0.00	100.00%
1.50"	0.00	100.00%
1.00"	0.00	100.00%
0.75"	4.02	95.98%
0.50"	14.88	81.09%
0.375"	8.52	72.57%
No. 4	17.75	54.82%
No. 8	17.35	37.47%
No. 16	11.97	25.49%
No. 30	7.66	17.84%
No. 50	4.79	13.05%
No. 100	3.10	9.95%
No. 200	1.98	7.97%
Pan	7.91	---

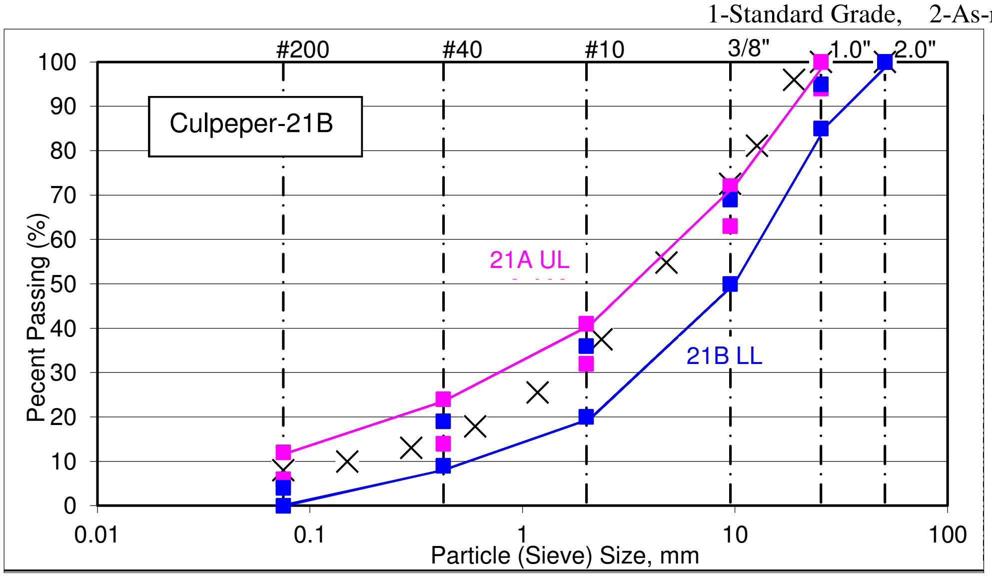
Proctor Results:
Maximum Dry Density = 138.3 pcf
Optimum Moisture Content = 7.80%



Specific Gravity (AASHTO T 84 and T 85)							
Dry Bulk		SSD		Apparent		Absorption (%)	
+4	-4	+4	-4	+4	-4	+4	-4
2.699	2.652	2.728	2.702	2.780	2.790	1.068	1.856

Un-compacted Void Content (%)			
+4 (AASHTO T 326)		-4 (AASHTO T 304)	
Method A[1]	Method C[2]	Method A[1]	Method C[2]
48.7	48.0	45.5	39.4

1-Standard Grade, 2-As-received Grade



Resilient Modulus Test Results (AASHTO T 307):

Test Moisture	MEPDG Model: $M_r = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2}\left(\frac{\tau_{oct}}{P_a}+1\right)^{k_3}$			Model Parameters	Confining (σ_3) : 5 psi Deviator (σ_d): 15 psi
	K_1	K_2	K_3	P_a = 14.7 psi	M_r
OMC	933.1	0.60	0.181	$\theta = (3\sigma_3 + \sigma_d)$	22566
OMC -1%	1085.9	0.52	0.248	$\tau_{oct} = (\sqrt{2}/3)\sigma_d$	25509

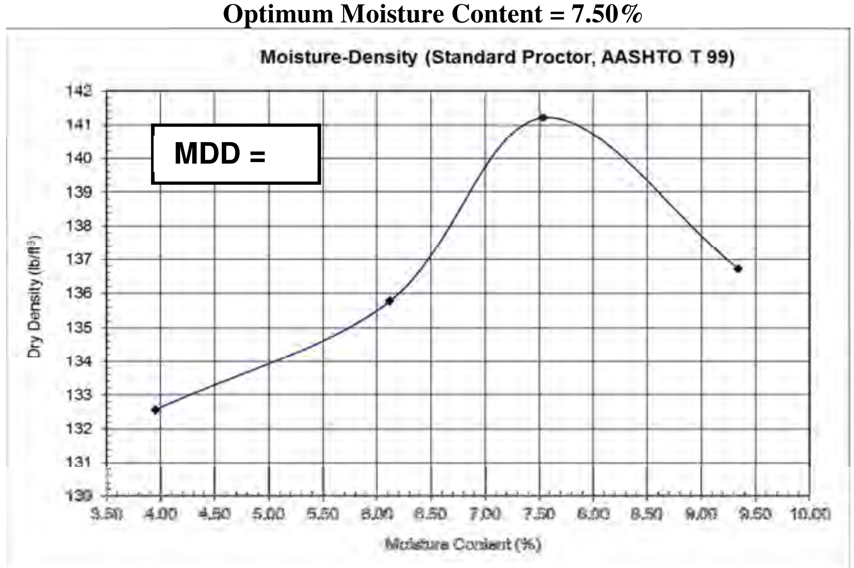
SUMMARY SHEET: DOSWELL, ASHLAND (RICHMOND DISTRICT)

Rock type: Granitic gneiss

Comments: Coarse-medium grained, 20% thin, flat particles

Gradation (AASHTO T 27)		
Sieve Size	Percent Retained	Percent Passing
2.00”	0.00	100.00
1.50”	0.00	100.00
1.00”	0.00	100.00
0.75”	3.73	96.27
0.50”	11.98	84.29
0.375”	8.40	75.88
No. 4	14.00	61.88
No. 8	17.39	44.50
No. 16	11.85	32.64
No. 30	8.22	24.42
No. 50	5.94	18.48
No. 100	4.72	13.76
No. 200	3.64	10.12
Pan	10.14	---

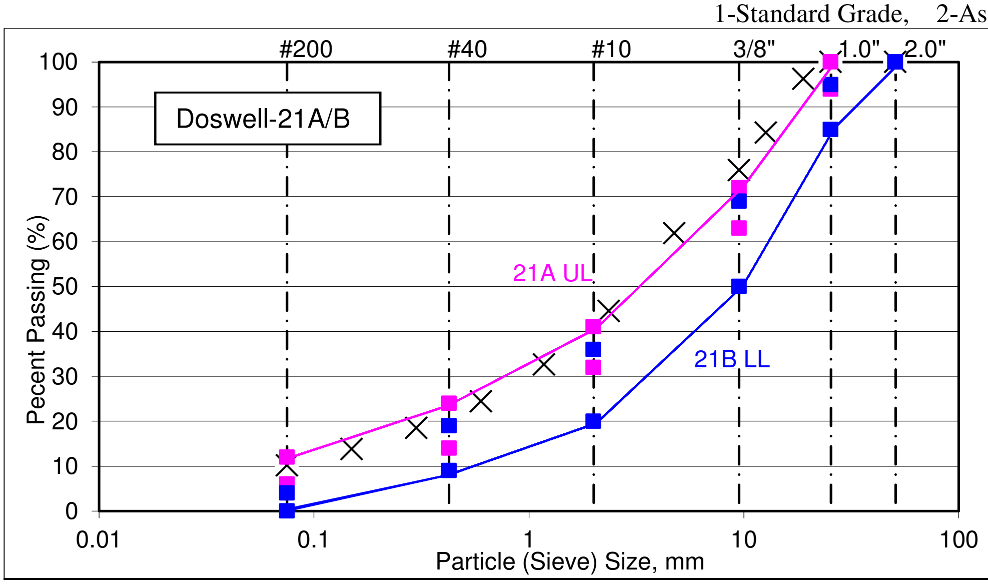
Proctor Results:
Maximum Dry Density = 141.2 pcf
Optimum Moisture Content = 7.50%



Specific Gravity (AASHTO T 84 and T 85)							
Dry Bulk		SSD		Apparent		Absorption (%)	
+4	-4	+4	-4	+4	-4	+4	-4
2.711	2.698	2.727	2.722	2.755	2.765	0.591	0.902

Un-compacted Void Content (%)			
+4 (AASHTO T 326)		-4 (AASHTO T 304)	
Method A[1]	Method C[2]	Method A[1]	Method C[2]
50.9	51.0	45.0	40.6

1-Standard Grade, 2-As-received Grade



Resilient Modulus Test Results (AASHTO T 307):

Test Moisture	MEPDG Model: $M_r = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2}\left(\frac{\tau_{oct}}{P_a}+1\right)^{k_3}$			Model Parameters	Confining (σ_3) : 5 psi Deviator (σ_d): 15 psi
	K_1	K_2	K_3	P_a = 14.7 psi	M_r
OMC	795.6	0.63	0.120	$\theta = (3\sigma_3 + \sigma_d)$	19213
OMC -1%	1063.9	0.55	0.157	$\tau_{oct} = (\sqrt{2}/3)\sigma_d$	24620

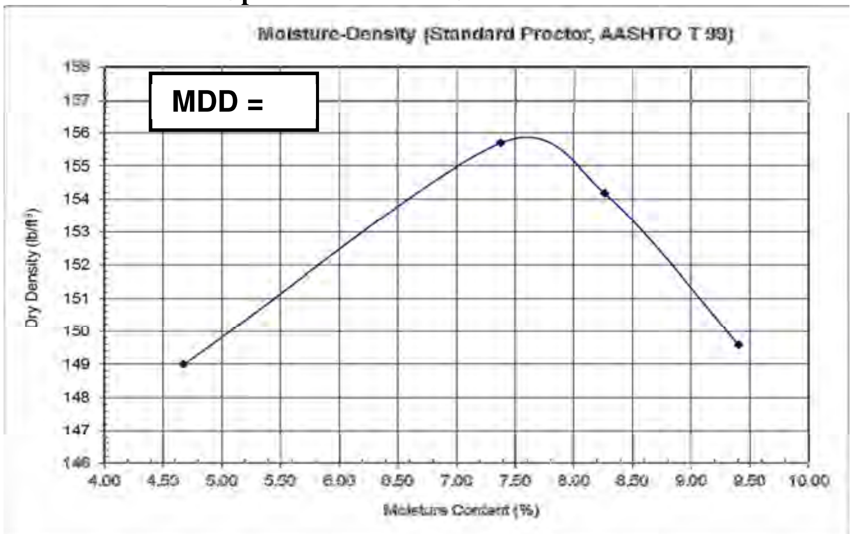
SUMMARY SHEET: GLADEHILL, JACKS MTN. (SALEM DISTRICT)

Rock type: Amphibolites gneiss

Comments: 45% fairly hard and equant particles; 25% fairly hard, thin, tablet-shaped particles (10:6:1); 30% rounded particles with weathered feldspar

Gradation (AASHTO T 27)		
Sieve Size	Percent Retained	Percent Passing
2.00”	0.00	100.00%
1.50”	0.00	100.00%
1.00”	0.00	100.00%
0.75”	4.82	95.18%
0.50”	15.51	79.67%
0.375”	9.13	70.54%
No. 4	18.54	52.01%
No. 8	9.95	42.05%
No. 16	6.02	36.04%
No. 30	4.14	31.90%
No. 50	2.91	28.99%
No. 100	3.72	25.27%
No. 200	6.25	19.02%
Pan	18.90	---

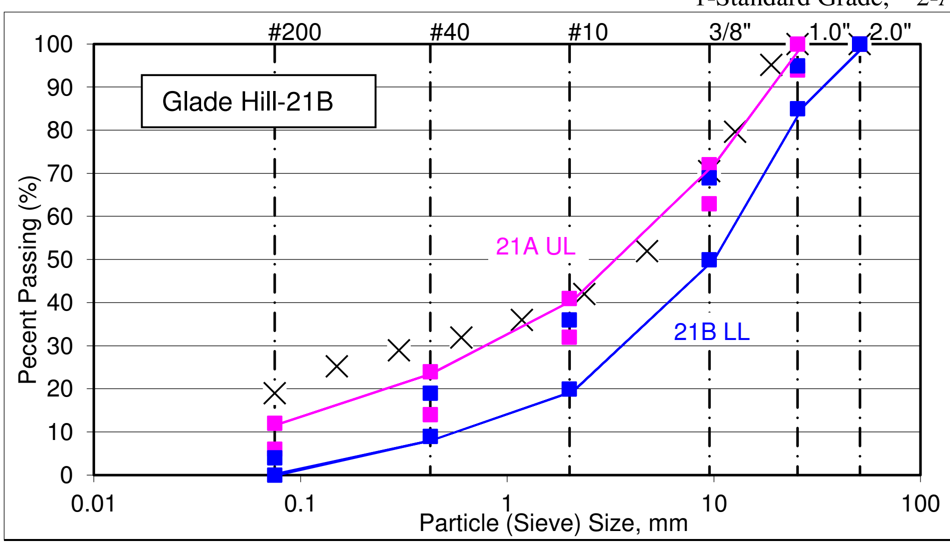
Proctor Results:
Maximum Dry Density = 155.8 pcf
Optimum Moisture Content = 7.60%



Specific Gravity (AASHTO T 84 and T 85)							
Dry Bulk		SSD		Apparent		Absorption (%)	
+4	-4	+4	-4	+4	-4	+4	-4
3.016	2.974	3.043	3.013	3.102	3.095	0.916	1.306

Un-compacted Void Content (%)			
+4 (AASHTO T 326)		-4 (AASHTO T 304)	
Method A[1]	Method C[2]	Method A[1]	Method C[2]
51.2	51.2	48.8	40.1

1-Standard Grade, 2-As-received Grade



Resilient Modulus Test Results (AASHTO T 307):

Test Moisture	MEPDG Model: $M_r = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a}+1\right)^{k_3}$			Model Parameters	Confining (σ_3) : 5 psi Deviator (σ_d): 15 psi
	K_1	K_2	K_3	P_a = 14.7 psi	M_r
OMC	536.2	0.40	1.156	$\theta = (3\sigma_3 + \sigma_d)$	16552
OMC -1%	780.4	0.71	0.186	$\tau_{oct} = (\sqrt{2}/3)\sigma_d$	20413

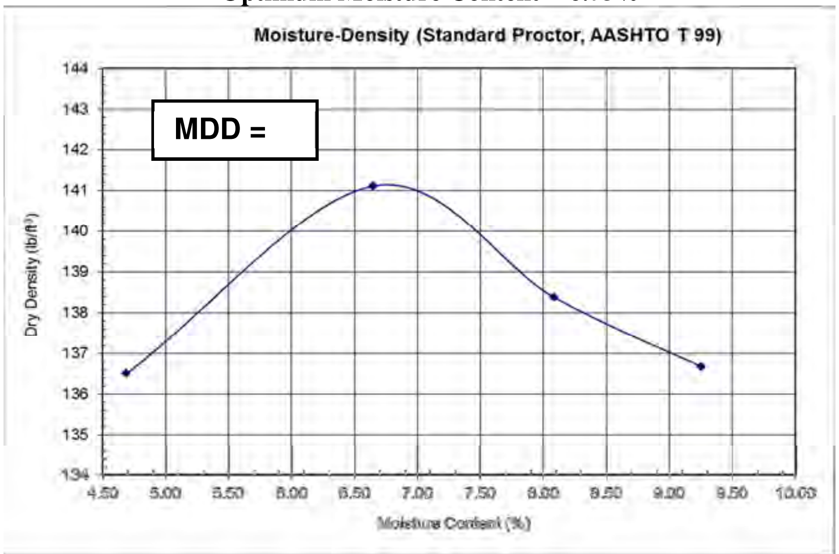
SUMMARY SHEET: GRAHAM-OCCOQUAN (21A) (NOVA DISTRICT)

Rock type: Granite

Comments: Some gneissic foliation, fairly equant particles

Gradation (AASHTO T 27)		
Sieve Size	Percent Retained	Percent Passing
2.00"	0.00	100.00%
1.50"	0.00	100.00%
1.00"	0.00	100.00%
0.75"	12.89	87.11%
0.50"	10.56	76.55%
0.375"	5.51	71.04%
No. 4	13.75	57.30%
No. 8	12.85	44.45%
No. 16	8.11	36.34%
No. 30	6.39	29.95%
No. 50	5.48	24.47%
No. 100	4.91	19.56%
No. 200	5.47	14.08%
Pan	14.06	---

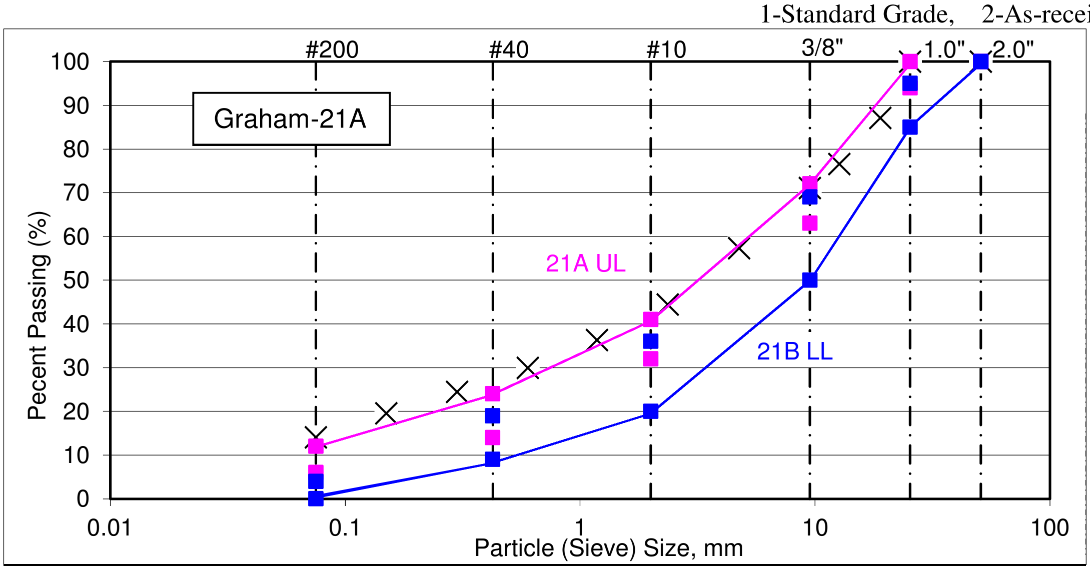
Proctor Results:
Maximum Dry Density = 141.2 pcf
Optimum Moisture Content = 6.75%



Specific Gravity (AASHTO T 84 and T 85)							
Dry Bulk		SSD		Apparent		Absorption (%)	
+4	-4	+4	-4	+4	-4	+4	-4
2.640	2.683	2.656	2.700	2.682	2.731	0.588	0.662

Un-compacted Void Content (%)			
+4 (AASHTO T 326)		-4 (AASHTO T 304)	
Method A[1]	Method C[2]	Method A[1]	Method C[2]
49.0	47.5	46.7	38.4

1-Standard Grade, 2-As-received Grade



Resilient Modulus Test Results (AASHTO T 307):

Test Moisture	MEPDG Model: $M_r = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a} + 1\right)^{k_3}$			Model Parameters	Confining (σ_3) : 5 psi Deviator (σ_d): 15 psi
	K_1	K_2	K_3	P_a = 14.7 psi	M_r
OMC	474.6	0.27	1.137	$\theta = (3\sigma_3 + \sigma_d)$	13265
OMC -1%	979.6	0.63	0.062	$\tau_{oct} = (\sqrt{2}/3)\sigma_d$	23133

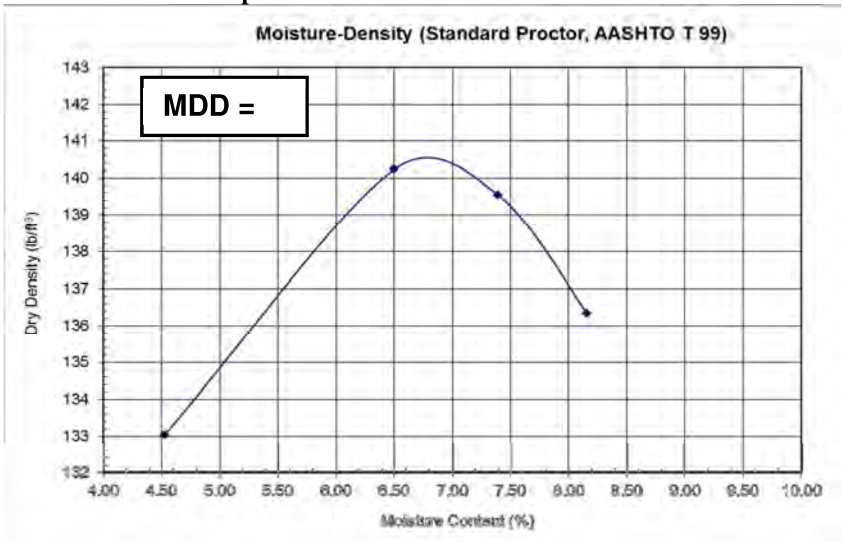
SUMMARY SHEET: GRAHAM-OCCOQUAN (21B) (NOVA DISTRICT)

Rock type: Granite

Comments: Some gneissic foliation, fairly equant particles

Gradation (AASHTO T 27)		
Sieve Size	Percent Retained	Percent Passing
2.00”	0.00	100.00%
1.50”	0.00	100.00%
1.00”	0.00	100.00%
0.75”	20.14	79.86%
0.50”	21.57	58.29%
0.375”	8.14	50.15%
No. 4	13.22	36.93%
No. 8	9.28	27.65%
No. 16	5.49	22.16%
No. 30	4.18	17.99%
No. 50	3.59	14.40%
No. 100	3.28	11.12%
No. 200	3.14	7.98%
Pan	7.98	---

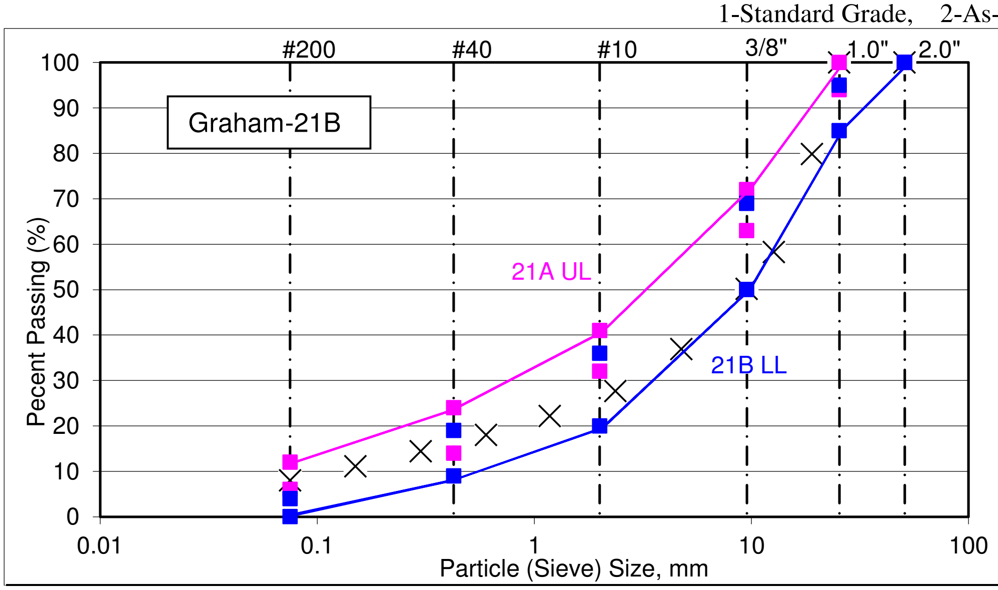
Proctor Results:
Maximum Dry Density = 140.5 pcf
Optimum Moisture Content = 6.75%



Specific Gravity (AASHTO T 84 and T 85)							
Dry Bulk		SSD		Apparent		Absorption (%)	
+4	-4	+4	-4	+4	-4	+4	-4
2.653	2.680	2.667	2.700	2.691	2.735	0.535	0.753

Un-compacted Void Content (%)			
+4 (AASHTO T 326)		-4 (AASHTO T 304)	
Method A[1]	Method C[2]	Method A[1]	Method C[2]
47.4	46.6	47.0	38.2

1-Standard Grade, 2-As-received Grade



Resilient Modulus Test Results (AASHTO T 307):

Test Moisture	MEPDG Model: $M_r = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2} \left(\frac{\tau_{oct}}{P_a}+1\right)^{k_3}$			Model Parameters	Confining (σ_3) : 5 psi Deviator (σ_d): 15 psi
	K_1	K_2	K_3	P_a = 14.7 psi	M_r
OMC	628.5	0.49	0.434	$\theta = (3\sigma_3 + \sigma_d)$	15527
OMC -1%	808.5	0.59	0.169	$\tau_{oct} = (\sqrt{2}/3)\sigma_d$	19356

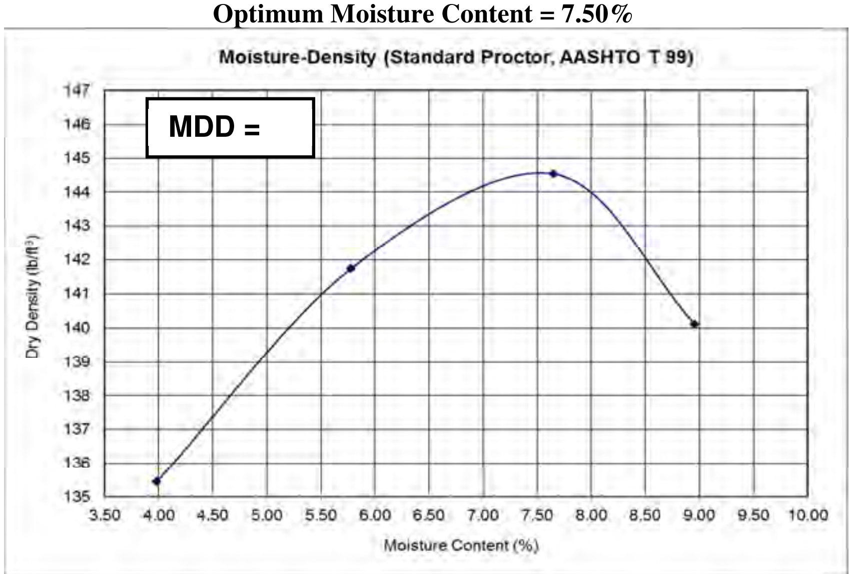
SUMMARY SHEET: SOUTH BOSTON, HALIFAX (LYNCHBURG DISTRICT)

Rock type: Granite

Comments: Fine-medium grained

Gradation (AASHTO T 27)		
Sieve Size	Percent Retained	Percent Passing
2.00”	0.00	100.00
1.50”	0.00	100.00
1.00”	0.00	100.00
0.75”	18.51	81.49
0.50”	15.13	66.36
0.375”	8.55	57.81
No. 4	13.30	44.51
No. 8	9.36	35.14
No. 16	7.82	27.32
No. 30	5.81	21.51
No. 50	4.37	17.15
No. 100	3.87	13.28
No. 200	3.36	9.92
Pan	10.65	---

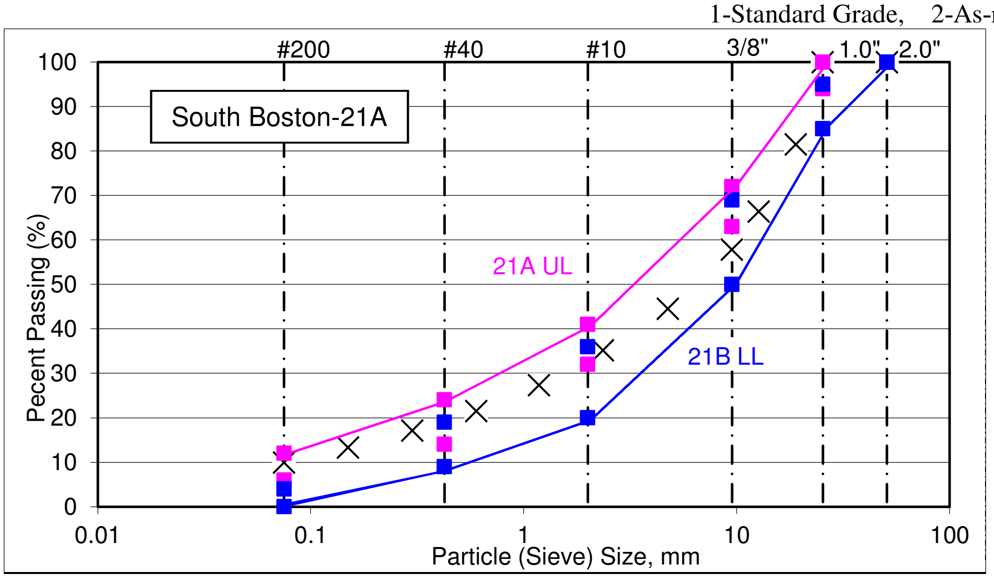
Proctor Results:
Maximum Dry Density = 144.5 pcf
Optimum Moisture Content = 7.50%



Specific Gravity (AASHTO T 84 and T 85)							
Dry Bulk		SSD		Apparent		Absorption (%)	
+4	-4	+4	-4	+4	-4	+4	-4
2.737	2.788	2.758	2.811	2.794	2.856	0.740	0.855

Un-compacted Void Content (%)			
+4 (AASHTO T 326)		-4 (AASHTO T 304)	
Method A[1]	Method C[2]	Method A[1]	Method C[2]
47.6	49.2	48.5	39.8

1-Standard Grade, 2-As-received Grade



Resilient Modulus Test Results (AASHTO T 307):

Test Moisture	MEPDG Model: $M_r = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2}\left(\frac{\tau_{oct}}{P_a}+1\right)^{k_3}$			Model Parameters	Confining (σ_3) : 5 psi Deviator (σ_d): 15 psi
	K_1	K_2	K_3	P_a = 14.7 psi	M_r
OMC	549.8	0.46	0.843	$\theta = (3\sigma_3 + \sigma_d)$	15571
OMC -1%	585.1	0.52	0.658	$\tau_{oct} = (\sqrt{2}/3)\sigma_d$	16100

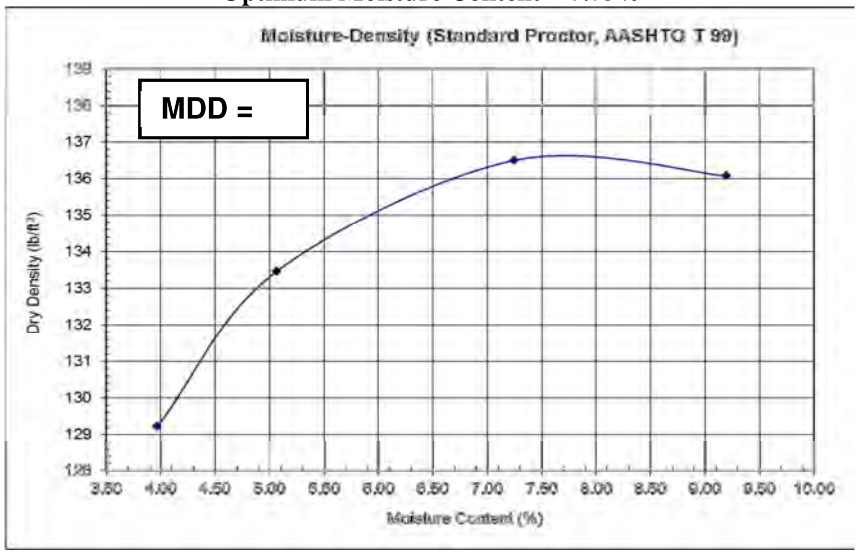
SUMMARY SHEET: STAUNTON (STAUNTON DISTRICT)

Rock type: Limestone

Comments: Micritic, 20% thin, slat particles

Gradation (AASHTO T 27)		
Sieve Size	Percent Retained	Percent Passing
2.00”	0.00	100.00%
1.50”	0.00	100.00%
1.00”	0.00	100.00%
0.75”	5.76	94.24%
0.50”	14.94	79.30%
0.375”	8.85	70.45%
No. 4	18.20	52.25%
No. 8	18.87	33.37%
No. 16	11.46	21.91%
No. 30	6.54	15.37%
No. 50	3.68	11.69%
No. 100	2.26	9.43%
No. 200	1.35	8.08%
Pan	0.08	---

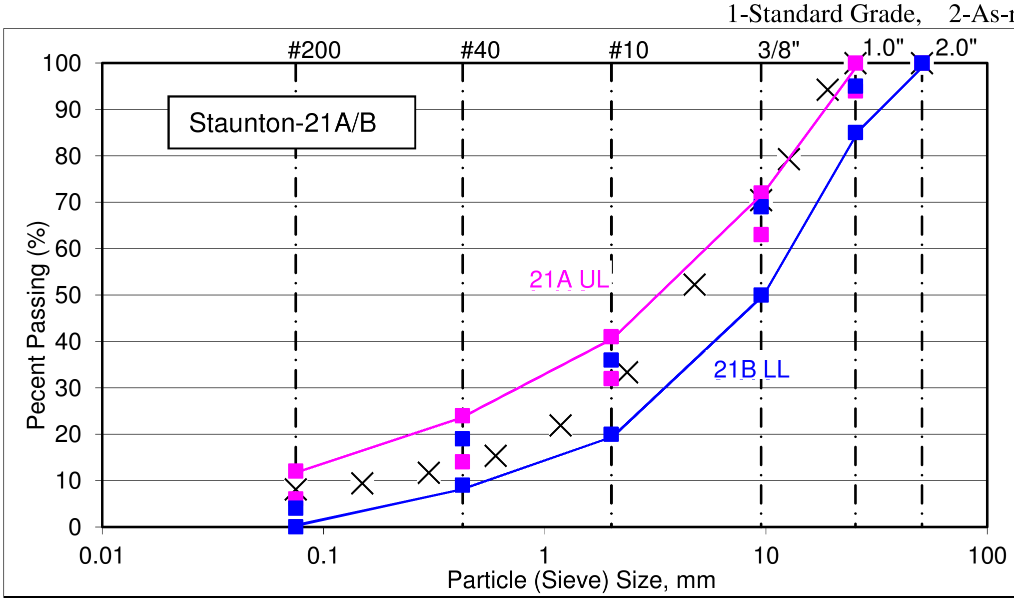
Proctor Results:
Maximum Dry Density = 136.6 pcf
Optimum Moisture Content = 7.75%



Specific Gravity (AASHTO T 84 and T 85)							
Dry Bulk		SSD		Apparent		Absorption (%)	
+4	-4	+4	-4	+4	-4	+4	-4
2.668	2.687	2.692	2.723	2.734	2.788	0.908	1.362

Un-compacted Void Content (%)			
+4 (AASHTO T 326)		-4 (AASHTO T 304)	
Method A[1]	Method C[2]	Method A[1]	Method C[2]
49.8	49.3	46.2	40.8

1-Standard Grade, 2-As-received Grade



Resilient Modulus Test Results (AASHTO T 307):

Test Moisture	MEPDG Model: $M_r = k_1 P_a \left(\frac{\theta}{P_a}\right)^{k_2}\left(\frac{\tau_{oct}}{P_a}+1\right)^{k_3}$			Model Parameters	Confining (σ_3) : 5 psi Deviator (σ_d): 15 psi
	K_1	K_2	K_3	$P_a = 14.7$ psi	M_r
OMC	1369.3	0.54	0.038	$\theta = (3\sigma_3 + \sigma_d)$	30034
OMC -1%	1403.0	0.43	0.229	$\tau_{oct} = (\sqrt{2}/3)\sigma_d$	30732