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EVALUATION OF TEST METHODS FOR STIFFNESS PROPERTIES OF HOT MIX ASPHALT (HMA)

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16 Abstract

The current *1993 AASHTO Design Guide for Design of Pavement Structures* uses resilient modulus to assign an "a" coefficient to hot mix asphalt (HMA) to determine the required thickness of the HMA layer for a given traffic loading and subgrade support condition. There are several methods to determine the modulus of a mix for use in determining the "a" coefficient. Modulus results are a function of the test method and curing conditions. Therefore, the test method and curing conditions would have an effect on the "a" coefficient used in thickness design and, hence, the thickness of the pavement layers.

A need was voiced by KDOT to evaluate the available test methods for determination of the stiffness properties of HMA. The laboratory stiffness properties of a coarse and fine, 19 mm HMA mixture were evaluated. One indirect method used total external horizontal deflections and the other both inner horizontal and inner vertical deflections. In addition, two experimental procedures were evaluated; they were a direct measurement procedure using a GeoGauge™ and a pulse-velocity procedure described in ASTM C 1383 and ASTM C 597.

The study was terminated by KDOT prior to completion of the initial test plan with the major reason being the emphasis being placed on complex dynamic modulus by the forthcoming 2002 Design Guide. Conclusions based on the limited test data indicated that the short-term oven aging protocol of AASHTO TP4 resulted in significantly higher modulus values than previously report. The direct measurement procedure gave similar results to the pulse-velocity procedures of ASTM C 1383 and C 597.

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EVALUATION OF TEST METHODS FOR STIFFNESS PROPERTIES OF HOT MIX ASPHALT (HMA)

Final Report

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PREFACE

The Kansas Department of Transportation's (KDOT) Kansas Transportation Research and New-Developments (K-TRAN) Research Program funded this research project. It is an ongoing, cooperative and comprehensive research program addressing transportation needs of the state of Kansas utilizing academic and research resources from KDOT, Kansas State University and the University of Kansas. Transportation professionals in KDOT and the universities jointly develop the projects included in the research program.

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ABSTRACT

The current *1993 AASHTO Design Guide for Design of Pavement Structures* uses resilient modulus to assign an "a" coefficient to hot mix asphalt (HMA) to determine the required thickness of the HMA layer for a given traffic loading and subgrade support condition. There are several methods to determine the modulus of a mix for use in determining the "a" coefficient. Modulus results are a function of the test method and curing conditions. Therefore, the test method and curing conditions would have an effect on the "a" coefficient used in thickness design and, hence, the thickness of the pavement layers.

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INTRODUCTION

The current *1993 AASHTO Design Guide for Design of Pavement Structures* uses resilient modulus to assign an "a" coefficient to hot mix asphalt (HMA) to determine the required thickness of the HMA layer for a given traffic loading and subgrade support condition. There are several methods to determine the modulus of a mix for use in determining the "a" coefficient. These methods include the procedure developed as a part of the Strategic Highway Research Program (SHRP). The current "a" coefficients used by the Kansas Department of Transportation (KDOT) were developed prior to the new Superpave mixture compaction protocols of AASHTO TP 4.

Modulus results are a function of the test method and curing conditions. Therefore, the test method and curing conditions would have an effect on the "a" coefficient used in thickness design and, hence, the thickness of the pavement layers.

With the current development of the *2002 AASHTO Design Guide for Design of Pavement Structures*, researchers are investigating the complex dynamic modulus as a material input parameter. A need was voiced by KDOT to evaluate the available test methods for determination of the stiffness properties of HMA and to prepare for the adoption and implementation of complex dynamic modulus for use with the *2002 AASHTO Design Guide for Design of Pavement Structures*.

PROJECT OBJECTIVES

There are several methods currently being used to determine the stiffness properties of HMA, each with their own advantages and disadvantages. The most common methods include direct measurement using cylindrical specimens and indirect measurement using either external total horizontal deflection or inner horizontal and vertical deflection.

SCOPE

The scope of this project consisted of evaluating the test data from stiffness or modulus testing of two KDOT mixtures using a direct method and two indirect methods. One indirect method used total external horizontal deflections and the other both inner horizontal and inner vertical deflections. In addition, two experimental procedures were evaluated; they were a direct measurement procedure using a GeoGauge™ and a pulse-velocity procedure described in ASTM C 1383 and ASTM C 597.

WORK PLAN

Materials

Two mixtures, a SM-19A mix and a SM-19B mix were selected by KDOT for testing. The mixtures were made using a PG 58-22 binder. All mix designs, fabrication and testing of samples were the responsibility of KDOT. The gradations of the two mixes and void properties at optimum asphalt content are shown in table 1. A plot of the grain-size distribution curves for the two mixtures are shown in figure 1.

Laboratory Evaluation

Samples were prepared for testing in general accordance with the procedures of AASHTO TP4, including the short-term aging protocol. Samples were tested at ambient temperatures, approximately 25°C, and KDOT personnel performed all testing. The modulus of each sample was determined using the following five methods. The code used to identify the test methods in the data analysis is shown in **bold**:

Table 1. Mix gradations and void properties.

Sieve Size (mm)	SM-19A	SM-19B
	Percent Retained	
25	0	0
19	1	1
12.5	11	23
9.5	20	33
4.75	44	47
2.36	53	67
1.18	65	83
0.600	82	88
0.300	90	92
0.150	94	94
0.075	96.1	95.6
AC (%)	6.25	6.1
VTM (%)	4.0	4.0
VMA (%)	13.7	13.8
VFA (%)	70.0	71.1
DP	0.9	1.0

1) **Direct,** using 150-mm diameter by 300-mm high cylinders. Spacers (75-mm high) made of similar materials were used to facilitate sample fabrication.
2) Indirect using total horizontal deflection (**ASTM D 4123**). Samples were 150-mm diameter.
3) Indirect using both inner horizontal and vertical deflections, as recommended by **SHRP**.
4) An experimental procedure using the **GeoGauge™**, a vibratory technique for determining the modulus of soil. The manufacturer's literature stated that laboratory compacted soil samples could be evaluated using the GeoGauge™; therefore, the procedure was evaluated on HMA samples. The test was performed in accordance with the manufacturer's

recommendations.

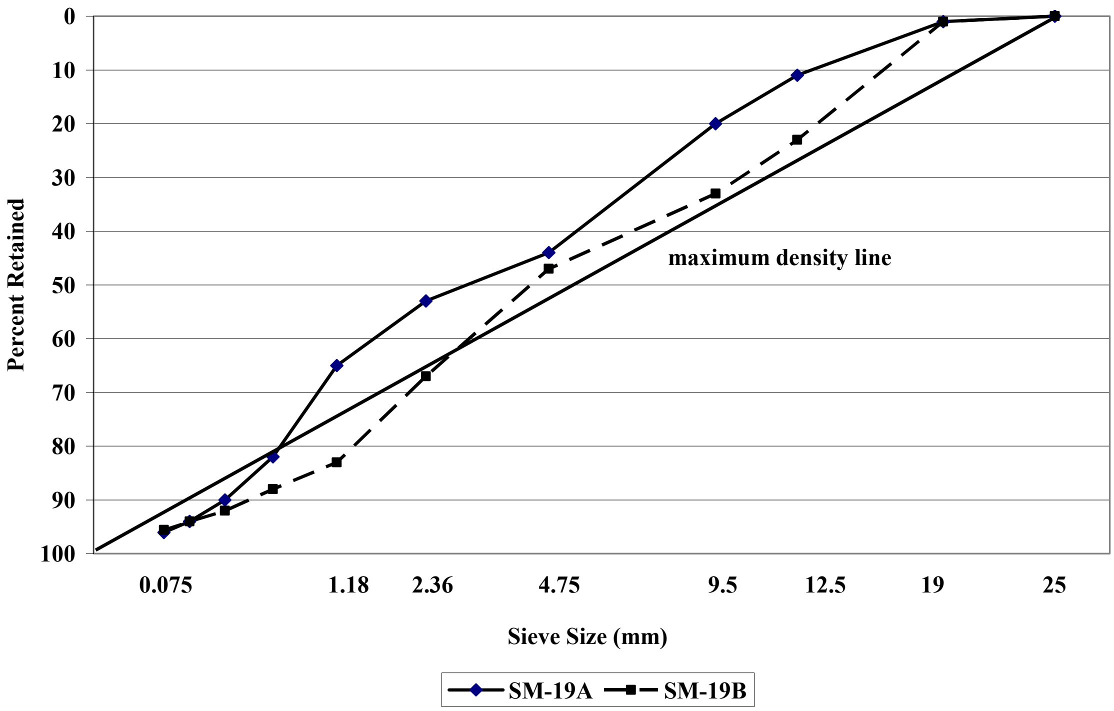

Figure 1. Grain-size distribution curves.

5) An experimental procedure using a pulse-velocity procedure described in ASTM C 1383 and **ASTM C 597**. The procedures describe a method of measuring the velocity of P-waves through concrete. Knowing the thickness and density of the sample, the modulus can be calculated from the velocity using the following formula:

$$E = (t*2*f)^2 \div \rho \qquad [1]$$

where:

E = Young's modulus in Pa

t = sample thickness in cm

f = frequency in Hz

ρ = density in g/cm^3

Phase One

Phase one testing consisted of testing samples made at optimum asphalt content and compacted to 98, 96, 93 and 90 percent of the maximum theoretical specific gravity (Gmm) of each mix.

Phase Two

Phase two consisted of testing samples compacted to 96 percent Gmm at optimum asphalt content and at optimum plus 0.5 percent and at optimum minus 0.5 and 1.0 percent.

TEST RESULTS

The study was terminated by KDOT prior to completion of the initial test plan with the major reason being the emphasis being placed on complex dynamic modulus by the forthcoming 2002 Design Guide. The entire phase one test plan was completed for the SM-19A mix and only two of the five modulus test procedures, **direct** and indirect (**ASTM D 4123**), were performed on the SM-19B mix. The results from the phase one testing are shown in table 2. The phase two testing was carried out on the SM-19A mix only. As with the phase one SM-19B mix, only the **direct** and indirect (**ASTM D 4123**) modulus test procedures were performed. The analysis was performed on the available data from the above tests.

Table 2. Results from phase one testing.

Mix	Sample	Gmm (%)	VTM (%)	Average Modulus (MPa) Direct	ASTM D 4123	SHRP	ASTM C 597	Geogauge
SM-19A	1A	90	8.6	4296	4709	3896	5408	297
SM-19A	1B	90	9.2	5378	3165	3234	5282	286
SM-19A	1C	90	9.1	5978	2779	3020	14058	312
SM-19A	1D	90	9.1	5247	4054	2792	3539	401
SM-19A	1E	90	9.2	6819	4227	3647	*	320
SM-19A	2A	93	6.1	5950	5668	5026	4909	370
SM-19A	2B	93	6.9	7385	4813	4351	8637	378
SM-19A	2C	93	7.2	5868	4323	3978	3599	375
SM-19A	2D	93	5.3	7088	5240	4544	7074	325
SM-19A	2E	93	7.0	6364	4385	3923	5635	368
SM-19A	3A	96	3.7	6481	5647	5730	*	355
SM-19A	3B	96	3.8	11653	5013	5599	6453	347
SM-19A	3C	96	3.8	6647	5495	6219	5322	329
SM-19A	3D	96	3.8	7219	5937	5688	4317	344
SM-19A	4A	98	2.1	6916	6426	4695	3670	330
SM-19A	4B	98	2.2	4785	6509	4944	7160	332
SM-19A	4C	98	2.0	5475	6847	6109	*	308
SM-19A	4D	98	2.0	7591	6343	6323	*	294
SM-19B	90A	90	10.0	3592	3613	*	*	*
SM-19B	90B	90	9.2	3944	3765	*	*	*
SM-19B	90C	90	9.6	4985	3682	*	*	*
SM-19B	90D	90	9.5	5213	4013	*	*	*
SM-19B	90E	90	10.0	5916	3758	*	*	*
SM-19B	90F	90	10.0	8950	4302	*	*	*
SM-19B	93A	93	7.5	4978	4468	*	*	*
SM-19B	93B	93	7.0	6509	4695	*	*	*
SM-19B	93C	93	7.0	5550	4489	*	*	*
SM-19B	93D	93	7.0	7750	4502	*	*	*
SM-19B	96A	96	4.0	18479	5364	*	*	*
SM-19B	96B	96	4.0	11218	5626	*	*	*
SM-19B	96C	96	4.0	6957	5840	*	*	*
SM-19B	96D	96	4.0	8557	5054	*	*	*
SM-19B	98A	98	2.0	8646	6543	*	*	*
SM-19B	98B	98	2.0	8115	6502	*	*	*
SM-19B	98C	98	2.0	8757	6778	*	*	*
SM-19B	98D	98	2.0	15148	6226	*	*	*

* Not tested

DATA ANALYSIS

Phase One

An analysis of variance (ANOVA) was performed on the data from phase one. Due to the early termination of the testing, only two modulus test methods can be evaluated. The experiment contained two mixes, two modulus measurement tests and five compaction levels. All two-way and three-way interactions were evaluated. The results are shown in table 3.

Table 3. ANOVA for SM-19A and SM-19B mix.

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Pr > F
Mix	1	1,137,847	1,137,847	2.59	0.1132
Method	1	12,764,086	12,764,086	29.05	0.0001
Gmm	3	15,553,589	5,184,530	11.80	0.0001
Mix*Method	1	1,634,225	1,634,225	3.72	0.0589
Mix*Gmm	3	2,978,509	992,836	2.26	0.0915
Method*Gmm	3	2,849,407	949,802	2.16	0.1027
3-Way Interaction	3	2,327,504	775,835	1.77	0.1642
Error	56	24,607,552	439,421		
Total	71	63,852,720			

As shown in table 3, the main effects of test method and compaction level (%Gmm) had a significant effect on modulus at a confidence limit of 95 percent ($\alpha = 0.05$). There was not a significant difference in mix type at a 95 percent confidence level, but mix type was significant at a confidence level of 89 percent ($\alpha = 0.11$). None of the interactions had a significant effect on the modulus results at a confidence limit of 95 percent ($\alpha = 0.05$). This means that the trends in modulus values were consistent between test methods, mixes and percent compaction.

Table 4 shows the results of Duncan's multiple range test for the main effects. Duncan's multiple range test indicates which means or effects are significantly different from each other, using a confidence limit of 95 percent ($\alpha = 0.05$). Groupings with the same letter are not significantly different. The results show that the **direct** method results in higher modulus values than indirect (**ASTM D 4123**), 7,234 MPa to 5,022 MPa, respectively. Both values are significantly higher than the typical range reported in the *1993 AASHTO Design Guide for Design of Pavement Structures*. The modulus values shown in the 1993 design guide are for samples tested without the short-term oven aging that is now a standard part of Superpave mix compaction methods as outlined in AASHTO TP4.

Table 4. Results of Duncan's multiple range test
for SM-19A and SM-19B mixes.

Main Effects	Levels	Mean (MPa)	n	Grouping*
Mix	SM-19B	6,458	36	A
	SM-19A	5,798	36	A
Method	Direct	7,234	36	A
	ASTM D 4123	5,022	36	A
Gmm	96	7,574	16	A
	98	7,351	16	A
	93	5,387	20	B
	90	4,734	20	B

*Groupings with same letter are not significantly different

Percent compaction, as measured by percent Gmm, had a significant effect on modulus values. The results are shown in table 4 as well. Samples compacted to 96 percent Gmm (4% VTM) had the highest modulus values, followed by samples compacted to 98 percent Gmm (2% VTM); however, the results were not significantly different from each other. The samples compacted to lower percent compaction (higher VTM), 93 and 90 percent Gmm, were not significantly different from each other, but had modulus values significantly less than the samples compacted to 96 and 98 percent Gmm. Based on the results from the interactions, this trend held true regardless of mix or test method.

The relationship between percent compaction and test method is presented in figure 2. Linear relationships are shown because the statistical analysis did not indicate a strong polynomial trend. The data depicts much more scatter in the **direct** modulus results than in the indirect (**ASTM D 4123**) as indicated by the R^2 values, 0.22 for the **direct** and 0.85 for **ASTM D 4123**. The coefficient of variation for the **direct** method was 41.2 percent compared to 21.8 percent for **ASTM D 4123**.

SM-19A Mix

Due to the abbreviated test schedule, only two modulus test methods could be evaluated using both mixes. Therefore, the results were analyzed by mix type, even though the limited experimental test data showed no significant difference in modulus based on mix type. This allowed the evaluation of all five modulus procedures for the SM-19A mix. The results of the ANOVA performed on the SM-19A mix are provided in table 5.

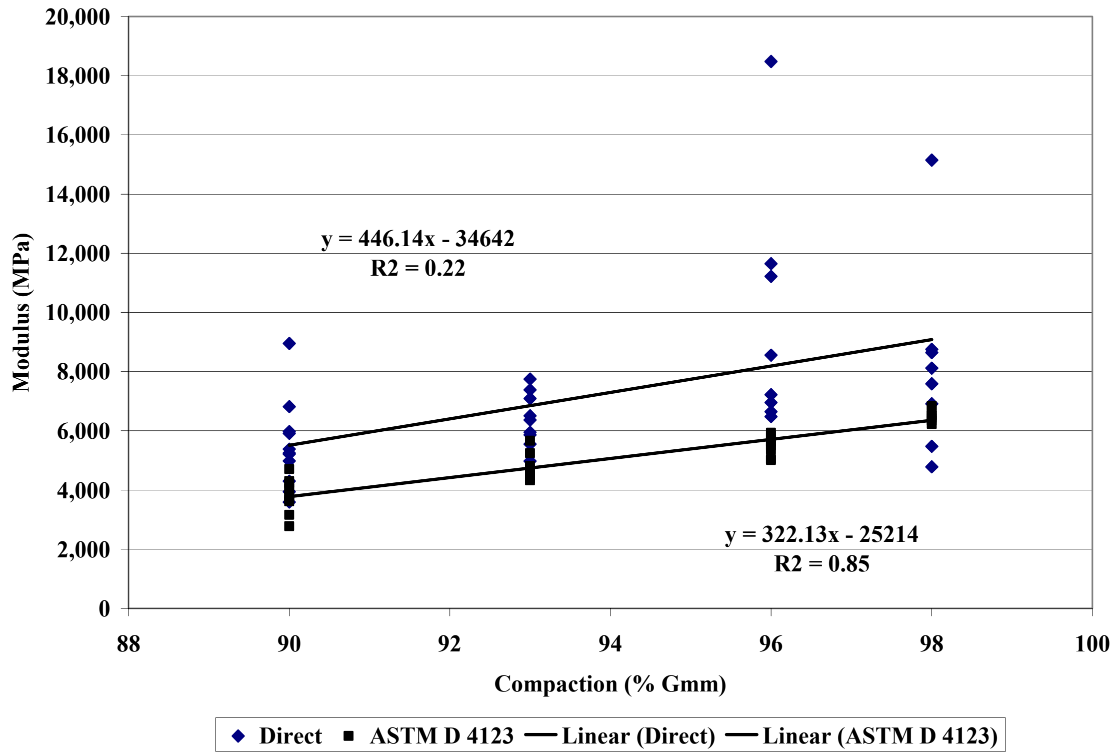

Figure 2. Percent compaction vs. modulus, by test method.

Table 5. ANOVA for SM-19A mix.

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Pr > F
Method	4	61,737,340	15,434,335	55.06	0.0001
Gmm	3	2,393,130	797,710	2.85	0.0442
Method*Gmm	12	5,699,910	474,993	1.69	0.0882
Error	66	18,501,505	280,326		
Total	85	88,331,886			

The ANOVA indicates that the main effects of test method and percent Gmm had a significant effect on modulus values at a 95 percent confidence limit ($\alpha = 0.05$). The interaction was significant at a 91.2 percent confidence limit ($\alpha = 0.088$).

The results of Duncan's multiple range test on percent compaction and test method are shown in table 6. The percent compaction had the same ranking on the SM-19A mix as the previous model. The results of the modulus test methods shown that the **direct** method again gave the highest modulus (6508 MPa) followed by the pulse-velocity procedure of **ASTM C 597** (6075 MPa). The difference was not significant at a 95 percent confidence limit. Both indirect methods, using horizontal measurements (**ASTM D 4123**) and the **SHRP** procedure, gave results significantly less than the **direct** and pulse-velocity procedures (**ASTM C597**). Although the **ASTM D 4123** procedure produced a larger modulus than the **SHRP** procedure, 5088 MPa to 4651 MPa, respectively, the difference was not statistically significant.

The **GeoGauge**™ procedure resulted in modulus values significantly lower than the other four procedures and significantly lower than usually reported in the literature, even though the samples had undergone short-term oven aging. It appears that the **GeoGauge**™ will require modification to the current test procedure before use on HMA.

<u>SM-19B Mix</u>

The same statistical analysis was repeated on the SM-19B mix. Only the **direct** and **ASTM D 4123** modulus test methods were evaluated on the SM-19B mix. The results of the ANOVA are shown in table 7 and the results from Duncan's multiple range test in table 8. The results are similar to the analysis with the SM-19A data included.

Table 6. Results of Duncan's multiple range test for SM-19A mix.

Main Effects	Levels	Mean (MPa)	n	Grouping*
Method	Direct	6,508	18	A
	ASTM C 597	6,075	14	A
	ASTM D 4123	5,088	18	B
	SHRP	4,651	18	B
	Geogauge	337	18	C
Gmm	96	4,989	19	A
	98	4,725	18	A & B
	93	4,423	25	A & B
	90	3,881	24	B

*Groupings with same letter are not significantly different

Table 7. ANOVA for SM-19B mix.

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Pr > F
Method	1	11,766,366	11,766,366	16.60	0.0003
Gmm	3	15,213,873	5,071,291	7.15	0.0010
Method*Gmm	3	3,895,227	1,298,409	1.83	0.1643
Error	28	19,847,637	708,844		
Total	35	50,723,102			

Table 8. Results of Duncan's multiple range test for SM-19B mix.

Main Effects	Levels	Mean (MPa)	n	Grouping*
Method	Direct	7,959	18	A
	ASTM D 4123	4,957	18	B
Gmm	96	8,387	8	A
	98	8,340	8	A
	93	5,065	10	B
	90	4,802	10	B

*Groupings with same letter are not significantly different

Phase Two

Phase two testing was performed on the SM-19A mix using the direct and ASTM D 4123 procedures only. The percent compaction was held constant at 96 percent Gmm and the asphalt content was varied from optimum asphalt content (6.25 percent) to optimum minus 0.5 and 1.0 percent to optimum plus 0.5 percent. The results of the ANOVA are shown in table 9.

Table 9. ANOVA for asphalt content, SM-19A mix.

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Pr > F
Method	1	9,317,944	9,317,944	21.68	0.0016
AC	3	1,999,136	666,379	1.55	0.2751
Method*AC	3	709,916	236,639	0.55	0.6617
Error	8	3,437,833	429,729		
Total	15	15,464,830			

Surprisingly, asphalt content did not have a significant effect on modulus values. Test method again had a significant effect on modulus, with the **direct** method producing larger modulus values than **ASTM D 4123**. The interaction was not significant, indicating the same effect of asphalt content, regardless of test method.

CONCLUSIONS

Although the testing was terminated prior to completion of the original test plan, some limited conclusions can be drawn from the study.

1. The short-term oven aging procedure described in AASHTO TP 4 resulted in higher modulus values than reported in the *1993 AASHTO Design Guide for Design of Pavement Structures*. If it were desired to use the mix preparation protocol of AASHTO TP 4 to determine the resilient modulus for selection of an "a" coefficient, modification of Figure 2.5 of the *1993 AASHTO Design Guide for Design of Pavement Structures*, or development of a new relationship would be required.
2. The **direct** method gave similar results to the pulse-velocity procedures of ASTM C 1383 and **ASTM C 597**, indicating the potential for a simplified procedure for determining modulus of HMA.
3. The indirect procedure of **ASTM D 4123** gave similar results to the more complicated **SHRP** procedure. The **SHRP** procedure has been reported as more precise. The coefficient of variation was similar, 21.8% for **ASTM D 4123** compared to 24.2% for the **SHRP** procedure. Evaluation of the precision of the test methods was outside the scope of this study.
4. Percent compaction had a significant effect on modulus with low compaction, 90 and 93 percent Gmm, affecting the modulus to a higher degree than high compaction, 98 percent Gmm.
5. Based on the very limited experiment, asphalt content did not have a significant effect on modulus.

IMPLEMENTATION

Due to the study being terminated, any implementation recommendations made at this time would be premature. However, the results from this study would be useful as a supplement to dynamic modulus testing and evaluation when the procedure is finalized.