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Field Shear Test for Hot Mix Asphalt

This digest summarizes the findings from NCHRP Project 9-18, "Field Shear Test for Hot Mix Asphalt," conducted by the Pennsylvania Transportation Institute of Pennsylvania State University.This digest was prepared by Dr. Donald W. Christensen Jr., formerly of the Pennsylvania Transportation Institute, Dr. Ramon F. Bonaquist of Advanced Asphalt Technologies, LLC, and Dr. Titin Handojo, formerly of the Pennsylvania Transportation Institute, from the text of the final report of the research project.

BACKGROUND

This digest summarizes key results of NCHRP Project 9-18, "Field Shear Test for Hot Mix Asphalt." Of particular interest, it describes the redesign of the field shear test (FST) device developed as a potential quality control and quality assurance (QC/QA) tool in NCHRP Project 9-7 to improve its test configuration and increase the precision of its measurements. The redesigned FST was found capable of performing a variety of tests, but the best results were obtained from the frequency sweep procedure described in AASHTO TP7 at high temperatures and high frequencies. Under these conditions, the equipment produced dynamic modulus values and phase angles in the same range as those generated using the full-sized Superpave shear test equipment described in AASHTO TP7; moreover, these results were found to be fairly sensitive to changes in hot mix asphalt (HMA) composition. However, while the data repeatability of the redesigned FST is similar to other methods for measuring HMA stiffness, it remains too high for QC/QA testing.

SUMMARY

The field shear test, or FST, was originally developed during NCHRP Project 9-7 as a simple and inexpensive alternative to the Superpave shear test (SST), suitable for use in QC/QA testing of HMA mixtures. The first FST prototype, developed during NCHRP 9-7 and found to be promising in some ways, nevertheless exhibited several serious problems. The objective of NCHRP Project 9-18 was to refine and evaluate the FST and make it suitable for QC/QA testing in a construction environment.

During NCHRP 9-18, the original FST prototype was evaluated and a second, improved FST prototype was developed. This prototype is a significant improvement over the first device. It is compact, rugged, and extremely quick and easy to operate. In executing tests with the new FST, gyratory specimens are placed directly in the device and are held in place by hydraulic clamps. The testing geometry is similar to that used in the SST, though the distribution of stresses and strains is quite complex, and test data generated with the FST should therefore be considered approximate. Average shear strain in the FST can be estimated by dividing the deflection by the distance between the grips, 21.3 mm in the prototype device. The best results with the FST were obtained for frequency sweep data at 40°C and 5 to 10 Hz. Under these conditions, dynamic modulus ($|G^*|$) data generated with the FST were typically about 40 percent higher than those produced in the SST, while phase angles were 5° to 15° lower. Because of the highly variable nature of modulus data for HMA, these results should be interpreted with care. Additional research is needed to establish correlations among data gathered using the FST, SST, and uniaxial test methods. Variability in modulus data from the FST is comparable to that seen in other modulus measurements.

In commercial production, the cost of the FST is estimated to be between $25,000 and $50,000, depending on the number of units produced and

sold. For a market size of 1,000 units or more, the cost is estimated to be $25,000 to $30,000—similar to that of a gyratory compactor. These prices include the cost of an environmental chamber, computer, and other necessary accessories. Once a specimen is conditioned, a test can be completed in less than 10 min, if limited to high-frequency testing. Specimen conditioning depends on the protocol used. Bringing a specimen to 40°C from 120°C requires about 2-$^1/_2$ hours in a chamber. Equilibrating to 40°C from room temperature requires about 1-$^1/_2$ hours. Conditioning times are much less if water baths are used; in either case, equilibrium is reached within 30 min. If it is found that submerging FST specimens in water affects the modulus measurement, the specimens could be vacuum-sealed in plastic prior to conditioning. By conditioning the specimens in a water bath, the total time from compaction to completion of FST testing can be kept to less than 40 min.

Data gathered during sensitivity testing showed that FST data are fairly sensitive to changes in asphalt concrete composition, especially coarse aggregate content and binder content. However, variability in HMA modulus data—produced with the FST or any other device—appears too high for QC purposes. Most of this variability is probably caused by varying amounts of steric hardening among the HMA specimens, nonuniform distribution of air voids, and large aggregate particles within specimens. Two simple modifications in the testing protocol should improve the precision of FST modulus data: (1) keeping the time between mixing, compaction, and FST testing to between 2 and 4 hours, as would normally be done during QC testing; and (2) reporting the average of four repeat determinations on a specimen, rotating or flipping the specimen between each measurement. Because of the simple operation of the FST, four determinations can be completed in less than 10 min, and would greatly reduce variability in test data due to specimen nonuniformity.

Because the only problem encountered in NCHRP 9-18 was the marginal precision of the FST, which likely can be improved with simple and appropriate modifications in the test protocol, a future project is recommended. The initial tasks of this project should include verifying that adequate precision with the FST can be achieved with the suggested QC protocol and establishing reasonable relationships among FST, SST, and uniaxial modulus data. Additional research is also needed on the effects of specimen height on FST test results. Continuation of the research to field demonstrations should be contingent on a successful outcome of the initial laboratory test program demonstrating the accuracy and precision of the FST.

CHAPTER ONE
INTRODUCTION AND RESEARCH APPROACH

Problem and Purpose

Although many of the tests, devices, procedures, and models developed during the Strategic Highway Research Program (SHRP) were later found to be of limited value in the design and construction of more durable pavements, the SST has become widely used. In particular, the frequency sweep test and repeated shear at constant height (RSCH) procedure have been successfully used by many laboratories for predicting the rut resistance of HMA mixtures. However, the SST device is too large, complex, and expensive for use in QC/QA testing. As a result, NCHRP Project 9-7 developed the FST several years ago as a simple method of providing test data comparable to those produced by the SST but more quickly and at a substantially lower cost. The original FST prototype had several shortcomings and required further refinement before it would be suitable for use in QC testing of HMAC. The purpose of this report is to document research performed during NCHRP Project 9-18 to further evaluate and refine the FST.

Scope and Research Approach

NCHRP Project 9-18 consisted of seven tasks: (1) Reviewing prototype development and performing a literature search, (2) Performing stress analyses, (3) Modifying and refining FST hardware and procedure, (4) Performing preliminary evaluation of the redesigned FST, (5) Compiling an interim report, (6) Conducting sensitivity testing, and (7) Compiling a final report.

The final report includes detailed information on the results of each of these tasks. This digest summarizes important findings made in completing each task; several figures and tables are included to illustrate and emphasize key findings. Detailed documentation of the various project activities is provided in the appendices of the agency final report. These appendices are available for loan on request to NCHRP.

NCHRP Project 9-18 was planned as a multiphase project. Contingent upon successful completion of the first phase of the project and availability of funding, a second phase of research would be performed to validate the FST under field conditions and to facilitate implementation of the test device and method. Thus, the final report includes specific recommendations for continuing research aimed at validating and implementing the FST for use in QC/QA testing of HMA paving mixtures.

CHAPTER TWO
FINDINGS

In this chapter, the key findings of NCHRP Project 9-18 are summarized. Detailed documentation of each of the various project activities is provided in the appendices of the agency final report. A discussion of the practical ramifications of these findings is given in Chapter Three of this digest, while an extension of the findings to general conclusions and recommendations is presented in Chapter Four.

The SST

The SST was developed during SHRP, a $50-million nationally coordinated research project completed in 1993 (*1*). SHRP was geared toward developing improved tests and specifications for HMA paving materials. The SST was designed to perform a variety of performance-related tests on HMA, including characterization of the complex modulus and phase angle, determination of the bulk modulus, and evaluation of various aspects of the nonlinear, plastic behavior typical of granular materials such as HMA at high temperatures. Data gathered using the SST, along with a variety of other information, were in turn used as input to a computer program meant to provide performance predictions for a given pavement system as a function of time. Unfortunately, a number of serious problems were found in some of the test procedures and in the computer program, which resulted in unreliable predictions of rut depth and fatigue cracking. Work has continued on the concepts evolved during SHRP within NCHRP Projects 9-19 and 1-37A. The completion of these projects will result in a set of more rugged and reliable test methods and models that can be implemented in a coherent system of materials characterization and pavement design and analysis.

Although many of the tests performed with the SST were found to be unreliable, two of the procedures were shown to be reasonably accurate and to relate well to various aspects of pavement performance: (1) the frequency sweep test and (2) the RSCH test (*2*, *3*, *4*). The frequency sweep test is a technique for evaluating the complex shear modulus, $G^*(\omega)$, of HMA. The shear modulus defines the relationship between shear stress and shear strain and is essential information in analyzing the behavior of a pavement system under traffic loading and during changes in temperature. The RSCH test is a repeated load test designed to characterize the resistance of an HMA mixture to permanent deformation at high temperatures. Numerous studies have shown that the maximum permanent shear strain (MPSS) determined after the 5,000-cycle RSCH test is a good predictor of the rut resistance of HMA mixtures test (*2*, *3*, *4*). The magnitude of the complex modulus ($|G^*|$) at high temperatures has also been related to rut resistance, although the relationship is not as good as that for MPSS.

Both of these tests are described in *AASHTO TP7-94*: *Test Method for Determining the Permanent Deformation and Fatigue Cracking Characteristics of Hot Mix Asphalt (HMA) Using the Simple Shear Test (SST) Device*. The SST tests are usually performed on 50-mm-thick, 150-mm-diameter specimens taken from a 115-mm-high standard specimen as produced by the Superpave gyratory compactor (SGC). Specimen preparation for the SST is complex and time-consuming, requiring careful sawing of the gyratory specimen, gluing platens onto the specimen, and, in some cases, fastening transducers onto the sides of the specimen. Figure 1 is a sketch showing two different approaches to mounting transducers on SST specimens (*5*). Furthermore, the SST device itself is a large, complex, and expensive servohydraulic testing system not suitable for routine use in state highway laboratories or hot mix plants. Research following SHRP pointed out the need for a simpler, quicker means for evaluating the performance-related properties of HMA.

HMA is a complicated material, exhibiting differing degrees of viscoelastic and nonlinear plastic behavior, depending upon the temperature and level of applied stress

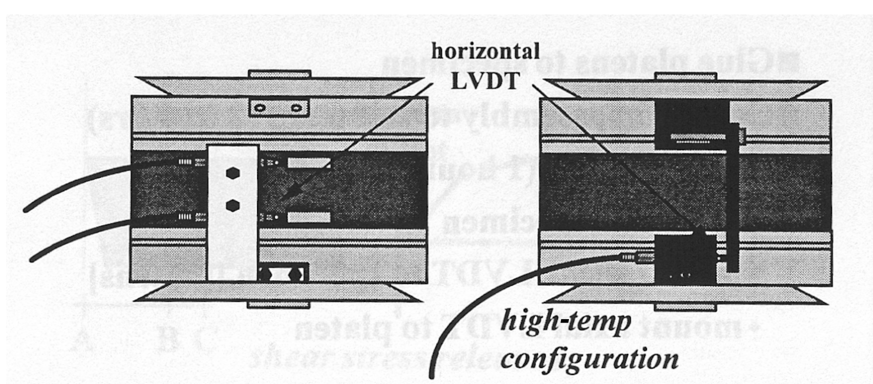


Figure 1. SST specimens showing two different approaches for mounting transducers (LVDTs) for deflection measurements (5).

and strain. It is, therefore, critical to determine the proper loading conditions for a given test procedure and to control these conditions carefully during the test. In the SST simple shear test, which is similar to a creep or constant stress test, the maximum shear stress applied is 35 ± 1 kPa. In the RSCH test, a pulse loading is used, with duration of 0.1 s and dwell time of 0.6 s. The maximum shear stress generated during the RSCH test is 68 ± 5 kPa. During the SST frequency sweep protocol, the shear strain is limited to a maximum of 0.01 percent. These limits were developed during SHRP to try to ensure linear behavior during testing and were based largely on experience and judgment (*1*). Later research suggests that these limits were too conservative, and that higher stresses and larger strains can be used during these and similar tests (*6*, *7*). This finding is important to the development of practical tests, since using larger stresses and strains during a test means that simpler, less-expensive equipment can be used, and that the results will probably be more accurate. As documented in Appendix A of the final report, researchers in the past have typically used compressive stresses of 100 to 200 kPa in creep tests on HMA, significantly higher than the 35 kPa used in the SST simple shear test, even after accounting for the difference between shear and compressive stresses. Furthermore, research at Pennsylvania State University suggests that essentially linear behavior can be maintained in testing HMA at stresses up to 100 kPa and strains up to about 0.1 percent, both substantially higher than the limits used in the SST (*7*). Because load-controlled testing is easier to perform on servohydraulic and servopneumatic systems, the NCHRP 9-18 research team suggested that the FST use an applied shear stress of 100 kPa for creep and frequency sweep tests. This increase in stress should result in a simpler, less-expensive test device and improved data quality while still maintaining linear behavior during testing.

NCHRP Project 9-7 and the Original FST

By the mid-1990s, 28 states were using Superpave binder and mixture tests (*8*). NCHRP Project 9-7 was undertaken in 1993 to develop improved QC/QA procedures for Superpave projects. During Phase I of that project, the NCHRP 9-7 research team decided that a simple performance test was necessary to augment the volumetric data used for QC of Superpave mixtures; the FST was the result.

A diagram of the original FST is shown in Figure 2 (*8*). The original FST used an unusual diametral shear geometry in which the specimen was held in two semicircular clamps and sheared across the diameter. This approach was used to allow direct testing of a gyratory specimen without sawing, coring, or gluing, so that the test could be executed simply and quickly. The original prototype lacked a temperature chamber; specimens were conditioned prior to testing and then placed in the test device.

The original FST was found to not provide accurate measurements of complex modulus or maximum permanent shear strain (*8*, *9*). Figure 3 is a plot in which $|G^*|$ values determined using the FST and the SST are compared, showing typical serious discrepancies in the values (*8*). This was probably, in part, due to poor performance of the servo-pneumatic loading system at high frequencies and loads, combined with relatively poor resolution of the deflection measurements. Additionally, it is likely that the unusual geometry contributed to the problems observed with the first FST device.

As part of NCHRP Project 9-18, a survey was conducted of seven engineers and technicians involved in the development and evaluation of the first FST prototype. The purpose of this survey was to gain insight into what improvements these key personnel believed were needed in the test device and procedure. The results of this survey are

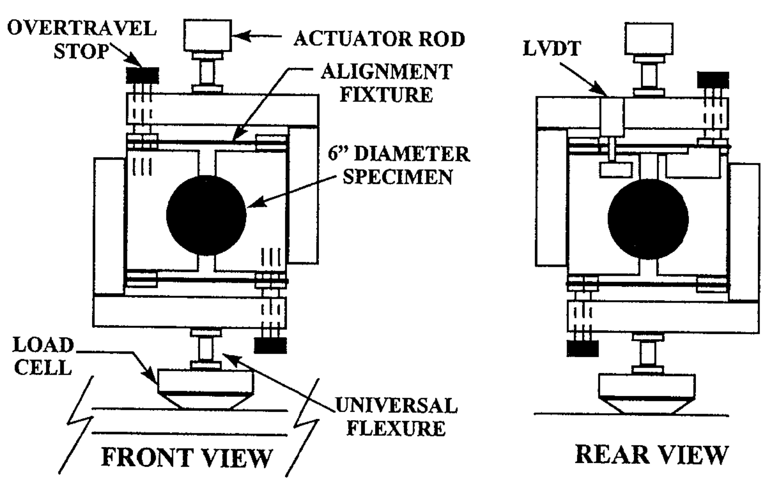


Figure 2. Sketch of the original FST developed during NCHRP Project 9-7 (8).

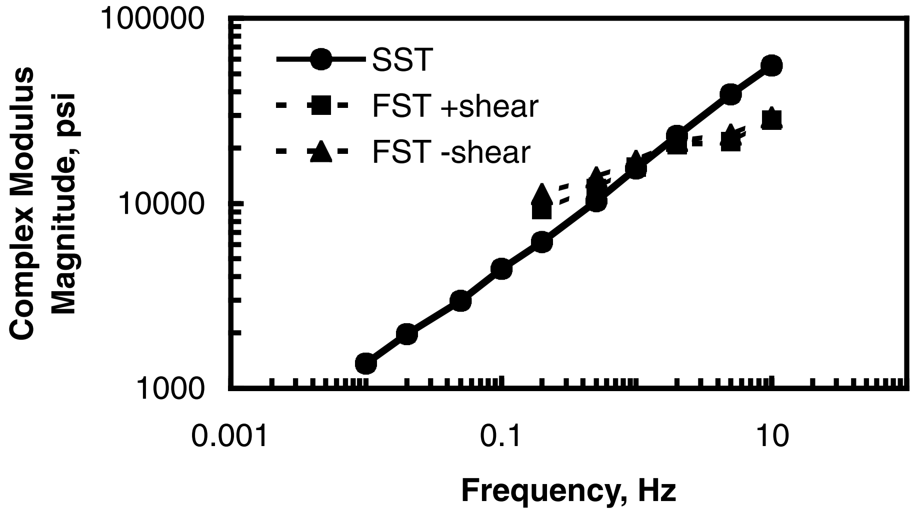


Figure 3. Plot of complex modulus as measured using the original FST prototype and using the SST (8).

presented in their entirety in Appendix C of the agency final report. Although there was, in some cases, significant disagreement among those surveyed, most agreed to the following findings:

- The FST test geometry should be changed to more closely resemble that used in the SST, where the direction of shearing is parallel to the ends of the specimen.
- The FST should retain the ability to perform the frequency sweep test, the repeated shear test, and the simple shear (creep) test commonly performed on the SST. Of these protocols, the frequency sweep test is the most likely candidate for QC/QA testing of HMA mixtures.
- A simpler specimen-mounting procedure is needed.
- The device and procedure should be kept as simple and rugged as possible.
- The cost of the FST should be in the range of $35,000 to $50,000.

Based on the review of the original FST and its development, it was decided that a major redesign of the FST was needed. The design of the new FST would incorporate the findings of the survey, and would also address other shortcomings of the first prototype, including a better specimen-clamping system, better system response, improved transducer resolution, and a good temperature-control system. Above all else, it was felt that the new FST should be simple and rugged, appropriate for use by technicians within a typical HMA plant. The new FST developed on the basis of these findings is described in the section on sensitivity testing. Prior to development of the new FST, however, a number of theoretical stress analyses were conducted to verify the shortcomings of the original FST geometry, evaluate the possible alternatives, and compare the results for these test geometries with the stresses and strains occurring in the SST.

Stress Analyses

The NCHRP 9-18 research team decided prior to starting the stress analyses that the most promising alternative geometry for the FST involved holding the ends of a gyratory specimen in cups or clamps while shearing it parallel to its ends, as shown in Figure 4. The specimen in this proposed FST geometry was assumed to be a 115-mm-high by 150-mm-diameter gyratory specimen, with a gap between the grips of 22 mm. In order to evaluate the distribution of stresses and strains generated in the original FST test, the new FST geometry, and the SST test, Dr. Chandra Desai of

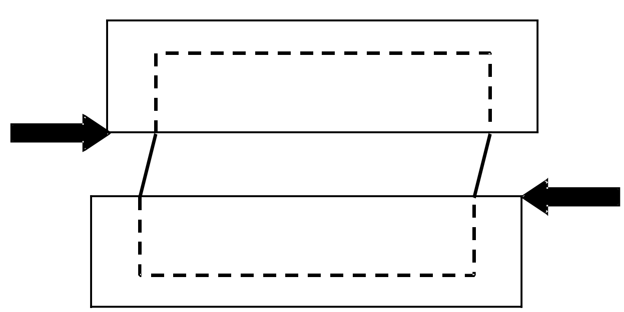


Figure 4. Sketch of proposed geometry for the new FST, as considered in stress analyses.

the University of Arizona performed several finite-element analyses. The results of these analyses are discussed in the final report, available by loan upon request from NCHRP. To simplify the analysis, plane strain conditions were assumed, so the results of the analyses should be considered as approximate. Initial analyses were performed assuming a much higher stress level than what is normally used when testing HMA, especially at high temperatures. Not surprisingly, this approach resulted in significant nonlinearity in both the original FST geometry and the proposed alternative. However, it was clear that in the proposed FST geometry, shearing stresses and strains would tend to expand into the ends of the specimens, so that deflections would tend to be larger than those determined from equivalent loading in the SST.

The SST test, although exhibiting fairly uniform stresses, did not exhibit ideal behavior. Figure 5 shows the magnitude of shear stresses through the center and across the top of an SST specimen under loading. This was part of the first series of analyses; the shear modulus of the specimen was assumed to be 269 MPa, and the stresses shown were as calculated for a 1-mm deflection. The shear strain applied was thus 2 percent, about 200 times what is normally used in the SST, whereas the resulting average shear stress of 5.4 MPa is about 150 times that used in the SST. In this particular case, linear behavior was assumed so the resulting stress distribution, though showing unusually large values, is representative for the SST. Because of the relatively large aspect ratio and lack of complementary shearing on the specimen sides, it was found that the shear stresses fall off substantially toward the edge of the specimen. This results in a lower overall load being generated than would occur under pure shearing. Therefore, modulus measurements made with the SST will typically be about 10 percent too low. Preliminary evaluation of the stresses in the original FST (diametral shearing) showed very poor and nonuniform distribution of stresses, as expected. For this reason, the original FST geometry was not included in subsequent analyses.

In analyzing preliminary test data from the modified FST, as discussed in the next section, it became clear that deflections from this test were significantly lower than expected based on the results of the initial stress analyses. This finding appeared to be caused by confinement of the HMA mixture within the clamps on the specimen ends. This confinement would significantly increase the stiffness of the mixture in the specimen ends, improving the distribution of stresses in the FST specimen and reducing resulting deflections. Because of this finding, Dr. Desai considered two different cases in the final series of stress analyses: (1) a constant uniaxial modulus (E) of 100 MPa throughout the specimen and (2) a uniaxial modulus of 100 MPa in the material sheared between the clamps, and 260 MPa for the material confined within the clamps. Furthermore, a constant load of 1200 N was assumed, which would result in an average shear stress under ideal conditions of 68 kPa, as is used in the SST simple shear test. Both linear and nonlinear analyses were performed. However, subsequent testing during the project clearly showed that deflections in the FST were quite low, and that linear behavior was a more realistic assumption. These data also confirmed that there was significant specimen confinement within the clamps that, in some cases, even extended into the sheared area between the clamps. (See section on sensitivity testing.) This resulted in the elastic case being the most accurate of the stress analyses performed, with an increased modulus assumed for the material confined within the clamps. The resulting stress distributions are plotted in Figure 6 (center of specimen) and Figure 7 (across the specimen at the edge of the lower clamp). The stress distribution in the center of the speci-

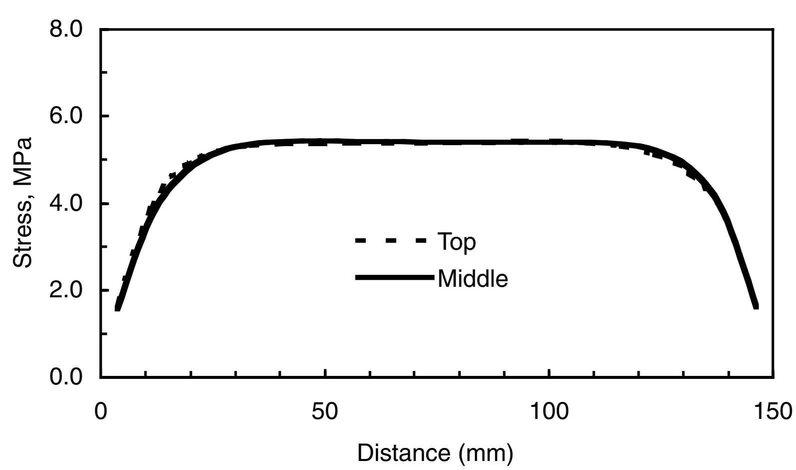


Figure 5. Stresses generated in an SST specimen for the linear-elastic case, with E = 700 MPa and a 1-mm deflection.

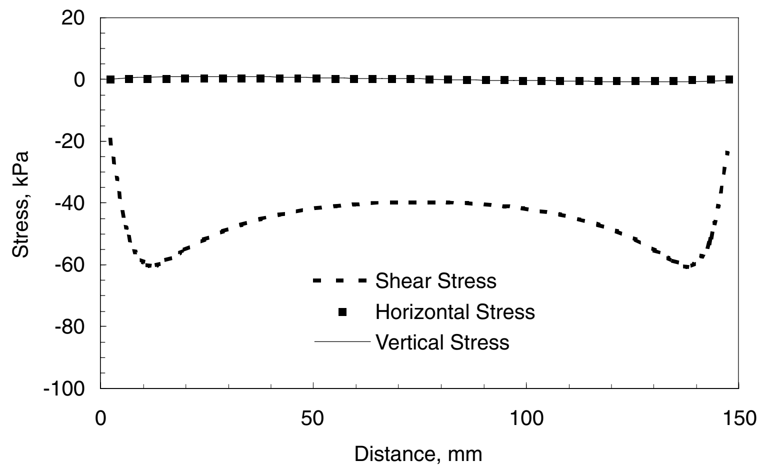


Figure 6. Stresses through center plane of FST specimen, linear analysis; modulus of 260 MPa within clamps and 100 MPa between clamps.

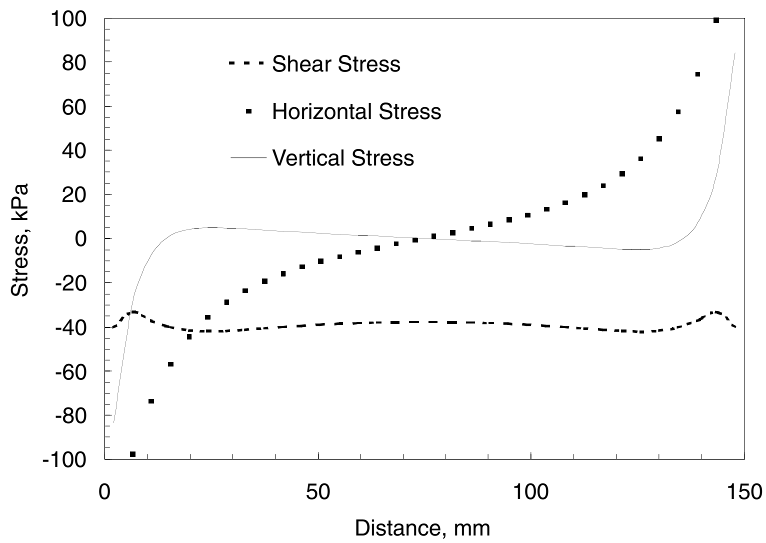


Figure 7. Stresses through plane at top of lower clamp in FST specimen, linear analysis; modulus of 260 MPa within clamps and 100 MPa between clamps.

men, although far from ideal, is reasonable. The shear stresses rise from the edge to a maximum of about 60 kPa, and then gradually decrease to about 40 kPa in the center of the specimen. Vertical and horizontal stresses are negligible. The stress distribution across the specimen at the clamp edge is more complex. Shear stresses are fairly constant at about 40 kPa, but significant horizontal stresses exist, especially at the specimen edge. These horizontal stresses are a result of the end of the specimen being "pushed" by the clamp, rather than having a more ideal shear stress applied as it is in the SST.

The results of the stress analysis indicated that the new FST geometry, although not providing an ideal stress distribution, was probably suitable for QC/QA testing. The stress distribution is, however, more complex and substantially different from that in the SST. For practical purposes, the most important part of the stress analysis is determining an effective gage length, which represents the thickness that should be used when calculating average shear strains in the FST:

average shear strain = shear deflection/effective gage length

Table 1 summarizes the results of the stress analysis in terms of effective gage length for the FST. Included in this table

TABLE 1 Results of equivalent gage length analysis for FST stress analysis

Analysis	HMA Shear Mod. (MPa) Between Clamps	Within Clamps	Defl. (mm)	Thick./Gage Length (mm)	App. Strain	App. Shear Mod. (MPa)	Effective Gage Length (mm)
FST-Ideal	38.5	:	0.038	21.3	0.00177	38.5	21.3
Linear	38.5	38.5	0.074	21.3	0.00336	20.2	41.9
Linear	38.5	100	0.047	21.3	0.00214	31.8	26.6
Non-linear	38.5	38.5	0.128	21.3	0.00582	11.7	72.5
Non-linear	38.5	100	0.076	21.3	0.00345	19.7	43.0
SST	38.5	N/A	0.010	50.0	0.00200	34.0	56.5

are the "ideal" case, which assumes that the FST specimen is sheared only between the grip collars, and an analysis of the SST. The SST data illustrate that the stress distribution from this device, although more uniform than that for the FST, is also not ideal. As mentioned previously, limited data suggest that the linear analysis with confinement provides the best agreement with experimental data. Test results gathered during the gage-length experiment indicate that deflections for the FST are sometimes even smaller than would be calculated for the ideal case, resulting in an effective gage length less than the 21.3-mm collar separation. Considering the results of both the stress analyses and the limited experimental data gathered, the effective gage length (thickness) used in calculating average shear strain for the FST should be the same as the collar separation, 21.3 mm. It should be understood that this approach is an approximation and depends, to some extent, on confinement of the HMA within the FST grips.

Redesigned FST

The new design of the FST incorporated a number of significant changes to address the various problems observed in the performance of the first prototype. Most importantly, the geometry of the new FST involved shearing of a gyratory specimen parallel to its ends, as is done in the SST. EnduraTEC Systems Corporation, in consultation with the project team, developed the new FST device and lent the prototype to Advanced Asphalt Technologies for evaluation and use in sensitivity testing. This prototype is shown in Figure 8. A summary of key features of the new FST is presented in Table 2.

After an initial evaluation of this device, EnduraTEC corrected several minor problems with the instrumentation and software. Details of this preliminary evaluation are provided in Appendix E. The evaluation's objectives were to verify that the new version of the FST was operating properly and to make limited comparisons between data from the improved FST and the SST. The testing included evaluation of the redesigned FST as originally supplied by

Figure 8. Photograph of the new FST device.

TABLE 2 Key features of the improved FST

Characteristic	Values
Size (w × d × h)	30 × 30 × 40 cm
Weight	50 kg
Loading Mechanism	Servopneumatic
Power Requirements	110 VAC with 550 kPa air
Specimen Diameter	150 mm
Specimen Height	50 mm to 122 mm
Maximum Shear Stress	1260 kPa, with calibrated ranges of 1260, 630, 252, and 126 kPa
Maximum Axial Stress	550 kPa (available air)
Maximum Shear Displacement	±1.25 mm with calibrated ranges of ±1.25 and ±0.25 mm)
Resolution	12 bit

EnduraTEC, and the final version of the FST after minor modifications had been completed. The following paragraphs summarize the findings of the preliminary evaluation testing.

1. The redesigned FST is a compact, user-friendly device and in these respects is well suited to QC/QA applications. The equipment can conduct frequency sweep, repeated shear, and creep tests directly on standard Superpave gyratory specimens without the need for special specimen preparation. The software logically prompts the user through the steps required for specimen setup and testing. The unique hydraulic clamps greatly simplify testing operations. Midlevel technicians can now easily operate the FST.
2. The limited comparison of data collected during the preliminary evaluation showed that specimens of the same material have consistently stiffer response in the FST compared to the SST. Shear moduli were higher and phase angles were lower for comparable specimens tested in the improved FST compared to the SST. Creep and repeated shear deformations were lower in FSTs compared to SSTs. The stiffer response in the improved FST appears to be related to specimen confinement produced by the hydraulic clamps. Measured responses in the new version of the FST are sensitive to clamping pressure. A pressure of 10.3 MPa is recommended for general use in the FST and was used for the sensitivity testing conducted during this project.
3. Data from the redesigned FST can be related to data from the SST and other tests through the use of an effective gage length. The effective gage length decreases with decreasing specimen stiffness. At high stiffness, effective gage lengths from experimental data compare reasonably well with those calculated from elastic analyses. For high-temperature testing using a clamping pressure of 10.3 MPa, an effective gage length of 21 mm was calculated from data collected during the preliminary evaluation.
4. In the preliminary evaluation of the FST, the test results showed a level of repeatability similar to that observed for the SST and similar tests. Coefficients of variation (CVs) for the small sample size of three ranged from 5 percent to 15 percent. This finding is similar to data from the SST and other tests such as the uniaxial dynamic modulus and repeated load tests recommended in Project 9-19. The sensitivity study, with its large number of replicates, will provide more definitive information on the repeatability of the improved FSTs.

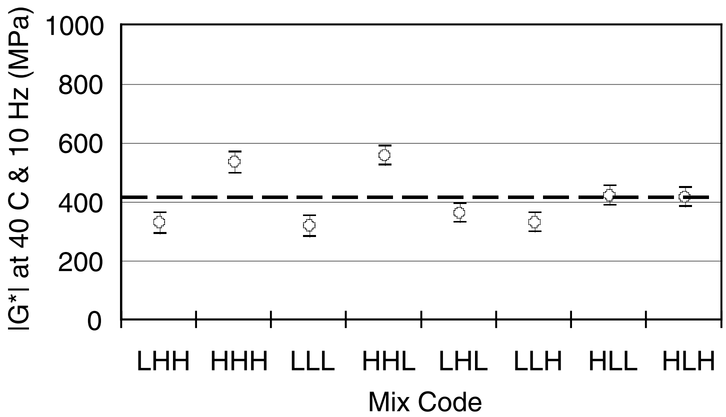
Sensitivity Testing

After the new FST device had been evaluated, modified, and found to be performing reasonably well, a testing program was performed to evaluate the sensitivity of this device to changes in HMA composition. Four different materials—9.5-mm, 12.5-mm, 19-mm, and 25-mm NMAS Superpave mixtures—were tested. For each of these, the design aggregate gradation and binder contents were systematically varied to produce a total of eight mixture variations.

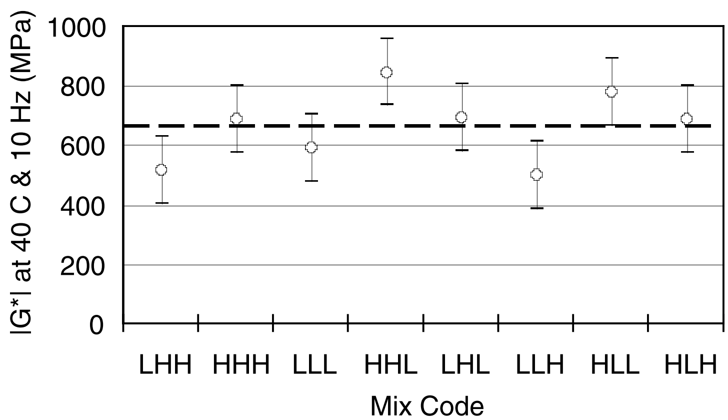
The following factors were varied in the testing: coarse aggregate content (± 6 percent on the 2.36-mm sieve), mineral filler content (± 2 percent on the 0.075-mm sieve), and binder content (± 0.5). The FST and RSCH test were performed with the new FST, both at a temperature of 40°C. The RSCH test was performed at the maximum 7-day average pavement temperature for Northern Virginia, 54°C. The results of the sensitivity testing are provided in Appendix F of the agency final report.

Analysis of the results of the sensitivity testing demonstrated that the FST is sensitive to changes in mixture composition. The best sensitivity was found using $|G^*|$ data at 5 Hz and 10 Hz. Analysis of variance models including mixture composition as predictor variables for $|G^*|$, along with compaction order and test time, gave r^2 values ranging from 55 percent to 91 percent; values for models for MPSS from the RSCH ranged from 47 percent to 68 percent. The dynamic modulus was quite sensitive to changes in coarse aggregate content and binder content, and in some cases mineral filler and various interactions of these factors. The results of the sensitivity testing are presented graphically for two of the mixtures in Figure 9 (complete plots are included Appendix F). This plot shows average $|G^*|$ values at 40°C and 10 Hz for the eight variations of the 25- and 12.5-mm mixtures. Included on the plot are error bars representing two standard deviation $\left(\pm 2s/\sqrt{4}\right)$ confidence intervals about the mean. The average for all mixture types is also shown on each plot. Because the eight mix variations represent significant differences in mixture composition, the error bars should not overlap for most of the mixtures if the $|G^*|$ measurements are in fact sensitive to these compositional changes. Conversely, extensive overlap of the error bars indicates that the modulus measurement shows little or no sensitivity to changes in composition. Otherwise, it is unlikely that the test would be useful in QC. For the 25-mm mixture, six of the eight mix types varied significantly from the mean value, but for the 12.5-mm mixture, only three showed significant variation from the mean. The sensitivity of the 9.5-mm mix, like that for the 25-mm mix, was good. The sensitivity of the 19-mm mix, on the other hand, was poor—closer to that observed for the 12.5-mm mix.

Although the results of the sensitivity testing showed that the FST is sensitive to changes in mixture composition, very good precision is needed for effective QC testing, and the variability in the test data is too high to allow the FST to be used for QC/QA testing at this time. This is evident, for example, in Figure 9(b), where the error bars for the various mix types are quite large compared to the difference among their responses. This is not a problem unique to the FST—the same problem exists for virtually all test methods currently used to measure the stiffness of HMA mixtures. The



(a) 25-mm Mixture



(b) 12.5-mm Mixture

Figure 9. Average complex modulus at 10 Hz and 40°C with 2s-error bars for the mean. (Mix code represents high (H) or low (L) values for coarse aggregate, mineral filler, or binder content respectively. Dash lines represent mean value for mixture types.)

CV for |*G**| measured with the FST was found in this study to range from 7 percent to 17 percent. For SST testing on selected companion specimens, the CV was found to be in the same range, 5 percent to 18 percent, with most values tending toward the higher end of this range. Mehta and Christensen reported similar values in testing using the SST (*7*).

Most of the variability in HMA modulus data is probably due not to inherent problems in the FST or other mixture tests, but to variability in the HMA specimens themselves. This variation is believed to have two sources: (1) variations in steric hardening due to differences in the time between specimen preparation and testing and (2) nonuniformity within specimens in the distribution of air voids and large aggregate particles. The first of these problems should not exist under QC testing conditions, where specimens will be mixed, compacted, and tested within a few hours. The second problem can be effectively addressed with the FST by performing four repeat determinations on each specimen, rotating or flipping the specimen between each test. The reported |G*| values would be the average of these four measurements. With the ease of operation of the FST system, including the clamps, these replicate tests can be performed within 10 min total. The initial tasks in any project should focus on evaluating variability in FST data using this slightly modified protocol. If the precision of the FST is not significantly improved by these changes, it is not likely that it can be successfully implemented as a QC test, and further FST development should be discontinued.

An experiment related to the sensitivity testing was performed to more thoroughly compare test data generated with the new FST to those generated with the SST. The objective of this testing was to determine, if possible, an average effective gage length for the FST, so that data generated with this test can be compared with those generated with the SST and other devices. This experiment involved testing two variations of the 9.5- and 25-mm mixtures using the SST frequency sweep and repeated shear tests. These data

were then compared directly with the matching data generated during sensitivity testing with the FST. The results of this experiment for one of the 9.5-mm mix types are shown in Figure 10, in which |*G**| values from the SST and FST are compared. The effective gage length used in calculating FST shear strains and modulus values was 21.3 mm, the same as the grip separation distance. In this case, the modulus values for the FST were consistently greater than those found from the SST by about a factor of two. The results for all four mixtures tested are summarized in Figure 11, in which the ratio of |*G**| values (FST/SST) is plotted as a function of frequency. The FST always produces significantly higher modulus values than the SST. This effect is most pronounced for the 25-mm mixture at low frequencies, where the FST modulus exceeds the SST-measured value by as much as four times. This may result from the confinement effects spreading out from the clamps into the sheared region, which would be more pronounced for mixtures with larger aggregate particles. However, at frequencies of 5 Hz and 10 Hz, there is better agreement, with an average modulus ratio of 1.39, indicating that at high frequencies the FST will provide |*G**| values about 40 percent greater than those given by the SST. This corresponds to an effective gage length of 15.8 mm. However, as discussed previously, modulus values determined using the SST are potentially lower than actual values, and modulus tests on HMAC are in general highly variable. Because of these limitations, at this time it can only be concluded that modulus values determined using the FST and SST are in the same range, although there is some indication that the FST might produce somewhat higher values for |G*|. Any future research should involve a thorough comparison of modulus values measured using the FST, SST, and uniaxial compression.

In general, phase angles measured with the FST at 5 Hz and 10 Hz are 5° to 15° lower than those determined with the SST, again suggesting that confinement causes signifi-

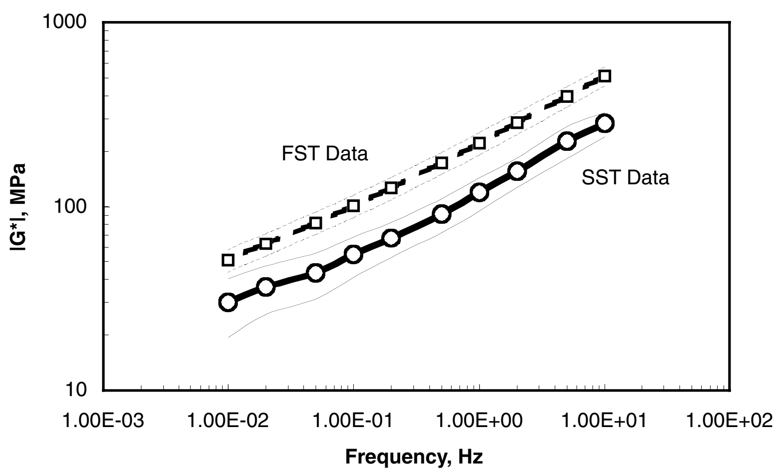


Figure 10. |G| at 40°C on 9.5-mm HLL mix, using SST and FST devices. (Plots show average and ± 2s error bars for the mean.)*

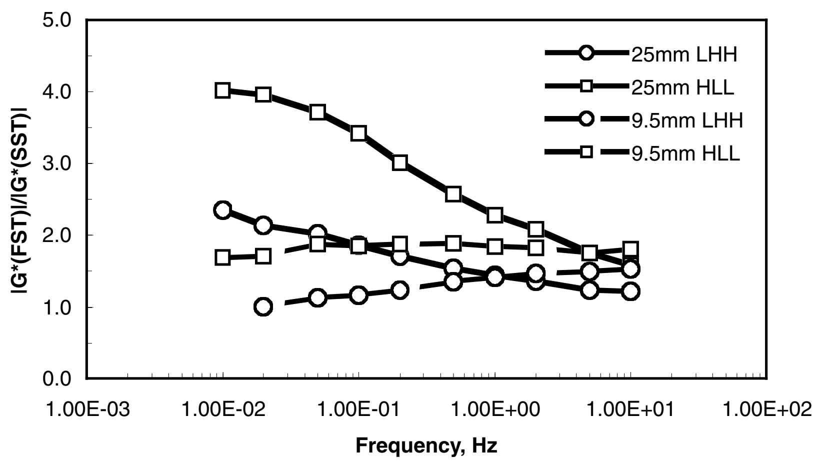


Figure 11. Ratio of |G| as determined with the FST to that determined with the SST, as a function of frequency.*

cant stiffening of the mixture during the FST test. Maximum permanent shear strains measured with the FST were lower than those determined using the SST by a factor ranging from 4 to 12 times. The RSCH test performed using the FST device does not produce reliable data.

The final experiment associated with the sensitivity testing was an evaluation of the effect of different specimen heights on the quality of FST data. The ability to evaluate thin specimens, such as field cores from thin pavement layers using the FST, is a useful capability for QA testing and forensic studies. In this experiment, gyratory specimens of three different thicknesses were tested in the FST: 75, 50, and 38 mm. Two different variations of the 9.5-mm mixture were used in the study. For one series of tests, both the average value of and variability in $|G^*|$ were similar for all specimen heights and agreed well with the original series of tests, performed on 115-mm-thick specimens. In the second series of tests, the $|G^*|$ values for the three shorter specimens were in general agreement, but were lower than for the original (115-mm-thick specimens) test data. This was probably the result of a very low air void level in the thickness experiment specimens—less than 1 percent—compared to an air void level of 2.6 percent in the first series of specimens. However, in this test series the CV for the 38-mm specimen was 35 percent, which is quite high. Therefore, caution should be used in testing specimens thinner than 50 mm using the FST device. Additional research is needed to verify the effects of specimen height on FST data for 9.5-mm mixtures and to extend this part of the study to mixtures with larger aggregate sizes. Furthermore, it should be recognized that the FST probably will not be useful for testing thin field cores.

CHAPTER THREE INTERPRETATION, APPRAISAL, AND APPLICATIONS

The new FST, as produced in prototype by EnduraTEC Systems, is a simple, effective device for measurement of the dynamic shear modulus of HMA, $|G^*|$. It is small, rugged, and easy to operate. No hardware is mounted on the specimen. Tests can be performed very quickly if specimens are conditioned in a separate chamber prior to testing. The FST is no more difficult to operate than a gyratory compactor. It is suggested that in the future, four repeat measurements be performed on each specimen, rotating or flipping the specimen between each replicate. The average of these four measurements would be reported. Even with four repeat measurements, a complete FST test could be performed in less than 10 min.

The amount of time required for conditioning FST specimens depends on the protocol used. Cooling specimens in air from 120°C to 40°C requires about 2-$^1/_2$ hours. This is perhaps longer than some engineers and technicians would like, but this is currently necessary in order to perform specific gravity measurements. Bringing specimens to 40°C from room temperature requires about 1-$^1/_2$ hours. These conditioning times could be reduced substantially by using a water bath to condition the specimens, rather than a convection oven. If water appears to affect the measurement of modulus, the specimen could be vacuum-sealed in plastic during conditioning to protect it from water damage. Conditioning in a water bath from either 120°C or room temperature to equilibrium at 40°C takes 30 min. Thus, by using a water bath for conditioning specimens, a complete FST modulus test could be completed within 40 min of compaction.

The FST should be used only for measuring complex modulus, and not for repeated shear or creep testing. Furthermore, the most reliable measurements of $|G^*|$ with the FST are obtained at 5 Hz and 10 Hz. Very limited testing indicated that HMA moduli measured with the FST under these conditions were about 40 percent higher than those measured using the SST, while phase angles were about 5° to 15° lower. Additional testing is needed to more thoroughly establish the relationships among FST, SST, and uniaxial modulus data. Variability in test data using the FST is comparable to that seen in other methods of measuring mixture modulus, such as the SST.

The sensitivity testing of the FST was successful. Modulus values measured with the FST are clearly sensitive to changes in mixture composition, especially coarse aggregate content and binder content. However, the level of variability currently found in HMA modulus measurements, whether determined using the FST or any other available device, is currently too high for QC/QA testing purposes. It is imperative that QC tests be highly repeatable, so that reasonable control limits can be established to aid the engineer in evaluating whether or not the process is in control. Current test methods do not provide the required level of precision.

However, most of the variability in FST modulus measurements is probably not the result of problems with the test device, but is caused by variability among and within test specimens. As discussed in Chapter Two of this report, it is likely that the precision of the FST can be improved with two simple modifications in the testing protocol, both entirely consistent with implementation as a QC test. The first modification is simply to mix, compact, and test FST specimens within 2 to 4 hours, eliminating variations in steric hardening. The second modification involves taking the average of four repeat measurements made with the FST, rather than a single value. Future research should focus on evaluating whether or not this simple change in the protocol will be effective in improving the precision of FST measurements to an acceptable level. Two other related future experiments that are needed are an FST/SST/uniaxial test correlation experiment and a more thorough evaluation of the effect of specimen height on FST data. The research should then only be continued if the results of the laboratory tests indicate that FST data have sufficient precision for use

in QC testing, and also correlate reasonably well with modulus data gathered using the SST and uniaxial methods.

CHAPTER FOUR
CONCLUSIONS

Conclusions

- The redesigned FST device is small, extremely easy to use, and appears to be fairly rugged and well designed, and in these respects is well suited for QC/QA testing of HMA mixtures.
- The distributions of stresses and strains in the FST are fairly complex, especially near the grips, but are suitable for a QC/QA test. Because of the uncertainty in the exact stresses and strains existing during testing, the FST should be considered an appropriate method for determining HMA modulus.
- To calculate average strain for the FST, an effective gage length, or specimen thickness, of 21.3 mm should be used, which is the same as the distance between the grips. This appears to provide shear modulus values in the same range as those produced using the SST, though limited testing indicates that the FST may provide somewhat higher values for |G*| than the SST. More research is needed to develop correlations between data generated using the FST, SST and other test procedures.
- The FST is best suited for measuring complex modulus (G*) at temperatures of about 40°C and frequencies of 5 Hz to 10 Hz.
- The variability in |G*| data gathered with the FST at 40°C and 10 Hz is similar to that seen in modulus data found using the SST and other devices, with CVs ranging from 7 percent to 17 percent. This variability in |*G**| data is too high for use in effective QC.
- The precision of the FST can probably be improved significantly by two slight modifications in the testing protocol. The first is to keep the time between specimen mixing, compaction, and testing to within 2 to 4 hours, which would normally be done during QC testing. The second modification involves testing each specimen four times, rotating or flipping the specimen between each repeat determination, and reporting the average of these four values.
- By using this suggested protocol and conditioning the specimens in a water bath rather than an oven, a complete modulus measurement can be made with the FST in less than 40 min from the time of specimen compaction.

UNPUBLISHED MATERIAL

Appendices A–H of the agency final report are not published herein, but they are available for loan on request to NCHRP, Transportation Research Board, Box 289, Washington, D.C. 20055.

Appendix A: Literature Review
Appendix B: Annotated Bibliography
Appendix C: Prototype Development
Appendix D: Stress Analysis
Appendix E: Preliminary Evaluation of the Improved Field Shear Test
Appendix F: Sensitivity Testing
Appendix G: Calibration and Validation Procedures for the Field Shear Test
Appendix H: Implementation

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