# NCHRP 9-30A
# CALIBRATION OF RUTTING MODELS FOR HMA STRUCTURAL AND MIXTURE DESIGN

# APPENDIX I
# SIMPLE PERFORMANCE TEST SYSTEM INSTRUMENTATION

Prepared for:
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One of the key products from NCHRP project 9-30A was to recommend instrumentation needed in collecting uniaxial and triaxial test data to simplify on the determination of hot mix asphalt (HMA) mixture properties in support of the rut depth transfer functions that are applicable for incorporating into the Mechanistic-Empirical Pavement Design Guide (MEPDG). The project management team was supported by individuals who conducted the instrumentation study for the uniaxial and traixial compression tests (both the dynamic modulus and permanent deformation). This study consisted of two experiments; one for the dynamic modulus test and the other for the repeated load permanent deformation test. All of the testing completed for the two experiments was completed by Advanced Asphalt Technologies, LLC (AAT). Drs. Ramon Bonaquist and Donald Christenson were the primary authors of Appendix I.

All members of the research team also acknowledge and greatly appreciate the support and effort for helping bring this project to completion by Dr. Edward Harrigan with NCHRP and the NCHRP panel members.

# ABSTRACT

The objective of NCHRP Project 9-30A was to recommend revisions to the hot mix asphalt (HMA) rut depth transfer function in the Mechanistic-Empirical Pavement Design Guide Software (MEPDG). The recommended revisions were based on the calibration and validation of rut depth transfer functions with laboratory measured mixture properties and performance data from existing field and other full-scale pavement sections that incorporate modified as well as unmodified asphalt binders. As part of this objective, two laboratory experiments were designed and executed to improve and simplify on the HMA mixture testing in support of the MEPDG. The objective of each experiment is listed below.

1. Quantify the effect of the gauge length on the dynamic modulus and phase angle.
2. Determine if permanent stains based on the actuator displacement are comparable to those based on specimen mounted displacements.

The documentation for NCHRP Project 9-30A consists of a research report and eleven appendices (Appendices A through K). This appendix (Appendix I) documents the experiments, the laboratory test program, data analysis and interpretation, and results from the two experiments.

# Executive Summary

This appendix documents work performed by Advanced Asphalt Technologies, LLC at the request of the National Cooperative Highway Research Program (NCHRP) Project 9-30A panel to recommend instrumentation to be used in collecting uniaxial and triaxial compression dynamic modulus and permanent deformation data. The research team designed and executed two experiments. The first was an experiment to determine the effect of gauge length on the measured dynamic modulus and phase angle. Gauge lengths of 70 mm as used in the Simple Performance Test System (SPT) and 100 mm as specified in AASHTO TP62 were used. The second experiment was designed to determine if permanent strains obtained from the actuator displacement were comparable to those obtained with specimen mounted instrumentation. Both experiments were designed as paired difference experiments and involved collecting data from the same specimens using both types of instrumentation. Two mixtures, a dense graded 12.5 mm and a Stone Matrix Asphalt (SMA) were used in both experiments.

The dynamic modulus experiment concluded that there was no significant difference in the dynamic modulus or phase angle for 70 mm gauge length data compared to 100 mm gauge length data. Based on this conclusion and its ease of use, SPT was recommended for collecting dynamic modulus test data for NCHRP Project 9-30A.

Conclusions were not as clear for the permanent deformation experiment. A paired difference analysis showed significant differences in the magnitude of the permanent strains early in the test for the dense graded mixture and throughout the test for the SMA mixture. However, the flow number for the dense graded mixture and the permanent strains during most of the testing of the dense graded mixture were not significantly different. Although the paired difference analysis was able to detect significant differences, a similar analysis assuming independent samples did not. Therefore, it is unlikely that data from separate independent samples tested using the actuator and specimen mounted instrumentation would be significantly different when sample to sample variability is considered. A very important conclusion from the permanent deformation experiment was spring loaded LVDTs cannot be used with specimen mounted instrumentation for permanent deformation testing. At the high temperatures used in permanent deformation testing, the spring force causes significant creep of the gauge points and large errors in the resulting permanent strain measurements. Light weight, loose core LVDTs must be used to make these measurements. The installation of this instrumentation is very tedious and not acceptable for routine testing. Based on these conclusions, the SPT was also recommended for collecting the permanent deformation data for NCHRP 9-30A.

It appears that many of the differences in this study are the result of the non-uniform distribution of air voids in gyratory compacted specimens. Dynamic moduli were generally higher, but not significantly higher for the 70 mm gauge length, and permanent strains were higher when based on the actuator displacement. Both of these effects are likely the result of the higher air voids that are present at the ends of gyratory compacted

specimens. Previous studies have shown that air voids are higher near the ends of the specimens compared to the middle. Further refinement of the test specimen preparation procedures are needed to minimize air void gradients and to eliminate areas of relatively high air voids that might be present at the ends of the test specimens.

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**National Cooperative Highway Research Program**
**NCHRP 9-30A**
**Calibration of Rutting Models for HMA Structural and Mixture Design**

# Appendix I
# Simple Performance Test System Instrumentation Study

## I-1 Introduction

This appendix documents work performed by Advanced Asphalt Technologies, LLC at the request of the NCHRP Project 9-30A panel to recommend instrumentation to be used in collecting uniaxial and triaxial compression dynamic modulus and permanent deformation data. During discussions at the July 27, 2006 NCHRP 9-30A project panel meeting, the research team recommended that the Simple Performance Test System (SPT) developed in NCHRP Project 9-29 be used to obtain dynamic modulus and permanent deformation data for recalibration of the current rutting model in the Mechanistic-Empirical Pavement Design Guide (MEPDG) and enhanced versions of this model that will be investigated during the project. The research team presented three justifications for this recommendation.

1. The SPT has the capability to perform both dynamic modulus and repeated load permanent deformation tests.
2. The equipment is much less expensive than general purpose servo-hydraulic testing equipment.
3. The equipment was designed to be user friendly and includes software and other features that have the potential to make these types of tests routine and to reduce testing variability.

By using the SPT equipment in NCHRP Project 9-30A, the research team can demonstrate to highway agencies that Level 1 testing in support of the MEPDG can be performed using equipment that is within the budget of highway agencies and can be operated by agency technicians without substantial additional training. The NCHRP project 9-30A panel tentatively accepted this recommendation, but requested that data supporting the use of the SPT be supplied prior to the start of the production testing for the validation and calibration of the different rut depth transfer functions recommended from the facilitated workshop (refer to Appendix G of the NCHRP Project 9-30A appendices).

## I-2 Differences between the SPT and the Recommended MEPDG Test Methods

The SPT was developed in NCHRP Project 9-29 to be a low cost system for performing the three candidate simple performance tests recommended in NCHRP Project 9-19. These are: dynamic modulus, flow number, and flow time. The dynamic modulus and a repeated load permanent

strain curve from the flow number test are also needed in support of the MEPDG. A dynamic modulus master curve from AASHTO TP62 (*1*) is the primary input for the flexible pavement performance models. The rutting model in the MEPDG is based on analysis of numerous repeated load permanent deformation tests conducted in accordance with the test method described in Appendix B of NCHRP Report #465 (*2*). In developing the specifications for the SPT, several simplifications and improvements were made in an effort to make it possible to reduce the cost of the equipment, improve the reliability of the data, and to simplify the operation. These changes and improvements have not been incorporated into the published test methods. The sections below describe these differences.

### *I-2.1 Dynamic Modulus*

The provisional standard test method for the testing and analysis required to develop a dynamic modulus master curve for the MEPDG is given in AASHTO TP 62. Table I-1 compares key requirements of the equipment specified in AASHTO TP 62 with the capabilities of the SPT. As shown in Table I-1, the SPT departs from the AASHTO TP 62 equipment in three areas. First, the low temperature range for the SPT is 4 °C compared to –10 °C in AASHTO TP 62. Because the SPT does not perform tests at extremely low temperatures, the capacity of the equipment is less than specified in AASHTO TP 62. Finally, the gauge length for measuring deformation and computing modulus in the SPT is 70 mm compared to 100 mm in AASHTO TP 62.

**Table I-1. Comparison of Key Requirements of AASHTO TP 62 and the SPT**

| Item | AASHTO TP62 (*1*) | SPT (*3*) |
|---|---|---|
| Equipment Type | Servo-hydraulic | Servo-hydraulic |
| Capacity | 25 kN | 13.5 kN |
| Frequency | 0.1 to 25 Hz | 0.01 to 25 Hz |
| Load Accuracy | 1 percent | 1 percent |
| Load Resolution | 5 N | 0.6 N |
| Deformation Measurement | Minimum 2 specimen mounted LVDT's | Minimum of 2 specimen mounted LVDT's |
| Gauge Length | 100 mm | 70 mm |
| Deformation Range | 1 mm | 1 mm |
| Deformation Accuracy | Not specified | 0.0025 mm |
| Deformation Resolution | 0.0010 mm | 0.0002 mm |
| Temperature Range | -10 to 60 °C | 4 to 60 °C |
| Temperature Control | ± 0.5 °C | ± 0.5 °C |
| Confinement | Unconfined | Unconfined to 210 kPa |
| Confining Pressure Control | NA | ± 2 % |

In developing the SPT specifications, the low temperature range and the capacity of the machine were major factors governing the cost and complexity of the equipment. Higher load capacity is needed for testing at lower temperatures. A low temperature range of 4 °C was selected in NCHRP Project 9-29 as a compromise to provide sufficient low temperature data for master curve construction, but to maintain a reasonable cost for the environmental control system. The cost of environmental control increases with the low temperature range, and at temperatures

below freezing, additional humidity control is needed to keep ice from forming on specimens and deformation measuring equipment. The cost of the temperature control provided in the SPT is approximately $5,000, which is a factor of 10 to 15 less than the cost of environmental control for a temperature range down to –10 °C. A methodology for developing master curves with the SPT that are comparable to those obtained from AASHTO TP62 was developed in NCHRP Project 9-29 (*4*). Similar master curves are produced with the two procedures, except for cases where unrealistic data is obtained at - 10 °C. For the convenience of the reader, a copy of Reference 4 is provided as Appendix I-A of this report.

The other major difference between AASHTO TP62 and the SPT is a gauge length of 70 mm is used in the SPT instead of a gauge length of 100 mm as specified in AASHTO TP62. The shorter gauge length was used in the SPT in an attempt to provide less variable data. By moving the instrumentation further from the specimen ends, imperfections in the specimen ends should have less effect on the measured data. The use of 70 mm for the gauge length was supported by data generated in NCHRP Project 9-19 (*5*). In this study uniaxial compression dynamic modulus and repeated load permanent deformation tests were performed on specimens with diameters of 70, 100, and 150 mm. Testing at each specimen diameter included height to diameter ratios of 1.0, 1.5, 2.0, and 3.0. In the testing, the gauge length was equal to the specimen diameter. Three mixtures with nominal maximum aggregate sizes of 12.5 mm, 19.0 mm, and 37.5 mm were included in the experiment.

Dynamic modulus data was obtained at 4 °C with 16 Hz loading and 40 °C with 0.1 Hz loading. For the dynamic modulus, the study concluded that specimens 70 mm in diameter with a height to diameter ratio of 1.5 and a gauge length of 70 mm were acceptable for mixtures with nominal maximum aggregate sizes up to 37.5 mm (*5*). For permanent deformation tests, the required sample size was 100 mm in diameter with a height to diameter ratio of 1.5 and a gauge length of 100 mm (*5*). To simplify specimen fabrication, 100 mm diameter by 150 mm high specimens were specified for both tests.

Several important parts of the equipment requirements for the repeated load test in Appendix B of NCHRP Report #465 are not specified. These are the range, accuracy, and resolution of the axial measuring devices, and the required control for the confining pressure system. The range for the SPT was selected to allow permanent strains up to 8 percent. Tests conducted in NCHRP Project 9-19 showed flow occurred at permanent strain levels of approximately 1 percent for unconfined tests and 5 percent for confined tests (*6*). The accuracy and resolution for the SPT deformation measuring equipment are consistent with the measuring range. The confining pressure control in the SPT was set at ± 2 percent, which is about twice the accuracy of typical pressure sensors.

### *I-2.2 Repeated Load Permanent Deformation*

The standard test method for the testing and analysis used to develop the permanent deformation curves that form the basis of the MEPDG rutting model is given in Appendix B of NCHRP Report #465 (*2*). Table I-2 compares key requirements of this test method with the capabilities of the SPT.

**Table I-2. Comparison of Key Requirements of Appendix B of NCHRP Report 465 and the SPT**

| Item | Appendix B of NCHRP Report 465 (*3*) | SPT (*3*) |
|---|---|---|
| Equipment Type | Servo-hydraulic | Servo-hydraulic |
| Capacity | 25 kN | 13.5 kN |
| Load Form | 0.1 sec pulse with 0.9 sec dwell | 0.1 sec pulse with 0.9 sec dwell |
| Load Accuracy | 1 percent | 1 percent |
| Load Resolution | Not specified | 0.6 N |
| Deformation Measurement | Minimum 2 specimen mounted LVDT's | Actuator mounted LVDT |
| Gauge Length | 100 mm | NA |
| Deformation Range | Not specified | 12 mm |
| Deformation Accuracy | Not specified | 0.03 mm |
| Deformation Resolution | Not specified | 0.0025 mm |
| Temperature Range | 25 to 60 °C | 4 to 60 °C |
| Temperature Control | ± 0.5 °C | ± 0.5 °C |
| Confinement | Unconfined to 207 kPa | Unconfined to 210 kPa |
| Confining Pressure Control | Not specified | ± 2 % |

The major difference between the equipment for the repeated load test in Appendix B of NCHRP Report #465 and the SPT is the SPT uses the movement of the actuator to monitor permanent deformation, while the repeated load test in Appendix B of NCHRP Report #465 uses specimen mounted LVDTs. The SPT was originally developed to measure the flow number, which is the number of cycles to the onset of tertiary flow in the specimen. Work conducted in NCHRP Project 9-19 showed that this point can be detected using three measurements: specimen mounted axial LVDTs, radial LVDTs, or an LVDT tracking the actuator movement (*6*). Since mounting deformation measuring equipment is very difficult for confined tests, the actuator movement was selected for use in the SPT.

## I-3 Considerations in This Study

At the request of the NCHRP Project 9-30A panel, the research team designed and executed two experiments. The first was an experiment to determine the effect of gauge length on the measured dynamic modulus. Gauge lengths of 70 mm as used in the SPT and 100 mm as specified in AASHTO TP62 were used. The second experiment was designed to determine if permanent strains obtained from the actuator displacement were comparable to those obtained with specimen mounted instrumentation.

# I-4 Materials and Methods

## *I-4.1 Materials*

Two mixtures were used in both experiments: a dense graded 12.5 mm Superpave mixture and a Stone Matrix Asphalt (SMA) mixture. The dense graded mixture was produced with diabase coarse aggregate and a combination of diabase and natural sand fine aggregate. Both aggregates were from Northern Virginia. The binder for this mixture was a neat PG 64-22 binder obtained from the Paulsboro, New Jersey refinery of the Citgo Asphalt Refining Company. The SMA mixture was produced with a combination of Northern Virginia diabase and West Virginia limestone aggregates. The binder for this mixture was Citgoflex PG 76-22 obtained from the Paulsboro, New Jersey refinery of the Citgo Asphalt Refining Company. This binder is a styrene-butadiene-styrene (SBS) modified binder. Table I-3 presents binder content and gradation data for the two mixtures. Figure I-1 shows the gradation for the two mixtures. These mixtures were used extensively in the ruggedness study for the SPT that is being conducted in NCHRP Project 9-29 (*7*).

**Table I-3. Mixtures Included in the SPT Instrumentation Experiment.**

| Property | | Dense Graded | SMA |
|---|---|---|---|
| Gradation | Sieve Size, mm | % passing | % passing |
| | 19 | 100.0 | 100.0 |
| | 12.5 | 100.0 | 97.1 |
| | 9.5 | 89.6 | 80.9 |
| | 4.75 | 50.7 | 30.0 |
| | 2.36 | 39.7 | 18.6 |
| | 1.18 | 31.5 | 14.7 |
| | 0.6 | 22.9 | 13.2 |
| | 0.3 | 12.1 | 12.0 |
| | 0.15 | 7.7 | 10.1 |
| | 0.075 | 5.3 | 8.3 |
| Asphalt Content, % | | 5.7 | 6.5 |

## *I-4.2 Test Specimens*

All test specimens for the study were fabricated using standard procedures adopted by Advanced Asphalt Technologies, LLC (AAT). The sections that follow discuss procedures used in the specimen fabrication process for:

- Handling of binders and aggregates;
- Laboratory mixing, aging, and compaction;
- Fabrication of test specimens

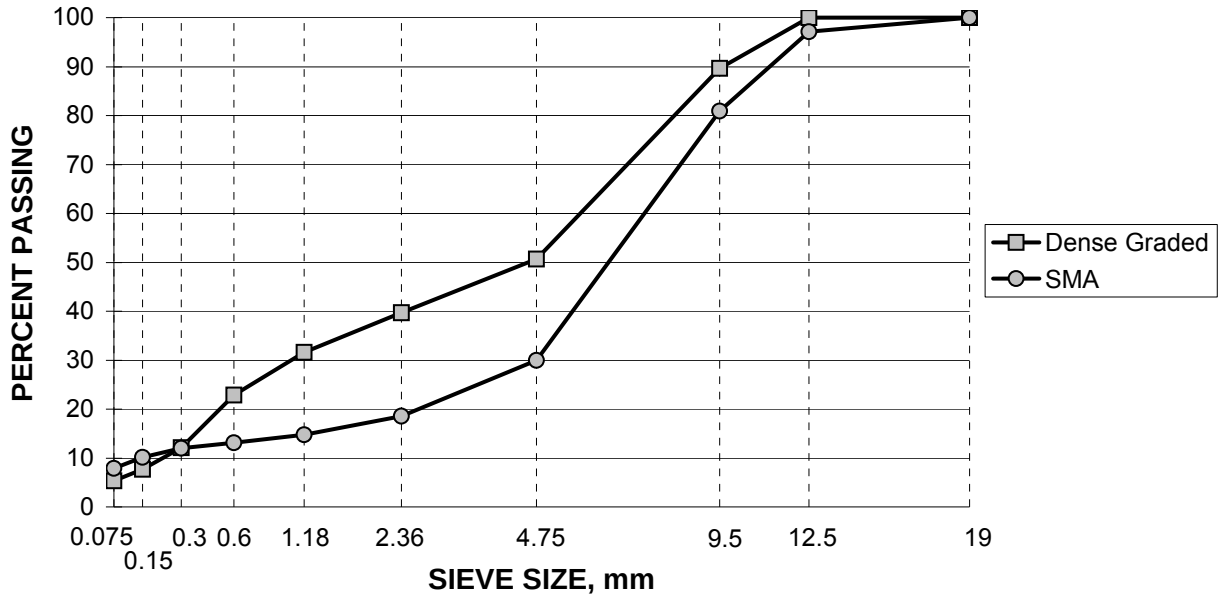


**Figure I-1. Gradation of the Ruggedness Study Mixtures**

### I-4.2.1 Binder Handling

Samples of the binder used in each mixture were shipped to AAT by representatives of Citgo Asphalt Refining Company in 5-gallon metal cans. Upon receipt at AAT, the binder samples were divided into quart containers by heating the original container in an oven set at 135°C, stirring with a mechanical stirrer, and pouring the binder into individual quart containers. The quart containers were then used in the preparation of laboratory mixture batches. Quart containers were only heated once. Excess binder in the quart containers was discarded.

### I-4.2.2 Aggregate Handling

Representative samples of the aggregates used in each mixture were obtained by AAT technicians from the respective suppliers. The procedures described in the Appendix of *Asphalt Institute Publication MS-2* (*8*) were used to prepare the aggregate samples for laboratory batching. Coarse aggregate samples were separated into individual sizes, while individual samples of fine aggregate were mixed together to produce a homogeneous supply for subsequent batching.

Specimen batches were made using the proportions given in the mixture design and washed gradations analyses. The gradation of the blends was verified by performing washed sieve analysis on one of the batches.

### I-4.2.3 Mixing, Aging, and Compaction

Specimens for the dynamic modulus and repeated load permanent deformation tests were cored and sawed from the middle of gyratory samples that were 150 mm in diameter by 165 mm high. All gyratory specimens were prepared to a target air void content of 6.0 percent in accordance

with AASHTO T312. An Interlaken compactor meeting the requirements of AASHTO T312 was used.

Mixing and compaction temperatures for the PG 64-22 binder were determined from viscosities measured at 135, 150, and 165°C in accordance with ASTM D316. Mixing and compaction temperatures for the PG 76-22 binder were obtained from the manufacturer's certificate of analysis submitted with the binder samples. Prior to compaction, materials for all specimens were short-term oven-aged in accordance with AASHTO R30 for two hours at the compaction temperature.

### I-4.2.4 Sawing and Coring of Test Specimens

The test specimens were manufactured by coring and sawing 100 mm diameter by 150 mm high test specimens from the middle of gyratory compacted specimens that were 150 mm in diameter by 165 mm high. The procedure for preparing dynamic modulus specimens is described in AASHTO TP62. The test specimens were prepared to the dimensional tolerances listed in Table I-4. These are somewhat different from those specified in AASHTO TP62 and are the result of a study performed in NCHRP Project 9-29 to determine practical tolerances for dynamic modulus specimen preparation (*9*).

**Table I-4. Project 9-29 Specimen Dimension Tolerances (*9*)**

| Item | Specification | Remarks |
|---|---|---|
| Average Diameter | 100 mm to 104 mm (3.94 in to 4.09 in) | See note 1 |
| Standard Deviation of Diameter | 0.5 mm (0.02 in) | See note 1 |
| Height | 147.5 mm to 152.5 mm (5.81 in to 6.00 in) | See note 2 |
| End Flatness | 0.5 mm (0.02 in) | See note 3 |
| End Perpendicularity | 1.0 mm (0.40 in) | See note 4 |

Notes:

1. Measure the diameter at the center and third points of the test specimen along axes that are 90 degrees apart. Record each of the six measurements to the nearest 0.1 mm. Calculate the average and the standard deviation of the six measurements. The standard deviation shall be less than 0.5 mm. The average diameter, reported to the nearest 0.1 mm, shall be used in all material property calculations.
2. Measure the height of the test specimen in accordance with Section 6.1.2 of ASTM D3459. Record the average height.
3. Using a straightedge and feeler gauges, measure the flatness of each specimen end. Place a straightedge across the diameter at three locations approximately 120 degrees apart and measure the maximum departure of the specimen end from the straightedge using tapered end feeler gauges. For each end record the maximum departure along the three locations as the end flatness.
4. Using a combination square and feeler gauges, measure the perpendicularity of each end. At two locations approximately 90 degrees apart, place the blade of the combination square in contact with the specimen along the axis of the cylinder, and the head in contact with the highest point of the end of the cylinder. Measure the distance between the head of the square and the lowest point on the end of the cylinder using tapered end feeler gauges. For each end, record the maximum measurement from the two locations as the end perpendicularity.

Several laboratories have adapted equipment for preparing dynamic modulus test specimens. The various approaches range from elaborate feed-control drills combined with sophisticated

holders and double-bladed saws to standard drills and single-bladed saws with simple clamping arrangements. For this study, specimens meeting the tolerances listed in Table I-4 were prepared using a portable core-drilling machine, and a double-bladed saw. As shown in Figure I-2, the portable core-drilling machine was mounted to a heavy stand on the laboratory floor to facilitate vertical drilling of the specimen. The gyratory compacted specimen of 150 mm diameter by 165 mm high was held in place under the drill by blocks of wood cut to provide a tight fit between the gyratory specimen and the stand. A sophisticated clamp for holding the gyratory specimen is not needed to obtain the tolerances on the specimen diameter listed in Table I-4. Figure I-3 shows the 100-mm diameter core and the waste portion of the gyratory specimen.

Reasonably smooth, parallel ends for the test specimen were then provided by trimming the 100-mm diameter core using the double-bladed saw shown in Figure I-4. This step is more critical than the coring step and requires the 100-mm diameter core to fit tightly in the saw clamp, and sufficient waste material on each end to keep the saw blades from bending.

All coring and sawing were done using water to cool the cutting tools. After all cutting was complete, the bulk specific gravity of the finished specimen was determined in accordance with AASHTO T166 by first measuring the immersed mass, then the saturated surface dry mass, and finally the dry mass. A completed test specimen is shown in Figure I-5.

**Figure I-2. Portable Core Drilling Machine and Stand**

**Figure I-3. 100-mm-Diameter Core and Waste Ring**

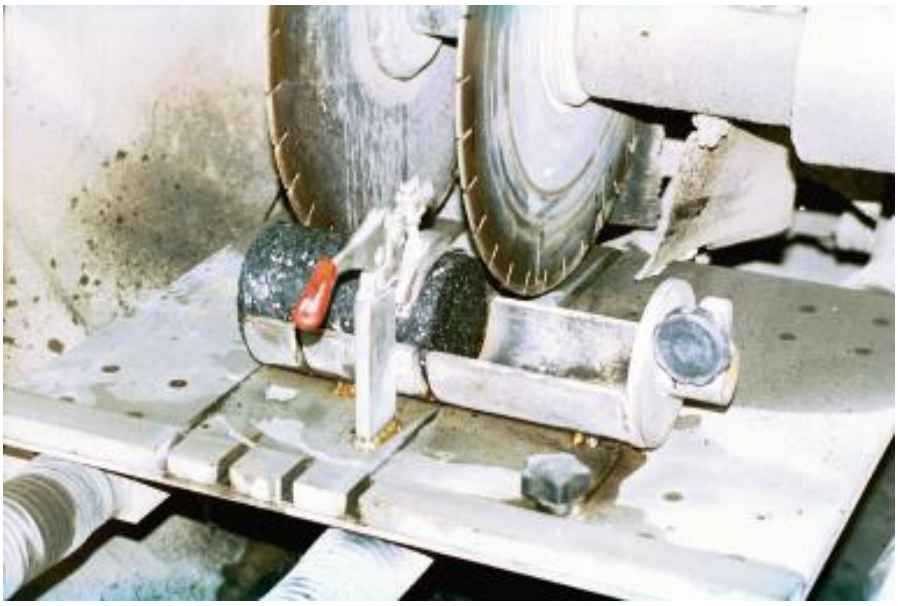

**Figure I-4. Double-Bladed Saw with 100-mm Core**

**Figure I-5. Final Dynamic Modulus Test Specimen**

### *I-4.3 Testing*

All testing was performed with Advanced Asphalt Technologies, LLC's general purpose servo-hydraulic load system shown in Figure I-6. It consists of a top loading Interlaken Model 3310 load frame with a 25 kN actuator and load cell, and a Bemco environmental control chamber with temperature range from –10 to 70 $^{o}$C. The system uses Interlaken's DDC 4000 Controller with a microcomputer workstation running Interlaken's Universal Test Program, UTP-IV, for control and data acquisition. This system can be configured to conduct AASHTO TP62 and the repeated load test in Appendix B of NCHRP Report #465. It can also be configured to simulate the dynamic modulus and repeated load tests as conducted in the SPT.

**Figure I-6. AAT's General Purpose Servo-Hydraulic Testing System**

## I-5 Dynamic Modulus Gauge Length Study

### *I-5.1 Testing*

The dynamic modulus gauge length study was designed to investigate differences in the dynamic modulus and phase angle obtained from tests on the same specimens using two different gauge lengths. Gauge points were glued on the specimens to provide 70 mm and 100 mm gauge lengths. Two sets of each gauge points were glued on the specimens 180 degrees apart. The 70 and 100 mm gauge points were offset by 90 degrees. A total of four specimens, two for the dense graded mixture and two for the SMA mixture were instrumented and tested. Dynamic modulus tests were performed on each sample for the conditions listed in Table I-5. All tests were performed in load control with a target strain level of 100 μmm/mm. Teflon™ friction reducers were used in the testing. The ruggedness testing conducted in NCHRP Report 9-29

concluded that either Teflon™ or greased latex membranes as specified in AASHTO TP62 can be used as end friction reducers in the dynamic modulus test (*10*).

**Table I-5. Conditions for the Dynamic Modulus Testing**

| Temperature, C | Frequency, Hz |
|---|---|
| 4 | 10 |
| | 1 |
| | 0.1 |
| 20 | 10 |
| | 1 |
| | 0.1 |
| 40 | 10 |
| | 1 |
| | 0.1 |
| | 0.01 |

The resulting data are summarized in Tables I-6 and I-7 for the dense graded and SMA mixtures, respectively. This data includes the measured dynamic modulus and phase angle; the strain level induced in the specimen; and four indicators of the quality of the resulting data: load standard error, deformation standard error, deformation uniformity, and phase uniformity. The load standard error and deformation standard error are measures of how well the applied loading and resulting deformations approximate the sinusoidal loading that is assumed in the dynamic modulus test. Higher load and deformation standard errors are associated with poorer quality data. Maximum values for both of 10 percent have been recommended for the highest quality data (*9*).

The deformation uniformity and phase uniformity are measures of how close the individual measurements on a sample agree with one another. The deformation uniformity is the coefficient of variation of the individual deformation measurements, and the phase uniformity is the standard deviation of the individual phase angle measurements. Higher deformation and phase uniformity values indicate poorer quality data. Maximum values of 20 percent and 3 degrees have been recommended for the highest quality data (*9*). As shown in Tables I-6 and I-7, the data quality indicators for some of the tests exceed these recommendations for high quality data. In collecting the data for this study, tests were not repeated to obtain better quality data.

### *I-5.2 Statistical Analysis*

The dynamic modulus experiment was designed as a paired difference experiment. For each sample, dynamic modulus test data was obtained at each temperature and frequency using 100 mm and 70 mm gauge lengths. The appropriate statistical test for this data is the paired difference t-test which is summarized below (*11*):

## Table I-6. Dynamic Modulus Data for the Dense Graded Mixture

| | | | | Dynamic | Phase | | Load | Deformation | Deformation | Phase |
|---|---|---|---|---|---|---|---|---|---|---|
| Specimen | Gage Length | Temperature | Frequency | Modulus | Angle | Strain | Se | Se | Uniformity | Uniformity |
| | mm | C | Hz | MPa | Degree | μ mm/mm | % | % | % | Degree |
| 6 | 100 | 4.0 | 0.1 | 5683.9 | 22.8 | 98.0 | 1.2 | 3.0 | 20.0 | 0.6 |
| 6 | 100 | 4.0 | 1 | 8988.7 | 15.8 | 104.3 | 0.3 | 2.3 | 16.9 | 0.4 |
| 6 | 100 | 4.0 | 10 | 12701.5 | 11.1 | 108.0 | 1.4 | 3.4 | 16.8 | 0.2 |
| 6 | 100 | 20.0 | 0.1 | 1042.1 | 33.2 | 107.3 | 2.1 | 4.6 | 16.1 | 2.5 |
| 6 | 100 | 20.0 | 1 | 2648.1 | 28.4 | 104.2 | 1.3 | 2.8 | 11.3 | 1.1 |
| 6 | 100 | 20.0 | 10 | 5229.0 | 23.4 | 106.5 | 2.6 | 3.4 | 9.8 | 0.7 |
| 6 | 100 | 40.0 | 0.01 | 71.6 | 19.5 | 108.8 | 11.4 | 7.2 | 20.1 | 0.4 |
| 6 | 100 | 40.0 | 0.1 | 121.4 | 27.8 | 113.3 | 13.1 | 8.2 | 6.7 | 0.1 |
| 6 | 100 | 40.0 | 1 | 282.5 | 33.3 | 109.0 | 6.8 | 4.9 | 8.9 | 0.2 |
| 6 | 100 | 40.0 | 10 | 868.7 | 35.3 | 95.1 | 18.3 | 14.3 | 15.2 | 1.6 |
| 8 | 100 | 4.0 | 0.1 | 5160.7 | 22.5 | 108.2 | 1.6 | 3.2 | 13.7 | 0.8 |
| 8 | 100 | 4.0 | 1 | 8370.6 | 15.8 | 99.2 | 0.3 | 2.3 | 16.6 | 0.1 |
| 8 | 100 | 4.0 | 10 | 11661.4 | 12.0 | 105.0 | 2.8 | 3.6 | 17.0 | 0.1 |
| 8 | 100 | 20.0 | 0.1 | 993.3 | 32.7 | 101.5 | 2.2 | 4.7 | 13.4 | 3.1 |
| 8 | 100 | 20.0 | 1 | 2484.1 | 28.1 | 89.4 | 1.0 | 3.5 | 17.3 | 0.6 |
| 8 | 100 | 20.0 | 10 | 5086.1 | 22.7 | 110.0 | 1.5 | 2.3 | 17.3 | 0.1 |
| 8 | 100 | 40.0 | 0.01 | 71.2 | 20.8 | 109.3 | 14.0 | 7.6 | 51.4 | 11.4 |
| 8 | 100 | 40.0 | 0.1 | 130.9 | 27.9 | 104.6 | 11.9 | 7.4 | 33.0 | 16.1 |
| 8 | 100 | 40.0 | 1 | 332.8 | 33.8 | 109.1 | 4.4 | 8.5 | 1.1 | 15.0 |
| 8 | 100 | 40.0 | 10 | 989.1 | 33.3 | 106.2 | 12.1 | 9.6 | 1.4 | 6.3 |
| 6 | 70 | 4.0 | 0.1 | 5482.2 | 22.6 | 101.6 | 1.6 | 3.5 | 3.8 | 0.5 |
| 6 | 70 | 4.0 | 1 | 8637.5 | 15.9 | 108.6 | 0.3 | 3.0 | 3.5 | 0.5 |
| 6 | 70 | 4.0 | 10 | 12049.7 | 11.5 | 111.8 | 1.8 | 3.9 | 2.9 | 0.4 |
| 6 | 70 | 20.0 | 0.1 | 1136.1 | 35.6 | 98.6 | 1.9 | 5.7 | 9.8 | 9.0 |
| 6 | 70 | 20.0 | 1 | 2788.3 | 29.0 | 99.2 | 1.3 | 4.2 | 2.6 | 3.6 |
| 6 | 70 | 20.0 | 10 | 5492.4 | 23.0 | 102.9 | 1.5 | 3.6 | 6.7 | 1.8 |
| 6 | 70 | 40.0 | 0.01 | 59.6 | 23.9 | 114.0 | 15.4 | 12.0 | 40.8 | 6.4 |
| 6 | 70 | 40.0 | 0.1 | 115.8 | 32.7 | 98.9 | 12.7 | 9.9 | 23.7 | 11.2 |
| 6 | 70 | 40.0 | 1 | 330.8 | 38.1 | 108.8 | 5.0 | 6.6 | 8.3 | 12.3 |
| 6 | 70 | 40.0 | 10 | 1056.5 | 37.0 | 98.4 | 10.5 | 9.3 | 16.4 | 7.8 |
| 8 | 70 | 4.0 | 0.1 | 6008.4 | 22.7 | 93.0 | 1.2 | 3.5 | 10.0 | 0.6 |
| 8 | 70 | 4.0 | 1 | 9472.1 | 15.7 | 99.1 | 0.3 | 3.5 | 7.9 | 0.7 |
| 8 | 70 | 4.0 | 10 | 13303.4 | 11.1 | 102.8 | 1.5 | 4.1 | 5.8 | 0.5 |
| 8 | 70 | 20.0 | 0.1 | 1179.5 | 33.5 | 94.8 | 2.1 | 4.9 | 6.6 | 2.2 |
| 8 | 70 | 20.0 | 1 | 2884.1 | 29.3 | 96.0 | 0.8 | 3.6 | 7.9 | 1.9 |
| 8 | 70 | 20.0 | 10 | 5761.9 | 22.3 | 98.8 | 1.6 | 4.3 | 3.0 | 1.2 |
| 8 | 70 | 40.0 | 0.01 | 77.6 | 21.7 | 100.6 | 11.2 | 7.2 | 35.5 | 3.6 |
| 8 | 70 | 40.0 | 0.1 | 141.4 | 29.0 | 96.9 | 11.2 | 6.8 | 24.8 | 5.6 |
| 8 | 70 | 40.0 | 1 | 360.0 | 34.1 | 100.8 | 4.5 | 6.2 | 7.1 | 5.2 |
| 8 | 70 | 40.0 | 10 | 1124.1 | 34.5 | 94.8 | 10.8 | 9.0 | 5.5 | 3.5 |

## Table I-7. Dynamic Modulus Data for the SMA Mixture

| | | | | Dynamic | Phase | | Load | Deformation | Deformation | Phase |
|---|---|---|---|---|---|---|---|---|---|---|
| Specimen | Gage Length | Temperature | Frequency | Modulus | Angle | Strain | Se | Se | Uniformity | Uniformity |
| | mm | C | Hz | MPa | Degree | μ mm/mm | % | % | % | Degree |
| 10 | 100 | 4.4 | 0.1 | 6452.2 | 20.7 | 104.4 | 1.2 | 2.7 | 3.7 | 0.5 |
| 10 | 100 | 4.4 | 1 | 9840.0 | 15.2 | 112.8 | 0.3 | 2.5 | 3.5 | 0.3 |
| 10 | 100 | 4.4 | 10 | 13879.3 | 11.3 | 103.2 | 1.5 | 3.5 | 3.4 | 0.3 |
| 10 | 100 | 20.0 | 0.1 | 1452.0 | 29.1 | 96.8 | 1.8 | 5.6 | 2.2 | 5.6 |
| 10 | 100 | 20.0 | 1 | 3085.0 | 25.5 | 108.4 | 2.7 | 4.2 | 4.1 | 2.7 |
| 10 | 100 | 20.0 | 10 | 5633.2 | 21.9 | 101.3 | 2.3 | 3.4 | 6.8 | 1.3 |
| 10 | 100 | 40.0 | 0.01 | 173.1 | 20.5 | 116.7 | 4.7 | 7.7 | 0.9 | 0.8 |
| 10 | 100 | 40.0 | 0.1 | 272.8 | 24.6 | 103.9 | 5.4 | 7.1 | 0.4 | 0.9 |
| 10 | 100 | 40.0 | 1 | 588.6 | 26.7 | 98.7 | 4.1 | 8.0 | 0.0 | 0.4 |
| 10 | 100 | 40.0 | 10 | 1382.8 | 28.4 | 108.4 | 4.8 | 6.0 | 4.8 | 0.4 |
| 12 | 100 | 4.4 | 0.1 | 5081.4 | 21.0 | 110.6 | 1.2 | 2.3 | 5.1 | 0.6 |
| 12 | 100 | 4.4 | 1 | 7933.0 | 15.4 | 105.2 | 0.3 | 2.1 | 6.7 | 0.7 |
| 12 | 100 | 4.4 | 10 | 10913.5 | 11.6 | 104.0 | 1.5 | 3.0 | 8.2 | 0.5 |
| 12 | 100 | 20.0 | 0.1 | 1183.2 | 29.5 | 95.2 | 1.7 | 4.5 | 9.2 | 1.0 |
| 12 | 100 | 20.0 | 1 | 2610.7 | 26.0 | 106.8 | 1.1 | 2.9 | 7.8 | 0.4 |
| 12 | 100 | 20.0 | 10 | 4953.4 | 22.3 | 111.1 | 2.5 | 3.6 | 8.1 | 0.8 |
| 12 | 100 | 40.0 | 0.01 | 157.9 | 19.8 | 106.7 | 6.6 | 6.6 | 30.3 | 2.6 |
| 12 | 100 | 40.0 | 0.1 | 246.4 | 24.1 | 97.1 | 8.8 | 6.9 | 29.4 | 3.0 |
| 12 | 100 | 40.0 | 1 | 510.6 | 26.2 | 104.1 | 4.4 | 7.0 | 20.3 | 0.8 |
| 12 | 100 | 40.0 | 10 | 1183.7 | 27.9 | 102.4 | 8.2 | 7.4 | 11.7 | 0.7 |
| 10 | 70 | 4.4 | 0.1 | 5518.1 | 20.8 | 101.7 | 1.6 | 3.2 | 12.7 | 1.5 |
| 10 | 70 | 4.4 | 1 | 8482.6 | 15.0 | 104.9 | 0.3 | 3.6 | 10.8 | 1.8 |
| 10 | 70 | 4.4 | 10 | 11530.3 | 10.9 | 114.4 | 1.3 | 3.5 | 8.6 | 1.4 |
| 10 | 70 | 20.0 | 0.1 | 1453.9 | 29.6 | 96.9 | 1.6 | 4.7 | 15.5 | 2.3 |
| 10 | 70 | 20.0 | 1 | 3015.1 | 25.3 | 92.5 | 1.1 | 3.3 | 16.6 | 1.3 |
| 10 | 70 | 20.0 | 10 | 5434.2 | 21.0 | 100.7 | 2.6 | 4.2 | 18.2 | 1.5 |
| 10 | 70 | 40.0 | 0.01 | 160.8 | 21.5 | 104.0 | 7.2 | 6.8 | 25.3 | 8.3 |
| 10 | 70 | 40.0 | 0.1 | 271.3 | 25.3 | 104.3 | 5.7 | 6.4 | 18.5 | 10.1 |
| 10 | 70 | 40.0 | 1 | 585.0 | 28.7 | 99.1 | 4.0 | 8.3 | 6.2 | 10.6 |
| 10 | 70 | 40.0 | 10 | 1396.0 | 28.3 | 104.6 | 3.5 | 5.3 | 9.2 | 7.9 |
| 12 | 70 | 4.4 | 0.1 | 6035.6 | 19.9 | 93.0 | 1.2 | 3.5 | 5.4 | 0.0 |
| 12 | 70 | 4.4 | 1 | 9168.2 | 14.8 | 96.8 | 0.3 | 3.2 | 5.6 | 0.5 |
| 12 | 70 | 4.4 | 10 | 12330.5 | 11.5 | 109.6 | 2.4 | 3.9 | 5.4 | 0.8 |
| 12 | 70 | 20.0 | 0.1 | 1570.3 | 28.2 | 89.7 | 1.7 | 5.0 | 20.1 | 2.5 |
| 12 | 70 | 20.0 | 1 | 3275.0 | 24.7 | 102.0 | 0.9 | 3.2 | 23.2 | 1.2 |
| 12 | 70 | 20.0 | 10 | 5894.2 | 20.7 | 94.8 | 1.8 | 3.6 | 23.0 | 0.8 |
| 12 | 70 | 40.0 | 0.01 | 179.9 | 20.8 | 103.0 | 5.7 | 6.9 | 0.5 | 2.1 |
| 12 | 70 | 40.0 | 0.1 | 300.6 | 24.3 | 94.7 | 6.8 | 6.6 | 2.4 | 1.6 |
| 12 | 70 | 40.0 | 1 | 631.6 | 26.9 | 92.2 | 4.3 | 8.4 | 3.7 | 0.9 |
| 12 | 70 | 40.0 | 10 | 1450.1 | 27.0 | 99.3 | 3.2 | 5.0 | 2.0 | 1.2 |

Null Hypothesis: $\mu_d = \mu_{70} - \mu_{100} = 0$

Alternative Hypothesis: $\mu_d > 0$

Test Statistic: $t = \dfrac{\bar{d}}{\dfrac{s_d}{\sqrt{n}}}$

Rejection Region: Reject $H_o$ if $|t| > t_\alpha$ for n-1 degrees of freedom.

Where:

$\mu$ = population difference
$\mu_{100}$ = population mean for 100 mm gauge length measurements
$\mu_{70}$ = population mean for 70 mm gauge length measurements
$\bar{d}$ = average of the sample differences
$s_d$ = standard deviation of the differences
n = number of samples
$\alpha$ = level of significance (typically 5 percent)

For the data collected in the dynamic modulus experiment, four paired differences can be computed for each test temperature and frequency of loading. For n=4 tests, the critical value of the t statistic for a level of significance of 5 percent is 2.353. Tables I-8 and I-9 summarize the results of the statistical analysis for the dynamic modulus and phase angle, respectively. These tables show that gauge length had a significant effect in only 1 of the 10 conditions tested. Gauge length was significant for the dynamic modulus measured at 40 °C and 10 Hz loading. In this case the dynamic modulus for 70 mm gauge length was significantly higher compared to that for 100 mm gauge length. Gauge length was also significant for the phase angle measured at 20 °C and 10 Hz loading. In this case, the phase angle was significantly higher for the 100 mm gauge length data.

It should be noted that the average dynamic modulus differences in Table I-8 are always positive, indicating that dynamic modulus from the 70 mm gauge length are higher, but not significantly higher, than those for the 100 mm gauge length. This is reasonable considering typical air void gradients in gyratory compacted specimens. Air voids are higher at the ends of the specimens compared to the middle. The generally higher dynamic modulus measured for the 70 mm gauge length probably reflects the lower air voids in this region of the specimen.

Similar statistical analyses were performed for the four data quality indicators: load standard error, deformation standard error, deformation uniformity, and phase uniformity. The results are summarized in Tables I-10 through I-13. These analyses show that there is little difference in the quality of the data for tests using 70 mm and 100 mm gauge lengths. In some cases, the load and deformation standard errors were significantly larger for the 100 mm test data and the deformation uniformity was larger in the 70 mm test data, but the magnitudes were small compared to the ranges discussed previously for the highest quality data.

## Table I-8. Statistical Analysis of Dynamic Modulus Data

| | | Dynamic Modulus Difference, MPa | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Temperature | Frequency | Dense | Dense | SMA | SMA | | Standard | Calculated | Critical | |
| C | Hz | 6 | 8 | 10 | 12 | Average | Deviation | t | t | Conclusion |
| 4 | 0.1 | -201.7 | 847.7 | -934.1 | 954.1 | 166.5 | 900.27 | 0.370 | 2.353 | no difference |
| 4 | 1 | -351.2 | 1101.6 | -1357.4 | 1235.2 | 157.0 | 1239.15 | 0.253 | 2.353 | no difference |
| 4 | 10 | -651.8 | 1642.0 | -2349.0 | 1417.0 | 14.5 | 1883.80 | 0.015 | 2.353 | no difference |
| 20 | 0.1 | 94.0 | 186.2 | 1.9 | 387.1 | 167.3 | 164.75 | 2.031 | 2.353 | no difference |
| 20 | 1 | 140.2 | 400.0 | -69.9 | 664.3 | 283.7 | 318.32 | 1.782 | 2.353 | no difference |
| 20 | 10 | 263.4 | 675.7 | -199.0 | 940.8 | 420.2 | 498.11 | 1.687 | 2.353 | no difference |
| 40 | 0.01 | -12.1 | 6.4 | -12.3 | 22.0 | 1.0 | 16.50 | 0.120 | 2.353 | no difference |
| 40 | 0.1 | -5.6 | 10.5 | -1.4 | 54.2 | 14.4 | 27.40 | 1.052 | 2.353 | no difference |
| 40 | 1 | 48.3 | 27.1 | -3.7 | 121.1 | 48.2 | 53.04 | 1.817 | 2.353 | no difference |
| 40 | 10 | 187.8 | 134.9 | 13.2 | 266.4 | 150.6 | 106.34 | 2.832 | 2.353 | 70 mm > 100 mm |

## Table I-9. Statistical Analysis of Phase Angle Data

| | | Phase Angle Difference, Degree | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Temperature | Frequency | Dense | Dense | SMA | SMA | | Standard | Calculated | Critical | |
| C | Hz | 6 | 8 | 10 | 12 | Average | Deviation | t | t | Conclusion |
| 4 | 0.1 | -0.2 | 0.2 | 0.1 | -1.1 | -0.2 | 0.59 | -0.818 | 2.353 | no difference |
| 4 | 1 | 0.1 | -0.1 | -0.1 | -0.6 | -0.2 | 0.31 | -1.213 | 2.353 | no difference |
| 4 | 10 | 0.4 | -0.9 | -0.4 | -0.1 | -0.2 | 0.52 | -0.916 | 2.353 | no difference |
| 20 | 0.1 | 2.4 | 0.8 | 0.4 | -1.3 | 0.6 | 1.51 | 0.746 | 2.353 | no difference |
| 20 | 1 | 0.6 | 1.2 | -0.2 | -1.3 | 0.1 | 1.09 | 0.120 | 2.353 | no difference |
| 20 | 10 | -0.4 | -0.4 | -0.9 | -1.6 | -0.8 | 0.57 | -2.916 | 2.353 | 100 mm > 70 mm |
| 40 | 0.01 | 4.4 | 0.9 | 1.0 | 1.0 | 1.9 | 1.71 | 2.164 | 2.353 | no difference |
| 40 | 0.1 | 4.9 | 1.2 | 0.8 | 0.2 | 1.8 | 2.13 | 1.659 | 2.353 | no difference |
| 40 | 1 | 4.8 | 0.2 | 2.0 | 0.7 | 1.9 | 2.06 | 1.893 | 2.353 | no difference |
| 40 | 10 | 1.7 | 1.2 | 0.0 | -0.9 | 0.5 | 1.18 | 0.867 | 2.353 | no difference |

## Table I-10. Statistical Analysis of Load Standard Error Data

| | | Load Standard Error Difference, % | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Temperature | Frequency | Dense | Dense | SMA | SMA | | Standard | Calculated | Critical | |
| C | Hz | 6 | 8 | 10 | 12 | Average | Deviation | t | t | Conclusion |
| 4 | 0.1 | 0.3 | -0.3 | 0.4 | 0.0 | 0.1 | 0.33 | 0.574 | 2.353 | no difference |
| 4 | 1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.00 | 0.770 | 2.353 | no difference |
| 4 | 10 | 0.4 | -1.3 | -0.2 | 0.8 | -0.1 | 0.91 | -0.171 | 2.353 | no difference |
| 20 | 0.1 | -0.3 | -0.2 | -0.2 | 0.0 | -0.2 | 0.09 | -3.339 | 2.353 | 100 mm > 70 mm |
| 20 | 1 | 0.0 | -0.2 | -1.6 | -0.2 | -0.5 | 0.72 | -1.428 | 2.353 | no difference |
| 20 | 10 | -1.0 | 0.1 | 0.4 | -0.7 | -0.3 | 0.68 | -0.968 | 2.353 | no difference |
| 40 | 0.01 | 4.0 | -2.8 | 2.5 | -0.9 | 0.7 | 3.13 | 0.449 | 2.353 | no difference |
| 40 | 0.1 | -0.4 | -0.7 | 0.3 | -2.0 | -0.7 | 0.97 | -1.448 | 2.353 | no difference |
| 40 | 1 | -1.7 | 0.0 | -0.1 | -0.1 | -0.5 | 0.83 | -1.143 | 2.353 | no difference |
| 40 | 10 | -7.8 | -1.2 | -1.3 | -5.0 | -3.8 | 3.21 | -2.398 | 2.353 | 100 mm > 70 mm |

**Table I-11. Statistical Analysis of the Deformation Standard Error Data**

| | | Deformation Standard Error Difference, % | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Temperature | Frequency | Dense | Dense | SMA | SMA | | Standard | Calculated | Critical | |
| C | Hz | 6 | 8 | 10 | 12 | Average | Deviation | t | t | Conclusion |
| 4 | 0.1 | 0.6 | 0.4 | 0.5 | 1.2 | 0.7 | 0.38 | 3.457 | 2.353 | 70 mm > 100 mm |
| 4 | 1 | 0.7 | 1.2 | 1.0 | 1.1 | 1.0 | 0.24 | 8.343 | 2.353 | 70 mm > 100 mm |
| 4 | 10 | 0.5 | 0.5 | -0.1 | 0.9 | 0.5 | 0.39 | 2.320 | 2.353 | no difference |
| 20 | 0.1 | 1.1 | 0.2 | -0.9 | 0.5 | 0.2 | 0.81 | 0.533 | 2.353 | no difference |
| 20 | 1 | 1.4 | 0.1 | -0.8 | 0.4 | 0.3 | 0.90 | 0.567 | 2.353 | no difference |
| 20 | 10 | 0.1 | 2.0 | 0.8 | 0.0 | 0.7 | 0.93 | 1.587 | 2.353 | no difference |
| 40 | 0.01 | 4.8 | -0.4 | -0.9 | 0.3 | 0.9 | 2.60 | 0.720 | 2.353 | no difference |
| 40 | 0.1 | 1.7 | -0.6 | -0.7 | -0.3 | 0.0 | 1.13 | 0.047 | 2.353 | no difference |
| 40 | 1 | 1.7 | -2.3 | 0.3 | 1.4 | 0.2 | 1.83 | 0.262 | 2.353 | no difference |
| 40 | 10 | -5.1 | -0.6 | -0.6 | -2.4 | -2.2 | 2.11 | -2.086 | 2.353 | no difference |

**Table I-12. Statistical Analysis of the Deformation Uniformity Data**

| | | Deformation Uniformity Difference, % | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Temperature | Frequency | Dense | Dense | SMA | SMA | | Standard | Calculated | Critical | |
| C | Hz | 6 | 8 | 10 | 12 | Average | Deviation | t | t | Conclusion |
| 4 | 0.1 | -16.2 | -3.7 | 9.0 | 0.3 | -2.6 | 10.48 | -0.502 | 2.353 | no difference |
| 4 | 1 | -13.4 | -8.7 | 7.3 | -1.1 | -4.0 | 9.08 | -0.871 | 2.353 | no difference |
| 4 | 10 | -13.8 | -11.2 | 5.3 | -2.8 | -5.6 | 8.66 | -1.301 | 2.353 | no difference |
| 20 | 0.1 | -6.3 | -6.8 | 13.3 | 10.9 | 2.8 | 10.81 | 0.516 | 2.353 | no difference |
| 20 | 1 | -8.7 | -9.5 | 12.5 | 15.4 | 2.4 | 13.38 | 0.366 | 2.353 | no difference |
| 20 | 10 | -3.1 | -14.3 | 11.4 | 15.0 | 2.2 | 13.52 | 0.332 | 2.353 | no difference |
| 40 | 0.01 | 20.7 | -15.9 | 24.4 | -29.8 | -0.1 | 26.86 | -0.010 | 2.353 | no difference |
| 40 | 0.1 | 17.0 | -8.1 | 18.1 | -27.0 | 0.0 | 21.70 | 0.000 | 2.353 | no difference |
| 40 | 1 | -0.6 | 6.0 | 6.2 | -16.6 | -1.2 | 10.70 | -0.228 | 2.353 | no difference |
| 40 | 10 | 1.2 | 4.1 | 4.4 | -9.8 | 0.0 | 6.67 | -0.003 | 2.353 | no difference |

**Table I-13. Statistical Analysis of the Phase Uniformity Data**

| | | Phase Uniformity Difference, % | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Temperature | Frequency | Dense | Dense | SMA | SMA | | Standard | Calculated | Critical | |
| C | Hz | 6 | 8 | 10 | 12 | Average | Deviation | t | t | Conclusion |
| 4 | 0.1 | -0.1 | -0.3 | 1.0 | -0.6 | 0.0 | 0.69 | 0.043 | 2.353 | no difference |
| 4 | 1 | 0.1 | 0.6 | 1.5 | -0.2 | 0.5 | 0.75 | 1.378 | 2.353 | no difference |
| 4 | 10 | 0.2 | 0.5 | 1.2 | 0.3 | 0.5 | 0.44 | 2.382 | 2.353 | 70 mm > 100 mm |
| 20 | 0.1 | 6.5 | -0.9 | -3.4 | 1.4 | 0.9 | 4.20 | 0.435 | 2.353 | no difference |
| 20 | 1 | 2.5 | 1.2 | -1.4 | 0.8 | 0.8 | 1.64 | 0.949 | 2.353 | no difference |
| 20 | 10 | 1.1 | 1.1 | 0.1 | 0.0 | 0.6 | 0.60 | 1.967 | 2.353 | no difference |
| 40 | 0.01 | 5.9 | -7.7 | 7.5 | -0.5 | 1.3 | 6.95 | 0.373 | 2.353 | no difference |
| 40 | 0.1 | 11.0 | -10.5 | 9.2 | -1.3 | 2.1 | 10.01 | 0.422 | 2.353 | no difference |
| 40 | 1 | 12.1 | -9.8 | 10.2 | 0.1 | 3.1 | 10.11 | 0.621 | 2.353 | no difference |
| 40 | 10 | 6.2 | -2.8 | 7.5 | 0.5 | 2.9 | 4.84 | 1.182 | 2.353 | no difference |

### *I-5.3 Master Curves*

To demonstrate the effect of gauge length on the input data to the MEPDG, master curves were developed using the average data from each specimen. These data are summarized in Tables I-

14 and I-15 for the dense graded and SMA mixtures, respectively. The master curves were fitted using the approach recommended for use with the SPT (*4*). In this approach, the limiting maximum modulus for the master curve is estimated from a limiting binder modulus of 1 GPa and the volumetric properties of the mixture. The master curve is then given by Equation I-1.

$$\log(E^*) = \log\delta + \frac{(\log Max - \log\delta)}{1 + e^{\beta+\gamma\omega_r}} \quad \text{(I-1)}$$

Where:

E* = dynamic modulus
$\omega_r$ = reduced frequency, Hz
*Max* = limiting maximum modulus
$\delta$, $\beta$, $\gamma$ = fitting parameters

The Arrhenius equation can be used to compute the reduced frequency:

$$\log\omega_r = \log(\omega) + \frac{\Delta E_a}{19.14714}\left[\left(\frac{1}{T}\right) - \left(\frac{1}{T_r}\right)\right] \quad \text{(I-2)}$$

Where:

$\omega_r$ = reduced frequency, Hz
$\omega$ = test frequency, Hz
$T_r$ = reference temperature, °K
T = test temperature, °K
$\Delta E_a$ = activation energy

Substituting equation I-2 into equation I-1 and using a reference temperature of 20 °C, yields Equation I-3 for the master curve. Equation I-3 can be solved for the four fitting parameters using non-linear least squares. A Microsoft EXCEL spreadsheet for performing the fitting was developed in NCHRP Project 9-29 (*4*).

$$\log(E^*) = \log\delta + \frac{\left(\log Max - \log\delta\right)}{1 + e^{\beta+\gamma\left\{\log(\omega)+\frac{\Delta E_a}{19.14714}\left[\left(\frac{1}{T}\right)-\left(\frac{1}{295.25}\right)\right]\right\}}} \quad \text{(I-3)}$$

Where:

E* = dynamic modulus
*Max* = limiting maximum modulus
$\omega$ = test frequency, Hz
$\delta$, $\beta$, $\gamma$ and $\Delta E_a$ = fitting parameters

Tables I-14 and I-15 summarize the dynamic modulus data needed for the development of master curves for the dense graded and SMA mixtures, respectively. Master curves of the form of equation I-3 were developed for the four combinations of mixture and gauge length. The resulting master curve parameters are summarized in Table I-16.

**Table I-14. Dynamic Modulus Data for Master Curve Construction for the Dense Graded Mixture**

| Gauge | | | Specimen 6 | | Specimen 8 | | Average | | Standard Deviation | | Coefficient of Variation | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Length | Temp | Freq | Modulus | Phase | Modulus | Phase | Modulus | Phase | Modulus | Phase | Modulus | Phase |
| mm | C | Hz | MPa | Degree | MPa | Degree | MPa | Degree | MPa | Degree | Percent | Percent |
| 100 | 4 | 0.1 | 5683.9 | 22.8 | 5160.7 | 22.5 | 5422.3 | 22.7 | 370.0 | 0.2 | 6.8 | 1.1 |
| | 4 | 1 | 8988.7 | 15.8 | 8370.6 | 15.8 | 8679.6 | 15.8 | 437.1 | 0.0 | 5.0 | 0.2 |
| | 4 | 10 | 12701.5 | 11.1 | 11661.4 | 12.0 | 12181.5 | 11.5 | 735.5 | 0.6 | 6.0 | 5.4 |
| | 20 | 0.1 | 1042.1 | 33.2 | 993.3 | 32.7 | 1017.7 | 32.9 | 34.5 | 0.4 | 3.4 | 1.2 |
| | 20 | 1 | 2648.1 | 28.4 | 2484.1 | 28.1 | 2566.1 | 28.3 | 116.0 | 0.2 | 4.5 | 0.8 |
| | 20 | 10 | 5229.0 | 23.4 | 5086.1 | 22.7 | 5157.6 | 23.0 | 101.0 | 0.5 | 2.0 | 2.2 |
| | 40 | 0.01 | 71.6 | 19.5 | 71.2 | 20.8 | 71.4 | 20.1 | 0.3 | 0.9 | 0.4 | 4.6 |
| | 40 | 0.1 | 121.4 | 27.8 | 130.9 | 27.9 | 126.2 | 27.8 | 6.7 | 0.1 | 5.3 | 0.3 |
| | 40 | 1 | 282.5 | 33.3 | 332.8 | 33.8 | 307.7 | 33.5 | 35.6 | 0.4 | 11.6 | 1.2 |
| | 40 | 10 | 868.7 | 35.3 | 989.1 | 33.3 | 928.9 | 34.3 | 85.2 | 1.4 | 9.2 | 4.0 |
| 70 | 4 | 0.1 | 5482.2 | 22.6 | 6008.4 | 22.7 | 5745.3 | 22.7 | 372.1 | 0.0 | 6.5 | 0.2 |
| | 4 | 1 | 8637.5 | 15.9 | 9472.1 | 15.7 | 9054.8 | 15.8 | 590.2 | 0.2 | 6.5 | 1.0 |
| | 4 | 10 | 12049.7 | 11.5 | 13303.4 | 11.1 | 12676.6 | 11.3 | 886.5 | 0.3 | 7.0 | 2.3 |
| | 20 | 0.1 | 1136.1 | 35.6 | 1179.5 | 33.5 | 1157.8 | 34.5 | 30.7 | 1.5 | 2.7 | 4.3 |
| | 20 | 1 | 2788.3 | 29.0 | 2884.1 | 29.3 | 2836.2 | 29.1 | 67.7 | 0.2 | 2.4 | 0.8 |
| | 20 | 10 | 5492.4 | 23.0 | 5761.9 | 22.3 | 5627.1 | 22.6 | 190.5 | 0.5 | 3.4 | 2.4 |
| | 40 | 0.01 | 59.6 | 23.9 | 77.6 | 21.7 | 68.6 | 22.8 | 12.7 | 1.5 | 18.6 | 6.7 |
| | 40 | 0.1 | 115.8 | 32.7 | 141.4 | 29.0 | 128.6 | 30.8 | 18.1 | 2.6 | 14.1 | 8.3 |
| | 40 | 1 | 330.8 | 38.1 | 360.0 | 34.1 | 345.4 | 36.1 | 20.6 | 2.8 | 6.0 | 7.8 |
| | 40 | 10 | 1056.5 | 37.0 | 1124.1 | 34.5 | 1090.3 | 35.8 | 47.8 | 1.7 | 4.4 | 4.8 |

The master curves are compared graphically in Figure I-7. This figure shows the master curve for each gauge length for both mixtures. The error bars shown in Figure I-7 are 95 percent confidence intervals based on an overall pooled coefficient of variation of 8.7 percent for the data in Tables I-14 and I-15. This coefficient of variation is somewhat smaller than previously reported values of 13.0 percent (*4*). Figure I-7 shows the 95 percent confidence intervals for the 100 mm master curves contain the 70 mm master curve indicating the master curves are the same considering the variability in the test data. Over the range of the measured data, the 70 mm master curves are slightly stiffer, but the difference is not significant based on the confidence intervals.

## I-6 Repeated Load Permanent Deformation Study

### *I-6.1 Testing*

The repeated load permanent deformation study was designed to investigate differences in the permanent strain response measured by the movement of the actuator and from gauge points glued to the specimen with a 100 mm gauge length over the middle of the specimen. For each specimen tested, data was simultaneously collected from the actuator LVDT and two miniature-loose core LVDTs mounted 180 degrees apart on the specimen. Miniature-loose core LVDTs were used after it was determined that there was substantial creep in the gauge points, approximately 0.5 percent strain, when spring loaded LVDTs were used at the test temperature.

**Table I-15. Dynamic Modulus Data for Master Curve Construction for the SMA Mixture**

| Gauge | | | Specimen 10 | | Specimen 12 | | Average | | Standard Deviation | | Coefficient of Variation | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Length | Temp | Freq | Modulus | Phase | Modulus | Phase | Modulus | Phase | Modulus | Phase | Modulus | Phase |
| mm | C | Hz | MPa | Degree | MPa | Degree | MPa | Degree | MPa | Degree | Percent | Percent |
| 100 | 4 | 0.1 | 6452.2 | 20.7 | 5081.4 | 21.0 | 5766.8 | 20.9 | 969.3 | 0.2 | 16.8 | 1.0 |
| | 4 | 1 | 9840.0 | 15.2 | 7933.0 | 15.4 | 8886.5 | 15.3 | 1348.5 | 0.2 | 15.2 | 1.3 |
| | 4 | 10 | 13879.3 | 11.3 | 10913.5 | 11.6 | 12396.4 | 11.5 | 2097.2 | 0.2 | 16.9 | 2.0 |
| | 20 | 0.1 | 1452.0 | 29.1 | 1183.2 | 29.5 | 1317.6 | 29.3 | 190.1 | 0.3 | 14.4 | 1.0 |
| | 20 | 1 | 3085.0 | 25.5 | 2610.7 | 26.0 | 2847.8 | 25.7 | 335.4 | 0.3 | 11.8 | 1.3 |
| | 20 | 10 | 5633.2 | 21.9 | 4953.4 | 22.3 | 5293.3 | 22.1 | 480.7 | 0.3 | 9.1 | 1.5 |
| | 40 | 0.01 | 173.1 | 20.5 | 157.9 | 19.8 | 165.5 | 20.1 | 10.8 | 0.5 | 6.5 | 2.5 |
| | 40 | 0.1 | 272.8 | 24.6 | 246.4 | 24.1 | 259.6 | 24.3 | 18.6 | 0.4 | 7.2 | 1.5 |
| | 40 | 1 | 588.6 | 26.7 | 510.6 | 26.2 | 549.6 | 26.5 | 55.2 | 0.3 | 10.0 | 1.2 |
| | 40 | 10 | 1382.8 | 28.4 | 1183.7 | 27.9 | 1283.2 | 28.1 | 140.8 | 0.3 | 11.0 | 1.2 |
| 70 | 4 | 0.1 | 5518.1 | 20.8 | 6035.6 | 19.9 | 5776.8 | 20.4 | 365.9 | 0.6 | 6.3 | 3.2 |
| | 4 | 1 | 8482.6 | 15.0 | 9168.2 | 14.8 | 8825.4 | 14.9 | 484.8 | 0.2 | 5.5 | 1.0 |
| | 4 | 10 | 11530.3 | 10.9 | 12330.5 | 11.5 | 11930.4 | 11.2 | 565.8 | 0.4 | 4.7 | 3.7 |
| | 20 | 0.1 | 1453.9 | 29.6 | 1570.3 | 28.2 | 1512.1 | 28.9 | 82.4 | 1.0 | 5.4 | 3.3 |
| | 20 | 1 | 3015.1 | 25.3 | 3275.0 | 24.7 | 3145.0 | 25.0 | 183.8 | 0.4 | 5.8 | 1.7 |
| | 20 | 10 | 5434.2 | 21.0 | 5894.2 | 20.7 | 5664.2 | 20.8 | 325.3 | 0.2 | 5.7 | 0.8 |
| | 40 | 0.01 | 160.8 | 21.5 | 179.9 | 20.8 | 170.3 | 21.1 | 13.5 | 0.5 | 7.9 | 2.3 |
| | 40 | 0.1 | 271.3 | 25.3 | 300.6 | 24.3 | 286.0 | 24.8 | 20.7 | 0.7 | 7.2 | 3.0 |
| | 40 | 1 | 585.0 | 28.7 | 631.6 | 26.9 | 608.3 | 27.8 | 33.0 | 1.3 | 5.4 | 4.6 |
| | 40 | 10 | 1396.0 | 28.3 | 1450.1 | 27.0 | 1423.1 | 27.7 | 38.3 | 0.9 | 2.7 | 3.3 |

**Table I-16. Summary of Master Curve Parameters for Reference Temperature of 20 °C**

| | Dense | | SMA 100 | |
|---|---|---|---|---|
| Parameter | 100 mm | 70 mm | 100 mm | 70 mm |
| Max, MPa | 23184.7 | 23184.7 | 22302.1 | 22302.1 |
| Delta, MPa | 17.6 | 13.3 | 58.2 | 43.0 |
| Beta | -0.8052 | -0.9324 | -0.6543 | -0.7843 |
| Gamma | -0.5451 | -0.5452 | -0.5400 | -0.5020 |
| EA | 191179.1 | 186978.7 | 188221.6 | 188660.2 |

The actuator movement was converted to strain by dividing by the specimen length. The data from the specimen mounted LVDTs was converted to strain by dividing by the gauge length of 100 mm. Three specimens for each mixture were tested unconfined at a temperature of 50 °C using an axial stress of 145 kPa. The load pulse had a duration of 0.1 sec with a dell time of 0.9 sec. Greased latex membranes were used as end friction reducers based on the findings of the NCHRP Project 9-29 ruggedness study for the repeated load permanent deformation test (*10*). The tests were carried out to 10,000 cycles unless flow occurred before 10,000 cycles.

Appendix I-B documents the complete permanent strain history for each sample from both types of measurements. Tables I-17 and I-18 present excerpts of the data at selected number of cycles to demonstrate the statistical analysis discussed in the next section. These tables include the measured permanent strains for each sample, averages for each mixture, and the flow number for the dense graded mixture. Flow did not occur in the SMA mixture for the conditions tested.

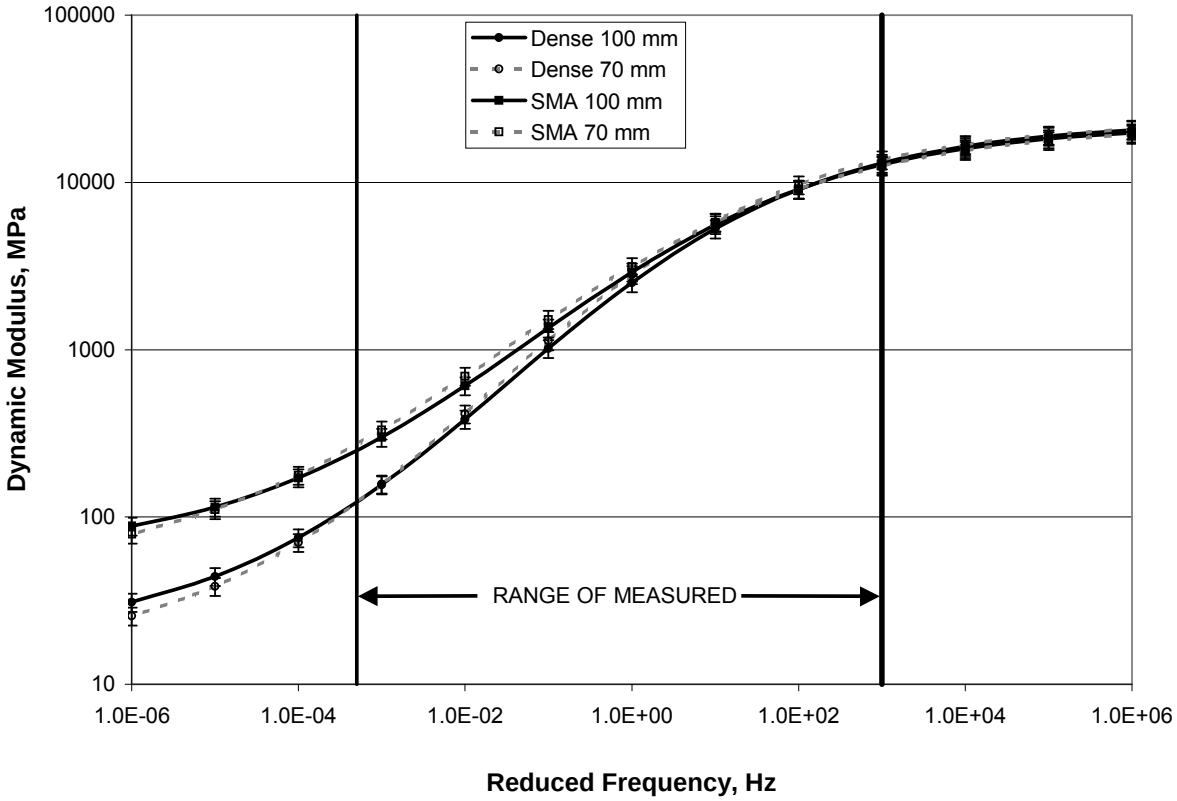


**Figure I-7. Comparison of Master Curves at Reference Temperature of 20 °C**

### *I-6.2 Statistical Analysis*

The permanent deformation experiment was also designed as a paired difference experiment. For each sample, permanent strains were measured using the actuator displacement and the deformation measured over a 100 mm gauge length. This data was analyzed using the paired difference t-test a described previously for the dynamic modulus experiment. For the data collected in the permanent deformation experiment, three paired differences can be computed for each mixture for each loading cycle. For the dense graded mixture the paired differences can also be computed for the flow number. For n=3 tests, the critical value of the t statistic for a level of significance of 5 percent is 2.920.

Tables I-19 and I-20 summarize results of the statistical analysis for the permanent deformation experiment for the HMA dense graded and SMA mixtures, respectively. These tables clearly show that the permanent strain from the actuator displacement was higher for all samples tested. This difference is likely due to the air void distribution in the samples. As discussed for the dynamic modulus test, air voids are highest near the ends of gyratory compacted specimens. Therefore, greater permanent deformation occurs near the ends of the test specimens, resulting in larger permanent strains when the actuator displacement is used to compute the permanent strain. The difference was statistically significant for the early load cycles for the dense graded mixture and for all of the load cycles for the SMA mixture. The difference was not significant after

about 800 load cycles for the dense graded mixture. A similar analysis for the flow number for the dense graded mixture concluded the flow number was not significantly different when determined using the actuator displacement or the specimen mounted instrumentation.

The paired difference analysis removes the effect of sample to sample variation from the analysis which as shown in Tables I-17 and I-18 can be relatively large in the permanent deformation test. The data from the experiment can also be analyzed as the difference between two population means: permanent strain from the actuator displacement compared to permanent strain over a 100 mm gauge length. This analysis includes the effect of sample to sample variations. In this case, the appropriate statistical test the t-test which is summarized below (*11*):

**Table I-17. Permanent Deformation Data at Selected Load Cycles for the Dense Graded Mixture**

| | Permanent Strain from Actuator Displacement, % | | | | | | Permanent Strain from 100 mm Gauge Points, % | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Coefficient | | | | | | Coefficient |
| Load | Specimen | Specimen | Specimen | Average | Standard | of | Specimen | Specimen | Specimen | Average | Standard | of |
| Cycle | 1 | 2 | 3 | | Deviation | Variation | 1 | 2 | 3 | | Deviation | Variation |
| 0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.000 | NA | 0.00 | 0.00 | 0.00 | 0.00 | 0.000 | NA |
| 30 | 0.06 | 0.06 | 0.06 | 0.06 | 0.003 | 4.5 | 0.06 | 0.04 | 0.05 | 0.05 | 0.008 | 15.5 |
| 60 | 0.11 | 0.10 | 0.11 | 0.11 | 0.006 | 5.4 | 0.10 | 0.07 | 0.09 | 0.08 | 0.014 | 16.1 |
| 90 | 0.14 | 0.13 | 0.15 | 0.14 | 0.010 | 7.1 | 0.13 | 0.09 | 0.12 | 0.11 | 0.019 | 16.9 |
| 120 | 0.17 | 0.15 | 0.18 | 0.17 | 0.013 | 7.5 | 0.15 | 0.11 | 0.14 | 0.14 | 0.022 | 16.1 |
| 150 | 0.19 | 0.18 | 0.20 | 0.19 | 0.013 | 6.5 | 0.18 | 0.13 | 0.17 | 0.16 | 0.027 | 16.6 |
| 180 | 0.22 | 0.20 | 0.23 | 0.22 | 0.015 | 7.1 | 0.20 | 0.15 | 0.19 | 0.18 | 0.029 | 16.2 |
| 210 | 0.24 | 0.22 | 0.25 | 0.24 | 0.015 | 6.5 | 0.22 | 0.16 | 0.20 | 0.20 | 0.031 | 15.8 |
| 300 | 0.29 | 0.26 | 0.30 | 0.28 | 0.018 | 6.3 | 0.27 | 0.20 | 0.25 | 0.24 | 0.037 | 15.5 |
| 600 | 0.41 | 0.38 | 0.43 | 0.41 | 0.028 | 6.8 | 0.39 | 0.29 | 0.38 | 0.35 | 0.052 | 14.8 |
| 900 | 0.51 | 0.46 | 0.53 | 0.50 | 0.033 | 6.6 | 0.48 | 0.36 | 0.47 | 0.44 | 0.066 | 15.0 |
| 1500 | 0.66 | 0.60 | 0.69 | 0.65 | 0.048 | 7.4 | 0.63 | 0.48 | 0.64 | 0.58 | 0.090 | 15.3 |
| 2010 | 0.77 | 0.70 | 0.82 | 0.76 | 0.060 | 7.9 | 0.74 | 0.56 | 0.76 | 0.69 | 0.110 | 16.0 |
| 2520 | 0.88 | 0.80 | 0.94 | 0.87 | 0.070 | 8.1 | 0.85 | 0.64 | 0.89 | 0.79 | 0.131 | 16.5 |
| 3000 | 0.99 | 0.88 | 1.06 | 0.98 | 0.088 | 9.0 | 0.95 | 0.72 | 1.01 | 0.89 | 0.153 | 17.2 |
| 3510 | 1.10 | 0.98 | 1.18 | 1.09 | 0.103 | 9.5 | 1.05 | 0.80 | 1.14 | 1.00 | 0.178 | 17.9 |
| 4020 | 1.22 | 1.07 | 1.32 | 1.20 | 0.123 | 10.2 | 1.17 | 0.87 | 1.27 | 1.10 | 0.209 | 18.9 |
| 4500 | 1.33 | 1.16 | 1.45 | 1.31 | 0.145 | 11.0 | 1.29 | 0.94 | 1.41 | 1.21 | 0.243 | 20.0 |
| 5010 | 1.46 | 1.27 | 1.60 | 1.44 | 0.168 | 11.6 | 1.42 | 1.03 | 1.57 | 1.34 | 0.280 | 21.0 |
| 5520 | 1.59 | 1.38 | 1.77 | 1.58 | 0.195 | 12.3 | 1.56 | 1.11 | 1.73 | 1.47 | 0.321 | 21.9 |
| 6000 | 1.73 | 1.49 | 1.94 | 1.72 | 0.227 | 13.2 | 1.70 | 1.19 | 1.91 | 1.60 | 0.366 | 22.9 |
| 6510 | 1.89 | 1.62 | 2.15 | 1.89 | 0.265 | 14.0 | 1.85 | 1.29 | 2.12 | 1.75 | 0.424 | 24.2 |
| | Flow Number from Actuator Displacement | | | | | | Flow Number from 100 mm Gauge Points | | | | | |
| | | | | | | Coefficient | | | | | | Coefficient |
| | Specimen | Specimen | Specimen | Average | Standard | of | Specimen | Specimen | Specimen | Average | Standard | of |
| | 1 | 2 | 3 | | Deviation | Variation | 1 | 2 | 3 | | Deviation | Variation |
| Cycle | 2640 | 3360 | 2760 | 2920 | 385.7 | 13.2 | 2460 | 3600 | 2370 | 2810 | 685.6 | 24.4 |

## Table I-18. Permanent Deformation Data at Selected Load Cycles for the SMA Mixture

| | Permanent Strain from Actuator Displacement, % | | | | | | Permanent Strain from 100 mm Gauge Points, % | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Coefficient | | | | | | Coefficient |
| Load | Specimen | Specimen | Specimen | Average | Standard | of | Specimen | Specimen | Specimen | Average | Standard | of |
| Cycle | 1 | 2 | 3 | | Deviation | Variation | 1 | 2 | 3 | | Deviation | Variation |
| 0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.000 | NA | 0.00 | 0.00 | 0.00 | 0.00 | 0.000 | NA |
| 30 | 0.03 | 0.05 | 0.02 | 0.03 | 0.013 | 37.9 | 0.02 | 0.03 | 0.01 | 0.02 | 0.012 | 57.5 |
| 60 | 0.05 | 0.09 | 0.04 | 0.06 | 0.024 | 40.7 | 0.04 | 0.06 | 0.03 | 0.04 | 0.015 | 35.6 |
| 90 | 0.07 | 0.11 | 0.05 | 0.08 | 0.028 | 36.4 | 0.05 | 0.07 | 0.03 | 0.05 | 0.023 | 44.2 |
| 120 | 0.08 | 0.13 | 0.06 | 0.09 | 0.033 | 35.7 | 0.06 | 0.09 | 0.04 | 0.06 | 0.027 | 43.0 |
| 150 | 0.10 | 0.14 | 0.07 | 0.11 | 0.035 | 33.3 | 0.07 | 0.10 | 0.05 | 0.07 | 0.028 | 37.1 |
| 180 | 0.11 | 0.16 | 0.08 | 0.12 | 0.038 | 32.3 | 0.08 | 0.11 | 0.05 | 0.08 | 0.034 | 42.2 |
| 210 | 0.12 | 0.17 | 0.09 | 0.13 | 0.043 | 33.7 | 0.09 | 0.12 | 0.06 | 0.09 | 0.032 | 35.1 |
| 300 | 0.14 | 0.21 | 0.11 | 0.15 | 0.051 | 32.8 | 0.10 | 0.15 | 0.08 | 0.11 | 0.033 | 29.5 |
| 600 | 0.20 | 0.27 | 0.16 | 0.21 | 0.058 | 27.6 | 0.15 | 0.20 | 0.13 | 0.16 | 0.041 | 25.6 |
| 900 | 0.23 | 0.32 | 0.19 | 0.25 | 0.066 | 26.6 | 0.17 | 0.24 | 0.15 | 0.19 | 0.046 | 24.3 |
| 1500 | 0.28 | 0.38 | 0.23 | 0.30 | 0.074 | 24.9 | 0.21 | 0.29 | 0.19 | 0.23 | 0.052 | 22.6 |
| 2010 | 0.30 | 0.41 | 0.26 | 0.33 | 0.078 | 23.7 | 0.23 | 0.32 | 0.21 | 0.25 | 0.056 | 21.8 |
| 2520 | 0.32 | 0.44 | 0.29 | 0.35 | 0.081 | 23.0 | 0.25 | 0.34 | 0.23 | 0.28 | 0.059 | 21.5 |
| 3000 | 0.34 | 0.46 | 0.31 | 0.37 | 0.081 | 21.8 | 0.27 | 0.36 | 0.25 | 0.29 | 0.061 | 20.7 |
| 3570 | 0.36 | 0.49 | 0.33 | 0.39 | 0.084 | 21.3 | 0.28 | 0.38 | 0.27 | 0.31 | 0.062 | 19.9 |
| 4080 | 0.37 | 0.51 | 0.35 | 0.41 | 0.086 | 20.9 | 0.29 | 0.40 | 0.28 | 0.33 | 0.064 | 19.7 |
| 4560 | 0.39 | 0.52 | 0.36 | 0.42 | 0.088 | 20.7 | 0.30 | 0.41 | 0.30 | 0.34 | 0.065 | 19.2 |
| 5070 | 0.40 | 0.54 | 0.37 | 0.44 | 0.089 | 20.3 | 0.32 | 0.43 | 0.31 | 0.35 | 0.065 | 18.3 |
| 5580 | 0.41 | 0.55 | 0.39 | 0.45 | 0.090 | 19.9 | 0.32 | 0.44 | 0.33 | 0.36 | 0.066 | 18.2 |
| 6060 | 0.42 | 0.57 | 0.40 | 0.46 | 0.093 | 20.1 | 0.33 | 0.45 | 0.34 | 0.37 | 0.066 | 17.6 |
| 6570 | 0.42 | 0.58 | 0.41 | 0.47 | 0.092 | 19.6 | 0.34 | 0.46 | 0.35 | 0.39 | 0.066 | 17.1 |
| 7020 | 0.43 | 0.59 | 0.42 | 0.48 | 0.097 | 20.0 | 0.35 | 0.47 | 0.36 | 0.39 | 0.067 | 17.0 |
| 7500 | 0.44 | 0.60 | 0.43 | 0.49 | 0.097 | 19.6 | 0.36 | 0.48 | 0.37 | 0.40 | 0.068 | 16.9 |
| 8010 | 0.44 | 0.61 | 0.44 | 0.50 | 0.098 | 19.6 | 0.36 | 0.49 | 0.38 | 0.41 | 0.070 | 16.9 |
| 8520 | 0.45 | 0.63 | 0.46 | 0.51 | 0.100 | 19.4 | 0.37 | 0.50 | 0.39 | 0.42 | 0.072 | 16.9 |
| 9090 | 0.46 | 0.64 | 0.47 | 0.52 | 0.101 | 19.3 | 0.38 | 0.52 | 0.41 | 0.43 | 0.073 | 16.8 |
| 9510 | 0.46 | 0.65 | 0.48 | 0.53 | 0.103 | 19.3 | 0.38 | 0.52 | 0.42 | 0.44 | 0.073 | 16.6 |
| 10020 | 0.47 | 0.66 | 0.49 | 0.54 | 0.103 | 19.0 | 0.39 | 0.53 | 0.42 | 0.45 | 0.074 | 16.5 |

## Table I-19. Statistical Analysis of the Permanent Strain and Flow Number Data for the Dense Graded Mixture

| | Permanent Strain Difference, % | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Load | Specimen | Specimen | Specimen | Average | Standard | t | tcr | Conclusion |
| Cycle | 1 | 2 | 3 | | Deviation | | | |
| 0 | 0 | 0 | 0 | 0 | 0 | NA | NA | NA |
| 30 | 0.01 | 0.02 | 0.01 | 0.01 | 0.005 | 4.841 | 2.920 | Actuator > 100 mm |
| 60 | 0.01 | 0.03 | 0.02 | 0.02 | 0.008 | 4.600 | 2.920 | Actuator > 100 mm |
| 90 | 0.01 | 0.04 | 0.03 | 0.03 | 0.015 | 3.102 | 2.920 | Actuator > 100 mm |
| 120 | 0.01 | 0.04 | 0.04 | 0.03 | 0.015 | 3.709 | 2.920 | Actuator > 100 mm |
| 150 | 0.01 | 0.05 | 0.04 | 0.03 | 0.019 | 3.059 | 2.920 | Actuator > 100 mm |
| 180 | 0.02 | 0.05 | 0.04 | 0.04 | 0.019 | 3.489 | 2.920 | Actuator > 100 mm |
| 210 | 0.02 | 0.06 | 0.04 | 0.04 | 0.021 | 3.382 | 2.920 | Actuator > 100 mm |
| 300 | 0.02 | 0.07 | 0.04 | 0.04 | 0.023 | 3.308 | 2.920 | Actuator > 100 mm |
| 600 | 0.02 | 0.09 | 0.06 | 0.06 | 0.031 | 3.080 | 2.920 | Actuator > 100 mm |
| 900 | 0.03 | 0.10 | 0.06 | 0.06 | 0.037 | 2.788 | 2.920 | No Difference |
| 1500 | 0.02 | 0.12 | 0.06 | 0.07 | 0.048 | 2.392 | 2.920 | No Difference |
| 2010 | 0.03 | 0.14 | 0.05 | 0.07 | 0.055 | 2.279 | 2.920 | No Difference |
| 2520 | 0.04 | 0.15 | 0.05 | 0.08 | 0.065 | 2.119 | 2.920 | No Difference |
| 3000 | 0.04 | 0.17 | 0.05 | 0.09 | 0.069 | 2.140 | 2.920 | No Difference |
| 3510 | 0.05 | 0.18 | 0.04 | 0.09 | 0.079 | 1.989 | 2.920 | No Difference |
| 4020 | 0.05 | 0.20 | 0.04 | 0.10 | 0.090 | 1.878 | 2.920 | No Difference |
| 4500 | 0.04 | 0.22 | 0.04 | 0.10 | 0.103 | 1.680 | 2.920 | No Difference |
| 5010 | 0.04 | 0.24 | 0.03 | 0.11 | 0.119 | 1.531 | 2.920 | No Difference |
| 5520 | 0.03 | 0.27 | 0.03 | 0.11 | 0.134 | 1.438 | 2.920 | No Difference |
| 6000 | 0.04 | 0.29 | 0.04 | 0.12 | 0.149 | 1.422 | 2.920 | No Difference |
| 6510 | 0.04 | 0.33 | 0.03 | 0.13 | 0.170 | 1.360 | 2.920 | No Difference |
| | | | | | | | | |
| | Flow Number Difference, Cycles | | | | | | | |
| | Specimen | Specimen | Specimen | Average | Standard | t | tcr | Conclusion |
| | 1 | 2 | 3 | | Deviation | | | |
| | 180.00 | -240.00 | 390.00 | 110.00 | 320.780 | 0.594 | 2.920 | No Difference |

**Table I-20. Statistical Analysis of the Permanent Strain Data for the SMA Mixture**

| | Permanent Strain Difference, % | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Load | Specimen | Specimen | Specimen | Average | Standard | t | tcr | Conclusion |
| Cycle | 1 | 2 | 3 | | Deviation | | | |
| 0 | 0 | 0 | 0 | 0 | 0 | NA | NA | NA |
| 30 | 0.01 | 0.02 | 0.02 | 0.01 | 0.005 | 5.393 | 2.920 | Actuator > 100 mm |
| 60 | 0.01 | 0.03 | 0.01 | 0.02 | 0.011 | 2.577 | 2.920 | Actuator > 100 mm |
| 90 | 0.02 | 0.04 | 0.03 | 0.03 | 0.008 | 5.705 | 2.920 | Actuator > 100 mm |
| 120 | 0.02 | 0.04 | 0.03 | 0.03 | 0.008 | 6.512 | 2.920 | Actuator > 100 mm |
| 150 | 0.03 | 0.04 | 0.03 | 0.03 | 0.008 | 6.918 | 2.920 | Actuator > 100 mm |
| 180 | 0.03 | 0.05 | 0.04 | 0.04 | 0.006 | 10.362 | 2.920 | Actuator > 100 mm |
| 210 | 0.03 | 0.05 | 0.03 | 0.04 | 0.012 | 5.661 | 2.920 | Actuator > 100 mm |
| 300 | 0.04 | 0.06 | 0.03 | 0.04 | 0.018 | 4.135 | 2.920 | Actuator > 100 mm |
| 600 | 0.05 | 0.07 | 0.03 | 0.05 | 0.018 | 5.047 | 2.920 | Actuator > 100 mm |
| 900 | 0.06 | 0.08 | 0.04 | 0.06 | 0.021 | 4.891 | 2.920 | Actuator > 100 mm |
| 1500 | 0.07 | 0.09 | 0.04 | 0.07 | 0.023 | 5.086 | 2.920 | Actuator > 100 mm |
| 2010 | 0.07 | 0.10 | 0.05 | 0.07 | 0.023 | 5.574 | 2.920 | Actuator > 100 mm |
| 2520 | 0.07 | 0.10 | 0.06 | 0.08 | 0.022 | 5.873 | 2.920 | Actuator > 100 mm |
| 3000 | 0.08 | 0.10 | 0.06 | 0.08 | 0.021 | 6.429 | 2.920 | Actuator > 100 mm |
| 3570 | 0.08 | 0.11 | 0.06 | 0.08 | 0.024 | 6.133 | 2.920 | Actuator > 100 mm |
| 4080 | 0.08 | 0.11 | 0.07 | 0.09 | 0.022 | 6.631 | 2.920 | Actuator > 100 mm |
| 4560 | 0.08 | 0.11 | 0.06 | 0.08 | 0.025 | 5.940 | 2.920 | Actuator > 100 mm |
| 5070 | 0.08 | 0.11 | 0.06 | 0.09 | 0.026 | 5.648 | 2.920 | Actuator > 100 mm |
| 5580 | 0.08 | 0.11 | 0.06 | 0.09 | 0.026 | 5.894 | 2.920 | Actuator > 100 mm |
| 6060 | 0.08 | 0.12 | 0.06 | 0.09 | 0.029 | 5.308 | 2.920 | Actuator > 100 mm |
| 6570 | 0.08 | 0.12 | 0.06 | 0.09 | 0.028 | 5.412 | 2.920 | Actuator > 100 mm |
| 7020 | 0.08 | 0.12 | 0.06 | 0.09 | 0.031 | 4.971 | 2.920 | Actuator > 100 mm |
| 7500 | 0.08 | 0.12 | 0.06 | 0.09 | 0.031 | 5.049 | 2.920 | Actuator > 100 mm |
| 8010 | 0.08 | 0.12 | 0.06 | 0.09 | 0.030 | 4.947 | 2.920 | Actuator > 100 mm |
| 8520 | 0.08 | 0.12 | 0.06 | 0.09 | 0.031 | 5.135 | 2.920 | Actuator > 100 mm |
| 9090 | 0.08 | 0.12 | 0.06 | 0.09 | 0.031 | 4.961 | 2.920 | Actuator > 100 mm |
| 9510 | 0.08 | 0.13 | 0.06 | 0.09 | 0.032 | 4.884 | 2.920 | Actuator > 100 mm |
| 10020 | 0.08 | 0.13 | 0.06 | 0.09 | 0.032 | 4.996 | 2.920 | Actuator > 100 mm |

Null Hypothesis: $\mu_{actuator} = \mu_{100}$

Alternative Hypothesis: $\mu_{actuator} > \mu_{100}$

Test Statistic: $$t = \frac{(\bar{y}_{actuator} - \bar{y}_{100})}{s\left[\left(\frac{1}{n_{actuator}}\right) + \left(\frac{1}{n_{100}}\right)\right]^{0.5}}$$

Rejection Region: Reject $H_o$ if $t > t_\alpha$ for $n_{actuator} + n_{100} - 2$ degrees of freedom.

Where:

$\mu_{actuator}$ = population mean for permanent strain from the actuator displacement
$\mu_{100}$ = population mean for permanent strain from 100 mm gauge length

$\bar{y}_{actuator}$ = sample mean for permanent strain from the actuator displacement

$\bar{y}_{100}$ = sample mean for permanent strain from 100 mm gauge length

$$s = \text{pooled standard deviation} = \left[ \frac{(n_{actuator} - 1)s_{actuator}^{\ 2} + (n_{100} - 1)s_{100}^{\ 2}}{n_{actuator} + n_{100} - 2} \right]^{0.5}$$

$s_{actuator}$ = sample standard deviation for permanent strain from the actuator displacement

$s_{100}$ = sample standard deviation for permanent strain from 100 mm gauge length

$n_{actuator}$ = number of samples for permanent strain from the actuator displacement

$n_{100}$ = number of samples for permanent strain for 100 mm gauge length

$\alpha$ = level of significance (typically 5 percent)

Tables I-21 and I-22 summarize results of this analysis for the HMA dense graded and SMA mixtures, respectively. For 4 degrees of freedom, the critical value of the t statistic for a level of significance of 5 percent is 2.132. The primary conclusion from this analysis is there is no significant difference in the permanent strains from the two measurements when the sample variability is considered except for the early portion of the test for the dense graded mixture. This portion of the data is usually not used in fitting permanent strain models of the form included in the MEPDG.

### *I-6.3 Permanent Strain Curves*

Figure I-8 presents permanent strain curves for the two mixtures. This figure includes the average permanent strain curves from both the specimen mounted instrumentation and the actuator displacement. It also includes 95 percent confidence intervals for the average permanent strain curve from the specimen mounted instrumentation using the pooled standard from the previous analysis. This figure shows that the permanent strain from the actuator displacement is larger than that obtained from the specimen mounted deformation measurements. However, the average from the actuator displacements is generally within the 95 percent confidence intervals for the specimen mounted data. This implies that data from tests on independent samples comparing the permanent strain from the actuator displacement with the permanent strain from the specimen mounted instrumented would not be significantly different.

## I-7 Summary and Conclusions

Paired difference experiments were conducted to evaluate the instrumentation used in the SPT for dynamic modulus and permanent deformation testing. The dynamic modulus experiment compared the 70 mm gauge length used in the SPT with the 100 mm gauge length specified in AASHTP TP62. The permanent deformation experiment compared permanent strains computed from the actuator displacement as used in the SPT with permanent strains from specimen mounted instrumentation with a 100 mm gauge length as specified in Appendix B of NCHRP Report #467. Two mixtures, a dense graded 12.5 mm Superpave and SMA, were used in both experiments.

**Table I-21. Statistical Analysis of the Permanent Strain Data for the Dense Graded Mixture Including Sample Variability**

| | Permanent Strain Analysis | | | | |
|---|---|---|---|---|---|
| Load | actuator-100 mm | | | | |
| Cycle | % | s | t | tcr | Conclusion |
| 0 | 0.00 | 0.000 | NA | | |
| 30 | 0.01 | 0.006 | 2.951 | 2.132 | Actuator > 100 mm |
| 60 | 0.02 | 0.010 | 2.609 | 2.132 | Actuator > 100 mm |
| 90 | 0.03 | 0.015 | 2.130 | 2.132 | Actuator > 100 mm |
| 120 | 0.03 | 0.018 | 2.132 | 2.132 | Actuator > 100 mm |
| 150 | 0.03 | 0.021 | 1.989 | 2.132 | No Difference |
| 180 | 0.04 | 0.023 | 2.012 | 2.132 | No Difference |
| 210 | 0.04 | 0.024 | 2.013 | 2.132 | No Difference |
| 300 | 0.04 | 0.029 | 1.827 | 2.132 | No Difference |
| 600 | 0.06 | 0.042 | 1.628 | 2.132 | No Difference |
| 900 | 0.06 | 0.052 | 1.409 | 2.132 | No Difference |
| 1500 | 0.07 | 0.072 | 1.120 | 2.132 | No Difference |
| 2010 | 0.07 | 0.089 | 1.002 | 2.132 | No Difference |
| 2520 | 0.08 | 0.105 | 0.924 | 2.132 | No Difference |
| 3000 | 0.09 | 0.125 | 0.839 | 2.132 | No Difference |
| 3510 | 0.09 | 0.145 | 0.767 | 2.132 | No Difference |
| 4020 | 0.10 | 0.172 | 0.700 | 2.132 | No Difference |
| 4500 | 0.10 | 0.200 | 0.614 | 2.132 | No Difference |
| 5010 | 0.11 | 0.231 | 0.558 | 2.132 | No Difference |
| 5520 | 0.11 | 0.265 | 0.515 | 2.132 | No Difference |
| 6000 | 0.12 | 0.304 | 0.491 | 2.132 | No Difference |
| 6510 | 0.13 | 0.353 | 0.463 | 2.132 | No Difference |
| | Flow Number Analysis | | | | |
| | actuator-100 mm | | | | |
| | cycles | s | t | tcr | Conclusion |
| | 110 | 556.3 | 0.242 | 2.132 | No Difference |

The dynamic modulus experiment showed that there was no significant difference in the dynamic modulus or phase angle for 70 mm gauge length data compared to 100 mm gauge length data. Dynamic moduli were generally higher for the 70 mm gauge length, but the magnitude of the difference was not statistically significant. The higher dynamic moduli for the 70 mm gauge length were likely the result of difference in air voids over the height of the test specimens. Air voids in gyratory compacted specimens are not uniform; higher air voids are present near the specimen ends. The average air void content over the 70 mm gauge length was likely lower than that over the 100 mm gauge length. The quality of the test data as measured by the NCHRP Project 9-29 data quality indicators was also not significantly different for the two gauge lengths.

**Table I-22. Statistical Analysis of the Permanent Strain Data for the SMA Mixture Including Sample Variability**

| | Permanent Strain Analysis | | | | |
|---|---|---|---|---|---|
| Load | actuator-100 mm | | | | |
| Cycle | % | s | t | tcr | Conclusion |
| 0 | 0.00 | 0.000 | NA | | |
| 30 | 0.01 | 0.013 | 1.390 | 2.132 | No Difference |
| 60 | 0.02 | 0.020 | 1.008 | 2.132 | No Difference |
| 90 | 0.03 | 0.026 | 1.273 | 2.132 | No Difference |
| 120 | 0.03 | 0.030 | 1.228 | 2.132 | No Difference |
| 150 | 0.03 | 0.032 | 1.237 | 2.132 | No Difference |
| 180 | 0.04 | 0.036 | 1.303 | 2.132 | No Difference |
| 210 | 0.04 | 0.038 | 1.220 | 2.132 | No Difference |
| 300 | 0.04 | 0.043 | 1.197 | 2.132 | No Difference |
| 600 | 0.05 | 0.050 | 1.275 | 2.132 | No Difference |
| 900 | 0.06 | 0.057 | 1.292 | 2.132 | No Difference |
| 1500 | 0.07 | 0.064 | 1.307 | 2.132 | No Difference |
| 2010 | 0.07 | 0.067 | 1.324 | 2.132 | No Difference |
| 2520 | 0.08 | 0.071 | 1.313 | 2.132 | No Difference |
| 3000 | 0.08 | 0.072 | 1.358 | 2.132 | No Difference |
| 3570 | 0.08 | 0.074 | 1.387 | 2.132 | No Difference |
| 4080 | 0.09 | 0.076 | 1.381 | 2.132 | No Difference |
| 4560 | 0.08 | 0.077 | 1.339 | 2.132 | No Difference |
| 5070 | 0.09 | 0.078 | 1.347 | 2.132 | No Difference |
| 5580 | 0.09 | 0.079 | 1.348 | 2.132 | No Difference |
| 6060 | 0.09 | 0.081 | 1.336 | 2.132 | No Difference |
| 6570 | 0.09 | 0.080 | 1.319 | 2.132 | No Difference |
| 7020 | 0.09 | 0.083 | 1.299 | 2.132 | No Difference |
| 7500 | 0.09 | 0.084 | 1.308 | 2.132 | No Difference |
| 8010 | 0.09 | 0.085 | 1.252 | 2.132 | No Difference |
| 8520 | 0.09 | 0.087 | 1.289 | 2.132 | No Difference |
| 9090 | 0.09 | 0.088 | 1.243 | 2.132 | No Difference |
| 9510 | 0.09 | 0.089 | 1.235 | 2.132 | No Difference |
| 10020 | 0.09 | 0.089 | 1.248 | 2.132 | No Difference |

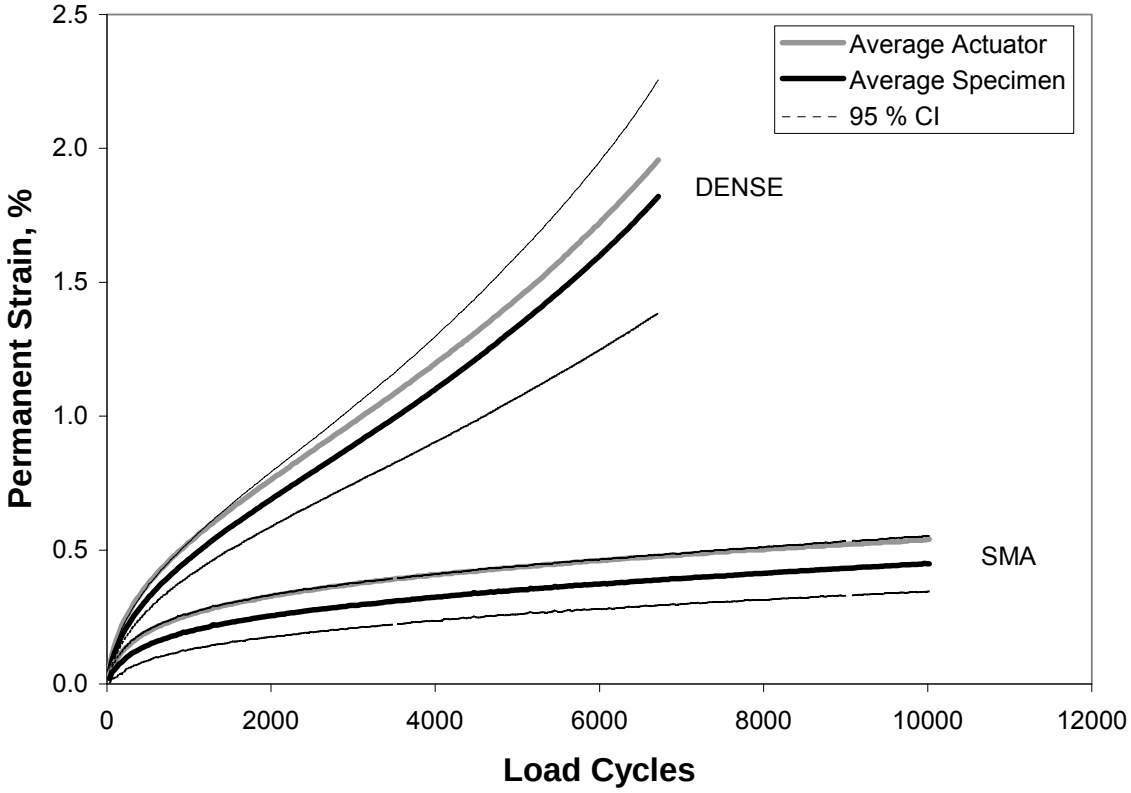


**Figure I-8. Permanent Strain Curves for the Dense Graded and SMA Mixtures**

Conclusions were not as clear for the permanent deformation experiment. The paired t-test analysis showed significant differences in the magnitude of the permanent strains early in the test for the dense graded mixture and throughout the test for the SMA mixture. The flow number for the dense graded mixture and the permanent strains during most of the testing of the dense graded mixture were not significantly different. Permanent strains computed from the actuator displacement were consistently higher than those measured over a 100 mm gauge length centered on the specimen. This effect was likely the result of the non-uniform distribution of air voids in gyratory compacted specimens. As discussed above, air voids are greatest near the ends of the specimens. The larger permanent strains from the actuator displacement were likely due to areas of higher air voids at the ends of the test specimen.

Although the paired t-test was able to detect significant differences, it is unlikely that data from separate independent samples tested using the actuator and specimen mounted instrumentation would be different. A t-test comparing mean data for strains from the actuator displacement and the specimen mounted deformations showed there was no significant difference in the permanent strain curves for both mixtures over the region normally modeled by permanent deformation models like the one included in the MEPDG. This analysis includes the effect of sample to sample variability, which is not included in the paired t-test analysis.

A very important conclusion from the permanent deformation experiment was spring loaded LVDTs cannot be used with specimen mounted instrumentation for permanent deformation testing. At the high temperatures used in permanent deformation testing, the spring force causes significant creep of the gauge points and substantial error in the resulting permanent strain measurements. Miniature, loose core LVDTs must be used to make these measurements. The installation of this instrumentation is very tedious and not acceptable for routine testing.

## I-8 Recommendations

Based on results of the dynamic modulus and permanent deformation experiments, the following recommendations are made:

1. The 70 mm gauge length used in the SPT for dynamic modulus testing is acceptable for use in NCHRP Project 9-30A. A paired t-test analysis of dynamic modulus and phase angle data found no significant difference between data collected using gauge lengths of 70 mm and 100 mm. The quality of the 70 mm gauge length data was also not significantly different than that for the 100 mm gauge length data.

2. Although permanent strains obtained from the actuator displacement were generally greater than those obtained over a 100 mm gauge length, the actuator displacement is recommended for use in NCHRP Project 9-30A. The paired t-test analysis of the permanent strains curves concluded significant differences, but a similar analysis assuming independent tests did not. The use of the actuator displacement to collect permanent strain data, results in a substantially simpler instrumentation system, having similar precision as the specimen mounted system. If specimen mounted instrumentation is used, it must incorporate light-weight, loose core LVDTs, which are very difficult to properly position on the test specimen, particularly in confined tests which are being considered for NCHRP Project 9-30A. The actuator displacement is clearly able to detect differences in the permanent strain response of different mixtures and has the potential to make the repeated load permanent deformation test a routine test for agency laboratories.

3. The differences found in this study appear to be the result of the non-uniform distribution of air voids in gyratory compacted specimens, not the instrumentation. Further refinement of the test specimen preparation procedures are needed to minimize air void gradients and to eliminate areas of relatively high air voids that might be present at the ends of the test specimens.

## References

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# APPENDIX I-A. Dynamic Modulus Master Curve Procedure for the SPT.

Appendix I-A is the paper that was submitted to the 2005 Annual meeting of the Transportation Research Board to determine the dynamic modulus master curve using the simple performance test.

# A Practical Procedure for Developing Dynamic Modulus Master Curves for Pavement Structural Design

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| Figures | 8 at 250 | 2000 |
| Total | | 7500 |

**Abstract**

A dynamic modulus master curve for asphalt concrete is a critical input for flexible pavement design in the Mechanistic-Empirical Pavement Design Guide developed in National Cooperative Highway Research Program (NCHRP) Project 1-37A. The recommended testing to develop the modulus master curve is presented in AASHTO Provisional Standard TP 62-03*"Standard Method of Test for Determining Dynamic Modulus of Hot-Mix Asphalt Concrete Mixtures."* It includes testing at least two replicate specimens at five temperatures between 14 and 130 °F (-10 and 54.4 °C) and six loading rates between 0.1 and 25 Hz. The master curve and shift factors are then developed from this database of 60 measured moduli using numerical optimization. This testing requires substantial effort, and there is much overlap in the measured data, which is not needed when numerical methods are used to perform the time-temperature shifting for the master curve. This paper presents an alternative to the testing sequence specified in AASHTO TP62-03. It requires testing at only three temperatures between 4 and 115 °F (4 and 46.6 °C) and four rates of loading between 0.01 and 10 Hz. An analysis of data collected using the two approaches shows that comparable master curves are obtained. This alternative testing sequence can be used in conjunction with the Simple Performance Test System developed in NCHRP Project 9-29 to develop master curves for structural design.

## INTRODUCTION

This paper describes an approach for reducing the amount of effort required to develop dynamic modulus master curves for pavement structural design. The modulus of asphalt concrete is a critical input for flexible pavement design in the Mechanistic-Empirical Pavement Design Guide developed in National Cooperative Highway Research Program (NCHRP) Project 1-37A. A dynamic modulus master curve is used to express the modulus of asphalt concrete as a function of temperature and loading rate. The dynamic modulus test protocol was developed in NCHRP Projects 9-19 and 1-37A and has been standardized as AASHTO Provisional Standard TP62-03, "*Standard Method of Test for Determining Dynamic Modulus of Hot-Mix Asphalt Concrete Mixtures*." The recommended test sequence in AASHTO TP62-03 consists of testing a minimum of 2 replicate specimens at temperatures of 14, 40, 70, 100, and 130 °F (–10, 4.4, 21.1, 37.8, and 54.4 °C) and loading frequencies of 25, 10, 5, 1.0, 0.5, and 0.1 Hz. This testing provides a database of 60 dynamic modulus measurements from which the parameters of the master curve are determined by numerical optimization.

It is desirable that equipment for performing dynamic modulus master curve testing be available to highway agencies at a reasonable cost, and that the test procedure be appropriate for agency laboratories. In a recently completed Federal Highway Administration (FHWA) pooled fund study, Dougan, et. al, (*1*) identified several issues associated with AASHTO TP62-03, and concluded that the overall time required to perform the testing must be shortened if highway agencies are going to use it for routine testing. In NCHRP Project 9-19, Witczak (*2*), has studied the minimum testing required to develop the dynamic modulus master curves and has concluded that reasonable master curves can be developed using tests a three temperatures 14, 70, and 130 °F (–10.0, 21.1, and 54.4 °C) and loading frequencies of 33, 2.22, 0.15, and 0.01 Hz. This reduced sequence still requires testing at 14 °F (–10 °C) which Dougan, et. al found difficult due to moisture condensation and ice formation (*1*). Additionally, low temperature testing significantly increases the cost of the environmental chamber and increases the loading capacity and cost of the testing equipment. If testing at this temperature can be eliminated, the cost of the equipment, the complexity of the procedure, and the overall time required to develop a master curve can be significantly reduced.

The approach described in this document takes advantage of the fact that, for engineering purposes, asphalt binders reach approximately the same glassy modulus at very low temperatures. Using this binder modulus and recently developed relationships to predict mixture dynamic modulus from binder modulus and volumetric data, an estimate of the limiting maximum modulus of the mixture can be made and used in the development of the dynamic modulus master curve.

## NCHRP PROJECT 1-37A DYNAMIC MODULUS MASTER CURVE

To account for temperature and rate of loading effects on the modulus of asphalt concrete, the Mechanistic-Empirical Pavement Design Guide uses a modulus determined from a master curve constructed from dynamic modulus measurements at multiple temperatures and loading rates. Master curves are constructed using the principle of time-temperature superposition. First a standard reference temperature is selected, in this case 70 °F (21.1 °C), then the measured data at various temperatures are shifted with respect to loading frequency until the curves merge into a single smooth function. The master curve of modulus as a function of frequency formed in this manner describes the loading rate dependency of the material. The amount of shifting at each temperature required to form the master curve describes the temperature dependency of the material. Thus, both the master curve and the shift factors are needed for a complete description of the rate and temperature effects. Figure 1 presents an example of a master curve constructed in this manner and the resulting shift factors.

In the Mechanistic-Empirical Pavement Design Guide, the sigmodial function in Equation 1 is used to describe the rate dependency of the modulus master curve (*3*).

$$\log(E^*) = \delta + \frac{\alpha}{1 + e^{\beta + \gamma(\log \omega_r)}} \quad (1)$$

where:

E* = dynamic modulus
$\omega_r$ = reduced frequency
$\delta$ = minimum value of E*
$\delta+\alpha$ = maximum value of E*

β, γ = parameters describing the shape of the sigmoidal function

The temperature dependency of the modulus is incorporated in the reduced frequency parameter, $\omega_r$, in Equation 1. Equation 2 defines the reduced frequency as the actual loading frequency multiplied by the time-temperature shift factor, a(T).

$$\omega_r = \omega \times a(T) \quad (2a)$$

$$\log(\omega_r) = \log(\omega) + \log[a(T)] \quad (2b)$$

where:

$\omega_r$ = reduced frequency

$\omega$= loading frequency

$a$(T) = shift factor as a function of temperature

T = temperature

The shift factors are a function of temperature. Various equations such as the Arrhenius function and the Williams-Landel-Ferry equation have been used with asphalt materials (*4*). In the Mechanistic-Empirical Pavement Design Guide, the shift factors were expressed as a function of the binder viscosity to allow aging over the life of the pavement to be considered using the Global Aging Model developed by Mirza and Witczak (*5*). Equation 3 presents the shift factor relationship used in the Mechanistic-Empirical Pavement Design Guide (*3*).

$$\log[a(T)] = c[\log(\eta) - \log(\eta_{70_{RTFOT}})] \quad (3)$$

where:

$a$(T) = shift factor as a function of temperature and age

$\eta$ = viscosity at the age and temperature of interest

$\eta_{70_{RTFOT}}$ = viscosity at the reference temperature of 70 °F (21.1 °C) and RTFO aging

c = fitting parameter

The viscosity as a function of temperature can be expressed using the ASTM viscosity-temperature relationship given in Equation 4 (*6*).

$$\log\log\eta = A + VTS\log T_R \quad (4)$$

where:

$\eta$ = viscosity, cP

$T_R$ = temperature, Rankine

A = regression intercept

VTS = regression slope of viscosity-temperature susceptibility

Combining Equations 3 and 4 yields the shift factor as a function of temperature relationship used in the Mechanistic-Empirical Pavement Design Guide for the construction of dynamic modulus master curves from laboratory test data.

$$\log[a(T)] = c[10^{A+VTS\log T_R} - \log(\eta_{70_{RTFOT}})] \quad (5)$$

where:

$a$(T) = shift factor as a function of temperature

$T_R$ = temperature, Rankine

$\eta_{70_{RTFOT}}$ = viscosity at the reference temperature of 70 °F (21.1 °C) for RTFO aging

A, VTS= viscosity-temperature susceptibility parameters for RTFOT aging

c = fitting parameter

Substituting Equation 5 into Equation 2b and the result into Equation 1 yields the form of the dynamic modulus master curve relationship used in the Mechanistic-Empirical Pavement Design Guide for the development of master curves from laboratory test data.

$$\log(E^*) = \delta + \frac{\alpha}{1 + e^{\beta+\gamma\left\{\log(\omega)+c\left[10^{A+VTS\log T_R}-\log(\eta_{70_{RTFOT}})\right]\right\}}} \quad (6)$$

where:

E* = dynamic modulus
ω = loading frequency
$T_R$ = temperature, Rankine
$\eta_{70_{RTFOT}}$ = viscosity at the reference temperature of 70 °F (21.1) °C for RTFO aging
A, VTS= viscosity-temperature susceptibility parameters for RTFOT aging
*c* = fitting parameter
δ = limiting minimum value of E*
δ+α = limiting maximum value of E*
β, γ = parameters describing the shape of the sigmoidal function

The fitting parameters (α, β, δ, γ, and c) are determined through numerical optimization of Equation 6 using mixture test data collected in accordance with AASHTO TP62-03. It is important to note that due to equipment limitations, neither the limiting maximum or limiting minimum modulus can be measured directly; therefore, these parameters are estimated through the curve fitting process.

**PROPOSED MODIFICATION**

The modification proposed in this paper is to estimate the limiting maximum modulus based on binder stiffness and mixture volumetric data using the Hirsch model developed by Chirstensen, et. al. in NCHRP Projects 9-25 and 9-31 (*7*). For a specified limiting maximum modulus, the master curve relationship given in Equation 6 reduces to:

$$\log(E^*) = \delta + \frac{(Max - \delta)}{1 + e^{\beta+\gamma\left\{\log(\omega)+c\left[10^{A+VTS\log T_R}-\log(\eta_{70_{RTFOT}})\right]\right\}}} \quad (7)$$

where:

E* = dynamic modulus
t = loading frequency
$T_R$ = temperature, Rankine
$\eta_{70_{RTFOT}}$ = viscosity at the reference temperature of 70 °F (21.1 °C) for RTFO aging
A, VTS = viscosity-temperature susceptibility parameters for RTFOT aging
*Max* = specified limiting maximum modulus
δ, β, γ and *c* fitting parameters

The four unknown fitting parameters are still estimated using numerical optimization of the test data, but since the limiting maximum modulus is specified, data at low test temperatures are no longer needed.

Equation 8 present the Hirsch model, which allows estimation of the modulus of asphalt concrete mixtures from binder stiffness data and volumetric properties.

$$|E^*|_{mix} = P_c\left[4{,}200{,}000\left(1-\frac{VMA}{100}\right)+3|G^*|_{binder}\left(\frac{VFA\ xVMA}{10{,}000}\right)\right]+\frac{1-P_c}{\left[\frac{\left(1-\frac{VMA}{100}\right)}{4{,}200{,}000}+\frac{VMA}{3VFA|G^*|_{binder}}\right]} \quad (8a)$$

where:

$$P_c = \frac{\left(20 + \frac{VFA\ x\ 3\,|G^*|_{binder}}{VMA}\right)^{0.58}}{650 + \left(\frac{VFA\ x\ 3\,|G^*|_{binder}}{VMA}\right)^{0.58}} \quad (8b)$$

VMA = voids in mineral aggregates, %
VFA = voids filled with asphalt, %
$|G^*|_{binder}$ = dynamic shear modulus of binder, psi

Based on research conducted during the Strategic Highway Research Program (SHRP) by Christensen and Andersen, a reasonable engineering estimate of the maximum dynamic shear modulus for asphalt binders is 145,000 psi (1 GPa) (*4*). This estimate is based on data collected on neat binders and care should be used when applying it to modified binders. Substituting this value into Equation 8 yields the recommended equation for estimating the limiting maximum modulus of asphalt concrete mixtures from volumetric data.

$$|E^*|_{max} = P_c\left[4{,}200{,}000\left(1 - \frac{VMA}{100}\right) + 435{,}000\left(\frac{VFA\ xVMA}{10{,}000}\right)\right] + \frac{1 - P_c}{\left[\frac{\left(1 - \frac{VMA}{100}\right)}{4{,}200{,}000} + \frac{VMA}{435{,}000(VFA)}\right]} \quad (9a)$$

where

$$P_c = \frac{\left(20 + \frac{435{,}000(VFA)}{VMA}\right)^{0.58}}{650 + \left(\frac{435{,}000(VFA)}{VMA}\right)^{0.58}} \quad (9b)$$

$|E^*|_{max}$ = limiting maximum mixture dynamic modulus
VMA = voids in mineral aggregates, %
VFA = voids filled with asphalt, %

The limiting maximum modulus computed from Equation 9 varies from about 3,000,000 (20.6 GPa) for mixtures with very high VMA and low VFA to about 3,800,000 (26.2 GPa) for mixtures with low VMA and high VFA. These limiting maximum modulus values appear very rational. For conditions with low VMA and high VFA, the limiting maximum modulus approaches the 4,000,000 psi (28 GPa) often assumed for Portland cement concrete.

**EFFECT OF ELIMINATING LOW TEMPERATURE TEST DATA ON MASTER CURVES**

This section compares master curves developed by fitting Equation 6 using the complete AASHTO TP62-03 data set and Equation 7 using a reduced data set obtained by eliminating the lowest temperature data from the AASHTO TP62-03 test series. For the reduced data set, the limiting maximum modulus was estimated using Equation 9. For the comparisons, the database of dynamic modulus measurements assembled by Pellinen for NCHRP Project 9-19 was used (*8*). This database includes test data from replicate samples tested at temperatures of 15.8, 40, 70, 100, and 130 °F (-9, 4.4, 21.1, 37.8, and 54.4 °C) and frequencies of 25, 10, 5, 1.0, 0.5, and 0.1 Hz. Pertinent properties of the mixtures included in the evaluation are summarized in Table 1. The mixtures include 5 mixtures from the MNRoad project, 11 mixtures from the FHWA Pavement Testing Facility, and 6 mixtures from the WesTrack project. This combination of mixtures has a range of nominal maximum aggregate sizes, binder type including two modified binders, and volumetric properties. Master curves for each mixture in Table 1 were fit using the two methods. Goodness of fit statistics for the individual master curves are summarized in the last four columns of Table 1. Two statistics are provided: the explained variance, $R^2$, and ratio of the standard error of estimate to the standard deviation of the measured values, Se/Sy. High $R^2$ and low Se/Sy values indicate good fitting of the master curve to the measured data. As shown in Table 1, both methods provide excellent fit to the measured data.

Although the two master curves provide excellent fit to the measured data, there are differences in some cases. Figures 2 and 3 present examples of the master curves generated. Figure 2 is for Lane 2 at the FHWA

Pavement Testing Facility and is an example of the worst agreement between the two methods. The limiting maximum modulus computed with the Hirsch model at 3,237,000 psi (223. GPa) is much lower than the 6,714,000 psi (46.4 GPa) limiting maximum modulus obtained from the complete AASHTO TP62-03 data set. As shown the difference in the limiting maximum modulus also affects the limiting minimum modulus. The limiting minimum modulus from the reduced data set is higher, 17,000 psi (117 MPa) compared to 2,000 psi (14 MPa) for the master curve developed using the complete AASHTO TP62-03 set. Both methods fit the measured data well over the temperature range from 40 to 130 °F (4.4 to 54.4 °C) and the shift factors for the two methods are essentially the same. Figure 3 is for Cell 17 at the MNRoad project, and is an example of best agreement between the two methods. In this case, the two approaches yield the same master curves.

To compare master curves for all of the mixtures, dynamic moduli were calculated for temperatures ranging from –30 to 150 °F (-34.4 to 65.6 °C) using loading rates of 25, 10, 1, 0.1, and 0.01 Hz. The results are shown in Figure 4. From Figure 4, the two approaches sometimes yield differences at high and low moduli primarily due to differences caused by the limiting maximum modulus.

Figure 5 compares limiting maximum moduli from the two procedures. The master curves developed using the complete AASHTO TP 62-03 data set yield unrealistically high moduli in four cases, ALF 2, ALF 3, ALF 10, and ALF 11. Master curves developed in this manner also yield unrealistically low values in two cases, ALF 8 and WSTR 2. Table 2 summarizes limiting modulus values averaged over similar mixtures. The master curves developed using the two approaches produce reasonably similar average limiting maximum modulus values except for the ALF mixtures, which had the four unrealistically high values when the complete AASHTO TP62-03 data set was used. The quality of the data for the low temperature test condition has a major impact on the limiting maximum modulus determined from the complete AASHTO TP62-03 data set. Pellinen reported higher coefficients of variation for data collected at 15.8 °F (-9 °C) and 130 °F (54.4 °C)(*8*). She also reported that strain levels for the 15.8 °F data were significantly lower than those at other temperatures. This coupled with potential friction in the LVDT guide rod used in the AASHTO TP62-03 recommended instrumentation is the most likely cause of the high variability in the low temperature measurements. The combined effects of low strains and friction probably also explain the unrealistically high moduli measured for four of the ALF mixtures.

The limiting maximum modulus also affects the limiting minimum modulus because the sigmoidal master curve function is symmetric. Figure 6 compares limiting minimum modulus values for individual mixtures from the two procedures. The largest differences between the two methods occur for the same mixtures that have the largest differences in the limiting maximum modulus. Limiting minimum modulus values averaged over similar mixtures are summarized in Table 2. The two approaches produce reasonably similar average limiting minimum modulus values. The limiting minimum modulus represent the stiffness of the aggregate structure in the absence of binder. Both procedures provide the same rankings for the mixtures compared in this evaluation.

**TESTING TEMPERATURES AND RATES FOR THE PROPOSED ALTERNATIVE APPROACH**

The previous section showed that reasonable dynamic modulus master curves can be obtained without low temperature test data by estimating the limiting maximum modulus using the Hirsch model. The measured data that were fitted were collected at temperatures of 40, 70, 100, and 130 °F (4.4, 21.1, and 37.8 °C) and frequencies of 25, 10, 5, 1.0, 0.5, and 0.1 Hz. However, these temperatures and loading rates may not be optimal. This section presents an analysis of the temperatures and loading rates that should be used in combination with the this proposed approach to efficiently develop dynamic modulus master curves.

In the proposed approach, a reasonable, rational estimate of the limiting maximum modulus is provided by the Hirsch model. This eliminates the need for testing at low temperatures, and the potential inaccuracies caused by these difficult testing conditions. To provide an accurate estimate of the limiting minimum modulus, data with this approach should be collected to the smallest reduced frequency possible. From Equation 2, the reduced frequency is a function of both temperature and frequency of loading. High temperature, slow frequency dynamic modulus tests result in the smallest reduced frequency values. For the testing conditions specified in AASHTO TP 62-03 the minimum reduced frequency for the mixtures included in this study ranged from $10^{-4}$ to $10^{-5}$ Hz. These appear to have been sufficient to define the limiting minimum modulus through fitting with the sigmodial function. The most efficient way to decrease the minimum reduced frequency in the testing program is to increase temperature; however, for the glued gage point instrumentation used in the dynamic modulus test, the maximum testing temperature appears to be approximately 115 °F (46.6 °C). Above this temperature, the gage points may loosen,

particularly when they are attached to the matrix of fine aggregate and binder. Higher temperatures may be possible when the gage points are attached to the coarse aggregate, but this cannot be assured in most mixtures. Figure 7 presents experimentally determined shift factors from the complete AASHTO TP62-03 data set for the mixtures included in this evaluation. As shown, the shift factor for the maximum recommended testing temperature of 115 °F (46.6 °C) ranges from about $10^{-2.3} = 0.005$ to $10^{-3.2} = 0.0006$. From Equation 2, this results in loading frequencies at 115 °F (46.6 °C) of approximately 0.02 Hz to obtain reduced frequencies at 70 °F (21.1°C) between $10^{-4}$ and $10^{-5}$ Hz, respectively. Thus, the use of a loading rate of 0.01 Hz at 115 °F (46.6 °C) will provide approximately the same lower range as the AASHTO TP62-03 approach.

Because the shift factor relationship is not linear, a minimum of three temperatures spaced as widely as possible should be used in the testing program. This will provide a reasonable estimate of the coefficient, *c*, in the shift factor relationship, Equation 3. A low testing temperature of temperature of 40 °F (4.4 °C) would allow reasonably priced environmental chambers to be used, and will eliminate the icing problems that occur when testing at temperatures below freezing. Also as shown in Figure 7, the log of the shift factors at this temperature have approximately the same magnitude, but opposite sign as those at the maximum temperature of 115 °F (46.6 °C).

Thus the recommended testing temperatures for the proposed approach are 40, 70, and 115 °F. (4.4, 21.1, and 46.6 °C) Based on the performance of typical LVDT deformation systems, the maximum frequency of loading should be limited to 10 Hz. Using loading frequencies of 10, 1, 0.1, and 0.01 Hz at each of the temperatures, results in well spaced data in reduced frequency with a minimum of overlap.

**EXAMPLE USING THE PROPOSED PROCEDURE**

This section illustrates the development of a master curve using the proposed procedure. The mixture that was tested was a coarse graded 9.5 mm limestone mixture made with a PG 70-22 binder. The viscosity-temperature susceptibility parameters for the binder were: A= 10.299 and VTS = -3.426. The test specimens were compacted at the optimum asphalt content of 5.5 percent to 4.0 percent air voids. For this condition the percent voids in the mineral aggregate was 15.8 and the percent voids filled with asphalt was 76.2. Table 3 presents dynamic modulus data measured on replicate samples using the combination of temperatures and loading rates recommended in the proposed approach.

The first step for fitting the master curve is to estimate the limiting maximum modulus using Equation 9. For a mixture with a VMA of 15.8 percent and a VFA of 76.2 percent, the limiting maximum modulus from Equation 9 is 3,376,743 psi. Using this value of the limiting maximum modulus, the viscosity-temperature susceptibility parameters, and the measured data, the master curve parameters can be obtained through numerical optimization of Equation 7. The optimization can be performed using the Solver function in Mircosoft EXCEL®. This is done by setting up a spreadsheet to compute the sum of the squared errors between the logarithm of the measured dynamic moduli and the values predicted by Equation 7. The Solver function is used to minimize the sum of the squared errors by varying the fitting parameters in Equation 7. The following initial estimates are recommended: $\delta = 0.5$, $\beta = -1.0$, $\gamma = 0.5$, and $c = 1.2$. The master curve developed from this example data is shown in Figure 8. The goodness of fit statistics show Equation 7 provides an excellent fit to the measured data with an $R^2$ greater than 0.99 and an Se/Sy less than 0.04. Using the proposed temperatures and loading rates, the measured data cover approximately 80 percent of the range defined by the fitted limiting minimum and computed limiting maximum moduli.

**EQUIPMENT REQUIREMENTS AND TESTING TIME**

Table 4 compares the requirements for equipment to perform the dynamic modulus master curve testing as specified in AASHTO TP62-03 and the proposed approach (*9*). The primary difference in the devices is the temperature range, and the required dynamic loading capacity. The substantial difference in the low temperature range of the environmental chamber is responsible for the difference in the estimated cost of the equipment. The increased dynamic loading capacity results in a nominal increase in the estimated cost of the equipment. The Simple Performance Test System developed in NCHRP Project 9-29 is capable of performing the dynamic modulus master curve testing described in the proposed approach.

The Simple Performance Test System software applies 10 cycles at each loading frequency. The first 5 cycles are used to adjust the load to produce strains within the specified range. The data from the second 5 cycles are then collected and used to compute the dynamic modulus and phase angle. The 4 loading frequencies

recommended in the proposed approach will require approximately 30 min per specimen at each testing temperature, including time for specimen instrumentation and chamber temperature equilibrium. Thus, a testing program including three replicate specimens will require 1.5 hours per temperature. Specimen fabrication including batching, preparation of over-height gyratory samples, sawing and coring of test specimens, specific gravity measurements for the final test specimens, and gluing gage points generally requires 3.0 hours per specimen. Thus, master curve testing using three specimens and the proposed approach will require approximately 13.5 man-hours of preparation and testing.

## SUMMARY AND CONCLUSIONS

This document presents an alternative to the testing sequence presented in AASHTO TP62-03 for developing dynamic modulus master curves. In this approach, the limiting maximum modulus for the mixture is estimated from mixture volumetric data using the Hirsch model (*7*) and a limiting binder shear modulus of 145,000 psi (1 GPa). Estimated limiting maximum mixture modulus values using the Hirsch model range from about 3,000,000 (20.6 GPa) for mixtures with very high VMA and low VFA to about 3,800,000 (26.2 GPa) for mixtures with low VMA and high VFA. These are very rational limiting maximum modulus values considering that the modulus of Portland cement concrete is often estimated at 4,000,000 psi (27.6 GPa).

By estimating the limiting maximum modulus, testing at extremely low temperatures is not needed to develop a master curve using the master curve equation contained in the Mechainstic-Empirical Pavement Design Guide. Testing at the lowest temperature in the AASHTO TP62-03 sequence, 14 °F (–10 °C), greatly increases the cost of the environmental chamber for the testing system, and increases the complexity and of testing. Moisture condensation and icing at temperatures below 32 °F (0 °C) make testing extremely challenging even for highly experienced technicians. Data published by Pellinen, (*8*) show substantially increased variability for testing at 15 °F (–9 °C), and some data exhibit unreasonably high moduli approaching 9,000,000 psi (62 GPa). Such high moduli also have a significant effect on the limiting minimum modulus extrapolated from the test data using the Mechainstic-Empirical Pavement Design Guide master curve equation.

The alternative approach presented in this paper requires testing at 40, 70, and 115 °F (4.4, 21.1, and 46.6 °C) using frequencies of 10, 1, 0.1, and 0.01 Hz. After substituting the limiting maximum modulus estimated from the Hirsch model, the Mechainstic-Empirical Pavement Design Guide master curve equation is fit to this data using the same numerical optimization techniques. Comparison of master curves using the reduced testing and the complete AASHTO TP62-03 data set for 22 mixtures yielded similar master curves except in cases were extremely high or low moduli were measured at 15.8 °F (–9 °C).

A testing machine capable of performing the testing required by the proposed approach is estimated to cost $50,000 compared to $125,000 for a machine to perform the testing in AASHTO TP62-03. Using the proposed approach and the software automation already incorporated in the Simple Performance Test System, specimen preparation and dynamic modulus master curve testing for a mixture using three replicate specimens is estimated to require a total of 13.5 man-hours of technician time.

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**TABLE 1. Summary of Master Curve Comparison Study.**

| Description | | | | Mix Volumetric Properties | | | | RTFOT BINDER PROPERTIES | | | MASTER CURVE GOODNESS OF FIT STATISTICS | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Project | ID | Binder | Mix Type | AC (%) | Va (%) | VMA (%) | VFA (%) | A | VTS | $\eta_{70_{RTFOT}}$ (cP) | Complete Data Set | | Reduced Data Set | |
| | | | | | | | | | | | $R^2$ | Se/Sy | $R^2$ | Se/Sy |
| MNRoad | Cell 16 | AC-20 | Fine 9.5 mm | 5.08 | 8.2 | 18.0 | 54.4 | 10.7826 | -3.6065 | 1.22E+09 | 0.9965 | 0.002 | 0.9959 | 0.004 |
| MNRoad | Cell 17 | AC-20 | Fine 9.5 mm | 5.45 | 7.7 | 18.2 | 57.6 | 10.7826 | -3.6065 | 1.22E+09 | 0.9938 | 0.004 | 0.9938 | 0.006 |
| MNRoad | Cell 18 | AC-20 | Fine 9.5 mm | 5.83 | 5.6 | 17.1 | 67.2 | 10.7826 | -3.6065 | 1.22E+09 | 0.9974 | 0.002 | 0.9974 | 0.002 |
| MNRoad | Cell 20 | 120/150 Pen | Fine 9.5 mm | 6.06 | 6.3 | 18.3 | 65.6 | 10.8101 | -3.6254 | 3.96E+08 | 0.9925 | 0.006 | 0.9924 | 0.008 |
| MNRoad | Cell 22 | 120/150 Pen | Fine 9.5 mm | 5.35 | 6.5 | 16.9 | 61.5 | 10.8101 | -3.6254 | 3.96E+08 | 0.9717 | 0.020 | 0.9692 | 0.028 |
| ALF | Lane 1 | AC-5 | Fine 19 mm | 4.75 | 6.1 | 16.9 | 63.9 | 10.6766 | -3.5740 | 5.35E+08 | 0.9801 | 0.013 | 0.9789 | 0.020 |
| ALF | Lane 2 | AC-20 | Fine 19 mm | 4.85 | 6.5 | 17.3 | 62.5 | 10.6569 | -3.5594 | 1.38E+09 | 0.9765 | 0.017 | 0.9610 | 0.040 |
| ALF | Lane 3 | AC-5 | Fine 19 mm | 4.75 | 7.7 | 18.3 | 57.9 | 10.6766 | -3.5740 | 5.35E+08 | 0.9856 | 0.011 | 0.9793 | 0.024 |
| ALF | Lane 4 | AC-20 | Fine 19 mm | 4.9 | 9.7 | 20.3 | 52.1 | 10.6569 | -3.5594 | 1.38E+09 | 0.9803 | 0.013 | 0.9800 | 0.019 |
| ALF | Lane 5 | AC-10 | Fine 19 mm | 4.8 | 8.6 | 19.0 | 54.7 | 10.7805 | -3.6116 | 5.72E+08 | 0.9922 | 0.005 | 0.9921 | 0.008 |
| ALF | Lane 7 | Styrelf | Fine 19 mm | 4.9 | 11.9 | 22.1 | 46.2 | 8.9064 | -2.9089 | 4.02E+09 | 0.9726 | 0.016 | 0.9723 | 0.023 |
| ALF | Lane 8 | Novophalt | Fine 19 mm | 4.7 | 11.9 | 21.6 | 45.0 | 8.8136 | -2.8817 | 1.58E+09 | 0.9929 | 0.004 | 0.9902 | 0.006 |
| ALF | Lane 9 | AC-5 | Fine 19 mm | 4.9 | 7.7 | 18.4 | 58.1 | 10.6766 | -3.5740 | 5.35E+08 | 0.9902 | 0.007 | 0.9902 | 0.010 |
| ALF | Lane 10 | AC-20 | Fine 19 mm | 4.9 | 9.3 | 19.8 | 53.0 | 10.6569 | -3.5594 | 1.38E+09 | 0.9960 | 0.003 | 0.9930 | 0.007 |
| ALF | Lane 11 | AC-5 | Fine 37.5 mm | 4.05 | 6.0 | 14.2 | 57.9 | 10.6766 | -3.5740 | 5.35E+08 | 0.9913 | 0.006 | 0.9839 | 0.017 |
| ALF | Lane 12 | AC-20 | Fine 37.5 mm | 4.05 | 7.4 | 15.5 | 52.3 | 10.6569 | -3.5594 | 1.38E+09 | 0.9844 | 0.009 | 0.9811 | 0.016 |
| WesTrack | Sec 2 | PG 64-22 | Fine 19 mm | 5.02 | 10.4 | 17.3 | 39.9 | 11.0757 | -3.7119 | 1.63E+09 | 0.9933 | 0.004 | 0.9893 | 0.008 |
| WesTrack | Sec 4 | PG 64-22 | Fine 19 mm | 5.24 | 6.6 | 14.3 | 53.8 | 11.0757 | -3.7119 | 1.63E+09 | 0.9899 | 0.006 | 0.9899 | 0.008 |
| WesTrack | Sec 7 | PG 64-22 | Coarse 19 mm | 6.28 | 6.9 | 15.9 | 56.6 | 11.0757 | -3.7119 | 1.63E+09 | 0.9547 | 0.029 | 0.9536 | 0.040 |
| WesTrack | Sec 15 | PG 64-22 | Fine 19 mm | 5.55 | 8.7 | 16.9 | 48.4 | 11.0757 | -3.7119 | 1.63E+09 | 0.9883 | 0.008 | 0.9877 | 0.012 |
| WesTrack | Sec 23 | PG 64-22 | Coarse 19 mm | 5.78 | 4.9 | 13.0 | 62.3 | 11.0757 | -3.7119 | 1.63E+09 | 0.9949 | 0.003 | 0.9949 | 0.004 |
| WesTrack | Sec 24 | PG 64-22 | Coarse 19 mm | 5.91 | 7.2 | 15.4 | 53.2 | 11.0757 | -3.7119 | 1.63E+09 | 0.9742 | 0.015 | 0.9735 | 0.022 |

**TABLE 2. Limiting Maximum and Minimum Modulus Values Averaged Over Mixture Type.**

| Mixture | Number | Limiting Maximum Modulus (psi) | | Limiting Maximum Modulus (psi) | |
|---|---|---|---|---|---|
| | | Full AASHTO TP 62-03 Data Set | Hirsch Model Estimate | Full AASHTO TP 62-03 Data Set | Reduced Data Set |
| MNRoad | 5 | 3,109,668 | 3,206,382 | 4,383 | 3,873 |
| ALF 19 mm | 9 | 3,867,636 | 3,077,348 | 11,247 | 11,044 |
| ALF 25 mm | 2 | 4,735,721 | 3,324,313 | 14,092 | 13,426 |
| WesTrack 19 mm Fine | 3 | 2,985,757 | 3,187,770 | 16,589 | 14,077 |
| WesTrack 19 mm Coarse | 3 | 2,934,664 | 3,345,151 | 19,101 | 15,569 |
| All Mixtures | 22 | 3,526,808 | 3,180,702 | 11,745 | 10,662 |

**TABLE 3. Example Dynamic Modulus Test Data Collected Using the Proposed Approach.**

| Temp. ( F) | Frequency (Hz) | Specimen 1 | | Specimen 2 | |
|---|---|---|---|---|---|
| | | Modulus (ksi) | Phase (degree) | Modulus (ksi) | Phase (degree) |
| 40 | 0.01 | 771.6 | 25.0 | 901.1 | 23.7 |
| 40 | 0.1 | 1274.9 | 19.0 | 1496.1 | 17.9 |
| 40 | 1 | 1861.7 | 13.9 | 2164.1 | 12.8 |
| 40 | 10 | 2458.2 | 9.6 | 2811.0 | 8.6 |
| 70 | 0.01 | 161.0 | 30.0 | 174.6 | 29.6 |
| 70 | 0.1 | 362.7 | 29.2 | 398.3 | 29.2 |
| 70 | 1 | 771.7 | 24.5 | 844.4 | 24.3 |
| 70 | 10 | 1332.1 | 18.0 | 1446.0 | 18.0 |
| 115 | 0.01 | 23.3 | 24.4 | 28.3 | 22.9 |
| 115 | 0.1 | 50.8 | 27.8 | 53.4 | 27.9 |
| 115 | 1 | 137.8 | 29.4 | 140.9 | 29.5 |
| 115 | 10 | 336.2 | 29.7 | 352.8 | 29.9 |

**TABLE 4. Comparison of Dynamic Modulus Testing Devices.**

| Characteristic | AASHTO TP62-30 | Proposed Procedure |
|---|---|---|
| Temperature Range | -10 to 60 $^{o}$C (14 to 140 $^{o}$F) | 4 to 60 $^{o}$C (40 to 140 $^{o}$F) |
| Temperature Control | ± 0.5 $^{o}$C (± 1.0 $^{o}$F) | ± 0.5 $^{o}$C (± 1.0 $^{o}$F) |
| Dynamic Load Capacity | 22.5 kN (5.0 kips) | 12.5 kN (2.8 kips) |
| Loading Rates | 0.1 to 25 Hz | 0.01 to 10 Hz |
| Estimated Cost | $125,000 | $50,000 |

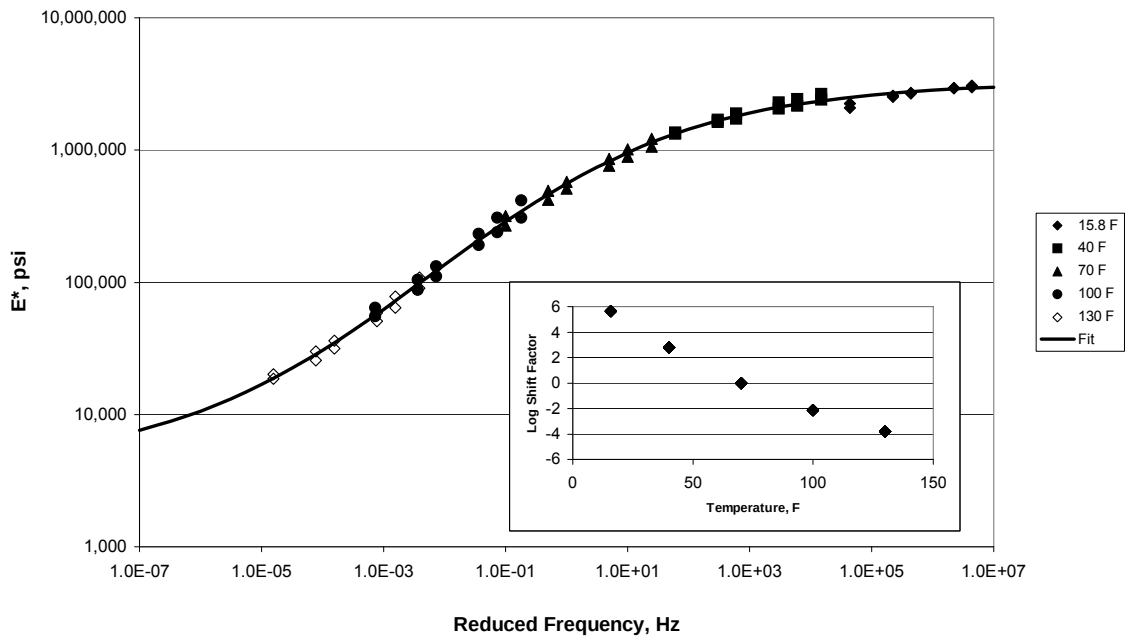


**Figure 1. Schematic of Master Curve and Shift Factors.**

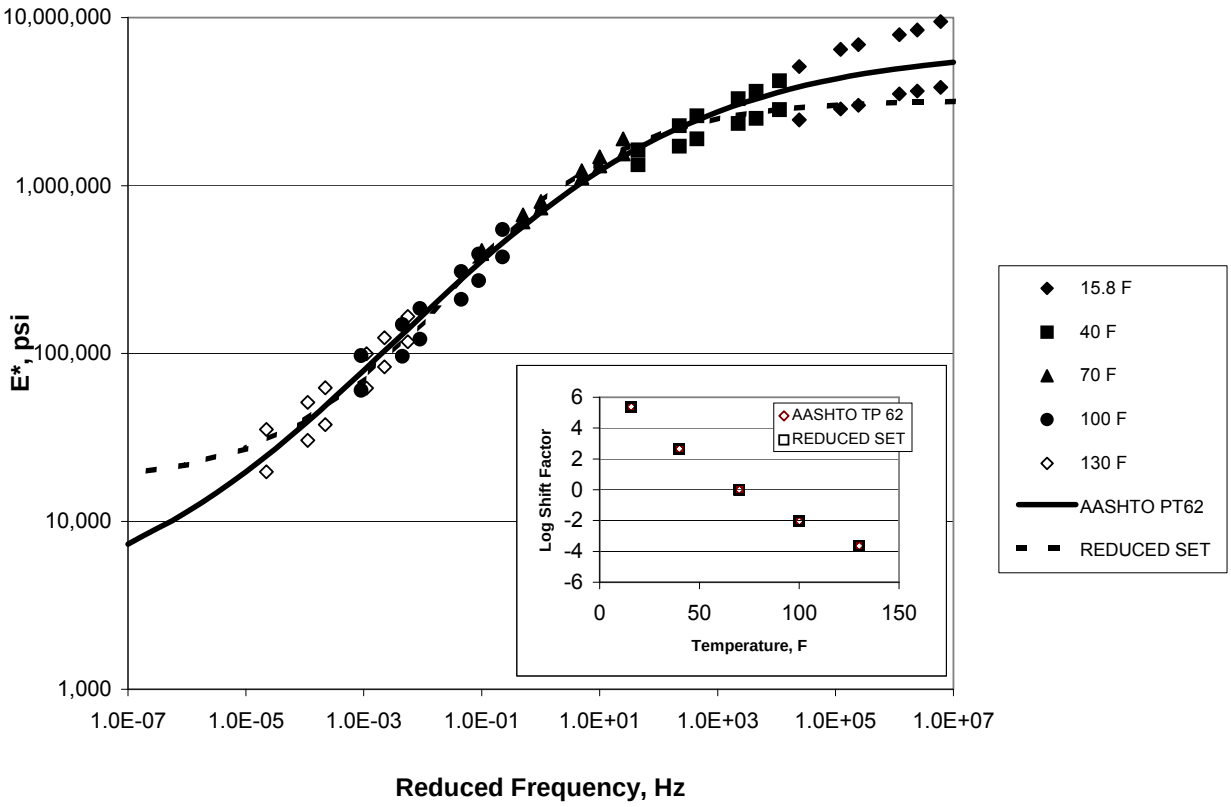


**Figure 2. Comparison of Fitted Master Curves Using Complete AASHTO TP 62-03 Data and the Reduced Data Set for Lane 2 From the FHWA Pavement Testing Facility.**

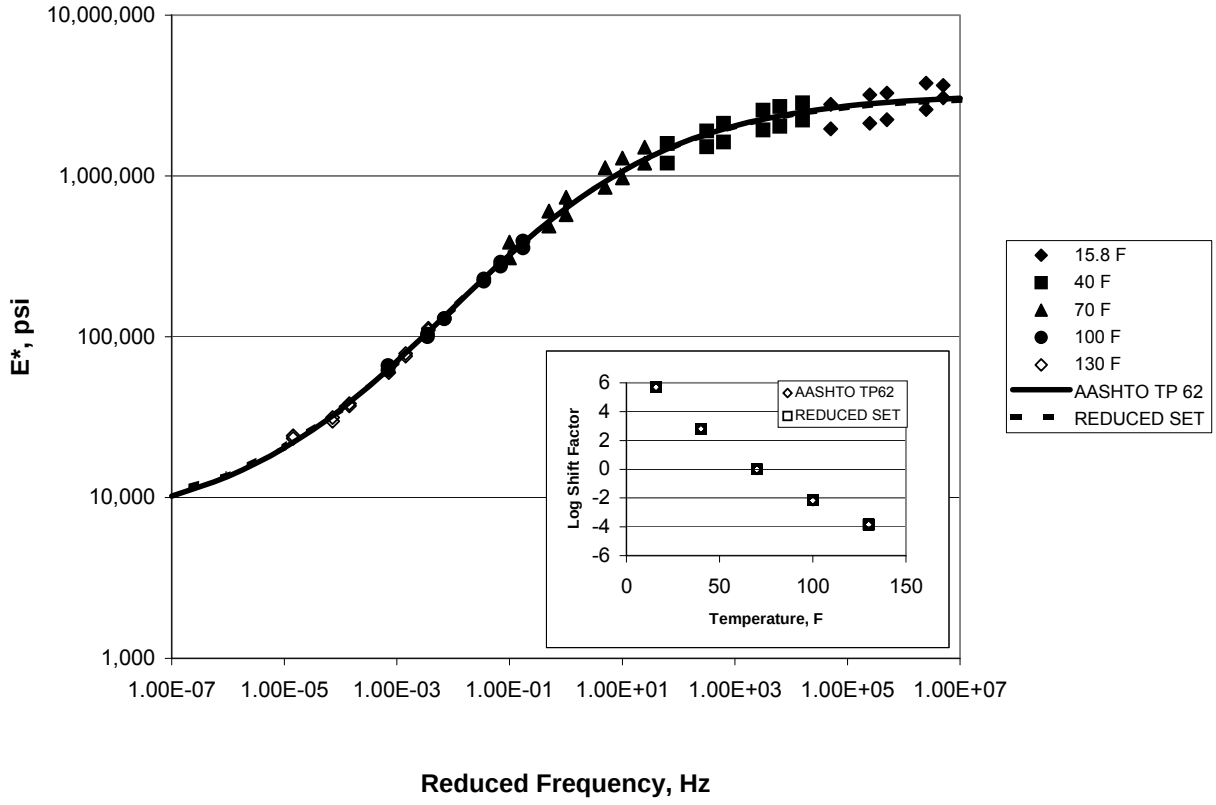


**Figure 3. Comparison of Fitted Master Curves Using Complete AASHTO TP 62-03 Data and the Reduced Data Set for Cell 17 From the MNRoad.**

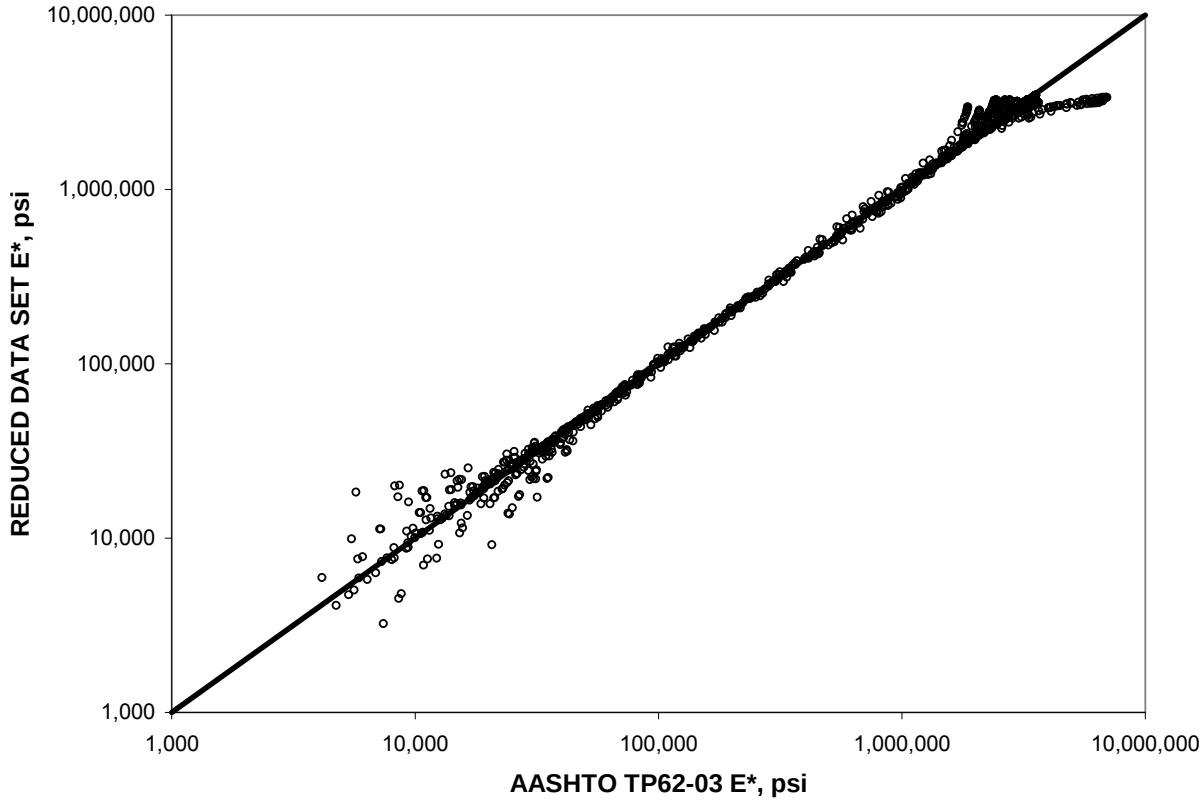


**Figure 4. Comparison of Dynamic Moduli From Fitted Master Curves.**

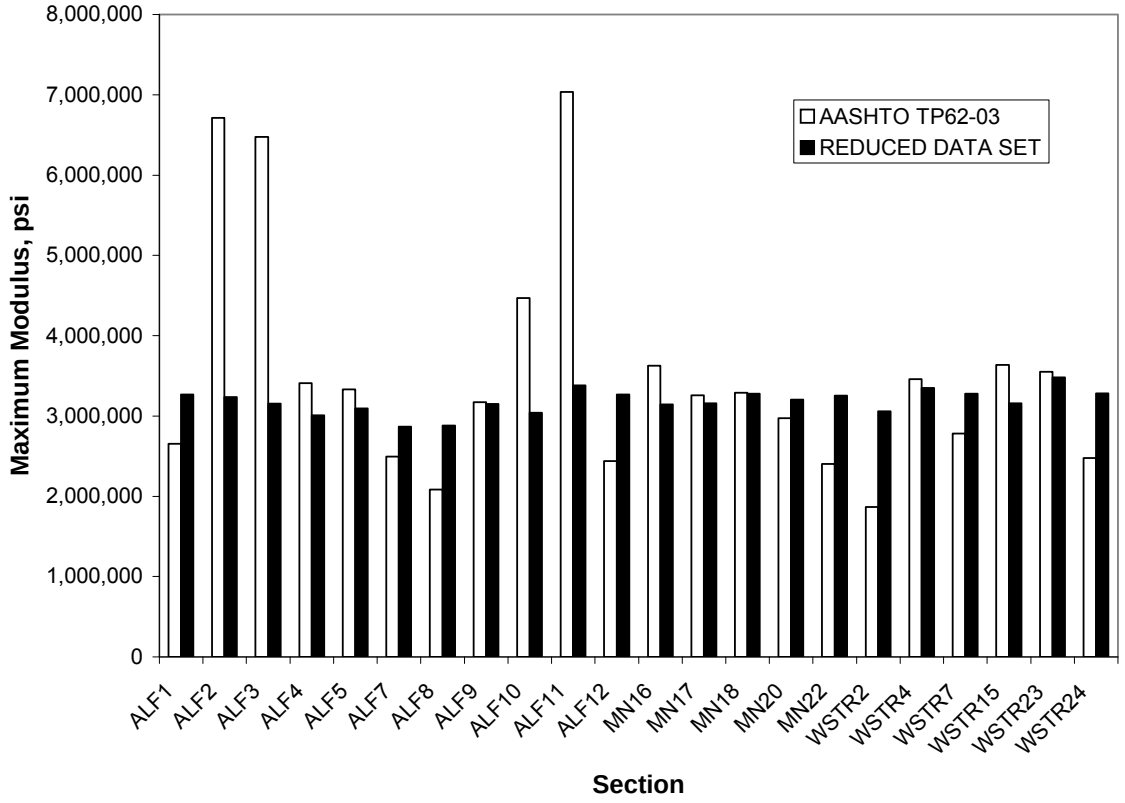


**Figure 5. Comparison of Limiting Maximum Moduli From the Two Procedures.**

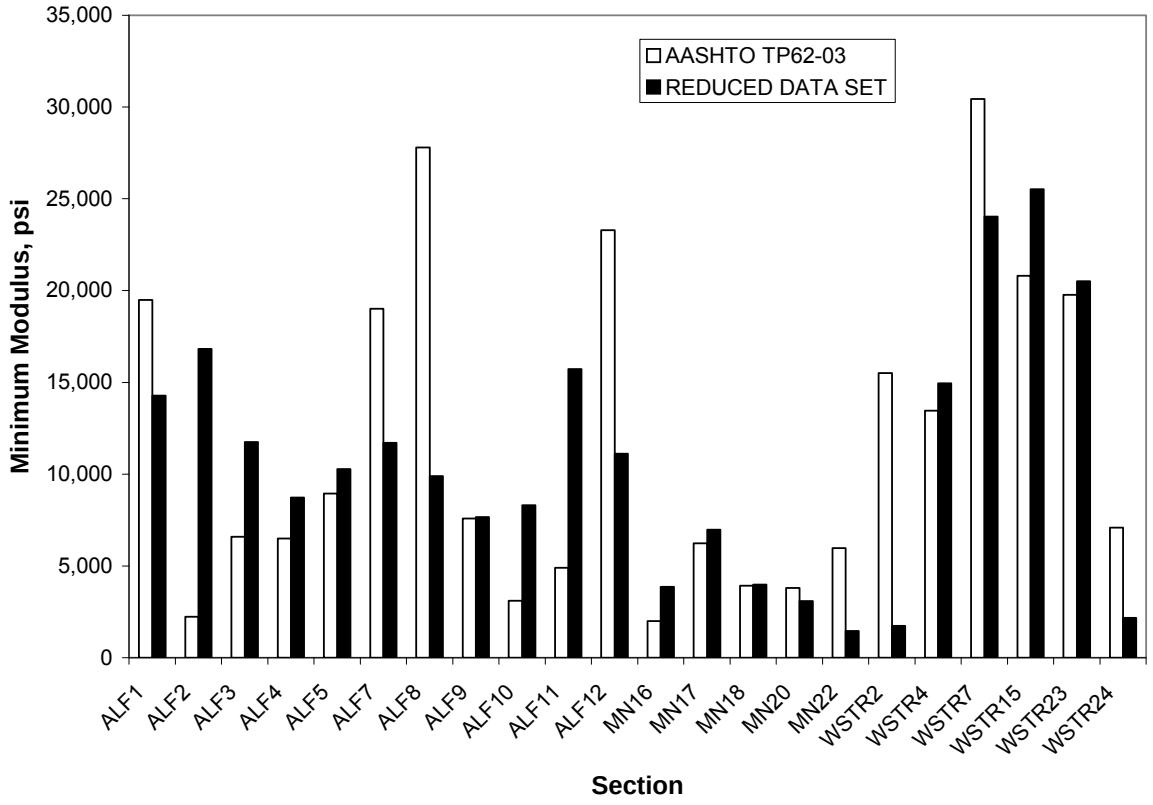


**Figure 6. Comparison of Limiting Minimum Moduli From the Two Procedures.**

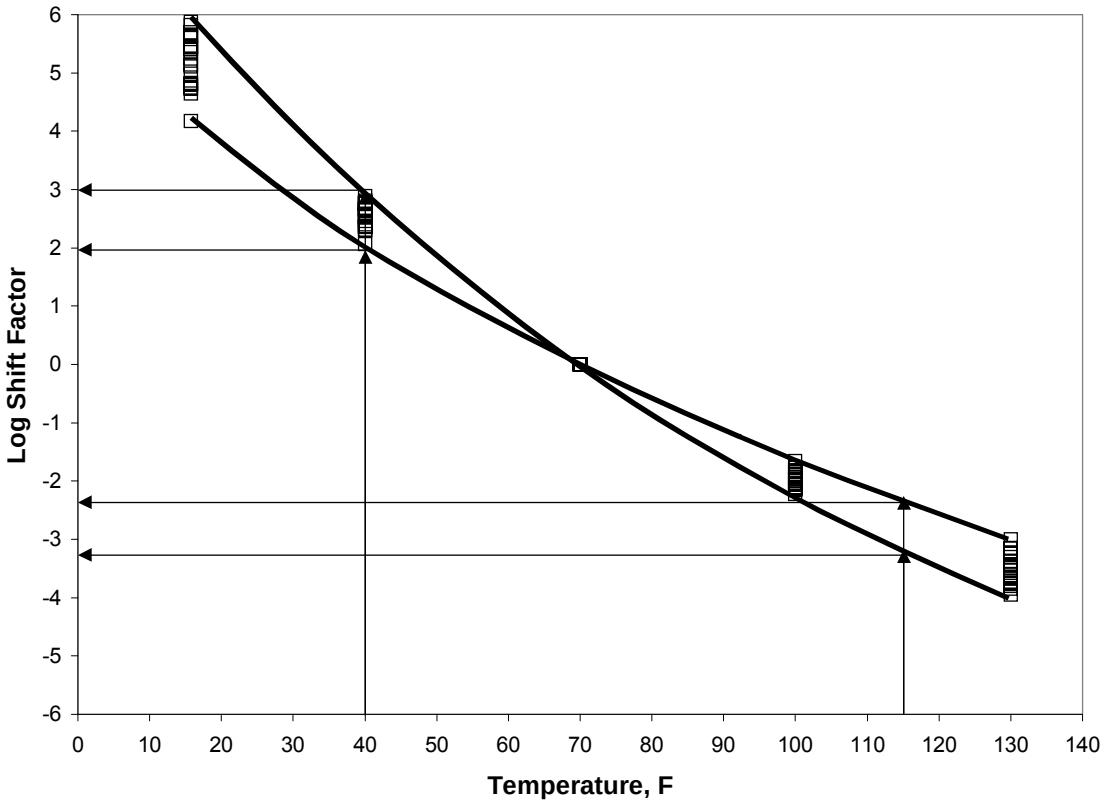


**Figure 7. Shift Factors as a Function of Temperature for the Mixtures in Table 1.**

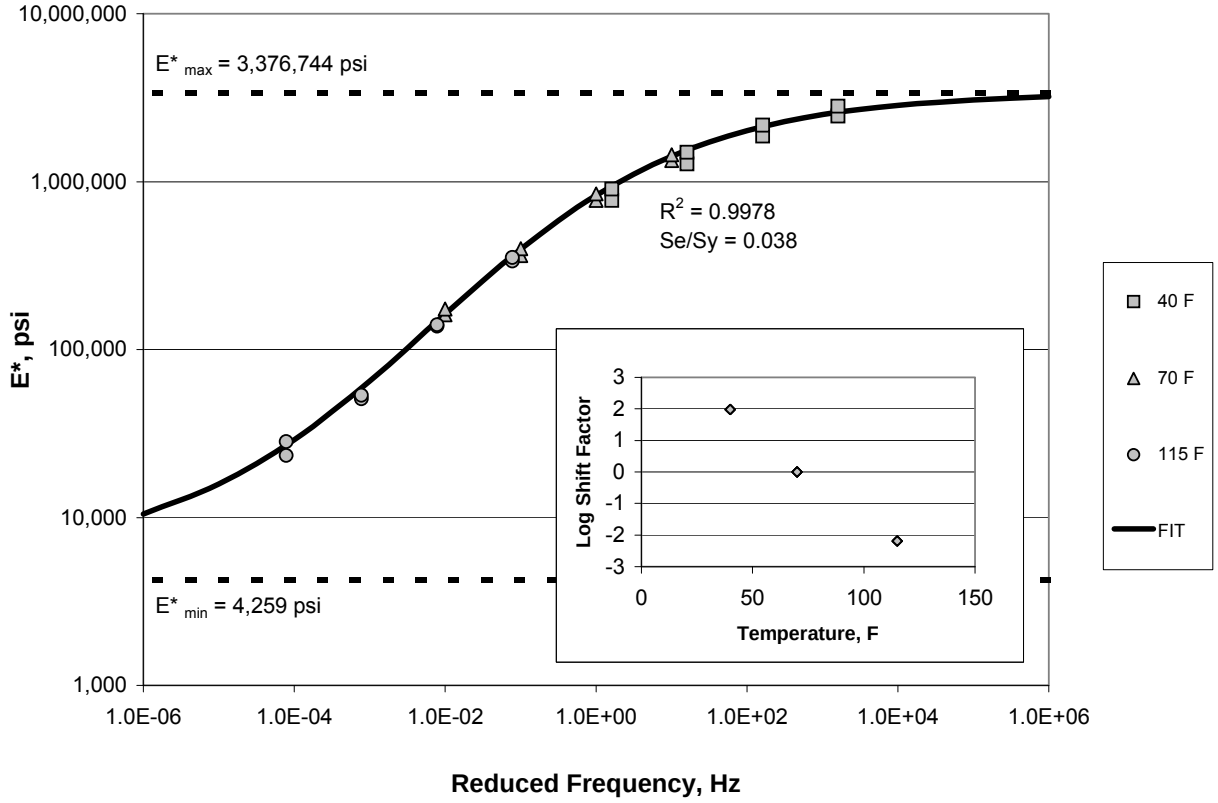


**Figure 8. Example Master Curve Using the Proposed Procedure.**

## APPENDIX I-B. Permanent Strain Data.

## Table I-B.1. Permanent Strain Data for the Dense Graded Mixture.

| | Permanent Strain from Actuator Displacement, % | | | | | | Permanent Strain from 100 mm Gauge Points, % | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Coefficient | | | | | | Coefficient |
| Load | Specimen | Specimen | Specimen | Average | Standard | of | Specimen | Specimen | Specimen | Average | Standard | of |
| Cycle | 1 | 2 | 3 | | Deviation | Variation | 1 | 2 | 3 | | Deviation | Variation |
| 0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.000 | NA | 0.00 | 0.00 | 0.00 | 0.00 | 0.0 | NA |
| 30 | 0.06 | 0.06 | 0.06 | 0.06 | 0.003 | 4.5 | 0.06 | 0.04 | 0.05 | 0.05 | 0.0 | 15.5 |
| 60 | 0.11 | 0.10 | 0.11 | 0.11 | 0.006 | 5.4 | 0.10 | 0.07 | 0.09 | 0.08 | 0.0 | 16.1 |
| 90 | 0.14 | 0.13 | 0.15 | 0.14 | 0.010 | 7.1 | 0.13 | 0.09 | 0.12 | 0.11 | 0.0 | 16.9 |
| 120 | 0.17 | 0.15 | 0.18 | 0.17 | 0.013 | 7.5 | 0.15 | 0.11 | 0.14 | 0.14 | 0.0 | 16.1 |
| 150 | 0.19 | 0.18 | 0.20 | 0.19 | 0.013 | 6.5 | 0.18 | 0.13 | 0.17 | 0.16 | 0.0 | 16.6 |
| 180 | 0.22 | 0.20 | 0.23 | 0.22 | 0.015 | 7.1 | 0.20 | 0.15 | 0.19 | 0.18 | 0.0 | 16.2 |
| 210 | 0.24 | 0.22 | 0.25 | 0.24 | 0.015 | 6.5 | 0.22 | 0.16 | 0.20 | 0.20 | 0.0 | 15.8 |
| 240 | 0.25 | 0.23 | 0.27 | 0.25 | 0.018 | 6.9 | 0.24 | 0.18 | 0.22 | 0.21 | 0.0 | 15.6 |
| 270 | 0.27 | 0.25 | 0.28 | 0.27 | 0.018 | 6.7 | 0.25 | 0.19 | 0.24 | 0.23 | 0.0 | 15.6 |
| 300 | 0.29 | 0.26 | 0.30 | 0.28 | 0.018 | 6.3 | 0.27 | 0.20 | 0.25 | 0.24 | 0.0 | 15.5 |
| 330 | 0.30 | 0.28 | 0.32 | 0.30 | 0.020 | 6.7 | 0.29 | 0.21 | 0.27 | 0.25 | 0.0 | 15.5 |
| 360 | 0.32 | 0.29 | 0.33 | 0.32 | 0.020 | 6.4 | 0.30 | 0.22 | 0.28 | 0.27 | 0.0 | 15.3 |
| 390 | 0.33 | 0.30 | 0.34 | 0.33 | 0.021 | 6.3 | 0.31 | 0.23 | 0.30 | 0.28 | 0.0 | 15.4 |
| 420 | 0.34 | 0.31 | 0.36 | 0.34 | 0.023 | 6.7 | 0.32 | 0.24 | 0.31 | 0.29 | 0.0 | 15.3 |
| 450 | 0.36 | 0.33 | 0.37 | 0.35 | 0.023 | 6.4 | 0.34 | 0.25 | 0.32 | 0.30 | 0.0 | 15.1 |
| 480 | 0.37 | 0.34 | 0.38 | 0.36 | 0.023 | 6.3 | 0.35 | 0.26 | 0.33 | 0.31 | 0.0 | 14.9 |
| 510 | 0.38 | 0.35 | 0.40 | 0.38 | 0.026 | 6.8 | 0.37 | 0.27 | 0.34 | 0.33 | 0.1 | 15.9 |
| 540 | 0.39 | 0.36 | 0.41 | 0.39 | 0.026 | 6.6 | 0.37 | 0.28 | 0.35 | 0.33 | 0.0 | 14.8 |
| 570 | 0.40 | 0.37 | 0.42 | 0.40 | 0.026 | 6.4 | 0.38 | 0.29 | 0.37 | 0.34 | 0.1 | 14.8 |
| 600 | 0.41 | 0.38 | 0.43 | 0.41 | 0.028 | 6.8 | 0.39 | 0.29 | 0.38 | 0.35 | 0.1 | 14.8 |
| 630 | 0.42 | 0.39 | 0.44 | 0.42 | 0.028 | 6.6 | 0.40 | 0.30 | 0.39 | 0.36 | 0.1 | 14.7 |
| 660 | 0.43 | 0.40 | 0.45 | 0.43 | 0.028 | 6.5 | 0.41 | 0.31 | 0.40 | 0.37 | 0.1 | 15.3 |
| 690 | 0.44 | 0.40 | 0.46 | 0.44 | 0.031 | 7.0 | 0.42 | 0.32 | 0.41 | 0.38 | 0.1 | 14.8 |
| 720 | 0.45 | 0.41 | 0.47 | 0.45 | 0.030 | 6.8 | 0.43 | 0.32 | 0.42 | 0.39 | 0.1 | 14.9 |
| 750 | 0.46 | 0.42 | 0.48 | 0.46 | 0.031 | 6.7 | 0.44 | 0.33 | 0.43 | 0.40 | 0.1 | 14.8 |
| 780 | 0.47 | 0.43 | 0.49 | 0.47 | 0.030 | 6.5 | 0.45 | 0.34 | 0.44 | 0.41 | 0.1 | 15.0 |
| 810 | 0.48 | 0.44 | 0.50 | 0.48 | 0.033 | 7.0 | 0.46 | 0.35 | 0.45 | 0.42 | 0.1 | 14.8 |

| | Permanent Strain from Actuator Displacement, % | | | | | | Permanent Strain from 100 mm Gauge Points, % | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Coefficient | | | | | | Coefficient |
| Load | Specimen | Specimen | Specimen | Average | Standard | of | Specimen | Specimen | Specimen | Average | Standard | of |
| Cycle | 1 | 2 | 3 | | Deviation | Variation | 1 | 2 | 3 | | Deviation | Variation |
| 840 | 0.49 | 0.45 | 0.51 | 0.48 | 0.033 | 6.7 | 0.47 | 0.35 | 0.45 | 0.42 | 0.1 | 14.8 |
| 870 | 0.50 | 0.46 | 0.52 | 0.49 | 0.031 | 6.2 | 0.47 | 0.36 | 0.46 | 0.43 | 0.1 | 14.8 |
| 900 | 0.51 | 0.46 | 0.53 | 0.50 | 0.033 | 6.6 | 0.48 | 0.36 | 0.47 | 0.44 | 0.1 | 15.0 |
| 930 | 0.51 | 0.47 | 0.54 | 0.51 | 0.035 | 7.0 | 0.49 | 0.37 | 0.48 | 0.45 | 0.1 | 15.0 |
| 960 | 0.52 | 0.48 | 0.55 | 0.52 | 0.035 | 6.8 | 0.50 | 0.38 | 0.49 | 0.46 | 0.1 | 14.9 |
| 990 | 0.53 | 0.49 | 0.56 | 0.53 | 0.035 | 6.7 | 0.51 | 0.38 | 0.50 | 0.46 | 0.1 | 14.9 |
| 1020 | 0.54 | 0.49 | 0.56 | 0.53 | 0.035 | 6.6 | 0.52 | 0.39 | 0.51 | 0.47 | 0.1 | 14.8 |
| 1050 | 0.55 | 0.50 | 0.57 | 0.54 | 0.038 | 7.0 | 0.52 | 0.40 | 0.52 | 0.48 | 0.1 | 15.0 |
| 1080 | 0.55 | 0.51 | 0.58 | 0.55 | 0.038 | 6.9 | 0.53 | 0.40 | 0.53 | 0.49 | 0.1 | 15.1 |
| 1110 | 0.56 | 0.51 | 0.59 | 0.56 | 0.040 | 7.2 | 0.54 | 0.41 | 0.54 | 0.49 | 0.1 | 15.1 |
| 1140 | 0.57 | 0.52 | 0.60 | 0.57 | 0.038 | 6.7 | 0.55 | 0.41 | 0.54 | 0.50 | 0.1 | 15.2 |
| 1170 | 0.58 | 0.53 | 0.61 | 0.57 | 0.040 | 7.0 | 0.56 | 0.42 | 0.55 | 0.51 | 0.1 | 15.1 |
| 1200 | 0.59 | 0.53 | 0.61 | 0.58 | 0.041 | 7.0 | 0.56 | 0.43 | 0.56 | 0.52 | 0.1 | 15.0 |
| 1230 | 0.59 | 0.54 | 0.62 | 0.59 | 0.040 | 6.9 | 0.57 | 0.43 | 0.57 | 0.52 | 0.1 | 15.3 |
| 1260 | 0.60 | 0.55 | 0.63 | 0.60 | 0.043 | 7.2 | 0.58 | 0.44 | 0.58 | 0.53 | 0.1 | 15.2 |
| 1290 | 0.61 | 0.55 | 0.64 | 0.60 | 0.043 | 7.2 | 0.58 | 0.44 | 0.58 | 0.54 | 0.1 | 15.1 |
| 1320 | 0.62 | 0.56 | 0.65 | 0.61 | 0.046 | 7.5 | 0.59 | 0.45 | 0.59 | 0.54 | 0.1 | 15.2 |
| 1350 | 0.62 | 0.57 | 0.65 | 0.62 | 0.043 | 7.0 | 0.60 | 0.45 | 0.60 | 0.55 | 0.1 | 15.2 |
| 1380 | 0.63 | 0.57 | 0.66 | 0.62 | 0.046 | 7.3 | 0.61 | 0.46 | 0.61 | 0.56 | 0.1 | 15.2 |
| 1410 | 0.64 | 0.58 | 0.67 | 0.63 | 0.046 | 7.3 | 0.61 | 0.47 | 0.62 | 0.56 | 0.1 | 15.2 |
| 1440 | 0.64 | 0.59 | 0.68 | 0.64 | 0.045 | 7.1 | 0.62 | 0.47 | 0.62 | 0.57 | 0.1 | 15.3 |
| 1470 | 0.65 | 0.59 | 0.68 | 0.64 | 0.046 | 7.1 | 0.63 | 0.48 | 0.63 | 0.58 | 0.1 | 15.2 |
| 1500 | 0.66 | 0.60 | 0.69 | 0.65 | 0.048 | 7.4 | 0.63 | 0.48 | 0.64 | 0.58 | 0.1 | 15.3 |
| 1530 | 0.67 | 0.60 | 0.70 | 0.66 | 0.051 | 7.7 | 0.64 | 0.49 | 0.65 | 0.59 | 0.1 | 15.3 |
| 1560 | 0.67 | 0.61 | 0.71 | 0.67 | 0.048 | 7.2 | 0.65 | 0.49 | 0.65 | 0.60 | 0.1 | 15.5 |
| 1590 | 0.68 | 0.62 | 0.72 | 0.67 | 0.050 | 7.5 | 0.65 | 0.49 | 0.66 | 0.60 | 0.1 | 15.6 |
| 1620 | 0.69 | 0.62 | 0.72 | 0.68 | 0.051 | 7.5 | 0.66 | 0.50 | 0.67 | 0.61 | 0.1 | 15.9 |
| 1650 | 0.69 | 0.63 | 0.73 | 0.69 | 0.053 | 7.7 | 0.67 | 0.51 | 0.68 | 0.62 | 0.1 | 15.6 |
| 1680 | 0.70 | 0.64 | 0.74 | 0.69 | 0.050 | 7.3 | 0.67 | 0.51 | 0.68 | 0.62 | 0.1 | 15.6 |
| 1710 | 0.71 | 0.64 | 0.74 | 0.70 | 0.051 | 7.3 | 0.68 | 0.52 | 0.69 | 0.63 | 0.1 | 15.6 |

| | Permanent Strain from Actuator Displacement, % | | | | | | Permanent Strain from 100 mm Gauge Points, % | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Coefficient | | | | | | Coefficient |
| Load | Specimen | Specimen | Specimen | Average | Standard | of | Specimen | Specimen | Specimen | Average | Standard | of |
| Cycle | 1 | 2 | 3 | | Deviation | Variation | 1 | 2 | 3 | | Deviation | Variation |
| 1740 | 0.71 | 0.65 | 0.75 | 0.71 | 0.053 | 7.5 | 0.69 | 0.52 | 0.70 | 0.64 | 0.1 | 15.7 |
| 1770 | 0.72 | 0.65 | 0.76 | 0.71 | 0.053 | 7.5 | 0.69 | 0.53 | 0.71 | 0.64 | 0.1 | 15.7 |
| 1800 | 0.73 | 0.66 | 0.77 | 0.72 | 0.056 | 7.7 | 0.70 | 0.53 | 0.71 | 0.65 | 0.1 | 15.9 |
| 1830 | 0.73 | 0.67 | 0.77 | 0.73 | 0.053 | 7.3 | 0.71 | 0.54 | 0.72 | 0.65 | 0.1 | 15.8 |
| 1860 | 0.74 | 0.67 | 0.78 | 0.73 | 0.056 | 7.6 | 0.71 | 0.54 | 0.73 | 0.66 | 0.1 | 15.8 |
| 1890 | 0.75 | 0.68 | 0.79 | 0.74 | 0.056 | 7.5 | 0.72 | 0.55 | 0.73 | 0.67 | 0.1 | 15.8 |
| 1920 | 0.75 | 0.68 | 0.80 | 0.75 | 0.058 | 7.8 | 0.73 | 0.55 | 0.74 | 0.67 | 0.1 | 15.8 |
| 1950 | 0.76 | 0.69 | 0.80 | 0.75 | 0.058 | 7.8 | 0.73 | 0.56 | 0.75 | 0.68 | 0.1 | 15.9 |
| 1980 | 0.77 | 0.69 | 0.81 | 0.76 | 0.061 | 8.0 | 0.74 | 0.56 | 0.76 | 0.68 | 0.1 | 15.9 |
| 2010 | 0.77 | 0.70 | 0.82 | 0.76 | 0.060 | 7.9 | 0.74 | 0.56 | 0.76 | 0.69 | 0.1 | 16.0 |
| 2040 | 0.78 | 0.70 | 0.83 | 0.77 | 0.063 | 8.2 | 0.75 | 0.57 | 0.77 | 0.70 | 0.1 | 16.0 |
| 2070 | 0.79 | 0.71 | 0.83 | 0.78 | 0.060 | 7.8 | 0.76 | 0.57 | 0.78 | 0.70 | 0.1 | 15.9 |
| 2100 | 0.79 | 0.72 | 0.84 | 0.78 | 0.060 | 7.7 | 0.76 | 0.58 | 0.79 | 0.71 | 0.1 | 16.0 |
| 2130 | 0.80 | 0.72 | 0.85 | 0.79 | 0.063 | 7.9 | 0.77 | 0.58 | 0.79 | 0.72 | 0.1 | 16.1 |
| 2160 | 0.80 | 0.73 | 0.85 | 0.80 | 0.063 | 7.9 | 0.78 | 0.59 | 0.80 | 0.72 | 0.1 | 16.0 |
| 2190 | 0.81 | 0.73 | 0.86 | 0.80 | 0.065 | 8.1 | 0.78 | 0.59 | 0.81 | 0.73 | 0.1 | 16.1 |
| 2220 | 0.82 | 0.74 | 0.87 | 0.81 | 0.065 | 8.1 | 0.79 | 0.60 | 0.82 | 0.73 | 0.1 | 16.2 |
| 2250 | 0.82 | 0.75 | 0.88 | 0.82 | 0.065 | 8.0 | 0.80 | 0.60 | 0.82 | 0.74 | 0.1 | 16.2 |
| 2280 | 0.83 | 0.75 | 0.88 | 0.82 | 0.065 | 8.0 | 0.80 | 0.61 | 0.83 | 0.75 | 0.1 | 16.1 |
| 2310 | 0.84 | 0.76 | 0.89 | 0.83 | 0.065 | 7.9 | 0.81 | 0.61 | 0.84 | 0.75 | 0.1 | 16.2 |
| 2340 | 0.85 | 0.76 | 0.90 | 0.84 | 0.068 | 8.1 | 0.81 | 0.62 | 0.85 | 0.76 | 0.1 | 16.3 |
| 2370 | 0.85 | 0.77 | 0.90 | 0.84 | 0.068 | 8.1 | 0.82 | 0.62 | 0.85 | 0.76 | 0.1 | 16.2 |
| 2400 | 0.86 | 0.77 | 0.91 | 0.85 | 0.070 | 8.3 | 0.83 | 0.63 | 0.86 | 0.77 | 0.1 | 16.4 |
| 2430 | 0.87 | 0.78 | 0.92 | 0.86 | 0.071 | 8.3 | 0.83 | 0.63 | 0.86 | 0.78 | 0.1 | 16.2 |
| 2460 | 0.87 | 0.78 | 0.93 | 0.86 | 0.073 | 8.5 | 0.84 | 0.64 | 0.87 | 0.78 | 0.1 | 16.3 |
| 2490 | 0.88 | 0.79 | 0.93 | 0.87 | 0.070 | 8.1 | 0.84 | 0.64 | 0.88 | 0.79 | 0.1 | 16.4 |
| 2520 | 0.88 | 0.80 | 0.94 | 0.87 | 0.070 | 8.1 | 0.85 | 0.64 | 0.89 | 0.79 | 0.1 | 16.5 |
| 2550 | 0.89 | 0.80 | 0.95 | 0.88 | 0.073 | 8.3 | 0.85 | 0.65 | 0.90 | 0.80 | 0.1 | 16.5 |
| 2580 | 0.90 | 0.81 | 0.96 | 0.89 | 0.075 | 8.5 | 0.86 | 0.65 | 0.90 | 0.81 | 0.1 | 16.5 |
| 2610 | 0.90 | 0.81 | 0.96 | 0.89 | 0.075 | 8.4 | 0.87 | 0.66 | 0.91 | 0.81 | 0.1 | 16.5 |

| | Permanent Strain from Actuator Displacement, % | | | | | | Permanent Strain from 100 mm Gauge Points, % | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Coefficient | | | | | | Coefficient |
| Load | Specimen | Specimen | Specimen | Average | Standard | of | Specimen | Specimen | Specimen | Average | Standard | of |
| Cycle | 1 | 2 | 3 | | Deviation | Variation | 1 | 2 | 3 | | Deviation | Variation |
| 2640 | 0.91 | 0.82 | 0.97 | 0.90 | 0.076 | 8.4 | 0.87 | 0.66 | 0.92 | 0.82 | 0.1 | 16.5 |
| 2670 | 0.92 | 0.82 | 0.98 | 0.91 | 0.078 | 8.6 | 0.88 | 0.67 | 0.93 | 0.82 | 0.1 | 16.7 |
| 2700 | 0.92 | 0.83 | 0.98 | 0.91 | 0.078 | 8.6 | 0.88 | 0.67 | 0.93 | 0.83 | 0.1 | 16.7 |
| 2730 | 0.93 | 0.83 | 0.99 | 0.92 | 0.080 | 8.7 | 0.89 | 0.68 | 0.94 | 0.84 | 0.1 | 16.7 |
| 2760 | 0.94 | 0.84 | 1.00 | 0.93 | 0.078 | 8.4 | 0.90 | 0.68 | 0.95 | 0.84 | 0.1 | 16.8 |
| 2790 | 0.94 | 0.85 | 1.01 | 0.93 | 0.080 | 8.6 | 0.90 | 0.69 | 0.96 | 0.85 | 0.1 | 16.8 |
| 2820 | 0.95 | 0.85 | 1.01 | 0.94 | 0.080 | 8.6 | 0.91 | 0.69 | 0.96 | 0.85 | 0.1 | 16.9 |
| 2850 | 0.96 | 0.86 | 1.02 | 0.94 | 0.081 | 8.5 | 0.92 | 0.70 | 0.97 | 0.86 | 0.1 | 17.0 |
| 2880 | 0.96 | 0.86 | 1.03 | 0.95 | 0.083 | 8.7 | 0.92 | 0.70 | 0.98 | 0.87 | 0.1 | 17.0 |
| 2910 | 0.97 | 0.87 | 1.03 | 0.96 | 0.083 | 8.7 | 0.93 | 0.70 | 0.99 | 0.87 | 0.1 | 17.1 |
| 2940 | 0.97 | 0.87 | 1.04 | 0.96 | 0.085 | 8.9 | 0.93 | 0.71 | 0.99 | 0.88 | 0.1 | 17.0 |
| 2970 | 0.98 | 0.88 | 1.05 | 0.97 | 0.086 | 8.8 | 0.94 | 0.71 | 1.00 | 0.88 | 0.2 | 17.1 |
| 3000 | 0.99 | 0.88 | 1.06 | 0.98 | 0.088 | 9.0 | 0.95 | 0.72 | 1.01 | 0.89 | 0.2 | 17.2 |
| 3030 | 0.99 | 0.89 | 1.06 | 0.98 | 0.088 | 9.0 | 0.95 | 0.72 | 1.02 | 0.90 | 0.2 | 17.2 |
| 3060 | 1.00 | 0.89 | 1.07 | 0.99 | 0.091 | 9.2 | 0.96 | 0.73 | 1.02 | 0.90 | 0.2 | 17.3 |
| 3090 | 1.01 | 0.90 | 1.08 | 1.00 | 0.088 | 8.8 | 0.96 | 0.73 | 1.03 | 0.91 | 0.2 | 17.3 |
| 3120 | 1.01 | 0.91 | 1.09 | 1.00 | 0.090 | 9.0 | 0.97 | 0.74 | 1.04 | 0.92 | 0.2 | 17.4 |
| 3150 | 1.02 | 0.91 | 1.09 | 1.01 | 0.091 | 9.0 | 0.98 | 0.74 | 1.05 | 0.92 | 0.2 | 17.4 |
| 3180 | 1.02 | 0.92 | 1.10 | 1.01 | 0.093 | 9.1 | 0.98 | 0.75 | 1.05 | 0.93 | 0.2 | 17.5 |
| 3210 | 1.03 | 0.92 | 1.11 | 1.02 | 0.093 | 9.1 | 0.99 | 0.75 | 1.06 | 0.93 | 0.2 | 17.5 |
| 3240 | 1.04 | 0.93 | 1.12 | 1.03 | 0.095 | 9.3 | 1.00 | 0.75 | 1.07 | 0.94 | 0.2 | 17.5 |
| 3270 | 1.05 | 0.93 | 1.12 | 1.03 | 0.095 | 9.2 | 1.00 | 0.76 | 1.08 | 0.95 | 0.2 | 17.6 |
| 3300 | 1.05 | 0.94 | 1.13 | 1.04 | 0.096 | 9.2 | 1.01 | 0.76 | 1.08 | 0.95 | 0.2 | 17.7 |
| 3330 | 1.06 | 0.94 | 1.14 | 1.05 | 0.098 | 9.4 | 1.02 | 0.77 | 1.09 | 0.96 | 0.2 | 17.7 |
| 3360 | 1.07 | 0.95 | 1.15 | 1.05 | 0.100 | 9.5 | 1.02 | 0.77 | 1.10 | 0.96 | 0.2 | 17.8 |
| 3390 | 1.07 | 0.95 | 1.15 | 1.06 | 0.100 | 9.5 | 1.03 | 0.78 | 1.11 | 0.97 | 0.2 | 17.9 |
| 3420 | 1.08 | 0.96 | 1.16 | 1.07 | 0.098 | 9.2 | 1.03 | 0.78 | 1.11 | 0.98 | 0.2 | 17.8 |
| 3450 | 1.09 | 0.96 | 1.17 | 1.07 | 0.103 | 9.6 | 1.04 | 0.78 | 1.12 | 0.98 | 0.2 | 18.0 |
| 3480 | 1.09 | 0.97 | 1.17 | 1.08 | 0.100 | 9.3 | 1.05 | 0.79 | 1.13 | 0.99 | 0.2 | 18.0 |
| 3510 | 1.10 | 0.98 | 1.18 | 1.09 | 0.103 | 9.5 | 1.05 | 0.80 | 1.14 | 1.00 | 0.2 | 17.9 |

| | Permanent Strain from Actuator Displacement, % | | | | | | Permanent Strain from 100 mm Gauge Points, % | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Coefficient | | | | | | Coefficient |
| Load | Specimen | Specimen | Specimen | Average | Standard | of | Specimen | Specimen | Specimen | Average | Standard | of |
| Cycle | 1 | 2 | 3 | | Deviation | Variation | 1 | 2 | 3 | | Deviation | Variation |
| 3540 | 1.11 | 0.98 | 1.19 | 1.09 | 0.103 | 9.4 | 1.06 | 0.80 | 1.15 | 1.00 | 0.2 | 18.1 |
| 3570 | 1.11 | 0.99 | 1.20 | 1.10 | 0.105 | 9.6 | 1.07 | 0.80 | 1.15 | 1.01 | 0.2 | 18.1 |
| 3600 | 1.12 | 0.99 | 1.21 | 1.11 | 0.108 | 9.7 | 1.07 | 0.81 | 1.16 | 1.01 | 0.2 | 18.2 |
| 3630 | 1.13 | 1.00 | 1.21 | 1.11 | 0.108 | 9.7 | 1.08 | 0.81 | 1.17 | 1.02 | 0.2 | 18.2 |
| 3660 | 1.13 | 1.00 | 1.22 | 1.12 | 0.110 | 9.9 | 1.09 | 0.82 | 1.18 | 1.03 | 0.2 | 18.3 |
| 3690 | 1.14 | 1.01 | 1.23 | 1.12 | 0.110 | 9.8 | 1.09 | 0.82 | 1.19 | 1.03 | 0.2 | 18.4 |
| 3720 | 1.14 | 1.02 | 1.24 | 1.13 | 0.110 | 9.7 | 1.10 | 0.82 | 1.19 | 1.04 | 0.2 | 18.4 |
| 3750 | 1.15 | 1.02 | 1.24 | 1.14 | 0.110 | 9.7 | 1.11 | 0.83 | 1.20 | 1.05 | 0.2 | 18.5 |
| 3780 | 1.16 | 1.03 | 1.25 | 1.15 | 0.113 | 9.9 | 1.11 | 0.83 | 1.21 | 1.05 | 0.2 | 18.6 |
| 3810 | 1.17 | 1.03 | 1.26 | 1.15 | 0.115 | 10.0 | 1.12 | 0.84 | 1.22 | 1.06 | 0.2 | 18.6 |
| 3840 | 1.17 | 1.04 | 1.27 | 1.16 | 0.115 | 9.9 | 1.13 | 0.84 | 1.23 | 1.07 | 0.2 | 18.7 |
| 3870 | 1.18 | 1.04 | 1.28 | 1.17 | 0.118 | 10.1 | 1.13 | 0.85 | 1.23 | 1.07 | 0.2 | 18.6 |
| 3900 | 1.19 | 1.05 | 1.28 | 1.17 | 0.118 | 10.1 | 1.14 | 0.85 | 1.24 | 1.08 | 0.2 | 18.8 |
| 3930 | 1.19 | 1.05 | 1.29 | 1.18 | 0.120 | 10.2 | 1.15 | 0.86 | 1.25 | 1.09 | 0.2 | 18.8 |
| 3960 | 1.20 | 1.06 | 1.30 | 1.19 | 0.118 | 9.9 | 1.16 | 0.86 | 1.26 | 1.09 | 0.2 | 18.8 |
| 3990 | 1.21 | 1.07 | 1.31 | 1.19 | 0.120 | 10.1 | 1.16 | 0.87 | 1.26 | 1.10 | 0.2 | 18.9 |
| 4020 | 1.22 | 1.07 | 1.32 | 1.20 | 0.123 | 10.2 | 1.17 | 0.87 | 1.27 | 1.10 | 0.2 | 18.9 |
| 4050 | 1.22 | 1.08 | 1.33 | 1.21 | 0.125 | 10.4 | 1.18 | 0.88 | 1.28 | 1.11 | 0.2 | 19.1 |
| 4080 | 1.23 | 1.08 | 1.33 | 1.21 | 0.125 | 10.3 | 1.19 | 0.88 | 1.29 | 1.12 | 0.2 | 19.1 |
| 4110 | 1.24 | 1.09 | 1.34 | 1.22 | 0.128 | 10.5 | 1.19 | 0.88 | 1.30 | 1.12 | 0.2 | 19.2 |
| 4140 | 1.24 | 1.09 | 1.35 | 1.23 | 0.128 | 10.4 | 1.20 | 0.89 | 1.31 | 1.13 | 0.2 | 19.3 |
| 4170 | 1.25 | 1.10 | 1.36 | 1.23 | 0.130 | 10.5 | 1.21 | 0.89 | 1.31 | 1.14 | 0.2 | 19.3 |
| 4200 | 1.26 | 1.11 | 1.37 | 1.24 | 0.130 | 10.5 | 1.21 | 0.90 | 1.32 | 1.14 | 0.2 | 19.4 |
| 4230 | 1.26 | 1.11 | 1.37 | 1.25 | 0.130 | 10.4 | 1.22 | 0.90 | 1.33 | 1.15 | 0.2 | 19.4 |
| 4260 | 1.27 | 1.12 | 1.38 | 1.26 | 0.133 | 10.6 | 1.23 | 0.91 | 1.34 | 1.16 | 0.2 | 19.5 |
| 4290 | 1.28 | 1.12 | 1.39 | 1.26 | 0.135 | 10.7 | 1.23 | 0.91 | 1.35 | 1.17 | 0.2 | 19.6 |
| 4320 | 1.28 | 1.13 | 1.40 | 1.27 | 0.135 | 10.7 | 1.24 | 0.92 | 1.36 | 1.17 | 0.2 | 19.6 |
| 4350 | 1.29 | 1.14 | 1.41 | 1.28 | 0.135 | 10.6 | 1.25 | 0.92 | 1.37 | 1.18 | 0.2 | 19.6 |
| 4380 | 1.30 | 1.14 | 1.42 | 1.28 | 0.140 | 10.9 | 1.26 | 0.92 | 1.38 | 1.19 | 0.2 | 19.7 |
| 4410 | 1.31 | 1.15 | 1.42 | 1.29 | 0.138 | 10.7 | 1.26 | 0.93 | 1.38 | 1.19 | 0.2 | 19.8 |

| | Permanent Strain from Actuator Displacement, % | | | | | | Permanent Strain from 100 mm Gauge Points, % | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Coefficient | | | | | | Coefficient |
| Load | Specimen | Specimen | Specimen | Average | Standard | of | Specimen | Specimen | Specimen | Average | Standard | of |
| Cycle | 1 | 2 | 3 | | Deviation | Variation | 1 | 2 | 3 | | Deviation | Variation |
| 4440 | 1.31 | 1.15 | 1.43 | 1.30 | 0.140 | 10.8 | 1.27 | 0.93 | 1.39 | 1.20 | 0.2 | 19.9 |
| 4470 | 1.32 | 1.16 | 1.44 | 1.31 | 0.143 | 10.9 | 1.28 | 0.94 | 1.40 | 1.21 | 0.2 | 19.8 |
| 4500 | 1.33 | 1.16 | 1.45 | 1.31 | 0.145 | 11.0 | 1.29 | 0.94 | 1.41 | 1.21 | 0.2 | 20.0 |
| 4530 | 1.34 | 1.17 | 1.46 | 1.32 | 0.145 | 11.0 | 1.29 | 0.95 | 1.42 | 1.22 | 0.2 | 20.0 |
| 4560 | 1.34 | 1.18 | 1.47 | 1.33 | 0.145 | 10.9 | 1.30 | 0.95 | 1.43 | 1.23 | 0.2 | 20.0 |
| 4590 | 1.35 | 1.18 | 1.48 | 1.34 | 0.148 | 11.0 | 1.31 | 0.96 | 1.44 | 1.24 | 0.2 | 20.1 |
| 4620 | 1.36 | 1.19 | 1.49 | 1.34 | 0.150 | 11.2 | 1.32 | 0.96 | 1.45 | 1.24 | 0.3 | 20.2 |
| 4650 | 1.36 | 1.19 | 1.49 | 1.35 | 0.150 | 11.1 | 1.33 | 0.97 | 1.46 | 1.25 | 0.3 | 20.3 |
| 4680 | 1.37 | 1.20 | 1.50 | 1.36 | 0.153 | 11.2 | 1.33 | 0.97 | 1.47 | 1.26 | 0.3 | 20.3 |
| 4710 | 1.38 | 1.21 | 1.51 | 1.37 | 0.153 | 11.2 | 1.34 | 0.98 | 1.47 | 1.26 | 0.3 | 20.3 |
| 4740 | 1.39 | 1.21 | 1.52 | 1.37 | 0.155 | 11.3 | 1.35 | 0.98 | 1.48 | 1.27 | 0.3 | 20.4 |
| 4770 | 1.39 | 1.22 | 1.53 | 1.38 | 0.155 | 11.2 | 1.36 | 0.99 | 1.49 | 1.28 | 0.3 | 20.5 |
| 4800 | 1.40 | 1.23 | 1.54 | 1.39 | 0.155 | 11.2 | 1.36 | 0.99 | 1.50 | 1.29 | 0.3 | 20.6 |
| 4830 | 1.41 | 1.23 | 1.55 | 1.40 | 0.158 | 11.3 | 1.37 | 1.00 | 1.51 | 1.29 | 0.3 | 20.6 |
| 4860 | 1.42 | 1.24 | 1.56 | 1.40 | 0.160 | 11.4 | 1.38 | 1.00 | 1.52 | 1.30 | 0.3 | 20.7 |
| 4890 | 1.43 | 1.24 | 1.56 | 1.41 | 0.160 | 11.4 | 1.39 | 1.01 | 1.53 | 1.31 | 0.3 | 20.8 |
| 4920 | 1.43 | 1.25 | 1.57 | 1.42 | 0.163 | 11.5 | 1.40 | 1.01 | 1.54 | 1.32 | 0.3 | 20.8 |
| 4950 | 1.44 | 1.26 | 1.58 | 1.43 | 0.163 | 11.4 | 1.40 | 1.02 | 1.55 | 1.32 | 0.3 | 20.8 |
| 4980 | 1.45 | 1.26 | 1.59 | 1.43 | 0.165 | 11.5 | 1.41 | 1.02 | 1.56 | 1.33 | 0.3 | 20.9 |
| 5010 | 1.46 | 1.27 | 1.60 | 1.44 | 0.168 | 11.6 | 1.42 | 1.03 | 1.57 | 1.34 | 0.3 | 21.0 |
| 5040 | 1.46 | 1.27 | 1.61 | 1.45 | 0.170 | 11.7 | 1.43 | 1.03 | 1.58 | 1.34 | 0.3 | 21.0 |
| 5070 | 1.47 | 1.28 | 1.62 | 1.46 | 0.170 | 11.7 | 1.43 | 1.04 | 1.59 | 1.35 | 0.3 | 21.1 |
| 5100 | 1.48 | 1.29 | 1.63 | 1.47 | 0.170 | 11.6 | 1.44 | 1.04 | 1.60 | 1.36 | 0.3 | 21.1 |
| 5130 | 1.49 | 1.29 | 1.64 | 1.47 | 0.173 | 11.7 | 1.45 | 1.04 | 1.61 | 1.37 | 0.3 | 21.2 |
| 5160 | 1.50 | 1.30 | 1.65 | 1.48 | 0.175 | 11.8 | 1.46 | 1.05 | 1.62 | 1.37 | 0.3 | 21.2 |
| 5190 | 1.50 | 1.31 | 1.66 | 1.49 | 0.175 | 11.8 | 1.47 | 1.05 | 1.63 | 1.38 | 0.3 | 21.3 |
| 5220 | 1.51 | 1.31 | 1.67 | 1.50 | 0.178 | 11.9 | 1.47 | 1.06 | 1.64 | 1.39 | 0.3 | 21.3 |
| 5250 | 1.52 | 1.32 | 1.68 | 1.50 | 0.180 | 12.0 | 1.48 | 1.07 | 1.65 | 1.40 | 0.3 | 21.4 |
| 5280 | 1.53 | 1.32 | 1.69 | 1.51 | 0.183 | 12.1 | 1.49 | 1.07 | 1.65 | 1.40 | 0.3 | 21.4 |
| 5310 | 1.53 | 1.33 | 1.70 | 1.52 | 0.182 | 12.0 | 1.50 | 1.08 | 1.66 | 1.41 | 0.3 | 21.5 |

| | Permanent Strain from Actuator Displacement, % | | | | | | Permanent Strain from 100 mm Gauge Points, % | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Coefficient | | | | | | Coefficient |
| Load | Specimen | Specimen | Specimen | Average | Standard | of | Specimen | Specimen | Specimen | Average | Standard | of |
| Cycle | 1 | 2 | 3 | | Deviation | Variation | 1 | 2 | 3 | | Deviation | Variation |
| 5340 | 1.54 | 1.34 | 1.71 | 1.53 | 0.185 | 12.1 | 1.51 | 1.08 | 1.67 | 1.42 | 0.3 | 21.5 |
| 5370 | 1.55 | 1.34 | 1.72 | 1.54 | 0.188 | 12.2 | 1.52 | 1.09 | 1.68 | 1.43 | 0.3 | 21.6 |
| 5400 | 1.56 | 1.35 | 1.73 | 1.55 | 0.188 | 12.1 | 1.52 | 1.09 | 1.69 | 1.44 | 0.3 | 21.6 |
| 5430 | 1.57 | 1.36 | 1.74 | 1.55 | 0.190 | 12.2 | 1.53 | 1.10 | 1.70 | 1.44 | 0.3 | 21.7 |
| 5460 | 1.58 | 1.36 | 1.75 | 1.56 | 0.193 | 12.3 | 1.54 | 1.10 | 1.71 | 1.45 | 0.3 | 21.8 |
| 5490 | 1.59 | 1.37 | 1.76 | 1.57 | 0.193 | 12.3 | 1.55 | 1.11 | 1.72 | 1.46 | 0.3 | 21.8 |
| 5520 | 1.59 | 1.38 | 1.77 | 1.58 | 0.195 | 12.3 | 1.56 | 1.11 | 1.73 | 1.47 | 0.3 | 21.9 |
| 5550 | 1.60 | 1.38 | 1.78 | 1.59 | 0.198 | 12.4 | 1.57 | 1.12 | 1.74 | 1.47 | 0.3 | 21.9 |
| 5580 | 1.61 | 1.39 | 1.79 | 1.60 | 0.200 | 12.5 | 1.58 | 1.12 | 1.75 | 1.48 | 0.3 | 22.0 |
| 5610 | 1.62 | 1.40 | 1.80 | 1.61 | 0.202 | 12.6 | 1.58 | 1.13 | 1.76 | 1.49 | 0.3 | 22.0 |
| 5640 | 1.63 | 1.41 | 1.81 | 1.62 | 0.202 | 12.5 | 1.59 | 1.13 | 1.78 | 1.50 | 0.3 | 22.1 |
| 5670 | 1.64 | 1.41 | 1.82 | 1.62 | 0.205 | 12.6 | 1.60 | 1.14 | 1.79 | 1.51 | 0.3 | 22.2 |
| 5700 | 1.65 | 1.42 | 1.83 | 1.63 | 0.207 | 12.7 | 1.61 | 1.14 | 1.80 | 1.52 | 0.3 | 22.3 |
| 5730 | 1.66 | 1.43 | 1.84 | 1.64 | 0.208 | 12.6 | 1.62 | 1.15 | 1.81 | 1.52 | 0.3 | 22.4 |
| 5760 | 1.66 | 1.43 | 1.85 | 1.65 | 0.210 | 12.7 | 1.63 | 1.15 | 1.82 | 1.53 | 0.3 | 22.3 |
| 5790 | 1.67 | 1.44 | 1.87 | 1.66 | 0.212 | 12.8 | 1.63 | 1.16 | 1.83 | 1.54 | 0.3 | 22.5 |
| 5820 | 1.68 | 1.45 | 1.88 | 1.67 | 0.215 | 12.9 | 1.64 | 1.16 | 1.84 | 1.55 | 0.3 | 22.6 |
| 5850 | 1.69 | 1.45 | 1.89 | 1.68 | 0.217 | 13.0 | 1.65 | 1.17 | 1.85 | 1.56 | 0.4 | 22.6 |
| 5880 | 1.70 | 1.46 | 1.90 | 1.69 | 0.217 | 12.9 | 1.66 | 1.17 | 1.86 | 1.57 | 0.4 | 22.7 |
| 5910 | 1.71 | 1.47 | 1.91 | 1.69 | 0.220 | 13.0 | 1.67 | 1.18 | 1.87 | 1.57 | 0.4 | 22.8 |
| 5940 | 1.72 | 1.48 | 1.92 | 1.71 | 0.222 | 13.0 | 1.68 | 1.18 | 1.88 | 1.58 | 0.4 | 22.8 |
| 5970 | 1.72 | 1.48 | 1.93 | 1.71 | 0.225 | 13.1 | 1.69 | 1.19 | 1.89 | 1.59 | 0.4 | 22.8 |
| 6000 | 1.73 | 1.49 | 1.94 | 1.72 | 0.227 | 13.2 | 1.70 | 1.19 | 1.91 | 1.60 | 0.4 | 22.9 |
| 6030 | 1.74 | 1.50 | 1.96 | 1.73 | 0.230 | 13.3 | 1.70 | 1.20 | 1.92 | 1.61 | 0.4 | 22.9 |
| 6060 | 1.75 | 1.50 | 1.97 | 1.74 | 0.232 | 13.3 | 1.71 | 1.20 | 1.93 | 1.62 | 0.4 | 23.1 |
| 6090 | 1.76 | 1.51 | 1.98 | 1.75 | 0.232 | 13.3 | 1.72 | 1.21 | 1.94 | 1.62 | 0.4 | 23.1 |
| 6120 | 1.77 | 1.52 | 1.99 | 1.76 | 0.235 | 13.4 | 1.73 | 1.21 | 1.95 | 1.63 | 0.4 | 23.2 |
| 6150 | 1.78 | 1.53 | 2.00 | 1.77 | 0.237 | 13.4 | 1.74 | 1.22 | 1.96 | 1.64 | 0.4 | 23.2 |
| 6180 | 1.79 | 1.53 | 2.01 | 1.78 | 0.240 | 13.5 | 1.75 | 1.23 | 1.98 | 1.65 | 0.4 | 23.3 |
| 6210 | 1.80 | 1.54 | 2.02 | 1.79 | 0.240 | 13.4 | 1.76 | 1.23 | 1.99 | 1.66 | 0.4 | 23.4 |

| | Permanent Strain from Actuator Displacement, % | | | | | | Permanent Strain from 100 mm Gauge Points, % | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Coefficient | | | | | | Coefficient |
| Load | Specimen | Specimen | Specimen | Average | Standard | of | Specimen | Specimen | Specimen | Average | Standard | of |
| Cycle | 1 | 2 | 3 | | Deviation | Variation | 1 | 2 | 3 | | Deviation | Variation |
| 6240 | 1.81 | 1.55 | 2.04 | 1.80 | 0.245 | 13.6 | 1.77 | 1.24 | 2.00 | 1.67 | 0.4 | 23.4 |
| 6270 | 1.82 | 1.56 | 2.05 | 1.81 | 0.245 | 13.5 | 1.77 | 1.24 | 2.01 | 1.68 | 0.4 | 23.5 |
| 6300 | 1.83 | 1.56 | 2.06 | 1.82 | 0.250 | 13.7 | 1.78 | 1.25 | 2.03 | 1.69 | 0.4 | 23.6 |
| 6330 | 1.84 | 1.57 | 2.07 | 1.83 | 0.250 | 13.7 | 1.79 | 1.25 | 2.04 | 1.70 | 0.4 | 23.6 |
| 6360 | 1.84 | 1.58 | 2.09 | 1.84 | 0.255 | 13.9 | 1.80 | 1.26 | 2.05 | 1.70 | 0.4 | 23.8 |
| 6390 | 1.85 | 1.59 | 2.10 | 1.85 | 0.255 | 13.8 | 1.81 | 1.27 | 2.06 | 1.71 | 0.4 | 23.8 |
| 6420 | 1.86 | 1.59 | 2.11 | 1.86 | 0.260 | 14.0 | 1.82 | 1.27 | 2.08 | 1.72 | 0.4 | 23.8 |
| 6450 | 1.87 | 1.60 | 2.12 | 1.87 | 0.260 | 13.9 | 1.83 | 1.28 | 2.09 | 1.73 | 0.4 | 24.0 |
| 6480 | 1.88 | 1.61 | 2.14 | 1.87 | 0.265 | 14.1 | 1.84 | 1.28 | 2.10 | 1.74 | 0.4 | 24.1 |
| 6510 | 1.89 | 1.62 | 2.15 | 1.89 | 0.265 | 14.0 | 1.85 | 1.29 | 2.12 | 1.75 | 0.4 | 24.2 |
| 6540 | 1.90 | 1.62 | 2.16 | 1.89 | 0.270 | 14.2 | 1.86 | 1.29 | 2.13 | 1.76 | 0.4 | 24.2 |
| 6570 | 1.91 | 1.63 | 2.17 | 1.90 | 0.270 | 14.2 | 1.87 | 1.30 | 2.15 | 1.77 | 0.4 | 24.4 |
| 6600 | 1.92 | 1.64 | 2.19 | 1.92 | 0.272 | 14.2 | 1.88 | 1.31 | 2.16 | 1.78 | 0.4 | 24.5 |
| 6630 | 1.93 | 1.65 | 2.20 | 1.92 | 0.275 | 14.3 | 1.89 | 1.31 | 2.17 | 1.79 | 0.4 | 24.5 |
| 6660 | 1.94 | 1.66 | 2.21 | 1.94 | 0.277 | 14.3 | 1.90 | 1.32 | 2.19 | 1.80 | 0.4 | 24.6 |
| 6690 | 1.95 | 1.66 | 2.23 | 1.95 | 0.282 | 14.5 | 1.91 | 1.32 | 2.20 | 1.81 | 0.4 | 24.7 |
| 6720 | 1.96 | 1.67 | 2.24 | 1.96 | 0.282 | 14.4 | 1.92 | 1.33 | 2.22 | 1.82 | 0.5 | 24.8 |

## Table I-B.2. Permanent Strain Data for the SMA Mixture.

| | Permanent Strain from Actuator Displacement, % | | | | | | Permanent Strain from 100 mm Gauge Points, % | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Coefficient | | | | | | Coefficient |
| Load | Specimen | Specimen | Specimen | Average | Standard | of | Specimen | Specimen | Specimen | Average | Standard | of |
| Cycle | 1 | 2 | 3 | | Deviation | Variation | 1 | 2 | 3 | | Deviation | Variation |
| 0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.000 | NA | 0.00 | 0.00 | 0.00 | 0.00 | 0.000 | NA |
| 30 | 0.03 | 0.05 | 0.02 | 0.03 | 0.013 | 37.9 | 0.02 | 0.03 | 0.01 | 0.02 | 0.012 | 57.5 |
| 60 | 0.05 | 0.09 | 0.04 | 0.06 | 0.024 | 40.7 | 0.04 | 0.06 | 0.03 | 0.04 | 0.015 | 35.6 |
| 90 | 0.07 | 0.11 | 0.05 | 0.08 | 0.028 | 36.4 | 0.05 | 0.07 | 0.03 | 0.05 | 0.023 | 44.2 |
| 120 | 0.08 | 0.13 | 0.06 | 0.09 | 0.033 | 35.7 | 0.06 | 0.09 | 0.04 | 0.06 | 0.027 | 43.0 |
| 150 | 0.10 | 0.14 | 0.07 | 0.11 | 0.035 | 33.3 | 0.07 | 0.10 | 0.05 | 0.07 | 0.028 | 37.1 |
| 180 | 0.11 | 0.16 | 0.08 | 0.12 | 0.038 | 32.3 | 0.08 | 0.11 | 0.05 | 0.08 | 0.034 | 42.2 |
| 210 | 0.12 | 0.17 | 0.09 | 0.13 | 0.043 | 33.7 | 0.09 | 0.12 | 0.06 | 0.09 | 0.032 | 35.1 |
| 240 | 0.13 | 0.18 | 0.10 | 0.14 | 0.043 | 31.2 | 0.09 | 0.13 | 0.07 | 0.10 | 0.031 | 31.5 |
| 270 | 0.13 | 0.19 | 0.10 | 0.14 | 0.046 | 31.6 | 0.10 | 0.14 | 0.08 | 0.11 | 0.032 | 29.9 |
| 300 | 0.14 | 0.21 | 0.11 | 0.15 | 0.051 | 32.8 | 0.10 | 0.15 | 0.08 | 0.11 | 0.033 | 29.5 |
| 330 | 0.15 | 0.21 | 0.12 | 0.16 | 0.049 | 30.1 | 0.11 | 0.16 | 0.09 | 0.12 | 0.034 | 29.0 |
| 360 | 0.16 | 0.22 | 0.12 | 0.17 | 0.053 | 31.5 | 0.12 | 0.16 | 0.09 | 0.12 | 0.035 | 28.1 |
| 390 | 0.16 | 0.23 | 0.13 | 0.18 | 0.053 | 30.2 | 0.12 | 0.17 | 0.10 | 0.13 | 0.037 | 28.6 |
| 420 | 0.17 | 0.24 | 0.13 | 0.18 | 0.053 | 29.5 | 0.12 | 0.18 | 0.10 | 0.13 | 0.037 | 27.9 |
| 450 | 0.17 | 0.25 | 0.14 | 0.19 | 0.056 | 29.8 | 0.13 | 0.18 | 0.11 | 0.14 | 0.038 | 27.1 |
| 480 | 0.18 | 0.25 | 0.14 | 0.19 | 0.058 | 30.5 | 0.13 | 0.19 | 0.11 | 0.14 | 0.039 | 27.1 |
| 510 | 0.18 | 0.26 | 0.14 | 0.20 | 0.058 | 29.7 | 0.14 | 0.19 | 0.11 | 0.15 | 0.039 | 26.9 |
| 540 | 0.19 | 0.26 | 0.15 | 0.20 | 0.058 | 29.0 | 0.14 | 0.20 | 0.12 | 0.15 | 0.040 | 26.5 |
| 570 | 0.19 | 0.27 | 0.15 | 0.21 | 0.058 | 28.3 | 0.14 | 0.20 | 0.12 | 0.15 | 0.040 | 26.1 |
| 600 | 0.20 | 0.27 | 0.16 | 0.21 | 0.058 | 27.6 | 0.15 | 0.20 | 0.13 | 0.16 | 0.041 | 25.6 |
| 630 | 0.20 | 0.28 | 0.16 | 0.22 | 0.063 | 29.2 | 0.15 | 0.21 | 0.13 | 0.16 | 0.041 | 25.3 |
| 660 | 0.20 | 0.28 | 0.16 | 0.22 | 0.061 | 28.0 | 0.15 | 0.21 | 0.13 | 0.16 | 0.042 | 25.6 |
| 690 | 0.21 | 0.29 | 0.17 | 0.22 | 0.064 | 28.4 | 0.15 | 0.22 | 0.13 | 0.17 | 0.042 | 25.3 |
| 720 | 0.21 | 0.29 | 0.17 | 0.23 | 0.063 | 27.9 | 0.16 | 0.22 | 0.14 | 0.17 | 0.044 | 25.6 |
| 750 | 0.21 | 0.30 | 0.17 | 0.23 | 0.064 | 27.8 | 0.16 | 0.22 | 0.14 | 0.17 | 0.044 | 25.0 |
| 780 | 0.22 | 0.30 | 0.18 | 0.23 | 0.064 | 27.2 | 0.16 | 0.23 | 0.14 | 0.18 | 0.044 | 24.9 |
| 810 | 0.22 | 0.31 | 0.18 | 0.24 | 0.066 | 27.7 | 0.16 | 0.23 | 0.14 | 0.18 | 0.044 | 24.7 |
| 840 | 0.22 | 0.31 | 0.18 | 0.24 | 0.066 | 27.6 | 0.17 | 0.23 | 0.15 | 0.18 | 0.045 | 24.9 |

| | Permanent Strain from Actuator Displacement, % | | | | | | Permanent Strain from 100 mm Gauge Points, % | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Coefficient | | | | | | Coefficient |
| Load | Specimen | Specimen | Specimen | Average | Standard | of | Specimen | Specimen | Specimen | Average | Standard | of |
| Cycle | 1 | 2 | 3 | | Deviation | Variation | 1 | 2 | 3 | | Deviation | Variation |
| 870 | 0.23 | 0.32 | 0.18 | 0.24 | 0.069 | 28.1 | 0.17 | 0.24 | 0.15 | 0.19 | 0.045 | 24.2 |
| 900 | 0.23 | 0.32 | 0.19 | 0.25 | 0.066 | 26.6 | 0.17 | 0.24 | 0.15 | 0.19 | 0.046 | 24.3 |
| 930 | 0.23 | 0.32 | 0.19 | 0.25 | 0.069 | 27.5 | 0.19 | 0.24 | 0.15 | 0.19 | 0.044 | 22.9 |
| 960 | 0.24 | 0.33 | 0.19 | 0.25 | 0.069 | 27.0 | 0.18 | 0.24 | 0.16 | 0.19 | 0.046 | 23.7 |
| 990 | 0.24 | 0.33 | 0.20 | 0.26 | 0.066 | 26.0 | 0.18 | 0.25 | 0.16 | 0.19 | 0.047 | 23.9 |
| 1020 | 0.24 | 0.33 | 0.20 | 0.26 | 0.069 | 26.4 | 0.18 | 0.25 | 0.16 | 0.20 | 0.047 | 23.7 |
| 1050 | 0.24 | 0.34 | 0.20 | 0.26 | 0.069 | 26.4 | 0.18 | 0.25 | 0.16 | 0.20 | 0.047 | 23.7 |
| 1080 | 0.25 | 0.34 | 0.20 | 0.26 | 0.069 | 26.0 | 0.19 | 0.25 | 0.16 | 0.20 | 0.046 | 22.4 |
| 1110 | 0.25 | 0.34 | 0.21 | 0.27 | 0.069 | 25.9 | 0.19 | 0.26 | 0.17 | 0.20 | 0.048 | 23.4 |
| 1140 | 0.25 | 0.35 | 0.21 | 0.27 | 0.071 | 26.3 | 0.19 | 0.26 | 0.17 | 0.21 | 0.048 | 23.5 |
| 1170 | 0.25 | 0.35 | 0.21 | 0.27 | 0.069 | 25.4 | 0.19 | 0.26 | 0.17 | 0.21 | 0.049 | 23.6 |
| 1200 | 0.26 | 0.35 | 0.21 | 0.28 | 0.071 | 25.8 | 0.19 | 0.27 | 0.17 | 0.21 | 0.050 | 23.7 |
| 1230 | 0.26 | 0.35 | 0.21 | 0.28 | 0.071 | 25.8 | 0.19 | 0.27 | 0.17 | 0.21 | 0.050 | 23.8 |
| 1260 | 0.26 | 0.36 | 0.22 | 0.28 | 0.071 | 25.4 | 0.20 | 0.27 | 0.18 | 0.21 | 0.049 | 23.0 |
| 1290 | 0.26 | 0.36 | 0.22 | 0.28 | 0.074 | 26.2 | 0.21 | 0.27 | 0.18 | 0.22 | 0.049 | 22.1 |
| 1320 | 0.27 | 0.36 | 0.22 | 0.29 | 0.071 | 25.0 | 0.20 | 0.28 | 0.18 | 0.22 | 0.050 | 23.0 |
| 1350 | 0.27 | 0.36 | 0.22 | 0.29 | 0.071 | 25.0 | 0.20 | 0.28 | 0.18 | 0.22 | 0.051 | 23.4 |
| 1380 | 0.27 | 0.37 | 0.23 | 0.29 | 0.072 | 24.9 | 0.20 | 0.28 | 0.18 | 0.22 | 0.051 | 23.2 |
| 1410 | 0.27 | 0.37 | 0.23 | 0.29 | 0.074 | 25.3 | 0.21 | 0.28 | 0.18 | 0.22 | 0.052 | 23.1 |
| 1440 | 0.27 | 0.37 | 0.23 | 0.29 | 0.074 | 25.3 | 0.21 | 0.29 | 0.19 | 0.23 | 0.053 | 23.4 |
| 1470 | 0.27 | 0.38 | 0.23 | 0.30 | 0.075 | 25.2 | 0.21 | 0.29 | 0.19 | 0.23 | 0.052 | 23.1 |
| 1500 | 0.28 | 0.38 | 0.23 | 0.30 | 0.074 | 24.9 | 0.21 | 0.29 | 0.19 | 0.23 | 0.052 | 22.6 |
| 1530 | 0.28 | 0.38 | 0.24 | 0.30 | 0.072 | 24.1 | 0.21 | 0.29 | 0.19 | 0.23 | 0.052 | 22.3 |
| 1560 | 0.28 | 0.38 | 0.24 | 0.30 | 0.074 | 24.5 | 0.21 | 0.29 | 0.19 | 0.23 | 0.053 | 23.0 |
| 1590 | 0.28 | 0.38 | 0.24 | 0.30 | 0.074 | 24.5 | 0.21 | 0.29 | 0.20 | 0.23 | 0.053 | 22.6 |
| 1620 | 0.28 | 0.39 | 0.24 | 0.31 | 0.075 | 24.5 | 0.21 | 0.30 | 0.20 | 0.24 | 0.054 | 22.7 |
| 1650 | 0.29 | 0.39 | 0.24 | 0.31 | 0.074 | 24.1 | 0.22 | 0.30 | 0.20 | 0.24 | 0.054 | 22.7 |
| 1680 | 0.29 | 0.39 | 0.24 | 0.31 | 0.077 | 24.9 | 0.22 | 0.30 | 0.20 | 0.24 | 0.053 | 22.2 |
| 1710 | 0.29 | 0.39 | 0.25 | 0.31 | 0.075 | 24.0 | 0.22 | 0.30 | 0.20 | 0.24 | 0.053 | 21.9 |
| 1740 | 0.29 | 0.39 | 0.25 | 0.31 | 0.074 | 23.7 | 0.22 | 0.30 | 0.20 | 0.24 | 0.054 | 22.2 |
| 1770 | 0.29 | 0.40 | 0.25 | 0.31 | 0.077 | 24.4 | 0.22 | 0.31 | 0.20 | 0.24 | 0.054 | 22.3 |

| | Permanent Strain from Actuator Displacement, % | | | | | | Permanent Strain from 100 mm Gauge Points, % | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Coefficient | | | | | | Coefficient |
| Load | Specimen | Specimen | Specimen | Average | Standard | of | Specimen | Specimen | Specimen | Average | Standard | of |
| Cycle | 1 | 2 | 3 | | Deviation | Variation | 1 | 2 | 3 | | Deviation | Variation |
| 1800 | 0.29 | 0.40 | 0.25 | 0.31 | 0.077 | 24.4 | 0.22 | 0.31 | 0.21 | 0.25 | 0.054 | 22.0 |
| 1830 | 0.30 | 0.40 | 0.25 | 0.32 | 0.077 | 24.1 | 0.23 | 0.31 | 0.20 | 0.25 | 0.055 | 22.2 |
| 1860 | 0.30 | 0.40 | 0.25 | 0.32 | 0.077 | 24.1 | 0.23 | 0.31 | 0.21 | 0.25 | 0.055 | 22.2 |
| 1890 | 0.30 | 0.41 | 0.26 | 0.32 | 0.078 | 24.0 | 0.23 | 0.31 | 0.21 | 0.25 | 0.055 | 22.2 |
| 1920 | 0.30 | 0.41 | 0.26 | 0.32 | 0.078 | 24.0 | 0.23 | 0.31 | 0.21 | 0.25 | 0.055 | 22.0 |
| 1950 | 0.30 | 0.41 | 0.26 | 0.32 | 0.077 | 23.7 | 0.23 | 0.32 | 0.21 | 0.25 | 0.056 | 22.1 |
| 1980 | 0.30 | 0.41 | 0.26 | 0.33 | 0.078 | 23.7 | 0.23 | 0.32 | 0.21 | 0.25 | 0.056 | 22.0 |
| 2010 | 0.30 | 0.41 | 0.26 | 0.33 | 0.078 | 23.7 | 0.23 | 0.32 | 0.21 | 0.25 | 0.056 | 21.8 |
| 2040 | 0.31 | 0.42 | 0.26 | 0.33 | 0.080 | 24.0 | 0.23 | 0.32 | 0.21 | 0.26 | 0.056 | 22.0 |
| 2070 | 0.31 | 0.42 | 0.27 | 0.33 | 0.078 | 23.3 | 0.23 | 0.32 | 0.22 | 0.26 | 0.057 | 22.0 |
| 2100 | 0.31 | 0.42 | 0.27 | 0.33 | 0.078 | 23.3 | 0.24 | 0.32 | 0.22 | 0.26 | 0.057 | 22.1 |
| 2130 | 0.31 | 0.42 | 0.27 | 0.33 | 0.080 | 24.0 | 0.24 | 0.32 | 0.22 | 0.26 | 0.057 | 21.9 |
| 2160 | 0.31 | 0.42 | 0.27 | 0.34 | 0.080 | 23.7 | 0.24 | 0.33 | 0.22 | 0.26 | 0.058 | 22.1 |
| 2190 | 0.31 | 0.42 | 0.27 | 0.34 | 0.078 | 23.0 | 0.24 | 0.33 | 0.22 | 0.26 | 0.058 | 21.9 |
| 2220 | 0.31 | 0.43 | 0.27 | 0.34 | 0.080 | 23.7 | 0.24 | 0.33 | 0.22 | 0.26 | 0.057 | 21.7 |
| 2250 | 0.31 | 0.43 | 0.27 | 0.34 | 0.080 | 23.7 | 0.24 | 0.33 | 0.22 | 0.27 | 0.058 | 21.7 |
| 2280 | 0.32 | 0.43 | 0.28 | 0.34 | 0.078 | 22.6 | 0.24 | 0.33 | 0.22 | 0.27 | 0.058 | 22.0 |
| 2310 | 0.32 | 0.43 | 0.28 | 0.34 | 0.080 | 23.3 | 0.24 | 0.33 | 0.23 | 0.27 | 0.059 | 22.0 |
| 2340 | 0.32 | 0.43 | 0.28 | 0.34 | 0.080 | 23.3 | 0.25 | 0.34 | 0.23 | 0.27 | 0.058 | 21.5 |
| 2370 | 0.32 | 0.43 | 0.28 | 0.35 | 0.080 | 23.0 | 0.25 | 0.34 | 0.23 | 0.27 | 0.058 | 21.5 |
| 2400 | 0.32 | 0.44 | 0.28 | 0.35 | 0.080 | 23.0 | 0.25 | 0.34 | 0.23 | 0.27 | 0.058 | 21.4 |
| 2430 | 0.32 | 0.44 | 0.28 | 0.35 | 0.080 | 23.0 | 0.25 | 0.34 | 0.23 | 0.27 | 0.058 | 21.4 |
| 2460 | 0.32 | 0.44 | 0.28 | 0.35 | 0.080 | 23.0 | 0.25 | 0.34 | 0.23 | 0.27 | 0.059 | 21.5 |
| 2490 | 0.32 | 0.44 | 0.29 | 0.35 | 0.078 | 22.3 | 0.25 | 0.34 | 0.23 | 0.28 | 0.060 | 21.7 |
| 2520 | 0.32 | 0.44 | 0.29 | 0.35 | 0.081 | 23.0 | 0.25 | 0.34 | 0.23 | 0.28 | 0.059 | 21.5 |
| 2550 | 0.33 | 0.44 | 0.29 | 0.35 | 0.080 | 22.7 | 0.25 | 0.34 | 0.23 | 0.28 | 0.059 | 21.4 |
| 2580 | 0.33 | 0.44 | 0.29 | 0.35 | 0.080 | 22.7 | 0.25 | 0.35 | 0.24 | 0.28 | 0.059 | 21.2 |
| 2610 | 0.33 | 0.45 | 0.29 | 0.36 | 0.081 | 22.7 | 0.25 | 0.35 | 0.24 | 0.28 | 0.059 | 21.3 |
| 2640 | 0.33 | 0.45 | 0.29 | 0.36 | 0.080 | 22.4 | 0.25 | 0.35 | 0.24 | 0.28 | 0.060 | 21.3 |
| 2670 | 0.33 | 0.45 | 0.29 | 0.36 | 0.080 | 22.4 | 0.26 | 0.35 | 0.24 | 0.28 | 0.060 | 21.4 |
| 2700 | 0.33 | 0.45 | 0.29 | 0.36 | 0.083 | 23.1 | 0.26 | 0.35 | 0.24 | 0.28 | 0.060 | 21.2 |

| | Permanent Strain from Actuator Displacement, % | | | | | | Permanent Strain from 100 mm Gauge Points, % | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Coefficient | | | | | | Coefficient |
| Load | Specimen | Specimen | Specimen | Average | Standard | of | Specimen | Specimen | Specimen | Average | Standard | of |
| Cycle | 1 | 2 | 3 | | Deviation | Variation | 1 | 2 | 3 | | Deviation | Variation |
| 2730 | 0.33 | 0.45 | 0.30 | 0.36 | 0.081 | 22.4 | 0.26 | 0.35 | 0.24 | 0.28 | 0.060 | 21.1 |
| 2760 | 0.34 | 0.45 | 0.30 | 0.36 | 0.080 | 22.1 | 0.26 | 0.35 | 0.24 | 0.28 | 0.060 | 21.1 |
| 2790 | 0.34 | 0.45 | 0.30 | 0.36 | 0.080 | 22.1 | 0.26 | 0.35 | 0.24 | 0.29 | 0.060 | 21.0 |
| 2820 | 0.34 | 0.46 | 0.30 | 0.37 | 0.083 | 22.7 | 0.26 | 0.36 | 0.24 | 0.29 | 0.060 | 21.0 |
| 2850 | 0.34 | 0.46 | 0.30 | 0.37 | 0.081 | 22.1 | 0.26 | 0.36 | 0.25 | 0.29 | 0.061 | 21.1 |
| 2880 | 0.34 | 0.46 | 0.30 | 0.37 | 0.081 | 22.1 | 0.26 | 0.36 | 0.25 | 0.29 | 0.061 | 21.1 |
| 2910 | 0.34 | 0.46 | 0.30 | 0.37 | 0.084 | 22.7 | 0.26 | 0.36 | 0.25 | 0.29 | 0.061 | 21.0 |
| 2940 | 0.34 | 0.46 | 0.30 | 0.37 | 0.083 | 22.4 | 0.26 | 0.36 | 0.25 | 0.29 | 0.061 | 21.0 |
| 2970 | 0.34 | 0.46 | 0.30 | 0.37 | 0.083 | 22.4 | 0.27 | 0.36 | 0.25 | 0.29 | 0.060 | 20.5 |
| 3000 | 0.34 | 0.46 | 0.31 | 0.37 | 0.081 | 21.8 | 0.27 | 0.36 | 0.25 | 0.29 | 0.061 | 20.7 |
| 3030 | 0.34 | 0.47 | 0.31 | 0.37 | 0.084 | 22.4 | 0.27 | 0.36 | 0.25 | 0.29 | 0.061 | 20.6 |
| 3060 | 0.35 | 0.47 | 0.31 | 0.38 | 0.083 | 22.1 | 0.27 | 0.36 | 0.25 | 0.29 | 0.061 | 20.8 |
| 3090 | 0.35 | 0.47 | 0.31 | 0.38 | 0.081 | 21.5 | 0.27 | 0.37 | 0.25 | 0.30 | 0.062 | 20.9 |
| 3120 | 0.35 | 0.47 | 0.31 | 0.38 | 0.081 | 21.5 | 0.27 | 0.37 | 0.25 | 0.30 | 0.061 | 20.5 |
| 3150 | 0.35 | 0.47 | 0.31 | 0.38 | 0.084 | 22.1 | 0.27 | 0.37 | 0.25 | 0.30 | 0.062 | 20.7 |
| 3180 | 0.35 | 0.47 | 0.31 | 0.38 | 0.084 | 22.1 | 0.27 | 0.37 | 0.26 | 0.30 | 0.062 | 20.8 |
| 3210 | 0.35 | 0.47 | 0.31 | 0.38 | 0.083 | 21.8 | 0.27 | 0.37 | 0.26 | 0.30 | 0.063 | 20.9 |
| 3240 | 0.35 | 0.47 | 0.32 | 0.38 | 0.081 | 21.2 | 0.27 | 0.37 | 0.26 | 0.30 | 0.062 | 20.8 |
| 3270 | 0.35 | 0.48 | 0.32 | 0.38 | 0.084 | 21.9 | 0.27 | 0.37 | 0.26 | 0.30 | 0.062 | 20.8 |
| 3300 | 0.35 | 0.48 | 0.32 | 0.38 | 0.084 | 21.9 | 0.27 | 0.37 | 0.26 | 0.30 | 0.062 | 20.4 |
| 3330 | 0.35 | 0.48 | 0.32 | 0.38 | 0.084 | 21.9 | 0.28 | 0.38 | 0.26 | 0.30 | 0.063 | 20.6 |
| 3360 | 0.36 | 0.48 | 0.32 | 0.39 | 0.083 | 21.5 | 0.28 | 0.38 | 0.26 | 0.30 | 0.063 | 20.5 |
| 3390 | 0.36 | 0.48 | 0.32 | 0.39 | 0.084 | 21.6 | 0.28 | 0.38 | 0.26 | 0.31 | 0.062 | 20.3 |
| 3420 | 0.36 | 0.48 | 0.32 | 0.39 | 0.084 | 21.6 | 0.28 | 0.38 | 0.26 | 0.31 | 0.062 | 20.3 |
| 3450 | 0.36 | 0.48 | 0.32 | 0.39 | 0.084 | 21.6 | 0.28 | 0.38 | 0.27 | 0.31 | 0.063 | 20.4 |
| 3540 | 0.36 | 0.49 | 0.33 | 0.39 | 0.084 | 21.3 | 0.28 | 0.38 | 0.27 | 0.31 | 0.062 | 20.0 |
| 3570 | 0.36 | 0.49 | 0.33 | 0.39 | 0.084 | 21.3 | 0.28 | 0.38 | 0.27 | 0.31 | 0.062 | 19.9 |
| 3600 | 0.36 | 0.49 | 0.33 | 0.39 | 0.084 | 21.3 | 0.28 | 0.38 | 0.27 | 0.31 | 0.063 | 20.3 |
| 3630 | 0.36 | 0.49 | 0.33 | 0.39 | 0.084 | 21.3 | 0.28 | 0.39 | 0.27 | 0.31 | 0.064 | 20.3 |
| 3660 | 0.36 | 0.49 | 0.33 | 0.40 | 0.085 | 21.4 | 0.28 | 0.39 | 0.27 | 0.31 | 0.063 | 20.2 |
| 3690 | 0.36 | 0.49 | 0.33 | 0.40 | 0.085 | 21.4 | 0.28 | 0.39 | 0.27 | 0.31 | 0.063 | 20.1 |

| | Permanent Strain from Actuator Displacement, % | | | | | | Permanent Strain from 100 mm Gauge Points, % | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Coefficient | | | | | | Coefficient |
| Load | Specimen | Specimen | Specimen | Average | Standard | of | Specimen | Specimen | Specimen | Average | Standard | of |
| Cycle | 1 | 2 | 3 | | Deviation | Variation | 1 | 2 | 3 | | Deviation | Variation |
| 3720 | 0.36 | 0.49 | 0.33 | 0.40 | 0.085 | 21.4 | 0.29 | 0.39 | 0.27 | 0.32 | 0.063 | 19.8 |
| 3750 | 0.37 | 0.49 | 0.33 | 0.40 | 0.084 | 21.0 | 0.29 | 0.39 | 0.27 | 0.32 | 0.063 | 20.0 |
| 3780 | 0.37 | 0.50 | 0.34 | 0.40 | 0.085 | 21.1 | 0.29 | 0.39 | 0.28 | 0.32 | 0.064 | 20.0 |
| 3810 | 0.37 | 0.50 | 0.34 | 0.40 | 0.085 | 21.1 | 0.29 | 0.39 | 0.28 | 0.32 | 0.064 | 20.1 |
| 3840 | 0.37 | 0.50 | 0.34 | 0.40 | 0.085 | 21.1 | 0.29 | 0.39 | 0.28 | 0.32 | 0.062 | 19.5 |
| 3870 | 0.37 | 0.50 | 0.34 | 0.40 | 0.085 | 21.1 | 0.29 | 0.39 | 0.28 | 0.32 | 0.063 | 19.7 |
| 3900 | 0.37 | 0.50 | 0.34 | 0.40 | 0.085 | 21.1 | 0.29 | 0.39 | 0.28 | 0.32 | 0.063 | 19.4 |
| 3930 | 0.37 | 0.50 | 0.34 | 0.41 | 0.085 | 20.9 | 0.29 | 0.40 | 0.28 | 0.32 | 0.064 | 19.8 |
| 3960 | 0.37 | 0.50 | 0.34 | 0.41 | 0.085 | 20.9 | 0.29 | 0.40 | 0.28 | 0.32 | 0.063 | 19.6 |
| 3990 | 0.37 | 0.50 | 0.34 | 0.41 | 0.085 | 20.9 | 0.29 | 0.40 | 0.28 | 0.32 | 0.064 | 19.7 |
| 4020 | 0.37 | 0.50 | 0.34 | 0.41 | 0.085 | 20.9 | 0.29 | 0.40 | 0.28 | 0.32 | 0.064 | 19.8 |
| 4050 | 0.37 | 0.50 | 0.34 | 0.41 | 0.085 | 20.9 | 0.29 | 0.40 | 0.28 | 0.32 | 0.065 | 19.9 |
| 4080 | 0.37 | 0.51 | 0.35 | 0.41 | 0.086 | 20.9 | 0.29 | 0.40 | 0.28 | 0.33 | 0.064 | 19.7 |
| 4110 | 0.38 | 0.51 | 0.35 | 0.41 | 0.085 | 20.6 | 0.30 | 0.40 | 0.29 | 0.33 | 0.063 | 19.3 |
| 4140 | 0.38 | 0.51 | 0.35 | 0.41 | 0.085 | 20.6 | 0.30 | 0.40 | 0.29 | 0.33 | 0.063 | 19.2 |
| 4170 | 0.38 | 0.51 | 0.35 | 0.41 | 0.085 | 20.6 | 0.30 | 0.40 | 0.29 | 0.33 | 0.064 | 19.6 |
| 4200 | 0.38 | 0.51 | 0.35 | 0.41 | 0.085 | 20.6 | 0.30 | 0.40 | 0.29 | 0.33 | 0.065 | 19.7 |
| 4230 | 0.38 | 0.51 | 0.35 | 0.42 | 0.086 | 20.7 | 0.30 | 0.41 | 0.29 | 0.33 | 0.064 | 19.4 |
| 4260 | 0.38 | 0.51 | 0.35 | 0.42 | 0.086 | 20.7 | 0.30 | 0.41 | 0.29 | 0.33 | 0.065 | 19.5 |
| 4290 | 0.38 | 0.51 | 0.35 | 0.42 | 0.086 | 20.7 | 0.30 | 0.41 | 0.29 | 0.33 | 0.065 | 19.6 |
| 4320 | 0.38 | 0.51 | 0.35 | 0.42 | 0.085 | 20.3 | 0.30 | 0.41 | 0.29 | 0.33 | 0.064 | 19.1 |
| 4350 | 0.38 | 0.51 | 0.35 | 0.42 | 0.085 | 20.3 | 0.30 | 0.41 | 0.29 | 0.33 | 0.064 | 19.1 |
| 4380 | 0.38 | 0.52 | 0.35 | 0.42 | 0.088 | 20.9 | 0.30 | 0.41 | 0.29 | 0.33 | 0.064 | 19.2 |
| 4410 | 0.38 | 0.52 | 0.36 | 0.42 | 0.086 | 20.4 | 0.30 | 0.41 | 0.29 | 0.34 | 0.063 | 18.9 |
| 4440 | 0.38 | 0.52 | 0.36 | 0.42 | 0.086 | 20.4 | 0.30 | 0.41 | 0.30 | 0.34 | 0.065 | 19.5 |
| 4470 | 0.38 | 0.52 | 0.36 | 0.42 | 0.086 | 20.4 | 0.31 | 0.41 | 0.30 | 0.34 | 0.062 | 18.3 |
| 4500 | 0.38 | 0.52 | 0.36 | 0.42 | 0.086 | 20.4 | 0.30 | 0.41 | 0.30 | 0.34 | 0.065 | 19.1 |
| 4530 | 0.38 | 0.52 | 0.36 | 0.42 | 0.089 | 21.0 | 0.30 | 0.41 | 0.30 | 0.34 | 0.064 | 19.0 |
| 4560 | 0.39 | 0.52 | 0.36 | 0.42 | 0.088 | 20.7 | 0.30 | 0.41 | 0.30 | 0.34 | 0.065 | 19.2 |
| 4590 | 0.39 | 0.52 | 0.36 | 0.42 | 0.088 | 20.7 | 0.30 | 0.42 | 0.30 | 0.34 | 0.065 | 19.2 |
| 4620 | 0.39 | 0.52 | 0.36 | 0.43 | 0.086 | 20.2 | 0.31 | 0.42 | 0.30 | 0.34 | 0.065 | 18.9 |

| | Permanent Strain from Actuator Displacement, % | | | | | | Permanent Strain from 100 mm Gauge Points, % | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Coefficient | | | | | | Coefficient |
| Load | Specimen | Specimen | Specimen | Average | Standard | of | Specimen | Specimen | Specimen | Average | Standard | of |
| Cycle | 1 | 2 | 3 | | Deviation | Variation | 1 | 2 | 3 | | Deviation | Variation |
| 4650 | 0.39 | 0.53 | 0.36 | 0.43 | 0.089 | 20.8 | 0.31 | 0.42 | 0.30 | 0.34 | 0.064 | 18.7 |
| 4680 | 0.39 | 0.53 | 0.36 | 0.43 | 0.089 | 20.8 | 0.31 | 0.42 | 0.30 | 0.34 | 0.064 | 18.6 |
| 4710 | 0.39 | 0.53 | 0.36 | 0.43 | 0.089 | 20.8 | 0.31 | 0.42 | 0.30 | 0.34 | 0.064 | 18.8 |
| 4740 | 0.39 | 0.53 | 0.36 | 0.43 | 0.088 | 20.4 | 0.31 | 0.42 | 0.30 | 0.34 | 0.064 | 18.7 |
| 4770 | 0.39 | 0.53 | 0.37 | 0.43 | 0.087 | 20.3 | 0.31 | 0.42 | 0.31 | 0.35 | 0.064 | 18.5 |
| 4800 | 0.39 | 0.53 | 0.37 | 0.43 | 0.086 | 19.9 | 0.31 | 0.42 | 0.31 | 0.35 | 0.065 | 18.9 |
| 4830 | 0.39 | 0.53 | 0.37 | 0.43 | 0.089 | 20.5 | 0.31 | 0.42 | 0.31 | 0.35 | 0.065 | 18.8 |
| 4860 | 0.39 | 0.53 | 0.37 | 0.43 | 0.089 | 20.5 | 0.31 | 0.42 | 0.31 | 0.35 | 0.066 | 19.0 |
| 4890 | 0.39 | 0.53 | 0.37 | 0.43 | 0.089 | 20.5 | 0.31 | 0.42 | 0.31 | 0.35 | 0.065 | 18.8 |
| 4920 | 0.39 | 0.53 | 0.37 | 0.43 | 0.089 | 20.5 | 0.31 | 0.42 | 0.31 | 0.35 | 0.065 | 18.6 |
| 4950 | 0.39 | 0.53 | 0.37 | 0.43 | 0.087 | 20.0 | 0.31 | 0.42 | 0.31 | 0.35 | 0.065 | 18.7 |
| 4980 | 0.39 | 0.54 | 0.37 | 0.44 | 0.090 | 20.6 | 0.31 | 0.43 | 0.31 | 0.35 | 0.065 | 18.6 |
| 5010 | 0.40 | 0.54 | 0.37 | 0.44 | 0.089 | 20.3 | 0.31 | 0.43 | 0.31 | 0.35 | 0.065 | 18.6 |
| 5040 | 0.40 | 0.54 | 0.37 | 0.44 | 0.089 | 20.3 | 0.32 | 0.43 | 0.31 | 0.35 | 0.065 | 18.4 |
| 5070 | 0.40 | 0.54 | 0.37 | 0.44 | 0.089 | 20.3 | 0.32 | 0.43 | 0.31 | 0.35 | 0.065 | 18.3 |
| 5100 | 0.40 | 0.54 | 0.37 | 0.44 | 0.089 | 20.3 | 0.32 | 0.43 | 0.31 | 0.35 | 0.064 | 18.3 |
| 5130 | 0.40 | 0.54 | 0.38 | 0.44 | 0.087 | 19.8 | 0.32 | 0.43 | 0.31 | 0.35 | 0.065 | 18.3 |
| 5160 | 0.40 | 0.54 | 0.38 | 0.44 | 0.087 | 19.8 | 0.33 | 0.43 | 0.32 | 0.36 | 0.064 | 17.8 |
| 5190 | 0.40 | 0.54 | 0.38 | 0.44 | 0.090 | 20.4 | 0.32 | 0.43 | 0.32 | 0.36 | 0.065 | 18.4 |
| 5220 | 0.40 | 0.54 | 0.38 | 0.44 | 0.090 | 20.4 | 0.32 | 0.43 | 0.32 | 0.36 | 0.066 | 18.6 |
| 5250 | 0.40 | 0.54 | 0.38 | 0.44 | 0.090 | 20.4 | 0.32 | 0.43 | 0.32 | 0.36 | 0.066 | 18.5 |
| 5280 | 0.40 | 0.54 | 0.38 | 0.44 | 0.089 | 20.1 | 0.32 | 0.43 | 0.32 | 0.36 | 0.066 | 18.4 |
| 5310 | 0.40 | 0.54 | 0.38 | 0.44 | 0.087 | 19.6 | 0.32 | 0.43 | 0.32 | 0.36 | 0.065 | 18.3 |
| 5340 | 0.40 | 0.55 | 0.38 | 0.45 | 0.090 | 20.2 | 0.32 | 0.43 | 0.32 | 0.36 | 0.066 | 18.3 |
| 5370 | 0.40 | 0.55 | 0.38 | 0.45 | 0.090 | 20.2 | 0.32 | 0.43 | 0.32 | 0.36 | 0.066 | 18.5 |
| 5400 | 0.40 | 0.55 | 0.38 | 0.45 | 0.090 | 20.2 | 0.32 | 0.44 | 0.32 | 0.36 | 0.066 | 18.3 |
| 5430 | 0.40 | 0.55 | 0.38 | 0.45 | 0.090 | 20.2 | 0.32 | 0.44 | 0.32 | 0.36 | 0.065 | 18.1 |
| 5460 | 0.40 | 0.55 | 0.38 | 0.45 | 0.090 | 20.2 | 0.34 | 0.44 | 0.32 | 0.36 | 0.063 | 17.2 |
| 5490 | 0.40 | 0.55 | 0.39 | 0.45 | 0.091 | 20.3 | 0.32 | 0.44 | 0.32 | 0.36 | 0.066 | 18.3 |
| 5520 | 0.40 | 0.55 | 0.39 | 0.45 | 0.091 | 20.3 | 0.32 | 0.44 | 0.32 | 0.36 | 0.066 | 18.3 |
| 5550 | 0.40 | 0.55 | 0.39 | 0.45 | 0.091 | 20.3 | 0.32 | 0.44 | 0.32 | 0.36 | 0.067 | 18.5 |

| | Permanent Strain from Actuator Displacement, % | | | | | | Permanent Strain from 100 mm Gauge Points, % | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Coefficient | | | | | | Coefficient |
| Load | Specimen | Specimen | Specimen | Average | Standard | of | Specimen | Specimen | Specimen | Average | Standard | of |
| Cycle | 1 | 2 | 3 | | Deviation | Variation | 1 | 2 | 3 | | Deviation | Variation |
| 5580 | 0.41 | 0.55 | 0.39 | 0.45 | 0.090 | 19.9 | 0.32 | 0.44 | 0.33 | 0.36 | 0.066 | 18.2 |
| 5610 | 0.41 | 0.55 | 0.39 | 0.45 | 0.090 | 19.9 | 0.33 | 0.44 | 0.33 | 0.37 | 0.065 | 17.8 |
| 5640 | 0.41 | 0.55 | 0.39 | 0.45 | 0.090 | 19.9 | 0.33 | 0.44 | 0.33 | 0.37 | 0.065 | 17.8 |
| 5670 | 0.41 | 0.56 | 0.39 | 0.45 | 0.093 | 20.5 | 0.33 | 0.44 | 0.33 | 0.37 | 0.067 | 18.3 |
| 5700 | 0.41 | 0.56 | 0.39 | 0.45 | 0.091 | 20.1 | 0.33 | 0.44 | 0.33 | 0.37 | 0.065 | 17.8 |
| 5730 | 0.41 | 0.56 | 0.39 | 0.46 | 0.090 | 19.7 | 0.33 | 0.44 | 0.33 | 0.37 | 0.065 | 17.6 |
| 5760 | 0.41 | 0.56 | 0.39 | 0.45 | 0.091 | 20.1 | 0.33 | 0.44 | 0.33 | 0.37 | 0.065 | 17.6 |
| 5790 | 0.41 | 0.56 | 0.39 | 0.46 | 0.090 | 19.7 | 0.33 | 0.44 | 0.33 | 0.37 | 0.067 | 18.1 |
| 5820 | 0.41 | 0.56 | 0.39 | 0.46 | 0.093 | 20.3 | 0.34 | 0.44 | 0.33 | 0.37 | 0.063 | 17.1 |
| 5850 | 0.41 | 0.56 | 0.39 | 0.46 | 0.093 | 20.3 | 0.33 | 0.44 | 0.33 | 0.37 | 0.065 | 17.7 |
| 5880 | 0.41 | 0.56 | 0.40 | 0.46 | 0.091 | 19.8 | 0.33 | 0.45 | 0.33 | 0.37 | 0.066 | 17.9 |
| 5910 | 0.41 | 0.56 | 0.40 | 0.46 | 0.091 | 19.8 | 0.33 | 0.45 | 0.33 | 0.37 | 0.067 | 18.0 |
| 5940 | 0.41 | 0.56 | 0.40 | 0.46 | 0.091 | 19.8 | 0.33 | 0.45 | 0.34 | 0.37 | 0.066 | 17.7 |
| 5970 | 0.41 | 0.56 | 0.40 | 0.46 | 0.091 | 19.8 | 0.33 | 0.45 | 0.34 | 0.37 | 0.067 | 17.9 |
| 6000 | 0.41 | 0.56 | 0.40 | 0.46 | 0.091 | 19.8 | 0.33 | 0.45 | 0.34 | 0.37 | 0.067 | 17.9 |
| 6030 | 0.41 | 0.57 | 0.40 | 0.46 | 0.094 | 20.4 | 0.33 | 0.45 | 0.34 | 0.37 | 0.067 | 17.9 |
| 6060 | 0.42 | 0.57 | 0.40 | 0.46 | 0.093 | 20.1 | 0.33 | 0.45 | 0.34 | 0.37 | 0.066 | 17.6 |
| 6090 | 0.41 | 0.57 | 0.40 | 0.46 | 0.094 | 20.4 | 0.33 | 0.45 | 0.34 | 0.37 | 0.067 | 17.8 |
| 6120 | 0.42 | 0.57 | 0.40 | 0.46 | 0.091 | 19.6 | 0.33 | 0.45 | 0.34 | 0.38 | 0.067 | 17.8 |
| 6150 | 0.42 | 0.57 | 0.40 | 0.46 | 0.091 | 19.6 | 0.33 | 0.45 | 0.34 | 0.37 | 0.068 | 18.0 |
| 6180 | 0.42 | 0.57 | 0.40 | 0.47 | 0.094 | 20.2 | 0.34 | 0.45 | 0.34 | 0.38 | 0.067 | 17.7 |
| 6210 | 0.42 | 0.57 | 0.40 | 0.47 | 0.094 | 20.2 | 0.34 | 0.45 | 0.34 | 0.38 | 0.066 | 17.4 |
| 6240 | 0.42 | 0.57 | 0.40 | 0.47 | 0.094 | 20.2 | 0.34 | 0.45 | 0.34 | 0.38 | 0.066 | 17.5 |
| 6270 | 0.42 | 0.57 | 0.41 | 0.47 | 0.092 | 19.8 | 0.34 | 0.46 | 0.34 | 0.38 | 0.067 | 17.7 |
| 6300 | 0.42 | 0.57 | 0.41 | 0.47 | 0.092 | 19.8 | 0.34 | 0.45 | 0.34 | 0.38 | 0.066 | 17.4 |
| 6330 | 0.42 | 0.57 | 0.41 | 0.47 | 0.091 | 19.4 | 0.34 | 0.45 | 0.34 | 0.38 | 0.065 | 17.2 |
| 6360 | 0.42 | 0.57 | 0.41 | 0.47 | 0.091 | 19.4 | 0.34 | 0.46 | 0.35 | 0.38 | 0.067 | 17.6 |
| 6390 | 0.42 | 0.58 | 0.41 | 0.47 | 0.094 | 20.0 | 0.34 | 0.46 | 0.35 | 0.38 | 0.066 | 17.4 |
| 6420 | 0.42 | 0.58 | 0.41 | 0.47 | 0.094 | 20.0 | 0.34 | 0.46 | 0.35 | 0.38 | 0.067 | 17.6 |
| 6450 | 0.42 | 0.58 | 0.41 | 0.47 | 0.094 | 20.0 | 0.34 | 0.46 | 0.35 | 0.38 | 0.066 | 17.3 |
| 6480 | 0.42 | 0.58 | 0.41 | 0.47 | 0.094 | 20.0 | 0.34 | 0.46 | 0.35 | 0.38 | 0.067 | 17.5 |

| | Permanent Strain from Actuator Displacement, % | | | | | | Permanent Strain from 100 mm Gauge Points, % | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Coefficient | | | | | | Coefficient |
| Load | Specimen | Specimen | Specimen | Average | Standard | of | Specimen | Specimen | Specimen | Average | Standard | of |
| Cycle | 1 | 2 | 3 | | Deviation | Variation | 1 | 2 | 3 | | Deviation | Variation |
| 6510 | 0.42 | 0.58 | 0.41 | 0.47 | 0.092 | 19.6 | 0.34 | 0.46 | 0.35 | 0.38 | 0.068 | 17.6 |
| 6540 | 0.42 | 0.58 | 0.41 | 0.47 | 0.092 | 19.6 | 0.34 | 0.46 | 0.35 | 0.38 | 0.067 | 17.3 |
| 6570 | 0.42 | 0.58 | 0.41 | 0.47 | 0.092 | 19.6 | 0.34 | 0.46 | 0.35 | 0.39 | 0.066 | 17.1 |
| 6600 | 0.42 | 0.58 | 0.41 | 0.47 | 0.095 | 20.1 | 0.34 | 0.46 | 0.35 | 0.39 | 0.066 | 17.1 |
| 6630 | 0.42 | 0.58 | 0.41 | 0.47 | 0.095 | 20.1 | 0.34 | 0.46 | 0.35 | 0.39 | 0.067 | 17.3 |
| 6660 | 0.43 | 0.58 | 0.41 | 0.48 | 0.094 | 19.7 | 0.34 | 0.46 | 0.35 | 0.39 | 0.067 | 17.4 |
| 6690 | 0.42 | 0.58 | 0.42 | 0.48 | 0.094 | 19.7 | 0.34 | 0.47 | 0.35 | 0.39 | 0.068 | 17.5 |
| 6720 | 0.43 | 0.58 | 0.42 | 0.48 | 0.092 | 19.3 | 0.34 | 0.47 | 0.35 | 0.39 | 0.067 | 17.4 |
| 6750 | 0.43 | 0.58 | 0.42 | 0.48 | 0.092 | 19.3 | 0.34 | 0.47 | 0.35 | 0.39 | 0.068 | 17.4 |
| 6780 | 0.43 | 0.58 | 0.42 | 0.48 | 0.092 | 19.3 | 0.35 | 0.47 | 0.36 | 0.39 | 0.067 | 17.3 |
| 6810 | 0.43 | 0.59 | 0.42 | 0.48 | 0.095 | 19.9 | 0.35 | 0.47 | 0.36 | 0.39 | 0.067 | 17.2 |
| 6840 | 0.43 | 0.59 | 0.42 | 0.48 | 0.095 | 19.9 | 0.35 | 0.47 | 0.36 | 0.39 | 0.068 | 17.3 |
| 6870 | 0.43 | 0.59 | 0.42 | 0.48 | 0.095 | 19.9 | 0.35 | 0.47 | 0.36 | 0.39 | 0.066 | 16.9 |
| 6900 | 0.43 | 0.59 | 0.42 | 0.48 | 0.095 | 19.9 | 0.35 | 0.47 | 0.36 | 0.39 | 0.067 | 17.0 |
| 6930 | 0.43 | 0.59 | 0.42 | 0.48 | 0.094 | 19.5 | 0.35 | 0.47 | 0.36 | 0.39 | 0.068 | 17.3 |
| 6960 | 0.43 | 0.59 | 0.42 | 0.48 | 0.094 | 19.5 | 0.35 | 0.47 | 0.36 | 0.39 | 0.068 | 17.4 |
| 6990 | 0.43 | 0.59 | 0.42 | 0.48 | 0.094 | 19.5 | 0.35 | 0.47 | 0.36 | 0.39 | 0.068 | 17.3 |
| 7020 | 0.43 | 0.59 | 0.42 | 0.48 | 0.097 | 20.0 | 0.35 | 0.47 | 0.36 | 0.39 | 0.067 | 17.0 |
| 7050 | 0.43 | 0.59 | 0.42 | 0.48 | 0.095 | 19.7 | 0.35 | 0.47 | 0.36 | 0.39 | 0.067 | 17.1 |
| 7080 | 0.43 | 0.59 | 0.42 | 0.48 | 0.095 | 19.7 | 0.35 | 0.47 | 0.36 | 0.40 | 0.067 | 16.9 |
| 7110 | 0.43 | 0.59 | 0.43 | 0.49 | 0.094 | 19.3 | 0.35 | 0.47 | 0.36 | 0.40 | 0.067 | 16.9 |
| 7140 | 0.43 | 0.59 | 0.43 | 0.49 | 0.094 | 19.3 | 0.35 | 0.48 | 0.36 | 0.40 | 0.068 | 17.2 |
| 7170 | 0.43 | 0.60 | 0.43 | 0.49 | 0.097 | 19.8 | 0.35 | 0.48 | 0.36 | 0.40 | 0.068 | 17.2 |
| 7200 | 0.43 | 0.59 | 0.43 | 0.49 | 0.094 | 19.3 | 0.35 | 0.48 | 0.36 | 0.40 | 0.068 | 17.0 |
| 7230 | 0.43 | 0.60 | 0.43 | 0.49 | 0.097 | 19.8 | 0.35 | 0.48 | 0.37 | 0.40 | 0.068 | 17.1 |
| 7260 | 0.43 | 0.60 | 0.43 | 0.49 | 0.097 | 19.8 | 0.35 | 0.48 | 0.37 | 0.40 | 0.068 | 17.0 |
| 7290 | 0.43 | 0.60 | 0.43 | 0.49 | 0.097 | 19.8 | 0.35 | 0.48 | 0.37 | 0.40 | 0.067 | 16.9 |
| 7320 | 0.44 | 0.60 | 0.43 | 0.49 | 0.095 | 19.5 | 0.35 | 0.48 | 0.37 | 0.40 | 0.068 | 17.0 |
| 7350 | 0.44 | 0.60 | 0.43 | 0.49 | 0.094 | 19.1 | 0.36 | 0.48 | 0.37 | 0.40 | 0.068 | 17.0 |
| 7380 | 0.44 | 0.60 | 0.43 | 0.49 | 0.094 | 19.1 | 0.35 | 0.48 | 0.37 | 0.40 | 0.069 | 17.1 |
| 7410 | 0.44 | 0.60 | 0.43 | 0.49 | 0.097 | 19.6 | 0.36 | 0.48 | 0.37 | 0.40 | 0.068 | 17.0 |

| | Permanent Strain from Actuator Displacement, % | | | | | | Permanent Strain from 100 mm Gauge Points, % | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Coefficient | | | | | | Coefficient |
| Load | Specimen | Specimen | Specimen | Average | Standard | of | Specimen | Specimen | Specimen | Average | Standard | of |
| Cycle | 1 | 2 | 3 | | Deviation | Variation | 1 | 2 | 3 | | Deviation | Variation |
| 7440 | 0.44 | 0.60 | 0.43 | 0.49 | 0.097 | 19.6 | 0.36 | 0.48 | 0.37 | 0.40 | 0.069 | 17.0 |
| 7470 | 0.44 | 0.60 | 0.43 | 0.49 | 0.097 | 19.6 | 0.36 | 0.48 | 0.37 | 0.40 | 0.069 | 17.1 |
| 7500 | 0.44 | 0.60 | 0.43 | 0.49 | 0.097 | 19.6 | 0.36 | 0.48 | 0.37 | 0.40 | 0.068 | 16.9 |
| 7530 | 0.44 | 0.60 | 0.43 | 0.49 | 0.097 | 19.6 | 0.36 | 0.48 | 0.37 | 0.40 | 0.068 | 16.9 |
| 7560 | 0.44 | 0.60 | 0.43 | 0.49 | 0.097 | 19.6 | 0.36 | 0.48 | 0.37 | 0.40 | 0.069 | 17.1 |
| 7590 | 0.44 | 0.61 | 0.44 | 0.50 | 0.098 | 19.8 | 0.36 | 0.49 | 0.37 | 0.41 | 0.069 | 17.1 |
| 7620 | 0.44 | 0.61 | 0.44 | 0.50 | 0.097 | 19.4 | 0.36 | 0.49 | 0.37 | 0.41 | 0.069 | 17.0 |
| 7650 | 0.44 | 0.61 | 0.44 | 0.50 | 0.097 | 19.4 | 0.36 | 0.49 | 0.38 | 0.41 | 0.070 | 17.1 |
| 7680 | 0.44 | 0.61 | 0.44 | 0.50 | 0.097 | 19.4 | 0.36 | 0.49 | 0.37 | 0.41 | 0.070 | 17.3 |
| 7710 | 0.44 | 0.61 | 0.44 | 0.50 | 0.097 | 19.4 | 0.36 | 0.49 | 0.37 | 0.41 | 0.069 | 17.0 |
| 7740 | 0.44 | 0.61 | 0.44 | 0.50 | 0.097 | 19.4 | 0.36 | 0.49 | 0.37 | 0.41 | 0.070 | 17.1 |
| 7770 | 0.44 | 0.61 | 0.44 | 0.50 | 0.097 | 19.4 | 0.36 | 0.49 | 0.38 | 0.41 | 0.070 | 17.0 |
| 7800 | 0.44 | 0.61 | 0.44 | 0.50 | 0.098 | 19.6 | 0.36 | 0.49 | 0.38 | 0.41 | 0.069 | 16.7 |
| 7830 | 0.44 | 0.61 | 0.44 | 0.50 | 0.098 | 19.6 | 0.36 | 0.49 | 0.38 | 0.41 | 0.070 | 16.9 |
| 7860 | 0.44 | 0.61 | 0.44 | 0.50 | 0.098 | 19.6 | 0.36 | 0.49 | 0.38 | 0.41 | 0.069 | 16.8 |
| 7890 | 0.44 | 0.61 | 0.44 | 0.50 | 0.098 | 19.6 | 0.36 | 0.49 | 0.38 | 0.41 | 0.069 | 16.8 |
| 7920 | 0.44 | 0.61 | 0.44 | 0.50 | 0.098 | 19.6 | 0.36 | 0.49 | 0.38 | 0.41 | 0.069 | 16.8 |
| 7950 | 0.44 | 0.61 | 0.44 | 0.50 | 0.098 | 19.6 | 0.36 | 0.49 | 0.38 | 0.41 | 0.069 | 16.7 |
| 7980 | 0.44 | 0.61 | 0.44 | 0.50 | 0.098 | 19.6 | 0.36 | 0.49 | 0.38 | 0.41 | 0.069 | 16.7 |
| 8010 | 0.44 | 0.61 | 0.44 | 0.50 | 0.098 | 19.6 | 0.36 | 0.49 | 0.38 | 0.41 | 0.070 | 16.9 |
| 8040 | 0.45 | 0.62 | 0.45 | 0.51 | 0.098 | 19.4 | 0.36 | 0.49 | 0.38 | 0.41 | 0.070 | 17.0 |
| 8070 | 0.44 | 0.62 | 0.45 | 0.50 | 0.099 | 19.7 | 0.36 | 0.49 | 0.38 | 0.41 | 0.070 | 16.9 |
| 8100 | 0.45 | 0.62 | 0.45 | 0.51 | 0.098 | 19.4 | 0.36 | 0.50 | 0.39 | 0.42 | 0.071 | 17.0 |
| 8130 | 0.45 | 0.62 | 0.45 | 0.51 | 0.098 | 19.4 | 0.36 | 0.50 | 0.39 | 0.42 | 0.071 | 17.0 |
| 8160 | 0.45 | 0.62 | 0.45 | 0.51 | 0.098 | 19.4 | 0.37 | 0.50 | 0.39 | 0.42 | 0.070 | 16.9 |
| 8190 | 0.45 | 0.62 | 0.45 | 0.51 | 0.098 | 19.4 | 0.37 | 0.50 | 0.39 | 0.42 | 0.071 | 16.9 |
| 8220 | 0.45 | 0.62 | 0.45 | 0.51 | 0.098 | 19.4 | 0.37 | 0.50 | 0.39 | 0.42 | 0.070 | 16.8 |
| 8250 | 0.45 | 0.62 | 0.45 | 0.51 | 0.098 | 19.4 | 0.37 | 0.50 | 0.39 | 0.42 | 0.070 | 16.8 |
| 8280 | 0.45 | 0.62 | 0.45 | 0.51 | 0.100 | 19.5 | 0.37 | 0.50 | 0.39 | 0.42 | 0.071 | 16.9 |
| 8310 | 0.45 | 0.62 | 0.45 | 0.51 | 0.100 | 19.5 | 0.37 | 0.50 | 0.39 | 0.42 | 0.070 | 16.8 |
| 8340 | 0.45 | 0.62 | 0.45 | 0.51 | 0.100 | 19.5 | 0.37 | 0.50 | 0.39 | 0.42 | 0.070 | 16.8 |

| | Permanent Strain from Actuator Displacement, % | | | | | | Permanent Strain from 100 mm Gauge Points, % | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Coefficient | | | | | | Coefficient |
| Load | Specimen | Specimen | Specimen | Average | Standard | of | Specimen | Specimen | Specimen | Average | Standard | of |
| Cycle | 1 | 2 | 3 | | Deviation | Variation | 1 | 2 | 3 | | Deviation | Variation |
| 8370 | 0.45 | 0.62 | 0.45 | 0.51 | 0.100 | 19.5 | 0.37 | 0.50 | 0.39 | 0.42 | 0.071 | 16.9 |
| 8400 | 0.45 | 0.62 | 0.45 | 0.51 | 0.100 | 19.5 | 0.37 | 0.50 | 0.39 | 0.42 | 0.071 | 17.0 |
| 8430 | 0.45 | 0.62 | 0.45 | 0.51 | 0.098 | 19.2 | 0.37 | 0.50 | 0.39 | 0.42 | 0.071 | 16.9 |
| 8460 | 0.45 | 0.62 | 0.45 | 0.51 | 0.098 | 19.2 | 0.37 | 0.50 | 0.39 | 0.42 | 0.071 | 16.8 |
| 8490 | 0.45 | 0.62 | 0.45 | 0.51 | 0.098 | 19.2 | 0.37 | 0.50 | 0.39 | 0.42 | 0.071 | 16.7 |
| 8520 | 0.45 | 0.63 | 0.46 | 0.51 | 0.100 | 19.4 | 0.37 | 0.50 | 0.39 | 0.42 | 0.072 | 16.9 |
| 8550 | 0.45 | 0.63 | 0.46 | 0.51 | 0.100 | 19.4 | 0.37 | 0.50 | 0.40 | 0.42 | 0.072 | 16.9 |
| 8580 | 0.45 | 0.63 | 0.46 | 0.51 | 0.100 | 19.4 | 0.37 | 0.51 | 0.40 | 0.42 | 0.071 | 16.7 |
| 8610 | 0.45 | 0.63 | 0.46 | 0.51 | 0.100 | 19.4 | 0.37 | 0.51 | 0.40 | 0.42 | 0.071 | 16.8 |
| 8640 | 0.45 | 0.63 | 0.46 | 0.51 | 0.100 | 19.4 | 0.37 | 0.51 | 0.40 | 0.43 | 0.072 | 16.8 |
| 8670 | 0.45 | 0.63 | 0.46 | 0.51 | 0.100 | 19.4 | 0.37 | 0.51 | 0.40 | 0.43 | 0.071 | 16.7 |
| 8700 | 0.45 | 0.63 | 0.46 | 0.51 | 0.100 | 19.4 | 0.38 | 0.51 | 0.40 | 0.43 | 0.071 | 16.6 |
| 8730 | 0.45 | 0.63 | 0.46 | 0.51 | 0.100 | 19.4 | 0.37 | 0.51 | 0.40 | 0.43 | 0.072 | 16.8 |
| 8760 | 0.45 | 0.63 | 0.46 | 0.52 | 0.101 | 19.5 | 0.37 | 0.51 | 0.40 | 0.43 | 0.072 | 16.7 |
| 8790 | 0.46 | 0.63 | 0.46 | 0.52 | 0.099 | 19.2 | 0.38 | 0.51 | 0.40 | 0.43 | 0.071 | 16.6 |
| 8820 | 0.46 | 0.63 | 0.46 | 0.52 | 0.099 | 19.2 | 0.37 | 0.51 | 0.40 | 0.43 | 0.072 | 16.7 |
| 8850 | 0.46 | 0.63 | 0.46 | 0.52 | 0.099 | 19.2 | 0.38 | 0.51 | 0.40 | 0.43 | 0.071 | 16.5 |
| 8880 | 0.46 | 0.63 | 0.46 | 0.52 | 0.099 | 19.2 | 0.38 | 0.51 | 0.40 | 0.43 | 0.071 | 16.6 |
| 8910 | 0.46 | 0.63 | 0.46 | 0.52 | 0.099 | 19.2 | 0.38 | 0.51 | 0.40 | 0.43 | 0.072 | 16.7 |
| 8940 | 0.46 | 0.63 | 0.46 | 0.52 | 0.099 | 19.2 | 0.38 | 0.51 | 0.40 | 0.43 | 0.072 | 16.6 |
| 8970 | 0.46 | 0.64 | 0.46 | 0.52 | 0.102 | 19.7 | 0.38 | 0.51 | 0.40 | 0.43 | 0.072 | 16.8 |
| 9090 | 0.46 | 0.64 | 0.47 | 0.52 | 0.101 | 19.3 | 0.38 | 0.52 | 0.41 | 0.43 | 0.073 | 16.8 |
| 9120 | 0.46 | 0.64 | 0.47 | 0.52 | 0.101 | 19.3 | 0.38 | 0.52 | 0.41 | 0.43 | 0.072 | 16.7 |
| 9150 | 0.46 | 0.64 | 0.47 | 0.52 | 0.101 | 19.3 | 0.38 | 0.52 | 0.41 | 0.43 | 0.072 | 16.6 |
| 9180 | 0.46 | 0.64 | 0.47 | 0.52 | 0.101 | 19.3 | 0.38 | 0.52 | 0.41 | 0.44 | 0.072 | 16.6 |
| 9210 | 0.46 | 0.64 | 0.47 | 0.52 | 0.101 | 19.3 | 0.38 | 0.52 | 0.41 | 0.44 | 0.072 | 16.5 |
| 9240 | 0.46 | 0.64 | 0.47 | 0.53 | 0.101 | 19.2 | 0.38 | 0.52 | 0.41 | 0.44 | 0.072 | 16.5 |
| 9270 | 0.46 | 0.64 | 0.47 | 0.53 | 0.102 | 19.5 | 0.38 | 0.52 | 0.41 | 0.44 | 0.072 | 16.5 |
| 9300 | 0.46 | 0.64 | 0.47 | 0.53 | 0.101 | 19.2 | 0.38 | 0.52 | 0.41 | 0.44 | 0.072 | 16.5 |
| 9330 | 0.46 | 0.64 | 0.47 | 0.53 | 0.101 | 19.2 | 0.38 | 0.52 | 0.41 | 0.44 | 0.072 | 16.4 |
| 9360 | 0.46 | 0.64 | 0.47 | 0.53 | 0.101 | 19.2 | 0.38 | 0.52 | 0.41 | 0.44 | 0.072 | 16.4 |

| | Permanent Strain from Actuator Displacement, % | | | | | | Permanent Strain from 100 mm Gauge Points, % | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Coefficient | | | | | | Coefficient |
| Load | Specimen | Specimen | Specimen | Average | Standard | of | Specimen | Specimen | Specimen | Average | Standard | of |
| Cycle | 1 | 2 | 3 | | Deviation | Variation | 1 | 2 | 3 | | Deviation | Variation |
| 9390 | 0.46 | 0.64 | 0.47 | 0.53 | 0.101 | 19.2 | 0.38 | 0.52 | 0.41 | 0.44 | 0.072 | 16.4 |
| 9420 | 0.46 | 0.64 | 0.47 | 0.53 | 0.101 | 19.2 | 0.38 | 0.52 | 0.41 | 0.44 | 0.073 | 16.7 |
| 9450 | 0.46 | 0.65 | 0.47 | 0.53 | 0.104 | 19.6 | 0.38 | 0.52 | 0.41 | 0.44 | 0.074 | 16.7 |
| 9480 | 0.46 | 0.65 | 0.48 | 0.53 | 0.103 | 19.3 | 0.38 | 0.52 | 0.42 | 0.44 | 0.073 | 16.5 |
| 9510 | 0.46 | 0.65 | 0.48 | 0.53 | 0.103 | 19.3 | 0.38 | 0.52 | 0.42 | 0.44 | 0.073 | 16.6 |
| 9540 | 0.46 | 0.65 | 0.48 | 0.53 | 0.103 | 19.3 | 0.39 | 0.52 | 0.42 | 0.44 | 0.073 | 16.6 |
| 9570 | 0.46 | 0.65 | 0.48 | 0.53 | 0.103 | 19.3 | 0.38 | 0.52 | 0.42 | 0.44 | 0.074 | 16.7 |
| 9600 | 0.46 | 0.65 | 0.48 | 0.53 | 0.103 | 19.3 | 0.39 | 0.52 | 0.41 | 0.44 | 0.073 | 16.6 |
| 9630 | 0.46 | 0.65 | 0.48 | 0.53 | 0.103 | 19.3 | 0.39 | 0.53 | 0.41 | 0.44 | 0.074 | 16.7 |
| 9660 | 0.46 | 0.65 | 0.48 | 0.53 | 0.103 | 19.3 | 0.39 | 0.53 | 0.42 | 0.44 | 0.073 | 16.6 |
| 9690 | 0.47 | 0.65 | 0.48 | 0.53 | 0.101 | 19.0 | 0.39 | 0.53 | 0.42 | 0.44 | 0.074 | 16.6 |
| 9720 | 0.47 | 0.65 | 0.48 | 0.53 | 0.104 | 19.5 | 0.39 | 0.53 | 0.42 | 0.44 | 0.074 | 16.6 |
| 9750 | 0.47 | 0.65 | 0.48 | 0.53 | 0.104 | 19.5 | 0.39 | 0.53 | 0.42 | 0.45 | 0.073 | 16.5 |
| 9780 | 0.47 | 0.65 | 0.48 | 0.54 | 0.103 | 19.1 | 0.39 | 0.53 | 0.42 | 0.45 | 0.074 | 16.6 |
| 9810 | 0.47 | 0.65 | 0.48 | 0.54 | 0.103 | 19.1 | 0.39 | 0.53 | 0.42 | 0.45 | 0.074 | 16.5 |
| 9840 | 0.47 | 0.65 | 0.48 | 0.54 | 0.103 | 19.1 | 0.39 | 0.53 | 0.42 | 0.45 | 0.074 | 16.5 |
| 9870 | 0.47 | 0.65 | 0.48 | 0.54 | 0.103 | 19.1 | 0.39 | 0.53 | 0.42 | 0.45 | 0.074 | 16.5 |
| 9900 | 0.47 | 0.65 | 0.48 | 0.54 | 0.103 | 19.1 | 0.39 | 0.53 | 0.42 | 0.45 | 0.075 | 16.7 |
| 9930 | 0.47 | 0.65 | 0.48 | 0.54 | 0.103 | 19.1 | 0.39 | 0.53 | 0.42 | 0.45 | 0.075 | 16.7 |
| 9960 | 0.47 | 0.66 | 0.48 | 0.54 | 0.106 | 19.6 | 0.39 | 0.53 | 0.42 | 0.45 | 0.074 | 16.3 |
| 9990 | 0.47 | 0.66 | 0.49 | 0.54 | 0.104 | 19.3 | 0.39 | 0.53 | 0.42 | 0.45 | 0.074 | 16.6 |
| 10020 | 0.47 | 0.66 | 0.49 | 0.54 | 0.103 | 19.0 | 0.39 | 0.53 | 0.42 | 0.45 | 0.074 | 16.5 |