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Mechanistic-Empirical Pavement Design: Materials Testing of Resilient and Dynamic Modulus

Study SD2008-10
Final Report

Prepared by
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16. Abstract

The Mechanistic-Empirical Pavement Design Guide (MEPDG) requires the resilient modulus (M_r) characterization of base and subgrade materials and the dynamic modulus (E*) characterization for hot mix asphalt (HMA). The purpose of this study is to determine the M_r and E* values for typical soil and construction materials used in South Dakota. The testing will allow the South Dakota Department of Transportation (SDDOT) to begin to build a database of the pertinent material input variables for future mechanistic-empirical designs.

This report includes materials testing conducted by South Dakota School of Mines and Technology (SDSM&T). SDSM&T recently acquired a Simple Performance Tester (SPT) machine manufactured by Interlaken Technology Corporation, Chaska, Minnesota. The SPT has the ability to perform the resilient modulus, dynamic modulus, and repeated load triaxial tests through the use of operational software developed specifically for the machine. This report includes testing of subgrade materials and hot mix asphalt (HMA) from across the state of South Dakota. It also includes dynamic modulus results for one warm mix asphalt (WMA).

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EXECUTIVE SUMMARY

INTRODUCTION

The Mechanistic-Empirical Pavement Design Guide (MEPDG) requires the resilient modulus (M_r) characterization of base and subgrade materials and the dynamic modulus (E*) characterization for asphalt mixes. The purpose of this study was to determine the resilient modulus and dynamic modulus values for typical soil and road construction materials in South Dakota. The testing will allow the South Dakota Department of Transportation (SDDOT) to begin to build a database of the pertinent material input variables for future mechanistic-empirical designs. This will ensure that the overall behavior of the multi-layer model includes a valid representation of the design site along with the operational intentions of the pavement system. It will also allow for a Level 1 or Level 2 pavement design within the MEPDG protocol.

This report includes testing of materials conducted by the South Dakota School of Mines and Technology (SDSM&T). SDSM&T possesses a Simple Performance Tester (SPT) machine manufactured by Interlaken Technology Corporation, Chaska, Minnesota. The SPT has the ability to perform the resilient modulus, dynamic modulus, and repeated load triaxial tests through the use of operational software developed specifically for the machine. In order, to evaluate SDSM&T's testing procedures and calibrate the new SPT machine, Task 4 of the research project consisted of concurrent HMA testing conducted at the Asphalt Research Consortium (ARC) at the University of Nevada-Reno (UNR). This report includes testing results from subgrade materials and hot mix asphalt (HMA) from across the state of South Dakota. It also includes dynamic modulus results for one warm mix asphalt (WMA). Through the course of testing, a predictive equation for the resilient modulus of South Dakota subgrade soils with a plasticity index (PI) less than 40 was developed.

OBJECTIVES

The objectives of this research include the following:

1) Obtain resilient modulus and dynamic modulus values for construction materials on HMA paving projects through tests performed with a Simple Performance Tester (SPT) at SDSM&T to correlate, calibrate, and validate these results from the new SPT through comparative analyses with similar work performed at the UNR for the SDDOT.

2) Obtain resilient modulus and dynamic modulus values of construction materials through tests performed with the SPT at SDSM&T on other HMA paving projects and typical soil types around the state to validate resultant data relative to the criteria defined for mechanistic-empirical pavement design processes and ultimate incorporation of the data into a mechanistic-empirical pavement design database.

3) Gain an assessment, jointly with the SDDOT Technical Implementation Group, on the possible need for acquisition of SPT or other materials testing equipment by the Department.

RESEARCH APPROACH

The first objective of the research project was accomplished by reviewing testing criteria, meeting with the Technical Implementation Group (TIG), reviewing testing procedures and protocols, and performing concurrent materials testing. Laboratory tests included particle size analyses, Atterberg Limits, moisture and density relationships, resilient modulus tests, and dynamic modulus tests.

The second objective was met by completing testing on 10 subgrade soils, 15 HMA pavement materials, and one WMA pavement material. Each soil sample was subjected to the following laboratory tests: particle size analyses, hydrometer analyses, Atterberg Limits, moisture and density relationships, California Bearing Ratio (CBR) determinations, and resilient modulus tests. Each HMA sample had the dynamic modulus and repeated load triaxial tests performed.

CONCLUSIONS

Based upon the research conducted, the following results were obtained. For the constitutive model utilized in the MEPDG for resilient modulus, the regression constants, k_1, k_2, and k_3 for each subgrade soil were determined as given below. An estimated magnitude for the M_r, using the constitutive equation with back-computed regression constants and assuming typical stress values for the subgrade layer within a multi-layered pavement, was also computed.

Average Resilient Modulus Coefficients

Material	k_1	k_2	k_3	M_r value with σ_3=2psi & σ_d=6psi
SD34 Lee's Corner	777.62	0.25	-1.27	8,690
I-90 by Blackhawk	1019.60	0.75	-1.50	9,886
SD11/SD42 Minnehaha	723.67	0.57	-1.90	6,787
SD44 E of Scenic	908.71	0.51	-0.47	11,096
SD20 E of Prairie City	1482.63	0.48	-0.51	18,064
US281 Wolsey	470.20	0.65	-3.42	3,321
SD34 Forestburg	639.28	0.78	-1.60	6,053
US212 Orman Dam	1399.58	0.50	-0.42	17,243
US83 Ft Pierre	1065.46	0.34	0.09	14,841

Material	k_1	k_2	k_3	M_r value with σ_3=2psi & σ_d=6psi*
US385 Custer/Hill City	723.64	0.70	-2.96	5,485
US212 Subgrade	1926.33	0.42	-0.50	22,045
US212 Base	1331.43	0.64	-0.45	26,693
US281 Subgrade	1918.37	0.68	-0.68	19,217
US281 Base	894.57	0.79	-0.50	19,944

For the dynamic modulus:

Average Dynamic Modulus Values

Averages		**Dynamic Modulus (psi)**					
Temp (^{o}C)	Frequency (Hz)	00H1	00H2	00H3	00HK	00J2	00J3
4.4	25	1,070,260	1,546,832	1,618,901	1,977,446	1,795,305	1,720,017
	10	849,172	1,353,958	1,417,817	1,814,742	1,601,447	1,572,734
	5	714,794	1,211,942	1,292,715	1,683,782	1,451,702	1,452,446
	1	455,798	895,979	1,026,544	1,392,811	1,137,483	1,171,096
	0.5	364,805	777,970	921,335	1,272,814	1,008,626	1,051,941
	0.1	234,923	545,140	680,143	969,445	742,385	798,663
21.1	25	472,739	685,570	801,293	1,099,024	837,529	968,824
	10	342,425	532,902	648,239	921,720	685,723	829,085
	5	262,934	433,016	542,182	795,902	564,129	718,605
	1	143,122	250,579	325,174	525,255	338,643	456,149
	0.5	113,227	205,732	254,443	432,939	273,525	372,253
	0.1	75,229	120,264	143,844	250,201	158,800	228,465
37.8	25	187,563	251,314	286,709	439,692	322,305	364,333
	10	121,485	148,758	187,977	327,421	213,736	257,520
	5	93,404	111,994	139,863	258,073	161,102	200,081
	1	56,049	59,249	70,608	141,477	85,315	107,301
	0.5	48,387	47,128	54,285	108,892	67,303	84,435
	0.1	39,303	32,858	35,678	66,977	45,430	51,513

Averages		**Dynamic Modulus (psi)**					
Temp (^{o}C)	Frequency (Hz)	00H1	00H2	00H3	00HK	00J2	00J3
54	25	107,826	80,871	99,201	161,912	139,685	124,966
	10	62,315	51,014	59,962	109,941	83,848	77,522
	5	44,579	39,835	44,344	85,534	62,313	59,123
	1	33,656	26,531	27,507	47,287	37,508	37,597
	0.5	32,776	24,018	23,389	39,454	31,956	32,359
	0.1	30,845	20,683	19,477	27,162	25,032	24,770

Averages		**Dynamic Modulus (psi)**					
Temp (^{o}C)	Frequency (Hz)	00J5	00J7	01CD	01CN	01CP	01CU
4.4	25	2,074,967	1,102,721	1,363,135	1,549,172	1,530,070	1,896,636
	10	1,803,955	952,207	1,197,286	1,427,586	1,312,090	1,786,851
	5	1,613,023	854,344	1,109,578	1,310,773	1,209,202	1,634,634
	1	1,223,585	629,126	868,475	1,003,288	929,576	1,355,221
	0.5	1,085,884	547,476	748,567	892,820	839,059	1,254,448
	0.1	727,860	391,530	550,100	651,546	620,670	982,440
21.1	25	819,362	530,338	672,815	688,346	771,385	887,043
	10	638,345	425,376	541,223	544,753	642,582	742,172
	5	517,799	353,578	456,787	451,527	542,068	633,851
	1	286,853	217,739	266,546	268,369	302,966	420,867
	0.5	218,007	180,564	207,291	214,016	244,577	342,124
	0.1	117,474	118,888	122,469	128,545	136,298	210,295
37.8	25	232,540	249,955	251,534	272,819	325,781	334,165
	10	158,151	176,541	166,540	187,624	215,682	248,044
	5	119,889	140,674	124,854	145,678	161,034	195,484
	1	66,101	84,284	66,057	80,067	81,675	110,754
	0.5	54,294	70,600	52,388	63,065	62,391	87,026
	0.1	37,949	50,467	35,885	42,391	40,012	55,850
54	25	68,599	196,717	114,197	114,080	133,213	127,542
	10	48,933	127,023	69,428	74,104	84,548	89,044
	5	38,687	98,293	50,627	54,869	60,676	67,412
	1	26,685	57,510	30,087	33,089	31,129	39,296
	0.5	23,911	50,662	25,821	27,650	26,073	32,090
	0.1	19,145	36,143	20,839	21,791	18,080	22,958

Averages		Dynamic Modulus (psi)				
Temp (°C)	Frequency (Hz)	001G	000M	5930	US281	WMA
4.4	25	765,478	2,064,076	1,238,713	1,196,265	1,797,673
	10	658,053	1,844,994	1,043,895	1,009,865	1,576,100
	5	565,985	1,718,620	908,425	875,621	1,407,589
	1	354,299	1,389,233	636,149	592,649	1,097,285
	0.5	313,068	1,275,655	534,065	488,942	970,749
	0.1	197,290	954,196	341,412	318,980	679,897
21.1	25	306,095	926,236	452,773	479,536	795,922
	10	222,120	765,555	342,580	330,107	635,605
	5	168,970	650,403	273,738	253,051	535,594
	1	91,077	416,558	152,657	140,533	321,015
	0.5	76,255	332,930	119,905	110,893	252,603
	0.1	50,621	195,580	74,648	72,156	143,584
37.8	25	71,328	362,022	144,276	188,688	203,032
	10	53,667	269,324	107,922	114,959	145,324
	5	44,383	212,038	88,395	83,638	115,235
	1	31,254	118,681	56,759	47,441	68,917
	0.5	30,165	92,082	50,319	40,179	58,373
	0.1	25,727	58,777	39,460	30,775	43,047
54	25	41,047	132,504	72,935	83,695	79,694
	10	32,794	91,128	49,078	51,714	60,104
	5	28,198	70,151	42,922	40,154	49,793
	1	22,074	41,690	31,627	28,269	36,307
	0.5	20,576	34,683	28,324	25,532	30,860
	0.1	18,771	26,520	22,649	21,757	25,467

For the constitutive equation utilized in the MEPDG for accumulated permanent or plastic vertical deformation (i.e. rutting), the field calibration parameters, a_1, a_2, and a_3 were determined as given below.

Average Permanent Deformation Model Coefficients

HMA Mix	a_1	a_2	a_3	R^2
00J2	-7.22	0.45	3.64	0.91
00J3	-4.23	0.43	2.03	0.88
00J5	-5.16	0.52	2.47	0.90
00J7	-0.86	0.34	0.41	0.58
00H1	-6.15	0.36	3.12	0.92
00H2	-10.48	0.65	4.73	0.95

HMA Mix	a_1	a_2	a_3	R^2
00H3	-8.97	0.57	4.34	0.84
00HK	-9.09	0.58	4.28	0.92
000M	-8.19	0.55	3.82	0.90
01CD	-6.77	0.47	3.38	0.91
01CN	-4.39	0.45	2.14	0.81
01CP	-7.27	0.53	3.42	0.84
01CU	-3.68	0.56	1.58	0.97
001G	-1.70	0.40	0.86	0.96
5930	-3.80	0.51	1.69	0.90

RECOMMENDATIONS

As a result of this project, it is recommended that the South Dakota Department of Transportation continue with the development of a material input parameter database for the Mechanistic-Empirical Pavement Design Guide. This would involve further testing of typical soil and road construction materials in South Dakota for resilient modulus and dynamic modulus, respectively. The additional testing and database development will ensure that proper material input values are utilized in future mechanistic-empirical pavement designs. The further testing of typical soil materials for resilient modulus will also allow for continued validation and refinement of a parametric relationship for the resilient modulus that was initially developed for low plasticity soils from this project's results. Additionally, it is highly recommended that testing of high plasticity soil subgrade materials be included in the future testing matrix in order to develop a parametric relationship for resilient modulus for these soils.

Finally, it is not recommended that the South Dakota Department of Transportation procure a Simple Performance Tester machine at this time. The South Dakota School of Mines and Technology is fully capable of completing any required resilient modulus, dynamic modulus, and repeated load triaxial tests for the database development.

CHAPTER 1 INTRODUCTION

1.1 Problem Statement

In the mid-1990s, the American Association of State Highway and Transportation Officials (AASHTO) Joint Task Force on Pavements proposed a research program to develop a pavement design guide based on mechanistic-empirical principles[1]. This was proposed in order to move beyond the limited data gained from the 1958 to 1960 AASHO Road Test. Currently, the primary document used to design new and rehabilitated pavements is the AASHTO *Guide for Design of Pavement Structures*. The 1972, 1986 and 1993 versions of the guide were empirically based on performance equations developed using the AASHO road test data. Alternatively, in a mechanistic-empirical design approach, the principles of engineering mechanics are used to evaluate the pavement system. Therefore, the pavement is analyzed as a multi-layer, linear elastic model where static equilibrium is satisfied at any given location within the system. Empirical methods are used to characterize site specific traffic, climate, and material behavior. Consequently, the mechanistic-empirical approach makes it possible to incorporate significant materials properties into the design procedure. This allows design optimization while more fully ensuring that specific distress types would not develop in the pavement system[2]. This type of analysis is not possible in the current AASHTO design procedure.

In 2004, the Mechanistic-Empirical Pavement Design Guide (MEPDG) was developed under the National Cooperative Highway Research Program (NCHRP) Project 1-37A. The MEPDG would allow agencies to design efficient pavement systems based on local materials and needs. To that end, specific characterization of the input parameters is extremely important to ensure that the model analysis and the theoretical computation of pavement deflection, stress, and strain are accurate and complete at certain critical locations within the pavement system. The South Dakota Department of Transportation (SDDOT) recognizes that the testing and development of pertinent material properties for inclusion in the mechanistic-empirical model is critical for future mechanistic-empirical pavement design processes.

The MEPDG features a hierarchical approach to design inputs. This approach provides the designer with flexibility in obtaining the design inputs based on the project criticality and the available resources. Level 1 inputs require laboratory or field testing and therefore provide for the highest level of accuracy and lowest level of uncertainty or error. Usually, Level 1 inputs are used for high-traffic load designs or where there are severe consequences if the pavement fails early. Level 2 inputs provide an intermediate level of accuracy. It compares with the typical procedures used with earlier editions of the AASHTO Guide. Level 2 inputs are generally obtained from an agency database, derived from a limited testing program, or estimated through correlations. This level could be used when resources or testing equipment are not available for tests required for a Level 1 design. An example would be estimating asphalt concrete dynamic modulus from binder, aggregate, and mix properties. Finally, Level 3 inputs are merely typical average values for the region or default values for a given parameter and leads to the lowest level of accuracy for the pavement design. An example of a Level 3 input would be to use default resilient modulus values for unbound materials[2]. For unbound material characterization, the input level affects the calculation procedure and therefore affects the predicted structural response of the pavement system[3].

The purpose of this study is to determine resilient modulus, dynamic modulus, and repeated load triaxial values for typical soil and road construction materials in South Dakota. The testing will allow the SDDOT to begin to build a database of the pertinent material input variables for future mechanistic-empirical designs. This will ensure that the overall behavior of the multi-layer model includes a valid representation of the design site along with the operational intentions of the pavement system.

The results in this report are from 12 subgrade soils, 2 base materials, and 16 HMA pavement materials sampled across South Dakota. Dynamic modulus testing was also conducted on one WMA pavement material. Tests were performed at South Dakota School of Mines and Technology (SDSM&T). Resilient modulus, dynamic modulus, and repeated load triaxial tests were conducted using a Simple Performance Tester manufactured by Interlaken Technology Corporation.

1.2 Objectives

The objectives of this research include the following:

1) Obtain resilient modulus and dynamic modulus values for construction materials on HMA paving projects through tests performed with a Simple Performance Tester (SPT) at SDSM&T to correlate, calibrate, and validate these results from the new SPT through comparative analyses with similar work performed at the UNR for the SDDOT.

2) Obtain resilient modulus and dynamic modulus values of construction materials through tests performed with the SPT at SDSM&T on other HMA paving projects and typical soil types around the state to validate resultant data relative to the criteria defined for mechanistic-empirical pavement design processes and ultimate incorporation of the data into a mechanistic-empirical pavement design database.

3) Gain an assessment, jointly with the SDDOT Technical Implementation Group, on the possible need for acquisition of SPT or other materials testing equipment by the Department.

CHAPTER 2 RESEARCH PLAN

2.1 Introduction

The work plan identified ten tasks required to accomplish the objectives of this research project. The following sections briefly describe the approach to accomplish the objectives.

2.2 Task 1 – Review Testing Criteria

Prior to initiating the project, researchers reviewed MEPDG testing criteria for obtaining resilient modulus values for subgrade and base course materials and dynamic modulus values of pavement aggregate materials relative to the design and construction of roadway projects. This involved a thorough review of AASHTO and ASTM specifications that were pertinent to the required testing. SD2005-01, *Mechanistic-Empirical Pavement Design Guide Implementation Plan* was also reviewed.

2.3 Task 2 – Meet with Project's Technical Implementation Group

Researchers reviewed the scope of work, delivery schedules for materials, and materials testing plans with appropriate members of the Technical Implementation Group (TIG) for mechanistic-empirical pavement design implementation at the SDDOT.

2.4 Task 3 – Review Testing Procedures

Researchers reviewed testing procedures and coordinated with Dr. Peter Sebaaly and Dr. Elie Hajj at the University of Nevada-Reno (UNR) concerning materials testing protocols, methodologies, and training requirements of laboratory testing technicians for work performed at SDSM&T and UNR laboratories.

2.5 Task 4 – Concurrent Materials Testing

Concurrent to materials tests performed at UNR, SDSM&T performed parallel materials tests with the SPT following the protocols established in Task 3. Results were compared and analyzed and refinements were performed. During the course of testing for this task at SDSM&T, some components of the SPT had to be replaced, the computer program code was adjusted, and the machine was tuned to obtain accurate results.

The materials testing involved two separate highway projects and included two subgrade materials, two base materials, and one HMA pavement material. The purpose of the parallel testing was to calibrate the SPT at SDSM&T and develop expertise within South Dakota on resilient modulus testing and dynamic modulus testing of construction materials for pavement design methods.

2.6 Task 5 – Prepare Interim Report

An interim report was prepared for this task that presented the findings of Tasks 1 through 4. The report was completed and submitted to the TIG June 15, 2009.

2.7 Task 6 – Pavement Materials Tests

Pavement material tests were performed with the SPT for dynamic modulus and asphalt flow number (i.e. repeated load triaxial test). Each pavement material sample had three testing iterations performed for dynamic modulus and three testing temperatures for the repeated load triaxial test.

2.8 Task 7 – Subgrade Materials Tests

Highway subgrade materials tests were performed on 10 different soils types. Each soil sample was classified and had three testing iterations performed for California Bearing Ratio (CBR) and three testing iterations performed for resilient modulus.

2.9 Task 8 – Statistical Analyses

Statistical analyses were performed on all test results to measure variability between the replicates within each testing protocol.

2.10 Task 9 – Prepare Final Report

This task was to prepare a report that presented the findings of Tasks 1 through 8. This report represents the completion of Task 9.

2.11 Task 10 – Executive Presentation to SDDOT Research Review Board

This task involved making an executive presentation to the South Dakota Department of Transportation Research Review Board at the conclusion of the research.

CHAPTER 3 TEST METHODS

3.1 Introduction

This chapter provides a description of each laboratory test performed during the project.

3.2 Particle Size Analysis

The sieve analysis was performed to determine the particle size distribution of unbound granular and subgrade materials. It consisted of shaking the soil sample through a set of sieves that have progressively smaller openings. The analysis was performed according to ASTM D421-85[4]. All material was initially wet sieved. A mass of 1000-grams of subgrade material and 2000-grams of base material was oven dried. The subgrade material was covered in water and soaked to dissolve any clumps. Subgrade material was wet sieved through the No. 40 sieve and the No. 200 sieve. Base material was wet sieved through the No. 10 sieve and the No. 200 sieve. Material retained on the sieves was oven dried, pulverized with a rubber-headed hammer, placed in a stack of sieves, and shaken with a mechanical sieve shaker. The mass retained on each sieve was measured and the percent passing was plotted with respect to grain diameter.

3.3 Hydrometer Analysis

The hydrometer analysis was conducted to determine the clay content of the subgrade soils. It was performed according to ASTM D422-63[4] except only minus No. 200 material was tested. A 50-gram sample of minus No. 200 material was prepared for the test by soaking the sample in 125 mL of solution for 16 hours. The solution consisted of 40-grams of sodium hexametaphosphate mixed in 1000 mL of distilled water. The soil, solution, and distilled water were thoroughly mixed and placed in a graduated cylinder. Hydrometer measurements were taken at 15 seconds, 30 seconds, 60 seconds, 2 minutes, 4 minutes, 8 minutes, 15 minutes, 30 minutes, 1 hour, 2 hours, 4 hours, 8 hours, 24 hours, and 48 hours. A zero reading was also taken at all these times with a base solution of sodium hexametaphosphate and distilled water to normalize the soil readings.

3.4 Atterberg Limits

The liquid limit and plastic limits of subgrade soils are collectively known as Atterberg limits. These limits specify the boundaries of consistency states (solid, semisolid, plastic, and liquid) of soils. The plasticity of the minus No. 40 (0.425mm) sieve size materials were determined according to ASTM D4318-05[4]. The dry preparation method was used for all samples and the material was sieved through the No. 40 sieve before beginning the test. Method A, the multipoint test, was used to determine the liquid limit and the hand method was used for the plastic limit. The numerical difference between the liquid limit and the plastic limit is called the plasticity index (PI). The PI indicates the magnitude of the range of moisture contents a material will remain in a plastic state.

3.5 Moisture/Density Relationship

The moisture density relationship for the base and subgrade materials was determined according to ASTM D1557-02[4]. The material was sieved through the ¾-inch sieve and five samples of approximately 5000-grams of material were prepared. A different percentage of water was added to each sample and thoroughly mixed. The soil samples were compacted in a 6-inch mold in five lifts of equal height. Each soil lift was subjected to fifty-six blows using a 10-pound rammer dropped from a height of 18-inches (modified Proctor). After compaction, excess material was trimmed and the mold was weighed. The material was removed from the mold and the moisture content for each sample was measured in three places: top, middle, and bottom of the sample. Dry density was plotted with respect to moisture content and the maximum dry density (MDD) and the optimum moisture content (OMC) of the material were obtained from these plots.

3.6 Soil Classifications

Soil classification is based on particle size distribution, liquid limit, and plasticity index of the material. Optimum moisture content and maximum dry density of the soil are characteristics needed to reconstitute soil specimens to perform resilient modulus and California Bearing Ratio tests. The soils were classified using the criteria given in Table 1, adapted from AASHTO M145[7], and Figures 1, 2, and 3, adapted from ASTM D2487[4].

Table 1: AASHTO Soil Classification

Table a - Classification of Soils and Soil-Aggregate Mixtures

General Classification	Granular Materials (35% or Less Passing 75mm)			Silt-Clay Materials (More than 35% Passing 75mm)			
Group Classification	A-1	A-3[a]	A-2	A-4	A-5	A-6	A-7
Sieve analysis, percent passing:							
2.00mm (No. 10)							
0.0425mm (No. 40)	50 max	51 max					
75 mm (No. 200)	25 max	10 max	35 max	36 min	36 min	36 min	36 min
Characteristics of fraction passing 0.425mm (No. 40):							
Liquid Limit				40 max	41 min	40 max	41 min
Plasticity Index	6 max	NP	[b]	10 max	10 max	11 min	11 min
General rating as subgrade	Excellent to Good			Fair to Poor			

[a] The placing of A-3 before A-2 is necessary in the "left to right elimination process"

[b] See Table b for values

Table b - Classification of Soils and Soil-Aggregate Mixtures

General Classification	Granular Materials (35% or Less Passing 75mm)							Silt-Clay Materials (More than 35% Passing 75mm)			
Group Classification	A-1		A-3	A-2				A-4	A-5	A-6	A-7
	A-1-a	A-1-b		A-2-4	A-2-5	A-2-6	A-2-7				A-7-5, A-7-6
Sieve analysis, percent passing:											
2.00mm (No. 10)	50 max										
0.0425mm (No. 40)	30 max	50 max	51 max								
75 mm (No. 200)	15 max	25 max	10 max	35 max	35 max	35 max	35 max	36 min	36 min	36 min	36 min
Characteristics of fraction passing 0.425mm (No. 40):											
Liquid Limit				40 max	41 min	40 max	41 min	40 max	41 min	40 max	41 min
Plasticity Index	6 max		NP	10 max	10 max	11 min	11 min	10 max	10 max	11 min	11 min[a]
Usual types of significant constituent materials	Stone fragments, gravel and sand		Fine sand	Silty or clayey gravel and sand				Silty soils		Clayey soils	
General rating as subgrade	Excellent to Good							Fair to Poor			

[a] Plasticity index of A-7-5 subgroup is equal to or less than LL minus 30. Plasticity index of A-7-6 subgroup is greater that LL minus 30.

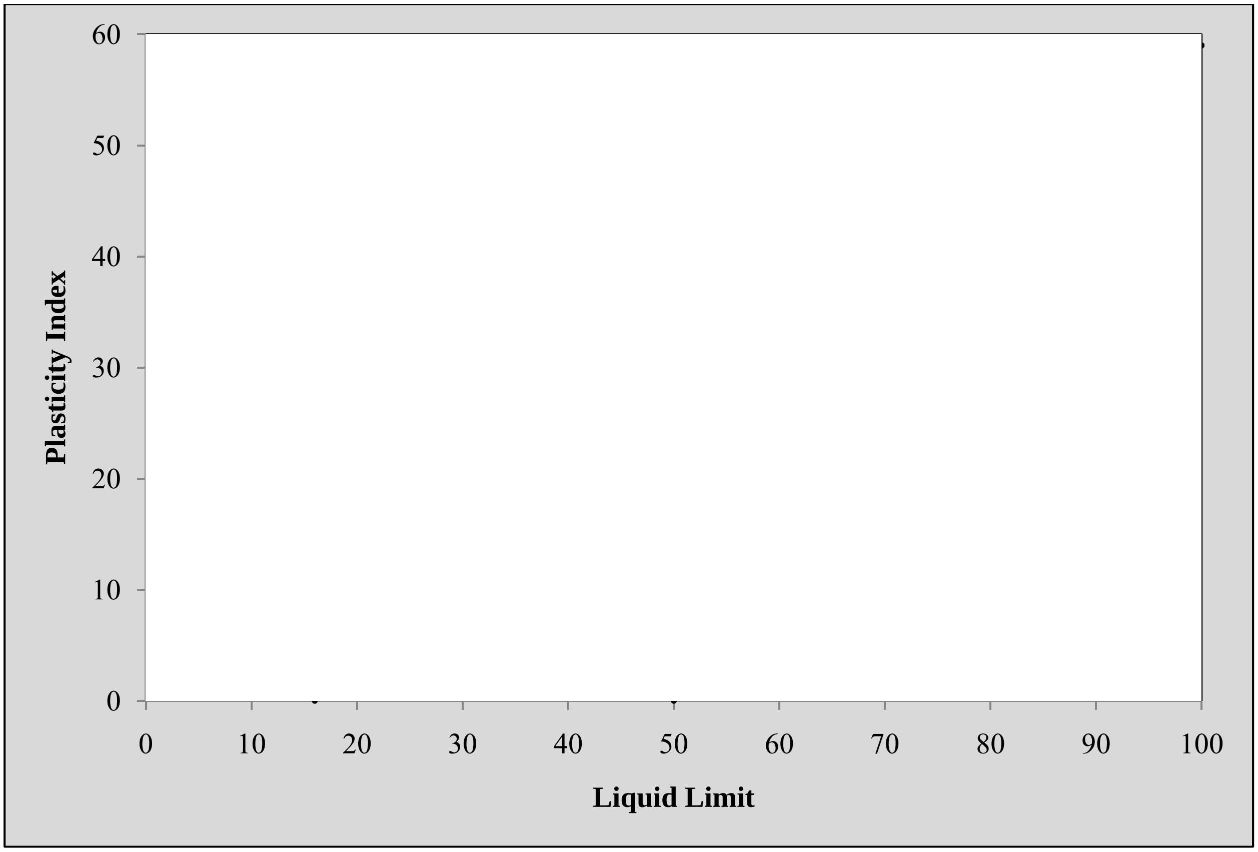


Figure 1: Plasticity Chart

In order to classify coarse-grained soils using the Unified Soil Classification, the coefficient of uniformity and the coefficient of curvature must also be known. Poorly graded soils have low coefficient of uniformity values, while well-graded soils have high values. Gap-graded soils will have a coefficient of curvature value either less than 1 or greater than 3. The following equations were used to determine the coefficients of uniformity and curvature:

$$C_u = \frac{D_{60}}{D_{10}} \quad (1)$$

$$C_c = \frac{(D_{30})^2}{D_{10} * D_{60}} \quad (2)$$

where:

C_u = coefficient of uniformity
C_c = coefficient of curvature
D_{10} = the grain size that corresponds to 10% passing
D_{30} = the grain size that corresponds to 30% passing
D_{60} = the grain size that corresponds to 60% passing

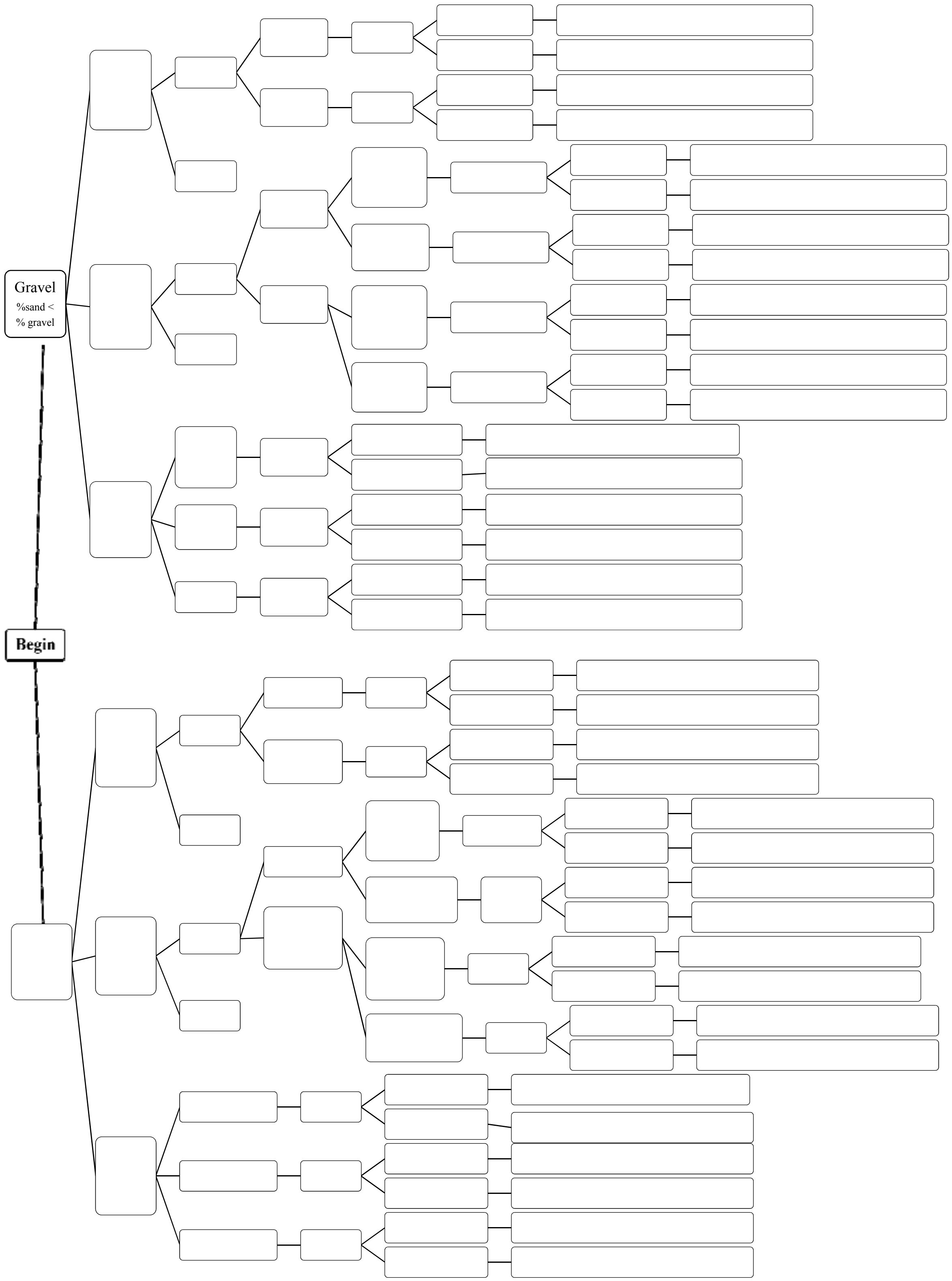


Figure 2: Unified Soil Classification System, Coarse-Grained Soils

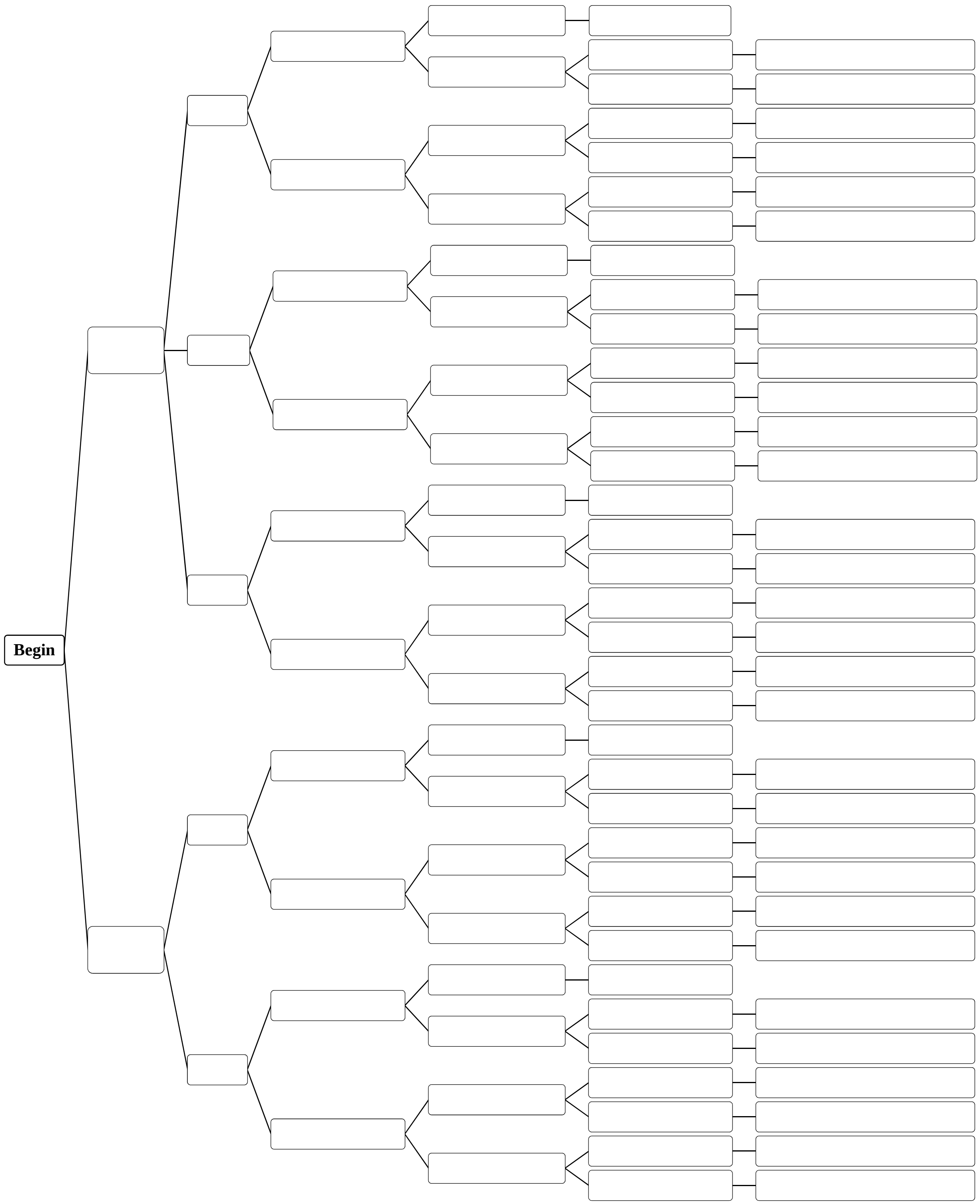


Figure 3: Unified Soil Classification System, Fine-Grained Soils

3.7 California Bearing Ratio

The California Bearing Ratio (CBR) is a measure of the shear strength of soil. The CBR tests were conducting according to AASHTO T193-93. The material for the bearing ratio and soaked bearing ratio tests was prepared at optimum moisture content. The samples were compacted according to AASHTO T180-93, the same procedure used for a modified Proctor test. Three specimens were compacted and tested for both the unsoaked and soaked tests and an average bearing ratio was computed. The soaked specimens were immersed in water for 96 hours with a 10-pound surcharge applied.

After testing, the corrected load values were determined for each sample at 0.10-inch and 0.20-inch penetration. The CBR values were calculated using the following equations:

$$\mathrm{CBR} = \frac{\text{Corrected Load Value at 0.10"}}{\text{1,000 psi}} * 100 \qquad (3)$$

$$\mathrm{CBR} = \frac{\text{Corrected Load Value at 0.20"}}{\text{1,000 psi}} * 100 \qquad (4)$$

The CBR value is generally selected at 0.10-inch penetration. If the ratio at 0.20-inch was greater than the one at 0.10-inch, the test was rerun. If the rerun test produced similar results, the ratio at 0.20-inch was reported.

3.8 Resilient Modulus Test

The resilient modulus (M_r) is an estimate of the elastic modulus of a material at a given stress state. Mathematically it is the ratio of the applied repeated deviator axial stress to the resulting recoverable axial strain[5]. The purpose of the resilient modulus test is to determine the nonlinear modulus properties for soils and base materials in a condition that simulates the actual response of the soils to applied wheel loads[2]. Resilient modulus is a required input to the structural response computation models in the MEPDG.

The resilient modulus parameter has been widely used to characterize unbound materials in pavement design because it can be used in mechanistic analyses of multi-layer pavement systems to predict pavement failure modes. The resilient modulus is obtained from laboratory repeated load resilient modulus tests, analysis or back calculation of non-destructive test (NDT) data, or correlations with other physical properties of the materials.

A Level 1 input for resilient modulus requires lab testing. The test is similar to the standard triaxial compression test, except that the vertical stress is cycled at several levels to model wheel load intensity and duration typically encountered in pavements. A Level 2 design would use general correlations that describe the relationship between soil strength properties and resilient modulus. The relationships could be direct or indirect. A Level 3 design simply uses a table for resilient modulus values. Table 2 provides the estimated resilient modulus values recommended by the MEPDG. However, caution should be used when utilizing Table 2 because the designer must select the resilient modulus value that represents the entire pavement foundation. For example, the MEPDG reports that if an A-1-a subgrade is truly semi-infinite (20 ft thick or more) then the use of a 40,000 psi M_r value may be justified[2]. Otherwise, a value from Table 2 may inaccurately estimate the stiffness and strength characteristics of the subgrade system.

Table 2: Typical M_r Values[2]

Material Classification	M_r Range (psi)	Typical M_r (psi)
A-1-a	38,500 - 42,000	40,000
A-1-b	35,500 - 40,000	28,000
A-2-4	28,000 - 37,500	32,000
A-2-5	24,000 - 33,000	28,000
A-2-6	21,500 - 28,000	26,000
A-3	24,500 - 35,500	29,000
A-4	21,500 - 29,000	24,000
A-5	17,000 - 25,500	20,000
A-6	13,500 - 24,000	17,000
A-7-5	8,000 - 17,500	12,000
A-7-6	5,000 - 13,500	8,000
CH	5,000 - 13,500	8,000
MH	8,000 - 17,500	11,500
CL	13,500 - 24,000	17,000
ML	17,000 - 25,500	20,000
SW	28,000 - 37,500	32,000
SP	24,000 - 33,000	28,000
SW-SC	21,500 - 31,000	25,500
SW-SM	24,000 - 33,000	28,000
SP-SC	21,500 - 31,000	25,500
SP-SM	24,000 - 33,000	28,000
SC	21,500 - 28,000	24,000
SM	28,000 - 37,500	32,000
GW	39,500 - 42,000	41,000
GP	35,500 - 40,000	38,000
GW-GC	28,000 - 40,000	34,500
GW-GM	35,500 - 40,500	38,500
GP-GC	28,000 - 39,000	34,000
GP-GM	31,000 - 40,000	36,000
GC	24,000 - 37,500	31,000
GM	33,000 - 42,000	38,500

The repeated load resilient modulus test was conducted for this study. Many constitutive models are available to calculate or predict the resilient modulus of base and subgrade material utilized the laboratory testing data. The model recommended by the MEPDG is:

$$M_r = k_1 \cdot Pa \cdot \left[\frac{\theta}{Pa}\right]^{k_2} \cdot \left[\frac{\tau_{oct}}{Pa} + 1\right]^{k_3} \quad (5)$$

where:

θ = bulk stress = $\sigma_1 + \sigma_2 + \sigma_3 = \sigma_d + 3\sigma_3$
σ_1 = major principal stress
σ_2 = intermediate principal stress = σ_3 for tests on cylindrical samples
σ_3 = minor principal stress (confining pressure)
σ_d = deviator (cyclic) stress
τ_{oct} = octahedral shear stress

$$= \frac{1}{3}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2} = \frac{\sqrt{2}}{3}\sigma_d \quad (6)$$

Pa = normalizing stress (atmospheric pressure)
k_1, k_2, k_3 = regression coefficients

The regression coefficients are determined for each test specimen using standard multi-variable regression and the multiple correlation coefficients should ideally exceed 0.90. The coefficient k_1 is proportional to Young's modulus and is therefore a positive number since the resilient modulus is never negative. The coefficient k_2 is also positive because an increase in bulk stress should stiffen the material. Increasing the shear stress usually softens the material; thus, k_3 is generally negative[2,6]. The MEPDG software requires the inputs of k_1, k_2, and k_3 for Level 1 design and not an actual resilient modulus value.

The resilient modulus testing was performed in accordance with AASHTO T307-99 (2003) [7]. The test consisted of applying a repeated axial cyclic stress for 0.1 second over a cycle of 1.0 second. All tests were conducted using a haversine-shaped load pulse. The specimen was also subjected to a static-confining stress. The deformation of the sample was measured by recording the movement of the lower platen. Each test consisted of a preconditioning phase and 15 testing sequences. One hundred repetitions of the cyclic axial stress were applied for each testing sequence. The last five cycles were recorded for each sequence and averaged to obtain a resilient modulus value for the sequence.

The SPT was used to conduct the tests on reconstituted samples. Three resilient modulus tests were performed for each soil type. If the coefficient of variability between the three samples exceeded 25%, additional tests were performed to obtain higher confidence in the data.

3.8.1 Base Material Resilient Modulus Test

Base material samples were molded in the laboratory at optimum moisture content and maximum dry density. The gradation of the base materials indicated that samples were categorized as material Type-1 in AASHTO T307 (less than 70% passing the No. 10 sieve, less than 20% passing the No. 200 sieve, and a PI of 10 or less). A 4-inch diameter sample size was chosen. Although AASHTO T307 requires a height to diameter ratio of 2:1, the SPT machine limits the sample height to 6-inches.

The required mass of dry soil was calculated using the expected volume of the compacted sample and the maximum dry density of the soil. The mass of water required was calculated using the mass of dry soil and the optimum moisture content. The material was first sieved through the ¾-inch sieve and the required amount of water was added to the dry soil and thoroughly mixed. The mixture was placed inside two plastic bags and sealed for 16 to 48 hours. The mass of the bags with the soil mixture was measured to ensure no loss of moisture during the curing period. Before compaction, three small samples were taken to confirm the moisture content of the sample.

A 4-inch diameter sample was vibratory compacted in a split-mold as shown in Figure 4. Compaction was accomplished in five equal lifts of material. Between each lift, the top surface of the lift was scarified to an approximate depth of 3-mm. After compaction, the mold was split, the sample was placed between porous stones and platens, and a latex membrane was applied to the sample. The membrane was sealed to the platens using O-rings to obtain an airtight seal. The sample was loaded into the SPT machine as shown in Figures 5a and 5b.

Figure 4: Split Mold with Vibratory Compactor for Base Sample Preparation

(a) (b)

Figure 5: M_r Specimen Assembled in SPT Machine Prior to Testing

During the test, the samples were subjected to fifteen loading sequences as shown in Table 3, using a haversine-shaped load pulse. Before the testing sequences began, the specimen was conditioned (sequence 0) to eliminate the effects of the interval between compaction and loading and to eliminate the effect of initial loading versus reloading. The conditioning phase also helped minimize the effect of initially imperfect contact between the platens and the specimen[8]. If the total vertical permanent strain reached 5% during conditioning, the testing was ended and a new sample fabricated.

Table 3: Testing Sequences for Base Materials

Sequence	Confining Pressure, σ_3 (psi)	Max Axial Stress, σ_{max} (psi)	Cyclic Stress, σ_{cyclic} (psi)	Constant Stress, $0.1\sigma_{max}$ (psi)	# of Load Applications
0	15	15	13.5	1.5	500-1000
1	3	3	2.7	0.3	100
2	3	6	5.4	0.6	100
3	3	9	8.1	0.9	100
4	5	5	4.5	0.5	100
5	5	10	9.0	1.0	100
6	5	15	13.5	1.5	100
7	10	10	9.0	1.0	100
8	10	20	18.0	2.0	100
9	10	30	27.0	3.0	100
10	15	10	9.0	1.0	100
11	15	15	13.5	1.5	100
12	15	30	27.0	3.0	100
13	20	15	13.5	1.5	100
14	20	20	18.0	2.0	100
15	20	40	36.0	4.0	100

To simulate drained conditions, the drainage valves to the specimen remained open to atmospheric pressure throughout the resilient modulus testing. As discussed earlier, the software recorded the last five pulses of each sequence and averaged these values to obtain a resilient modulus value for each sequence.

3.8.2 Subgrade Material Resilient Modulus Test

The subgrade samples were molded in the laboratory at optimum moisture content and maximum dry density. The gradation of the subgrade materials indicated that samples were categorized as material Type-2 (untreated soils not meeting the criteria for material Type-1). The sample preparation for the subgrade material followed the same procedure as the base material except for the method of compaction as specified by AASHTO T307 for Type-2 materials. A friable sample of the soil was pulverized with a rubber headed hammer to break up the clumps. The soil was sieved through the ¾-inch sieve. The soil water combination was mixed and cured in the same manner as the base material. A mold with a 3.937-inch (100-mm) internal diameter and a static compactor load frame were used to compact the test specimens as shown in Figure 6. The specimen was compacted in five equal lifts of soil with a final height of 6-inches (152.4-mm). The specimen was extruded from the mold and placed inside a membrane using the same technique employed with the base material.

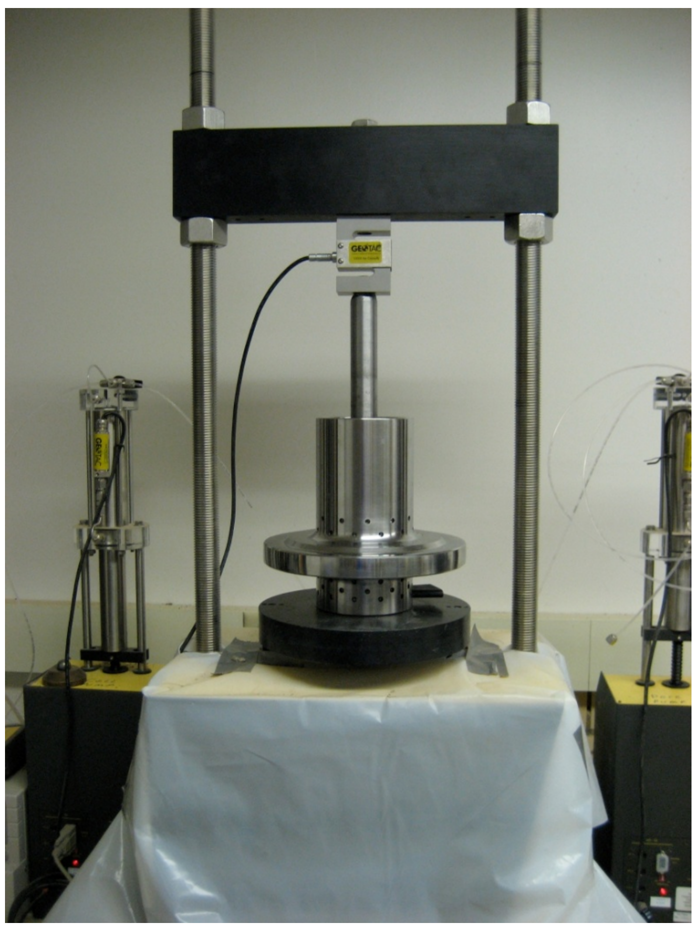


Figure 6: Assembly and Static Compactor for Subgrade Sample Preparation

The subgrade specimens were subjected to fifteen loading sequences as shown in Table 4. The sequences for subgrade materials differ from base materials in that the confining pressures are reduced over the series of the test for subgrade materials, while it is increased for base materials.

Table 4: Testing Sequences for Subgrade Materials

Sequence	Confining Pressure, σ_3 (psi)	Max Axial Stress, σ_{max} (psi)	Cyclic Stress, σ_{cyclic} (psi)	Constant Stress, $0.1\sigma_{max}$ (psi)	# of Load Applications
0	6	4	3.6	0.4	500-1000
1	6	2	1.8	0.2	100
2	6	4	3.6	0.4	100
3	6	6	5.4	0.6	100
4	6	8	7.2	0.8	100
5	6	10	9.0	1.0	100
6	4	2	1.8	0.2	100
7	4	4	3.6	0.4	100
8	4	6	5.4	0.6	100
9	4	8	7.2	0.8	100
10	4	10	9.0	1.0	100
11	2	2	1.8	0.2	100
12	2	4	3.6	0.4	100
13	2	6	5.4	0.6	100
14	2	8	7.2	0.8	100
15	2	10	9.0	1.0	100

3.9 Dynamic Modulus Test

The time-temperature dependent dynamic modulus (E*) is the primary stiffness property of interest for asphalt materials[2]. Dynamic modulus values can be used to characterize asphalt concrete for pavement thickness design and performance analysis. Level 1 designs require laboratory tests for dynamic modulus, binder complex shear modulus (G*) and phase angle testing on the binder. For Level 2 designs, the E* predictive equation is used instead of laboratory testing. Testing for G* and phase angle are still required because the dynamic modulus equation is combined with specific laboratory test data from the binder grade being considered for the use in the pavement to derive the E* values over the design life. There are no laboratory testing requirements for Level 3 designs. Instead, the E* predictive equation and typical values provided by the MEPDG software based on performance grade (PG), viscosity, or penetration grade of the binder are used.

Master curves are constructed using the principle of time-temperature superposition. First, a standard reference temperature is selected and data at various temperatures are shifted with respect to time until the curves merge into a single smooth function. The master curve of modulus as a function of time formed in this manner describes the time dependency of the material. The amount of shifting at each temperature required to form the master curve describes the temperature dependency of the material. Thus, both the master curve and the shift factors are needed for a complete description of the rate and temperature effects.

Samples were prepared and tested according to AASHTO TP 62-07[7], and NCHRP Project 9-29[9]. To prepare the samples, HMA obtained from SDDOT was heated at 110°C to 135°C long enough to make the material pliable, which was typically one to two hours. Approximately 1000-grams of material were removed from the oven to perform a maximum theoretical specific gravity test (the HMA density excluding air voids). This test was conducted according to the CoreLok Operator's Guide[11] developed by InstroTek Incorporated. The 1000-gram sample was broken apart, cooled, placed inside vacuum bags, and sealed within the CoreLok vacuum chamber as shown in Figure 7. The bags were cut open under water and a submerged weight was recorded. The weight of the sample in air and the submerged weight were used to calculate the maximum specific gravity, G_{mm}, of the asphalt mixture.

Figure 7: Maximum Theoretical Specific Gravity Sample in CoreLok Device

The target specimen size was 7-inches (177.8-mm) in height, 5.9-inches (150-mm) in diameter with an air void content of 7% ± 0.5%. The weight of material required for compaction was computed by the following equation:

$$\text{Weight} = \frac{G_{mm} \cdot \%G_{mm} \cdot \text{Volume}_{specimen} \cdot \gamma_{water}}{\text{Correction Factor}} \qquad (7)$$

where:

G_{mm} = maximum theoretical specific gravity

$\%G_{mm}$ = 93% (to obtain 7% air voids)

$\text{Volume}_{specimen} = {}^{\pi}/_{4}\,(\text{Diameter}^2)(\text{Height})$

γ_{water} = unit weight of water

The correction factor was computed as:

$$\text{Correction Factor} = \frac{\text{Bulk Specific Gravity (measured)}}{\text{Bulk Specific Gravity (estimated based on sample height and weight)}} \qquad (8)$$

The material and compaction mold were heated to compaction temperature, 150°C ± 6°C, for two hours. Compaction temperature for the WMA was approximately 130°C. Specimens were prepared by gyratory compaction according to AASHTO T312-04[7]. Figure 8 shows the loose HMA in the gyratory mold before compaction.

Figure 8: HMA in Gyratory Compaction Mold

After the sample cooled, a 4-inch diameter specimen was cored from the middle of the compacted sample as shown in Figure 9. Each end of the sample was trimmed by approximately 0.5-inch, as shown in Figure 10, so that the final specimen height was 6-inches.

Figure 9: HMA Coring

Figure 10: Sawing HMA Sample

After the sample had surface dried, a bulk specific gravity test was performed using the CoreLok[11]. The air void content was computed using Equation 9. The submerged HMA sample during a bulk specific gravity test is shown in Figure 11.

$$\%AV = 100 \cdot \frac{G_{mm} - G_{mb}}{G_{mm}} \quad (9)$$

where:

G_{mm} = maximum theoretical specific gravity
G_{mb} = bulk specific gravity

Figure 11: Bulk Specific Gravity, Submerged Weight of HMA Sample

The sample was air dried completely for approximately two days. After drying, the sample was subjected to a number of critical measurements. Sample specifications are outlined in Table 5.

Table 5: HMA Sample Specifications per NCHRP 9-29

Item	Specification
Average Diameter from 6 measurements	100 mm to 104 mm
Standard Deviation of Diameter	1.0 mm
Height	147.5 to 152.5
End Flatness	0.3 mm
End Parallelism	1 degree

The gage point glue fixture was used to glue the gage points onto the HMA specimens for the magnetic extensometers as shown in Figure 12. A quick setting epoxy was used to glue the gage points to the specimen as shown in Figure 13.

Figure 12: Gage Point Glue Fixture

Figure 13: Gage Points Placed on HMA Sample

Once the gage points were affixed, the samples were temperature conditioned according to Table 6[10] prior to dynamic modulus testing.

Table 6: Temperature Conditioning

Specimen Temperature (°C)	Time from Room Temperature (hrs)	Time from Previous Test (hrs)
4.4	Overnight	Overnight
21.1	1	3
37.8	2	2
54.0	3	1

Friction-reducing end treatments made from Teflon were placed on the top and bottom of the sample and the sample was placed between two platens. The sample was placed in the SPT and extensometers were attached as shown in Figure 14.

Figure 14: Dynamic Modulus Specimen Assembled in SPT Machine

The test consisted of applying a haversine axial compressive stress to the HMA specimen at a given temperature and loading frequency as given in Table 7[10]. The applied dynamic stress and the resulting recoverable axial strain response of the HMA specimen was measured and used to calculate the dynamic modulus and the phase angle.

Table 7: Dynamic Modulus Loading and Temperature Sequences

Temperature (^oC)	Typical Dynamic Stress Level (psi)
4.4	100-200
21.1	15-100
37.8	20-50
54.0	5-10
Frequency* (Hz)	**Number of Cycles**
25**	200
25	200
10	200
5	100
1	20
0.5	15
0.1	15

* All 7 frequencies run for each temperature
** Preconditioning sequence

The test series was conducted at 4.4, 21.1, 37.8, and 54.0^{o}C and at loading frequencies of 0.1, 0.5, 1, 5, 10, and 25 Hz at each temperature. Testing began at the coldest temperature and the highest frequency. AASHTO TP 62 mandated a preconditioning phase that consisted of 200 cycles at 25 Hz. All samples were unconfined during testing. A contact load equal to 5% of the dynamic load was applied to the sample prior to the application of the haversine loading. The dynamic stress was adjusted to obtain axial strains between 50 and 150 microstrain. The applied dynamic stress is a function of the sample stiffness; thus a higher stress was required at colder temperatures to reach the target axial strains.

Vertical deformation measurements were performed with two Epsilon Strain Gaged Extensometers (model 3909 Axial Asphalt Extensometer) placed 180^o apart on the sample. The extensometers have independent outputs capable of measuring specimen deformations in two locations. Magnets at each end of the extensometer snap in place onto steel gage points glued to the test sample. During the course of the dynamic modulus testing, if the cumulative unrecovered permanent strain of the sample exceeded 1500 microstrain, the sample was discarded and a new sample was used for the remaining temperatures[10].

For each frequency, 500 data points were recorded over 10 complete loading cycles. Data included vertical displacement, vertical load, extensometer readings, and the command load. Displacement data was corrected for drift by determining the average slope of local minima and maxima in the data and subtracting this slope from the original data. This eliminated mechanical and electrical drift from the analysis and resulted in more accurate analyses. Both load and displacement data were centered prior to analysis by subtracting the applicable average value.

After testing, the data quality indicators were reviewed for each test frequency and compared to the recommended values listed in Table 8[9].

Table 8: Maximum Values for Data Quality Indicators

Data Quality Indicator	Allowable Maximum Value
Load Standard Error	10%
Deformation Standard Error	10%
Load Drift	3%
Deformation Drift	400%
Deformation Uniformity	20%
Phase Uniformity	3^o

The dynamic modulus is the average result obtained from three test specimens[9].

3.10 Repeated Load Triaxial Test

The repeated load triaxial test was conducted to develop coefficients for the MEPDG permanent deformation model. The repeated load triaxial test applies a repeated load of fixed magnitude and cycle duration to a test specimen prepared in the same way as the specimens for dynamic modulus tests. In order to develop the MEPDG permanent deformation model, samples need to be tested at three temperatures. Samples were temperature conditioned for one hour prior to testing. Testing stress conditions were assumed to be representative of the mixture at 2-inches below the pavement surface. However, the maximum confining pressure of the SPT is 25 psi and thus limited the magnitude of the confining stress. However, the purpose of the repeated load triaxial test is to cause the specimen to undergo tertiary flow, and thus the combination of confining stress and deviator stress is unrestricted. The testing conditions are outlined in Table 9 and picture of a sample during testing is shown in Figure 15.

Table 9: Repeated Load Triaxial Test Stress Conditions

Temperature ^oF (^oC)	Confining Pressure		Deviator Stress	
	kPa	psi	kPa	psi
93 (34)	170	25	655	95
106 (41)	170	25	550	80
125 (52)	170	25	520	75

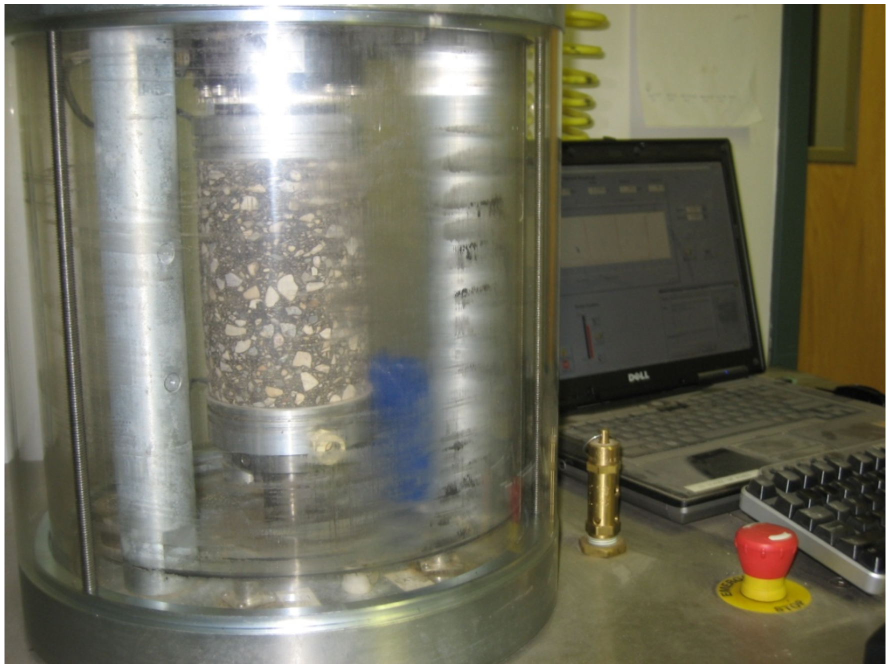


Figure 15: Repeated Load Triaxial Test Setup

The Flow Number testing module was used on the SPT to perform the repeated load triaxial tests. The deviator stress was applied every 0.9 seconds and was maintained for 0.1 seconds. Tests were run until the sample reached 5% strain which was assumed to be failure. This took anywhere from 300 to 30,000 pulses.

The constitutive equation used in the MEPDG to predict rutting is:

$$\frac{p}{r} = 10^{a_1} \cdot N^{a_2} \cdot T^{a_3} \tag{10}$$

where:

ε_p = accumulated plastic strain at N repetitions of load
ε_r = resilient strain of asphalt material
N = number of load repetitions
T = temperature (^{o}F)
a_i = non-linear regression coefficients

This relationship is based upon a field calibrated statistical analysis of laboratory repeated load tests[2]. The regression coefficients were determined for each test set using standard regression. A test set consisted of one sample tested at 34 degrees Celsius, one sample tested at 41 degrees Celsius, and one sample tested at 52 degrees Celsius. To ensure dependable results, three samples of each mix should be tested at each temperature requiring a minimum of nine samples of each mix.

CHAPTER 4 TASK 4 RESULTS

4.1 Introduction

The results in this chapter are from the materials testing of base and subgrade soils and HMA from two sites: US Highway 281 and US Highway 212 as shown in Figure 16. Samples of subgrade and base materials were obtained from both sites. HMA samples were obtained from US Highway 281 only. Concurrent tests were conducted on the US Highway 281 HMA material by the Asphalt Research Consortium (ARC) at the University of Nevada-Reno (UNR) in order evaluate SDSMT's testing procedures and calibrate the new SPT machine. UNR used an InstroTek SPT machine developed by IPC Global of Melbourne, Australia to conduct the dynamic modulus tests.

Figure 16: Task 4 Sampling Locations for Pavement Materials

4.2 Soil Test Results

Table 10 provides the results of the particle size analysis testing conducted on the four soil materials. The gradations of the base materials are illustrated in Figure 17 and the subgrade materials in Figure 18.

Table 10: Task 4 Particle Size Distributions

Sieve Size		US281 Base % Passing	US212 Base % Passing	US281 Subgrade % Passing	US212 Subgrade % Passing
No.	mm				
1.25"	31.75	100	100	100	100
1"	25.4	98.1	93.9	100	100
3/4"	19.1	90.0	86.5	100	100
1/2"	12.7	71.1	77.3	98.5	99.4
3/8"	9.51	59.6	70.1	97.9	99.4
#4	4.76	45.6	52.8	95.9	98.5
#8	2.36	37.7	41.1	93.6	97.2
#10	2	35.4	38.0	92.9	96.8
#16	1.19	30.0	31.0	90.9	95.4
#30	0.595	19.4	21.3	87.3	92.4
#40	0.42	13.5	16.7	84.8	89.9
#50	0.297	9.5	13.1	82.0	86.6
#100	0.149	5.7	8.2	74.1	76.0
#200	0.074	4.3	5.8	66.0	63.6

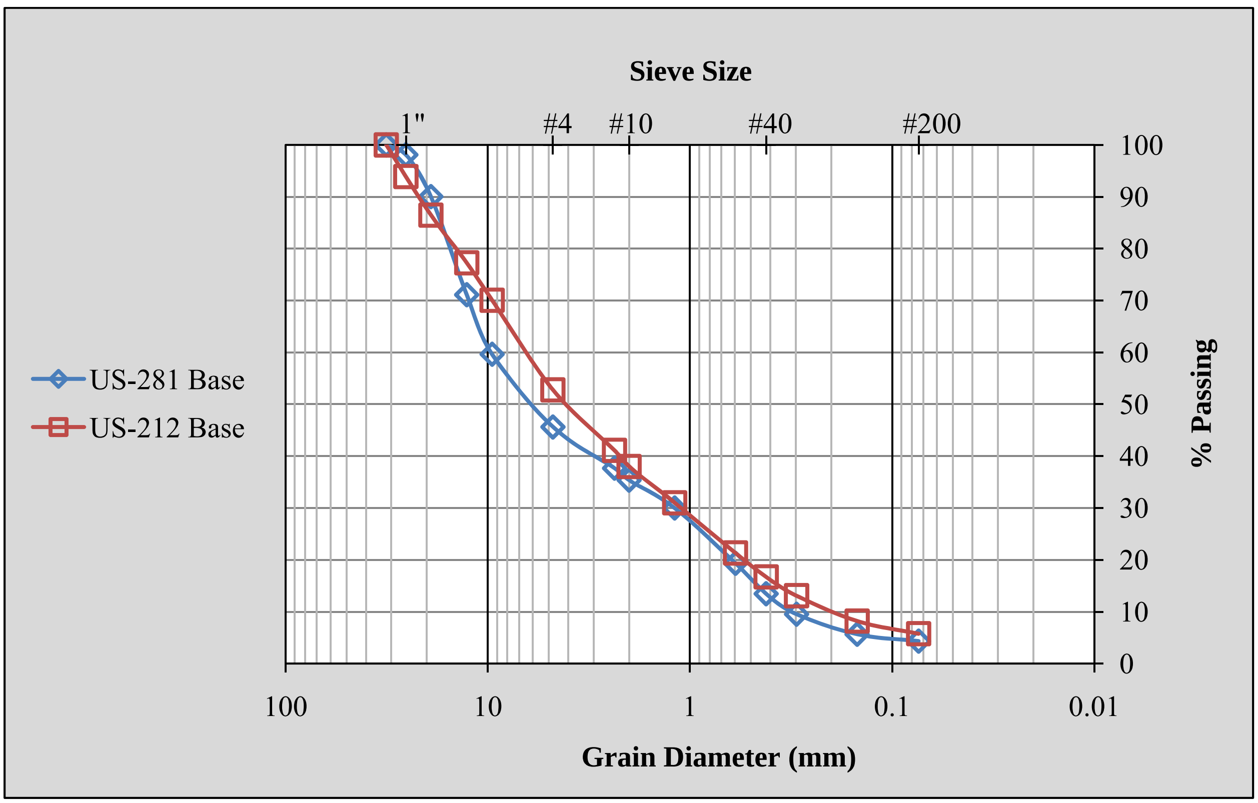


Figure 17: Task 4 Base Material Gradations

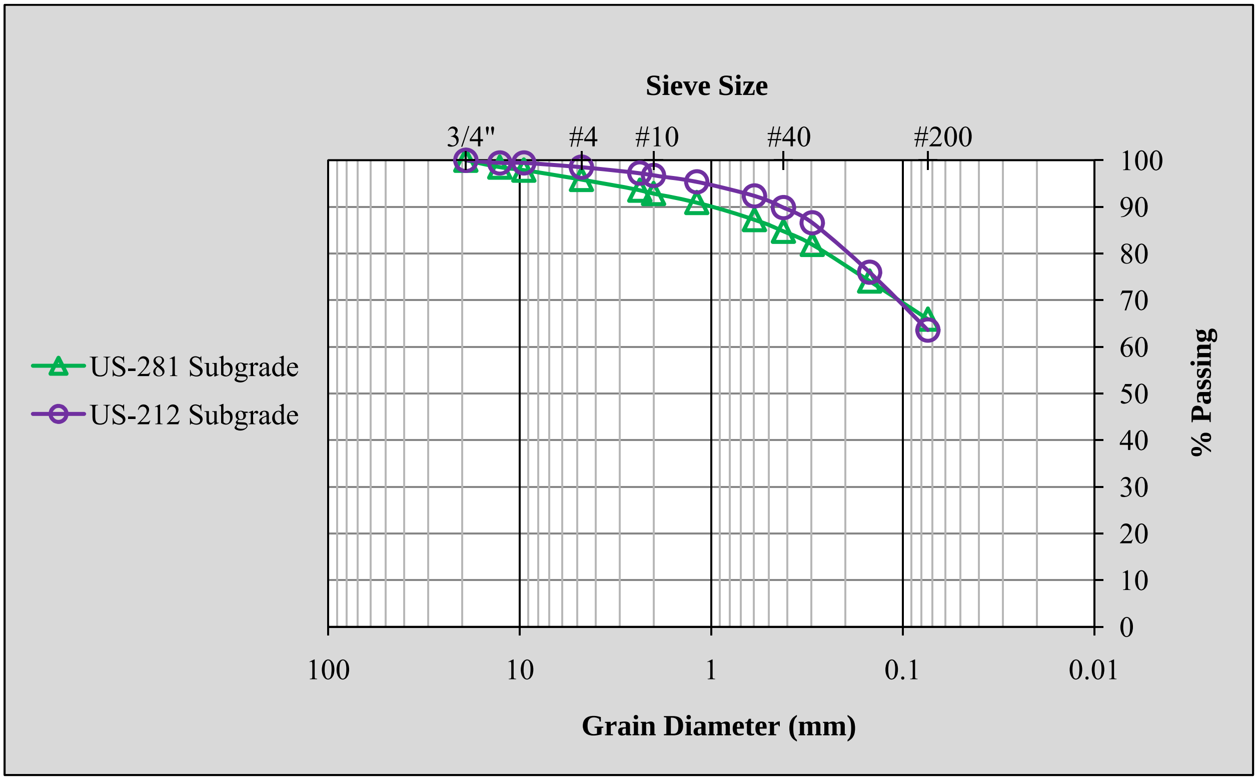


Figure 18: Task 4 Subgrade Material Gradations

The liquid limit test results for the subgrade materials are shown in Figures 19 and 20.

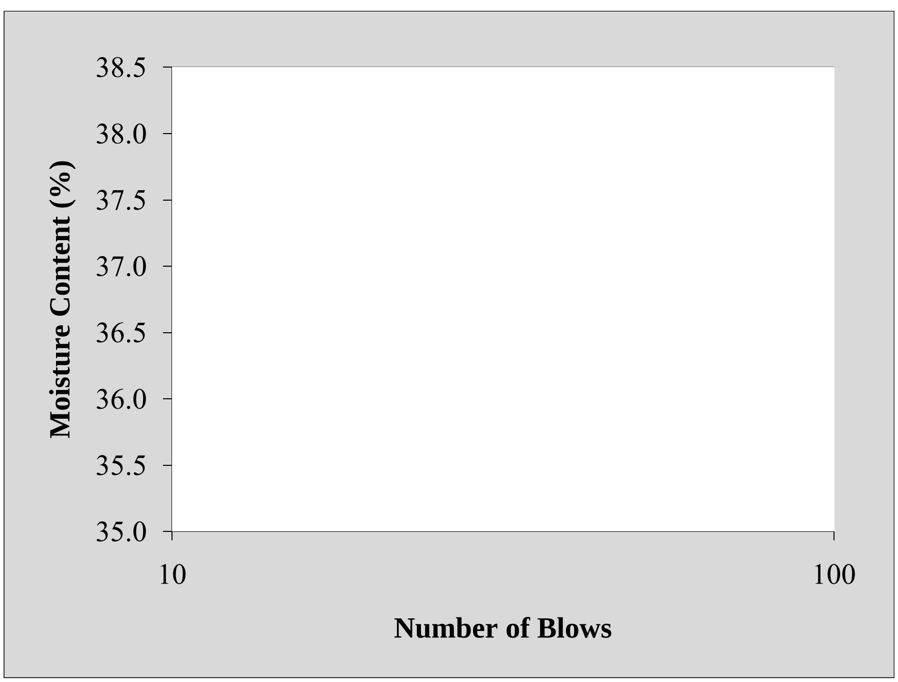


Figure 19: Liquid Limit Test Results, US281 Subgrade

The liquid limit for the US281 subgrade material was 37 and the plastic limit was 16. This corresponded to a PI of 21.

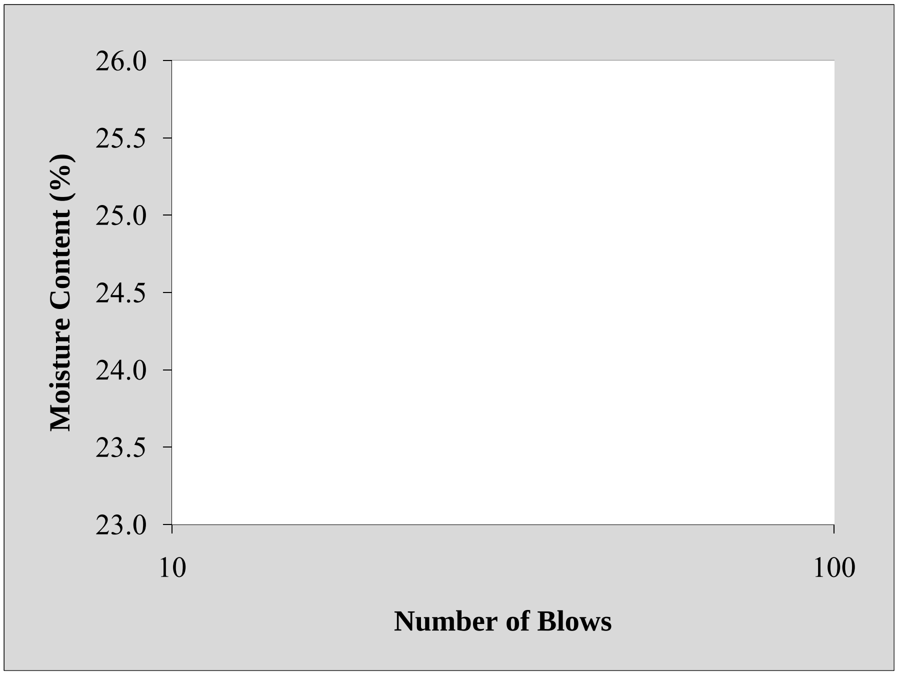


Figure 20: Liquid Limit Test Results, US212 Subgrade

The liquid limit for the US212 subgrade material was 25 and the plastic limit was 15. This corresponded to a PI of 10.

The moisture density relationship test results for the base and subgrade materials are illustrated in Figures 21 through 24.

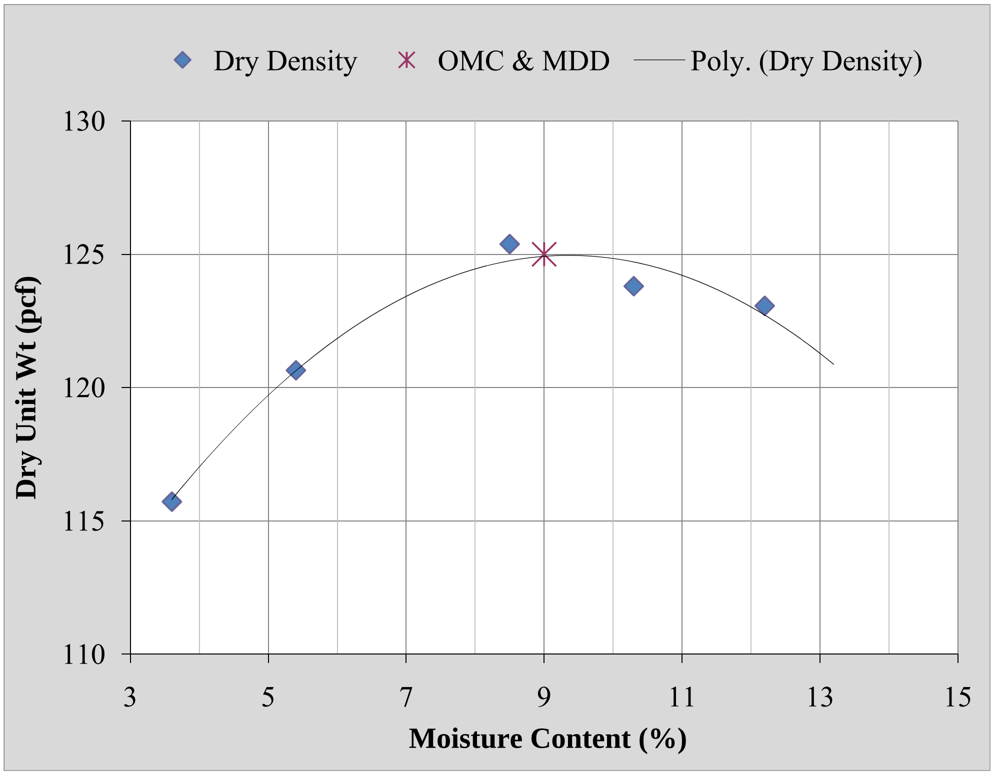


Figure 21: Dry Density vs. Moisture Content, US281 Base

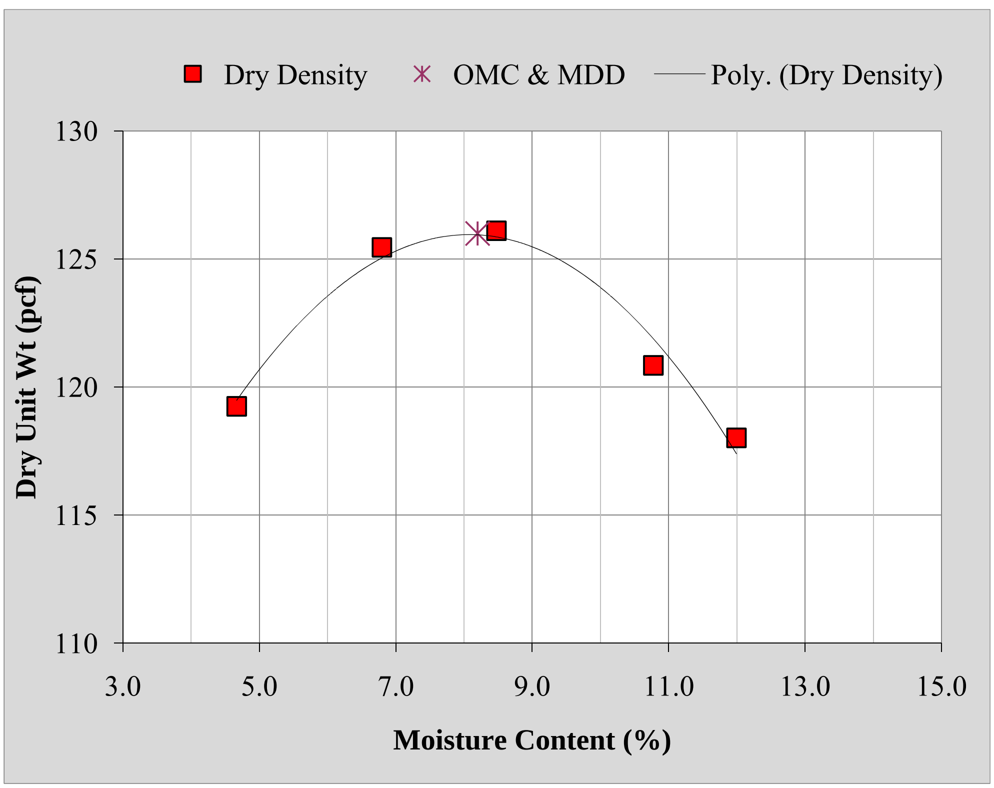


Figure 22: Dry Density vs. Moisture Content, US212 Base

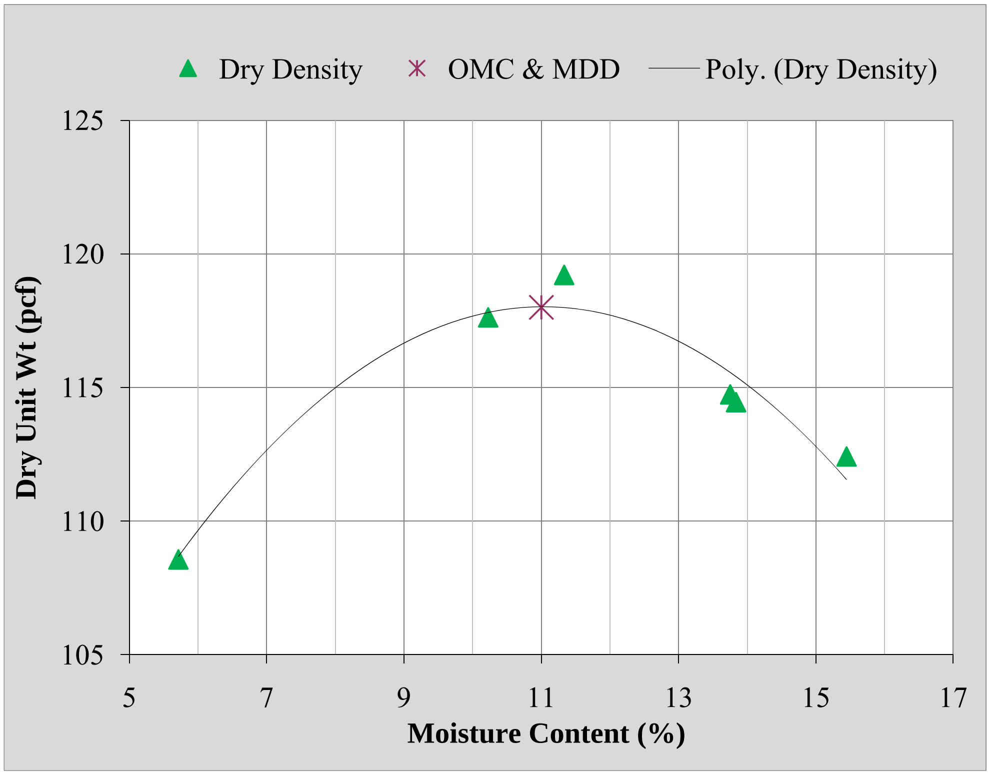


Figure 23: Dry Density vs. Moisture Content, US281 Subgrade

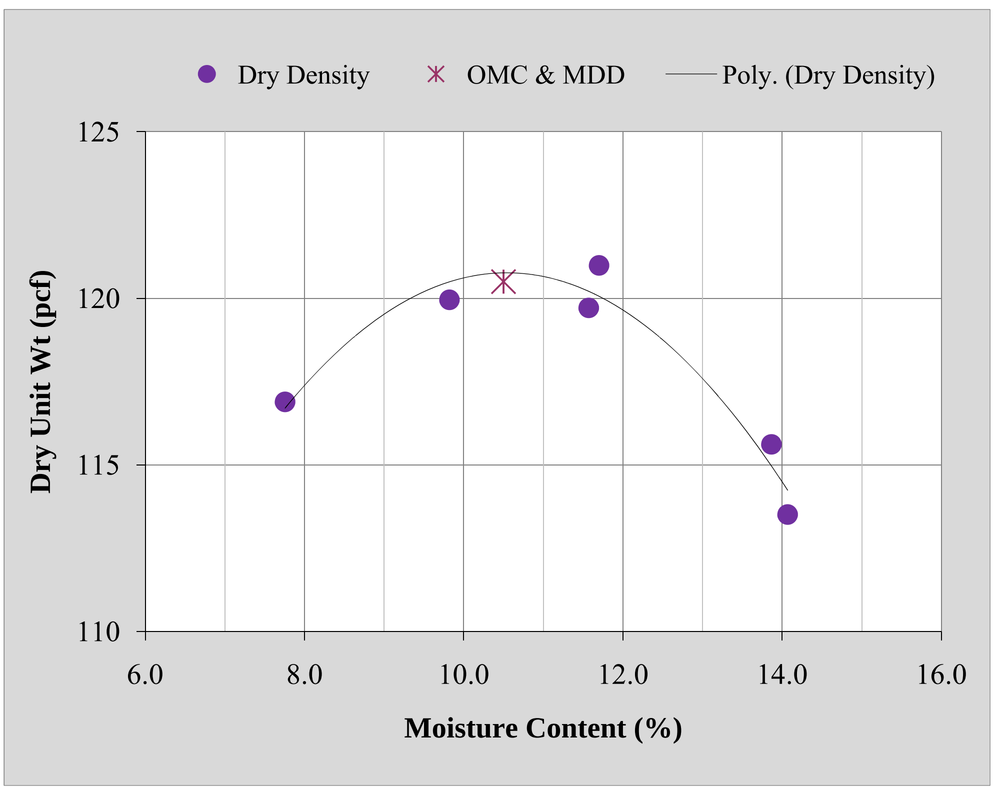


Figure 24: Dry Density vs. Moisture Content, US212 Subgrade

Tables 11 through 14 provide a summary of the classifications of soils used in Task 4.

Table 11: AASHTO & USCS Classification Criteria, Base Material

Sample	AASHTO			USCS				
	% Passing #10	% Passing #40	% Passing #200	% Gravel	% Sand	% Silt & Clay	Cu	Cc
US281 Base	35	14	4	54	41	4	32	0.5
US212 Base	38	17	6	47	47	6	25	1.4

Table 12: Soil Classification Summary, Base Material

Base Specimen	Classification		MDD (lb/ft^3)	OMC (%)
	AASHTO	USCS		
US281	A-1-a	GP poorly graded gravel with sand	125	9.0
US212	A-1-a	SW-SM well graded sand with silt and gravel	126	8.2

Table 13: AASHTO & USCS Classification Criteria, Subgrade Material

Sample	AASHTO			USCS		
	% Passing #10	% Passing #40	% Passing #200	% Gravel	% Sand	% Silt & Clay
US281 Subgrade	93	85	66	4	30	66
US212 Subgrade	97	90	64	1	35	64

Table 14: Soil Classification Summary, Subgrade Material

Subgrade Specimen	Classification		LL (%)	PL (%)	PI (%)	MDD (lb/ft^3)	OMC (%)
	AASHTO	USCS					
US281	A-6	CL sandy lean clay	37	16	21	118	11
US212	A-4	CL sandy lean clay	25	15	10	120.5	10.5

4.3 Resilient Modulus Test Results

4.3.1 Base Material

The resilient modulus values for US281 and US212 base materials are contained in Tables 15 through 21.

Table 15: Average M_r Values for Each Sequence, US281 Base Sample 1

Average Values					
Sequence	Confining Pressure, σ_3 (psi)	Deviator (cyclic) Stress, σ_d (psi)	Bulk Stress, θ (psi)	Resilient Strain (in/in)	M_r, Resilient Modulus (psi)
1	2.8	3.4	11.8	0.00034	9,826
2	3.0	6.4	15.4	0.00051	12,646
3	2.8	9.5	17.9	0.00073	12,991
4	4.9	5.4	20.1	0.00035	15,607
5	5.1	10.6	25.9	0.00058	18,284
6	4.9	15.7	30.4	0.00086	18,253
7	10.0	10.5	40.5	0.00041	25,458
8	9.8	20.4	49.8	0.00073	28,038
9	10.0	29.7	59.7	0.00103	28,885
10	15.0	10.8	55.8	0.00035	30,531
11	14.9	15.4	60.1	0.00048	31,755
12	15.0	30.9	75.9	0.00085	36,257
13	19.9	15.8	75.5	0.00042	37,744
14	19.9	20.6	80.3	0.00050	41,032
15	20.0	41.4	101.4	0.00096	42,948

Table 16: Average M_r Values for Each Sequence, US281 Base Sample 2

Average Values					
Sequence	Confining Pressure, σ_3 (psi)	Deviator (cyclic) Stress, σ_d (psi)	Bulk Stress, θ (psi)	Resilient Strain (in/in)	M_r, Resilient Modulus (psi)
1	3.1	3.4	12.7	0.00039	8,662
2	2.9	6.4	15.1	0.00065	9,741
3	3.0	9.7	18.7	0.00085	11,364
4	4.9	5.4	20.1	0.00042	13,076
5	4.7	10.7	24.8	0.00072	14,841
6	4.9	15.6	30.3	0.00105	14,828
7	9.7	10.5	39.6	0.00050	21,283
8	9.9	20.8	50.5	0.00090	23,063
9	10.1	29.7	60.0	0.00127	23,275
10	14.9	10.4	55.1	0.00040	26,140
11	15.0	15.5	60.5	0.00055	28,177
12	15.1	30.2	75.5	0.00098	30,721
13	20.3	15.0	75.9	0.00044	33,816
14	19.8	20.7	80.1	0.00056	37,216
15	19.9	39.7	99.4	0.00104	38,117

Table 17: Average M_r Values for Each Sequence, US281 Base Sample 3

Average Values					
Sequence	Confining Pressure, σ_3 (psi)	Deviator (cyclic) Stress, σ_d (psi)	Bulk Stress, θ (psi)	Resilient Strain (in/in)	M_r, Resilient Modulus (psi)
1	2.8	3.5	11.9	0.00039	9,064
2	2.9	6.2	14.9	0.00056	11,169
3	2.7	9.5	17.6	0.00073	13,040
4	4.8	5.2	19.6	0.00036	14,394
5	5.0	10.5	25.5	0.00063	16,732
6	4.8	15.5	29.9	0.00091	17,170
7	10.0	10.4	40.4	0.00042	25,080
8	9.8	20.2	49.6	0.00076	26,570
9	9.9	29.9	59.6	0.00111	27,024
10	14.9	10.4	55.1	0.00036	29,241
11	15.0	15.4	60.4	0.00051	30,470
12	15.1	30.2	75.5	0.00087	34,628
13	19.9	16.0	75.7	0.00043	37,003
14	19.9	20.5	80.2	0.00052	39,346
15	19.9	40.3	100.0	0.00096	41,995

Table 18: Average M_r Values for Each Sequence, US212 Base Sample 1

Average Values					
Sequence	Confining Pressure, σ_3 (psi)	Deviator (cyclic) Stress, σ_d (psi)	Bulk Stress, θ (psi)	Resilient Strain (in/in)	M_r, Resilient Modulus (psi)
1	3.0	2.9	11.9	0.00019	15,233
2	2.8	6.4	14.8	0.00038	16,607
3	3.0	9.5	18.5	0.00054	17,588
4	4.9	5.4	20.1	0.00025	21,323
5	4.7	10.5	24.6	0.00045	23,217
6	4.9	15.5	30.2	0.00065	23,964
7	10.2	10.7	41.3	0.00032	33,763
8	9.9	20.4	50.1	0.00059	34,720
9	10.0	29.9	59.9	0.00086	34,950
10	14.9	10.7	55.4	0.00029	37,106
11	15.0	15.6	60.6	0.00038	40,595
12	15.2	29.9	75.5	0.00071	42,222
13	19.8	15.8	75.2	0.00034	46,162
14	19.8	20.1	79.5	0.00043	47,341
15	19.8	39.9	99.3	0.00083	48,270

Table 19: Average M_r Values for Each Sequence, US212 Base Sample 2

Average Values					
Sequence	Confining Pressure, σ_3 (psi)	Deviator (cyclic) Stress, σ_d (psi)	Bulk Stress, θ (psi)	Resilient Strain (in/in)	M_r, Resilient Modulus (psi)
1	2.9	3.3	12.0	0.00023	14,294
2	3.1	6.6	15.9	0.00037	17,993
3	2.9	9.5	18.2	0.00052	18,404
4	4.8	5.4	19.8	0.00023	23,490
5	5.0	10.6	25.6	0.00044	23,898
6	4.8	15.4	29.8	0.00064	24,029
7	10.1	10.4	40.7	0.00033	31,298
8	9.8	20.1	49.5	0.00061	33,291
9	9.9	30.1	59.8	0.00089	33,617
10	14.9	10.4	55.1	0.00029	36,366
11	15.0	15.6	60.6	0.00041	37,893
12	15.1	30.5	75.8	0.00074	41,092
13	19.8	15.5	74.9	0.00035	44,488
14	19.8	19.9	79.3	0.00044	45,442
15	19.9	38.9	98.6	0.00081	48,081

Table 20: Average M_r Values for Each Sequence, US212 Base Sample 3

Average Values					
Sequence	Confining Pressure, σ_3 (psi)	Deviator (cyclic) Stress, σ_d (psi)	Bulk Stress, θ (psi)	Resilient Strain (in/in)	M_r, Resilient Modulus (psi)
1	2.8	3.5	11.9	0.00026	13,358
2	2.9	6.5	15.2	0.00039	16,474
3	3.1	9.6	18.9	0.00057	16,972
4	4.9	5.4	20.1	0.00026	20,541
5	5.1	10.7	26.0	0.00047	22,505
6	4.9	15.6	30.3	0.00066	23,479
7	9.8	10.4	39.8	0.00033	31,293
8	9.9	20.2	49.9	0.00061	33,271
9	10.1	30.4	60.7	0.00090	33,636
10	14.9	10.4	55.1	0.00029	36,423
11	14.8	15.5	59.9	0.00041	38,096
12	15.0	30.4	75.4	0.00074	41,100
13	20.3	15.5	76.4	0.00035	43,996
14	19.9	20.6	80.3	0.00045	45,363
15	20.2	39.6	100.2	0.00088	45,008

Table 21: Average M_r Values for Each Sequence, US212 Base Sample 4

Average Values					
Sequence	Confining Pressure, σ_3 (psi)	Deviator (cyclic) Stress, σ_d (psi)	Bulk Stress, θ (psi)	Resilient Strain (in/in)	M_r, Resilient Modulus (psi)
1	3.0	3.2	12.2	0.00023	13,930
2	2.8	6.5	14.9	0.00039	16,709
3	3.0	9.4	18.4	0.00047	20,276
4	4.9	5.2	19.9	0.00024	21,391
5	4.8	10.6	25.0	0.00044	23,946
6	5.0	15.5	30.5	0.00062	25,024
7	10.1	10.6	40.9	0.00032	32,747
8	9.8	20.3	49.7	0.00061	32,965
9	10.0	29.6	59.6	0.00084	35,377
10	14.9	10.4	55.1	0.00029	35,992
11	15.1	15.3	60.6	0.00040	37,936
12	14.9	30.0	74.7	0.00073	41,222
13	20.0	16.2	76.2	0.00036	44,625
14	20.1	20.8	81.1	0.00044	46,942
15	19.9	39.9	99.6	0.00087	45,890

Graphically, these results can be seen in Figures 25 through 28 where the resilient modulus was plotted with respect to sequence and bulk stress.

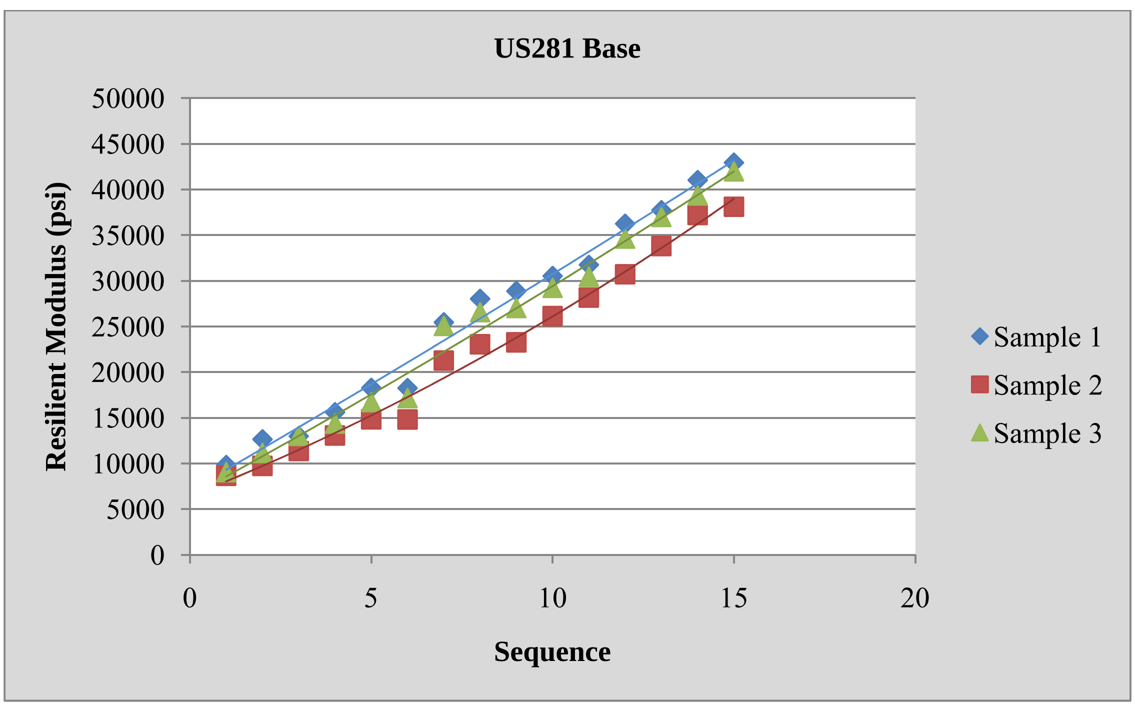


Figure 25: Resilient Modulus vs. Sequence, US281 Base

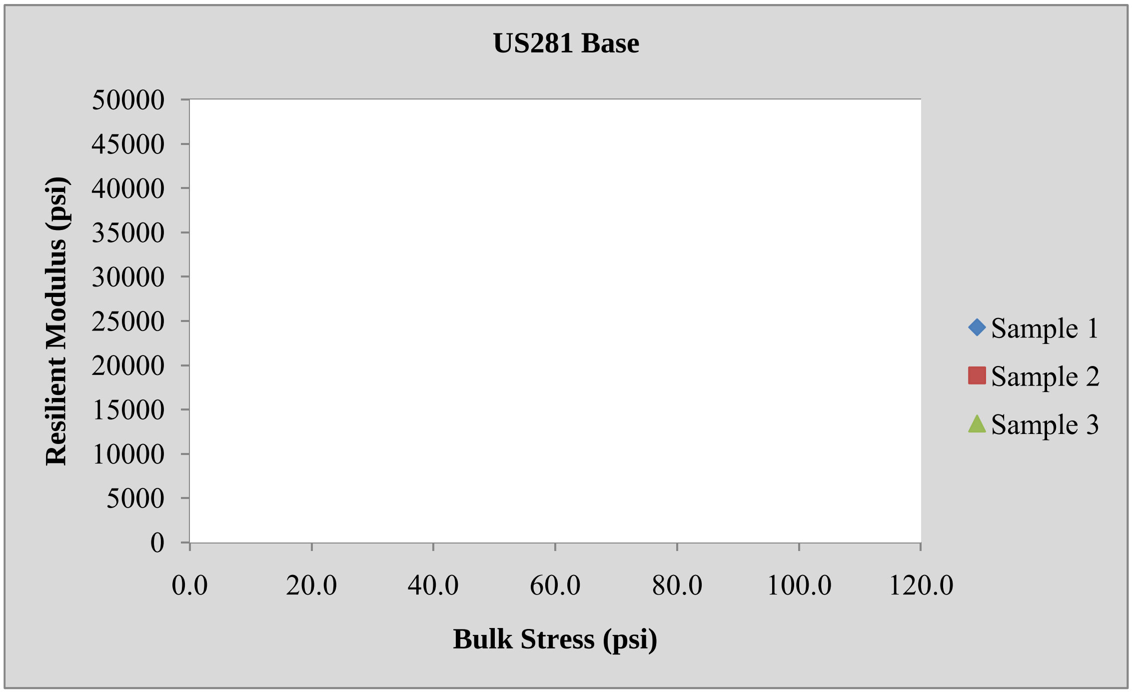


Figure 26: Resilient Modulus vs. Bulk Stress, US281 Base

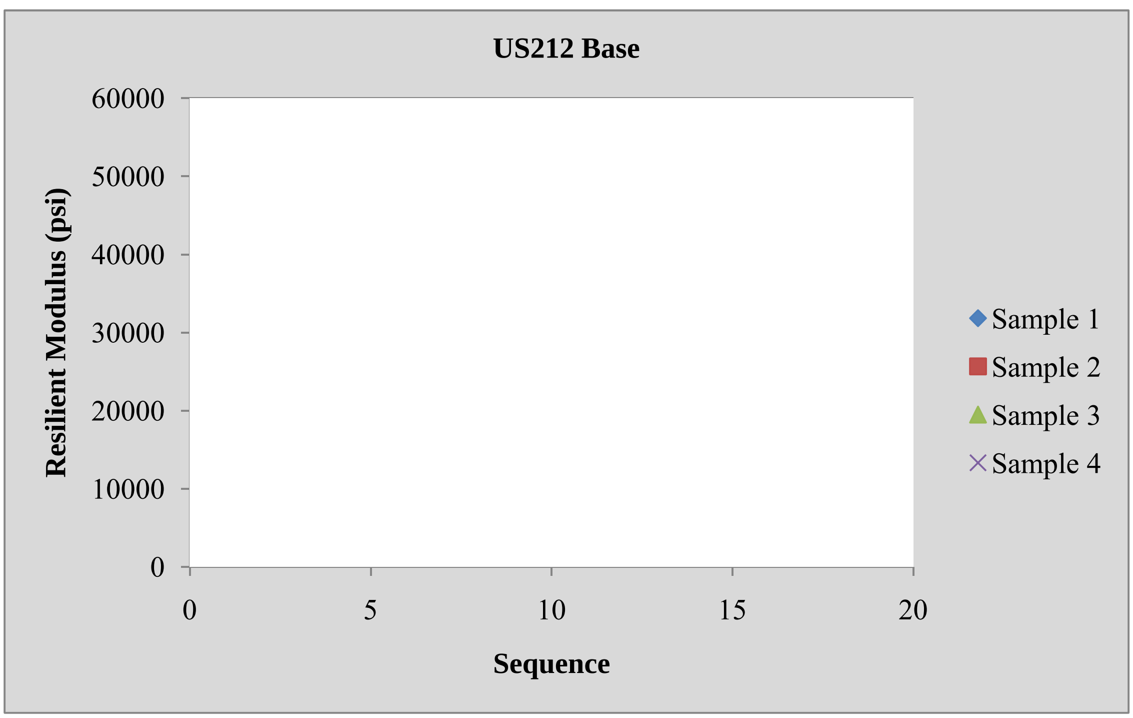


Figure 27: Resilient Modulus vs. Sequence, US212 Base

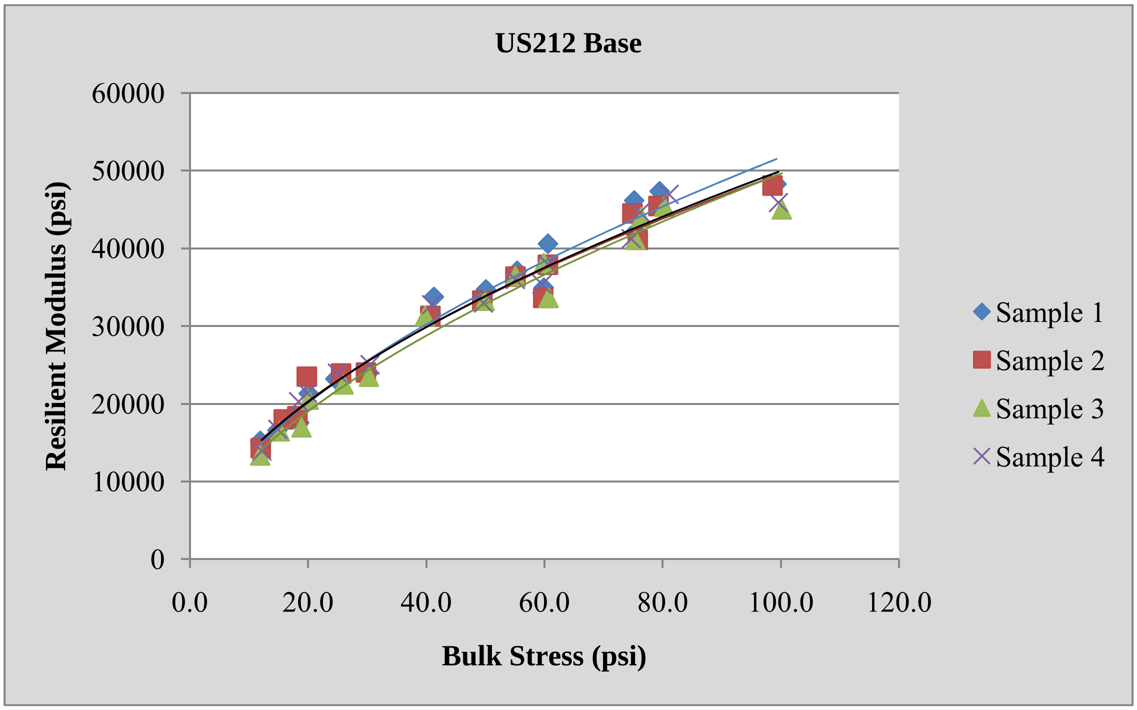


Figure 28: Resilient Modulus vs. Bulk Stress, US212 Base

Microsoft Excel was used to perform the multiple linear regression analysis to obtain the k_1, k_2, and k_3 regression coefficients. The results of the regression analysis are provided in Tables 22 and 23.

Table 22: Resilient Modulus Coefficients, US281 Base

Sample	k_1	k_2	k_3	w(%) target = 9 ± 1%	R^2	M_R value with σ_3=10psi & σ_d=35psi*
1	845.10	0.77	-0.30	8.7	0.99	31,138
2	702.00	0.84	-0.43	8.7	0.99	26,027
3	795.22	0.79	-0.33	8.7	0.99	29,510
average	780.77	0.80	-0.35	8.70		28,896
std dev	72.64	0.04	0.07	0.00		2,611
CV	9.30%	4.51%	19.26%	0.00%		9.04%

* Estimated typical stress values for base layer within a multi-layered pavement.

Table 23: Resilient Modulus Coefficients, US212 Base

Sample	k_1	k_2	k_3	w(%) target = 8.2 ± 1%	R^2	M_R value with σ_3=10psi & σ_d=35psi*
1	1215.03	0.69	-0.42	9.16	0.99	36,316
2	1226.22	0.64	-0.34	8.3	0.98	36,137
3	1148.33	0.70	-0.43	8.3	0.99	34,575
4	1208.39	0.64	-0.29	8.3	0.99	36,976
average	1199.49	0.67	-0.37	8.52		36,002
std dev	34.89	0.03	0.07	0.43		1,225
CV	2.91%	4.80%	18.06%	5.05%		3.40%

* Estimated typical stress values for base layer within a multi-layered pavement.

Both base materials classified as A-1-a in the AASHTO classification system. A typical resilient modulus value for this type of material is 38,500 to 42,000 psi (refer to Table 2). When a confining pressure of 10 psi and a deviator stress of 35 psi are substituted into the constitutive equation for the US281 base material, it resulted in a resilient modulus value of 28,896 psi. The discrepancy between these two values could be accounted for by the recycled asphalt content of the US281 base material. The US212 base material also classified as an A-1-a in the AASHTO system, but as a SW-SM in the USCS classification system. From Table 2, a typical resilient modulus value for SW-SM material is 24,000 to 33,000 psi. The estimated resilient modulus value for the US-212 base (using a confining pressure of 10 psi and a deviator stress of 35 psi) was 36,002 psi which fell between the expected ranges of SW-SM and A-1-a materials. The value of the squared correlation coefficient, R^2, for the linear regression were all above 0.90 indicating that the constitutive model adequately represented the stress-strain behavior of the base materials. Finally, the coefficient of variation (COV) between the samples was less than 20%, thus indicating that the results of the resilient modulus tests were repeatable.

4.3.2 Subgrade Material

The average resilient modulus values for each sequence are reported in Tables 24 through 29.

Table 24: Average M_r Values for Each Sequence, US281 Subgrade Sample 1

Average Values					
Sequence	Confining Pressure, σ_3 (psi)	Deviator (cyclic) Stress, σ_d (psi)	Bulk Stress, θ (psi)	Resilient Strain (in/in)	M_r, Resilient Modulus (psi)
1	6.0	2.1	20.1	0.00008	27,890
2	6.0	4.7	22.7	0.00015	31,655
3	5.7	6.8	23.9	0.00022	31,050
4	5.9	8.8	26.5	0.00027	32,643
5	5.8	10.8	28.2	0.00032	34,034
6	3.9	2.5	14.2	0.00012	21,625
7	3.9	4.7	16.4	0.00019	24,346
8	3.9	6.7	18.4	0.00024	28,143
9	4.0	8.9	20.9	0.00032	27,545
10	4.0	11.0	23.0	0.00038	28,715
11	1.9	2.1	7.8	0.00016	13,166
12	2.0	5.3	11.3	0.00030	17,704
13	2.0	7.3	13.3	0.00037	19,894
14	2.0	9.0	15.0	0.00042	21,342
15	2.0	11.0	17.0	0.00047	23,212

Table 25: Average M_r Values for Each Sequence, US281 Subgrade Sample 2

Average Values					
Sequence	Confining Pressure, σ_3 (psi)	Deviator (cyclic) Stress, σ_d (psi)	Bulk Stress, θ (psi)	Resilient Strain (in/in)	M_r, Resilient Modulus (psi)
1	5.7	2.8	19.9	0.00010	27,098
2	5.7	4.9	22.0	0.00017	28,209
3	5.7	6.9	24.0	0.00021	32,594
4	6.2	8.7	27.3	0.00027	31,801
5	6.1	10.7	29.0	0.00032	33,822
6	3.9	2.3	14.0	0.00010	22,235
7	3.9	4.8	16.5	0.00019	25,451
8	3.8	6.7	18.1	0.00026	25,811
9	3.8	8.6	20.0	0.00032	27,368
10	3.7	10.7	21.8	0.00036	30,161
11	1.9	2.1	7.8	0.00014	15,400
12	1.9	5.1	10.8	0.00029	17,743
13	1.9	6.9	12.6	0.00032	21,342
14	1.9	8.7	14.4	0.00040	21,871
15	1.9	10.7	16.4	0.00045	23,641

Table 26: Average M_r Values for Each Sequence, US281 Subgrade Sample 3

Average Values					
Sequence	Confining Pressure, σ_3 (psi)	Deviator (cyclic) Stress, σ_d (psi)	Bulk Stress, θ (psi)	Resilient Strain (in/in)	M_r, Resilient Modulus (psi)
1	6.0	2.3	20.3	0.00008	27,546
2	6.0	5.1	23.1	0.00016	30,507
3	6.1	6.8	25.1	0.00019	35,666
4	5.7	8.6	25.7	0.00026	33,417
5	5.8	10.7	28.1	0.00031	34,668
6	3.9	2.3	14.0	0.00011	19,737
7	4.0	4.4	16.4	0.00017	25,310
8	4.0	6.5	18.5	0.00023	29,097
9	4.0	8.6	20.6	0.00030	28,987
10	4.0	10.7	22.7	0.00033	32,144
11	1.8	2.1	7.5	0.00012	18,176
12	1.9	4.9	10.6	0.00022	21,689
13	1.9	6.8	12.5	0.00031	22,097
14	1.9	8.8	14.5	0.00037	23,707
15	1.9	10.7	16.4	0.00041	26,135

Table 27: Average M_r Values for Each Sequence, US212 Subgrade Sample 1

Average Values					
Sequence	Confining Pressure, σ_3 (psi)	Deviator (cyclic) Stress, σ_d (psi)	Bulk Stress, θ (psi)	Resilient Strain (in/in)	M_r, Resilient Modulus (psi)
1	6.0	2.5	20.5	0.00008	30,053
2	6.0	4.6	22.6	0.00015	31,215
3	6.0	6.6	24.6	0.00021	31,241
4	6.1	8.6	26.9	0.00028	30,620
5	5.7	8.5	25.6	0.00028	28,264
6	4.0	2.5	14.5	0.00011	23,148
7	4.0	4.5	16.5	0.00017	26,366
8	3.9	6.7	18.4	0.00023	28,886
9	4.0	8.6	20.6	0.00030	28,241
10	3.9	10.7	22.4	0.00038	28,043
11	1.9	1.8	7.5	0.00012	18,344
12	1.8	4.8	10.2	0.00023	20,815
13	1.9	6.9	12.6	0.00029	23,765
14	1.8	8.7	14.1	0.00035	24,922
15	1.8	10.6	16.0	0.00043	24,610

Table 28: Average M_r Values for Each Sequence, US212 Subgrade Sample 2

Average Values					
Sequence	Confining Pressure, σ_3 (psi)	Deviator (cyclic) Stress, σ_d (psi)	Bulk Stress, θ (psi)	Resilient Strain (in/in)	M_r, Resilient Modulus (psi)
1	5.9	2.1	19.8	0.00009	24,076
2	6.0	4.9	22.9	0.00017	29,512
3	6.0	6.8	24.8	0.00022	31,863
4	6.0	8.8	26.8	0.00027	32,189
5	6.1	10.7	29.0	0.00034	31,634
6	4.0	2.3	14.3	0.00009	26,395
7	3.9	5.0	16.7	0.00017	28,278
8	4.0	6.9	18.9	0.00023	29,304
9	3.9	8.7	20.4	0.00029	29,614
10	3.9	10.6	22.3	0.00036	29,758
11	1.9	2.1	7.8	0.00011	19,041
12	1.9	5.3	11.0	0.00022	23,511
13	1.9	7.0	12.7	0.00029	23,780
14	1.8	8.9	14.3	0.00036	24,653
15	1.9	10.5	16.2	0.00040	26,368

Table 29: Average M_r Values for Each Sequence, US212 Subgrade Sample 3

Average Values					
Sequence	Confining Pressure, σ_3 (psi)	Deviator (cyclic) Stress, σ_d (psi)	Bulk Stress, θ (psi)	Resilient Strain (in/in)	M_r, Resilient Modulus (psi)
1	5.8	2.7	20.1	0.00011	26,159
2	5.7	5.0	22.1	0.00016	30,279
3	5.8	7.1	24.5	0.00023	30,864
4	5.8	8.8	26.2	0.00029	30,013
5	5.8	10.6	28.0	0.00035	30,099
6	4.0	2.6	14.6	0.00012	22,575
7	3.9	4.9	16.6	0.00020	24,329
8	3.9	6.9	18.6	0.00026	26,299
9	3.8	8.7	20.1	0.00031	27,954
10	3.8	10.8	22.2	0.00039	27,951
11	1.8	2.2	7.6	0.00011	20,133
12	1.8	5.2	10.6	0.00023	22,852
13	1.8	7.1	12.5	0.00031	22,580
14	1.8	8.9	14.3	0.00036	24,870
15	1.7	9.0	14.1	0.00036	20,751

Since the confining pressures are reduced over the testing sequences for subgrade materials, the graph of resilient modulus versus the sequence number appeared rather erratic as shown in Figures 29 and 31. A plot of resilient modulus versus bulk stress, as shown in Figures 30 and 32, provided an improved indicator of material behavior.

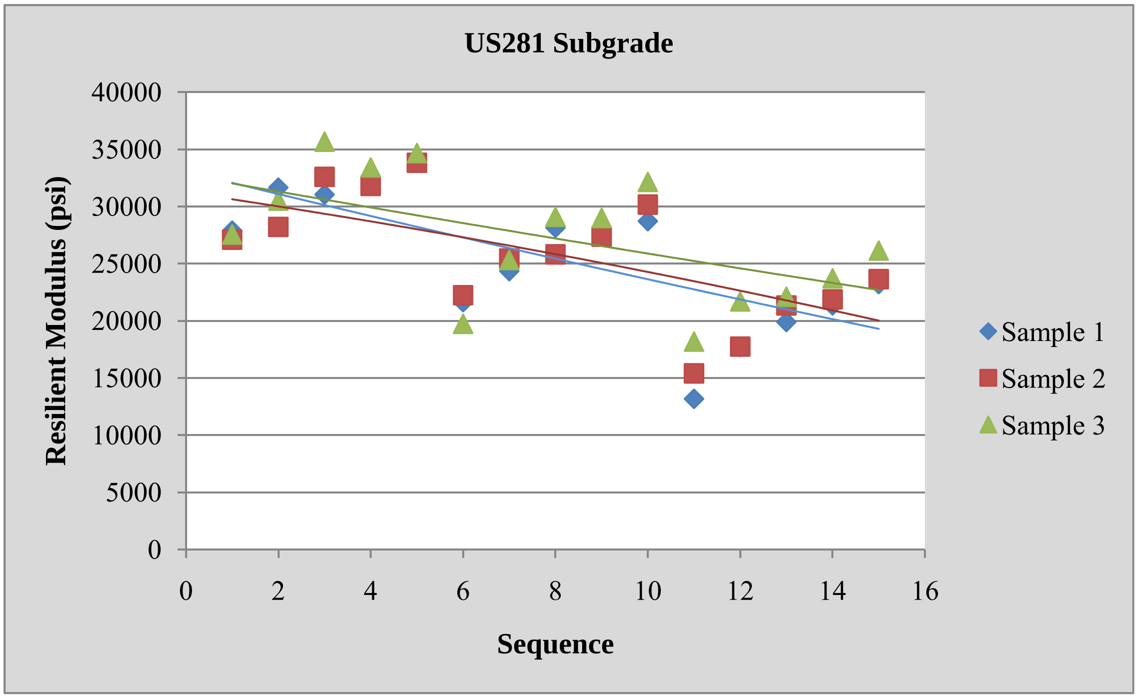


Figure 29: Resilient Modulus vs. Sequence, US281 Subgrade

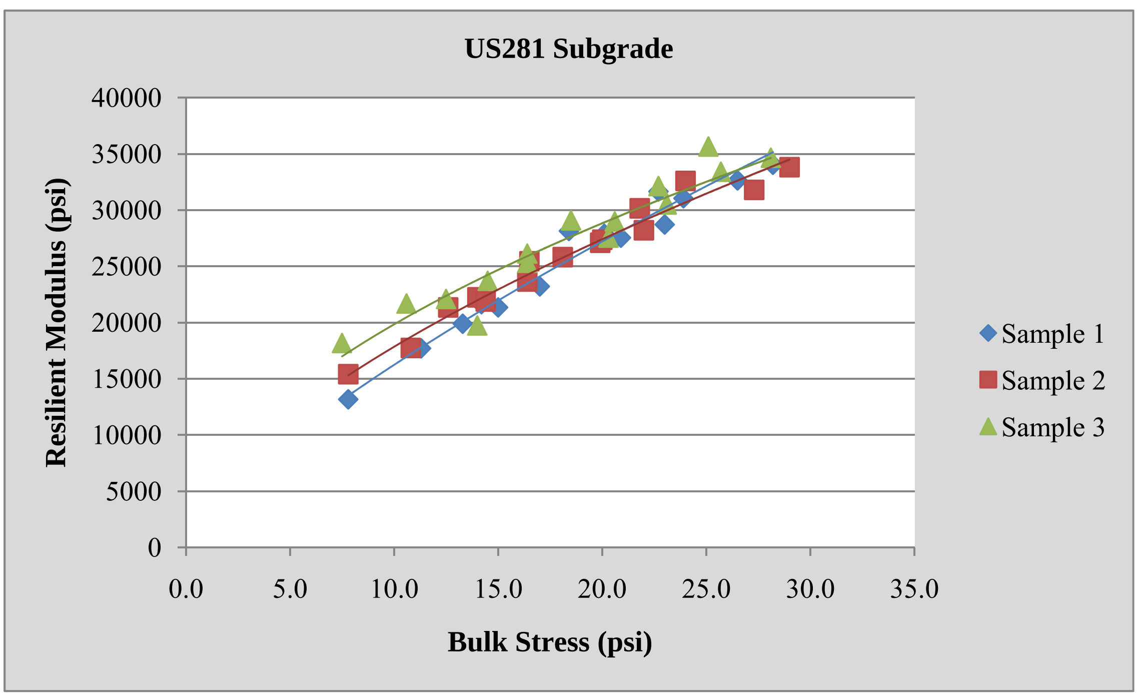


Figure 30: Resilient Modulus vs. Bulk Stress, US281 Subgrade

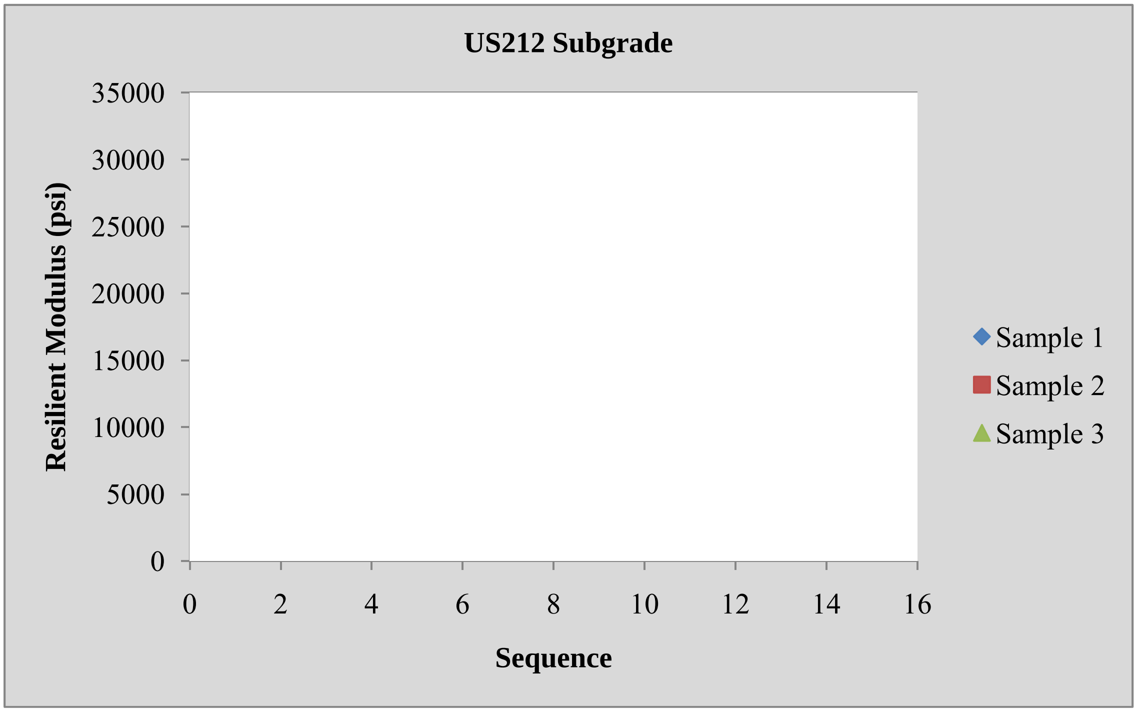


Figure 31: Resilient Modulus vs. Sequence, US212 Subgrade

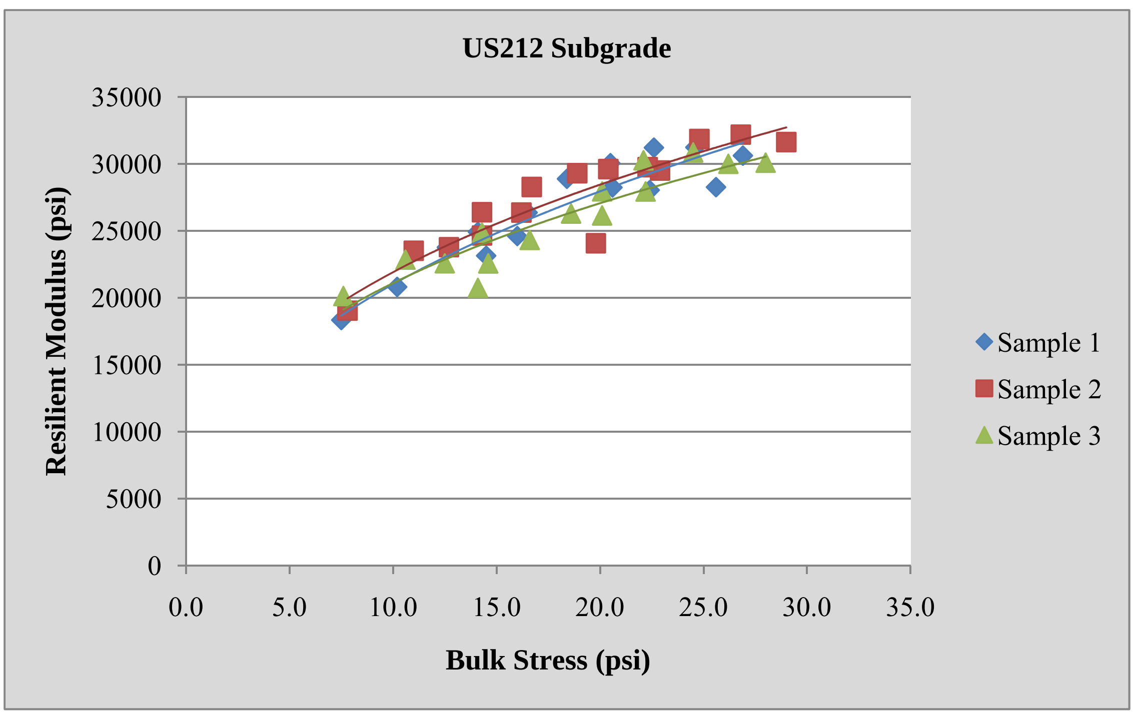


Figure 32: Resilient Modulus vs. Bulk Stress, US212 Subgrade

Microsoft Excel was used to perform the multiple linear regression analysis to obtain the k_1, k_2, and k_3 regression coefficients. The results of the regression analysis are provided in Tables 30 and 31.

Table 30: Resilient Modulus Coefficients, US281 Subgrade

Sample	k_1	k_2	k_3	w(%) target = 11 ± 0.5%	R^2	M_R value with σ_3=2psi & σ_d=6psi*
1	1561.27	0.79	-0.35	11.1	0.98	18,383
2	1554.49	0.63	-0.05	11.0	0.97	19,932
3	1562.78	0.50	0.36	11.0	0.98	22,114
average	1559.51	0.64	-0.01	11.03		20,085
std dev	4.41	0.15	0.36	0.06		1,875
CV	0.28%	22.70%	2673.13%	0.52%		9.34%

* Estimated typical stress values for subgrade layer within a multi-layered pavement.

Table 31: Resilient Modulus Coefficients, US212 Subgrade

Sample	k_1	k_2	k_3	w(%) target = 10.5 ± 0.5%	R^2	M_R value with σ_3=2psi & σ_d=6psi*
1	1737.48	0.43	-0.22	10.1	0.92	22,518
2	1654.45	0.35	0.24	10.1	0.87	23,630
3	1670.80	0.37	-0.08	10.7	0.84	22,466
average	1687.57	0.38	-0.02	10.30		22,870
std dev	43.99	0.04	0.24	0.35		658
CV	2.61%	10.86%	1178.98%	3.36%		2.88%

* Estimated typical stress values for subgrade layer within a multi-layered pavement.

The US281 subgrade classified as an A-6 material. A typical resilient modulus value for this type of material is 13,500 to 24,000 psi as reported in Table 2. When a confining pressure of 2 psi and a deviator stress of 6 psi are substituted into the constitutive equation for the US281 subgrade material, it resulted in a resilient modulus value of 20,085 psi, which fell within the expected range. The US212 subgrade classified as an A-4 material. A typical resilient modulus value for this type of material is 21,500 to 29,000 psi. The estimated resilient modulus value was 22,870 psi which also fell within the expected range. The value of the squared correlation coefficient, R^2, values for the US212 subgrade were slightly below 0.90. This may indicate that the constitutive model recommended by the MEPDG may not adequately represent the stress-strain behavior of all subgrade materials and another model may be better suited for these materials[5,12]. Further, fine-grained soils are generally stress softening and display a modulus decrease with increased stress[2]. Instead, the US281 and US212 subgrades were stress hardening.

4.4 Dynamic Modulus Test Results

Tables 32 through 34 provide the results of dynamic modulus testing conducted at SDSM&T for three specimens. Table 35 reports the average values from these three tests along with standard deviation and coefficient of variation for each testing temperature.

Table 32: Dynamic Modulus, US281 Sample 1 SDSM&T Testing

Temperature °C	Mixture E*, psi					
	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
4	1,055,832	889,287	762,878	506,672	419,828	275,050
21	474,204	328,274	251,611	140,721	111,445	72,337
37	196,070	120,307	88,446	49,959	42,279	32,237
54	90,169	56,010	43,969	31,372	28,238	23,749

Table 33: Dynamic Modulus, US281 Sample 2 SDSM&T Testing

Temperature °C	Mixture E*, psi					
	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
4	1,187,023	1,001,856	867,804	588,643	477,912	314,042
21	448,317	295,313	223,226	122,758	96,852	63,731
37	177,932	107,115	76,773	43,283	36,662	28,157
54	76,432	46,915	36,033	25,778	23,076	19,733

Table 34: Dynamic Modulus, US281 Sample 3 SDSM&T Testing

Temperature °C	Mixture E*, psi					
	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
4	1,345,939	1,138,452	996,182	682,632	569,086	367,848
21	516,086	366,734	284,316	158,121	124,383	80,399
37	192,063	117,454	85,694	49,082	41,598	31,931
54	84,483	52,217	40,461	27,658	25,283	21,790

Table 35: Average Dynamic Modulus Values, US281 Samples 1, 2, and 3, SDSM&T Testing

Temperature °C		Mixture E*, psi					
		25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
4	average	1,196,265	1,009,865	875,621	592,649	488,942	318,980
	std dev	145274	124776	116848	88048	75238	46596
	CV	12.1%	12.4%	13.3%	14.9%	15.4%	14.6%
21	average	479,536	330,107	253,051	140,533	110,893	72,156
	std dev	34198	35746	30570	17682	13773	8335
	CV	7.1%	10.8%	12.1%	12.6%	12.4%	11.6%
37	average	188,688	114,959	83,638	47,441	40,179	30,775
	std dev	9529	6941	6102	3628	3065	2273
	CV	5.0%	6.0%	7.3%	7.6%	7.6%	7.4%
54	average	83,695	51,714	40,154	28,269	25,532	21,757
	std dev	6902	4569	3977	2847	2590	2008
	CV	8.2%	8.8%	9.9%	10.1%	10.1%	9.2%

UNR also tested HMA material from US281. The average dynamic modulus values from three specimens are listed in Table 36. Table 37 shows the comparison between the values obtained at SDSM&T and UNR.

Table 36: Average Dynamic Modulus, US281 UNR Testing

Temperature °C	Mixture E*, psi					
	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
4	1,349,370	1,172,035	964,105	616,685	508,950	335,385
21	401,505	304,355	234,755	124,555	100,920	68,730
37	92,075	69,020	55,390	34,365	29,435	21,170
54	46,255	37,120	32,480	26,100	24,360	21,605

Table 37: Comparison of Dynamic Modulus Results, US281

Percentage Difference between UNR and SDSMT						
Temperature °C	Mixture E*, psi					
	25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
4	11%	14%	9%	4%	4%	5%
21	19%	8%	8%	13%	10%	5%
37	105%	67%	51%	38%	37%	45%
54	81%	39%	24%	8%	5%	1%

A plot of the E* Master Curves for both the SDSM&T data and UNR data is shown in Figure 33.

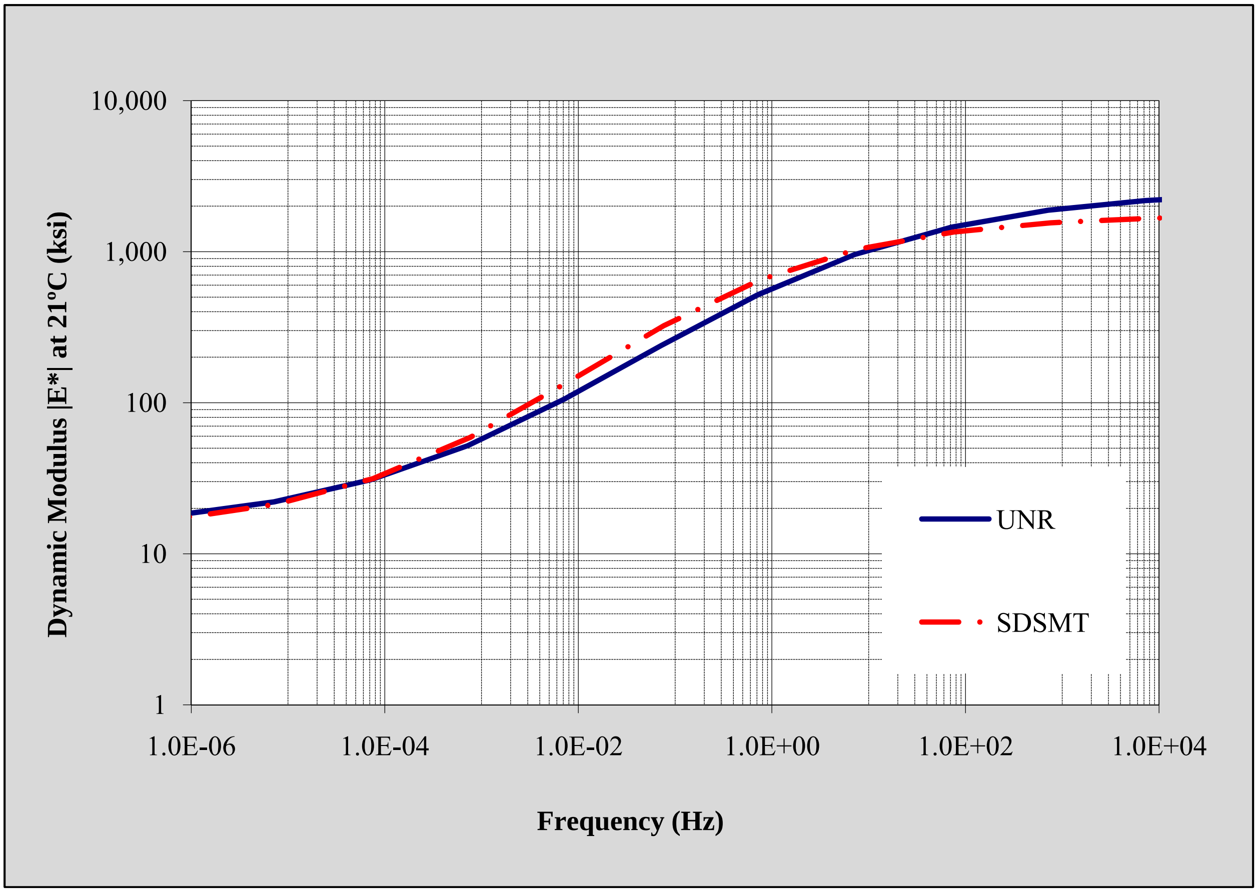


Figure 33: US281 Master Curves for UNR and SDSM&T Data

The dynamic modulus results for the US281 HMA were promising. The coefficients of variation between samples were fairly low with the highest being 15.4%. When compared to UNR's data, the results were similar especially for 4°C and 21°C. This is illustrated in the shifted master curves plotted in Figure 33.

4.5 Conclusions

The objective of Task 4 of the study was to obtain resilient modulus and dynamic modulus values for construction materials on HMA paving projects through tests performed with a Simple Performance Tester (SPT) at SDSM&T to correlate, calibrate, and validate these results from the new SPT through comparative analyses with similar work performed at the UNR for the SDDOT.

The final results of the Task 4 collaborative testing were as follows:

Table 38: Task 4 Average Resilient Modulus Coefficients

Material	k_1	k_2	k_3
US281 Base	780.77	0.80	-0.35
US212 Base	1199.49	0.67	-0.37
US281 Subgrade	1559.51	0.64	-0.01
US212 Subgrade	1687.57	0.38	-0.02

Table 39: Task 4 Average Dynamic Modulus Values

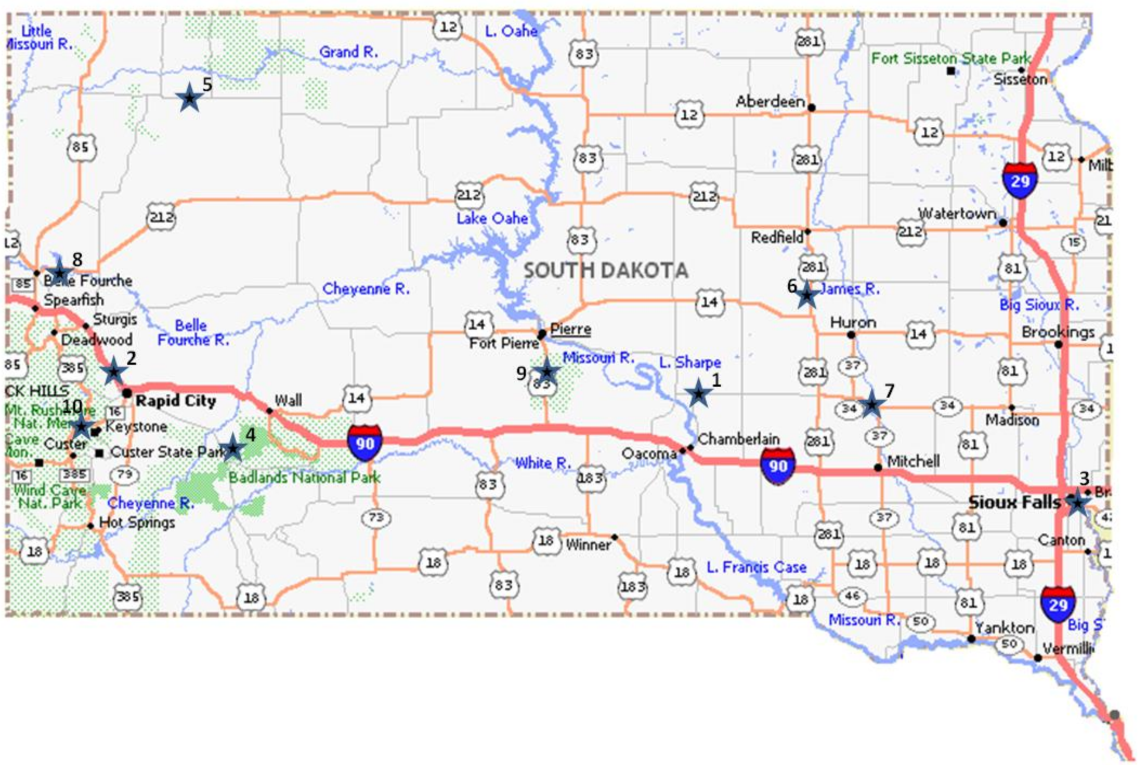
Temperature °C	Testing Facility	Mixture E*, psi					
		25 Hz	10 Hz	5 Hz	1 Hz	0.5 Hz	0.1 Hz
4	SDSM&T	1,196,265	1,009,865	875,621	592,649	488,942	318,980
	UNR	1,349,370	1,172,035	964,105	616,685	508,950	335,385
21	SDSM&T	479,536	330,107	253,051	140,533	110,893	72,156
	UNR	401,505	304,355	234,755	124,555	100,920	68,730
37	SDSM&T	188,688	114,959	83,638	47,441	40,179	30,775
	UNR	92,075	69,020	55,390	34,365	29,435	21,170
54	SDSM&T	83,695	51,714	40,154	28,269	25,532	21,757
	UNR	46,255	37,120	32,480	26,100	24,360	21,605

The results and repeatability of the tests completed on the US281 and US212 materials indicate that SDSM&T is capable of performing both resilient modulus and dynamic modulus tests. However, the concurrent testing did result in hydraulic tuning of the SPT at SDSM&T, along with replacement of the environmental control unit and reprogramming of the SPT software.

CHAPTER 5 SOIL TEST RESULTS AND ANALYSIS

5.1 Introduction

The chapter presents all results from the materials testing of subgrade soils sampled at ten sites as shown in Figure 34. The results include particle size analysis, hydrometer analysis, Atterburg limits, moisture density relationships, soil classifications, California Bearing Ratio tests, and resilient modulus tests.



1. SD34 East of Lee's Corner
2. I-90 Exit 51 by Blackhawk
3. SD11 South of SD42 in Minnehaha County
4. SD44 East of Scenic
5. SD20 East of Prairie City
6. US281 North of Wolsey
7. SD34 near Forestburg
8. US212 near Orman Dam
9. US83 South of Ft. Pierre
10. US385 between Custer and Hill City

Figure 34: Sampling Locations for Subgrade Materials

5.2 Particle Size Analysis

Tables 40 and 41, along with Figures 35 and 36, provide the gradations for the ten subgrades. The tables and charts contain results from five soils for clarity. Of the ten subgrades tested, seven of them had greater than 50% fines, classified as the percentage of material passing the No. 200 sieve.

Table 40: Particle Size Distributions for Subgrade Soils

Sieve Size		SD34 Lee's Corner	I-90 by Blackhawk	SD11/SD42 Minnehaha County	SD44 E of Scenic	SD20 E of Prairie City
No.	mm	% Passing				
1.5"	38.1	100	100	100	100	100
1"	25.4	100	100	100	100	100
3/4"	19.1	100	100	100	100	100
1/2"	12.7	99.3	100	100	100	100.0
3/8"	9.51	98.0	100	100	99.4	99.6
#4	4.76	93.5	99.8	99.8	98.8	97.4
#8	2.36	89.7	96.6	99.5	98.0	95.3
#10	2	88.7	95.3	99.5	97.8	94.6
#16	1.19	85.3	92.7	99.4	97.0	92.4
#30	0.595	79.3	90.3	99.2	94.8	91.1
#40	0.42	76.2	89.2	99.1	93.8	90.5
#50	0.297	73.5	82.6	98.9	93.0	89.9
#100	0.149	69.9	74.3	98.1	90.9	87.3
#200	0.074	68.2	69.2	93.2	87.5	77.6

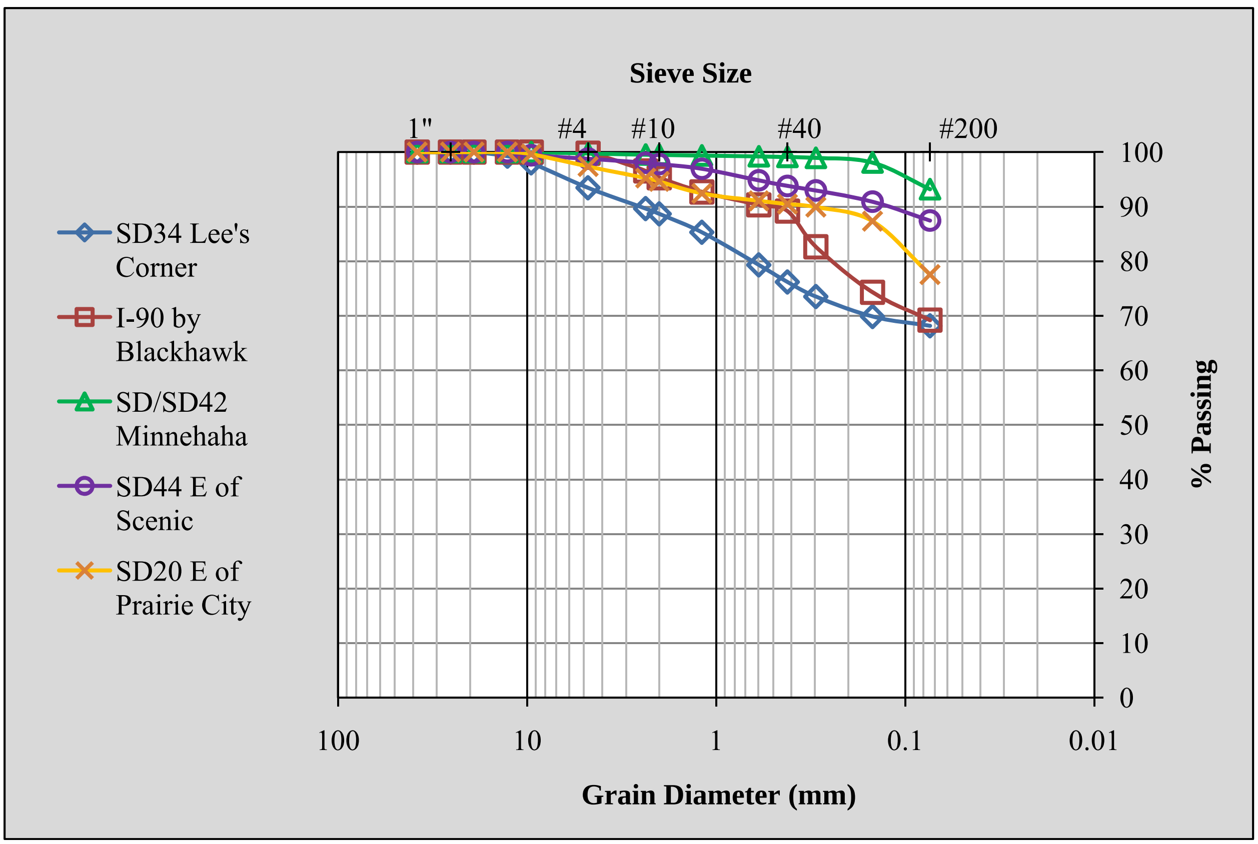


Figure 35: Gradations for Subgrade Soils

Table 41: Particle Size Distributions for Subgrade Soils

Sieve Size		US281 N of Wolsey	SD34 near Forestburg	US212 near Orman Dam	US83 S of Ft. Pierre	US385 Custer/Hill City
No.	mm	% Passing				
1.5"	38.1	100	100	100	100	97.3
1"	25.4	100	100	100	100	93.0
3/4"	19.1	100	100	96.3	100	82.6
1/2"	12.7	97.8	100	92.8	100	78.8
3/8"	9.51	94.8	99.7	91.7	100	74.7
#4	4.76	88.8	98.1	88.6	99.5	66.9
#8	2.36	82.9	96.9	86.5	99.0	61.8
#10	2	81.5	96.6	86.0	98.8	60.9
#16	1.19	77.4	95.2	84.2	98.0	58.2
#30	0.595	71.5	93.4	82.5	97.1	55.2
#40	0.42	68.2	90.6	81.1	96.5	53.8
#50	0.297	64.2	81.3	78.7	95.9	52.1
#100	0.149	50.0	40.0	67.5	94.9	45.6
#200	0.074	38.9	24.1	49.5	93.9	31.3

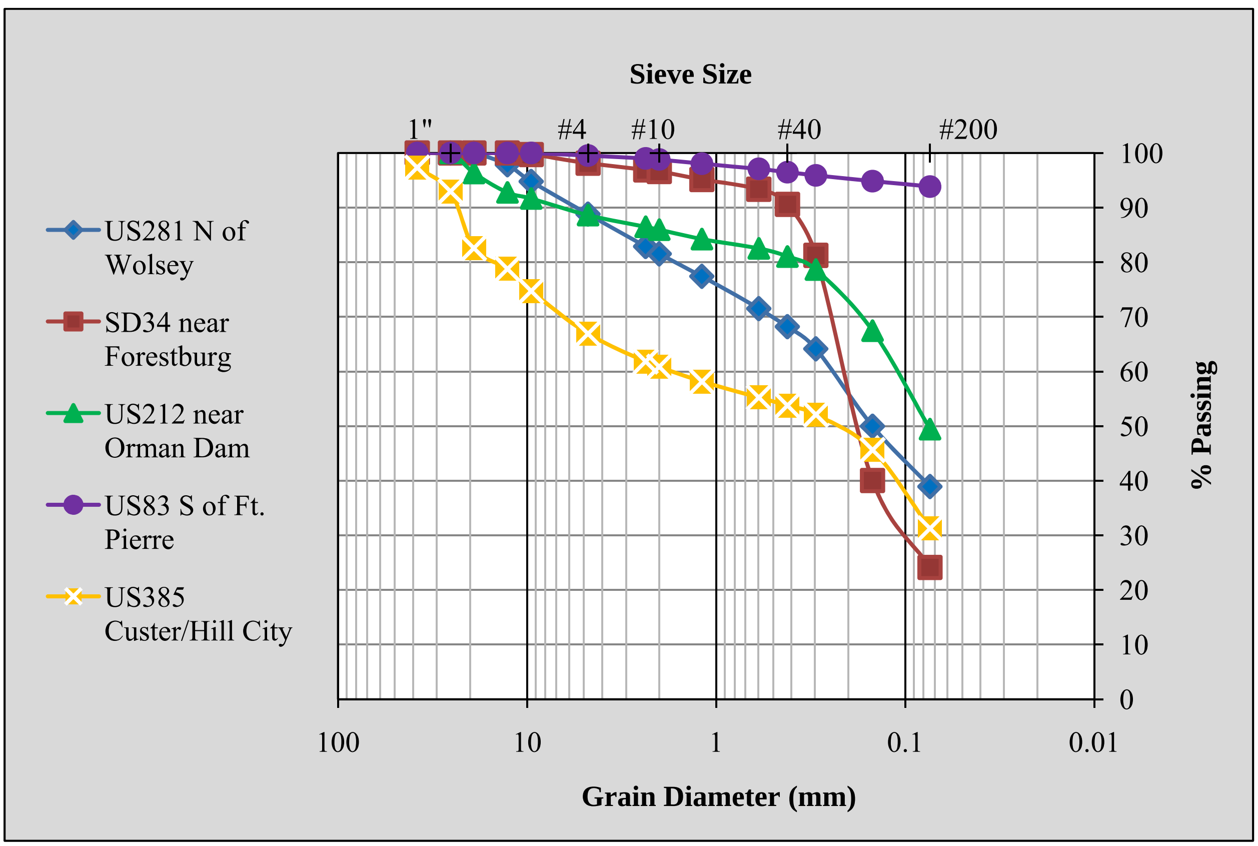


Figure 36: Gradations for Subgrade Soils

5.3 Hydrometer Analysis

All subgrade soils were subjected to a hydrometer analysis. Of the seven subgrade materials with over 50% fines, only three of the soils had substantial clay contents, of greater than or equal to 50%.

Table 42: Hydrometer Results

Material	% Fines (from sieve analysis)	% Silt (from hydrometer analysis)	% Clay (from hydrometer analysis)	Final % Silt	Final % Clay
SD34 Lee's Corner	68.2	29.3	70.7	20.0	48.2
I-90 by Blackhawk	69.2	80.4	19.6	55.6	13.6
SD11/SD42 Minnehaha County	93.2	80.4	19.6	74.9	18.3
SD44 E of Scenic	87.5	42	58	36.8	50.8
SD20 E of Prairie City	77.6	72.3	27.7	56.1	21.5
US281 Wolsey	38.9	56.8	43.2	22.1	16.8
SD34 Forestburg	24.1	58.3	41.7	14.1	10.0
US212 Orman Dam	49.5	69.7	30.3	34.5	15.0
US83 Ft Pierre	93.9	42.3	57.7	39.7	54.2
US385 Custer/Hill City	31.3	83.7	16.3	26.2	5.1
US212 Subgrade (from Task 4)	63.6	55.7	44.3	35.4	28.2

5.4 Atterberg Limits

Table 43 summarizes the Atterberg Limit values for all ten subgrade materials.

Table 43: Subgrade Atterberg Limit Values

Material	Liquid Limit	Plastic Limit	Plasticity Index
SD34 Lee's Corner	73	26	47
I-90 by Blackhawk	24	17	7
SD11/SD42 Minnehaha County	26	24	2
SD44 E of Scenic	93	20	73
SD20 E of Prairie City	29	18	11
US281 Wolsey	32	17	15
SD34 Forestburg	NA	NA	NP
US212 Orman Dam	24	17	7
US83 Ft Pierre	76	26	50
US385 Custer/Hill City	24	24	0

5.5 Moisture Density Relationship

Dry density was plotted with respect to moisture content for each subgrade material. The maximum dry density (MDD) and optimum moisture content (OMC) were obtained from and marked on Figures 37 to 46. The results from these tests were used to reconstitute soil samples for the resilient modulus and California Bearing Ratio tests.

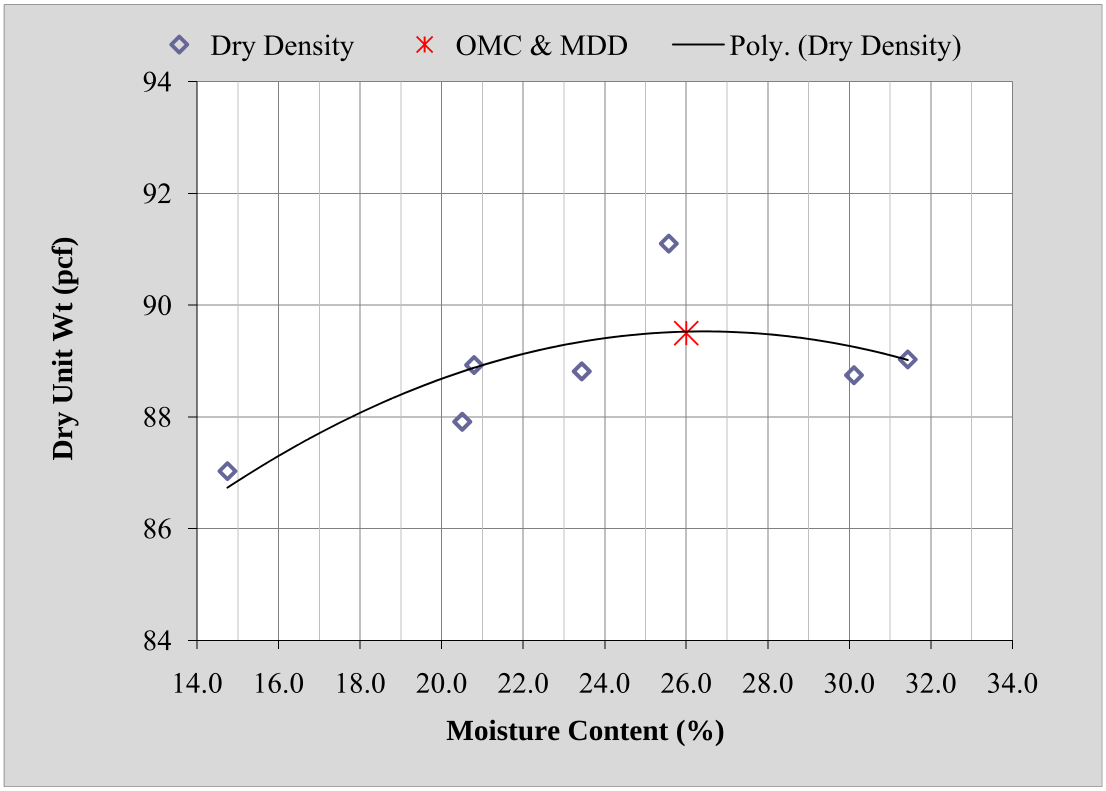


Figure 37: Dry Density vs. Moisture Content, SD34 Lee's Corner

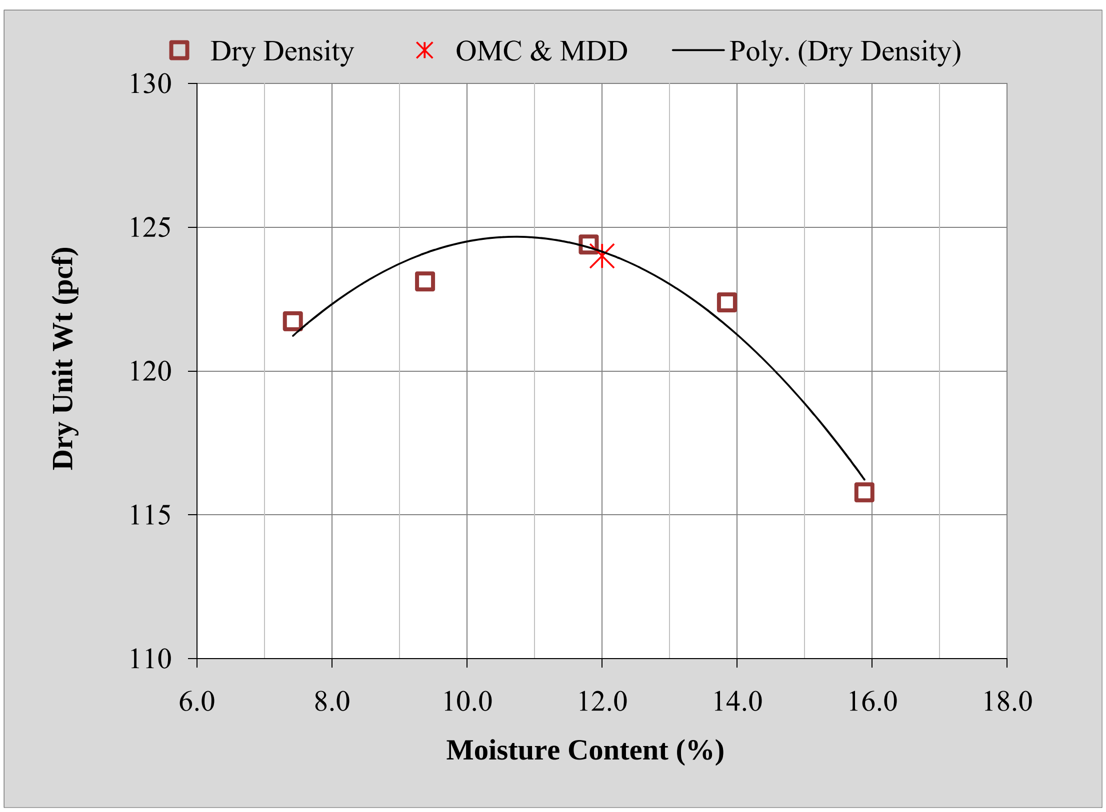


Figure 38: Dry Density vs. Moisture Content, I-90 Blackhawk

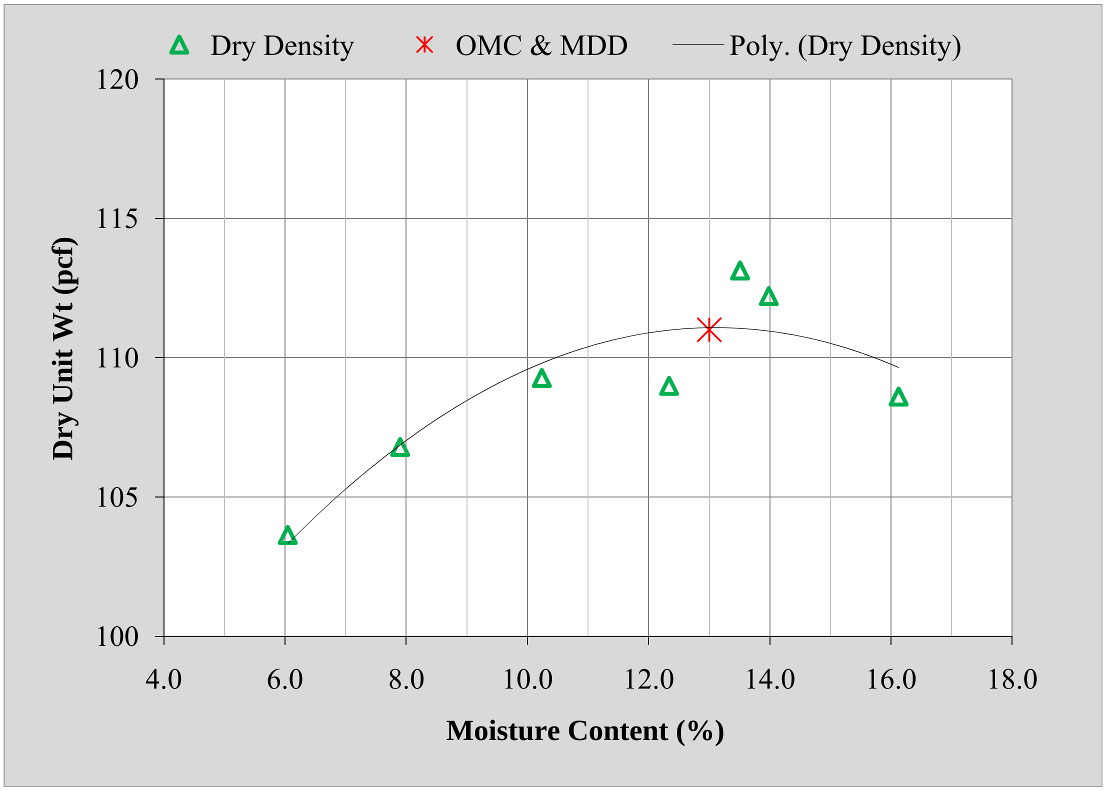


Figure 39: Dry Density vs. Moisture Content, SD11/SD42 Minnehaha County

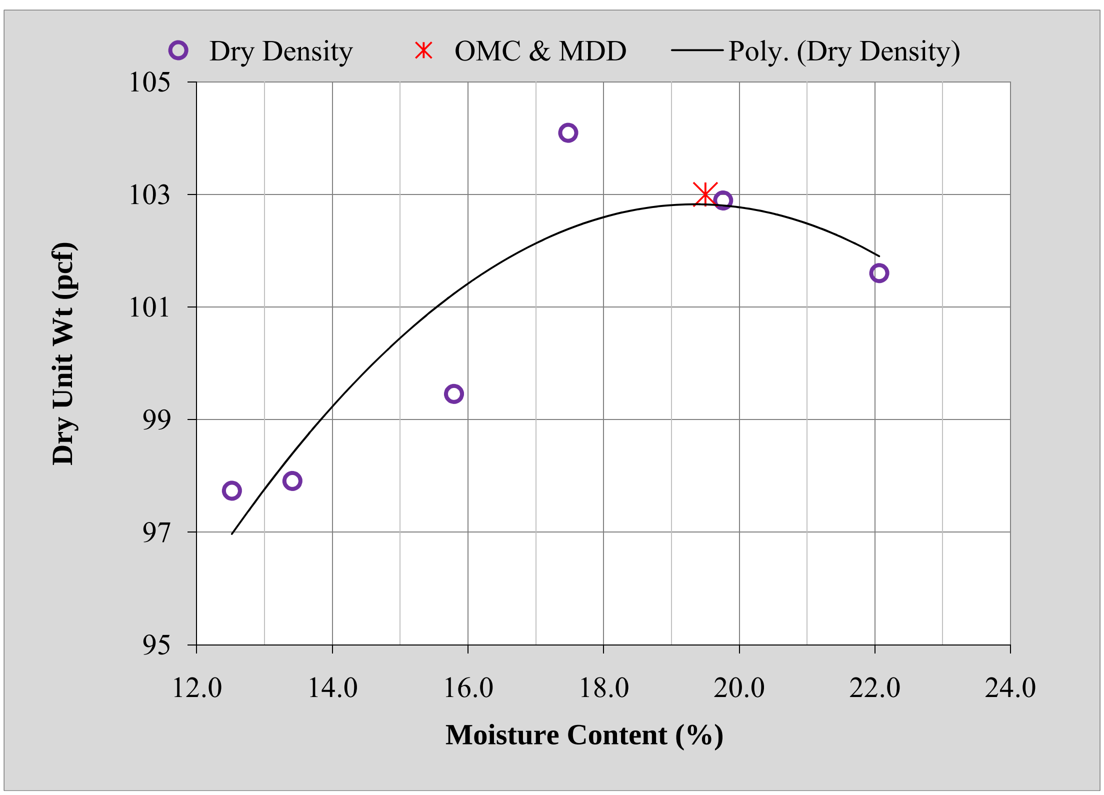


Figure 40: Dry Density vs. Moisture Content, SD44 Scenic

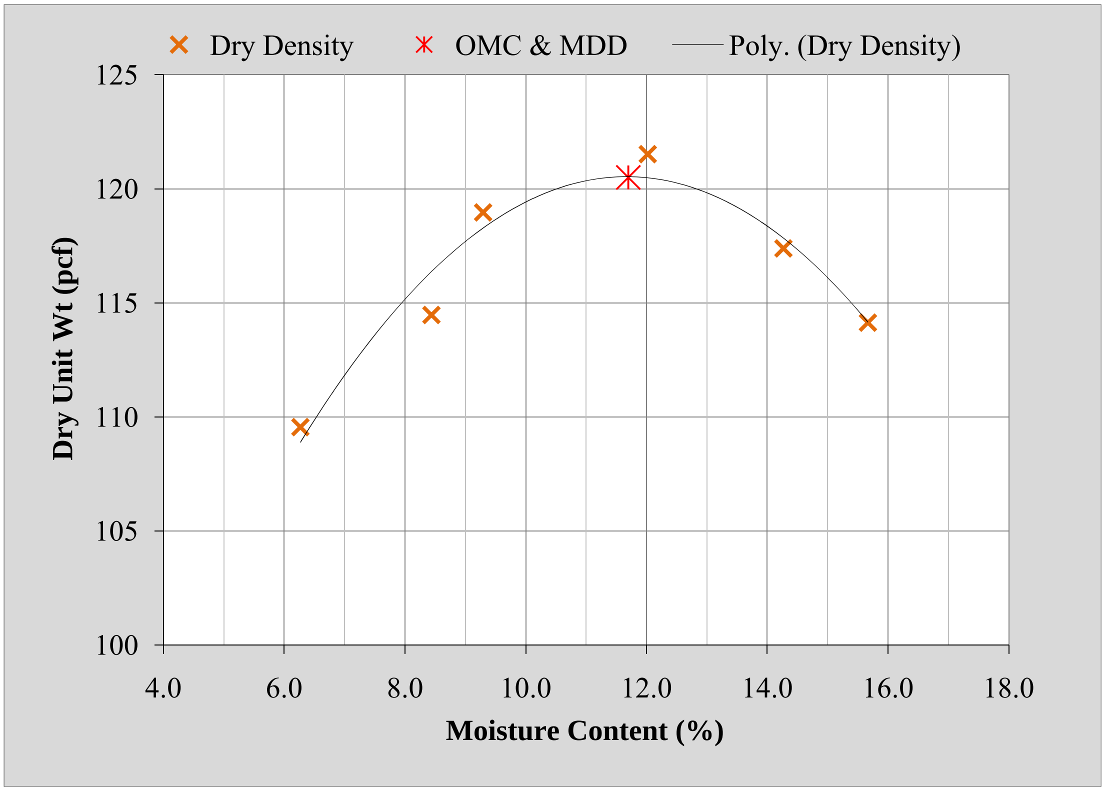


Figure 41: Dry Density vs. Moisture Content, SD20 Prairie City

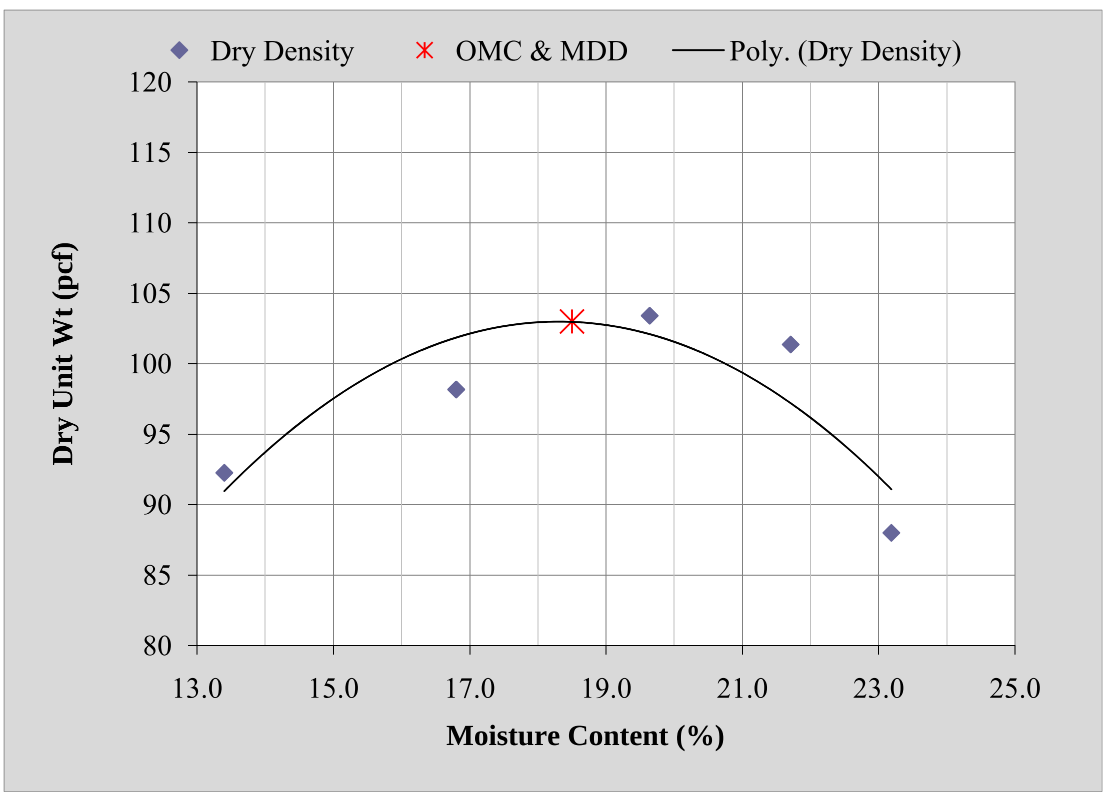


Figure 42: Dry Density vs. Moisture Content, US281 Wolsey

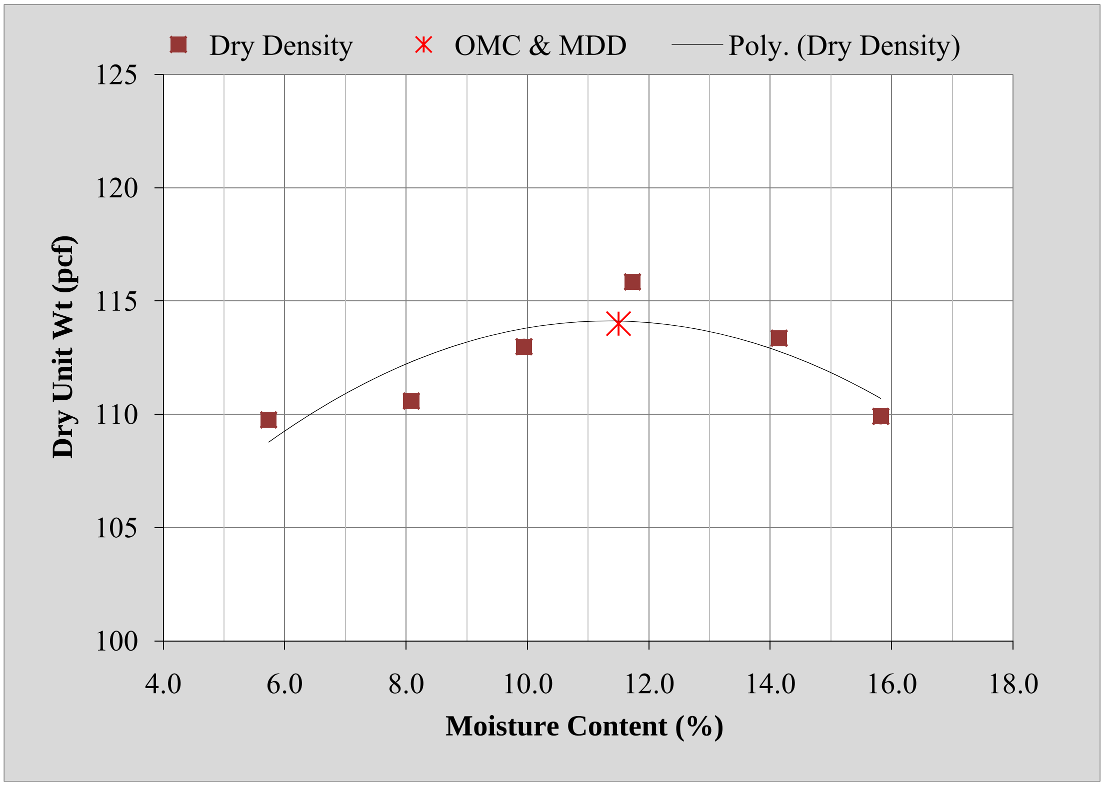


Figure 43: Dry Density vs. Moisture Content, SD34 Forestburg

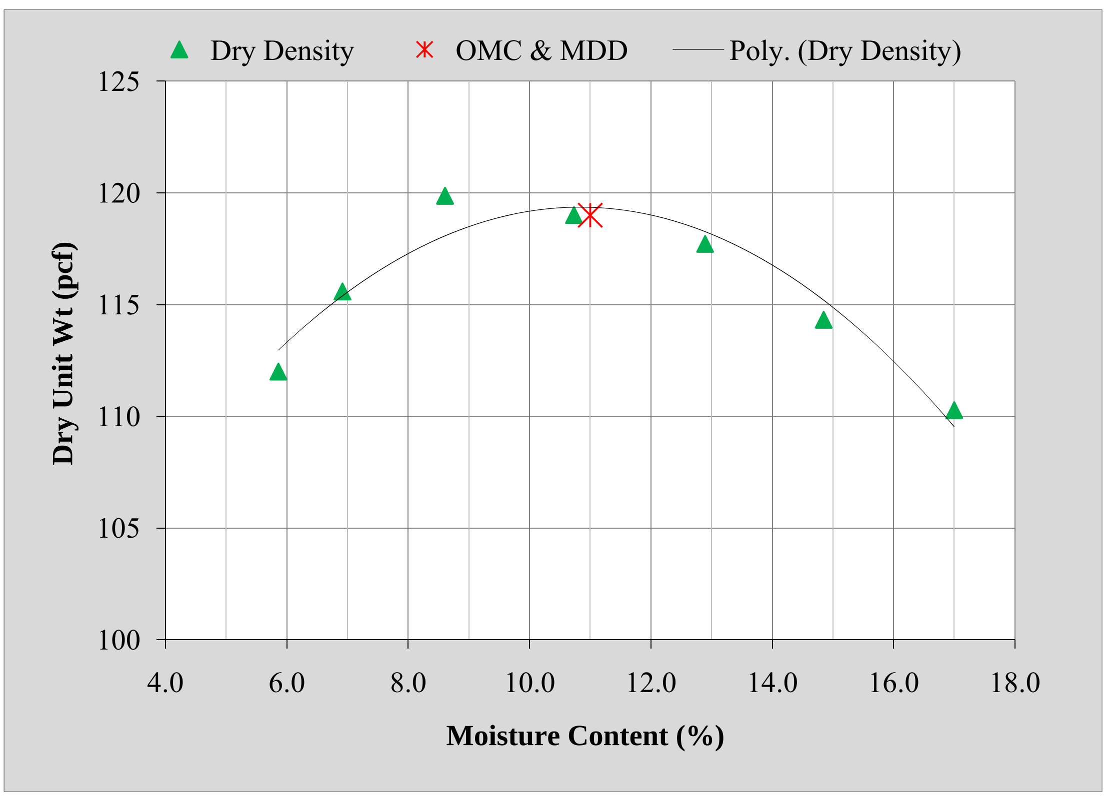


Figure 44: Dry Density vs. Moisture Content, US212 Orman Dam

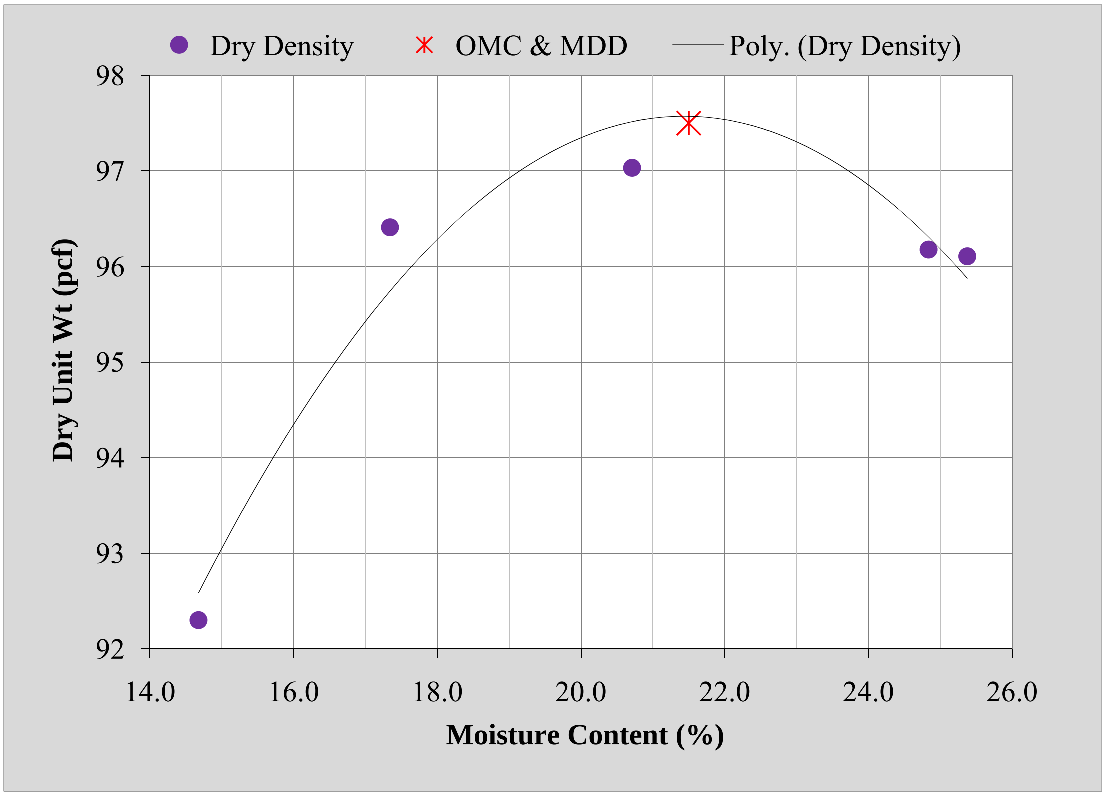


Figure 45: Dry Density vs. Moisture Content, US83 Ft. Pierre

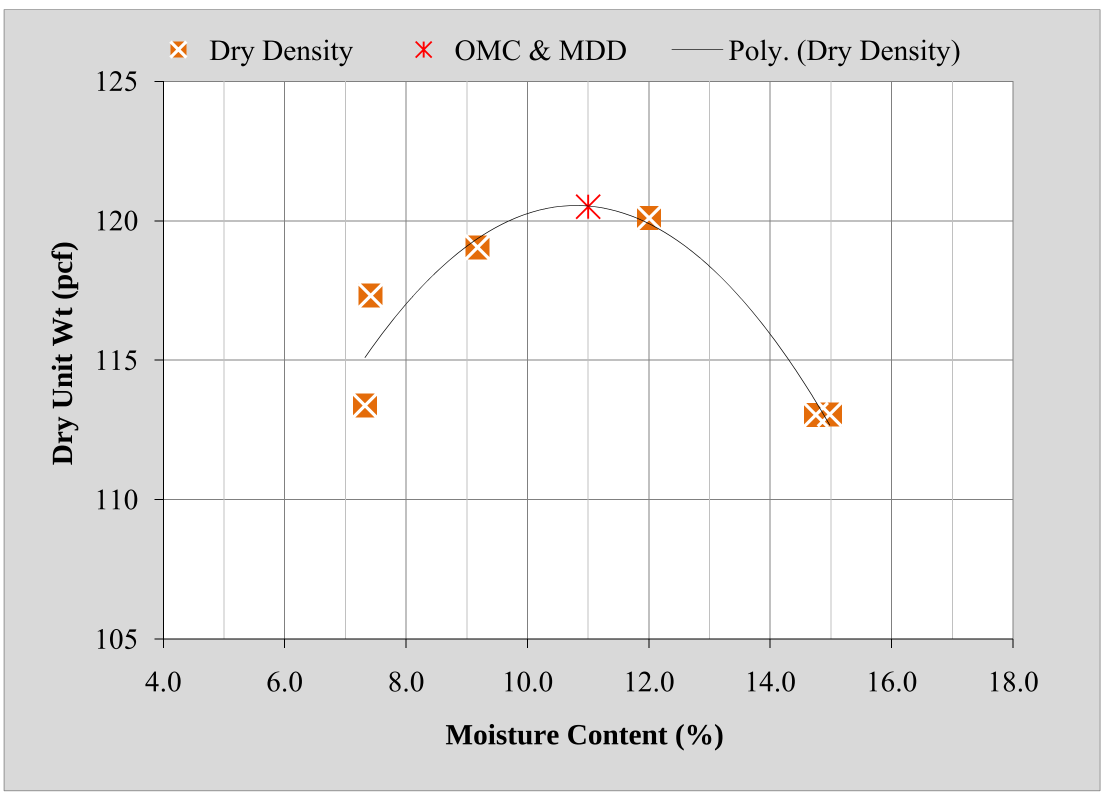


Figure 46: Dry Density vs. Moisture Content, US385 Custer/Hill City

5.6 Soil Classifications

The subgrade materials were classified using the results from the particle size analyses and Atterberg Limits.

Table 44: Subgrade Soil Classifications

Material	Classification	
	AASHTO	USCS
SD34 Lee's Corner	A-7-6	CH, sandy fat clay
I-90 by Blackhawk	A-4	CL-ML, sandy silty clay
SD11/SD42 Minnehaha County	A-4	ML silt
SD44 E of Scenic	A-7-5	CH, fat clay
SD20 E of Prairie City	A-6	CL, lean clay with sand
US281 Wolsey	A-6	CL SC, clayey sand
SD34 Forestburg	A-2-4	SM, silty sand
US212 Orman Dam	A-4	CL-ML, sandy silty clay
US83 Ft Pierre	A-7-6	CH, fat clay
US385 Custer/Hill City	A-2-4	SM, silty sand with gravel

5.7 California Bearing Ratio

For each subgrade material, three samples were tested for the CBR test and three for the saturated CBR test. The reported in Table 45 are the average values obtained from the respective testing of the three samples.

Table 45: Subgrade CBR Values

Material	CBR	Saturated CBR
SD34 Lee's Corner	13.9	2.3
I-90 by Blackhawk	24.7	9.7
SD11/SD42 Minnehaha County	22.9	16.6
SD44 E of Scenic	23.2	3.5
SD20 E of Prairie City	28.1	3.1
US281 Wolsey	2.2	2.4
SD34 Forestburg	10.3	6.9
US212 Orman Dam	21.8	7.3
US83 Ft Pierre	22.8	1.9
US385 Custer/Hill City	10.9	4.5
US212 Subgrade (from Task 4)	13.5	1.9

5.8 Resilient Modulus Test

The results of the resilient modulus tests are shown graphically in Figures 47 to 56 which are plots of resilient modulus versus bulk stress for each subgrade. Following each figure is a table with the regression coefficients for each sample, along with the average, standard deviation, and coefficient of variation for the regression coefficients. The value of the squared correlation coefficient, R^2, is reported for each sample's regression analysis. Finally, estimated values for the resilient modulus using the developed constitutive equation and a confining stress of 2 psi and a deviator stress of 6 psi are also provided.

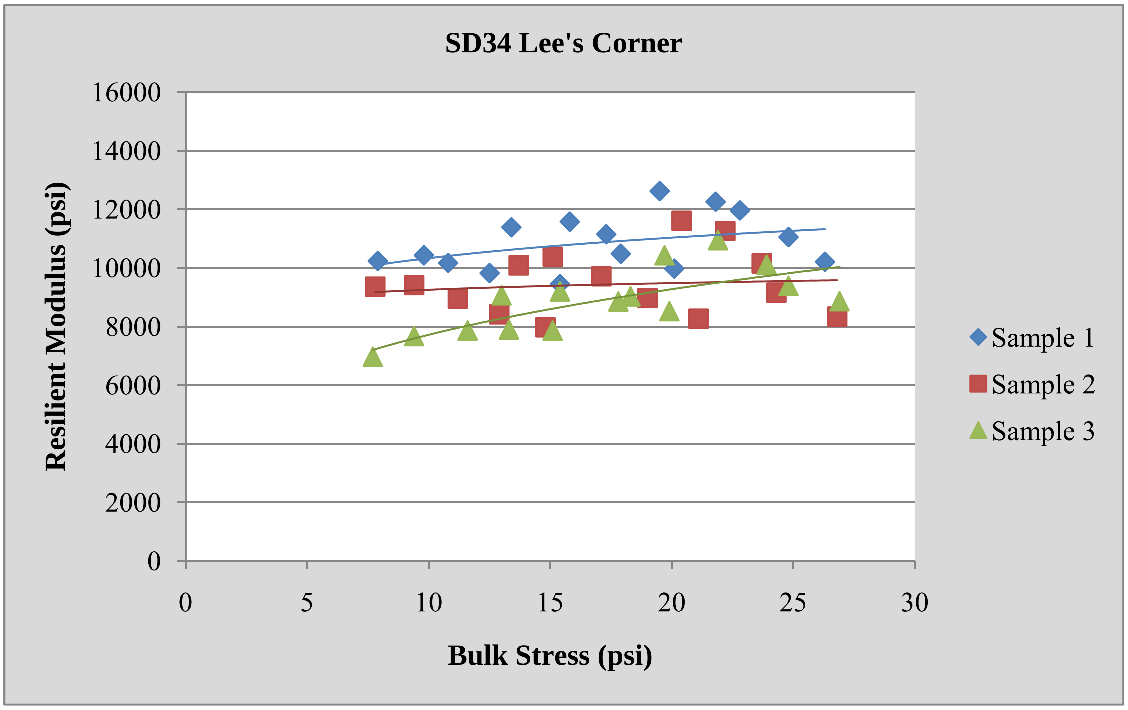


Figure 47: Resilient Modulus vs. Bulk Stress, SD34 Lee's Corner

Table 46: Resilient Modulus Coefficients, SD34 Lee's Corner

Sample	k_1	k_2	k_3	w(%) target = 26 ± 0.5%	R^2	M_R value with σ_3=2psi & σ_d=6psi*
1	860.20	0.20	-1.18	26	0.94	9,865
2	799.13	0.18	-1.60	25.6	0.91	8,547
3	673.54	0.36	-1.04	25.5	0.93	7,664
average	777.62	0.25	-1.27	25.70		8,690
std dev	95.17	0.10	0.29	0.26		1,107
CV	12.24%	40.00%	22.89%	1.03%		12.75%

* Estimated typical stress values for subgrade layer within a multi-layered pavement.

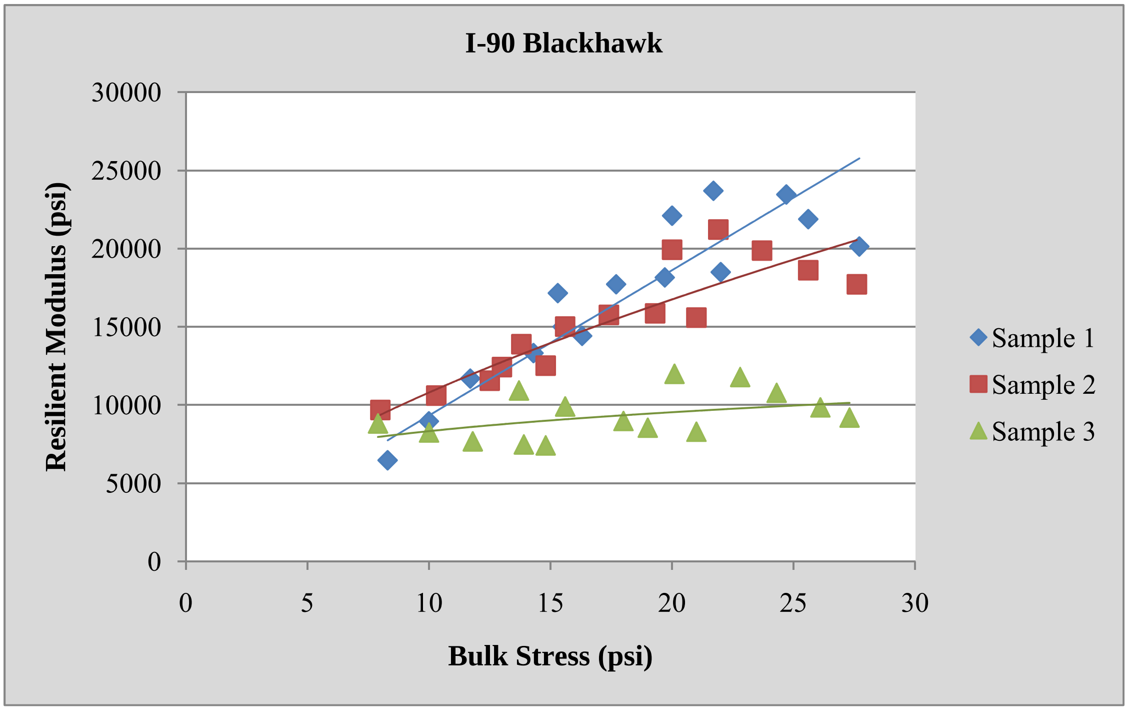


Figure 48: Resilient Modulus vs. Bulk Stress, I-90 Blackhawk

Table 47: Resilient Modulus Coefficients, I-90 Blackhawk

Sample	k_1	k_2	k_3	w(%) target = 12 ± 0.5%	R^2	M_R value with σ_3=2psi & σ_d=6psi*
1	1093.06	1.11	-1.10	11.6	0.92	10,570
2	1130.89	0.75	-1.27	11.9	0.96	11,418
3	834.83	0.39	-2.13	11.8	0.97	7,794
average	1019.60	0.75	-1.50	11.77		9,886
std dev	26.75	0.25	0.12	0.15		1,896
CV	2.62%	33.94%	8.01%	1.30%		19.18%

* Estimated typical stress values for subgrade layer within a multi-layered pavement.

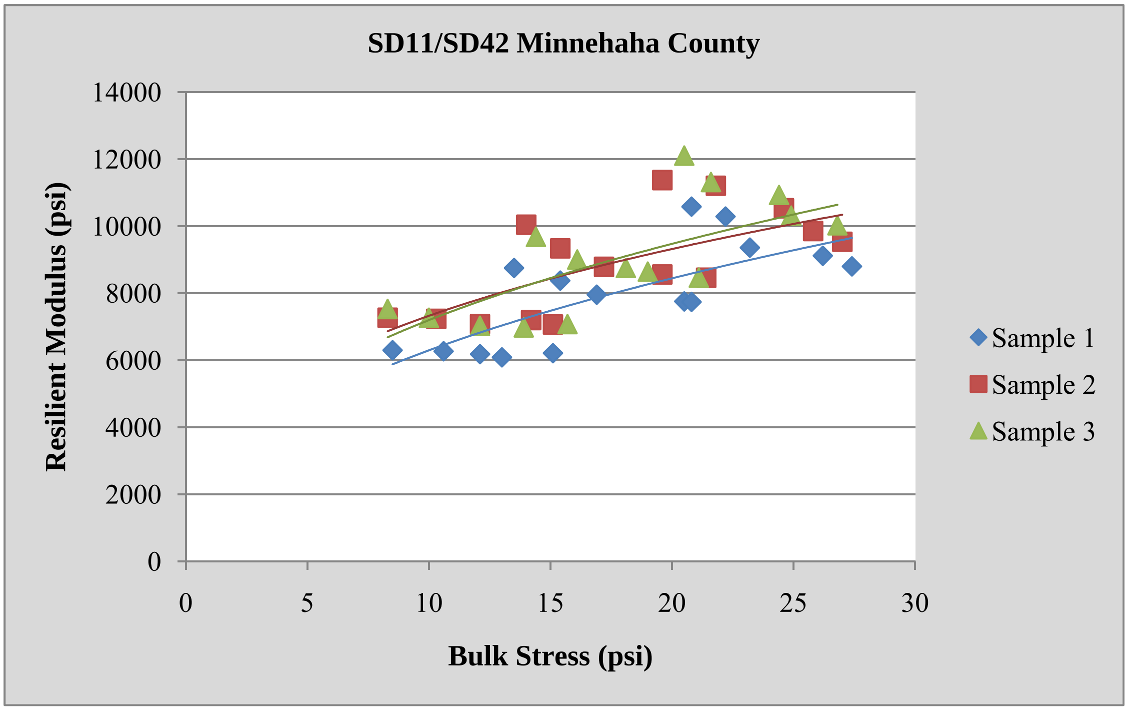


Figure 49: Resilient Modulus vs. Bulk Stress, SD11/SD42 Minnehaha

Table 48: Resilient Modulus Coefficients, SD11/SD42 Minnehaha

Sample	k_1	k_2	k_3	w(%) target = 13 ± 0.5%	R^2	M_R value with σ_3=2psi & σ_d=6psi*
1	666.44	0.60	-1.90	13.14	0.98	6,209
2	746.10	0.53	-1.86	13.09	0.97	7,100
3	758.48	0.58	-1.93	13.08	0.97	7,057
average	723.67	0.57	-1.90	13.10		6,787
std dev	49.95	0.04	0.04	0.03		503
CV	6.90%	6.33%	1.85%	0.25%		7.41%

* Estimated typical stress values for subgrade layer within a multi-layered pavement.

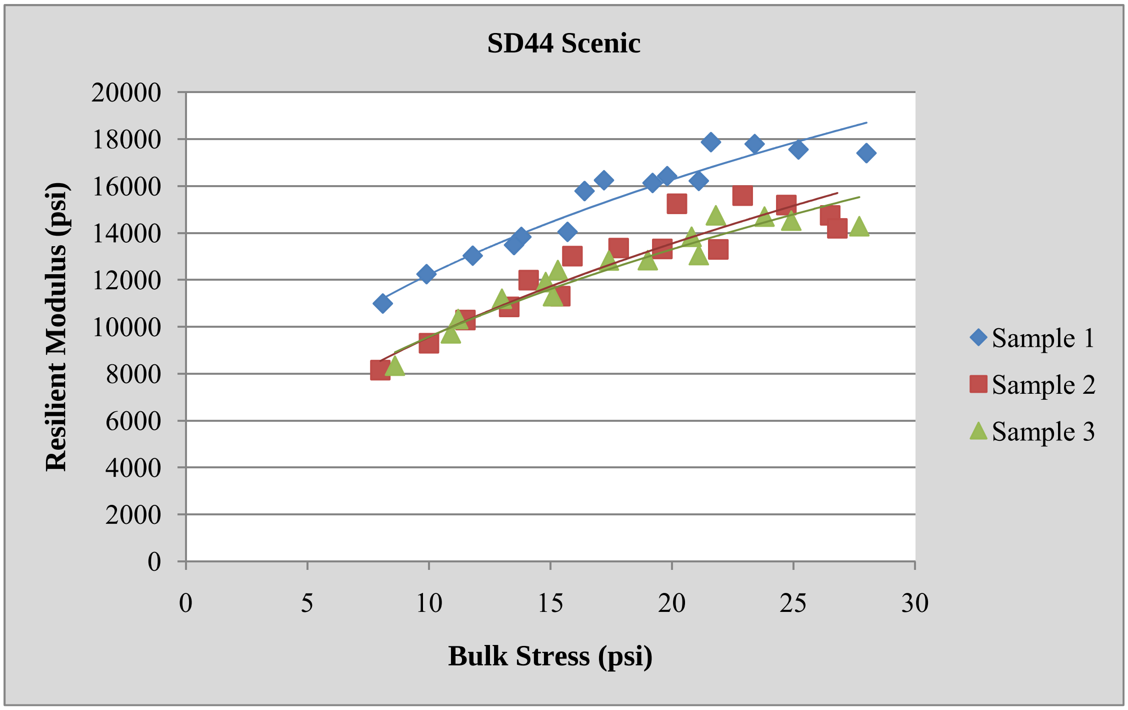


Figure 50: Resilient Modulus vs. Bulk Stress, SD44 Scenic

Table 49: Resilient Modulus Coefficients, SD44 Scenic

Sample	k_1	k_2	k_3	w(%) target = 19.5 ± 0.5%	R^2	M_R value with σ_3=2psi & σ_d=6psi*
1	1025.93	0.45	-0.35	18.99	0.96	12,943
2	881.70	0.57	-0.75	19.4	0.96	10,118
3	818.50	0.50	-0.31	19.9	0.95	10,294
average	908.71	0.51	-0.47	19.43		11,096
std dev	106.32	0.06	0.24	0.46		1,583
CV	11.70%	11.90%	51.77%	2.35%		14.26%

* Estimated typical stress values for subgrade layer within a multi-layered pavement.

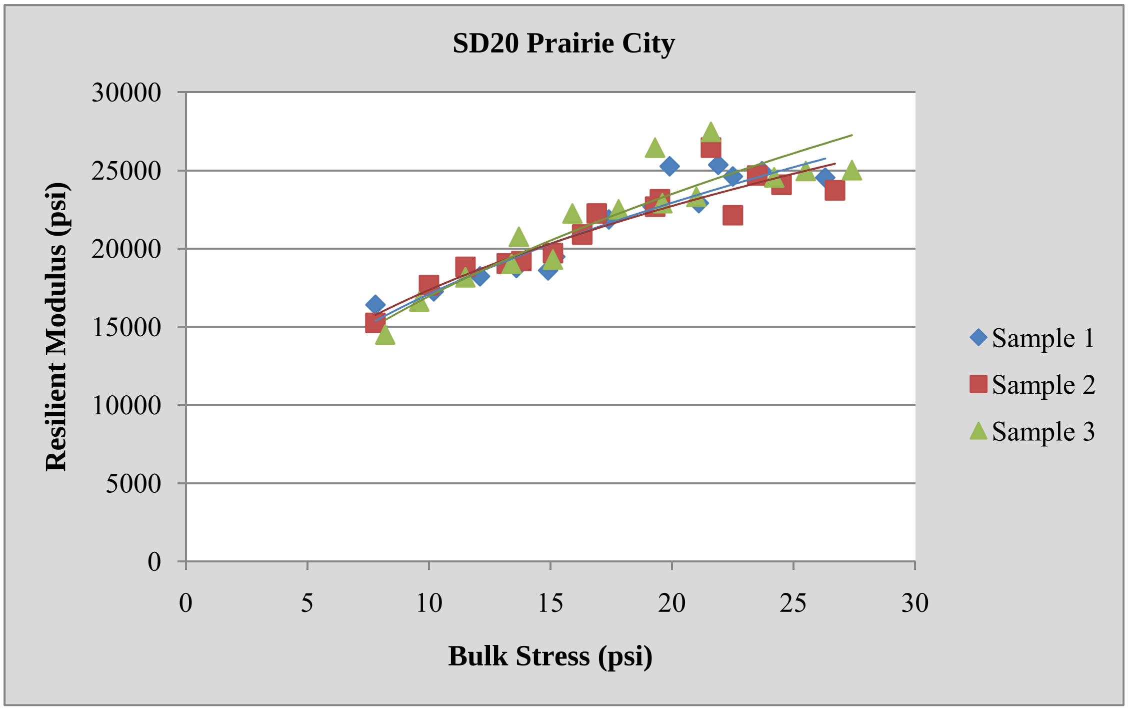


Figure 51: Resilient Modulus vs. Bulk Stress, SD20 Prairie City

Table 50: Resilient Modulus Coefficients, SD20 Prairie City

Sample	k_1	k_2	k_3	w(%) target = 11.7 ± 0.5%	R^2	M_R value with σ_3=2psi & σ_d=6psi*
1	1450.06	0.47	-0.40	11.4	0.92	18,060
2	1449.80	0.43	-0.37	11.8	0.92	18,300
3	1548.02	0.54	-0.77	11.2	0.94	17,810
average	1482.63	0.48	-0.51	11.47		18,064
std dev	56.63	0.06	0.22	0.31		245
CV	3.82%	11.60%	43.40%	2.66%		1.36%

* Estimated typical stress values for subgrade layer within a multi-layered pavement.

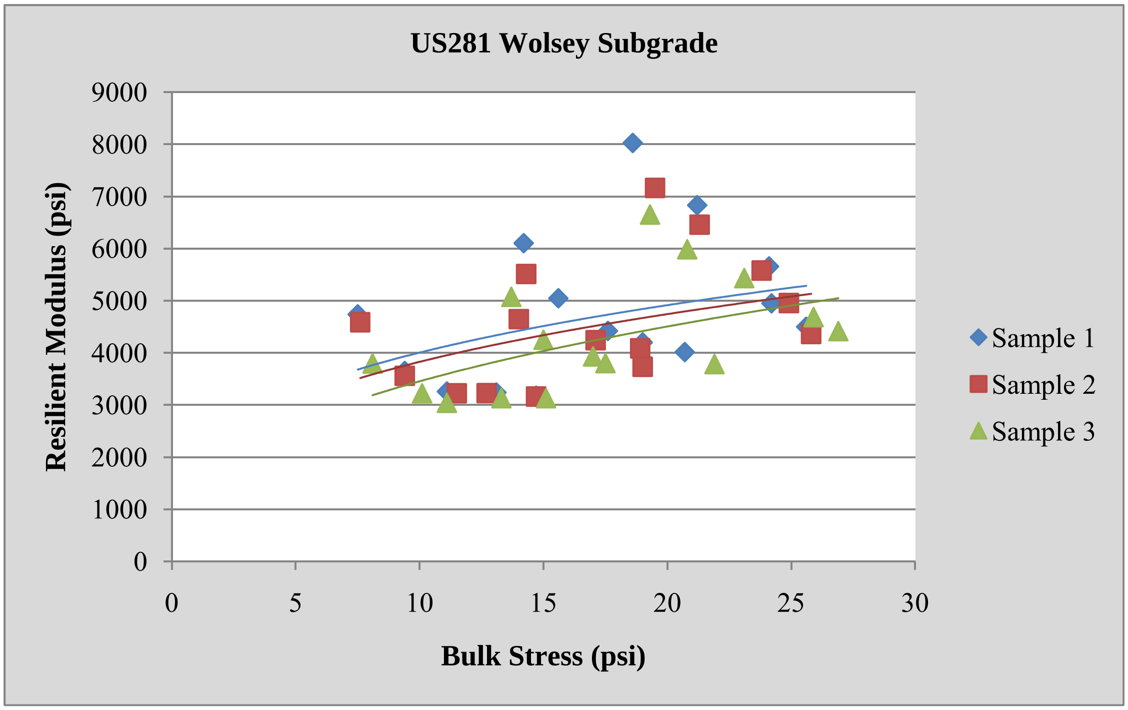


Figure 52: Resilient Modulus vs. Bulk Stress, US281 Wolsey Subgrade

Table 51: Resilient Modulus Coefficients, US281 Wolsey Subgrade

Sample	k_1	k_2	k_3	w(%) target = 18.5 ± 0.5%	R^2	M_R value with σ_3=2psi & σ_d=6psi*
1	517.07	0.65	-3.73	18.3	0.94	3,456
2	477.18	0.60	-3.46	18.1	0.93	3,378
3	416.33	0.69	-3.07	18.5	0.96	3,100
average	470.20	0.65	-3.42	18.30		3,321
std dev	50.73	0.05	0.33	0.20		188
CV	10.79%	6.97%	9.70%	1.09%		5.65%

* Estimated typical stress values for subgrade layer within a multi-layered pavement.

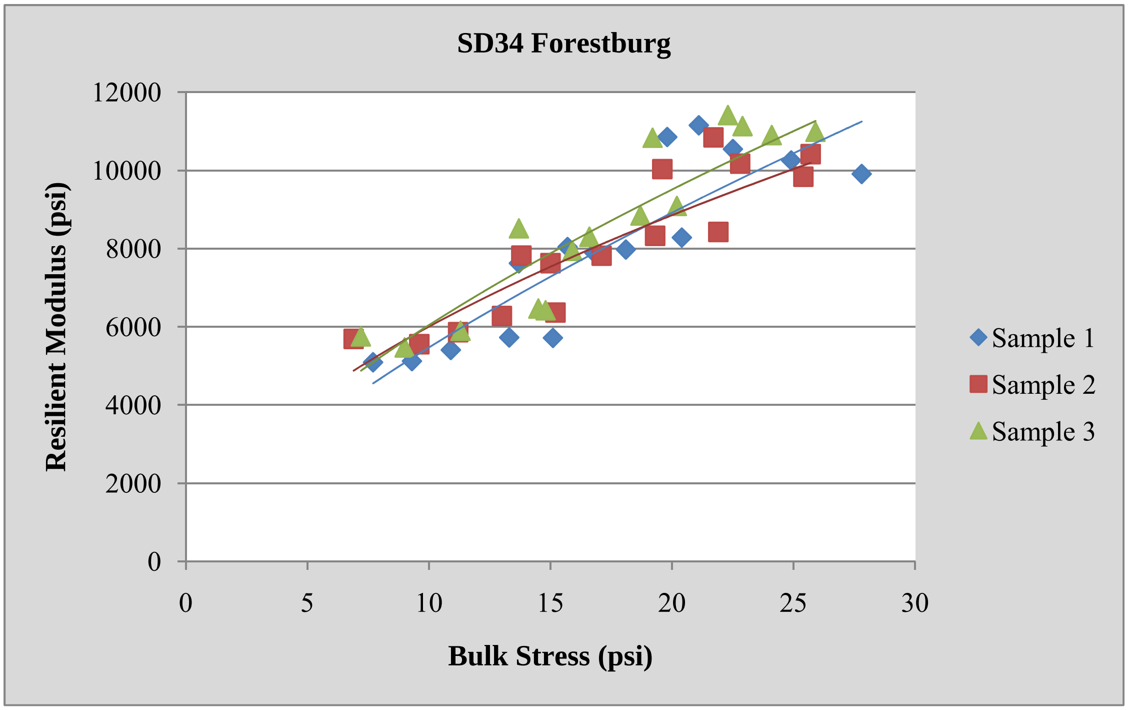


Figure 53: Resilient Modulus vs. Bulk Stress, SD34 Forestburg

Table 52: Resilient Modulus Coefficients, SD34 Forestburg

Sample	k_1	k_2	k_3	w(%) target = 11.5 ± 0.5%	R^2	M_R value with σ_3=2psi & σ_d=6psi*
1	645.21	0.88	-1.95	11.8	0.99	5,629
2	621.87	0.69	-1.41	11.3	0.95	6,201
3	650.77	0.78	-1.43	11.2	0.95	6,349
average	639.28	0.78	-1.60	11.43		6,053
std dev	15.34	0.10	0.31	0.32		380
CV	2.40%	12.13%	19.17%	2.81%		6.28%

* Estimated typical stress values for subgrade layer within a multi-layered pavement.

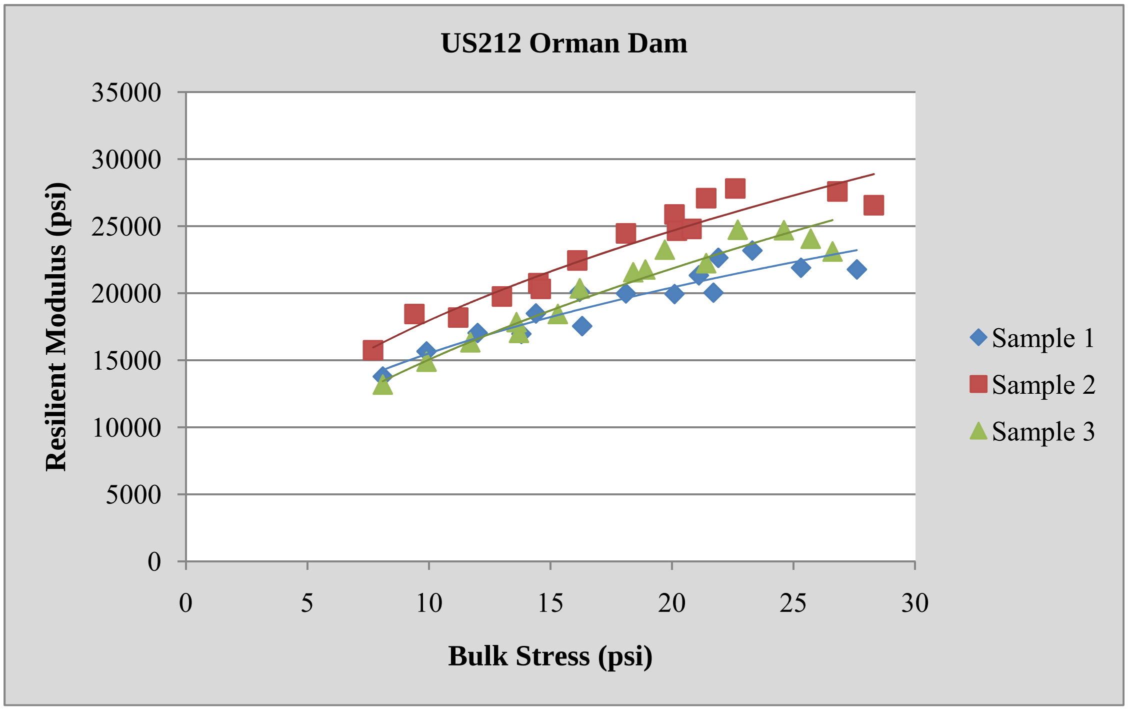


Figure 54: Resilient Modulus vs. Bulk Stress, US212 Orman Dam

Table 53: Resilient Modulus Coefficients, US212 Orman Dam

Sample	k_1	k_2	k_3	w(%) target = 11 ± 0.5%	R^2	M_R value with σ_3=2psi & σ_d=6psi*
1	1331.89	0.45	-0.55	10.6	0.95	16,222
2	1547.45	0.49	-0.40	10.5	0.96	19,194
3	1319.41	0.57	-0.32	11.1	0.96	16,331
average	1399.58	0.50	-0.42	10.73		17,243
std dev	128.21	0.06	0.12	0.32		1,686
CV	9.16%	12.14%	27.58%	2.99%		9.78%

* Estimated typical stress values for subgrade layer within a multi-layered pavement.

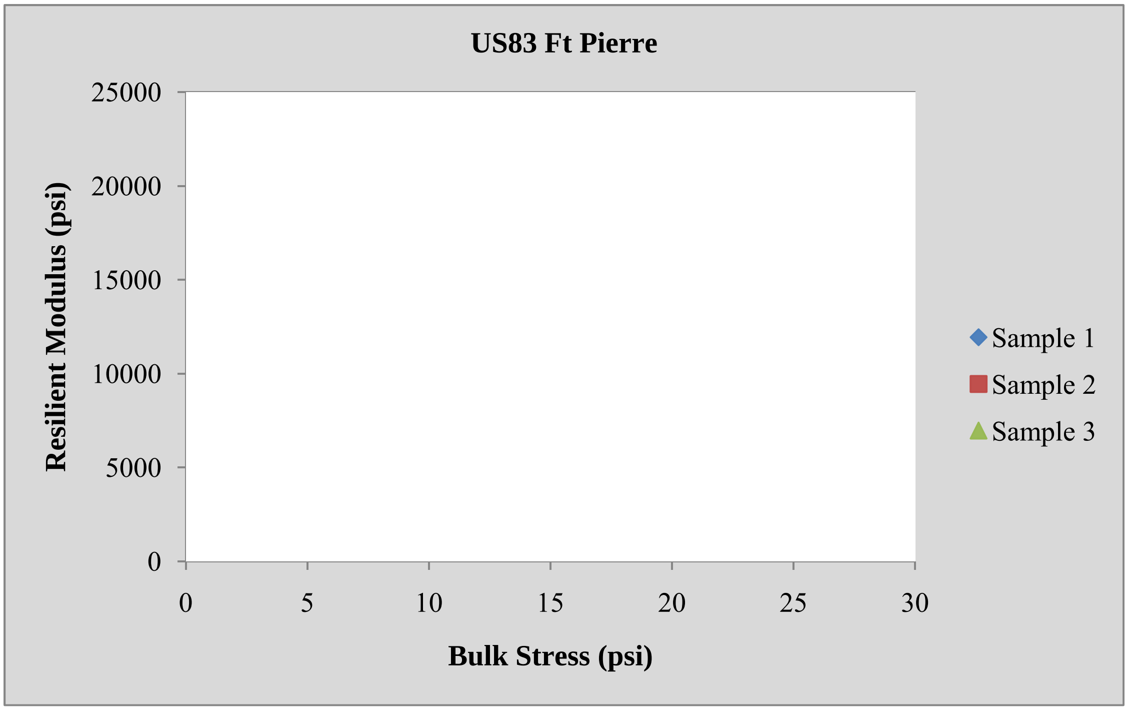


Figure 55: Resilient Modulus vs. Bulk Stress, US83 Ft Pierre

Table 54: Resilient Modulus Coefficients, US83 Ft Pierre

Sample	k_1	k_2	k_3	w(%) target = 21.5 ± 0.5%	R^2	M_R value with σ_3=2psi & σ_d=6psi*
1	1105.95	0.35	-0.06	21.2	0.92	14,984
2	1131.81	0.34	0.14	21.6	0.92	15,916
3	958.62	0.34	0.19	21.1	0.90	13,599
average	1065.46	0.34	0.09	21.30		14,841
std dev	93.42	0.01	0.13	0.26		1,165
CV	8.77%	1.68%	146.99%	1.24%		7.85%

* Estimated typical stress values for subgrade layer within a multi-layered pavement.

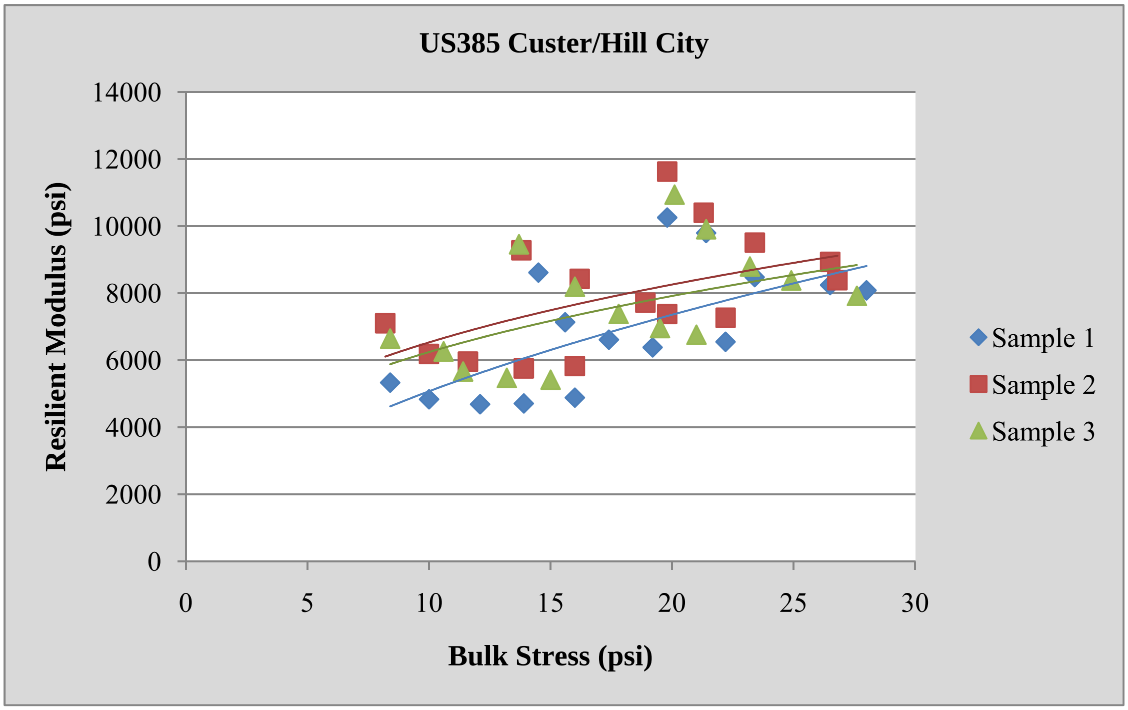


Figure 56: Resilient Modulus vs. Bulk Stress, US385 Custer/Hill City

Table 55: Resilient Modulus Coefficients, US385 Custer/Hill City

Sample	k_1	k_2	k_3	w(%) target = 11 ± 0.5%	R^2	M_R value with σ_3=2psi & σ_d=6psi*
1	673.85	0.86	-3.18	11.47	0.97	4,754
2	759.58	0.63	-2.83	10.7	0.97	5,971
3	737.48	0.61	-2.86	10.7	0.98	5,791
average	723.64	0.70	-2.96	10.96		5,485
std dev	44.51	0.14	0.19	0.44		657
CV	6.15%	19.85%	6.56%	4.06%		11.99%

* Estimated typical stress values for subgrade layer within a multi-layered pavement.

5.9 Summary

In general, it was possible to regress the data from all resilient modulus tests in order to obtain the k_1, k_2, and k_3 coefficients. As observed from Tables 46 to 55, the value of the squared correlation coefficient, R^2, was above 0.90 for all the regression analyses while the coefficient of variation (CV) values within samples were generally less than 30%. For comparison purposes, several additional constitutive models were utilized to regress and analyze the data. The additional constitutive models investigated included the following:

Virginia Model 1: $M_r = k_1 \cdot (\sigma_3)^{k2} \cdot (\sigma_d)^{k3}$

Virginia Model 2: $\mathrm{M_r} = \mathrm{k_1} \cdot \mathrm{Pa} \cdot \left[\frac{\theta}{\mathrm{Pa}}\right]^{\mathrm{k_2}} \cdot \left[\frac{\sigma_d}{\mathrm{Pa}}\right]^{\mathrm{k_3}}$

Virginia Model 1 (normalized): $\mathrm{M_r} = \mathrm{k_1} \cdot \left[\frac{\sigma_3}{\mathrm{Pa}}\right]^{\mathrm{k_2}} \cdot \left[\frac{\sigma_d}{\mathrm{Pa}}\right]^{\mathrm{k_3}}$

Moossazadeh & Witczak (1981): $\mathrm{M_r} = \mathrm{k_1} \cdot \left[\frac{\sigma_d}{\mathrm{Pa}}\right]^{\mathrm{k_2}}$

Seed (1967): $\mathrm{M_r} = \mathrm{k_1} \cdot \left[\frac{\theta}{\mathrm{Pa}}\right]^{\mathrm{k_2}}$

Seed (1967 without atmospheric pressure): $M_r = k_1 \cdot \theta^{k2}$

After performing a regression analysis with the additional models, the regression data indicated that the MEPDG model was the best statistical fit to the subgrade materials. The results of the regression analyses utilizing the additional models are provided in the Appendices.

Table 56 is a summary of all the soil properties for the subgrade materials tested.

Table 56: Summary of Soil Properties

Material	Classification	% Gravel	% Sand	% Silt	% Clay	PI	MDD, pcf	OMC, %	CBR	Saturated CBR	k_1	k_2	k_3	M_R value with σ_3=2psi & σ_d=6psi*
SD34 Lee's Corner	A-7-6 CH sandy fat clay	6.5	25.3	20.0	48.2	47	89.5	26	13.9	2.33	777.62	0.25	-1.27	8,690
I-90 by Blackhawk	A-4 CL-ML sandy silty clay	0.2	30.6	55.6	13.6	7	124	12	24.7	9.68	1019.60	0.75	-1.50	9,886
SD11/SD42 Minnehaha	A-4 ML silt	0.2	6.6	74.9	18.3	2	111	13	22.9	16.57	723.67	0.57	-1.90	6,787
SD44 E of Scenic	A-7-5 CH fat clay	1.2	11.3	36.8	50.8	73	103	19.5	23.2	3.49	908.71	0.51	-0.47	11,096
SD20 E of Prairie City	A-6 CL lean clay with sand	2.6	19.8	56.1	21.5	11	120.5	11.7	28.1	3.13	1482.63	0.48	-0.51	18,064
US281 Wolsey	A-6 CL SC clayey sand	11.2	49.9	22.1	16.8	15	103	18.5	2.2	2.37	470.20	0.65	-3.42	3,321
SD34 Forestburg	A-2-4 SM silty sand	1.9	74	14.1	10.0	NP	114	11.5	10.3	6.91	639.28	0.78	-1.60	6,053
US212 Orman Dam	A-4 CL-ML sandy silty clay	11.4	39.1	34.5	15.0	7	119	11	21.8	7.26	1399.58	0.50	-0.42	17,243
US83 Ft Pierre	A-7-6 CH fat clay	0.5	5.6	39.7	54.2	50	97.5	21.5	22.8	1.87	1065.46	0.34	0.09	14,841
US385 Custer/Hill City	A-2-4 SM silty sand with gravel	33.1	35.6	26.2	5.1	0	120.5	11	10.9	4.49	723.64	0.70	-2.96	5,485
US212 Subgrade (Task 4)	A-4 CL sandy lean clay	1.5	34.9	35.4	28.2	10	120.5	10.5	13.5	1.92	1687.57	0.38	-0.02	22,870

* Estimated typical stress values for subgrade layer within a multi-layered pavement.

A predictive equation was developed in order to provide a relationship between the resilient modulus and the gradation and CBR of the subgrade soils. Data from laboratory testing of the subgrade soils with a plasticity index (PI) less than 40 was utilized, along with multiple variable regression, to develop the predictive equation. The resilient modulus predictive equation for subgrade soils with a PI < 40 is:

$$M_r = 10^{0.089 \cdot Ret_{3/8} - 0.063 \cdot G - 0.013 \cdot M + 0.037 \cdot C + 0.035 \cdot CBR + 3.335} \quad (11)$$

where:

M_r = resilient modulus, psi
$Ret_{3/8}$ = percentage retained on 3/8 sieve
G = percentage of gravel
M = percentage of silt
C = percentage of clay
CBR = California Bearing Ratio at OMC

The value of the squared correlation coefficient, R^2, from the regression was 0.99. The pertinent statistical data from the regression analysis used to develop the predictive equation is given in Figure 57. The statistical data indicates all variables are significant and that the equation is a good fit to the data. Testing of additional subgrade materials may further validate the developed predictive equation.

Regression Statistics	
Multiple R	0.999323832
R Square	0.998648122
Adjusted R Square	0.995268426
Standard Error	0.020379561
Observations	8

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	5	0.613612913	0.122723	295.4846	0.00337627
Residual	2	0.000830653	0.000415		
Total	7	0.614443566			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	3.334635592	0.038635662	86.30978	0.000134
X Variable 1	0.088756807	0.008825302	10.05708	0.009743
X Variable 2	-0.062610877	0.007018727	-8.92055	0.012335
X Variable 3	-0.012713317	0.000649972	-19.5598	0.002604
X Variable 4	0.037116673	0.00147453	25.17187	0.001574
X Variable 5	0.034677991	0.001611929	21.51335	0.002154

Figure 57: M_r Predictive Equation Statistical Data

Since only three subgrade materials contained a PI > 40, a regression analysis was not entirely possible to develop at predictive equation for these materials. Further database development based on the laboratory testing of higher PI subgrade soils will allow for future development of such a predictive equation.

CHAPTER 6 DYNAMIC MODULUS TEST RESULTS AND ANALYSIS

6.1 Introduction

This chapter presents all results from the dynamic modulus testing of 15 HMA pavement materials and 1 WMA pavement material sampled at the sites shown in Figure 58.

00H1: SD79 from Maverick Junction south to the Buffalo Gap Junction
00H2: US81 from Salem north to the Minor County Line
00H3: US12 from north of the Grand River Bridge to the Missouri River Bridge
00HK: US281 from SD34 to US18
00J2: SD44 from east Scenic to Canola Road
00J3: SD44 from Lennox east to I-29
00J5: SD46 from Bersford east to Iowa State Line
00J7: SD73 from Howes north
01CD: SD44 from east of Wanblee to the SD73 junction
01CN: SD44 from the east junction of US281 to the junction of SD37
01CP: SD20 from SD45 to Brentford
01CU: Hwy 34 from Farm Island turnoff east to the West Bend turnoff
001G: US212 eastbound lane from west of Bristol to west of Webster
000M: I-90 eastbound and westbound, various locations between Vivian to west of Kadoka
5930: US212 from Frankfort east to Doland

Figure 58: Sampling Locations for HMA Material

6.2 Dynamic Modulus Test

The following tables contain the results from the dynamic modulus testing of each sample which includes the dynamic modulus and phase angle. The average values from the three tests along with the coefficient of variation of the dynamic modulus and phase angle from the testing are also included.

Table 57: Dynamic Modulus and Phase Angle Values, 00H1 HMA

00H1		Sample 1		Sample 2		Sample 3		Average		CV	
Temp (^{o}C)	Frequency (Hz)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus	Phase Angle
4.4	25	1,163,136	15.96	983,752	19.04	1,063,891	18.62	1,070,260	17.87	8.4%	9.3%
	10	898,272	19.85	799,591	22.22	849,652	22.15	849,172	21.41	5.8%	6.3%
	5	765,942	21.84	672,218	24.50	706,222	24.73	714,794	23.69	6.6%	6.8%
	1	524,648	26.40	412,680	30.23	430,065	29.74	455,798	28.79	13.2%	7.2%
	0.5	406,838	28.51	338,908	31.41	348,671	30.95	364,805	30.29	10.1%	5.1%
	0.1	257,773	30.19	223,951	31.79	223,045	30.93	234,923	30.97	8.4%	2.6%
21.1	25	471,830	25.09	526,346	25.15	420,041	27.24	472,739	25.83	11.2%	4.7%
	10	346,175	27.32	384,595	27.33	296,505	29.47	342,425	28.04	12.9%	4.4%
	5	266,670	29.00	296,669	29.21	225,463	31.26	262,934	29.82	13.6%	4.2%
	1	147,048	32.08	159,891	32.52	122,426	31.99	143,122	32.20	13.3%	0.9%
	0.5	116,010	31.91	126,142	32.25	97,529	31.13	113,227	31.76	12.8%	1.8%
	0.1	75,801	28.64	83,810	28.62	66,076	26.91	75,229	28.06	11.8%	3.5%
37.8	25	182,928	24.01	208,432	24.06	171,329	23.65	187,563	23.91	10.1%	0.9%
	10	117,903	25.02	137,256	25.05	109,295	24.64	121,485	24.90	11.8%	0.9%
	5	90,405	24.53	105,955	24.20	83,851	24.32	93,404	24.35	12.2%	0.7%
	1	53,869	23.37	63,436	23.51	50,841	23.43	56,049	23.44	11.7%	0.3%
	0.5	46,397	22.01	53,698	23.13	45,066	21.75	48,387	22.30	9.6%	3.3%
	0.1	37,327	17.89	43,076	19.25	37,505	18.28	39,303	18.47	8.3%	3.8%
54	25	105,409	15.28	117,411	14.79	100,658	14.05	107,826	14.71	8.0%	4.2%
	10	59,538	16.11	68,607	15.71	58,799	15.37	62,315	15.73	8.8%	2.4%
	5	41,210	17.11	49,811	16.41	42,716	16.17	44,579	16.56	10.3%	2.9%
	1	30,083	15.50	37,986	15.01	32,900	14.74	33,656	15.08	11.9%	2.6%
	0.5	29,376	13.78	37,038	13.73	31,914	13.70	32,776	13.74	11.9%	0.3%
	0.1	27,019	11.54	35,324	11.77	30,194	11.36	30,845	11.56	13.6%	1.8%

Table 58: Dynamic Modulus and Phase Angle Values, 00H2 HMA

00H2		Sample 1		Sample 2		Sample 3		Average		CV	
Temp (^{o}C)	Frequency (Hz)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus	Phase Angle
4.4	25	1,598,039	12.91	1,489,010	11.87	1,553,447	11.57	1,546,832	12.12	3.5%	5.8%
	10	1,388,038	15.08	1,289,933	13.14	1,383,903	12.83	1,353,958	13.68	4.1%	8.9%
	5	1,226,793	16.85	1,157,080	14.61	1,251,952	14.05	1,211,942	15.17	4.1%	9.8%
	1	873,912	21.61	855,587	17.41	958,436	17.15	895,979	18.72	6.1%	13.4%
	0.5	743,807	23.43	748,638	18.94	841,466	18.39	777,970	20.25	7.1%	13.7%
	0.1	495,761	26.77	525,878	22.43	613,781	21.20	545,140	23.47	11.2%	12.5%
21.1	25	717,990	23.23	619,369	21.77	719,350	20.87	685,570	21.96	8.4%	5.4%
	10	543,249	26.33	479,524	23.88	575,934	22.52	532,902	24.24	9.2%	8.0%
	5	429,671	28.66	391,281	25.59	478,096	24.18	433,016	26.14	10.0%	8.8%
	1	234,713	32.97	228,650	29.52	288,374	27.94	250,579	30.14	13.1%	8.5%
	0.5	179,294	33.50	205,647	29.29	232,256	28.75	205,732	30.51	12.9%	8.5%
	0.1	103,976	30.54	110,354	29.20	146,463	28.45	120,264	29.40	19.1%	3.6%
37.8	25	229,109	27.94	229,817	27.78	295,018	24.55	251,314	26.76	15.1%	7.1%
	10	125,858	33.57	146,000	29.94	174,415	29.07	148,758	30.86	16.4%	7.7%
	5	95,092	32.61	107,866	30.00	133,023	29.84	111,994	30.82	17.2%	5.0%
	1	50,317	28.72	55,300	29.72	72,130	29.58	59,249	29.34	19.3%	1.8%
	0.5	40,644	26.20	44,072	27.29	56,668	27.99	47,128	27.16	17.9%	3.3%
	0.1	28,323	19.43	34,675	20.30	35,577	23.92	32,858	21.22	12.0%	11.2%
54	25	69,080	25.24	79,099	25.27	94,434	24.46	80,871	24.99	15.8%	1.8%
	10	44,161	22.19	49,702	23.61	59,180	23.95	51,014	23.25	14.9%	4.0%
	5	34,739	19.84	38,663	21.44	46,101	22.25	39,835	21.18	14.5%	5.8%
	1	22,859	15.62	26,127	16.53	30,607	17.99	26,531	16.71	14.7%	7.2%
	0.5	21,190	13.70	23,716	14.57	27,149	16.21	24,018	14.83	12.5%	8.6%
	0.1	19,032	10.57	20,653	11.40	22,363	12.57	20,683	11.51	8.1%	8.7%

Table 59: Dynamic Modulus and Phase Angle Values, 00H3 HMA

00H3		Sample 1		Sample 2		Sample 3		Average		CV	
Temp (°C)	Frequency (Hz)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus	Phase Angle
4.4	25	1,498,383	10.12	1,650,404	8.41	1,707,916	7.67	1,618,901	8.73	6.7%	14.4%
	10	1,330,887	12.12	1,437,497	10.07	1,485,066	9.70	1,417,817	10.63	5.6%	12.3%
	5	1,209,963	13.51	1,292,693	10.92	1,375,490	10.41	1,292,715	11.61	6.4%	14.3%
	1	930,976	17.26	1,035,717	14.43	1,112,939	13.26	1,026,544	14.98	8.9%	13.7%
	0.5	831,381	18.80	926,477	15.62	1,006,147	14.72	921,335	16.38	9.5%	13.1%
	0.1	586,079	23.09	694,037	19.48	760,313	18.43	680,143	20.33	12.9%	12.0%
21.1	25	684,729	21.00	810,091	18.58	909,058	17.48	801,293	19.02	14.0%	9.5%
	10	549,611	23.66	666,946	20.99	728,159	19.71	648,239	21.45	14.0%	9.4%
	5	452,268	26.01	556,682	23.17	617,595	21.90	542,182	23.69	15.4%	8.9%
	1	263,319	31.29	329,880	28.58	382,321	27.12	325,174	29.00	18.3%	7.3%
	0.5	203,260	32.94	256,958	30.28	303,110	29.17	254,443	30.80	19.6%	6.3%
	0.1	112,597	33.01	142,867	31.48	176,067	31.07	143,844	31.85	22.1%	3.2%
37.8	25	234,950	29.31	299,443	28.18	325,733	27.40	286,709	28.30	16.3%	3.4%
	10	151,488	32.07	195,825	30.43	216,618	30.18	187,977	30.89	17.7%	3.3%
	5	111,917	32.19	145,331	30.95	162,342	31.32	139,863	31.49	18.3%	2.0%
	1	56,360	31.30	74,102	30.53	81,362	31.93	70,608	31.25	18.2%	2.2%
	0.5	44,134	29.26	56,861	29.25	61,859	30.89	54,285	29.80	16.8%	3.2%
	0.1	29,485	22.66	37,893	22.62	39,655	25.20	35,678	23.49	15.2%	6.3%
54	25	90,424	26.78	99,361	23.95	107,817	25.45	99,201	25.39	8.8%	5.6%
	10	54,063	27.19	59,926	23.54	65,896	25.11	59,962	25.28	9.9%	7.2%
	5	39,953	25.33	43,751	22.37	49,329	23.71	44,344	23.80	10.6%	6.2%
	1	23,979	20.61	27,352	18.20	31,192	20.53	27,507	19.78	13.1%	6.9%
	0.5	19,407	19.03	23,931	16.24	26,829	17.26	23,389	17.51	16.0%	8.1%
	0.1	16,222	13.86	20,058	12.17	22,153	13.10	19,477	13.04	15.4%	6.5%

Table 60: Dynamic Modulus and Phase Angle Values, 00HK HMA

00HK		Sample 1		Sample 2		Sample 3		Average		CV	
Temp (°C)	Frequency (Hz)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus	Phase Angle
4.4	25	1,871,742	8.35	2,275,502	9.81	1,785,096	8.11	1,977,446	8.76	13.2%	10.5%
	10	1,718,414	9.35	2,048,586	10.86	1,677,226	9.26	1,814,742	9.82	11.2%	9.2%
	5	1,593,896	10.07	1,885,135	11.67	1,572,317	10.34	1,683,782	10.69	10.4%	8.0%
	1	1,315,161	12.34	1,580,031	15.19	1,283,242	12.76	1,392,811	13.43	11.7%	11.5%
	0.5	1,195,793	13.58	1,460,830	16.43	1,161,820	13.82	1,272,814	14.61	12.9%	10.8%
	0.1	919,405	16.68	1,090,129	20.33	898,801	17.00	969,445	18.00	10.8%	11.2%
21.1	25	985,187	16.44	1,240,895	17.94	1,070,990	15.86	1,099,024	16.75	11.8%	6.4%
	10	822,177	18.43	1,029,943	19.17	913,041	17.93	921,720	18.51	11.3%	3.4%
	5	710,388	19.89	883,867	20.89	793,452	19.69	795,902	20.16	10.9%	3.2%
	1	471,344	25.02	604,603	27.09	499,819	25.91	525,255	26.01	13.4%	4.0%
	0.5	383,386	27.14	503,231	30.13	412,201	27.48	432,939	28.25	14.4%	5.8%
	0.1	222,594	31.74	285,063	33.43	242,945	31.32	250,201	32.16	12.7%	3.5%
37.8	25	392,876	26.66	466,884	28.17	459,315	26.11	439,692	26.98	9.3%	4.0%
	10	294,330	27.98	345,624	30.18	342,308	27.92	327,421	28.69	8.8%	4.5%
	5	234,278	28.74	270,142	31.41	269,798	29.01	258,073	29.72	8.0%	4.9%
	1	130,919	30.62	145,260	33.92	148,252	31.16	141,477	31.90	6.5%	5.5%
	0.5	102,284	29.77	111,399	33.66	112,992	30.84	108,892	31.42	5.3%	6.4%
	0.1	65,574	27.18	65,979	29.76	69,379	27.74	66,977	28.23	3.1%	4.8%
54	25	168,349	34.22	153,156	36.21	164,231	32.10	161,912	34.18	4.9%	6.0%
	10	117,751	33.99	99,722	36.12	112,350	31.75	109,941	33.95	8.4%	6.4%
	5	91,383	33.21	79,191	32.81	86,030	30.76	85,534	32.26	7.1%	4.1%
	1	53,116	32.61	43,557	29.49	45,187	28.61	47,287	30.24	10.8%	7.0%
	0.5	44,043	27.02	36,115	27.63	38,205	26.51	39,454	27.05	10.4%	2.1%
	0.1	29,669	27.05	24,995	20.73	26,821	20.25	27,162	22.68	8.7%	16.7%

Table 61: Dynamic Modulus and Phase Angle Values, 00J2 HMA

00J2		Sample 1		Sample 2		Sample 3		Average		CV	
Temp (^oC)	Frequency (Hz)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus	Phase Angle
4.4	25	1,950,679	10.56	1,701,281	8.62	1,733,955	8.12	1,795,305	9.10	7.6%	14.2%
	10	1,760,375	12.64	1,490,242	11.06	1,553,724	9.95	1,601,447	11.22	8.8%	12.1%
	5	1,594,389	13.98	1,365,592	12.25	1,395,126	11.08	1,451,702	12.44	8.6%	11.7%
	1	1,223,162	17.65	1,070,933	15.55	1,118,355	13.76	1,137,483	15.65	6.8%	12.4%
	0.5	1,065,414	19.27	952,847	17.19	1,007,616	15.12	1,008,626	17.19	5.6%	12.1%
	0.1	763,310	22.93	696,454	20.91	767,390	18.38	742,385	20.74	5.4%	11.0%
21.1	25	906,856	19.69	776,800	19.54	828,932	18.42	837,529	19.22	7.8%	3.6%
	10	716,353	22.42	654,656	21.85	686,160	20.58	685,723	21.62	4.5%	4.4%
	5	590,320	24.41	518,989	24.04	583,077	22.38	564,129	23.61	7.0%	4.6%
	1	344,399	29.75	309,101	28.83	362,429	27.59	338,643	28.72	8.0%	3.8%
	0.5	272,582	30.80	244,929	30.13	303,063	28.62	273,525	29.85	10.6%	3.7%
	0.1	152,969	31.66	144,802	30.95	178,629	30.66	158,800	31.09	11.1%	1.7%
37.8	25	302,766	26.76	304,920	26.37	359,227	25.58	322,305	26.24	9.9%	2.3%
	10	199,901	29.17	199,775	29.00	241,532	28.32	213,736	28.83	11.3%	1.6%
	5	150,497	29.33	150,399	29.37	182,409	29.30	161,102	29.33	11.5%	0.1%
	1	80,478	28.94	79,612	29.29	95,855	30.70	85,315	29.64	10.7%	3.1%
	0.5	63,729	27.55	63,109	27.86	75,070	29.87	67,303	28.43	10.0%	4.4%
	0.1	44,255	21.72	43,525	22.56	48,510	25.73	45,430	23.34	5.9%	9.1%
54	25	144,863	24.60	129,482	24.47	144,711	25.87	139,685	24.98	6.3%	3.1%
	10	87,518	25.66	77,723	24.43	86,302	27.08	83,848	25.72	6.4%	5.2%
	5	65,170	25.02	59,150	23.81	62,621	26.93	62,313	25.25	4.8%	6.2%
	1	39,478	21.26	36,929	20.10	36,116	24.15	37,508	21.84	4.7%	9.6%
	0.5	33,938	19.24	31,886	18.36	30,045	22.44	31,956	20.01	6.1%	10.7%
	0.1	27,019	14.43	25,476	13.82	22,602	17.98	25,032	15.41	9.0%	14.6%

Table 62: Dynamic Modulus and Phase Angle Values, 00J3 HMA

00J3		Sample 1		Sample 2		Sample 3		Average		CV	
Temp (°C)	Frequency (Hz)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus	Phase Angle
4.4	25	1,642,842	9.38	1,735,796	7.91	1,781,413	8.77	1,720,017	8.69	4.1%	8.5%
	10	1,491,208	10.67	1,602,927	9.61	1,624,067	11.00	1,572,734	10.43	4.5%	7.0%
	5	1,368,234	11.69	1,494,908	10.48	1,494,196	12.14	1,452,446	11.44	5.0%	7.5%
	1	1,089,352	14.31	1,232,196	13.01	1,191,739	15.23	1,171,096	14.18	6.3%	7.9%
	0.5	978,200	15.51	1,115,995	14.08	1,061,629	16.50	1,051,941	15.36	6.6%	7.9%
	0.1	741,851	18.71	866,051	17.04	788,086	19.84	798,663	18.53	7.9%	7.6%
21.1	25	784,325	18.54	1,132,295	16.55	989,852	23.06	968,824	19.38	18.1%	17.2%
	10	641,789	20.79	1,010,667	18.78	834,799	25.39	829,085	21.65	22.3%	15.6%
	5	579,173	21.53	869,873	20.67	706,768	27.83	718,605	23.34	20.3%	16.7%
	1	347,474	27.23	589,433	25.97	431,540	33.02	456,149	28.74	26.9%	13.1%
	0.5	282,612	28.92	489,740	28.45	344,406	34.54	372,253	30.64	28.6%	11.1%
	0.1	175,995	30.68	309,260	31.84	200,141	36.06	228,465	32.86	31.1%	8.6%
37.8	25	383,497	26.83	384,890	28.00	324,612	26.40	364,333	27.08	9.4%	3.1%
	10	271,622	29.30	277,812	30.73	223,127	29.15	257,520	29.73	11.6%	2.9%
	5	211,501	30.44	218,635	31.93	170,108	30.10	200,081	30.82	13.1%	3.2%
	1	115,288	32.35	116,957	35.35	89,660	31.24	107,301	32.98	14.3%	6.4%
	0.5	91,769	31.94	92,211	33.46	69,326	30.21	84,435	31.87	15.5%	5.1%
	0.1	56,401	28.92	55,751	31.84	42,388	25.96	51,513	28.91	15.4%	10.2%
54	25	131,550	27.25	130,758	25.59	112,590	25.71	124,966	26.18	8.6%	3.5%
	10	84,693	28.13	77,935	26.81	69,938	27.05	77,522	27.33	9.5%	2.6%
	5	64,945	27.13	59,352	25.87	53,072	25.67	59,123	26.22	10.0%	3.0%
	1	40,199	23.81	38,751	21.48	33,840	21.40	37,597	22.23	8.9%	6.2%
	0.5	33,437	27.86	34,005	19.87	29,634	19.44	32,359	22.39	7.3%	21.2%
	0.1	25,012	18.77	25,836	18.74	23,461	15.88	24,770	17.80	4.9%	9.3%

Table 63: Dynamic Modulus and Phase Angle Values, 00J5 HMA

00J5		Sample 1		Sample 2		Sample 3		Average		CV	
Temp (°C)	Frequency (Hz)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus	Phase Angle
4.4	25	1,923,409	11.94	2,224,510	10.58	2,076,982	12.46	2,074,967	11.66	7.3%	8.3%
	10	1,682,252	14.27	1,968,229	12.31	1,761,383	14.51	1,803,955	13.70	8.2%	8.8%
	5	1,508,950	15.69	1,773,169	13.71	1,556,950	15.99	1,613,023	15.13	8.7%	8.2%
	1	1,134,739	19.94	1,364,453	17.26	1,171,562	20.52	1,223,585	19.24	10.1%	9.0%
	0.5	1,009,631	21.86	1,207,777	18.79	1,040,244	22.60	1,085,884	21.08	9.8%	9.6%
	0.1	688,637	26.41	817,720	23.05	677,222	27.31	727,860	25.59	10.7%	8.8%
21.1	25	880,886	22.22	897,162	21.03	680,038	26.56	819,362	23.27	14.8%	12.5%
	10	694,301	24.69	708,691	23.56	512,043	28.87	638,345	25.71	17.2%	10.9%
	5	566,548	26.76	582,851	25.47	403,997	31.09	517,799	27.77	19.1%	10.6%
	1	312,352	33.45	332,884	31.75	215,322	36.02	286,853	33.74	21.9%	6.4%
	0.5	237,117	35.31	254,813	33.52	162,093	37.29	218,007	35.37	22.6%	5.3%
	0.1	125,473	35.39	139,092	34.41	87,857	34.53	117,474	34.78	22.6%	1.5%
37.8	25	274,411	31.51	234,479	32.43	188,729	34.82	232,540	32.92	18.4%	5.2%
	10	187,088	32.30	159,897	32.88	127,468	33.93	158,151	33.04	18.9%	2.5%
	5	142,381	31.69	121,880	32.11	95,405	32.85	119,889	32.22	19.6%	1.8%
	1	77,374	29.42	66,506	29.79	54,424	29.04	66,101	29.42	17.4%	1.3%
	0.5	62,873	27.03	54,461	27.34	45,548	25.79	54,294	26.72	16.0%	3.1%
	0.1	43,584	20.77	37,088	21.23	33,174	19.65	37,949	20.55	13.9%	4.0%
54	25	77,161	32.83	66,516	33.51	62,121	34.91	68,599	33.75	11.3%	3.1%
	10	55,545	29.02	46,959	30.69	44,296	30.50	48,933	30.07	12.0%	3.0%
	5	42,805	27.26	37,686	28.10	35,570	27.57	38,687	27.64	9.6%	1.5%
	1	29,578	20.54	25,988	24.48	24,490	21.84	26,685	22.29	9.8%	9.0%
	0.5	26,340	18.72	23,415	21.24	21,977	19.07	23,911	19.68	9.3%	6.9%
	0.1	21,252	12.97	19,019	15.81	17,163	16.04	19,145	14.94	10.7%	11.4%

Table 64: Dynamic Modulus and Phase Angle Values, 00J7 HMA

00J7		Sample 1		Sample 2		Sample 3		Average		CV	
Temp (^oC)	Frequency (Hz)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus	Phase Angle
4.4	25	1,062,058	12.91	1,014,193	11.62	1,231,912	14.53	1,102,721	13.02	10.4%	11.2%
	10	923,011	14.64	872,372	12.96	1,061,240	16.42	952,207	14.67	10.3%	11.8%
	5	837,220	16.08	781,303	13.86	944,508	18.24	854,344	16.06	9.7%	13.6%
	1	629,217	19.07	596,906	16.12	661,254	22.68	629,126	19.29	5.1%	17.0%
	0.5	536,490	20.13	531,229	17.05	574,710	24.50	547,476	20.56	4.3%	18.2%
	0.1	383,772	22.52	397,013	19.29	393,806	26.27	391,530	22.69	1.8%	15.4%
21.1	25	506,483	24.67	558,577	19.62	525,953	25.16	530,338	23.15	5.0%	13.2%
	10	407,168	26.29	454,480	21.10	414,480	26.72	425,376	24.70	6.0%	12.7%
	5	338,861	27.74	385,031	22.48	336,842	28.41	353,578	26.21	7.7%	12.4%
	1	222,996	29.51	237,658	26.95	192,563	32.70	217,739	29.72	10.6%	9.7%
	0.5	172,057	31.53	216,557	26.70	153,079	33.25	180,564	30.49	18.0%	11.1%
	0.1	120,390	29.98	133,757	28.62	102,517	30.80	118,888	29.80	13.2%	3.7%
37.8	25	222,047	23.16	263,202	22.77	264,616	28.11	249,955	24.68	9.7%	12.1%
	10	153,474	24.74	193,717	24.17	182,431	28.77	176,541	25.89	11.8%	9.7%
	5	121,895	25.31	157,525	24.75	142,603	28.91	140,674	26.32	12.7%	8.6%
	1	72,997	26.40	96,362	26.57	83,494	29.97	84,284	27.65	13.9%	7.3%
	0.5	60,680	25.79	81,304	26.16	69,816	29.36	70,600	27.10	14.6%	7.2%
	0.1	42,528	23.62	57,789	24.50	51,086	25.85	50,467	24.66	15.2%	4.6%
54	25	263,692	19.24	159,452	21.54	167,006	25.83	196,717	22.20	29.5%	15.1%
	10	158,889	21.52	109,749	23.06	112,433	26.69	127,023	23.76	21.8%	11.2%
	5	119,071	20.37	86,961	23.11	88,848	27.22	98,293	23.57	18.3%	14.6%
	1	69,018	20.12	48,641	24.23	54,870	29.41	57,510	24.59	18.2%	18.9%
	0.5	61,579	18.98	44,457	23.93	45,949	28.46	50,662	23.79	18.7%	19.9%
	0.1	42,808	15.76	32,325	21.68	33,295	23.22	36,143	20.22	16.0%	19.5%

Table 65: Dynamic Modulus and Phase Angle Values, 01CD HMA

01CD		Sample 1		Sample 2		Sample 3		Average		CV	
Temp (^{o}C)	Frequency (Hz)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus	Phase Angle
4.4	25	1,096,926	10.22	1,614,591	9.73	1,377,889	10.70	1,363,135	10.22	19.0%	4.7%
	10	945,550	11.75	1,449,174	11.50	1,197,134	12.91	1,197,286	12.05	21.0%	6.2%
	5	862,210	13.03	1,324,739	12.68	1,141,785	14.04	1,109,578	13.25	21.0%	5.3%
	1	721,760	15.88	1,070,095	15.55	813,572	18.13	868,475	16.52	20.8%	8.5%
	0.5	607,363	17.38	920,443	17.35	717,894	19.93	748,567	18.22	21.2%	8.1%
	0.1	450,507	20.87	687,398	20.76	512,396	23.97	550,100	21.87	22.3%	8.3%
21.1	25	620,401	18.79	747,672	19.72	650,373	22.07	672,815	20.19	9.9%	8.4%
	10	503,548	21.96	607,744	21.65	512,379	24.33	541,223	22.65	10.7%	6.5%
	5	441,207	23.79	510,333	23.53	418,820	26.45	456,787	24.59	10.4%	6.6%
	1	249,648	28.68	311,723	28.43	238,269	31.20	266,546	29.44	14.8%	5.2%
	0.5	197,652	30.24	241,064	29.98	183,157	32.32	207,291	30.85	14.5%	4.2%
	0.1	117,493	30.97	142,417	30.82	107,498	31.04	122,469	30.94	14.7%	0.4%
37.8	25	242,970	26.82	256,966	27.01	254,665	27.71	251,534	27.18	3.0%	1.7%
	10	158,849	29.54	174,444	28.23	166,326	30.08	166,540	29.28	4.7%	3.2%
	5	117,524	30.51	133,462	28.53	123,574	30.36	124,854	29.80	6.4%	3.7%
	1	61,172	30.27	72,855	28.16	64,144	29.56	66,057	29.33	9.2%	3.7%
	0.5	48,184	28.90	58,495	26.93	50,484	27.83	52,388	27.89	10.3%	3.5%
	0.1	32,661	23.11	39,799	21.88	35,197	21.75	35,885	22.25	10.1%	3.4%
54	25	106,710	25.13	122,840	24.07	113,039	25.53	114,197	24.91	7.1%	3.0%
	10	64,741	26.04	76,285	24.93	67,259	25.43	69,428	25.47	8.7%	2.2%
	5	46,576	25.57	56,187	24.22	49,119	24.36	50,627	24.72	9.8%	3.0%
	1	28,288	20.76	33,806	20.59	28,168	20.20	30,087	20.52	10.7%	1.4%
	0.5	24,389	18.21	28,137	18.84	24,936	17.85	25,821	18.30	7.8%	2.7%
	0.1	19,790	12.82	22,711	13.51	20,016	13.34	20,839	13.22	7.8%	2.7%

Table 66: Dynamic Modulus and Phase Angle Values, 01CN HMA

01CN		Sample 1		Sample 2		Sample 3		Average		CV	
Temp (°C)	Frequency (Hz)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus	Phase Angle
4.4	25	1,600,707	10.82	1,498,347	10.19	1,548,462	8.10	1,549,172	9.70	3.3%	14.7%
	10	1,465,057	12.81	1,412,947	11.98	1,404,755	8.98	1,427,586	11.26	2.3%	17.9%
	5	1,317,747	14.17	1,286,425	13.26	1,328,148	9.86	1,310,773	12.43	1.7%	18.3%
	1	994,329	18.09	924,082	17.45	1,091,453	11.88	1,003,288	15.81	8.4%	21.6%
	0.5	830,394	20.30	860,129	18.69	987,938	12.79	892,820	17.26	9.4%	22.9%
	0.1	587,848	23.84	597,024	22.87	769,765	15.36	651,546	20.69	15.7%	22.4%
21.1	25	681,925	21.52	654,388	21.06	728,725	17.54	688,346	20.04	5.5%	10.9%
	10	529,540	24.56	516,419	23.73	588,301	19.40	544,753	22.56	7.0%	12.3%
	5	428,864	26.63	423,602	25.50	502,115	20.94	451,527	24.36	9.7%	12.4%
	1	241,840	31.63	229,153	30.98	334,113	24.65	268,369	29.09	21.3%	13.3%
	0.5	185,202	32.85	186,584	31.54	270,262	26.02	214,016	30.14	22.8%	12.0%
	0.1	105,437	31.65	104,038	30.61	176,162	27.28	128,545	29.85	32.1%	7.6%
37.8	25	242,217	28.34	234,621	27.02	341,620	24.69	272,819	26.68	21.9%	6.9%
	10	152,895	30.23	151,927	29.06	258,050	25.93	187,624	28.41	32.5%	7.8%
	5	117,027	30.56	112,753	29.36	207,255	26.57	145,678	28.83	36.6%	7.1%
	1	60,867	30.01	58,760	28.40	120,573	28.19	80,067	28.87	43.8%	3.4%
	0.5	48,048	28.12	46,762	26.97	94,387	27.87	63,065	27.65	43.0%	2.2%
	0.1	33,026	21.85	33,329	20.30	60,819	25.65	42,391	22.60	37.6%	12.2%
54	25	108,727	25.04	103,755	22.99	129,757	30.81	114,080	26.28	12.1%	15.4%
	10	65,321	25.29	62,601	22.95	94,388	29.26	74,104	25.83	23.8%	12.3%
	5	45,682	24.13	45,674	22.20	73,250	28.46	54,869	24.93	29.0%	12.9%
	1	28,132	20.05	28,271	18.22	42,865	25.92	33,089	21.40	25.6%	18.8%
	0.5	23,756	17.66	24,339	15.89	34,853	24.75	27,650	19.43	22.6%	24.1%
	0.1	18,650	13.20	20,340	11.44	26,382	18.83	21,791	14.49	18.7%	26.6%

Table 67: Dynamic Modulus and Phase Angle Values, 01CP HMA

01CP		Sample 1		Sample 2		Sample 3		Average		CV	
Temp (°C)	Frequency (Hz)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus	Phase Angle
4.4	25	1,395,142	9.58	1,326,973	7.79	1,868,094	9.58	1,530,070	8.98	19.3%	11.5%
	10	1,185,149	11.53	1,126,841	9.15	1,624,280	11.46	1,312,090	10.71	20.7%	12.6%
	5	1,071,667	12.98	1,082,557	10.44	1,473,382	12.66	1,209,202	12.03	18.9%	11.5%
	1	816,090	16.53	821,970	12.68	1,150,667	15.96	929,576	15.06	20.6%	13.8%
	0.5	730,088	18.21	758,392	14.02	1,028,697	17.50	839,059	16.58	19.6%	13.5%
	0.1	538,311	22.13	584,232	17.36	739,468	21.35	620,670	20.28	17.0%	12.6%
21.1	25	740,985	20.09	708,019	17.94	865,151	20.89	771,385	19.64	10.7%	7.8%
	10	593,700	23.45	650,200	19.72	683,846	23.40	642,582	22.19	7.1%	9.6%
	5	518,073	26.08	548,482	21.61	559,648	25.73	542,068	24.47	4.0%	10.2%
	1	285,015	30.25	299,740	26.58	324,144	31.26	302,966	29.36	6.5%	8.4%
	0.5	223,293	31.81	259,585	27.85	250,853	32.67	244,577	30.78	7.7%	8.4%
	0.1	125,516	32.76	146,544	29.89	136,834	33.20	136,298	31.95	7.7%	5.6%
37.8	25	321,477	28.44	338,242	25.68	317,622	28.28	325,781	27.47	3.4%	5.6%
	10	211,809	30.63	227,026	27.92	208,210	30.72	215,682	29.76	4.6%	5.3%
	5	156,856	31.50	171,708	29.07	154,537	31.43	161,034	30.67	5.8%	4.5%
	1	78,558	32.10	88,814	30.42	77,653	31.51	81,675	31.34	7.6%	2.7%
	0.5	59,419	30.51	68,553	29.85	59,199	30.20	62,391	30.19	8.6%	1.1%
	0.1	38,141	24.64	43,711	25.85	38,185	23.83	40,012	24.77	8.0%	4.1%
54	25	139,605	28.81	140,037	27.65	119,996	25.95	133,213	27.47	8.6%	5.2%
	10	97,292	30.92	84,223	28.92	72,129	26.99	84,548	28.94	14.9%	6.8%
	5	68,926	30.54	61,087	28.35	52,016	25.41	60,676	28.10	13.9%	9.2%
	1	31,862	26.34	32,294	26.14	29,229	21.74	31,129	24.74	5.3%	10.5%
	0.5	27,533	25.21	25,894	24.54	24,792	19.90	26,073	23.22	5.3%	12.5%
	0.1	18,336	18.79	17,357	19.53	18,548	14.20	18,080	17.51	3.5%	16.5%

Table 68: Dynamic Modulus and Phase Angle Values, 01CU HMA

01CU		Sample 1		Sample 2		Sample 3		Average		CV	
Temp (°C)	Frequency (Hz)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus	Phase Angle
4.4	25	2,331,149	8.54	1,791,499	7.12	1,567,261	6.77	1,896,636	7.48	20.7%	12.5%
	10	2,211,706	9.47	1,679,883	8.43	1,468,964	7.96	1,786,851	8.62	21.4%	9.0%
	5	1,944,271	10.24	1,575,928	9.18	1,383,701	8.60	1,634,634	9.34	17.4%	8.9%
	1	1,640,401	12.79	1,309,311	11.06	1,115,951	10.33	1,355,221	11.39	19.6%	11.1%
	0.5	1,517,376	14.01	1,193,536	11.99	1,052,432	11.24	1,254,448	12.41	19.0%	11.5%
	0.1	1,161,487	17.30	937,439	14.80	848,394	13.46	982,440	15.19	16.4%	12.8%
21.1	25	1,043,493	18.10	795,620	17.57	822,015	16.23	887,043	17.30	15.3%	5.6%
	10	857,992	19.70	666,066	19.61	702,458	18.12	742,172	19.14	13.7%	4.6%
	5	734,961	21.44	579,760	21.39	586,830	19.69	633,851	20.84	13.8%	4.8%
	1	487,945	26.83	371,782	26.31	402,875	24.18	420,867	25.77	14.3%	5.4%
	0.5	401,020	29.04	298,800	27.92	326,552	26.06	342,124	27.67	15.5%	5.4%
	0.1	241,505	31.85	184,978	30.63	204,403	29.74	210,295	30.74	13.7%	3.4%
37.8	25	375,712	28.74	297,775	28.10	329,009	26.41	334,165	27.75	11.7%	4.3%
	10	271,566	30.00	218,244	29.10	254,323	27.58	248,044	28.89	11.0%	4.2%
	5	211,102	31.66	172,276	29.55	203,074	28.46	195,484	29.89	10.5%	5.4%
	1	120,618	31.24	95,843	30.25	115,800	29.90	110,754	30.46	11.9%	2.3%
	0.5	93,620	30.76	76,944	29.10	90,513	29.76	87,026	29.87	10.2%	2.8%
	0.1	59,677	26.44	50,007	25.59	57,865	27.25	55,850	26.43	9.2%	3.1%
54	25	138,145	35.61	112,160	31.68	132,319	30.48	127,542	32.59	10.7%	8.2%
	10	95,255	35.11	77,806	30.64	94,072	30.00	89,044	31.92	11.0%	8.7%
	5	72,111	33.79	57,342	30.45	72,783	29.28	67,412	31.17	12.9%	7.5%
	1	40,491	30.59	36,254	25.68	41,144	27.66	39,296	27.98	6.8%	8.8%
	0.5	31,798	27.88	30,311	23.75	34,160	26.05	32,090	25.89	6.0%	8.0%
	0.1	21,422	22.48	22,518	19.42	24,934	21.07	22,958	20.99	7.8%	7.3%

Table 69: Dynamic Modulus and Phase Angle Values, 001G HMA

001G		Sample 1		Sample 2		Sample 3		Average		CV	
Temp (°C)	Frequency (Hz)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus	Phase Angle
4.4	25	917,765	18.62	694,946	17.46	683,725	18.02	765,478	18.03	17.2%	3.2%
	10	752,187	20.51	590,577	18.94	631,396	19.91	658,053	19.79	12.8%	4.0%
	5	638,840	22.22	510,124	20.45	548,991	21.56	565,985	21.41	11.7%	4.2%
	1	406,243	25.90	316,393	24.38	340,260	25.49	354,299	25.26	13.1%	3.1%
	0.5	340,546	27.23	293,003	26.27	305,656	27.65	313,068	27.05	7.9%	2.6%
	0.1	214,000	28.52	188,232	28.27	189,639	29.47	197,290	28.75	7.3%	2.2%
21.1	25	309,393	28.71	344,488	30.15	264,405	29.28	306,095	29.38	13.1%	2.5%
	10	220,943	29.71	244,276	30.64	201,143	29.70	222,120	30.02	9.7%	1.8%
	5	169,561	30.21	185,462	32.38	151,885	30.28	168,970	30.96	9.9%	4.0%
	1	91,481	31.84	102,294	31.63	79,457	30.89	91,077	31.45	12.5%	1.6%
	0.5	77,318	29.19	82,666	29.90	68,780	29.47	76,255	29.52	9.2%	1.2%
	0.1	51,948	25.41	53,939	25.47	45,975	25.73	50,621	25.54	8.2%	0.7%
37.8	25	68,347	26.89	80,222	29.53	65,415	27.73	71,328	28.05	11.0%	4.8%
	10	51,002	24.66	59,957	25.97	50,042	24.69	53,667	25.11	10.2%	3.0%
	5	42,852	22.62	48,982	24.10	41,316	23.13	44,383	23.28	9.1%	3.2%
	1	29,654	19.60	34,578	20.28	29,530	19.28	31,254	19.72	9.2%	2.6%
	0.5	29,348	17.89	32,857	18.50	28,288	18.33	30,165	18.24	7.9%	1.7%
	0.1	24,614	14.67	27,660	15.12	24,908	15.08	25,727	14.96	6.5%	1.7%
54	25	48,509	26.97	38,937	23.60	35,696	25.35	41,047	25.31	16.2%	6.7%
	10	37,933	22.70	31,851	20.01	28,599	21.85	32,794	21.52	14.4%	6.4%
	5	31,958	20.49	27,341	19.24	25,294	20.40	28,198	20.04	12.1%	3.5%
	1	24,363	16.63	21,880	15.11	19,978	16.47	22,074	16.07	10.0%	5.2%
	0.5	22,598	16.02	20,408	14.63	18,722	16.54	20,576	15.73	9.4%	6.3%
	0.1	18,661	12.62	22,155	10.36	15,496	15.11	18,771	12.70	17.7%	18.7%

Table 70: Dynamic Modulus and Phase Angle Values, 000M HMA

000M		Sample 1		Sample 2		Sample 3		Average		CV	
Temp (°C)	Frequency (Hz)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus	Phase Angle
4.4	25	2,079,037	8.20	2,106,426	8.88	2,006,764	9.28	2,064,076	8.79	2.5%	6.2%
	10	1,839,617	9.70	1,888,772	10.05	1,806,593	10.03	1,844,994	9.93	2.2%	2.0%
	5	1,690,576	10.65	1,804,766	10.67	1,660,518	11.03	1,718,620	10.78	4.4%	2.0%
	1	1,381,767	13.16	1,424,897	13.80	1,361,035	13.65	1,389,233	13.54	2.3%	2.5%
	0.5	1,260,951	14.08	1,326,138	14.92	1,239,876	14.96	1,275,655	14.65	3.5%	3.4%
	0.1	960,888	17.22	967,587	18.81	934,114	18.23	954,196	18.09	1.9%	4.4%
21.1	25	965,029	18.22	905,762	19.04	907,917	18.50	926,236	18.59	3.6%	2.2%
	10	783,464	20.18	762,428	21.60	750,774	20.39	765,555	20.72	2.2%	3.7%
	5	670,338	21.80	633,729	23.48	647,142	22.64	650,403	22.64	2.8%	3.7%
	1	431,430	27.18	401,041	29.60	417,204	28.32	416,558	28.37	3.7%	4.3%
	0.5	346,020	29.22	317,848	31.82	334,921	30.30	332,930	30.45	4.3%	4.3%
	0.1	208,667	32.36	184,117	34.61	193,955	33.63	195,580	33.53	6.3%	3.4%
37.8	25	367,780	27.17	352,025	28.88	366,259	27.60	362,022	27.88	2.4%	3.2%
	10	275,465	28.84	258,494	30.12	274,012	28.64	269,324	29.20	3.5%	2.7%
	5	217,715	29.83	202,083	30.73	216,318	29.14	212,038	29.90	4.1%	2.7%
	1	122,274	31.28	111,568	31.53	122,200	30.20	118,681	31.00	5.2%	2.3%
	0.5	95,183	30.83	86,261	30.84	94,802	29.75	92,082	30.47	5.5%	2.1%
	0.1	60,103	27.80	54,723	27.66	61,506	25.94	58,777	27.13	6.1%	3.8%
54	25	146,645	32.30	121,353	34.72	129,515	31.24	132,504	32.75	9.7%	5.4%
	10	97,833	32.51	85,266	32.11	90,284	29.99	91,128	31.54	6.9%	4.3%
	5	77,688	30.42	65,413	30.73	67,353	29.53	70,151	30.23	9.4%	2.1%
	1	44,878	27.28	36,807	27.20	43,386	24.44	41,690	26.31	10.3%	6.1%
	0.5	36,599	25.56	31,221	24.41	36,229	22.53	34,683	24.17	8.7%	6.3%
	0.1	25,925	20.75	24,495	19.44	29,141	17.47	26,520	19.22	9.0%	8.6%

Table 71: Dynamic Modulus and Phase Angle Values, 5930 HMA

5930		Sample 1		Sample 2		Sample 3		Average		CV	
Temp (°C)	Frequency (Hz)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus	Phase Angle
4.4	25	1,023,817	16.10	1,172,678	14.49	1,519,645	19.87	1,238,713	16.82	20.5%	16.4%
	10	865,699	17.30	1,004,842	15.93	1,261,145	21.77	1,043,895	18.33	19.2%	16.7%
	5	759,385	18.72	889,047	17.08	1,076,842	23.33	908,425	19.71	17.6%	16.4%
	1	529,409	22.68	637,712	20.75	741,327	28.26	636,149	23.90	16.7%	16.3%
	0.5	442,626	24.46	542,835	22.70	616,736	29.95	534,065	25.70	16.4%	14.7%
	0.1	284,199	27.97	360,849	25.64	379,187	31.89	341,412	28.50	14.8%	11.1%
21.1	25	406,097	26.10	476,019	26.55	476,203	26.95	452,773	26.53	8.9%	1.6%
	10	307,664	27.73	363,928	27.55	356,149	28.67	342,580	27.98	8.9%	2.1%
	5	246,256	28.89	292,476	28.77	282,483	29.41	273,738	29.02	8.9%	1.2%
	1	135,215	32.07	164,785	32.15	157,971	32.22	152,657	32.15	10.1%	0.2%
	0.5	106,260	32.11	128,825	32.44	124,630	31.66	119,905	32.07	10.0%	1.2%
	0.1	65,289	30.45	79,687	30.36	78,968	28.71	74,648	29.84	10.9%	3.3%
37.8	25	124,425	30.73	146,776	28.31	161,627	28.84	144,276	29.29	13.0%	4.3%
	10	92,917	28.67	111,515	25.88	119,334	27.41	107,922	27.32	12.6%	5.1%
	5	75,436	27.23	92,422	24.10	97,326	26.00	88,395	25.78	13.0%	6.1%
	1	46,528	25.44	60,770	21.92	62,979	23.91	56,759	23.76	15.7%	7.4%
	0.5	41,540	24.30	54,179	20.42	55,237	22.27	50,319	22.33	15.1%	8.7%
	0.1	31,545	21.20	43,310	17.54	43,525	18.80	39,460	19.18	17.4%	9.7%
54	25	86,000	29.81	63,095	23.21	69,711	26.57	72,935	26.53	16.2%	12.4%
	10	45,502	26.74	51,219	20.53	50,512	25.83	49,078	24.37	6.4%	13.8%
	5	38,746	25.07	43,379	19.82	46,642	22.84	42,922	22.58	9.2%	11.7%
	1	27,918	25.36	32,650	17.87	34,314	19.24	31,627	20.82	10.5%	19.2%
	0.5	25,552	23.29	29,254	17.72	30,166	18.76	28,324	19.92	8.6%	14.9%
	0.1	19,234	20.92	24,111	15.25	24,601	15.90	22,649	17.36	13.1%	17.9%

Table 72: Dynamic Modulus and Phase Angle Values, WMA

WMA		Sample 1		Sample 2		Sample 3		Average		CV	
Temp (°C)	Frequency (Hz)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus (psi)	Phase Angle (deg)	Dynamic Modulus	Phase Angle
4.4	25	1,514,109	11.20	2,120,631	9.14	1,758,278	10.25	1,797,673	10.20	17.0%	10.1%
	10	1,319,132	13.21	1,851,845	11.69	1,557,323	12.60	1,576,100	12.50	16.9%	6.1%
	5	1,173,343	14.56	1,654,391	13.21	1,395,033	14.07	1,407,589	13.95	17.1%	4.9%
	1	893,727	18.06	1,318,572	16.54	1,079,556	17.81	1,097,285	17.47	19.4%	4.7%
	0.5	775,402	19.70	1,188,069	18.20	948,776	19.53	970,749	19.14	21.3%	4.3%
	0.1	533,102	23.71	847,866	21.90	658,722	22.88	679,897	22.83	23.3%	4.0%
21.1	25	691,375	20.51	914,308	19.74	782,083	20.61	795,922	20.29	14.1%	2.3%
	10	550,358	23.19	733,781	22.38	622,676	23.07	635,605	22.88	14.5%	1.9%
	5	476,728	24.90	612,988	24.07	517,065	24.83	535,594	24.60	13.1%	1.9%
	1	280,022	30.20	382,886	29.99	300,136	30.35	321,015	30.18	17.0%	0.6%
	0.5	216,932	31.49	310,173	32.23	230,704	31.95	252,603	31.89	19.9%	1.2%
	0.1	123,534	31.41	175,085	34.00	132,133	33.37	143,584	32.93	19.2%	4.1%
37.8	25	197,627	29.82	228,251	29.46	183,218	29.70	203,032	29.66	11.3%	0.6%
	10	143,324	29.22	160,820	29.98	131,829	29.56	145,324	29.59	10.0%	1.3%
	5	114,083	28.47	127,382	29.12	104,240	28.38	115,235	28.66	10.1%	1.4%
	1	67,983	26.92	76,104	27.34	62,663	26.49	68,917	26.92	9.8%	1.6%
	0.5	57,866	25.30	63,818	25.54	53,435	24.66	58,373	25.17	8.9%	1.8%
	0.1	42,590	21.68	46,708	21.69	39,844	20.52	43,047	21.30	8.0%	3.2%
54	25	65,474	28.49	98,959	27.86	74,649	27.47	79,694	27.94	21.7%	1.8%
	10	48,806	26.37	77,149	25.67	54,356	25.58	60,104	25.87	25.0%	1.7%
	5	40,294	24.83	63,518	24.38	45,568	23.57	49,793	24.26	24.5%	2.6%
	1	28,690	21.03	46,273	19.99	33,959	19.43	36,307	20.15	24.9%	4.0%
	0.5	25,021	20.01	38,085	18.29	29,475	18.76	30,860	19.02	21.5%	4.7%
	0.1	19,962	16.82	32,195	14.80	24,243	15.07	25,467	15.56	24.4%	7.0%

6.3 Summary

Figures 59 through 62 provide a plot of dynamic modulus versus frequency for each testing temperature. The dynamic modulus values shown are the average values for each asphalt material.

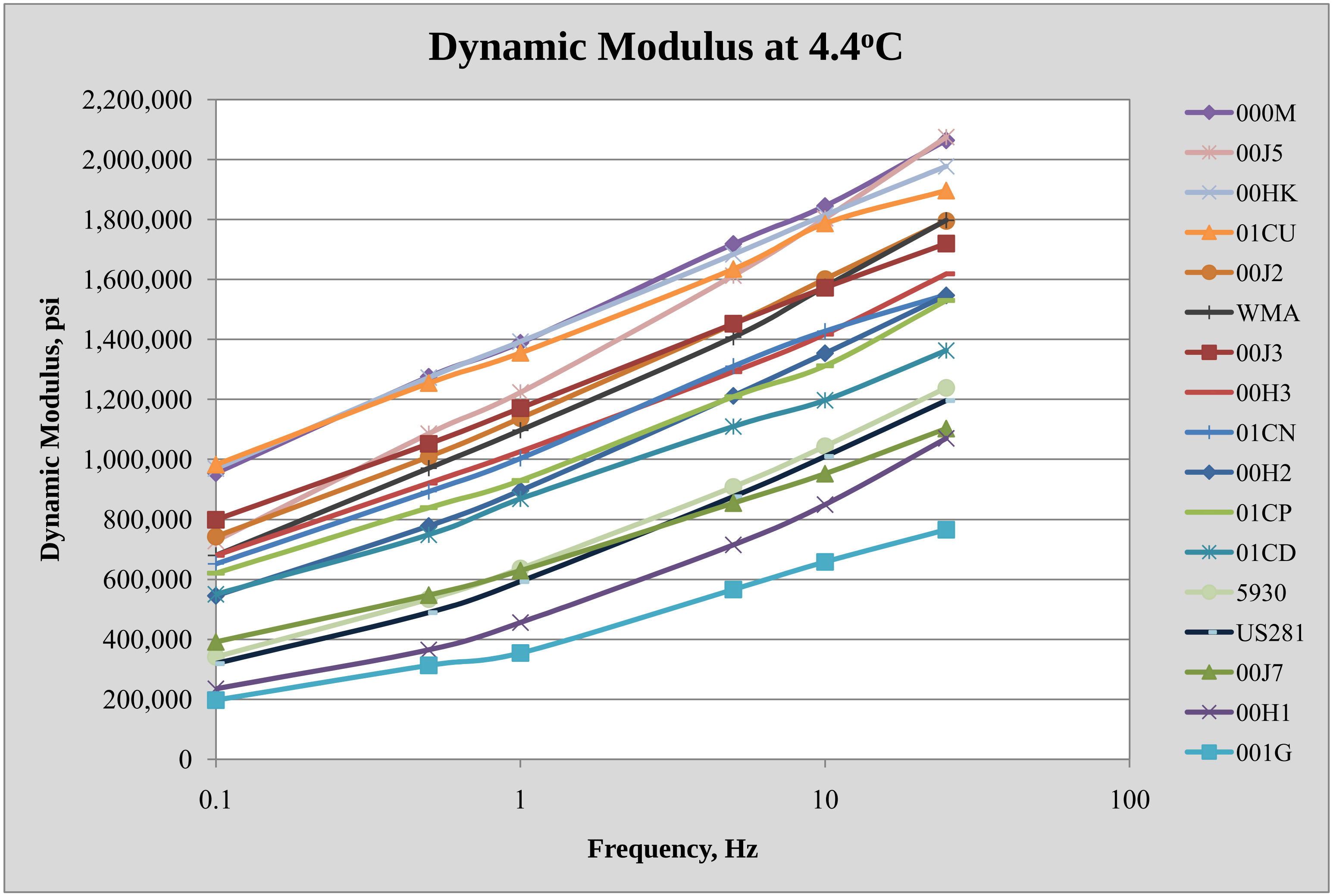


Figure 59: Dynamic Modulus vs. Frequency, 4.4ºC

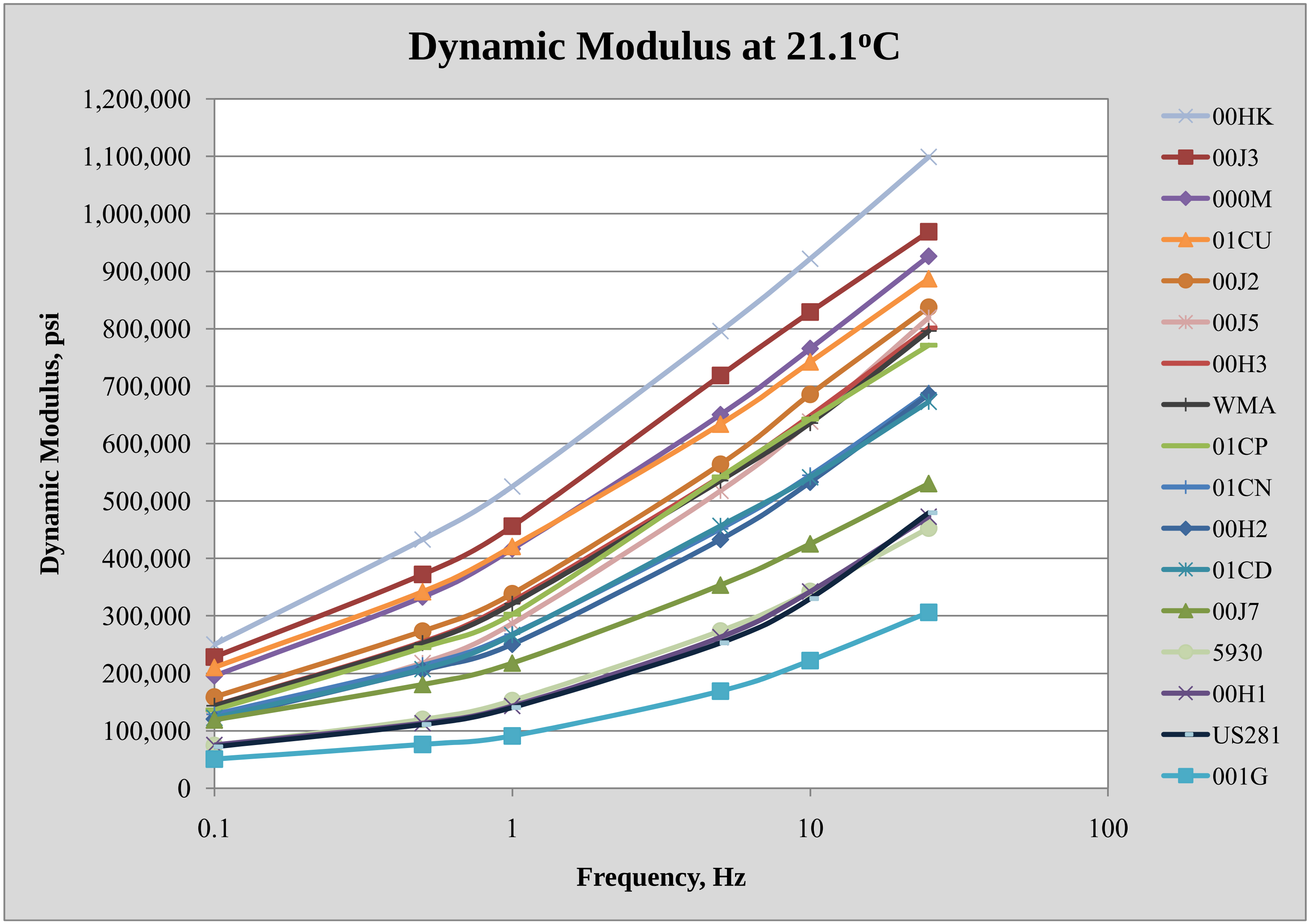


Figure 60: Dynamic Modulus vs. Frequency, 21.1°C

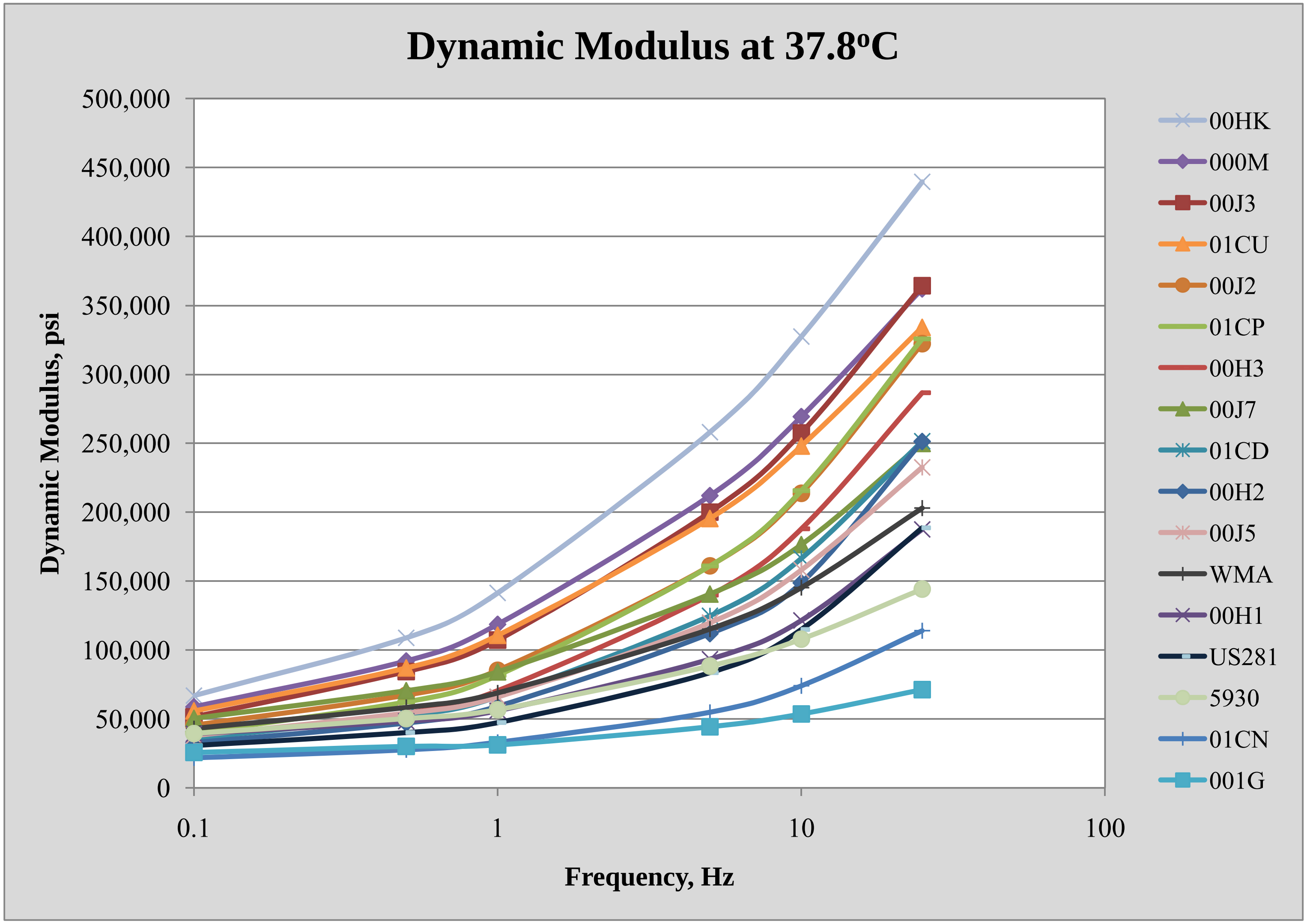


Figure 61: Dynamic Modulus vs. Frequency, 37.8°C

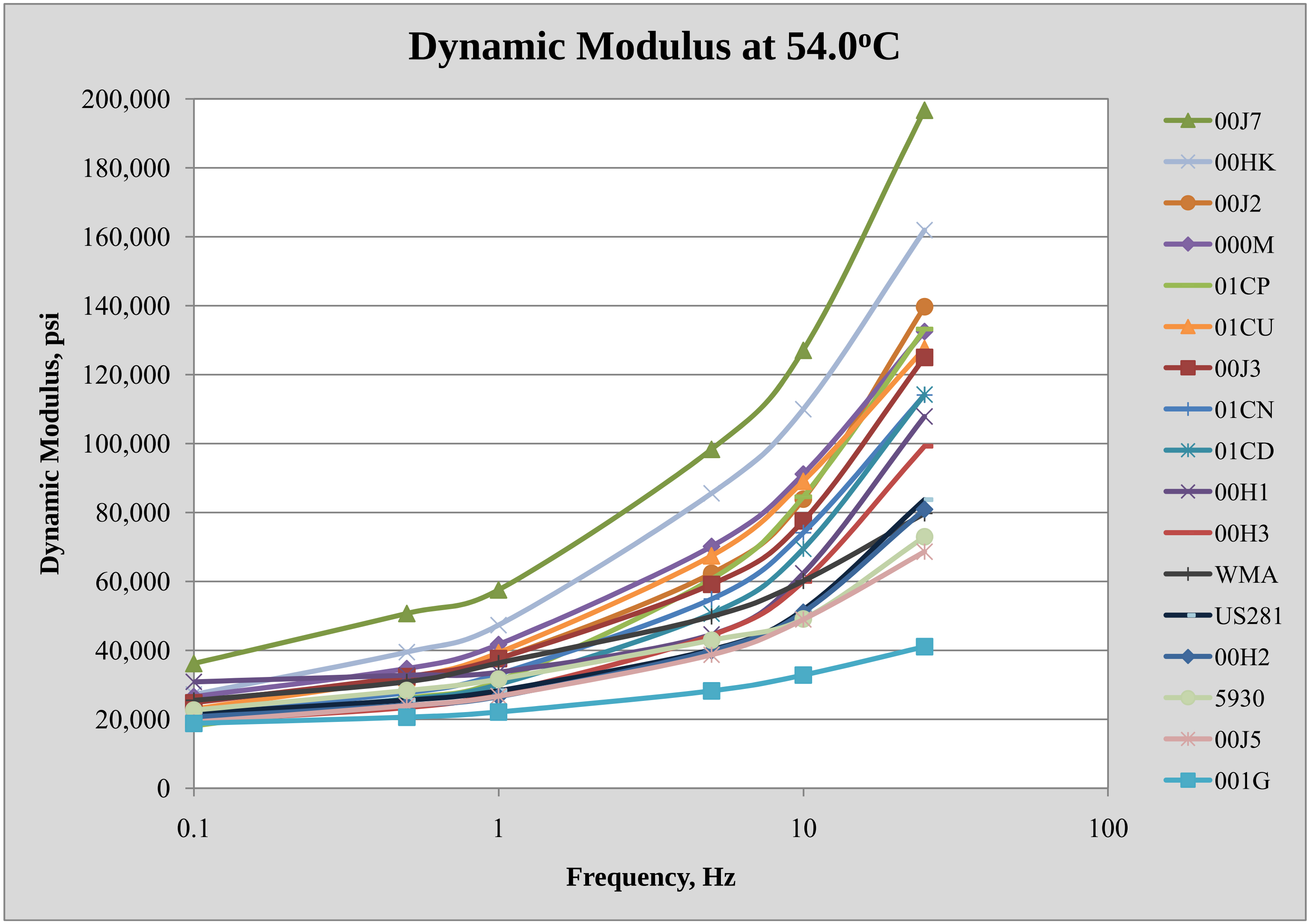


Figure 62: Dynamic Modulus vs. Frequency, 54.0°C

Figure 63 provides a plot of the E* Master Curves for all 17 asphalt material samples at a reference temperature of 70°F.

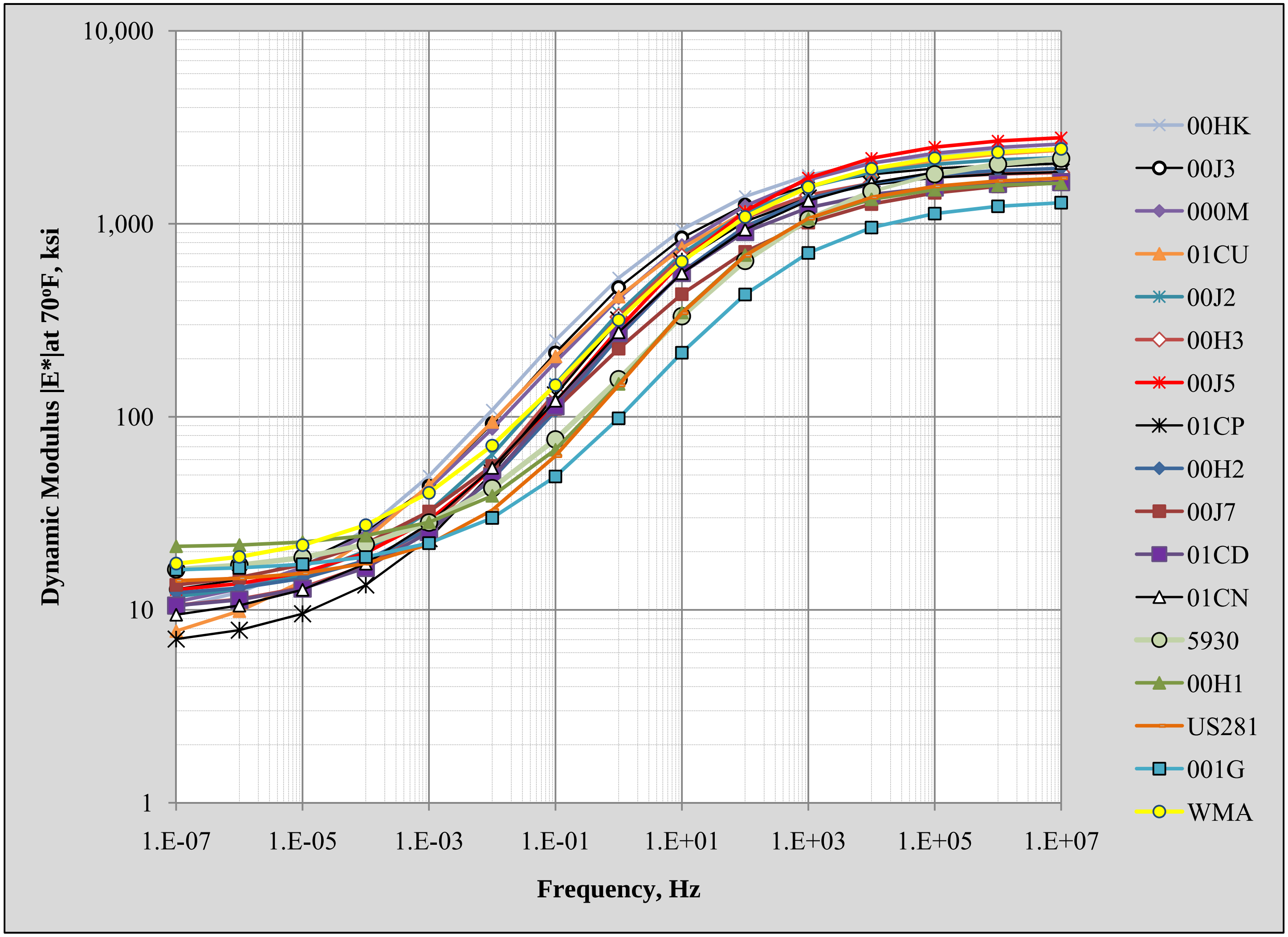


Figure 63: Master Curves

CHAPTER 7 REPEATED LOAD TRIAXIAL TEST RESULTS AND ANALYSIS

7.1 Introduction

This chapter presents all results from the repeated load triaxial testing of 15 HMA pavement materials. Ideally, three samples of each mix should be tested at each temperature thereby requiring a minimum of nine samples of each mix. However, due to limited material quantities sent to the SDSM&T, a maximum of six samples were available for testing for each mix. One mix had only two samples, two mixes had three samples, four mixes had four samples, and eight mixes had six samples. Out of these 72 samples, 46 samples had been previously used for dynamic modulus tests as shown in Table 73.

Table 73: Repeated Load Triaxial Samples

HMA Mix	Total Samples	Samples Previously Tested
00J2	6	1
00J3	6	4
00J5	4	3
00J7	3	3
00H1	6	3
00H2	2	2
00H3	6	3
00HK	3	3
000M	4	3
01CD	6	4
01CN	6	4
01CP	6	4
01CU	4	2
001G	6	4
5930	4	3

7.2 Repeated Load Triaxial Test

Due to the achievement of 5% strain during the repeated load triaxial testing, the sample will essentially achieve a failure condition. In Figure 64, a sample which has undergone the repeated load triaxial testing is shown on the right as compared to a non-tested sample. In addition, Figure 65 displays severe cracking throughout the binder matrix.

Figure 64: Repeated Load Triaxial Samples

Figure 65: Repeated Load Triaxial Sample After Testing

A summary of the regression analysis using the results of the repeated load triaxial testing is provided in Table 74.

Table 73: Permanent Deformation Model Coefficients

HMA Mix	a_1	a_2	a_3	R^2
00J2	-7.22	0.45	3.64	0.91
00J3	-4.23	0.43	2.03	0.88
00J5	-5.16	0.52	2.47	0.90
00J7	-0.86	0.34	0.41	0.58
00H1	-6.15	0.36	3.12	0.92
00H2	-10.48	0.65	4.73	0.95
00H3	-8.97	0.57	4.34	0.84
00HK	-9.09	0.58	4.28	0.92
000M	-8.19	0.55	3.82	0.90
01CD	-6.77	0.47	3.38	0.91
01CN	-4.39	0.45	2.14	0.81
01CP	-7.27	0.53	3.42	0.84
01CU	-3.68	0.56	1.58	0.97
001G	-1.70	0.40	0.86	0.96
5930	-3.80	0.51	1.69	0.90

7.3 Summary

As stated earlier, a majority of the samples subjected to the repeated load triaxial test were previously utilized in the dynamic modulus tests. Even though the dynamic modulus test is theoretically a nondestructive test, the behavior of a sample subjected to the dynamic modulus testing will likely differ from the behavior of a virgin specimen. Therefore, the results of the testing used to develop the MEPDG permanent deformation model coefficients in this project should be considered preliminary and further testing of new materials is strongly suggested.

CHAPTER 8 CONCLUSION AND RECOMMENDATIONS

8.1 Introduction

The objective of this study was to obtain resilient modulus and dynamic modulus values of construction materials through tests performed with the SPT at SDSM&T. These values were obtained through testing of HMA paving materials and typical soil types around the state in order to validate resultant data relative to the criteria defined for mechanistic-empirical pavement design processes and ultimate incorporation of the data into a mechanistic-empirical pavement design database.

The following sections present the conclusion and recommendations based on the research conducted to achieve this objective.

8.2 Conclusion

Based upon the research conducted the following results were obtained:

Table 75: Average Resilient Modulus Coefficients

Material	k_1	k_2	k_3	M_R value with σ_3=2psi & σ_d=6psi*
SD34 Lee's Corner	777.62	0.25	-1.27	8,690
I-90 by Blackhawk	1019.60	0.75	-1.50	9,886
SD11/SD42 Minnehaha	723.67	0.57	-1.90	6,787
SD44 E of Scenic	908.71	0.51	-0.47	11,096
SD20 E of Prairie City	1482.63	0.48	-0.51	18,064
US281 Wolsey	470.20	0.65	-3.42	3,321
SD34 Forestburg	639.28	0.78	-1.60	6,053
US212 Orman Dam	1399.58	0.50	-0.42	17,243
US83 Ft Pierre	1065.46	0.34	0.09	14,841
US385 Custer/Hill City	723.64	0.70	-2.96	5,485

Material	k_1	k_2	k_3	M_R value with σ_3=2psi & σ_d=6psi*
US212 Subgrade	1926.33	0.42	-0.50	22,045
US212 Base	1331.43	0.64	-0.45	26,693
US281 Subgrade	1918.37	0.68	-0.68	19,217
US281 Base	894.57	0.79	-0.50	19,944

Table 76: Average Dynamic Modulus Values

Averages		Dynamic Modulus (psi)					
Temp (^{o}C)	Frequency (Hz)	00H1	00H2	00H3	00HK	00J2	00J3
4.4	25	1,070,260	1,546,832	1,618,901	1,977,446	1,795,305	1,720,017
	10	849,172	1,353,958	1,417,817	1,814,742	1,601,447	1,572,734
	5	714,794	1,211,942	1,292,715	1,683,782	1,451,702	1,452,446
	1	455,798	895,979	1,026,544	1,392,811	1,137,483	1,171,096
	0.5	364,805	777,970	921,335	1,272,814	1,008,626	1,051,941
	0.1	234,923	545,140	680,143	969,445	742,385	798,663
21.1	25	472,739	685,570	801,293	1,099,024	837,529	968,824
	10	342,425	532,902	648,239	921,720	685,723	829,085
	5	262,934	433,016	542,182	795,902	564,129	718,605
	1	143,122	250,579	325,174	525,255	338,643	456,149
	0.5	113,227	205,732	254,443	432,939	273,525	372,253
	0.1	75,229	120,264	143,844	250,201	158,800	228,465
37.8	25	187,563	251,314	286,709	439,692	322,305	364,333
	10	121,485	148,758	187,977	327,421	213,736	257,520
	5	93,404	111,994	139,863	258,073	161,102	200,081
	1	56,049	59,249	70,608	141,477	85,315	107,301
	0.5	48,387	47,128	54,285	108,892	67,303	84,435
	0.1	39,303	32,858	35,678	66,977	45,430	51,513
54	25	107,826	80,871	99,201	161,912	139,685	124,966
	10	62,315	51,014	59,962	109,941	83,848	77,522
	5	44,579	39,835	44,344	85,534	62,313	59,123
	1	33,656	26,531	27,507	47,287	37,508	37,597
	0.5	32,776	24,018	23,389	39,454	31,956	32,359
	0.1	30,845	20,683	19,477	27,162	25,032	24,770

Averages		Dynamic Modulus (psi)					
Temp (^oC)	Frequency (Hz)	00J5	00J7	01CD	01CN	01CP	01CU
4.4	25	2,074,967	1,102,721	1,363,135	1,549,172	1,530,070	1,896,636
	10	1,803,955	952,207	1,197,286	1,427,586	1,312,090	1,786,851
	5	1,613,023	854,344	1,109,578	1,310,773	1,209,202	1,634,634
	1	1,223,585	629,126	868,475	1,003,288	929,576	1,355,221
	0.5	1,085,884	547,476	748,567	892,820	839,059	1,254,448
	0.1	727,860	391,530	550,100	651,546	620,670	982,440
21.1	25	819,362	530,338	672,815	688,346	771,385	887,043
	10	638,345	425,376	541,223	544,753	642,582	742,172
	5	517,799	353,578	456,787	451,527	542,068	633,851
	1	286,853	217,739	266,546	268,369	302,966	420,867
	0.5	218,007	180,564	207,291	214,016	244,577	342,124
	0.1	117,474	118,888	122,469	128,545	136,298	210,295
37.8	25	232,540	249,955	251,534	272,819	325,781	334,165
	10	158,151	176,541	166,540	187,624	215,682	248,044
	5	119,889	140,674	124,854	145,678	161,034	195,484
	1	66,101	84,284	66,057	80,067	81,675	110,754
	0.5	54,294	70,600	52,388	63,065	62,391	87,026
	0.1	37,949	50,467	35,885	42,391	40,012	55,850
54	25	68,599	196,717	114,197	114,080	133,213	127,542
	10	48,933	127,023	69,428	74,104	84,548	89,044
	5	38,687	98,293	50,627	54,869	60,676	67,412
	1	26,685	57,510	30,087	33,089	31,129	39,296
	0.5	23,911	50,662	25,821	27,650	26,073	32,090
	0.1	19,145	36,143	20,839	21,791	18,080	22,958

Averages		Dynamic Modulus (psi)				
Temp (^oC)	Frequency (Hz)	001G	000M	5930	US281	WMA
4.4	25	765,478	2,064,076	1,238,713	1,196,265	1,797,673
	10	658,053	1,844,994	1,043,895	1,009,865	1,576,100
	5	565,985	1,718,620	908,425	875,621	1,407,589
	1	354,299	1,389,233	636,149	592,649	1,097,285
	0.5	313,068	1,275,655	534,065	488,942	970,749
	0.1	197,290	954,196	341,412	318,980	679,897

Averages		Dynamic Modulus (psi)				
Temp (°C)	Frequency (Hz)	001G	000M	5930	US281	WMA
21.1	25	306,095	926,236	452,773	479,536	795,922
	10	222,120	765,555	342,580	330,107	635,605
	5	168,970	650,403	273,738	253,051	535,594
	1	91,077	416,558	152,657	140,533	321,015
	0.5	76,255	332,930	119,905	110,893	252,603
	0.1	50,621	195,580	74,648	72,156	143,584
37.8	25	71,328	362,022	144,276	188,688	203,032
	10	53,667	269,324	107,922	114,959	145,324
	5	44,383	212,038	88,395	83,638	115,235
	1	31,254	118,681	56,759	47,441	68,917
	0.5	30,165	92,082	50,319	40,179	58,373
	0.1	25,727	58,777	39,460	30,775	43,047
54	25	41,047	132,504	72,935	83,695	79,694
	10	32,794	91,128	49,078	51,714	60,104
	5	28,198	70,151	42,922	40,154	49,793
	1	22,074	41,690	31,627	28,269	36,307
	0.5	20,576	34,683	28,324	25,532	30,860
	0.1	18,771	26,520	22,649	21,757	25,467

Table 76: Average Permanent Deformation Model Coefficients

HMA Mix	a_1	a_2	a_3	R^2
00J2	-7.22	0.45	3.64	0.91
00J3	-4.23	0.43	2.03	0.88
00J5	-5.16	0.52	2.47	0.90
00J7	-0.86	0.34	0.41	0.58
00H1	-6.15	0.36	3.12	0.92
00H2	-10.48	0.65	4.73	0.95
00H3	-8.97	0.57	4.34	0.84
00HK	-9.09	0.58	4.28	0.92
000M	-8.19	0.55	3.82	0.90
01CD	-6.77	0.47	3.38	0.91
01CN	-4.39	0.45	2.14	0.81
01CP	-7.27	0.53	3.42	0.84
01CU	-3.68	0.56	1.58	0.97
001G	-1.70	0.40	0.86	0.96
5930	-3.80	0.51	1.69	0.90

8.3 Recommendations

As a result of this project, it is recommended that the South Dakota Department of Transportation continue with the development of a material input parameter database for the Mechanistic-Empirical Pavement Design Guide. This would involve further testing of typical soil and road construction materials in South Dakota for resilient modulus and dynamic modulus, respectively. The additional testing and database development will ensure that proper material input values are utilized in future mechanistic-empirical pavement designs. The further testing of typical soil materials for resilient modulus will also allow for continued validation and refinement of a parametric relationship for the resilient modulus that was initially developed for low plasticity soils from this project's results. Additionally, it is highly recommended that testing of high plasticity soil subgrade materials be included in the future testing matrix in order to develop a parametric relationship for resilient modulus for these soils.

Finally, it is not recommended that the South Dakota Department of Transportation procure a Simple Performance Tester machine at this time. The South Dakota School of Mines and Technology is fully capable of completing any required resilient modulus, dynamic modulus, and repeated load triaxial tests for the database development.

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