NCHRP Web Document 56 (Project 9-18[1]): Contractor's Final Report

Sensitivity Evaluation of Field Shear Test Using Improved Protocol and Indirect Tension Strength Test

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CONTENTS

ACKNOWLEDGMENTS

Dr. Donald W. Christensen served as Principal Investigator for NCRHP Project 9-18 and managed the short testing program summarized in this report, dealing with sensitivity testing of the field shear test (FST) and of the indirect tension strength test at high temperatures. Dr. Ramon Bonaquist provided substantial technical input during these efforts. Laboratory testing was performed and/or supervised by Mr. Kevin Knechtel, P.E., and Mr. Don Jack, both of AAT. The new FST device, as described in this report, was designed and built by EnduraTec, Inc., under the supervision of Kent Vilendrer, and was lent to AAT for use in NCHRP Project 9-18 and related research. The authors gratefully acknowledge the assistance of EnduraTec and various material suppliers in completing this research.

INTRODUCTION

There were two primary objectives for the research documented in this short report. One objective was to evaluate the sensitivity of complex modulus measurements made using the recently improved field shear test (FST), following a new and potentially more effective testing protocol. The other objective was to evaluate the sensitivity of the indirect tension (IDT) strength test, performed at high temperatures in order to evaluate mixture cohesion and rut resistance. Both of these tests are quick and simple—especially the IDT strength test—and are thus good candidates for use as field tests for quality control (QC) of asphalt concrete mixtures.

The FST device was originally developed during NCHRP Project 9-7, as a rugged, simple device for performing quality control testing on asphalt concrete specimens in the field (*1, 2*). The FST was designed to perform many of the same tests performed by the Superpave shear test (SST), a large and expensive device used to evaluate various performance related properties, such as complex shear modulus (|G*|) and resistance to permanent deformation (*3*). The original FST was promising—it was small, rugged, and relatively easy to use. However, there were a number of problems with the device. During NCHRP Project 9-18, the FST was improved and re-evaluated. Modulus measurements made with this device appeared to be well suited for quality control use, except that the variability appeared to be too high, a problem seen in virtually every other modulus measurement technique currently used on asphalt concrete (*4, 5*). In the NCHRP Project 9-18 final report, a recommendation was made to evaluate a new testing protocol for the FST. This procedure involves averaging four modulus determinations for each specimen tested, rotating and/or flipping the specimen between each determination, so that the specimen is sheared in a different sense and in a slightly different location each time. This procedure helps reduce variability caused by non-homogeneity and slight differences in test set-up (*4, 5*). One of the main purposes of the testing summarized in this report was to evaluate the sensitivity and precision of the FST using this improved protocol.

The IDT strength test was originally developed for measuring the tensile strength of portland cement concrete mixtures, and was later adopted for use in measuring the tensile strength and modulus of asphalt concrete mixtures. Recently, Christensen and his associates discovered very good relationships between IDT strength, mixture cohesion, and rut resistance—as measured in the laboratory and as indicated in a very limited field study, and in data generated at the Federal Highway Administrations Accelerated Loading Facility (ALF) (6, 7, 8). Because of the apparently good correlation between IDT strength and rut resistance, and because of the low cost and simplicity of the IDT test, it is an ideal candidate for use as a field QC test for asphalt concrete.

The test program used to evaluate the sensitivity of both the FST (new protocol) and IDT strength was straight forward, and followed in all important aspects the same sensitivity test plan used during the initial evaluation of the FST performed as part of NCHRP Project 9-18. In fact, the same set of specimens was used, though their modulus was somewhat higher due to gradual hardening of the mixtures over time. Four different aggregates were used in the test program, and the composition of each of the resulting four primary mixtures was varied in a consistent way, with changes in coarse aggregate, mineral filler, and asphalt binder content. Four replicate specimens were tested for each mixture variation, ensuring adequate degrees of freedom for statistical analyses. To date, only one FST prototype exists, so the results of this study should be considered preliminary. Additional evaluations of the FST under field conditions are needed, preferably using two or three devices and a number of different operators.

BACKGROUND

The FST sensitivity testing reported in this document represents the continuation of an engineering and research effort that was begun in 1994 on the quality control of Superpave asphalt concrete mixtures. This effort was begun with NCHRP Project 9-7 “Field Procedures and Equipment to Implement SHRP Asphalt Specifications,” which was one of the earliest efforts to investigate quality control and acceptance procedures for mixtures produced using the Superpave system (*1*). As part of NCHRP Project 9-7, the original field shear test was developed as a simple and rapid procedure for evaluating several performance-related properties of asphalt concrete mixtures, for use in quality control and acceptance testing. The FST was designed to perform the same basic battery of tests performed using the Superpave Shear Tester (SST), including the frequency sweep test for determining dynamic complex modulus (|G*|) and phase angle, and the repeated shear at constant height (RSCH) test, which measures permanent deformation under repeated loading at high temperatures. Both procedures can be used to evaluate rut resistance of overall mixture quality (*1, 2, 3*).

The SST is relatively complicated and expensive piece of equipment. Also, preparing specimens for testing using the SST involved compacting asphalt concrete mixture using the Superpave gyratory compactor to a 150-mm diameter specimen, sawing a 50-mm high disc from the specimen, and gluing this disc to two aluminum or stainless steel platens. Three transducers are mounted to this specimen for measuring horizontal and vertical deformations. A sketch of a typical SST specimen is shown in Figure 1 (*9*). Because of the time and expense involved in performing these tests, the SST is unsuitable for use as a quality control and acceptance test for asphalt concrete mixtures. The original FST was designed to shear gyratory specimens across their diameter, as shown in Figure 2. Specimens could be tested using this device without any sawing or gluing, and the device itself was smaller, simpler to operate and less expensive than the SST, and so was potentially appropriate for QC and acceptance testing. However, initial evaluations of the FST during NCHRP Project 9-7 revealed several problems. Modulus values determined with the FST did not always compare well with those found using the FST, and exhibited relatively poor precision (*1*, 2). The device did not include a temperature control chamber, which probably explained some of the problems with the test data. Furthermore, the extent of testing was not adequate for evaluating the sensitivity of the device to changes in mixture composition. It was decided that although the FST was a promising test for QC and acceptance testing, further evaluation and refinement of the device and procedure were needed.

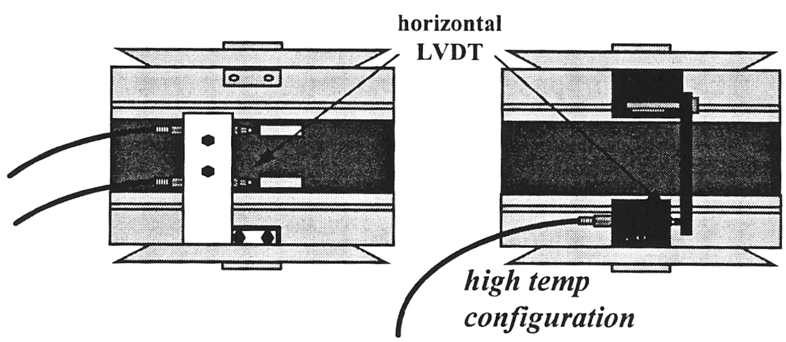


Figure 1. SST Specimens Showing Two Different Approaches for Mounting Linear Variable Differential Transforms (LVDTs) for Deflection Measurements (9).

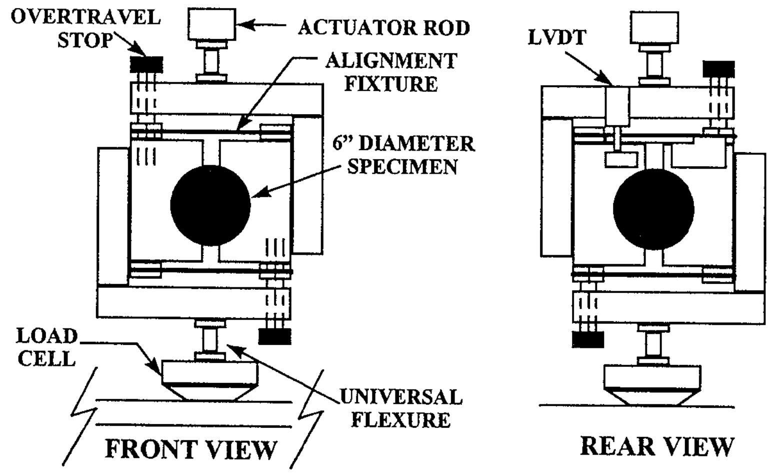


Figure 2. Sketch of Original Field Shear Test Developed During NCHRP Project 9-7 (*1*).

NCHRP Project 9-18 was begun in 1999, with the objective of evaluating and refining the FST to produce a device better suited for quality control and acceptance testing of Superpave asphalt concrete mixtures in the field (*4*, *5*). After a review of the design of the original FST, which included surveys of engineers and technicians and stress analyses of the FST test geometry and possible alternatives, it was determined that a different test geometry was needed, and the FST was redesigned. The new FST developed during NCHRP Project 9-18 shears a gyratory specimen in the same plane and sense as the SST. However, as in the original FST the test is performed directly on a standard gyratory specimen, without sawing or gluing. The redesigned FST uses hydraulic clamps to hold the gyratory specimen around each end, and a servo-pneumatic system to apply the sinusoidal load to the specimen. It is compact and easy to use, and initial results showed improvement over the original FST in terms of accuracy and repeatability. A sketch of the new FST geometry and a photograph of the device are shown in Figure 3. RSCH test data produced with the new FST was not of good quality; better results were obtained in measuring |G*| values. Although modulus data determined using the new FST were somewhat sensitive to changes in mixtures composition, the precision was found to be inadequate for quality control and acceptance testing (*4*, *5*). But towards the conclusion of NCHRP Project 9-18, it was realized that because the frequency sweep test could be performed so quickly using the new FST, multiple determinations could be made with this device, and an average value calculated and reported. Between each determination, the specimen could be rotated and/or flipped, so that the variations due to uneven air void distribution and other non-homogeneities could be greatly reduced. One of the recommendations of NCHRP Project 9-18 was to perform follow-up testing to evaluate this new protocol, to determine if it would significantly improve the precision and sensitivity of modulus measurements made using the new FST.

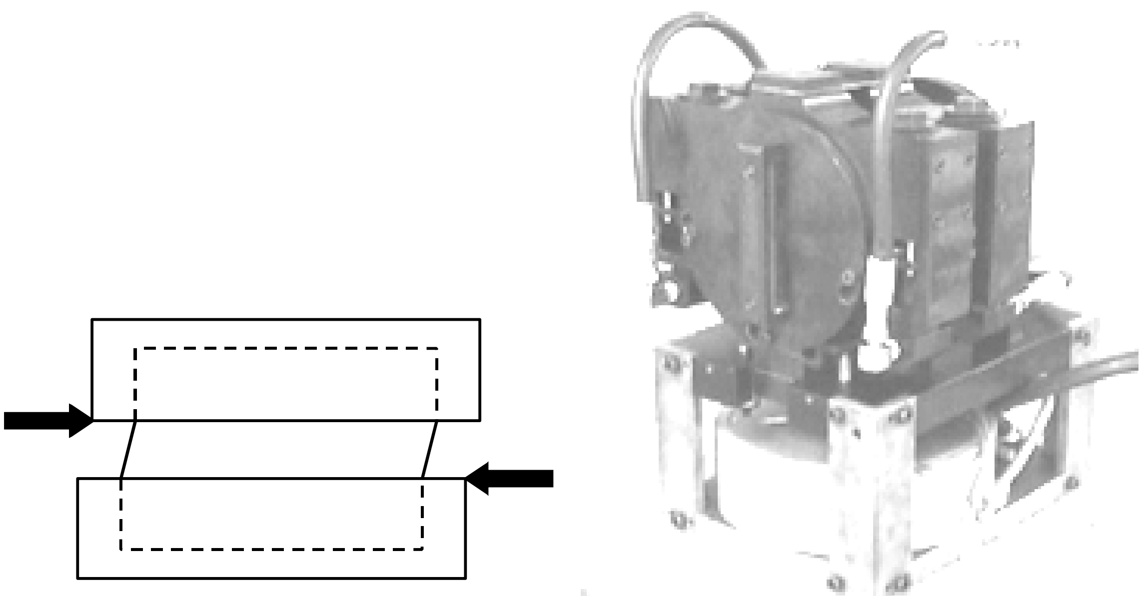


Figure 3. Sketch of Geometry (left) and Photograph (right) of the New FST.

The initial research effort on the high-temperature IDT strength test was performed as part of an evaluation of the triaxial strength test as a possible simple performance test on asphalt concrete mixtures (*6, 7*). A simplified approach towards determining mixture cohesion was proposed, which involved using only unconfined compressive strength and IDT strength to determine the Mohr-Coulomb failure parameters—cohesion and angle of internal friction. This abbreviated protocol was reasonably effective, but more importantly, it was found that mixture cohesion appeared to relate much better to rut resistance than did internal friction, probably because of the relatively good quality of aggregates now used in producing asphalt concrete mixtures. Furthermore, it was also found that IDT strength was a very good indicator of mixture cohesion, and also correlated very well to rut resistance, both as indicated in a limited field study and as characterized through other laboratory tests (*6, 7*). Additional research was performed to verify the findings of this study, that included evaluation of additional mixtures, and also IDT testing of mixtures used in a rutting study performed by FHWA at their ALF facility in McLean, Virginia (8*, 10*). This research confirmed the findings of the initial research, and showed good correlations between IDT strength and the rutting observed in the FHWA ALF study. Although the results of these two projects on IDT strength and rut resistance were promising, additional work was needed to evaluate the use of the IDT test as a standard procedure for evaluating mixture cohesion and rut resistance. One important aspect of the test needed to evaluate its usefulness is its sensitivity to changes in mixture composition

To evaluate the effectiveness of the FST using the new protocol, and also to evaluate the sensitivity of the IDT strength test, a short project was initiated in which the original set of specimens used in NCHRP Project 9-18 were to be retested to determine the dynamic complex modulus in shear (|G*|) using the FST, and tensile strength using the IDT procedure. The results of this test program are summarized in this report. The experiment design and analysis used were identical to that used in the original sensitivity testing performed as part of NCHRP Project 9-18. Details of the test program to evaluate the precision and sensitivity of the FST |G*| measurements using the improved protocol, and of the IDT strength data are given below.

MATERIALS, METHODS AND EXPERIMENT DESIGN

The sensitivity test program involved testing a total of four different materials: 9.5-mm, 12.5-mm, 19-mm and 25-mm Superpave mixtures. The aggregate sources were different for each of these. The aggregate types, volumetric factors, and gradations for the mixtures are summarized in Table 1. For each of the four primary mixtures, the design aggregate gradation and binder contents were systematically varied to produce a total of eight mixture types or variants. The factors that were varied were coarse aggregate content (± 6% on the 2.36-mm sieve), mineral filler content (± 2% on the 0.075-mm sieve) and binder content (± 0.5). The improved protocol was used to perform the frequency sweep test at a temperature of 40 °C; the RSCH test was not done.

A total of four replicate specimens were prepared using an Interlaken gyratory compactor, following procedures as outlined in AASHTO TP4, except that the mass of the batches was adjusted to obtain specimens with a nominal height of 115 mm. After mixing, the material was short-term oven aged in accordance with AASHTO PP2 at a temperature of 135 ^{o}C for 4 hours. The mixtures required different levels of compaction effort to produce specimens within the specified air void tolerance of 4.0 ± 0.5 percent.

Table 1. Volumetric Properties of Design Mixtures.

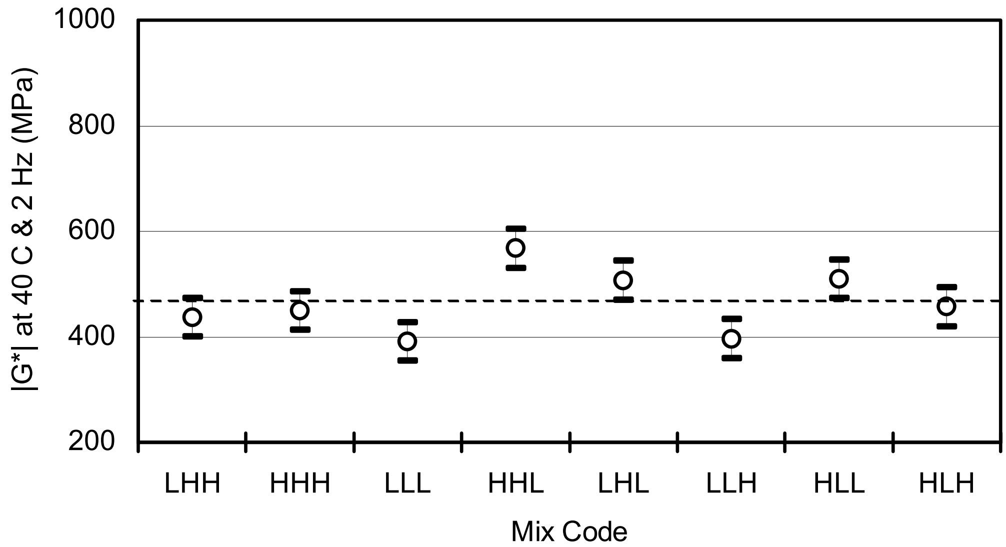
Property	9.5 mm	12.5 mm	19.0 mm	25.0 mm
N_{design}	65	75	96	100
Binder Grade	PG 64-22	PG 76-22	PG 64-22	PG 64-22
Coarse aggregate type	Crushed limestone	Crushed stone	Crushed stone	Crushed gravel
Fine aggregate type	Crushed limestone	Crushed stone and natural sand	Crushed stone	Crushed limestone
Coarse Aggregate Angularity. One Face/ Two Face	100/100	100/100	100/100	95/80
Fine Aggregate Angularity	45.0	47.2	52.1	45.0
Flat & Elongated, % (Ratio 5: 1)	1.6	3.0	1.9	1.4
Sand Equivalent, %	83	55	80	74
Binder Content, %	6.2%	4.75%	4.4%	4.4%
Compaction, % G_{mm}				
N_{ini}	85.2%	86.4 %	85.9%	85.4 %
N_{des}	96.0%	96.0 %	95.8%	96.0 %
N_{max}	97.8%	97.3 %	97.2%	97.0 %
Voids in Mineral Aggregate (VMA), %	17.2	14.6	14.5	12.8
Voids in Total Mixture (VTM), %	4.0	4.0	4.2	4.0
Voids Filled with Asphalt (VFA), %	76.7	72.6	71.0	68.8
Fines to Effective Binder Ratio (F/A)	1.2	1.2	1.1	0.8
Sieve Size, mm	Gradation, % Passing:			
37.5	100	100	100	100
25	100	100	100	97
19	100	100	94	86
12.5	100	97	73	63
9.5	97	75	52	46
4.75	62	39	33	33
2.36	42	30	24	26
1.18	27	24	17	16
0.6	18	18	14	10
0.3	11	11	10	7
0.15	8	7	6	4
0.075	6.8	5.3	3.6	3.0

Prior to FST testing, the specimens were conditioned at 40 °C in an environmental chamber for a minimum of two hours. The specimens were then placed in the FST, and the hydraulic clamps closed on the specimen with a pressure of 10.3 MPa (this is the pressure of the hydraulic fluid, not of the clamps on the specimen). The door to the environmental chamber holding the FST was then closed, and the specimen allowed to equilibrate for about 5 minutes. A frequency sweep test was then performed. The hydraulic clamps were then loosened, and the specimen rotated 90°, and the clamps retightened. The door to the chamber was then closed, the specimen equilibrated again for 5 minutes, and the frequency sweep repeated. A third frequency sweep was performed after flipping the specimen front-to back, and a fourth after again rotating the specimen 90°. In this way, four separate frequency sweep determinations were made on each specimen. The final frequency sweep values were the average of these four determinations.

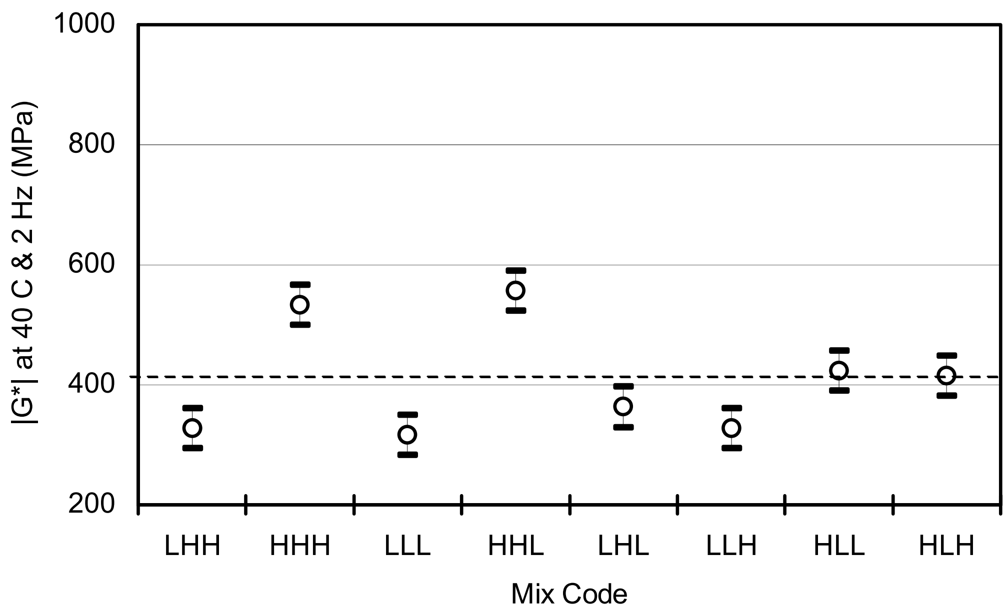
Prior to IDT strength tests, the specimens were conditioned at 34 °C for a minimum of two hours in an environmental chamber. The IDT strength tests were performed at 34 °C, on a servo-hydraulic test system equipped with a standard Lottman breaking head for 150-mm diameter specimens (ASTM D 4123, AASHTO T283). A loading rate of 3.75 mm/min was used to perform the IDT strength tests.

FINDINGS

The results of the sensitivity testing were first analyzed graphically, as shown in Figure 4. This plot shows average $|G^*|$ values at 40 °C and 10 Hz for the eight variations of each mixture, using the original FST testing protocol. Included on the plot are error bars representing ± 2s confidence intervals for the mean (n = 4 replicates), and the overall average for the mixture

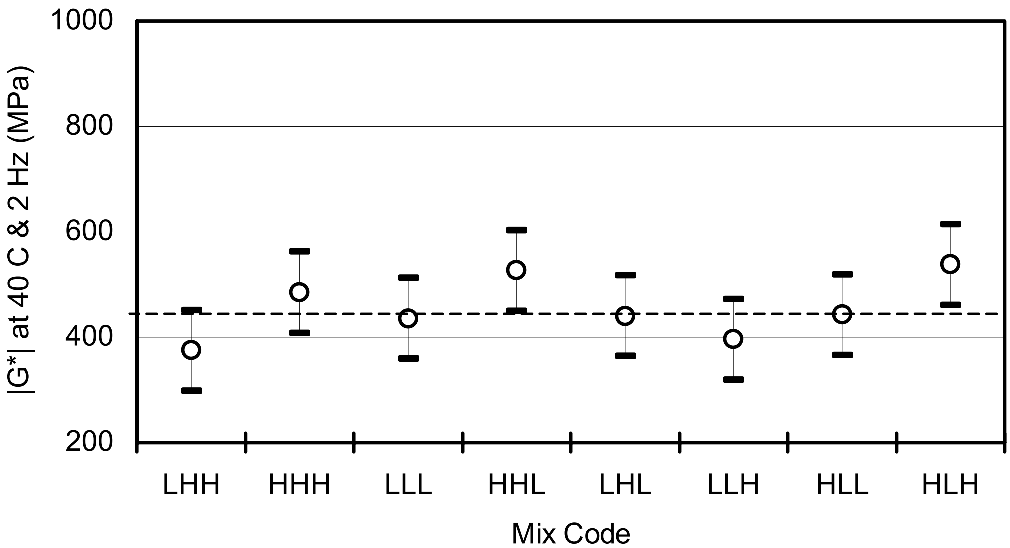


(a) 9.5-mm Mixture

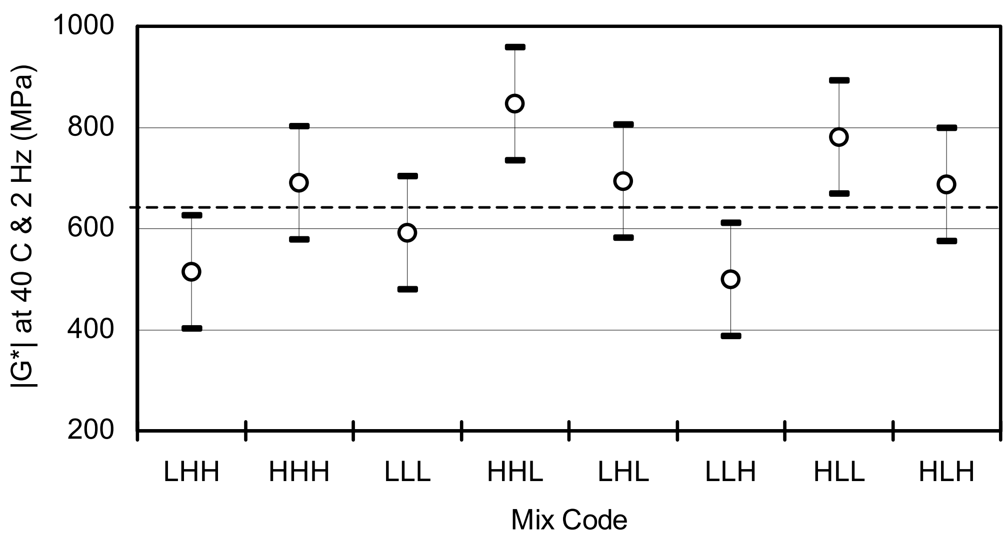


(b) 25-mm Mixture

Figure 4. Average Complex Modulus (new protocol) at 10 Hz and 40 °C with 2s-error bars; mixture code represents high (H) or low (L) values for coarse aggregate, mineral filler, or binder content, respectively. Dashed line represents mean value for mixture.



(c) 19-mm Mixture

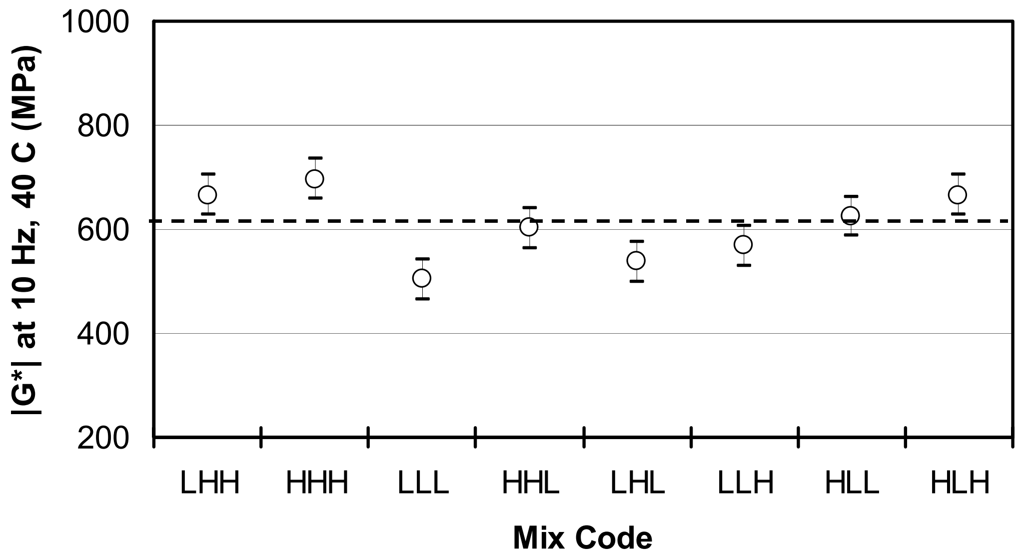


(d) 12.5-mm Mixture

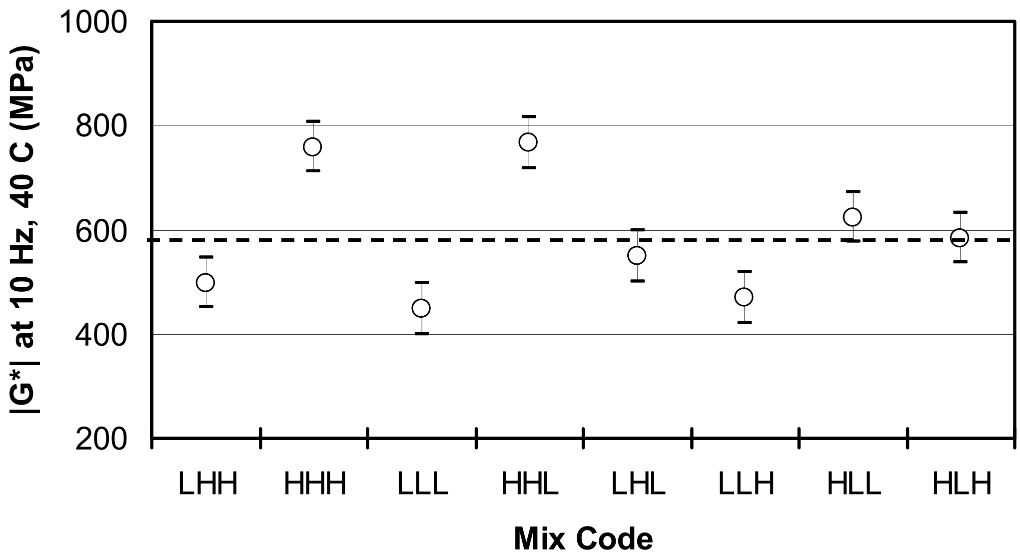
Figure 4 (continued). Average Complex Modulus (new protocol) at 10 Hz and 40 °C with 2s-error bars; mixture code represents high (H) or low (L) values for coarse aggregate, mineral filler, or binder content, respectively. Dashed line represents mean value for mixture.

(dashed line). Since the eight mixture types vary substantially in composition, good sensitivity is indicated when the error bars do not in general overlap, and when the error bars for the eight variations tend not to include the overall average. Large error bars that overlap for most mixtures indicate poor sensitivity. In the analysis of the initial set of modulus data (original protocol), as shown in Figure 4, it was found that the sensitivity of the FST appears to vary substantially from mixture to mixture. Best results were obtained with the 9.5-mm and 25-mm mixtures. The results for the 19-mm and 12.5-mm mixtures were not as good; the sensitivity of $|G^*|$ to changes in composition was probably not adequate for quality control purposes in these cases. The lack of sensitivity for these mixtures was probably because of the high variability in the modulus data, increasing the width of the error bars compared to the changes occurring in the mean response for the different mixture variations. Because of the large differences in variability among the four mixtures, it was decided to retest two of the mixtures at the end of the project, to see if the degree of variation was similar to that seen in initial testing. These retests in fact confirmed that there were real and repeatable differences in the variability exhibited by the four mixtures. However, as discussed later in this report, test data gathered using the new protocol produced data with more uniform variability among the four mixtures.

The graphical analyses of the FST $|G^*|$ data collected using the improved protocol are shown in Figure 5. The sensitivity for the 9.5 and 25 mm mixtures appears similar to that observed for data gathered using the original protocol, but the sensitivity for the 19 and 12.5 mm mixtures is significantly improved. For three of the mixtures, confidence intervals for six of the eight mixture variations do not include the overall mean, while for the fourth (the 25-mm mixture), confidence intervals for five of the eight variations exclude the mean. Thus, the $|G^*|$ value measured with the improved protocol differentiated 23 of 32 mixture variations. This

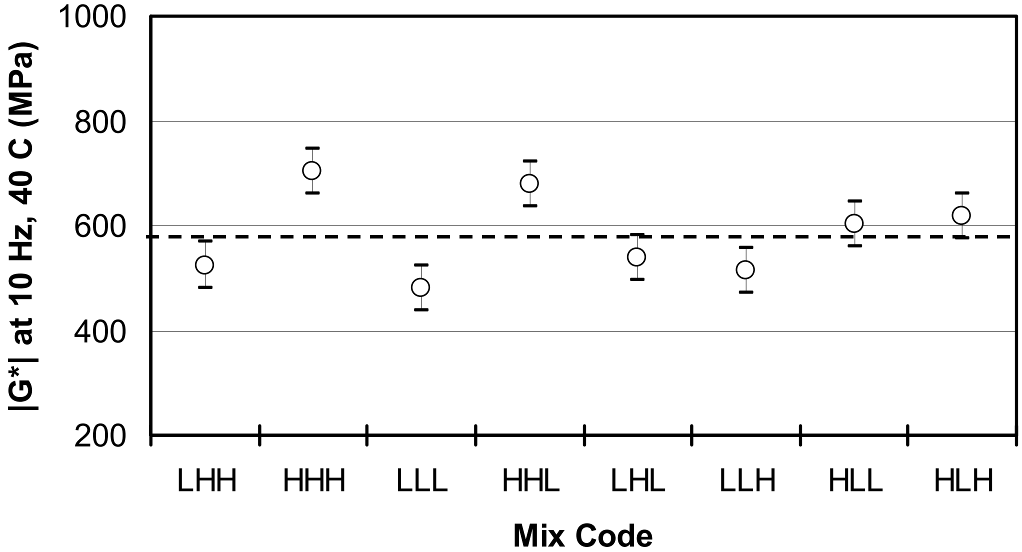


(a) 9.5-mm Mixture

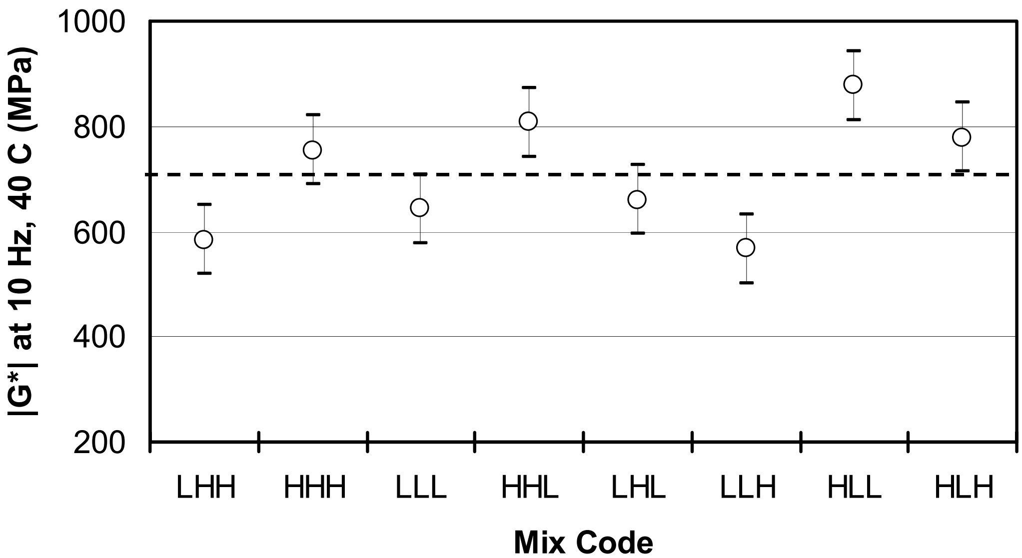


(b) 25-mm Mixture

Figure 5. Average Complex Modulus (original protocol) at 10 Hz and 40 °C with 2s-Error Bars: mixture code represents high (H) or low (L) values for coarse aggregate, mineral filler, or binder content, respectively. Dashed line represents mean value for mixture.



(a) 19-mm Mixture



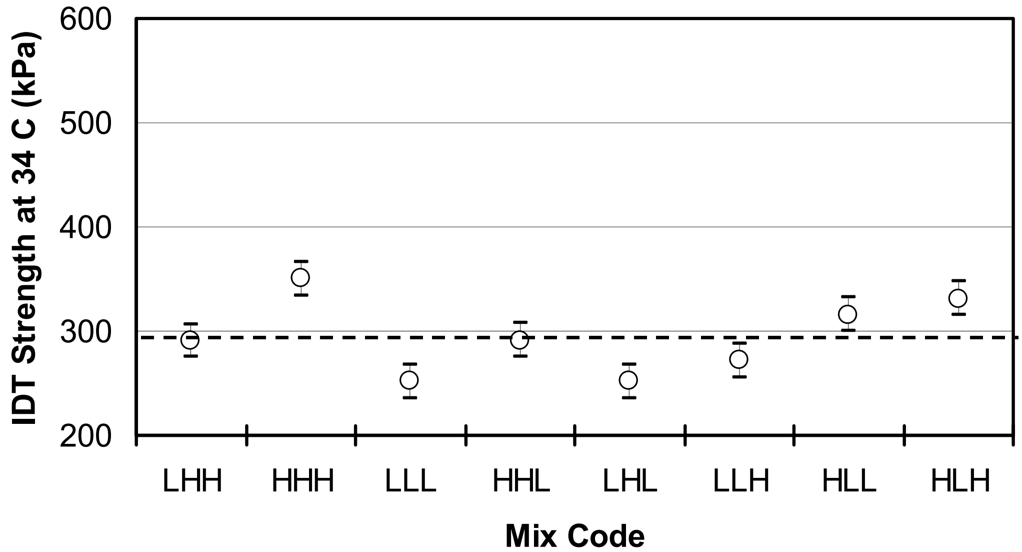
(b) 12.5-mm Mixture

Figure 5 (continued). Average Complex Modulus (original protocol) at 10 Hz and 40 °C with 2s-Error Bars: mixture code represents high (H) or low (L) values for coarse aggregate, mineral filler, or binder content, respectively. Dashed line represents mean value for mixture.

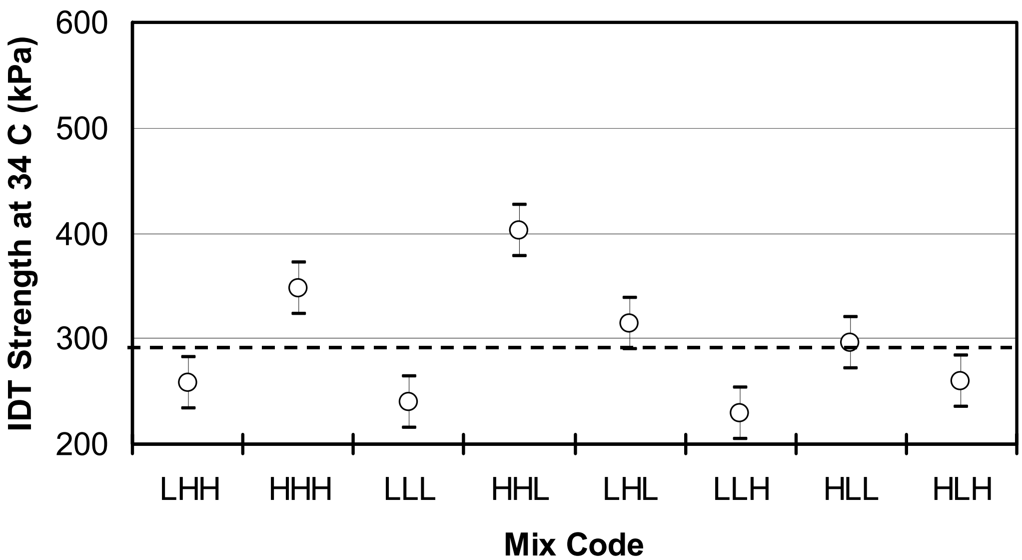
indicates a good degree of sensitivity for all mixtures, in that changes in mixture composition in general produced changes in modulus that were statistically significant. For comparison, in the first round of sensitivity testing, as shown in Figure 4, differentiation was observed in only 17 of 32 mixtures. Examining and comparing Figures 4 (b) and 5 (b), it is also appears that the sensitivity using the new protocol is more uniform among the four mixture types, which increases the confidence with which the FST can be used for QC testing.

Confidence intervals for the IDT strength data are shown in Figure 6. The sensitivity for this test appears to be very similar to that for the |G*| measurements made using the new protocol. Overall, the procedure differentiated 24 of the 32 mixtures.

For the original test protocol, the coefficient of variation (C.V.) values for |G*| measurements made with the FST ranged from 7.9 to 16.9 %, with an overall value (based upon the pooled standard deviation and grand average) of 14.5 %. Using the new protocol, the C.V. values ranged from 6.3 to 9.2 %, with an overall value of 8.0 %. Therefore, the new protocol appears to have significantly improved the precision of complex modulus measurements made using the FST. The C.V. for IDT strength for the four mixtures ranges from 5.5 % to 8.4 %, with an overall value of 7.3 %. For use in quality control, where a lot average is typically based on n = 5 tests, the 2 standard deviation error (based on the standard deviation of the mean) would be 13 % using the original protocol, whereas using the new procedure, this value is reduced to 7.2 %. For IDT strength, the 2 standard deviation error for the mean of one lot (n = 5) would be 6.5 %. The improved sensitivity with the new protocol for the FST appears to be a result of the reduced variability in the data. The precision of modulus measurements made with the FST using the new protocol appears to be very good compared to other techniques, and is probably adequate for quality control purposes. The precision for IDT strength measurements at high

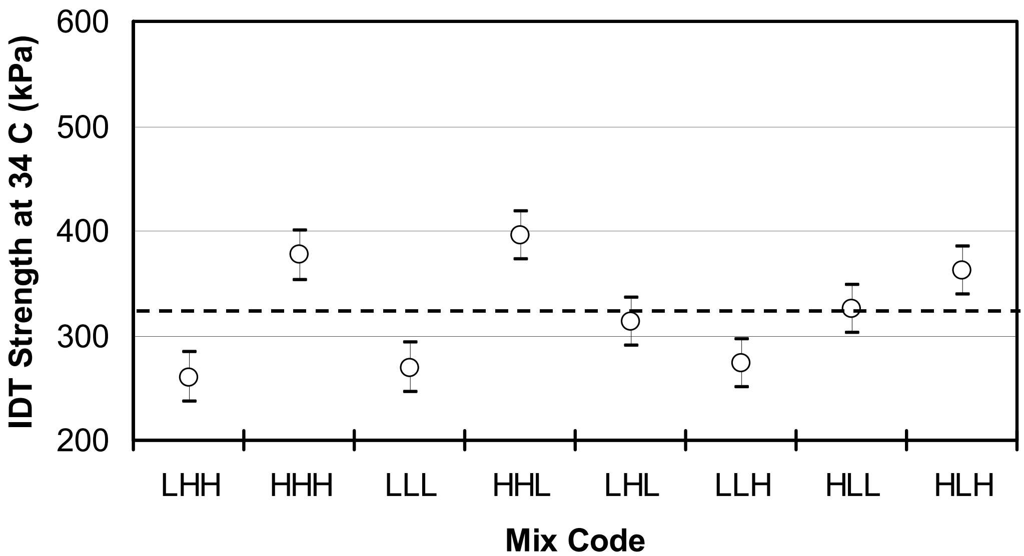


(a) 9.5-mm Mixture

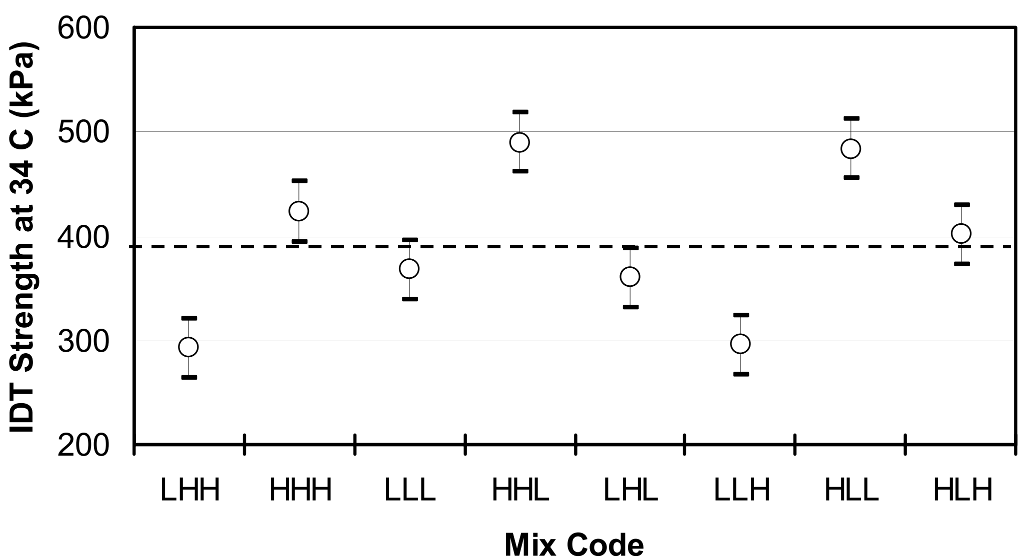


(b) 25-mm Mixture

Figure 6. Average IDT Strength at 34 °C and 3.75 mm/min with 2s-Error Bars: mixture code represents high (H) or low (L) values for coarse aggregate, mineral filler, or binder content, respectively. Dashed line represents mean value for mixture.



(a) 19-mm Mixture



(b) 12.5-mm Mixture

Figure 6 (continued). Average IDT Strength at 34 °C and 3.75 mm/min with 2s-Error Bars: mixture code represents high (H) or low (L) values for coarse aggregate, mineral filler, or binder content, respectively. Dashed line represents mean value for mixture.

temperature appears to be similar to that for modulus measurements made with the FST using the new protocol, and is also probably adequate for quality control purposes.

The second phase of the data analysis involved using statistical methods to evaluate the sensitivity of the FST and IDT to changes in mixture composition. In the initial analysis of FST data performed during NCHRP Project 9-18, a preliminary analysis of complex modulus data indicated that the most reliable data was produced at frequencies of 5 or 10 Hz. Since 10 Hz is more commonly used for dynamic measurements on asphalt concrete, this value was used in all analyses reported here. These preliminary analyses also showed that testing time or order, or some related factor such as compaction sequence, had a significant effect on the results of the frequency sweep test. Different testing protocols were used to try to determine the source of this variability, but the results were unclear. Possible sources include differences in steric hardening of the mixtures prior to testing; variability in the performance of the FST due to changes in temperature; differences in the amount of binder hardening among specimens compacted through the course of a day; differences in the amount of fines incorporated into specimens through the course of the day. Various methods were evaluated for accounting for this testing order effect in the statistical models. Ultimately, it was determined that the best approach involved including a variable for testing time and another for specimen/compaction order. This allows some evaluation of whether the source of variability was in fact compaction order, or some other systematic variation in specimen preparation, or testing time. The resulting general regression model, using indicator variables for specimen, for the various analyses can be represented by the following equation:

$$\begin{aligned} Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \beta_3 X_{i3} + \beta_4 X_{i1} X_{i2} + \beta_5 X_{i1} X_{i3} + \beta_6 X_{i2} X_{i3} \\ + \beta_7 X_{i1} X_{i2} X_{i3} + \beta_8 X_{i4} + \beta_9 X_{i5} + \beta_{10} X_{i6} + \beta_{11} X_{i7} + \varepsilon_i \end{aligned} \tag{1}$$

Where:

Y_i = the value of the dependent variable (modulus or IDT strength) for the i^{th} observation

β_k = the ten regression coefficients: β_1, β_2, β_3, etc.

X_{ik} = the value of the 10 independent variables for i^{th} observation

The next step in the statistical analysis of the FST data was to evaluate the coefficients for the regression model for complex modulus at 10 Hz for each of the three mixtures. The results of the regression analysis for complex modulus are summarized in Tables 2 and 3—Table 2 showing data generated using the original testing protocol, and Table 3 showing data generated using the new protocol. The regression analysis for IDT strength is summarized in Table 4. In all three tables, significant factors ($p \leq 0.1$) are shown in boldface. Factors with $p > 0.1$, but part of a significant interaction term, are also shown in boldface type.

The results summarized in Tables 2 through 4 confirm the graphical analyses presented previously. The new protocol for measuring complex shear modulus with the FST using the improved protocol provide better and more consistent sensitivity in evaluating the effect of changes in mixture composition, compared to the original protocol. The precision of the data and sensitivity of the data are probably adequate for QC testing. The sensitivity of IDT strength to changes in mixture composition is similar to that for modulus measurements made with the FST using the new protocol; the IDT strength test also appears suitable for QC purposes.

Table 2. Summary of Regression Analyses for Sensitivity of Complex Modulus at 10 Hz and 40 °C, Original Protocol.

Factor	9.5-mm Mixture		25-mm Mixture	
	Coef.	p	Coef.	p
Constant	**422**	**0.00**	**638**	**0.00**
Coarse Agg. (CA)	**30.8**	**0.00**	**81.4**	**0.00**
Mineral Filler (MF)	**22.6**	**0.00**	**34.9**	**0.00**
Asphalt Binder (AC)	**-26.5**	**0.00**	**-8.2**	**0.11**
CA×MF	**-14.0**	**0.00**	**31.0**	**0.00**
CA×AC	**-11.3**	**0.02**	**-2.8**	**0.57**
MF×AC	**-14.9**	**0.01**	**-9.2**	**0.07**
CA×MF×AC	0.1	0.98	-1.9	0.71
Test Time	7.0	0.47	**-20.6**	**0.00**
Compaction Order 2	-20.2	0.12	13.6	0.34
Compaction Order 3	**-69.6**	**0.00**	22.2	0.13
Compaction Order 4	**-84.0**	**0.00**	21.2	0.14
r^2 (Adj. For d.f.)	90.5%		91.4%	

Factor	19-mm Mixture		12.5-mm Mixture	
	Coef.	p	Coef.	p
Constant	**454**	**0.00**	**672**	**0.09**
Coarse Agg. (CA)	**32.9**	**0.00**	**88.1**	**0.00**
Mineral Filler (MF)	-8.3	0.37	23.1	0.19
Asphalt Binder (AC)	**3.5**	**0.71**	**-65.1**	**0.00**
CA×MF	-4.0	0.67	-5.8	0.74
CA×AC	**30.1**	**0.00**	2.4	0.89
MF×AC	-10.1	0.28	-18.7	0.28
CA×MF×AC	-3.7	0.69	2.6	0.89
Test Time	-5.9	0.57	-2.2	0.95
Compaction Order 2	**99.5**	**0.00**	37.2	0.51
Compaction Order 3	**45.5**	**0.10**	-70.3	0.17
Compaction Order 4	**89.1**	**0.00**	**99.6**	**0.06**
r^2 (Adj. For d.f.)	55.3%		60.6%	

Table 3. Summary of Regression Analyses for Sensitivity of Complex Modulus at 10 Hz and 40 °C, New Protocol.

Factor	9.5-mm Mixture		25-mm Mixture	
	Coef.	p	Coef.	p
Constant	**604**	**0.00**	**564**	**0.00**
Coarse Agg. (CA)	**38.7**	**0.00**	**94.3**	**0.00**
Mineral Filler (MF)	**15.6**	**0.08**	**56.6**	**0.00**
Asphalt Binder (AC)	**42.8**	**0.00**	**-9.3**	**0.24**
CA×MF	**-15.9**	**0.01**	**22.2**	**0.01**
CA×AC	-6.3	0.34	-1.9	0.81
MF×AC	**16.1**	**0.04**	-4.6	0.56
CA×MF×AC	-2.1	0.73	**14.4**	**0.10**
Test Time	3.9	0.78	**5.2**	**0.58**
Compaction Order 2	**-51.9**	**0.01**	**-61.2**	**0.01**
Compaction Order 3	**-68.7**	**0.04**	**-47.7**	**0.04**
Compaction Order 4	-58.1	0.16	**-45.7**	**0.06**
R^2 (Adj. For d.f.)	83.4%		87.5%	

Factor	19-mm Mixture		12.5-mm Mixture	
	Coef.	p	Coef.	p
Constant	**684**	**0.00**	**881**	**0.00**
Coarse Agg. (CA)	**69.4**	**0.00**	**95.7**	**0.00**
Mineral Filler (MF)	**29.6**	**0.00**	-7.0	0.54
Asphalt Binder (AC)	6.1	0.33	-37.9	**0.00**
CA×MF	**12.8**	**0.05**	-14.5	0.22
CA×AC	1.3	0.84	-1.1	0.93
MF×AC	-5.7	0.36	6.4	0.58
CA×MF×AC	6.0	0.34	2.6	0.83
Test Time	-6.4	0.35	-14.7	0.51
Compaction Order 2	**-46.2**	**0.01**	43.0	0.21
Compaction Order 3	**-45.0**	**0.02**	-37.2	0.33
Compaction Order 4	-14.7	0.42	-28.3	0.40
r^2 (Adj. For d.f.)	84.2%		72.4%	

Table 4. Summary of Regression Analyses for Sensitivity of IDT Strength at 34 °C at 3.75 mm/min.

Factor	9.5-mm Mixture		25-mm Mixture	
	Coef.	p	Coef.	p
Constant	**352**	**0.00**	**327**	**0.00**
Coarse Agg. (CA)	**28.1**	**0.00**	**33.6**	**0.00**
Mineral Filler (MF)	**3.6**	**0.37**	**37.2**	**0.00**
Asphalt Binder (AC)	**14.9**	**0.00**	**-19.8**	**0.00**
CA×MF	-2.7	0.31	**11.8**	**0.01**
CA×AC	1.0	0.74	-3.2	0.42
MF×AC	**6.4**	**0.08**	**-8.1**	**0.05**
CA×MF×AC	3.9	0.17	3.0	0.47
Test Time	-4.0	0.55	**-1.3**	**0.78**
Compaction Order 2	-10.8	0.21	**-30.7**	**0.01**
Compaction Order 3	-13.8	0.34	-14.3	0.21
Compaction Order 4	-9.8	0.61	**-29.0**	**0.01**
r^2 (Adj. For d.f.)	85.9%		87.1%	

Factor	19-mm Mixture		12.5-mm Mixture	
	Coef.	p	Coef.	p
Constant	**359**	**0.00**	**350**	**0.01**
Coarse Agg. (CA)	**43.2**	**0.00**	**54.8**	**0.00**
Mineral Filler (MF)	**14.8**	**0.00**	7.4	0.19
Asphalt Binder (AC)	**-4.3**	**0.31**	**-30.5**	**0.00**
CA×MF	**7.4**	**0.09**	-1.0	0.86
CA×AC	**7.9**	**0.07**	-6.4	0.26
MF×AC	**-14.5**	**0.00**	7.9	0.16
CA×MF×AC	-0.3	0.94	-3.3	0.58
Test Time	-2.4	0.60	3.3	0.75
Compaction Order 2	-4.1	0.97	-1.6	0.92
Compaction Order 3	-20.4	0.11	10.8	0.54
Compaction Order 4	-14.8	0.23	18.4	0.26
r^2 (Adj. For d.f.)	81.6%		82.0%	

Further examination shows that modulus measurements made with the FST provide very similar information to that provided by the IDT strength test. Figure 7 is a plot of |G*| at 40 °C and 10 Hz made using the FST (new protocol) against IDT strength at 34 °C and 3.75 mm/min. The R^2 value of 83 % is quite high, indicating that these factors are very closely related. Figure 8 is another comparison of these data, showing variations in both |G*| and IDT strength with changes in mixture type and composition. It is clear that for these data, complex modulus and IDT strength provide not only similar sensitivity to changes in mixture composition, but the magnitude and sense of the relationships are quite similar—in simple terms, IDT strength seems to be a good surrogate for complex modulus. Although this might at first seem surprising, strength and modulus are often closely related within a given class of materials. A good example is portland cement concrete, for which many engineering properties have been related to unconfined compressive strength, including modulus. The reason compressive strength is commonly used for specification purposes for portland cement concrete, rather than modulus or other related properties, is because it can be measured quickly and reliably at a relatively low cost. Serious consideration should be given to using IDT strength in a similar manner for asphalt concrete mixtures—as a general indicator of mixture cohesion, rut resistance and overall quality that can be empirically related to various other properties of interest.

Additional research must be done on both the FST and IDT tests before full implementation. In both cases, field evaluations are needed in which the tests are evaluated in realistic QC testing conditions, and the results correlated to other indicators of mixture performance. A major research project on the IDT test, funded by the Pennsylvania Department of Transportation, is currently pending. This project will involve testing the IDT strength of a large number field cores from various projects in Pennsylvania, and correlating the results to calculated field rutting rates. Another important part of this project is an evaluation of a simplified test procedure, using a loading rate of 50 mm/min and a 10 °C higher test temperature than that used in previous studies. This method would also involve conditioning in a water bath prior to rapid testing, without use of a temperature-controlled chamber. This procedure would, if successful, would be ideal for use by a wide range of contractors, commercial testing labs, and highway departments. It would involve the use of existing equipment and procedures, and would provide important information directly related to mixture cohesion and rut resistance.

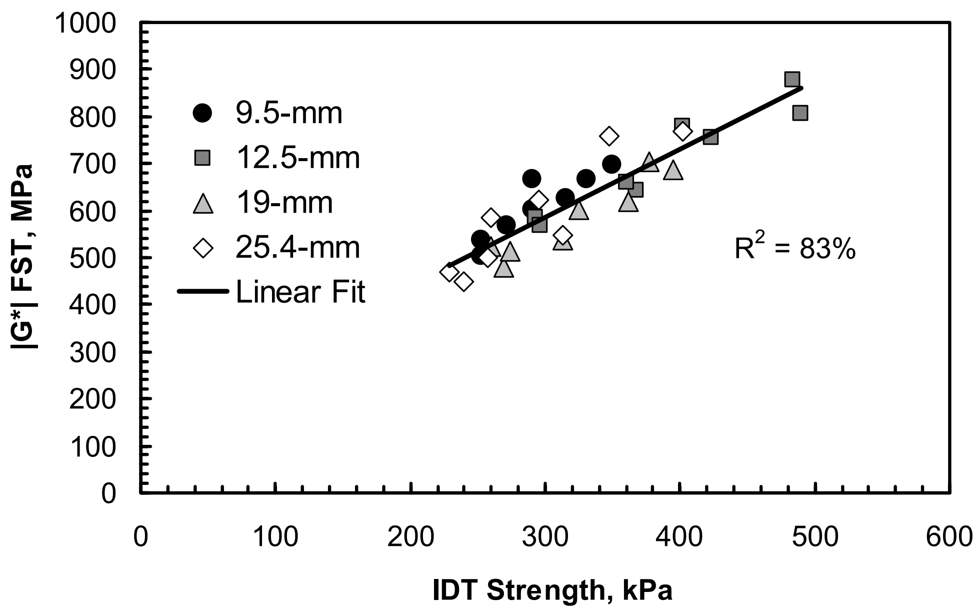


Figure 7. Plot of Complex Modulus at 40 °C and 10 Hz Against IDT Strength at 34 °C and 3.75 mm/min.

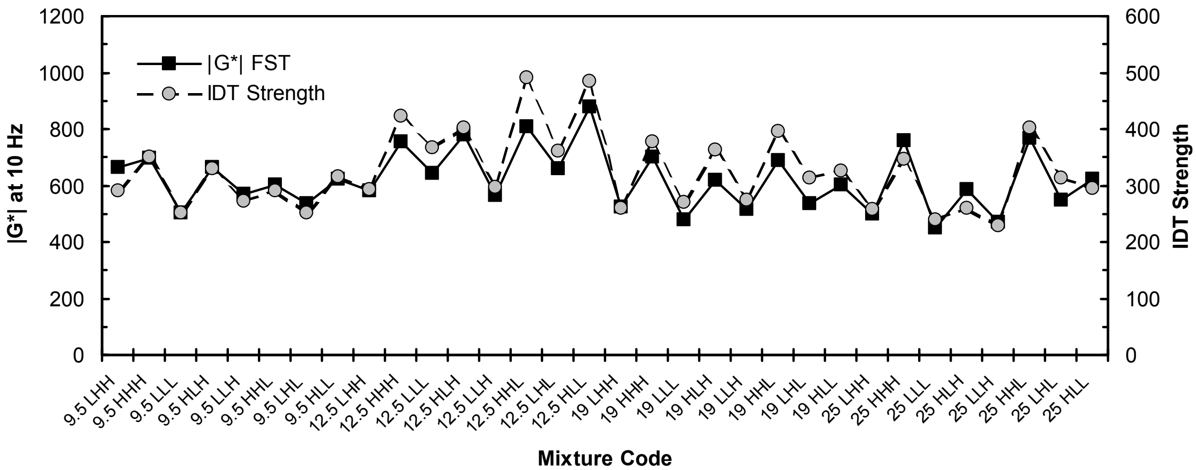


Figure 8. Plot Showing Variation Over All Mixtures Tested for Complex Modulus at 40 °C and 10 Hz and IDT Strength at 34 °C and 3.75 mm/min.

CONCLUSIONS, RECOMMENDATIONS AND SUGGESTIONS FOR FURTHER RESEARCH

The data and analysis presented in this report leads to the following conclusions and recommendations:

- A new protocol has been developed for use in making complex modulus (|G*|) measurements with the FST, which involves averaging four determinations for each specimen tested, rotating and/or flipping the specimen between each determination. Because of the ease of use of the FST, the testing can be completed within about 10 minutes even when taking four different readings.

- The new protocol produces |G*| data which is significantly more precise than that produced using the earlier protocol, which involved taking only one measurement per specimen.
- Complex modulus measurements made using the new FST and the new protocol are sensitive to changes in mixture composition, especially changes in coarse aggregate content and mineral filler content, and to a lesser degree, asphalt binder content.
- The overall coefficient of variation for |G*| values at 10 Hz and 40 °C, determined using the FST and the new protocol was found to be 8.0 %, which is quite good for modulus measurements on asphalt concrete specimens.
- Using the new protocol, |G*| measurements made using the FST appear to be suitable for quality control purposes.
- IDT strength, measured at 20 °C below the 7-day average high pavement temperature at a loading rate of 3.75 mm/min, is also sensitive to changes in mixture composition. IDT is similar in sensitivity to |G*| as measured with the FST using the improved protocol, and also correlates well to these data.
- Additional research should be done to evaluate the effectiveness of both |G*| measurements made using the FST and IDT strength measurements in field projects designed to simulate quality control and/or acceptance testing. The purpose of this research should be to further evaluate the reliability and precision of the FST and IDT strength tests, and to compare these data to other quality control data, such as air voids and VMA.

- Research soon to be initiated by the Pennsylvania Department of Transportation will evaluate using a simplified protocol for the IDT strength test, using a loading rate of 50 mm/min at a temperature 10 °C below the 7-day average high pavement temperature. This would allow use of Marshall presses to perform the IDT test, conditioning the specimens in a high temperature bath prior to testing—without the use of a temperature control chamber. Further evaluation of the IDT strength test for QC purposes should consider this potential modification in the IDT strength test.

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