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Effects of Material Properties, Specimen Geometry, and Specimen Preparation Variables on Asphalt Concrete Tests for Rutting

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Effects of Material Properties, Specimen Geometry, and Specimen Preparation Variables on Asphalt Concrete Tests for Rutting

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By:

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1.0 EXECUTIVE SUMMARY

This report presents the results of laboratory tests and analyses performed as a part of the effort by the Federal Highway Administration (FHWA) to develop simple performance tests for asphalt concrete mix analysis and design for highway pavement applications. Three specific areas are addressed, namely:

1. The non-linearity of shape distortion (shear) properties, information required to assess the use of indirect methods to measure the shear response of asphalt mixes;
2. appropriate shape an specimen size for use in a simple performance test; and
3. comparison of mix rutting performance determined from specimens prepared using the Superpave gyratory compactor (SGC) and specimens of the same mix obtained by coring from a pavement section

To assess the non-linearity of mix response to shear, (Chapter 3), frequency sweep tests were performed in the simple shear test on pavement cores. Three temperatures (20, 40, and 57°C), three strain levels (0.01, 0.05, and 0.1 percent), and ten frequencies (in the range 10 to 0.01 Hz) were utilized.

Results of the tests indicated that the complex modulus, G*, exhibited non-linear behavior for these ranges of temperatures, strain levels, and frequencies. Generally, G* decreased as the strain level was increased. This reduction, percentage wise, was larger as the temperature increased and the frequency decreased. Only at the lowest temperature and higher frequencies was it possible to deduce the complex Young's modulus, E*, from the measured value of G* assuming the applicability of linear elastic behavior.

To evaluate the influence of specimen size and shape (Chapter 4) on the variability of results obtained in the repeated simple shear test at constant height (RSST-CH), cylindrical specimens 150 and 200 mm in diameter by 50 mm in height were utilized. Two shapes were obtained by trimming the sides of some of the cores to obtain an “almost” prismatic shape. Two sets of specimens were utilized; the groups were obtained by coring from slabs prepared by rolling wheel compaction during the SHRP research program while the other group was obtained from a test pavement used for accelerated pavement testing with the Heavy Vehicle Simulator (HVS).

The RSST-CH test showed a large difference in the response between the two mixes, this in spite of the large variance in test results. Variance in the test results was about the same for the 150 and 200 mm diameter specimens as was the case for the results obtained using the cylindrical and more prismatic-shaped specimens. These results suggest that the sizes of the specimens were not sufficiently large as compared to the representative volume element (RVE) for the maximum size of aggregate (19 mm) used.

The intent of the FHWA is to use the SGC for mix quality control in the field and for preparation of test specimens to be used in the simple performance test. Chapter 5 describes the results of a study to evaluate the comparative performance in the RSST-CH tests of specimens of the same mix prepared with the SGC and obtained from field cores. RSST-CH tests were performed at three temperatures (40, 50 and 65°C).

In general, the permanent deformation resistance of specimens prepared by the SGC was larger than that of field core specimens at comparable degrees of compaction at all three temperatures. The difference was largest at 40°C, approximately 10 orders of magnitude, and decreasing at 65°C to almost 2 to 3 orders of magnitude. In addition, variance of the test results is much larger for the SGC than for the field cores, due in part to the larger permanent resistance of the SGC-prepared specimens.

Based on the results presented in this report and a report submitted earlier by Symplectic Engineering Corporation as a part of this project, Chapter 6 contains recommendations for additional studies.

Specific recommendations for the simple performance test include:

- The permanent (shear) deformation resistance of most mixes is a useful property to measure at test temperatures that are greater than about 30°C. Therefore, only heating is required for the test apparatus, and no cooling capability is required.
- The tests performed by the simple shear performance tester should include purely shear kinematics, in order to obtain direct measures of shape distortion properties.
- To reduce variance in test results, the equipment should be capable of testing specimens larger than the current 150 mm diameter by 50 mm tall specimens produced by field coring of the by the Superpave gyratory compactor. This will preserve the ability to test larger specimens in order to reduce the variance of the results by using specimen dimensions closer to those of the RVE, although those dimensions have not yet been determined for typical paving mixes.
- While it is possible to reduce the variance of test results from the Repeated Simple Shear Test at Constant Height (RSST-CH) by increasing the size of the specimens and by testing at higher temperatures, it must be kept in mind that the test is extremely sensitive to mix variables, given that the response of the mix varies

exponentially. That is, the variance is larger (in a logarithmic scale) the greater the resistance to permanent deformation.

2.0 INTRODUCTION

This final report presents the results of laboratory tests and analyses performed for the Federal Highway Administration, Office of Technology Applications, as part of the work plan for the second year of the Pacific Coast SHRP Superpave Facility at the University of California at Berkeley. A draft of this report was submitted to the Federal Highway Administration, Office of Technology Applications in February, 1998.

The work performed for this project is part of a larger ongoing effort by the Federal Highway Administration to develop simple performance tests for asphalt concrete mix design and analysis for highway pavement applications. The following attributes have been identified by the pavement community as being required for the successful implementation of the equipment and test methods:

- The tests must provide a strong link between test results and the rutting performance of the mix in the field.
- The equipment must be relatively inexpensive, with a total cost of less than about $ 50,000 as a target.
- The equipment must be robust in terms of the test results and performance predictions, and with respect to the equipment dependability, when used in a field laboratory environment.
- The equipment must be able to make use of specimens that can be prepared in the field, with use of Superpave gyratory specimens as a minimum requirement.

Specific tasks for this study have included the following: *(1)*

- prepare a summary of rutting performance, particularly with regard to the conditions under which it occurs in the field, and the relative contributions of volume decrease and deviatoric (shear) deformation;
- evaluate the need for a simple performance test to apply volumetric or deviatoric strains, or a combination of both;
- assess the best test configuration to evaluate the permanent deformation characteristics of asphalt concrete mixes;
- conduct a numerical study to identify appropriate test conditions; and
- develop an experimental plan and criteria for evaluation of simple performance test equipment.

This report together with Reference *(2)* completes the first four tasks listed above. A technical memorandum on the final task will be submitted in the near future.

The purpose of the work included in this report is to provide test and analysis results regarding three specific issues for the simple performance test, and its ability to meet the requirements listed above. These specific issues are:

1. non-linearity of shape distortion (shear) properties, information required to assess the use of indirect methods for measurement of shear properties;
2. shape and specimen sizes appropriate for use in the simple performance tester; and
3. prediction of mix rutting performance using specimens prepared with the Superpave gyratory compactor as compared to specimens prepared from field cores.

Results of research performed by the University of California, Berkeley (UCB), the Symplectic Engineering Corporation and others as part of the SHRP project together with subsequent studies performed o ver the last two years have led to the conclusion that shape distortion, (i.e., the shear properties of asphalt concrete) is the critical factor in determining rutting performance. This is the underlying assumption of the work included in this report, and is based on both theoretical analyses and field observations. *(2, 3, 4)*

To provide a measure of the shape distortion properties of a mix, a simple performance test must be able to separate the shape distortion properties from other properties. For the extraction procedure to be reliable, shape distortion response must be the primary mode of deformation in the test so that shape distortion properties are not masked by other properties. In particular, laboratory tests conducted by UCB for the SHRP project demonstrate that resistance to volume change is much larger at elevated temperatures than is resistance to shape distortion. Additionally, analysis of the relative importance of volume change versus shape distortion indicates that shape distortion is the controlling deformation mode in rut development. *(4)* Thus, a simple performance test must limit the extent to which volume change determines the response of the mix to the test as compared to shape distortion. Thus for the circumstances in which a simple performance test is required to characterize the expected performance of the mix with respect to rutting, lack of sensitivity to the shape distortion properties can make it very difficult to rank mixes or develop robust correlations to field observations.

Resistance to shape distortion can be measured directly through use of a test in which the kinematics are purely shape distortion or a close approximation thereof. An example of a simple test that provides a close approximation to a pure shape distortion test is the test configuration of the SHRP-developed shear test.

Resistance to shape distortion can potentially be measured indirectly as well, using a test configuration in which the kinematics are not purely those of shape distortion, such as the triaxial test. However, to extract shape distortion properties from such a test, an adequate constitutive relation must be available. Unfortunately, such a relation for asphalt concrete at elevated temperatures is not available at this date although development of an applicable constitutive relation was begun during SHRP, and is a large part of the work underway by the FHWA models contractor at the University of Maryland. *(5)*

In the interim, the University of Maryland team has recommended that linear elasticity be used to extract shape distortion properties from the results of an indirect test used as a simple performance test. Accordingly, in Chapter 3 results of an investigation of the linearity of the complex shear modulus – a shape distortion property of an asphalt concrete mix – is reported considering the effects of strain level, load frequency, and temperature. If the material exhibits highly non-linear response to these three parameters, then the ability to extract meaningful shape distortion properties from an indirect test using the assumption of linear elasticity is placed in question.

It has already been documented that the simple shear test has imperfections and exhibits relatively large variances in test results. *(4, 6, 7)* These imperfections are associated primarily with the lack of complementary shear tractions on the vertical surfaces of the specimen, and with the circular shape of typical specimens obtained from coring or produced by gyratory compaction. The large variance has been attributed primarily to the relation between the size of the largest aggregates in a specimen and the current specimen dimensions. It is likely that the specimen dimensions result in less than a representative volume element (RVE) for typical maximum aggregate sizes.

Another source of variance may exist in the data obtained from field cores. Some data suggest that different properties may exist in the direction of rolling as compared to the perpendicular direction. *(6)* If this asymmetry in the horizontal plane is not accounted for in the shear test by testing all specimens in the same direction, another source of variance is introduced.

It must be emphasized that RVE and specimen orientation considerations are applicable to any test configuration.

Some aspects of specimen size relative to RVE and specimen shape are examined in Chapter 4. Two specimen sizes (150 mm and 200 mm diameter) have been included in the study. Alternative specimen shapes were obtained by cutting away the sides of the cylindrical specimens to produce a more prismatic shape. The effects of shape change have been evaluated in terms of the mean and variance of the test results.

Two mixes were evaluated in this study, results of which provided a comparison of test variance and the difference in the mean response for the two mixes. However, the number of replicates included in the study was limited due to budget constraints. If the mean responses for the two specimen shapes are quite different, interpretation of the results should be assisted by analytical studies of specimen shape [e.g., like those noted in Reference *(2)*] to insure reasonable conclusions.

If the test variance is reduced by increased specimen size or by the use of a prismatic (versus circular) shape, guidance would be provided for modification of specimen size and shape relative to that in current use. If there are no significant reductions in variance, then the test results would likely suggest that specimen sizes utilized herein may still be less than the RVE.

The Superpave gyratory compactor (SGC) is the methodology adapted for mix compaction in the Superpave volumetric mix design procedure and is being deployed as a field quality control tool to replace the Marshall compaction device. In the original SHRP Superpave methodology for Levels 2 and 3 of the mix design and analysis procedure, specimens for performance testing were to be prepared by the SGC. It is the intent of the FHWA to continue this practice when the simple performance test or tests have been developed. Thus, if performance estimates are to be made from test results obtained from these specimens, it is important to compare these results with those obtained from specimens of the mix as it is compacted in the field. Understanding of differences, if any, is particularly important if field cores as well as SGC specimens are to be used to estimate mix performance.

To contribute to this understanding, Chapter 5 of this report presents a comparison of test results from the Repeated Simple Shear Test at Constant Height (RSST-CH)[1] using both SGC specimens and field cores of the same mix.

Conclusions drawn from the information presented in Chapters 3, 4, and 5 are presented in Chapter 6. Recommendations for action and for future work are also included in this chapter.

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[1] Note: At the suggestion of FHWA reviewers, the RSST-CH has been renamed from the Repetitive Simple Shear Test at Constant Height to the Repeated Simple Shear Test at Constant Height.

3.0 EFFECTS OF FREQUENCY, TEMPERATURE AND STRAIN ON SHEAR STIFFNESS

3.1 Objectives

The objective of this study is to define the combined effects of test temperature, load frequency, and shear strain level on mix shear stiffness. Accordingly, frequency sweep tests were performed in the simple shear test on pavement cores at three temperatures, ten frequencies, and three strain levels. Results of these tests should provide information to evaluate non-linearity in the shear behavior of asphalt concrete at elevated temperatures. If the results suggest that asphalt concrete is highly non-linear under these conditions, then the use of indirect tests to obtain shape distortion (shear) properties is difficult since an acceptable non-linear constitutive relation has not yet been developed to permit determination of these properties from such tests.

3.2 Experiment Design

Specimens used in this study were cored from the dense-graded asphalt concrete overlay being evaluated as part of Goal 3 of the CAL/APT program. *(8)* The mix, construction, and sampling are described in Chapter 5. All specimens tested were obtained six months after construction and were 150 mm in diameter and 50 mm in height with air void contents between 6.0 and 7.3 percent.

3.2.1 Factor Levels

Three temperatures were used in the study – 20°, 40°, and 57°C. At each temperature, frequency sweeps were conducted at shear strains of 0.01, 0.05, and 0.10 percent.[2]

Each specimen was tested at one temperature and at all three strains, starting with the smallest strain. Three replicates were tested for each cell of the experiment. The test matrix is shown in Table 3.1.

Table 3.1 Experiment design and specimens tested

	Temperature		
Shear Strain	20°C	40°C	57°C
0.01%	G-31 (6.0)* G-33 (6.2) G-35 (6.6)	G-40 (6.0) G-43 (6.8) G-25 (7.3)	G-29 (6.6) G-42 (6.8) G-39 (7.0)
0.05%	G-31 (6.0) G-33 (6.2) G-35 (6.6)	G-40 (6.0) G-43 (6.8) G-25 (7.3)	G-29 (6.6) G-42 (6.8) G-39 (7.0)
0.1%	G-31 (6.0) G-33 (6.2) G-35 (6.6)	G-40 (6.0) G-43 (6.8) G-25 (7.3)	G-29 (6.6) G-42 (6.8) G-39 (7.0)

*The figure in parentheses is the air-void content (percent); the term G represents the Goal 3 designation.

3.2.2 Test Method – Shear Frequency Sweep (FS-S)

The test method used is described in AASHTO TP7-94, except that no preconditioning was performed and deformation was measured across the metal platens and not on the side of the specimen. This arrangement was used in order to provide an average measurement of specimen response across the entire specimen rather than the local response obtained when the LVDT is

[2] The AASHTO TP7-94 procedure currently calls for a shear strain of 0.005 percent for the frequency sweep tests. Our results suggest that this level is too small to measure with precision using LVDT instrumentation available in the simple shear test machines presently in use.

mounted on the side of the specimen.[3] A 37 mm gauge length was still used for shear strain determination since UCB experience indicates that the specimen deformation is controlled by the epoxy bond in the 6.5 mm adjacent to each of the platens.

The shear frequency sweep test is performed by applying a repeated sinusoidal deformation wave to the specimen and the load required to produce the desired shear strain is measured. The test begins with zero shear load and zero applied shear strain. The sinusoidal deformation and load oscillate around zero, with the deformation offset in time relative to the load by the phase angle. Ten frequencies are used in this test, applied in the following order: 10, 5, 2, 1, 0.5, 0.2, 0.1, 0.05, 0.02, and 0.01 Hz. Numbers of repetitions of the sine wave are varied depending upon the frequency, with 100 repetitions at 10 Hz and one repetition at 0.01 Hz, because high frequencies require more time to stabilize the wave form. The temperature was kept constant during each test.

Complex shear moduli (G*) were calculated by the ATS software. *(9)* Each specimen is maintained at a constant height throughout the test.

[3] This method of mounting the LVDT probably helps reduce the variability of the SGC specimens, which have uncut surfaces along the sides of the cylinder.

3.3 Results

3.3.1 Strain, Temperature and Frequency Effects

Frequency sweep test results for each specimen are included in Table A-1 in the Appendix. Average test results for each set of three replicate specimens are shown in Table 3.2, and are plotted in Figure 3.1. Effects of strain level on complex shear modulus (G*) versus frequency are shown in Figures 3.2, 3.3, and 3.4 for temperatures of 20°, 40°, and 57°C, respectively.

In Figure 3.1 it will be noted that G* increases with decreased temperature, increased frequency, and smaller shear strains. At low temperatures and high frequencies the shear stiffness (G) should be about one-third of the Young's modulus (E) at corresponding conditions. From Figure 3.1 it will be noted, for example, that the value of G* at a temperature of 20°C and

Table 3.2 Average Values of the Three Replicate Specimens.

Average of Three Replicate Tests									
	0.0001 Shear Strain			0.0005 Shear Strain			0.001 Shear Strain		
	20C	40C	57C	20C	40C	57C	20C	40C	57C
Frequency	Complex Shear Modulus (kPa)			Complex Shear Modulus (kPa)			Complex Shear Modulus (kPa)		
10	2,289,697	257,980	54,129	2,240,240	199,914	27,884	955,890	178,675	23,692
5	1,918,313	175,294	42,402	1,666,067	130,792	19,150	668,267	113,083	15,857
2	1,464,797	103,062	32,642	1,172,647	74,010	12,845	508,977	64,026	10,133
1	1,171,507	69,602	27,421	891,840	48,323	10,433	396,706	41,186	7,837
0.5	921,246	48,120	24,995	693,644	36,822	8,641	314,093	26,758	6,641
0.2	629,521	31,997	22,504	479,886	22,541	7,677	223,865	15,791	5,761
0.1	445,438	24,823	20,646	354,065	16,818	6,964	167,692	11,324	5,450
0.05	283,278	20,832	21,674	232,138	13,086	6,520	118,295	8,491	5,089
0.02	176,141	17,996	21,219	147,613	10,599	6,469	76,310	6,734	4,905
0.01	108,691	16,173	17,828	100,449	9,375	6,016	63,876	5,949	4,742
	Shear Phase Angle (degrees)			Shear Phase Angle (degrees)			Shear Phase Angle (degrees)		
10	27.2	54.8	54.8	20.3	60.5	60.3	14.2	60.3	62.1
5	29.3	56.8	48.2	22.4	60.7	54.4	16.3	62.5	57.0
2	32.0	56.9	41.1	27.1	61.9	46.4	21.8	63.6	47.6
1	34.8	55.2	38.2	30.9	61.1	41.6	27.2	63.3	41.0
0.5	38.3	51.3	35.4	35.2	56.2	36.8	31.4	61.5	33.6
0.2	43.5	45.6	32.4	40.9	51.2	30.9	36.4	56.5	28.1
0.1	46.5	38.8	31.0	44.5	46.8	28.1	40.1	51.1	26.7
0.05	38.4	36.2	27.1	47.1	40.4	24.9	42.9	44.0	23.1
0.02	45.0	36.7	31.1	51.2	35.4	26.3	47.1	36.1	22.0
0.01	45.6	35.8	30.4	53.8	31.7	25.5	49.1	30.5	21.0

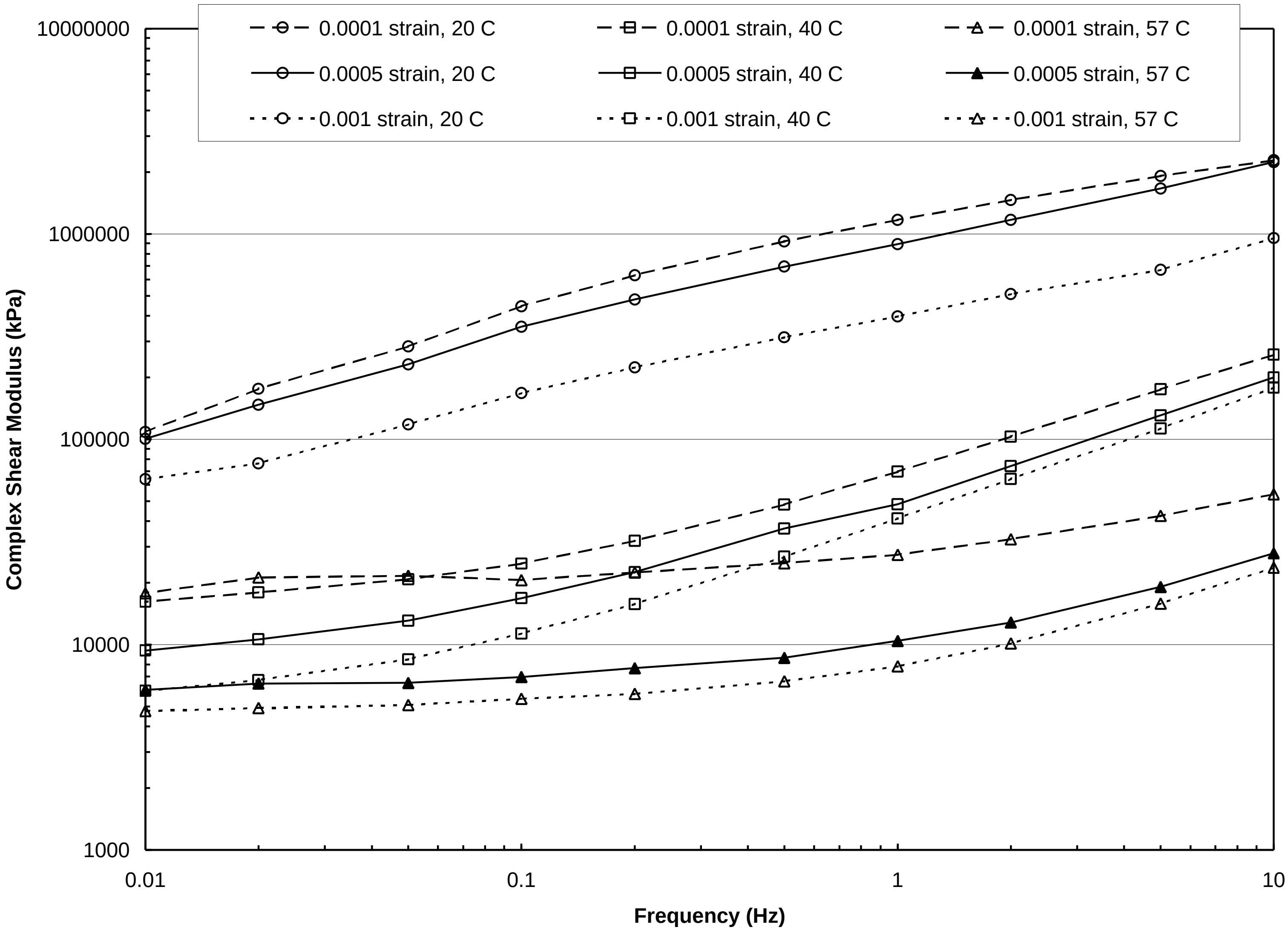

Figure 3.1. Averaged Results of the Three Replicate Specimens for Each Strain and Temperature.

a frequency of 10 Hz is about 2.2 GPa. The complex modulus (E*) determined in flexure in the same mix for the same temperature and frequency and at a strain of 0.015 percent is about 6.5 GPa suggesting that the linear elasticity assumption is reasonable for these conditions. However, as the temperature and strain amplitude increase, this assumption becomes less valid. At 20°C, G* at a strain of 0.1 percent is only about one-third of its value at 0.01 percent.

Figures 3.2, 3.3, and 3.4 as well as Figure 3.1 illustrate the non-linear behavior of shear stiffness, G* as a function of temperature (as well as strain level). While the data at a particular strain level can be used to construct master curves of G* versus frequency using the concept of interchangeability of time and temperature,[4] it must be emphasized that such relationships cannot be used to directly determine the correct values of the complex Young's modulus, E*, since the material exhibits non-linear response. This of course also applies in reverse. That is, if the complex Young's modulus is measured, determination of a correct shear modulus to define the shape distortion characteristics is questionable.

That the dependency of shear stiffness is non-linear on both frequency and temperature is also illustrated in Table 3.3. In this table, ratios of G* measured at 0.05 percent and 0.10 percent to that measured at 0.01 percent strain are shown. In general, it will be noted that as the strain and temperature increase and the frequency decreases, the modulus ratio decreases.

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[4] Strictly speaking, time-temperature superposition is only valid for linear viscoelastic materials.

3.3.2 Variability

Variability of G* in the shear frequency tests can be assessed from the data included in Table A-1 in the appendix and results of the analyses of these data shown in Figures 3.5 through 3.8. Figures 3.5 and 3.6 show values for the standard deviation of G* from replicate test results as a function of strain level, temperature, and frequency. Similarly, Figures 3.7 and 3.8 contain plots of the coefficient of variation (COV) for the same variables. The plots show that variability in G* is largest at high frequencies and low temperatures, conditions of high shear stiffness.

This variability may be due in part to the ability of the equipment to control the tests under the larger loads for these conditions. It should be noted that the equipment used for the testing is the prototype SST and is not as stiff as the newer full-scale SSTs.

It should also be noted that variability is larger for smaller shear strains. The prototype SST used in this investigation exhibits somewhat higher friction in the shear table bearings than the newer equipment. This may also contribute to the greater variability at small strains.

Table 3.3. Ratios of Complex Shear Modulus G* at 0.05 and 0.1 Percent Strain to that Measured at 0.01 Percent Strain.

Frequency (Hz)	**Complex Shear Modulus Ratio**					
	$\frac{G^* \, at \, 0.05\% \, strain}{G^* \, at \, 0.01\% \, strain}$			$\frac{G^* \, at \, 0.1\% \, strain}{G^* \, at \, 0.01\% \, strain}$		
	20°C	**40°C**	**57°C**	**20°C**	**40°C**	**57°C**
10	0.98	0.77	0.51	0.42	0.69	0.44
5	0.87	0.75	0.45	0.35	0.64	0.37
2	0.80	0.72	0.39	0.35	0.62	0.31
1	0.76	0.69	0.38	0.34	0.59	0.29
0.5	0.75	0.76	0.35	0.34	0.56	0.27
0.2	0.76	0.70	0.34	0.35	0.49	0.26
0.1	0.79	0.68	0.34	0.38	0.46	0.26
0.05	0.82	0.63	0.30	0.42	0.41	0.23
0.02	0.84	0.59	0.30	0.43	0.37	0.23
0.01	0.92	0.58	0.34	0.58	0.37	0.27

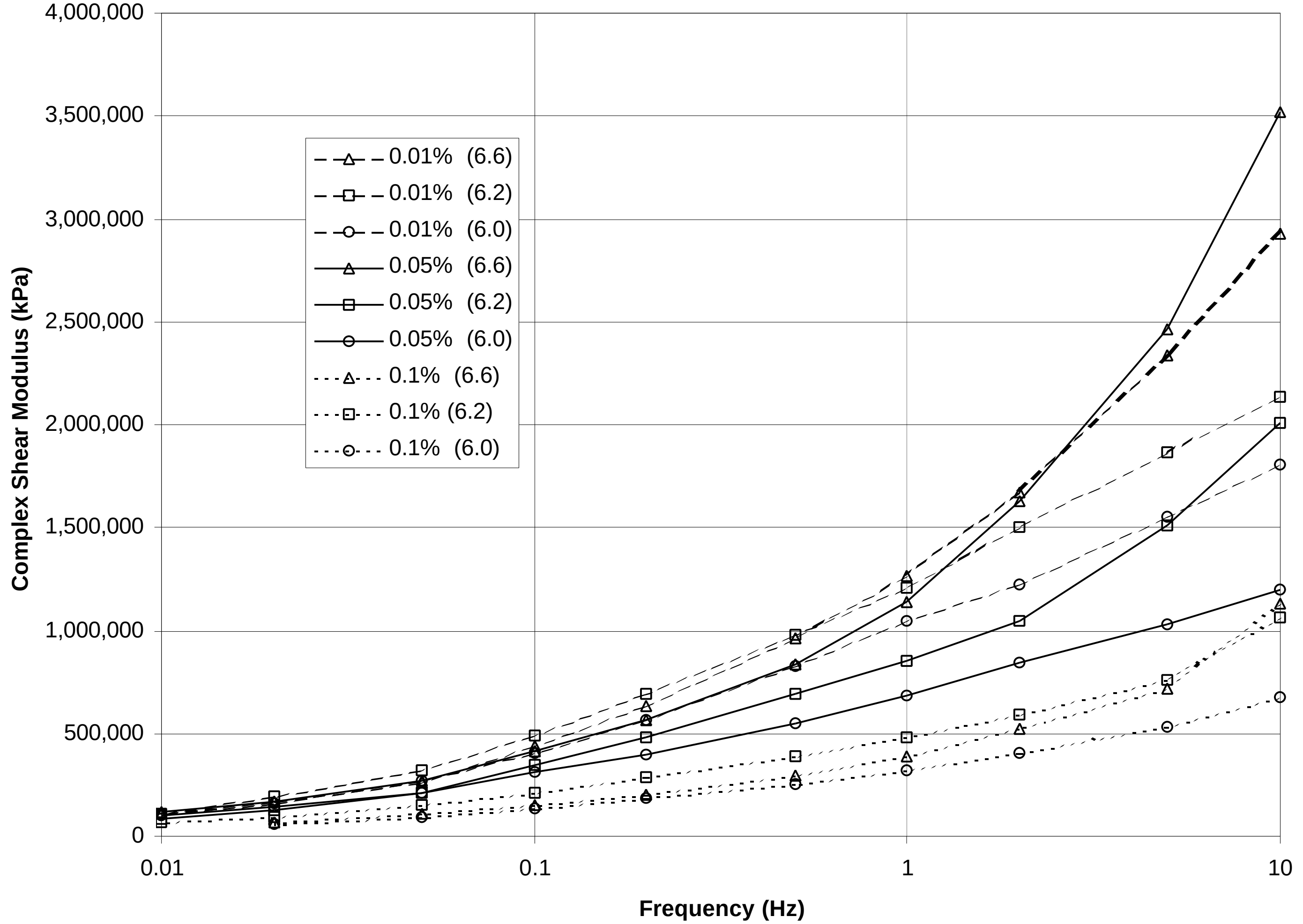

Figure 3.2. Complex Shear Modulus versus Frequency at 20° C.

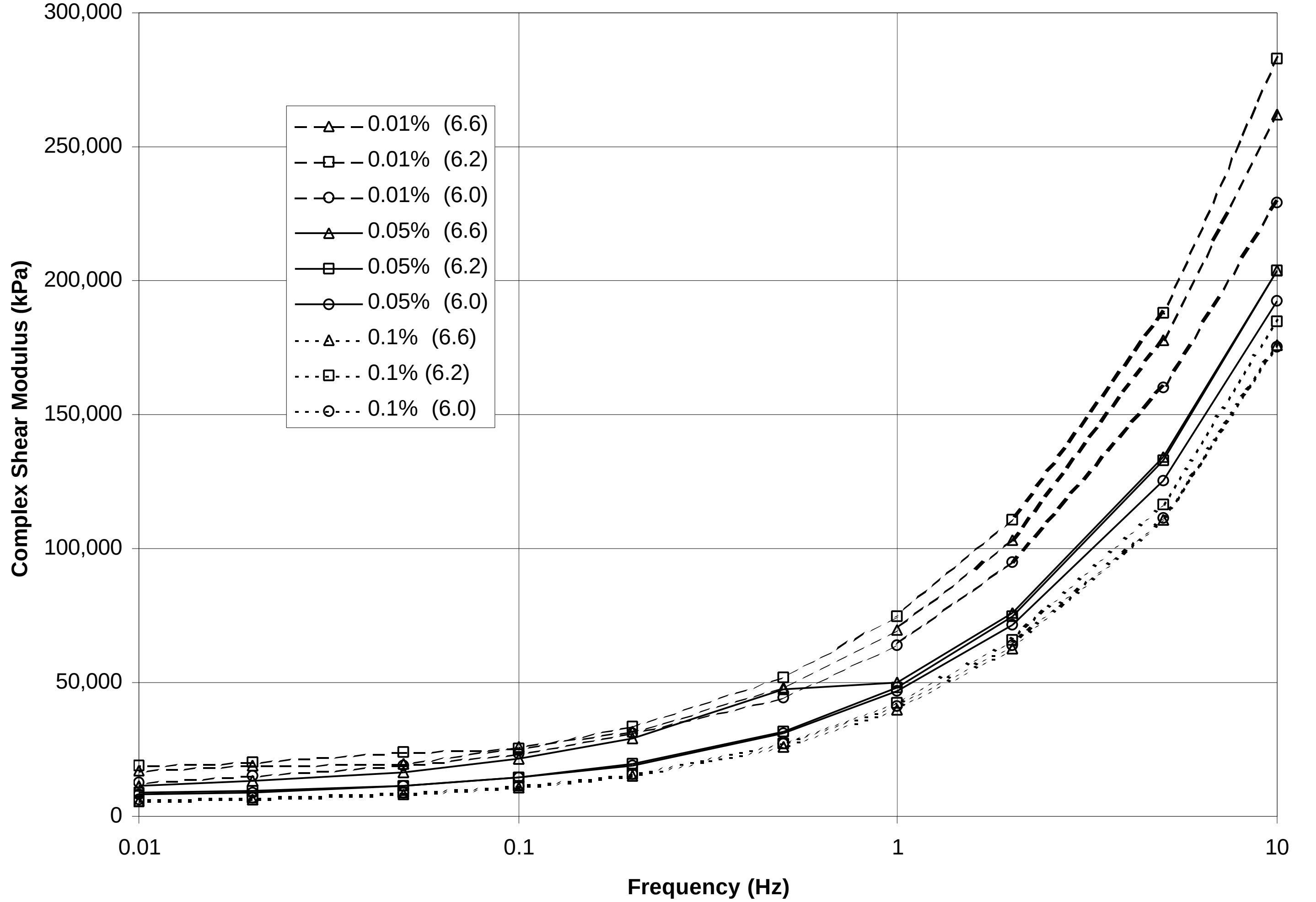

Figure 3.3. Complex Shear Modulus versus Frequency at 40° C.

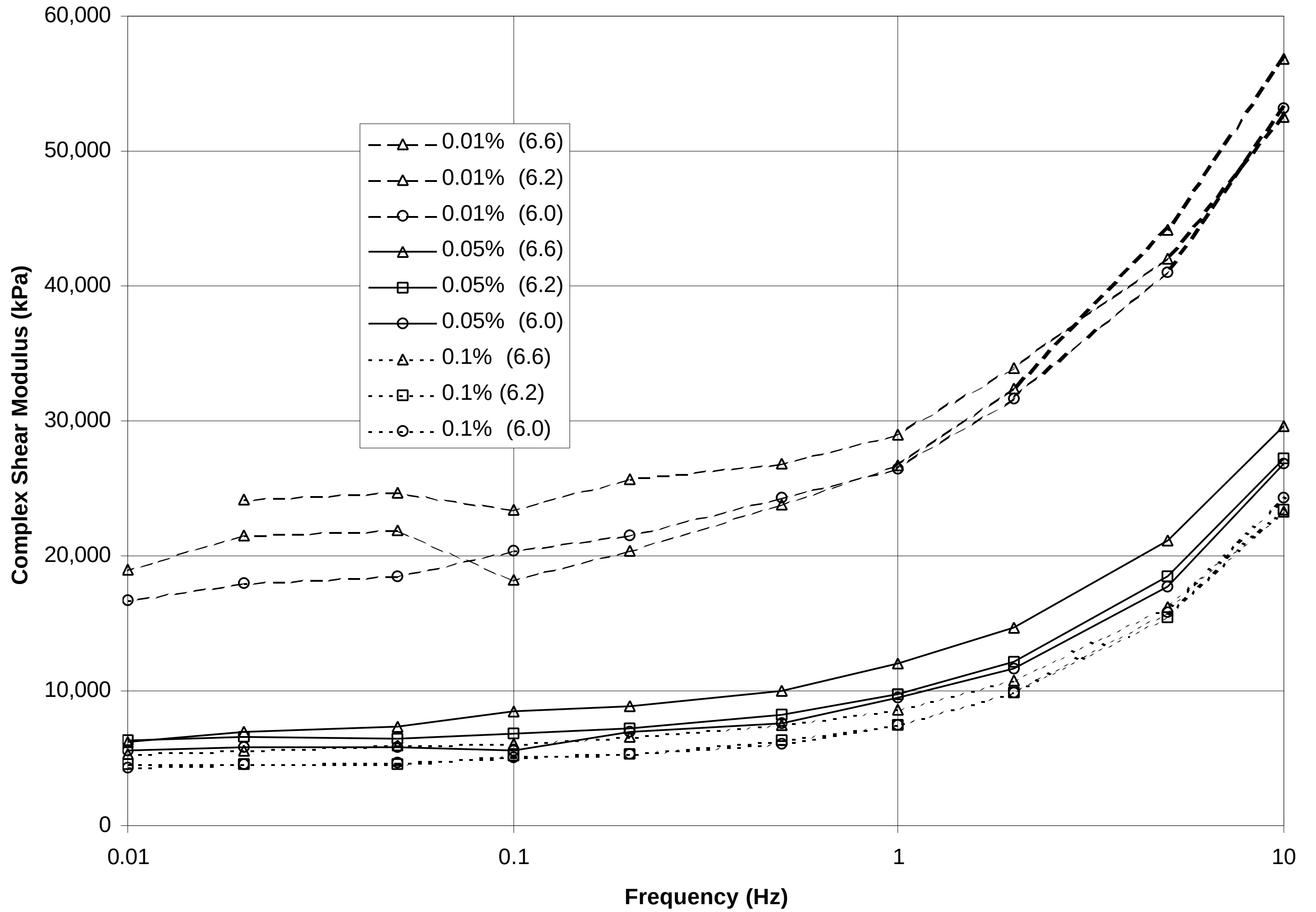

Figure 3.4. Complex Shear Modulus versus Frequency at 57° C.

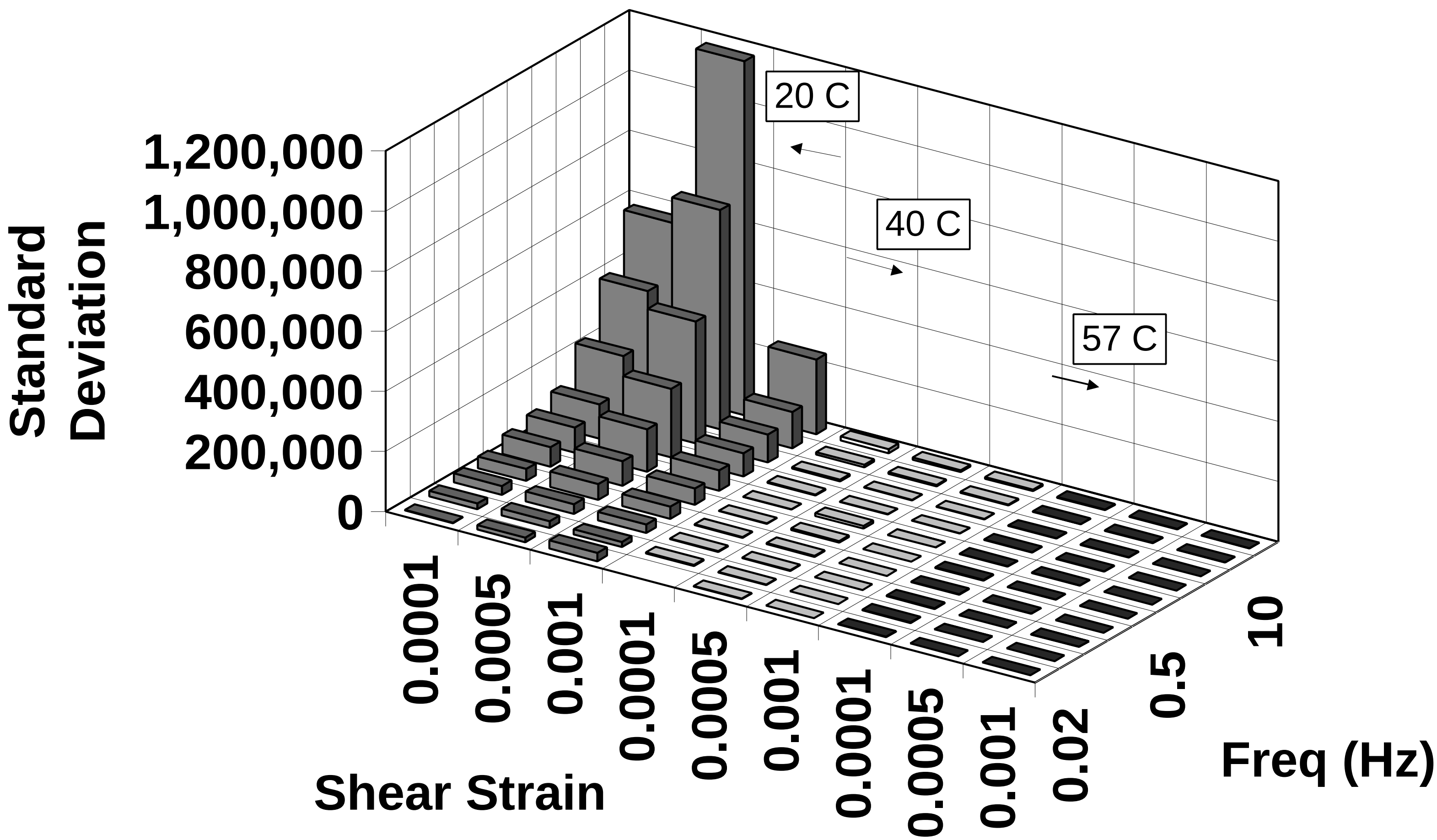

Figure 3.5. Standard Deviation versus Shear Strain and Frequency

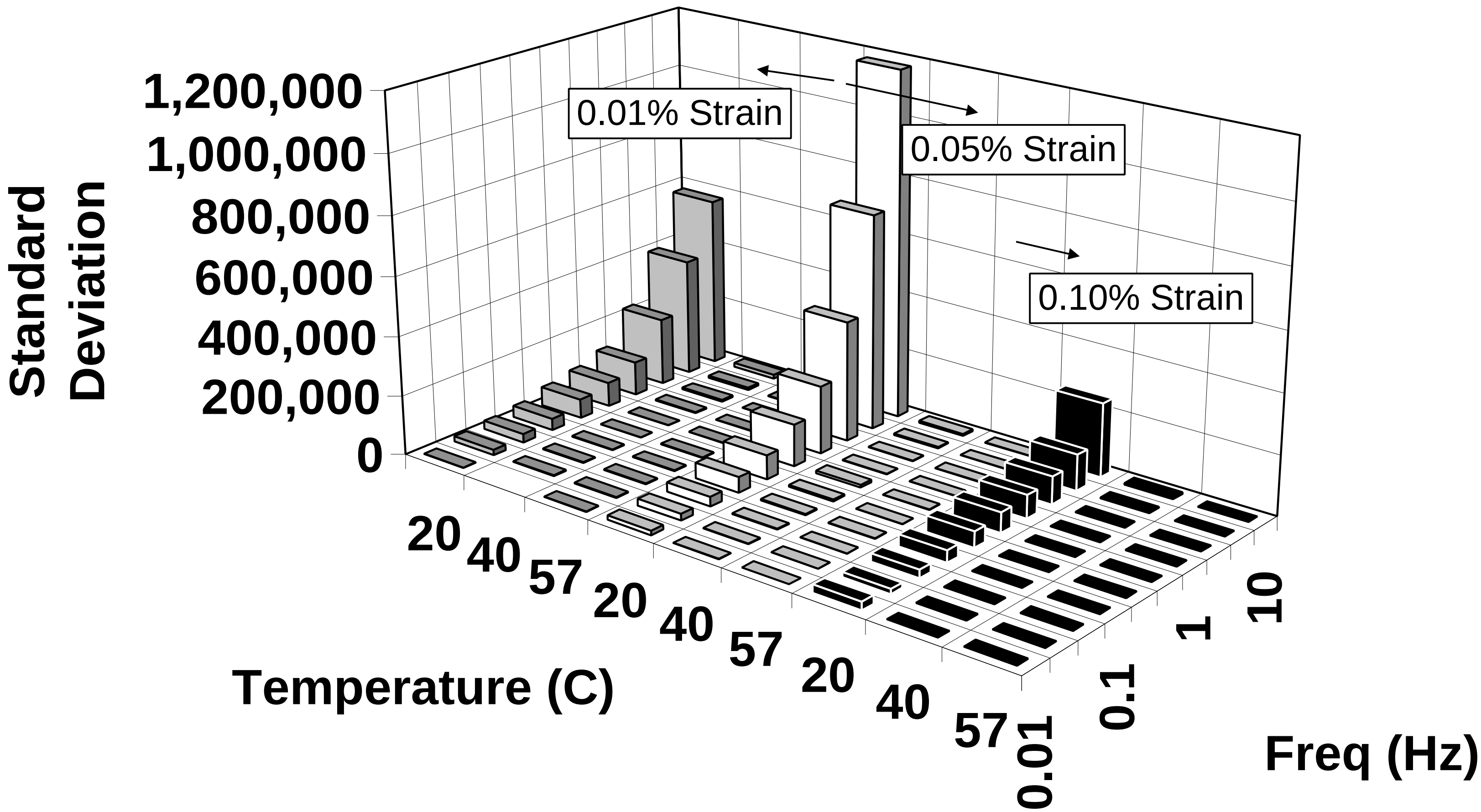

Figure 3.6. Standard Deviation versus Temperature and Frequency.

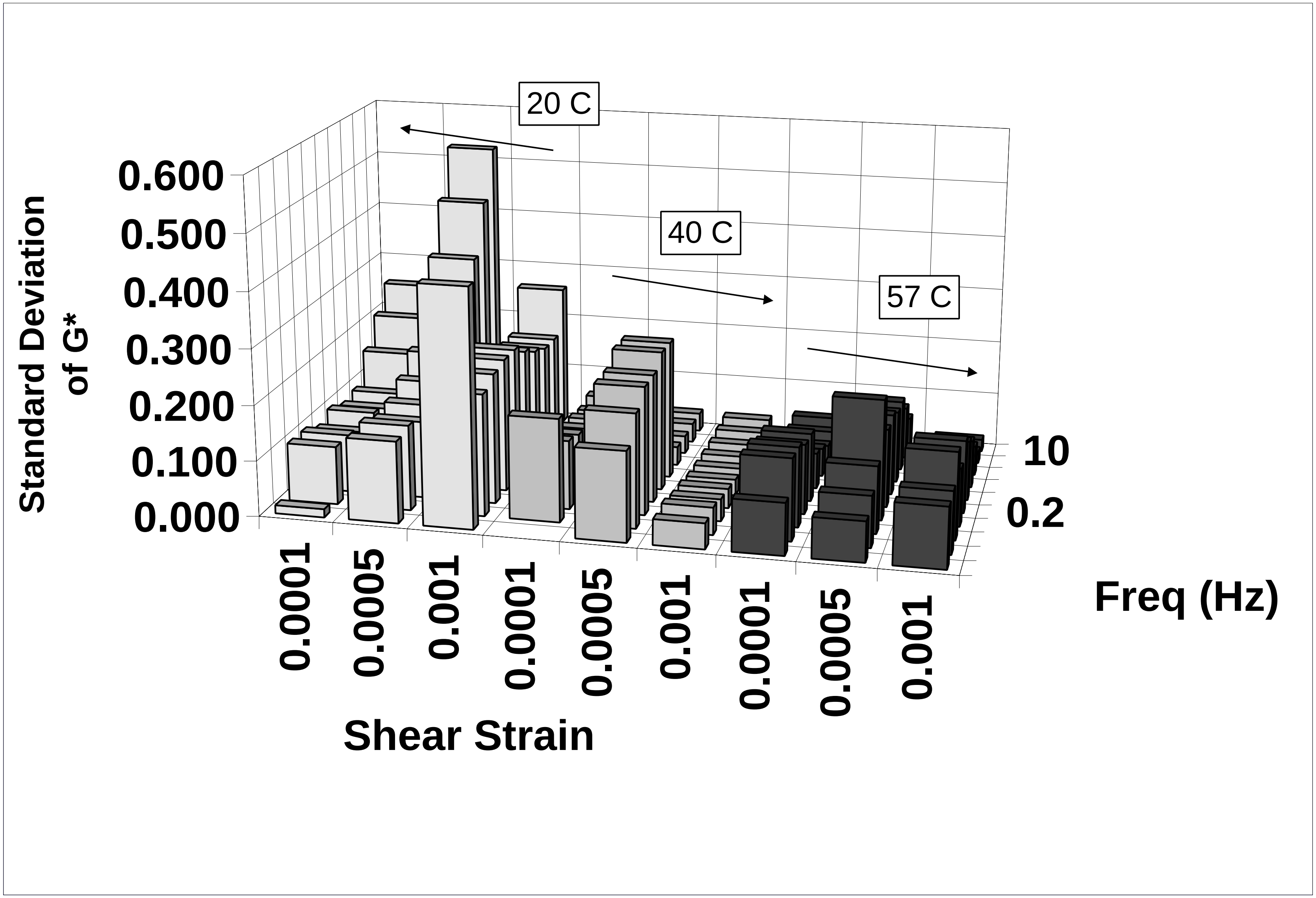

Figure 3.7. Coefficient of Variation versus Shear Strain and Frequency.

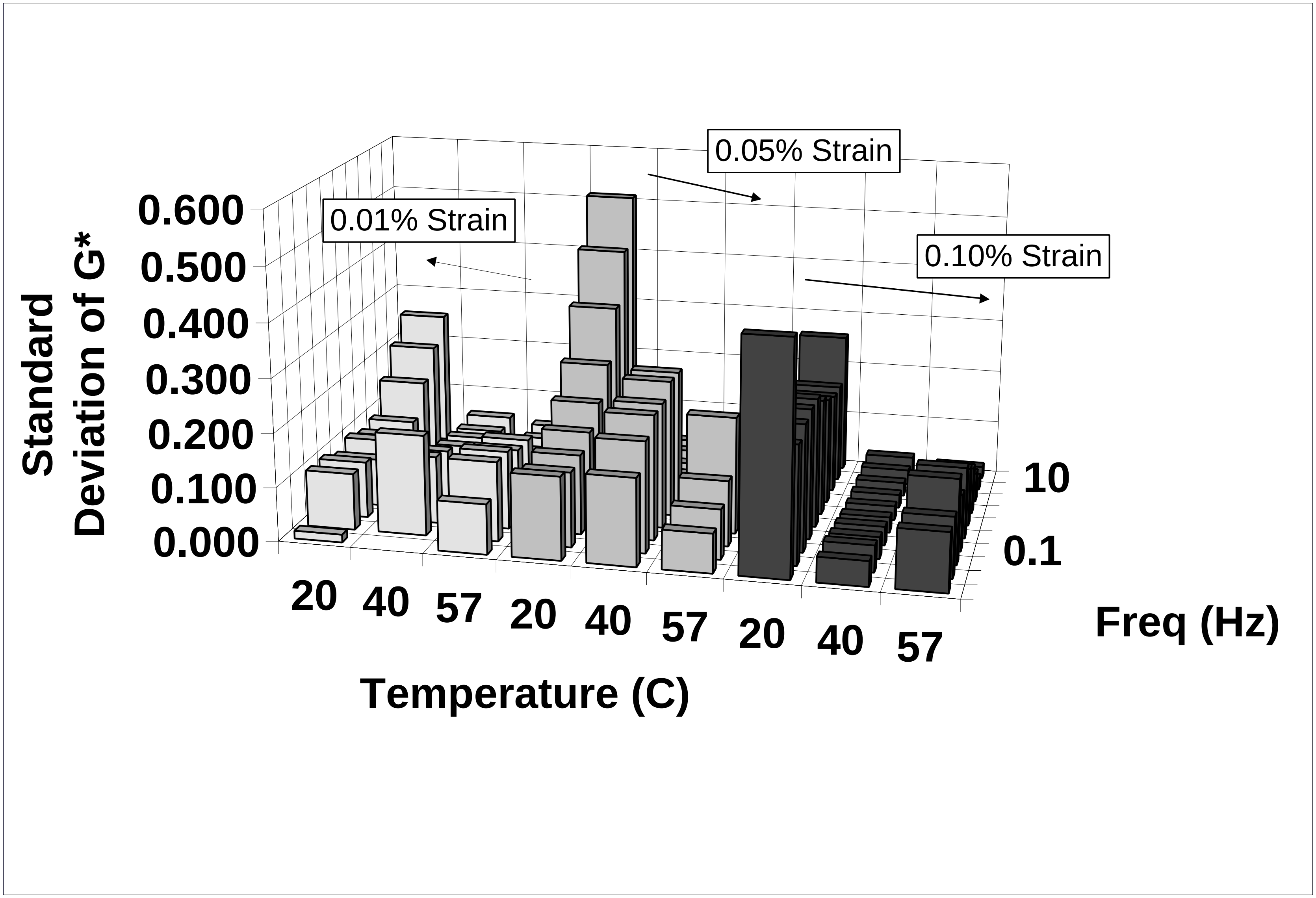

Figure 3.8. Coefficient of variation versus Temperature and Frequency.

3.4 Findings

The findings from the results presented in this chapter include the following:

- At 20° C and 10 Hz frequency, the complex shear stiffness (G*) measured using the shear frequency sweep was approximately one third of the complex flexural stiffness measured using the flexural beam device. This indicates that the measured G* corresponds with the complex Young’s modulus (E*), assuming linear elasticity and a Poisson’s ratio of about 0.5. This compatibility of G* and E* assuming linear elasticity was found to be valid only at low temperatures and high frequencies.
- Direct measurements of complex shear modulus show it to be non-linear with respect to frequency, temperature, and strain level, between 20° and 57° C, 0.01 and 10 Hz, and 0.01 and 0.1 percent shear strain.
- G* was found to decrease with larger shear strains. This decrease in G* with larger strains was influenced by both temperature and frequency. Changes in G* were not monotonic with frequency at a given strain and temperature. G* monotonically decreased with respect to temperature at a given frequency and strain.
- The variability of G* measured in the test varied with the mean value of G*; this variability was largest at high frequencies and low temperatures, which are also the conditions under which G* exhibits its largest values. The coefficient of variation, which is the standard deviation normalized by the mean, tended to be larger at low temperatures and high frequencies.

4.0 ALTERNATIVE SHEAR SPECIMEN SIZES AND SHAPES

4.1 Objectives

The objective of this experiment was to evaluate the influence of specimen size and shape on the variability of results obtained in the Repeated Simple Shear Test at Constant Height (RSST-CH). These results provide useful information needed for the selection of specimen shape and size for the simple performance tester. Results from two different mixes were evaluated and include data from tests performed on cores from slabs prepared by rolling wheel compaction and from tests performed on cores from a field-compacted Heavy Vehicle Simulator test section. Two specimen sizes were used, 150 and 200 mm in diameter; two shapes were obtained by using cylinders as cored and by trimming the sides to obtain an "almost" prismatic shape.

While small numbers of replicates were used to evaluate the effects of size and shape on variability and bias, as will be seen herein, useful information was obtained from this study.

4.2 Considerations of Specimen Size and Shape

In Reference *(2)*, a discussion of the importance of the representative volume element (RVE) in materials evaluation was presented. In this discussion, the RVE was defined as *the smallest material volume large enough so that global characteristics of the material remain constant, regardless of the location of the RVE.* When specimens are smaller than the RVE, random results will be obtained, i.e., some specimens may exhibit low values of the property considered while others may yield high values. Because of the random nature of the results obtained for small specimens, to obtain a statistically meaningful property value, a large number of tests specimens must be evaluated. Unfortunately, this approach has two drawbacks:

1. A relatively large number of specimens may be required, thus making the use of small specimens impractical.
2. Any averaging process would ignore bias in the test procedure. This bias, which may be the result of test imperfections, may cause large errors in predicted properties.

Thus, it is important to use a specimen that is at least as large as the RVE in order to reduce the variance in test results. Dimensions of the RVE for asphalt concrete mixes with different aggregate sizes and shapes, and at different temperatures, have not yet been determined. Unfortunately, though desirable, a comprehensive and sufficiently detailed project to determine the RVE for asphalt concrete has not been undertaken to date.

A major advantage resulting from the inclusion of specimens at or above the RVE in any study to evaluate RVE is that an indication of the variance of the material will be obtained. This then provides an essential component of the variance of test results for specimens that are smaller than the RVE.

The need for inclusion of some specimens larger than the RVE is illustrated by a simplified exercise to investigate the effects of specimen size and number of replicate specimens, shown in Figure 4.1. This figure shows the standard error of the mean for stiffness of a theoretical one-dimensional specimen consisting of two components: asphalt and aggregate. The one-dimensional specimen can be visualized as a stack of coins with two types of coins, asphalt and aggregate, and the aggregates and asphalt randomly distributed in the stack following a pattern determined from measurements at random locations on actual specimens in the vertical direction. The aggregate sizes and relative proportions of asphalt and aggregate were measured on specimens with a 19 mm maximum size aggregate (MSA) and a dense aggregate gradation. The stiffness of the aggregate was assumed to be 100 times greater than the stiffness of the asphalt.

Figure 4.1 shows the standard error of the mean one dimensional stiffness for tests using 2, 3, 4, 10, and 100 replicate specimens with the aggregates and asphalt randomly distributed. The use of 100 replicate specimens results in a relatively low error. In addition, increasing the length over which the stiffness is measured also decreases the error.

It can be seen from this relatively simple exercise that small numbers of replicates and a gauge length considerably less than the RVE result in a large standard error. The exercise also suggests that larger numbers of specimens, and inclusion of some specimens with large gauge lengths relative to the maximum size aggregate will be necessary to evaluate RVE dimensions [note: gauge lengths that are two, three, and five times the maximum size aggregate (MSA) are indicated in Figure 4.1]. If these factors are not included in future experiments, it will be difficult to establish statistical estimates of variance attributable to the material, and to separate variance due to the specimen size and variance due to the material itself.

In Reference *(2)* it was demonstrated that for cylindrical or prismatic specimens, a larger length-to-height ratio reduces the effect of the missing shear couple at the front and back of the specimen. While the kinematics of the test configuration remain predominantly shape distortion, the longer specimen provides a more uniform stress state within the specimen as well. This factor may contribute to more variance in cylindrical as compared to prismatic specimens as noted in the following paragraph.

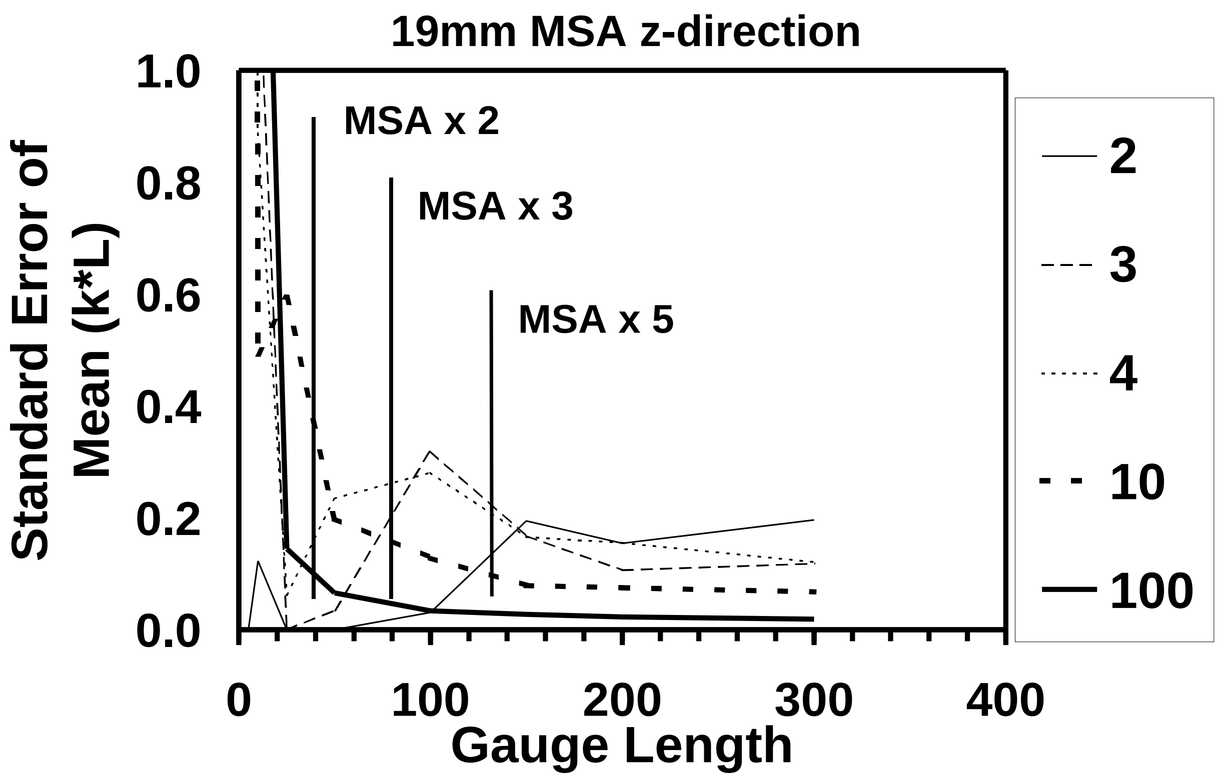

Figure 4.1. Effects of Specimen Height (Gauge Length) and Number of Replicates on Variance of Mean Results for a One-dimensional Theoretical Specimen.

In Reference *(2)* evidence is presented indicating that specimen shape may also contribute to test variability. Circular specimens have different length-to-height ratios moving from the center of the specimen perpendicular to the direction of shear because the length changes along the perimeter of the specimen while the height remains the same. A more prismatic specimen, longer in the direction of shear, should produce a less variable stress distribution and hence provide better measurements of shape distortion material properties.

It is for this reason that some cylindrical specimens had their sides shaved to reduce variability in the shear stress distribution across the specimen during shear testing.

4.3 Experiment Design

This experiment compared RSST-CH results and variance for 150 mm diameter cylindrical specimens, 200 mm diameter specimens trimmed to 190 mm width to fit in the UCB simple shear tester, and “cut” 150 mm and 200 mm diameter cylinders which were shaved along the length in the direction of shearing so that the specimen width equaled 100 mm. Thus, for the “cut” specimens, 25 mm was shaved off either side of the 150mm specimens, and 50 mm was shaved off the 200mm specimens. Specimen shape and dimensions are shown in Figure 4.2.

The first set of specimens was taken from a previously prepared SHRP asphalt mix compacted in two lifts into a 600 mm × 495 mm × 150 mm thick slab using rolling wheel compaction. The mix in the slab had contained an AC-8 (SHRP-MRL designation AAC) asphalt binder and a partially crushed gravel aggregate (SHRP-MRL designation RH). The specimens were labeled “CP”, for the AAC asphalt and aggregate source in Pleasanton, California. The nominal maximum aggregate size was 19 mm and the gradation met Caltrans Type A, 19 mm maximum aggregate size “coarse” specifications. This gradation is not as coarse as Superpave coarse gradations and passes through the restricted zone. The asphalt content was 4.9 percent by mass of mix. Five 150 mm and seven 200 mm diameter cores were taken and grouped according to measured air void contents, as shown in Table 4.1. Air-void contents were between 3.2 and 5.9 percent, spanning the range of 4.55 ± 1.35 percent.

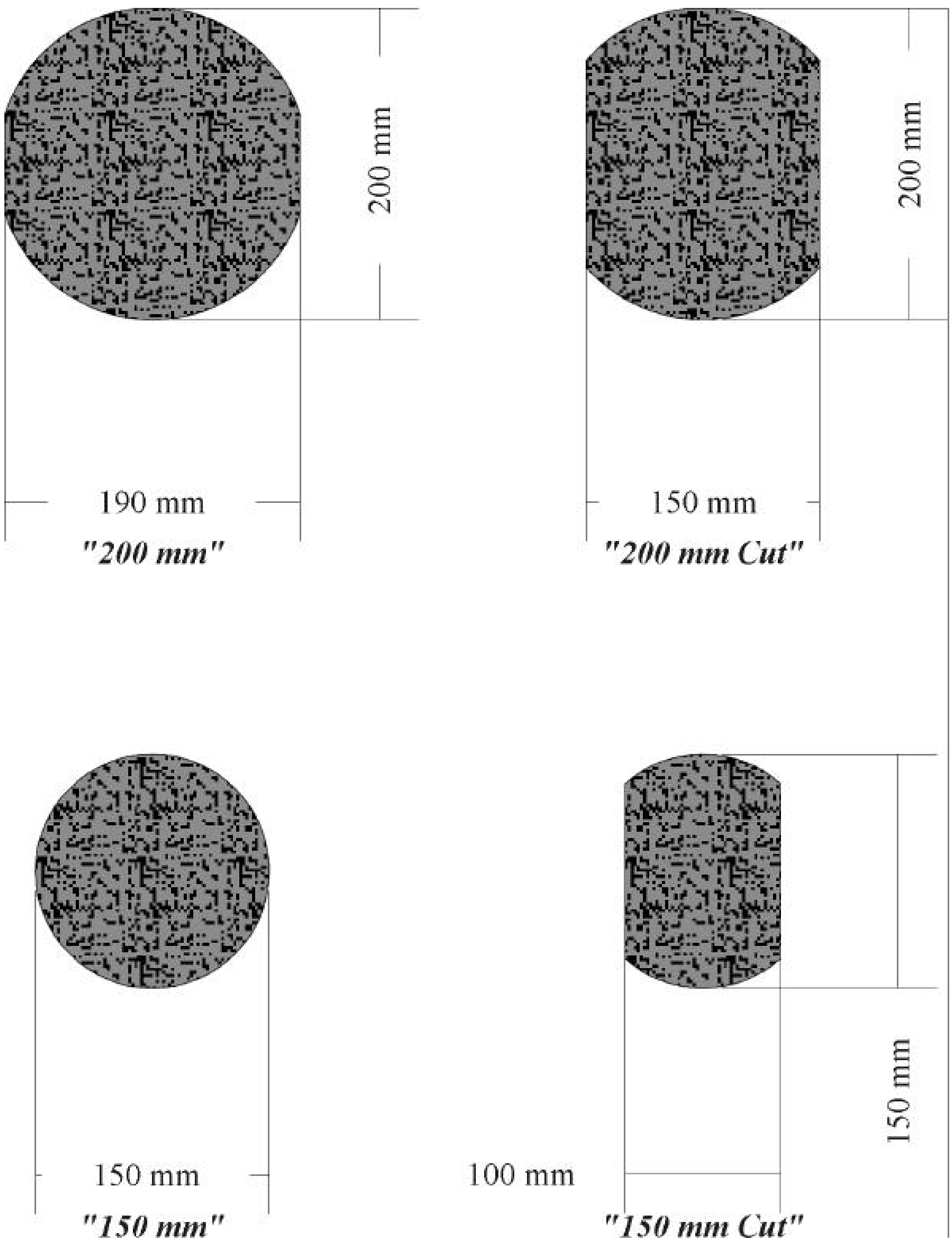

Figure 4.2. Specimen Shapes and Dimensions.

Table 4.1 Specimens for Experiment.

Specimen Size (mm)	Specimen Shape	Specimen Number	Air-void (%)	Temp. (C)	RSST-CH Reps to Permanent Shear Strain*			Ln (Repetitions)	
					1%	**2%**	**5%**	**2%**	**5%**
CP									
150	Cylindrical	CP1-B	3.6	50	46	113	793	4.73	6.68
150	Cylindrical	CP2-T	5.9	50	19	42	202	3.74	5.31
150	Cut	CP3-B	3.7	50	33	92	681	4.52	6.52
150	Cut	CP2-B	4.2	50	9	32	290	3.47	5.67
150	Cut	CP3-T	5.9	50	7	21	106	3.04	4.66
200	Cylindrical	CP7-B	3.2	50	14	64	1072	4.16	6.98
200	Cylindrical	CP6-B	4.2	50	9	35	394	3.56	5.98
200	Cylindrical	CP6-T	5.4	50	6	20	156	3.00	5.05
200	Cut	CP5-B	3.4	50	11	47	626	3.85	6.44
200	Cut	CP4-B	3.5	50	14	50	527	3.91	6.27
200	Cut	CP5-T	4.5	50	10	32	238	3.47	5.47
200	Cut	CP4-T	5.6	50	7	21	140	3.04	4.94
HVS									
150	Cylindrical	28-T	4.1	50	80	559	33878	6.33	10.43
150	Cylindrical	26-T	4.2	50	92	1116	**82598**	7.02	11.32
150	Cylindrical	25-T	4.3	50	81	917	**69212**	6.82	11.14
150	Cylindrical	2-T	4.4	50	87	590	15779	6.38	9.67
150	Cylindrical	23-T	4.6	50	128	1112	29831	7.01	10.30
150	Cylindrical	20-T	4.6	50	153	1612	**91775**	7.39	11.43
150	Cut	14-T	4.1	50	78	699	**53568**	6.55	10.89
150	Cut	6-T	4.6	50	142	726	8947	6.59	9.10
150	Cut	13-T	4.8	50	99	566	11501	6.34	9.35
150	Cut	5-T	4.9	50	41	219	6957	5.39	8.85
150	Cut	19-T	4.9	50	37	226	15428	5.42	9.64
200	Cylindrical	11-T	4.6	50	144	862	**34267**	6.76	10.44
200	Cylindrical	7-T	4.9	50	22	61	641	4.11	6.46
200	Cut	10-T	4.0	50	111	761	**14590**	6.64	9.59
200	Cut	5-T	4.0	50	153	1529	**196626**	7.33	12.19
200	Cut	1-T	4.7	50	109	960	38738	6.87	10.56
HVS Outliers									
200	Cylindrical	12-T	4.9	50	7002	16002	**60881**	9.68	11.02
200	Cut	9-T	4.9	50	3039	9928	**42410**	9.20	10.66

* Bold indicates that the value was extrapolated.

The second set of specimens was taken from the Caltrans Accelerated Pavement Testing project (CAL/APT) test section at the Richmond Field Station at the University of California, Berkeley. *(8)* The specimens are labeled as “HVS.” This mix also meets the specifications for the Caltrans 19mm maximum size, coarse gradation for Type A asphalt concrete. *(10)* The asphalt content is 4.8 percent by mass of mix. However, the HVS mix was produced at a commercial plant, and placed and compacted by a paving contractor following Caltrans “method” compaction specifications. The asphalt cement was an AR-4000.

The HVS specimens were grouped according to air-void content as shown in Table 4.1. Specimens were selected for this experiment from a much larger set based on air-void content. The air-void contents are between 4.0 and 4.9 percent, spanning a range of 4.45 ± 0.45 percent, and thus are much more tightly controlled for air-voids than are the CP specimens.

All tests were performed at 50°C according to AASHTO TP7-94 (without preconditioning), following the same procedure described in Chapter 3. Because of the differences in area, the load applied to obtain a 69 kPa shear stress varied according to Table 4.2. Laboratory test results shown in Table 4.1 had a vertical gauge length two times greater than the nominal 19 mm maximum size aggregate (MSA), (37 mm measure on specimens 50 mm in height), and include two to four replicate specimens.[5]

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[5] The ratio of vertical dimension of the RSST-CH specimen to the maximum size aggregate can be increased in future RVE experiments by either increasing the height of the specimens, or by decreasing aggregate size.

Table 4.2 Load Required to Obtain a 69 kPa Shear Stress in Specimens of Varying Dimensions.

Size	**Area (cm^2)**	**Load**
150 mm	182.39	1300
150 mm Cut	142.45	1015
200 mm	324.32	2311
200 mm Cut	197.48	1409

4.4 Results

The RSST-CH results are summarized in Table 4.1; extrapolated values are indicated in bold type.

RSST-CH repetitions to a two percent permanent shear strain are shown for the CP material in Figure 4.3, and for the HVS test pavement material in Figure 4.4. Both figures are plotted on a linear scale. In Figure 4.3, for example, it can be seen in that there is a clear trend of increased shear resistance with increased compaction, regardless of specimen shape or size. The CP material has relatively low resistance to permanent shear strain at the test temperature of 50°C compared to the HVS material.

The results shown in Table 4.1 indicate two outlier points (labeled 9T and 12T) in the two percent shear strain results, with repetitions approximately one order of magnitude greater than other specimens. Both of the specimens considered outliers are 200 mm in diameter. This suggests that increasing only one or two dimensions above the size of the RVE, and not all three, may not help reduce variance much for the current configuration. In this case the width and length of the specimens were increased without increasing the height (the shortest dimension). These points have not been included in Figure 4.4.

There is no clear trend between the means of the cut or uncut shapes, or the 150 mm or 200 mm specimens. It may appear from Figure 4.2 and Table 4.1 that the 200 mm specimens have somewhat less resistance, however only two to four replicate specimens were available for testing – too few to make general statements.

There appears to be considerable variance in the results when plotted on the linear plot. In Table 4.1, the standard deviation of the repetitions to a two percent permanent shear strain are of the same order of magnitude as the means for both the CP and HVS materials. The observations regarding repetitions to a five percent permanent shear strain are similar to those described for the two percent strain results (Figures 4.5 and 4.6), i.e.,:

a. no clear reduction in variance occurred for the cut or 200 mm specimens compared to the circular and 150 mm specimens;

b. no trend exists regarding specimen shape or size versus the mean repetitions to a given permanent shear strain; and

c. greater resistance to permanent shear strain and larger variance was observed for the HVS material than the CP material.

There is a clear trend of increased shear resistance with increased compaction for the CP material and repetitions to five percent permanent shear strain (Figure 4.5) across a broader range of air-void contents than was included in the replicates for the HVS material (Figure 4.6).

The fact that the variance was not reduced by using longer and wider specimens is probably because specimen heights were not increased. The cut specimens may also be smaller than the RVE in the lateral direction. This suggests that if the assumption that specimen size below the representative volume element (RVE) is a major contributor to test variance, then

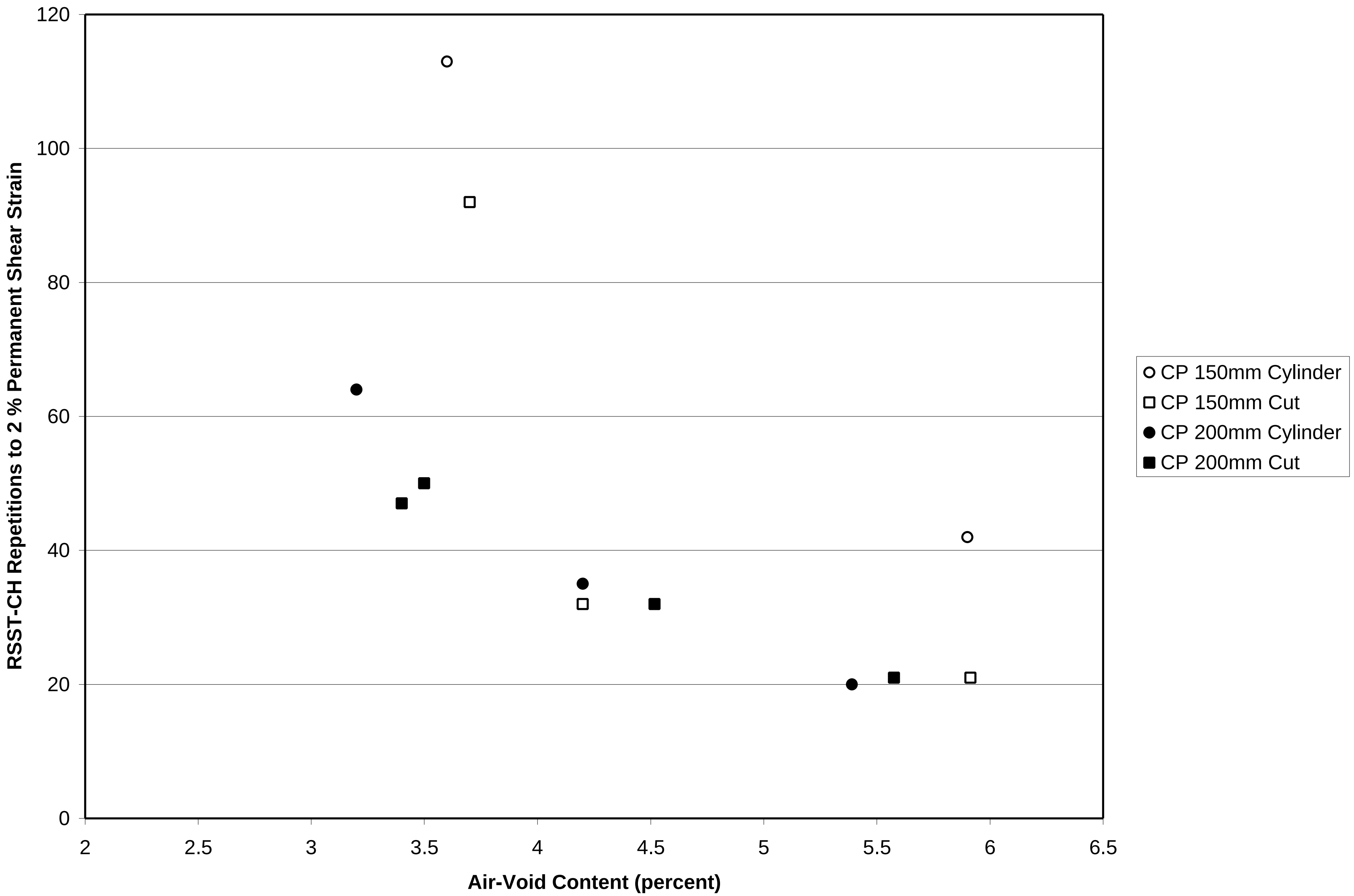

Figure 4.3. RSST-CH Repetitions to Two Percent Permanent Shear Strain at 50° C for Cut, Cylindrical, 150 and 200 mm Specimens, CP Material.

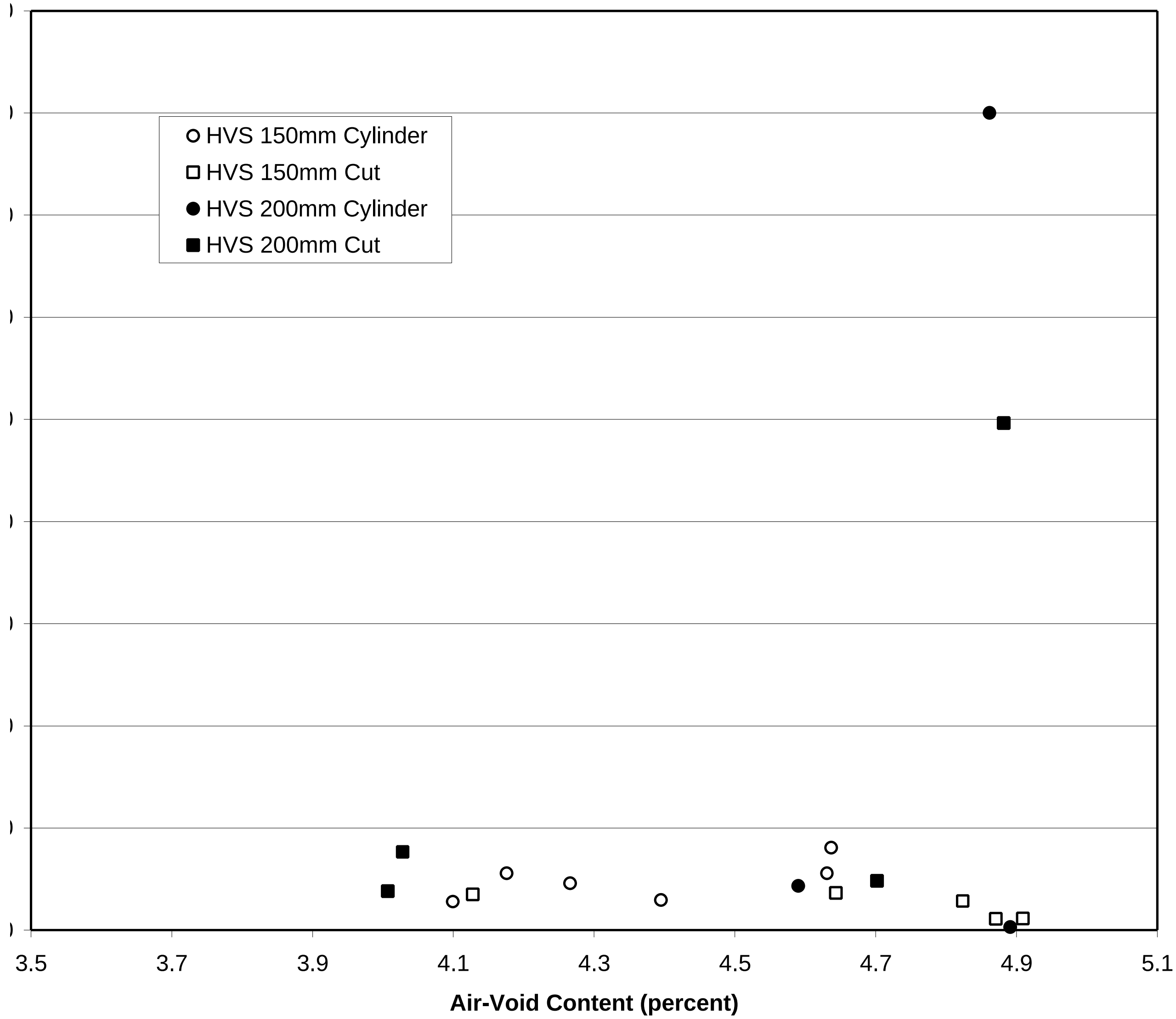

Figure 4.4. RSST-CH Repetitions to Two Percent Permanent Shear Strain at 50° C for Cut, Cylindrical, 150 and 200 mm Specimens, HVS Material.

height is the specimen dimension likely to be the most responsible for the variance because it is less than the specimen width and length. Future tests to evaluate the RVE should include specimens compacted in lift thickness greater than 50 mm for 19 mm maximum size aggregate gradations, and include specimens of up to 75 mm height. Increases in length and width in future tests should be proportional to the increase in height.

Alternatively, smaller aggregates, such as 12 or 9.5 mm maximum size gradations can be used in specimens compacted to 50 mm height. Preparation of new specimens was beyond the budget of this project, which had to rely on previously prepared specimens from other projects.

A greater number of replicates than the two to four normally included in a mix design study should be included in any future experiments to evaluate RVE. Ten to 15 replicates are desirable as compared to the three to five permitted by the budget for this project. This recommendation also applies to the work planned by the University of Maryland FHWA Models Contract Team to evaluate representative volume element dimensions. That work, to be performed by the Advanced Asphalt Technologies using triaxial tests, should provide additional useful information. *(7)*

All of the results have been plotted together on a linear plot in Figure 4.7. It will be noted that the data are extremely variable. However, plotting of the RSST-CH results from this experiment on a log scale versus air-voids shows clearer trends, as shown in Figure 4.8.

It can be seen in Table 4.3 and Figure 4.8 that although both mixes meet the same requirements for aggregate gradation and have similar asphalt contents, the HVS mix on average was more deformation resistant, requiring 2 orders of magnitude more repetitions to reach 5 percent shear strain than did the CP mix at the same air-void content. While the standard

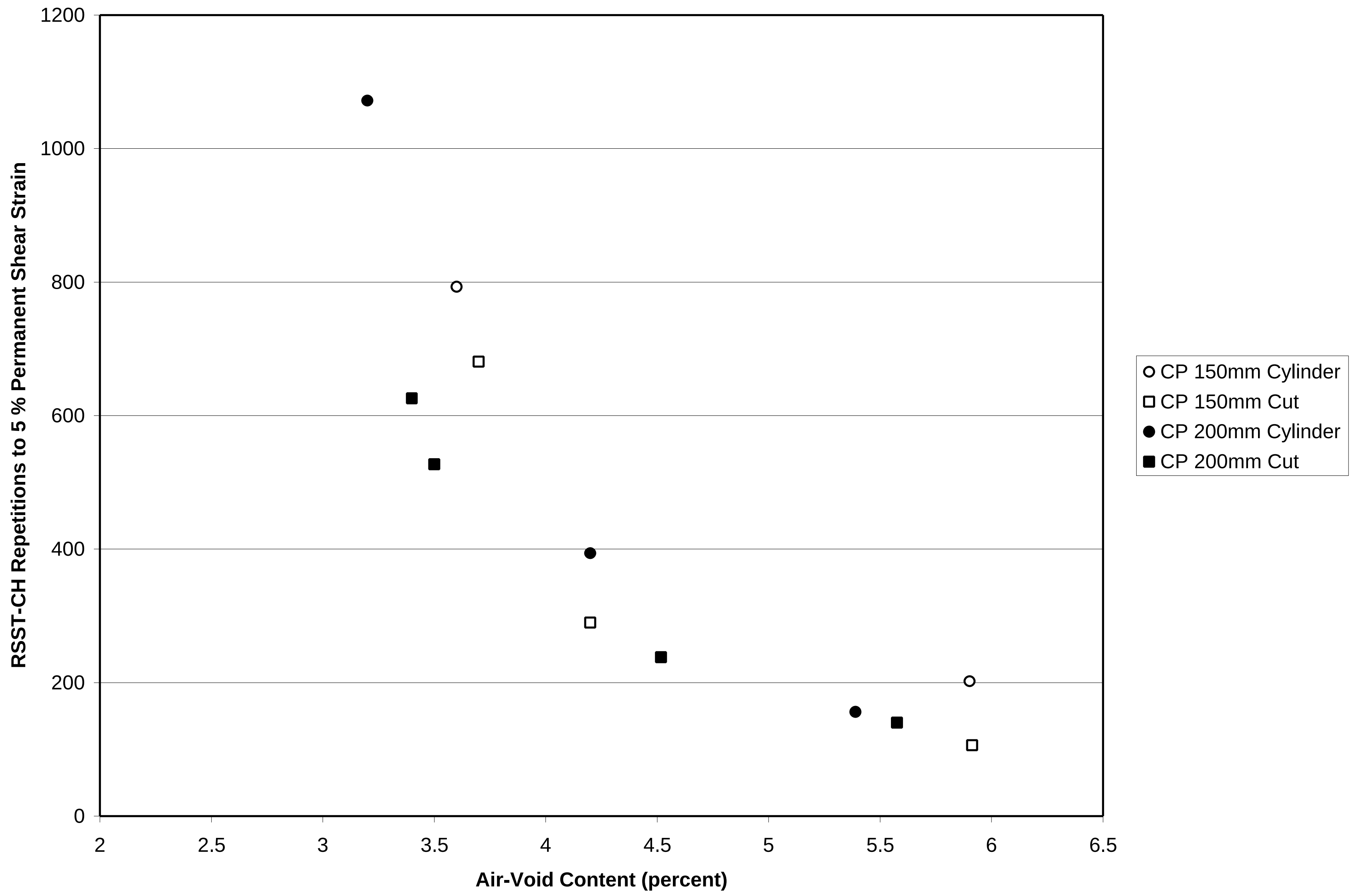

Figure 4.5. RSST-CH Repetitions to Five Percent Permanent Shear Strain at 50° C for Cut, Cylindrical, 150 and 200 mm Specimens, CP Material.

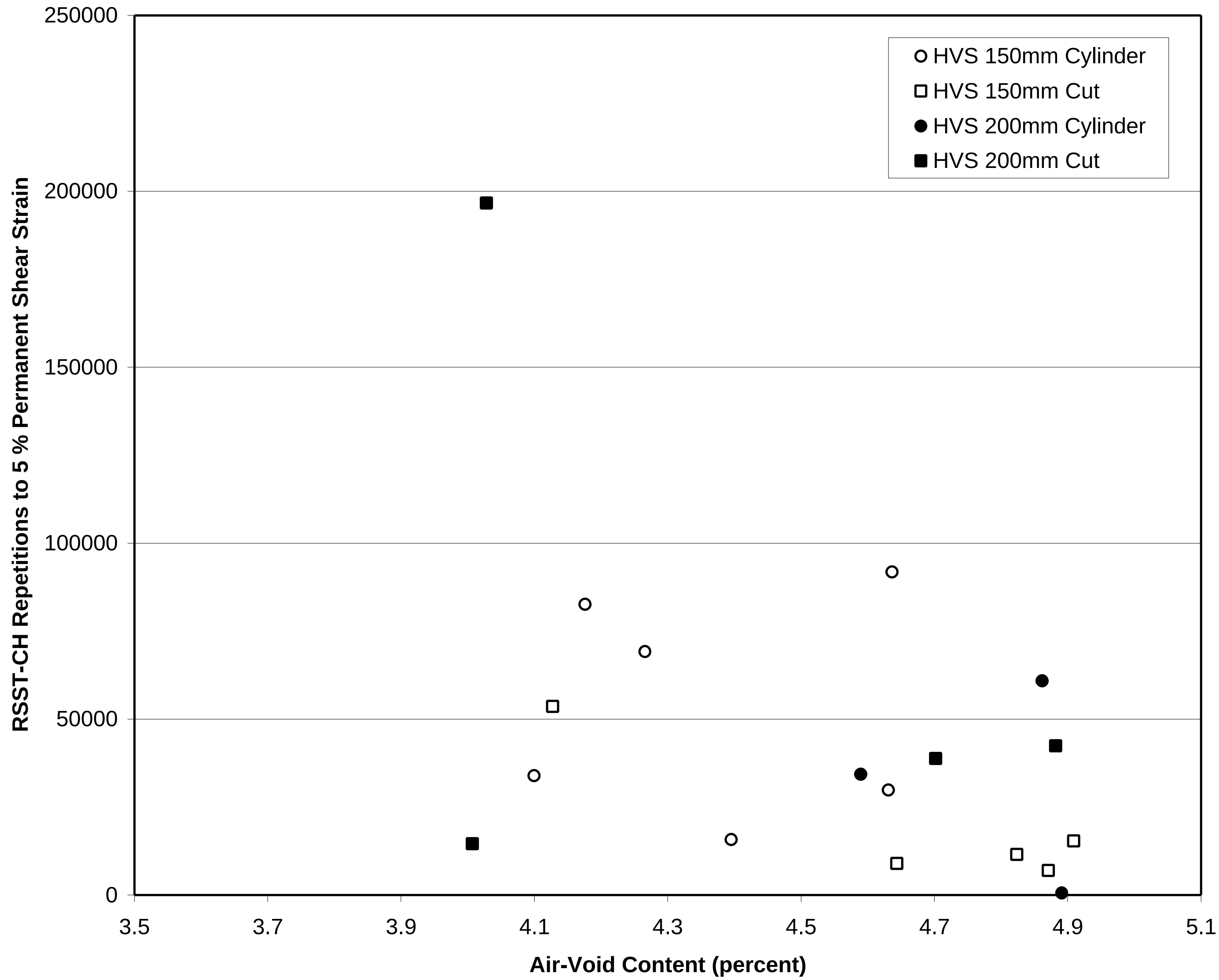

Figure 4.6. RSST-CH Repetitions to Five Percent Permanent Shear Strain at 50° C for Cut, Cylindrical, 150 and 200 mm Specimens, HVS Material.

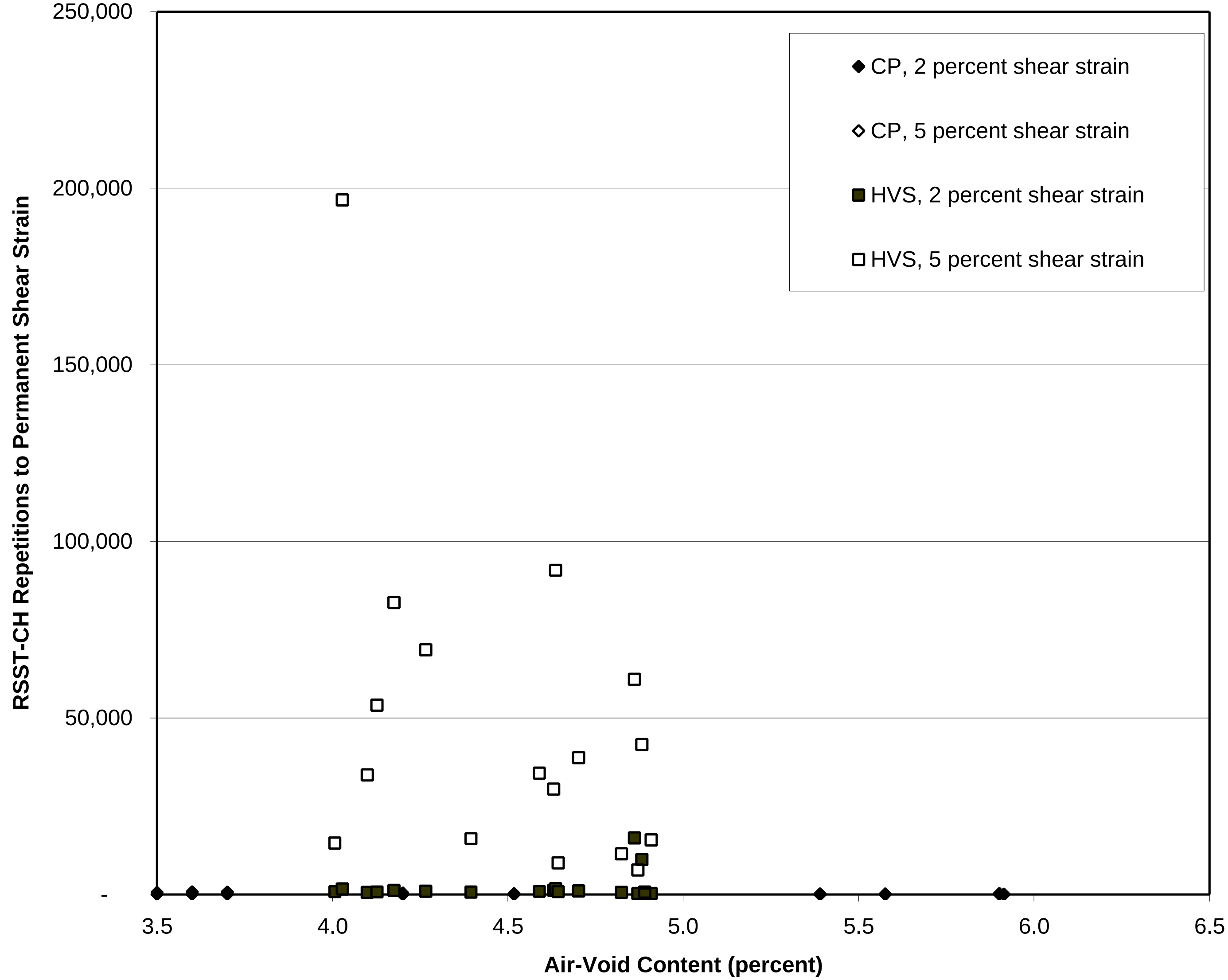

Figure 4.7. Linear Plot of RSST-CH Repetitions to Two and Five Percent Permanent Shear Strain at 50° C.

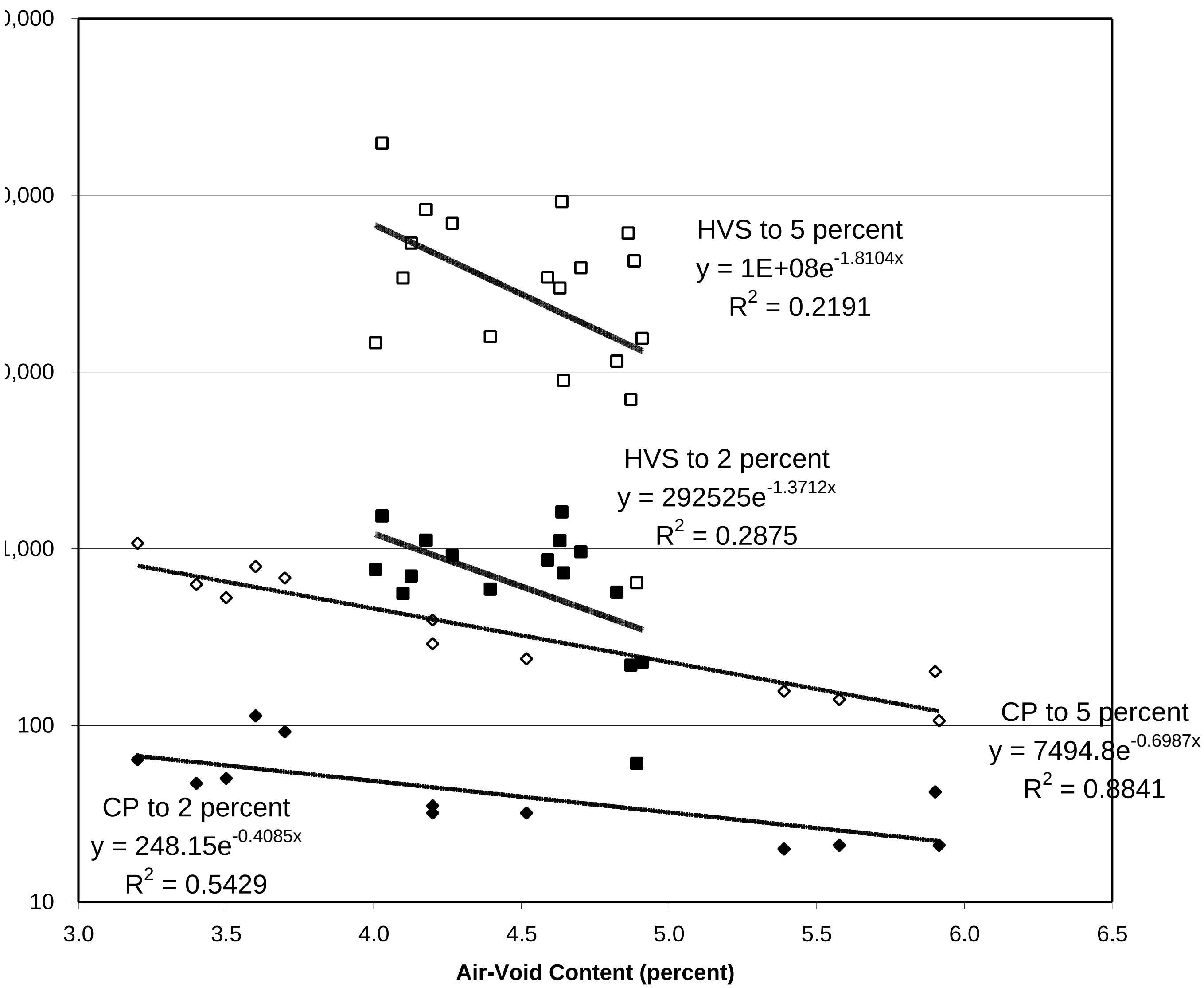

Figure 4.8. Logarithmic Plot of RSST-CH Repetitions to Two and Five Percent Permanent Shear Strain at 50° C.

Table 4.3 Comparison of Variability of Response for One Mix and Between Mixes.

Mix	**Mean Repetitions to 5 Percent Shear Strain**	**Standard Deviation of Repetitions to 5 Percent Shear Strain**	**Ratio of Standard Deviation to Mean (COV)**	**Ratio of Mean for HVS Mixes to Mean for CP Mixes**
CP	435	306	0.703	
HVS	44021	49149	1.116	101.2

deviation of the response of these mixes may be about the same magnitude as their mean response, the difference in resistance to permanent deformation between the means of the two mixes is several orders of magnitude.

The proportional relation between the mean response and variance is illustrated in Table 4.4 by comparison of the mean responses at four percent air-voids calculated using the trend equations from Figure 4.8 and the standard deviation of the responses of the two mixes for repetitions to five percent shear strains shown in Table 4.3. This means that the difference in the response between mixes, albeit mixes with very different binders, can be distinguished despite the relatively large variances.

The responses of a given mix to different permanent shear strains also differ on an exponential basis, as illustrated in Table 4.4 for each mix for the ratio of repetitions to two and five percent permanent shear strains, and between mixes for repetitions to two and five percent permanent shear strain.

The exponential relation between RSST-CH repetitions to a specific shear strain and degree of compaction indicates that by limiting the range of air-void contents in a sample of specimens to be tested to determine a mean and variance of the response will greatly aid in reducing the variance. The air-void content ranges included in this experiment were 2.7 percent

Table 4.4 Comparison of Variability of Response for One Mix and Between Two and Five Percent Permanent Shear Strains (with Two Outliers Removed).

Mix and Shear Strain	Mean Repetitions at 4 Percent Air-voids	Standard Deviation of Repetitions at 4 Percent Air-voids	Ratio of Standard Deviation to Mean	Within Mix - Ratio of Means for 5 Percent to 2 Percent Shear Strain	Between Mixes - Ratio of Means for 2 Percent and 5 Percent Shear Strain
CP 2 %	48	29	0.599		
CP 5 %	458	306	0.668	9.5	
HVS 2 %	1214	433	0.357		14.9
HVS 5 %	71616	46342	0.647	59.0	160.6

(3.2 to 5.9 percent) for the CP mix and 0.9 percent (4.0 to 4.9 percent) for the HVS mix. Air-void content ranges for a sample beyond about 1.5 percent typically will produce large variances, due to the sensitivity of the permanent deformation performance of the material to degree of compaction.

The response of a mix to design variables such as asphalt type, asphalt content, degree of compaction and gradation to the two most commonly used mix design stability tests is essentially linear. For example, changing the asphalt type or aggregate type, as was done in this experiment for the CP and HVS mixes, might result in a change in Hveem stabilometer “S” value from 25 to 35, or in Marshall stability from 2,000 to 2,800 lbs. A standard deviation for replicate specimens of only 10 for the Hveem stabilometer values or 800 lbs. for the Marshall stability would be very important, because the change in mean response is only 10 for the Hveem test and 800 for the Marshall test. Thus, for these tests, which are linearly sensitive to mix properties, the coefficient of variation (standard deviation divided by the mean) for the test results would need to be small, on the order of 0.10, because the change in the mean is small, on the order of 0.40 (10/25 for the Hveem example and 800/2000 for the Marshall example).

Because of the exponential sensitivity of RSST-CH results to mix variables, and the relatively high variability of the results, the coefficient of variation is typically between 0.5 and 1.5. However, this must be compared to the change in mean response to mix variables which is on the order of 15 to 160 (Table 4.4). The large variances associated with the RSST-CH, and the much greater sensitivity to mix variables, is not untypical for asphalt concrete tests that involve repeated loading.

An example of this sensitivity is illustrated by the beam fatigue test in which the average coefficient of variation for repetitions to fatigue failure from a large beam fatigue experiment was 0.27. *(10)* When a large number of repetitions is needed to reach the desired final condition, the coefficient of variation is often larger. This occurs when, for example, a mix is very resistant to shear deformation, the test temperature is low in the RSST-CH, or the strain is small in the fatigue test. In the same fatigue experiment referred to above, the average coefficient of variation was 0.11 when the tensile strain was 0.0003 (shorter fatigue lives) and 0.42 when the tensile strain was 0.00015 (longer fatigue lives and some extrapolation required).

A literature search for triaxial permanent deformation data was not within the scope of this project. The results of triaxial testing to be obtained by the University of Maryland Models Contract Team should provide data from sufficiently large project to provide an estimate of the variance and means from that configuration. In this investigation, it is important that the variability of the data be compared to the sensitivity of the mean response of the test to mix variables and temperature.

The observation that differences of response between mixes and between permanent shear strains are large compared to the variance of the response does not mean that the variance of the response must not be reduced. The variance of RSST-CH results should be reduced to the greatest extent possible in order to reduce the number of specimens required to obtain an acceptable standard error of the mean. The standard error of the mean is the sample standard deviation (s) divided by the number of replicate tests (n) in the sample, i.e.:

$$\frac{s}{\sqrt{n}}$$

A lower standard deviation of the mean increases the usefulness of the results in a quality control/quality assurance system, and reduces the cost of mix designs and QC/QA because fewer specimens need to be tested to obtain reliable results. This point was illustrated in the one-dimensional example shown in Figure 4.1, where a smaller standard error of the mean could be obtained by testing more replicate specimens, or by testing across a larger gauge length.

4.5 Check of Assumption of Constant Volume

It was observed during initial RSST-CH testing for this project that some specimens appeared to have bulged laterally when removed from the simple shear tester. If bulging occurred, then the basic assumption that the RSST-CH is a nearly pure shape distortion test in which the specimen retains a constant volume and is subjected solely to shear deformations would not be fulfilled. The degree to which bulging would affect the results is not known given that the RSST-CH is really a first order approximation of a pure shape distortion test. To investigate this observation, seven additional specimens of the HVS mix were tested at 50°C and lateral bulging was measured. The specimen sizes and shapes are shown in Table 4.5, with the lateral dimensions measured before and after testing.

Table 4.5 Change in Average Lateral Dimension for RSST-CH Specimens During Testing, HVS Mix.

	150 mm Diameter Specimens			200 mm Diameter Specimens		
	Before Test	**After Test**	**Difference**	**Before Test**	**After Test**	**Difference**
Cylindrical	150.1*	150.7	0.6	192.0	193.0	1.0
	142.1	143.4	1.3	190.0	192.1	2.1
Cut	99.1	100.1	1.0	100.5	101.1	0.6
	100.1	100.7	0.6	103.1	103.9	0.8

* (Dimensions in mm)

As before, specimens of both diameters were cut to provide a 100 mm width. Because bulging in some of the initial tests was observed on specimens after removal from the simple shear tester, it was thought that some of the bulging observed in the earlier tests may have been due to large axial stresses applied to the specimen during unclamping and removal. In these tests little care was taken to prevent large axial stresses during unclamping from the machine after test completion. A lateral bulge of 0.7 percent around the entire perimeter would result in a 1.4 percent change in volume. A lateral bulge of 0.7 percent in a prismatic specimen, with no change in the longitudinal dimension would result in a 0.7 percent change in volume. The specimen widths shown in Table 4.5 were measured with calipers after the specimen had been clamped into the machine, and again after the test had been completed but before unclamping and removal from the machine. All tests were carried out to 5,000 to 10,000 repetitions or 5 percent permanent shear strain.

The increase in the lateral dimension averages 0.7 percent for the cylindrical 150 mm diameter specimens, 0.9 percent for the cut 150 mm diameter specimens, 0.8 percent for the cylindrical 200 mm diameter specimen, and 0.7 percent for the 200 mm diameter cut specimens. These results indicate that there is little difference in lateral width change between the cylindrical and cut specimens, and there is about 0.7 percent change in the lateral dimension for all of the specimen sizes and shapes.

4.6 Findings

The findings from the results presented in this chapter are as follows:

- The Repeated Simple Shear Test at Constant Height (RSST-CH) showed a large difference in response between the two mixes tested. The mixes had similar aggregate gradations and asphalt contents, but different aggregates and binders.
- The variances for results of load repetitions for the two mixes to two different permanent shear strains were relatively large, and variance increased with larger mean numbers of repetitions. The standard deviations were between 0.5 and 1.0 times the value of the mean number of repetitions.
- The means vary exponentially between mixes, and for a given mix between two and five percent permanent shear strains. After adjusting for air-void content differences, between the two mixes, the mean repetitions to a two percent shear strain was 14.9 times different, and to a five percent shear strain was 161 times different. For a given mix, the mean number of repetitions between two and five percent permanent shear strains was 9.5 times different for the CP mix, and 59 times different for the HVS mix. The large variances for the mean repetitions is offset by the exponential sensitivity of the mixes to the test, which separates their performance despite the large variance.

- Increasing the diameter of the specimens from 150 to 200 mm did not appear to reduce the variance of the results. This is probably because the specimen heights were not increased relative to the maximum aggregate size (MSA).
- Cutting the edges of the specimens to produce a more prismatic shape with a more uniform length to width ratio also did not appear to reduce the variance of the results. This apparent result is also probably due to any benefit of the shape change being overwhelmed by the variance caused by the small ratio of specimen height to maximum aggregate size.
- The potential for bulging at the sides of the more prismatic specimens compared to the circular specimens was found to be about the same as for cylindrical specimens. Across all specimen sizes and shapes, the lateral dimension changed about 0.7 percent.
- Future work investigating the Representative Volume Element (RVE) for asphalt concrete mixes should include:

  a. specimens with increased ratios of height to maximum size aggregate, which can be obtained by increasing the height of the specimens as well as the length and width , or use of smaller aggregates,

  b. greater numbers of replicate specimens, on the order of 10 to 20 for smaller specimens with dimensions below those of the RVE, if possible, and

  c. inclusion of some specimens with dimensions greater than those of the RVE.

- Inclusion of more replicates and some specimens larger than the RVE will enable statistical evaluation of the effects of specimen size and numbers of replicates on the variance of RSST-CH results.

5.0 COMPARISON OF FIELD CORES AND SUPERPAVE GYRATORY COMPACTED SPECIMENS

5.1 Objective

The objective of this study is to compare performance test results from field cores and from samples compacted using the Superpave Gyratory Compactor (SGC). To complete this objective, the Repeated Simple Shear Test at Constant Height (RSST-CH) was performed on field specimens and SGC specimens compacted to the same air-voids content. The results of these tests were then analyzed. The intent of the FHWA is to use the SGC in the field for quality control and for preparation of test specimens for the simple performance tester. Some agencies may opt to use field cores for some part of their quality control procedure, or to prepare specimens for the simple performance tester. The results of this study are intended to provide an indication of the interchangeability of SGC specimens and field cores. Differences in properties of specimens from the two sources indicates that performance predictions must be developed for both, and that the two types of specimens cannot be used interchangeably. Any significant differences suggest that further study of the properties of SGC specimens is warranted given that field cores will exhibit the properties of the mix as it will be placed in the field and expected to perform.

5.2 Experiment Design

Compaction method, test temperature and air-void content were the independent variables included in this experiment. These variables were evaluated in terms of their influence on permanent shear strain versus load repetitions in the Repeated Simple Shear Test at Constant Height (RSST-CH).

5.2.1 Factor Levels

Factor levels for the independent variables in a full factorial experiment included:

Test temperature: 40° C and 50° C;

Air-void content: 3.4% (±0.5% allowable variation from target) and 4.6% (±0.5%); and

Compaction method: Superpave Gyratory Compactor (SGC) and field cores (FC).

Three replicate specimens were prepared and tested for each factor level combination in the experiment. Some additional Superpave Gyratory Compactor specimens and field cores were also tested to provide results at higher air-void contents; however, insufficient specimens were available at those air-void contents to provide three replicates.

5.2.2 Material and Specimen Preparation

Samples of the field mix used to prepare the Superpave Gyratory Compactor (SGC) specimens were collected during placement of the overlays for the Caltrans Accelerated Loading Program (CAL/APT) Goal 3 study at the Richmond Field Station at the University of California, Berkeley. *(8)* This mix is from an overlay placed by a large commercial paving contractor experienced in Caltrans highway projects. The dense-graded asphalt concrete mix was produced by a large commercial drier drum plant located about 10 km from the paving site.

The asphalt concrete met Caltrans Standard Specifications for 19 mm (3/4 in.) coarse gradation, Type A material. The asphalt cement was an AR-4000. The mix design was based on a 4 percent air-voids content, minimum Hveem stabilometer "S" value of 37 and on visual observation of flushing of asphalt from compacted specimens of the mix, following California Test Method 367. The job mix formula and extracted aggregate gradation and asphalt content are shown in Table 5.1.

The overlay was compacted following the method specification described in the Caltrans Standard Specifications. *(11)* It consisted of one 3.7-m wide lane, 80 m in length. The overlay, 75 mm thick, was compacted in one lift. The following rolling pattern was used:

1. first pass: at about 170° C, Caterpillar CB-534 roller, vibratory mode;
2. second pass: at about 155° C, Caterpillar CB-534 roller, vibratory mode; and
3. third pass: at about 135° C, Caterpillar CB-534 roller, non-vibratory mode.

As seen above, all of the compaction passes were made at relatively high temperatures. Reasons for this include: 1) the mix was produced at a relatively high temperature at the plant; 2) the plant was a short distance from the site; 3) little wind was present inside the building (although there was adequate ventilation through large roll-up doors); and 4) the pavement section length was relatively short. The increased compaction temperatures resulted in better compaction than would typically be obtained using the Caltrans method specification in a field location, although the same equipment and procedures were used.

The field cores used for shear testing were taken approximately six months after construction. During this six month period, the air temperatures near the overlay ranged from approximately 15° to 25° C. The roof of the building prevented direct sunlight from reaching the

Table 5.1 Mix Design for Goal 3 Dense-Graded Asphalt Concrete Overlay.

TEST NO. 500-603

DATE RECEIVED DEC 0 5 1996
CALC. ____ APPROV. ____
DATE REPORTED DEC 1 6 1996

REPORT OF TESTS ON

Drier Drum A.C Aggregate

IF CONTRACT, USE CONTRACT ITEM

SOURCE	CHARGE	EXPENDITURE AUTHORIZATION

SPECIAL DESIGNATION (USE WHEN APPLICABLE)	ACTIVITY OR OBJECT	AMOUNT

☐ DISTRICT ENGINEER ☐ H & R DEPT.
☐ DIST. MAT'LS. ENGINEER ☐ PAYMENT
☐ RESIDENT ENGINEER ☐ ACCOUNTING
☐ CONSTRUCTION DEPT. ☐

☒ 310 / 202.1 EXT. & GRADE
☐ 217 S.E.
☐ 302 FILM STRIP
☒ 304.1 STAB. (CONTROL)
☒ 304.2 STAB. (DESIGN)
☒ 307 M.V.S.
☒ 308 SP. GR.
☒ 305 SWELL
☒ 206 SG; 311 moist.
☒ 209 SG; 303 CK.E
☒ 205 crushed part.
☒ 211 L.A.

	AS RECEIVED	RET. CRUSHED	AS USED BY VOL.	AS USED BY WT.	SPECIF. ☐ LIMITS ☐ SOURCE	SURFACE AREA FACTORS	SURFACE AREA
2						NOTE: ALL SURFACE AREA FACTORS MUST BE USED IN CALCULATIONS	
1½							
1					100		
¾	100				90-100		
½	93						
⅜	73				60-75		
¼	–						2.0
4	50				45-55	2	1.0
8	39				31-41	4	1.6
16	27					8	2.2
30	18				13-23	16	2.5
50	11					30	3.3
100	6					50	3.6
200	5				3-7	160	8.0
BITUMEN						SURFACE AREA SQ. FT./LB.	24.2

SPECIMEN	A	B	C *	D *	E
TEMPERATURE	—	140°	—		
MOISTURE					
BIT. GRADE	—	AR	4000	—	
BIT. RATIO	4.6	5.1	5.6	6.1	
SP. GR. BRIQ.	2.33	2.35	2.36	2.38	
SPECIF.		STABILOMETER			
37	45	44	40	41	
		VOIDS			
	7.5	6.6	4.8	3.3	
SPECIF.		SWELL			
0.030"		0.005			

MOISTURE VAPOR SUSCEPT

HOURS	75			SPECIF.
MOIST. ABSORB.	0.5			
STABILOMETER	35			30
BIT. RATIO				
SP. GR. BRIQ.				

Kc = 1.1 Kf = 1.1 Km = 1.1 Spec 1.7

SPECIFIC GRAVITY AGGREGATE
AS RECEIVED F 2.79 C- 2.62
RET. CRUSHED F C-

ABRASION TESTS % LOSS		SPECIF.
LOS ANGELES—100R	9	10
LOS ANGELES—500R	15	45
"B"		

FILM STRIPPING

CRUSHED PARTICLES
(+) 4 100 %, 1-+4 100 %, COMB.
SAND EQUIVALENT VALUE = 69 SPECIF. = 50
RECOMMENDED BITUMEN CONTENT 5.0-5.3

GRADING AS USED WAS OBTAINED BY COMBINING SAMPLES AS FOLLOWS

% WT.	% VOL.	TEST NO.	DESCRIPTION

REMARKS:
*Specimen "C" flushed asphalt moderately and specimen "D" flushed asphalt heavily while being compacted.

TL-101 (REV. 4-76)
STATE OF CALIFORNIA
DEPARTMENT OF TRANSPORTATION

SAMPLE IDENTIFICATION CARD NO. C[illegible]

☐ PRELIMINARY TESTS
☐ PROCESS TESTS
☐ ACCEPTANCE TESTS
INDEPENDENT ASSURANCE TESTS
☐ DIST. LAB
☐ TRANS. LAB
☐ SPECIAL TESTS

SAMPLE SENT TO
☐ HDQTRS. LAB
☐ BRANCH LAB.
☐ DIST. LAB

FIELD NO. ____
DIST. LAB NO. 500-603
LOT NO. ____
SHIPMENT NO. ____
P. O. OR REQ. NO. ____
AUTHORIZATION NO. ____

SAMPLE OF Drier Drum A.C Aggregate
FOR USE IN 3/4" max Coarse A.C. Type A
SAMPLE FROM Bauman Landscape, Five Star Asphalt plant, Richmond
DEPTH ____
LOCATION OF SOURCE Pt Richmond & Tidewater

THIS SAMPLE IS SHIPPED IS ____ AND IS ONE OF A GROUP OF ____ SAMPLES REPRESENTING ____

OWNER OR MANUFACTURER Bauman Landscape Inc.
TOTAL QUANTITY AVAILABLE ____ TEST RESULTS DESIRED ☒ NORMAL ☐ PRIORITY DATE NEEDED ____
REMARKS A.C mix design
AR-4000 Asphalt oil
(OTHER ADDITIONAL INFORMATION WITH LETTER)
DATE SAMPLED ____
BY ____ TITLE ____
DIST., CO., RTE., P.M. CAL/APT Goal 3 HVS Study Test Job, U.C.
LIMITS ____
CONT. NO. ____
FED. NO. ____
RES. ENGR. OR SUPT. ____
ADDRESS 1353 South 46th St Richmond, CA 94804
CONTRACTOR Bauman Landscape Inc.
MAIL TO SAME DESTINATION

E. R. SOWKO
MATERIALS ENGINEER

overlay at the locations where the cores were taken. The field cores were stored 20° C and trimmed to 50 mm height immediately prior to shear testing. Field mix was stored in the laboratory in closed cardboard boxes at 20° C for the six month period. Prior to compaction of field mix in the SGC, the mix was heated at 138° C for two hours. Field mix for SGC compaction was used from the same locations that the field cores were taken. No splitting of the mix was performed prior to SGC compaction because each cardboard box contained only enough material for about three SGC specimens and the boxes were filled within about 5 m of the core locations.

Superpave Gyratory Compactor (SGC) cylinders were compacted following AASHTO TP4, including the recently adopted steps to prevent segregation, with two exceptions. The first exception is that compaction was continued until a final height was reached that was estimated to provide an air-voids content matching the field cores. The diameter of the SGC specimens is 150 mm, the same as the field cores. The final height obtained was usually between about 115 and 140 mm. The second exception is that the compaction temperature was selected to match the compaction temperatures measured during the construction of the field pavement from which the field cores were taken.

The approximately 125 mm high SGC cylinders were cut into two 50mm specimens and labeled “B” for bottom and “T” for top. The bottom specimen typically had a lower measured air-void content than the top specimen. At times the difference approached 1.5 percent.

5.2.3 Distribution of Air-Voids

The distribution of air voids within individual SGC specimens in this comparison is worth noting. The calculations used to design the SGC specimens were based on the mass and volume and were intended to produce the same air-voids contents in the SGC specimens as in the field cores. However, the calculated air-voids for the SGC specimens did not match the measured air-voids contents of the final specimens very well. Boundary effects of the mold walls caused larger air-voids contents at the uncut sides of the SGC specimens. These boundary effects resulted in smaller air-void contents in the centers of the specimens.

Air-void contents in field cores typically exhibit a small vertical gradient, with the top of a 75 mm lift often having up to one to two percent less air-voids than the bottom; there is no horizontal gradient of air-voids in field cores.

5.2.4 Test Method - Repeated Simple Shear Test at Constant Height (RSST-CH)

All tests were performed according to AASHTO TP7-94, except that no preconditioning was used.[6] The form of applied loading in the RSST-CH test is shown in Figure 5.1.

Each specimen is loaded with a shear stress of 69 kPa (10 psi) having a haversine waveform and applied for 0.1 seconds with a 0.6 second rest period. This load wave was somewhat arbitrarily selected during the SHRP A-003A project to simulate traffic loading while providing for reasonable test times. *(4)* The height of both the field cores and SGC specimens

[6] No preconditioning is recommended by PRC staff (12, 13)

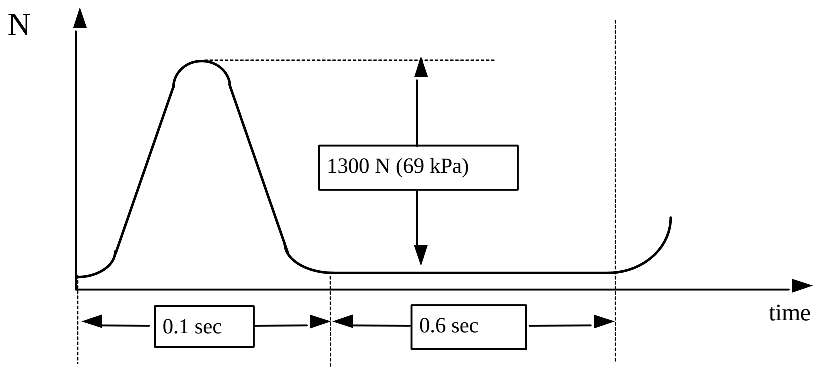

Figure 5.1. RSST-CH Load Wave.

was 50 mm, and the diameter was 150 mm. Loading was continued until five percent permanent shear strain, or 5,000 repetitions was reached. For some specimens, the loading was continued past 5,000 repetitions. When five percent permanent shear strain has not been achieved by the end of the test, extrapolation of these data was accomplished using a linear log-log trend. Specimen height was monitored with an axial LVDT, and the axial load was varied to maintain constant height. Shear strain was measured between the two metal platens for the specimens that were all 50 mm in height, and not directly on the side of the specimen. The shear gauge length was assumed to be 37 mm (see Chapter 3).

5.3 Results

The test results are presented in Table A-2 in the Appendix, in terms of the load repetitions to reach one, two, and five percent permanent shear strain for each specimen. The load repetitions to two and five percent permanent shear strain are shown versus air-voids content in Figures 5.2 and 5.3 for 40° C and Figures 5.4 and 5.5 for 50° C, respectively. These figures include the additional specimens at higher air-voids contents for which insufficient replicates were available.

5.3.1 Analysis of Resistance to Permanent Shear Deformation

The results in Table A-2 and the figures show that the permanent shear deformation resistance of the SGC specimens is considerably greater than that of the field cores at the same air-void contents. The differences are particularly large at 40° C as compared to 50° C, and at larger permanent shear strains. A comparison of the average number of RSST-CH repetitions to strains of one, two, and five percent for SGC specimens and field cores is shown in Table 5.2. It should be remembered that any results with more than about 10,000 repetitions have been extrapolated. At 40° C, the SGC specimens have much greater shear resistance than do the corresponding field cores. The very large numbers of repetitions for the SGC specimens at 40° C should be taken to indicate that they will likely not reach five percent shear strain. This can be compared with the field cores that do continue to show increasing permanent shear strain with more repetitions. At 50° C, the SGC specimens have between 70 and 3,400 times more shear resistance than do the corresponding field cores. Again, most of the field cores were tested to a five percent permanent shear strain, whereas most of the SGC specimens had much greater shear resistance, and the results had to be extrapolated to a five percent shear strain.

These results are similar to those obtained in a similar study performed in 1992, in which SGC specimens compacted from field mix from an Arizona DOT project had approximately 600 times more shear resistance than did corresponding field cores for two percent permanent shear

Table 5.2 Comparison of RSST-CH Repetitions to One, Two, and Five Percent for Superpave Gyratory Compacted and Field Core Specimens.

	Air-Voids (%)	RSST-CH Repetitions to Permanent Shear Strain 1%	2%	5%
Superpave Gyratory at 40 C				
Average	3.6	1.134E+11	4.301E+13	1.104E+17
Variation		0.58	0.58	0.58
Field Core at 40 C				
Average	3.5	1.100E+04	6.175E+05	1.279E+08
Variation		0.59	0.58	0.58
Superpave Gyratory at 40 C				
Average	4.8	3.695E+11	2.094E+14	9.137E+17
Variation		0.58	0.58	0.58
Field Core at 40 C				
Average	4.6	2.663E+02	1.696E+03	4.691E+04
Variation		1.55	1.63	1.16
Superpave Gyratory at 50 C				
Average	3.8	3.229E+03	8.134E+04	4.713E+06
Variation		1.43	0.92	0.70
Field Core at 50 C				
Average	3.5	4.734E+01	2.119E+02	1.372E+03
Variation		0.99	0.91	1.39
Superpave Gyratory at 50 C				
Average	5.0	5.460E+03	9.703E+04	3.153E+06
Variation		1.25	1.24	1.26
Field Core at 50 C				
Average	4.6	3.529E+01	1.562E+02	1.297E+03
Variation		2.20	1.63	1.63

strain. *(14)* In the Arizona DOT study, seven SGC specimens and six field cores with air-voids contents between 5.3 and 7.8 percent were tested at 65° C. Figure 5.6 presents a plot of the Arizona results. The results are summarized in Table A-3 in the Appendix.

The results from the testing for this project and the Arizona project indicate that the relative permanent shear deformation resistance of SGC specimens compared to field cores of the same mix tested under the same conditions varies depending on the mix and on the test temperature. They also indicate that the relative resistance is a function of test temperature, permanent shear strain, air-voids content, and mix type, and potential interactions of at least

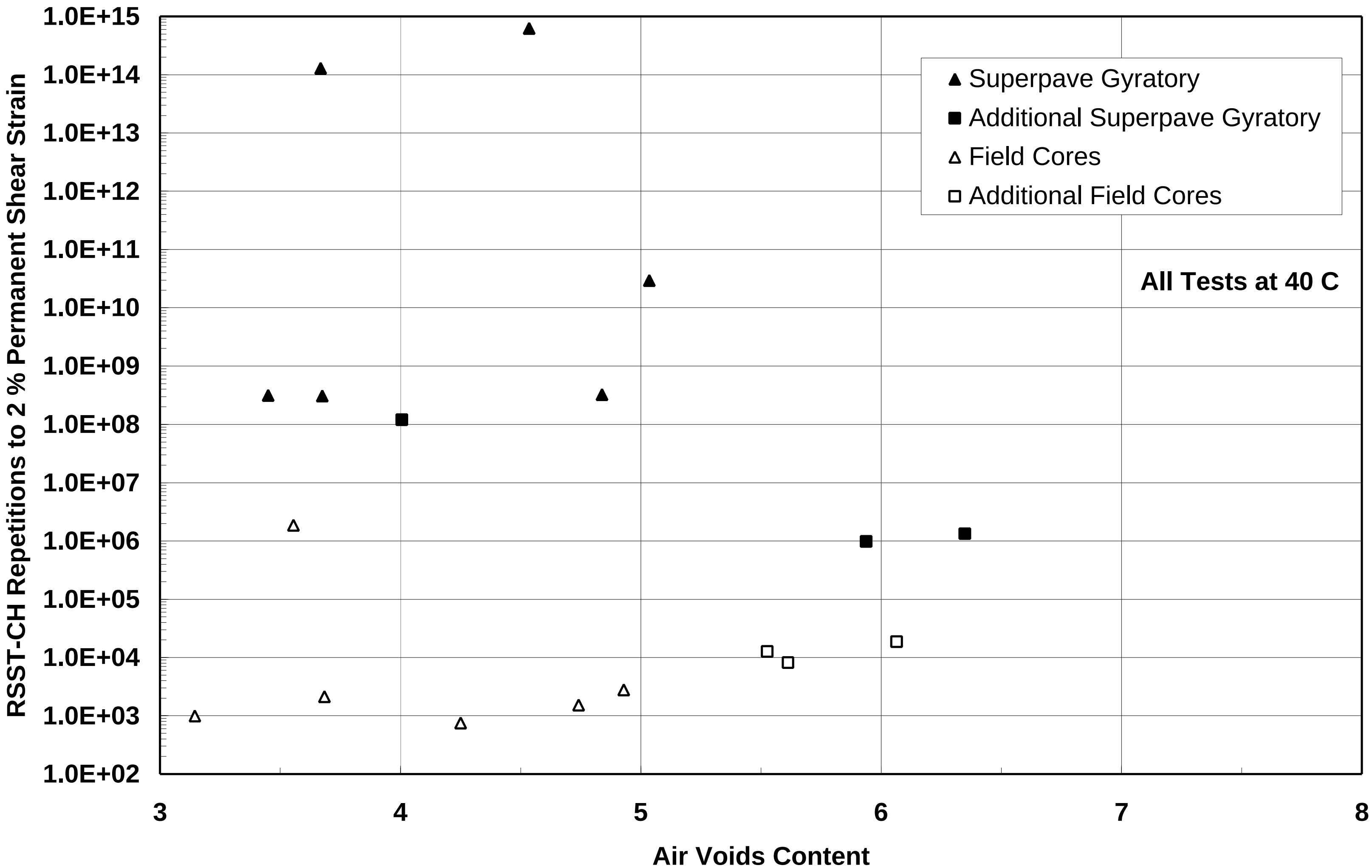

Figure 5.2. RSST-CH Repetitions to Two Percent (2%) Permanent Deformation versus Air-Voids, Tested at 40° C.

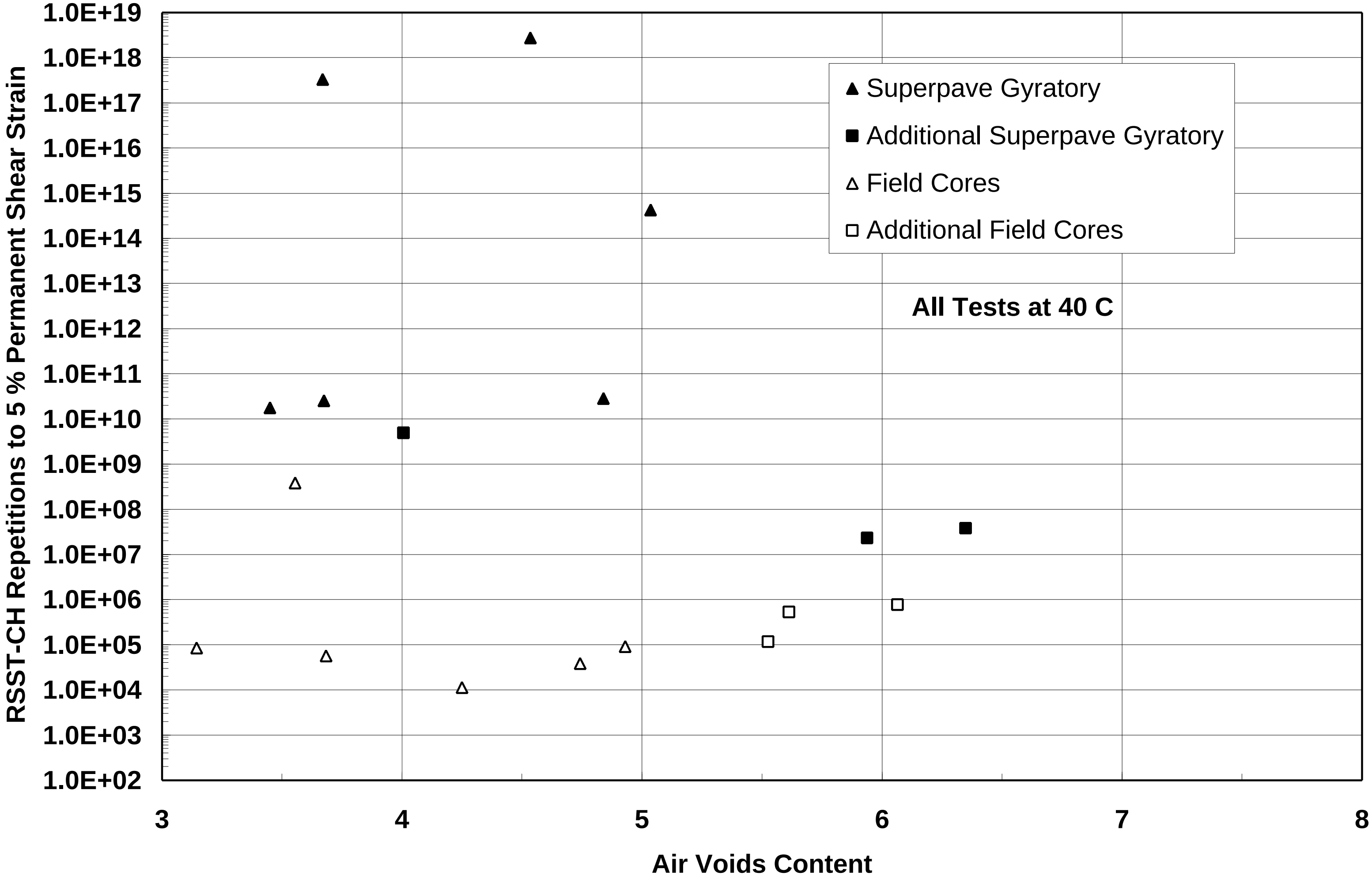

Figure 5.3. RSST-CH Repetitions to Five Percent (5%) Permanent Deformation versus Air-Voids, Tested at 40° C.

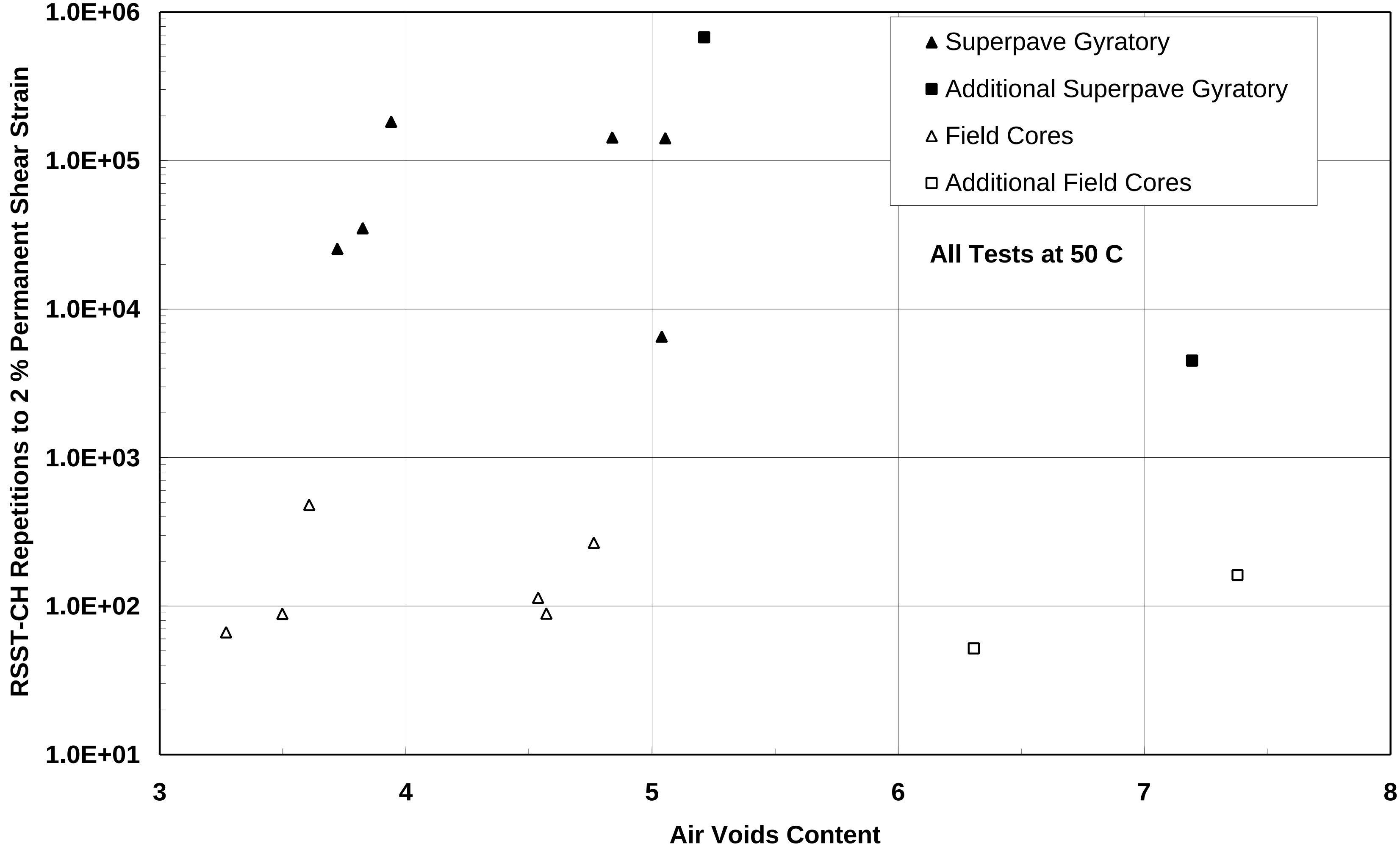

Figure 5.4. RSST-CH Repetitions to Two Percent (2%) Permanent Deformation versus Air-Voids, Tested at 50° C.

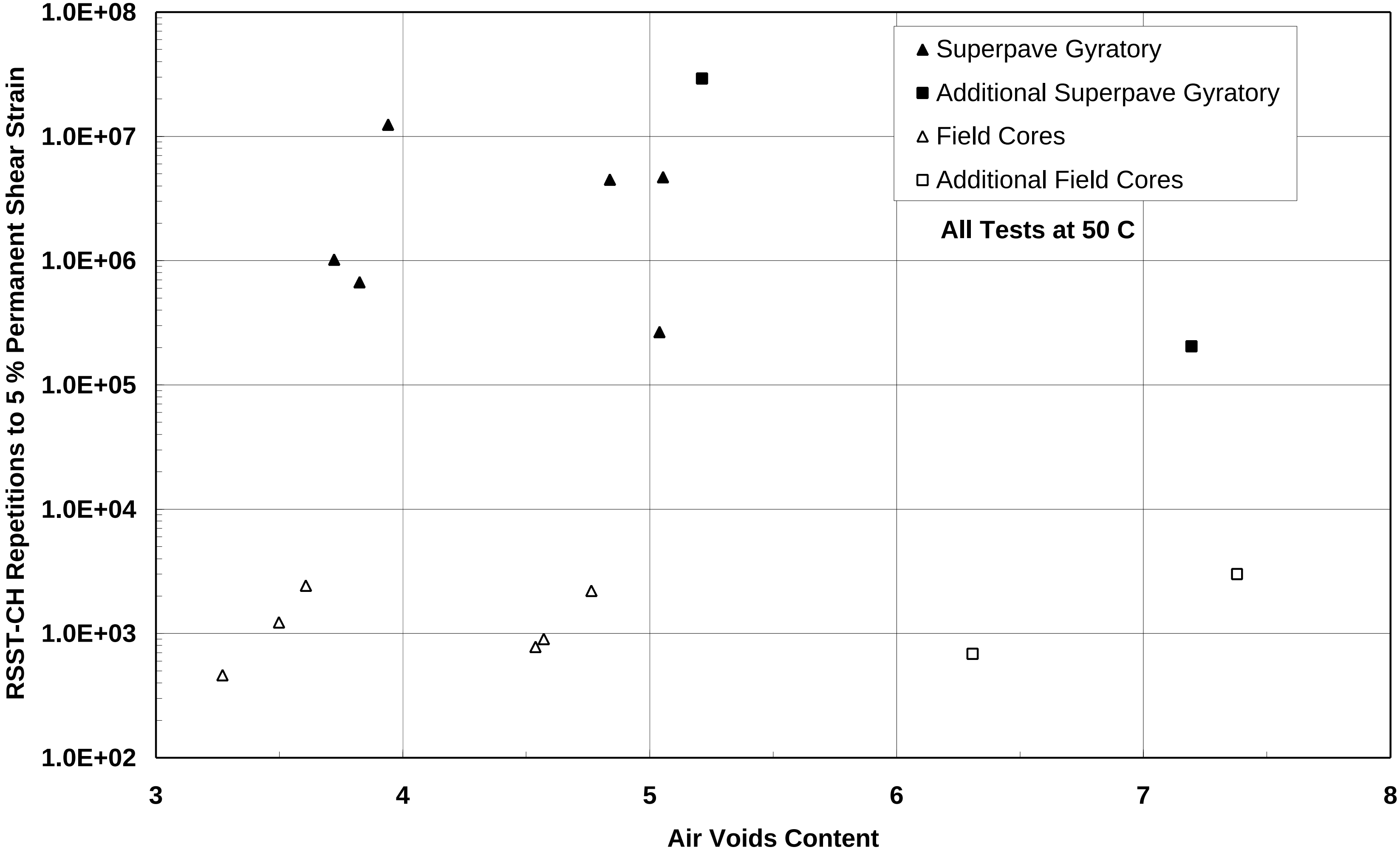

Figure 5.5. RSST-CH Repetitions to Five Percent (5%) Permanent Deformation versus Air-Voids, Tested at 50° C.

some of these variables. The non-linearity of the shear resistance with respect to each of these variables is probable.

The reasons for the large increase in resistance to shear deformation for SGC specimens relative to the field cores can be attributed to three potential causes:

- different distributions and orientation of aggregates;
- different interface conditions between aggregates, and asphalt and aggregates; and
- reheating of the mix.

Reheating the field mix for laboratory compaction ages the binder to some degree. It is doubtful that the field cores for this project and for the Arizona DOT project were significantly aged in the field, given that they were maintained at relatively low temperatures or cored just after construction. Extraction and binder tests to assess the difference in binder properties between the field cores and SGC compacted specimens were beyond the scope and budget of this project, but should be included in any larger project of this type.

Results from the Arizona DOT project indicate that Texas gyratory, kneading, and rolling wheel compacted specimens typically did not have more permanent shear deformation resistance than the field cores when tested at 65° C. The effect of binder aging would be expected to have a stronger effect on permanent shear resistance at lower test temperatures because the binder stiffness will be considerably increased at lower temperature, while at higher temperatures the aggregate structure will play the predominant role in shear resistance to permanent deformation. This may, at least in part, explain the larger difference between the SGC specimens and the field cores at 40° C compared to 50° C.

Assuming that aging of the binder caused by mix reheating does not account for all of the difference in the RSST-CH results between the SGC specimens and field cores, then differences in aggregate orientation and distribution, and in the properties of the interfaces between aggregates and between asphalt and aggregates are probably responsible. It has been shown that Texas gyratory specimens produce different aggregate and voids structures between the center of the specimen and the areas in contact with the mold and ram surfaces. *(15)* Permanent shear resistance increases considerably with increased compaction. It is likely that SGC specimens compacted for this project and the Arizona DOT project were very well compacted near the center and less well compacted near those areas that were in contact with the mold walls. While the average air-voids content for the specimen may match that of the field cores, a very well compacted central portion of the SGC specimens may be providing increased permanent shear resistance. A detailed study of air-void content differences between different regions within SGC specimens has not been performed as it has been for rolling wheel and Texas gyratory specimens.

Data that strongly suggest that reheating of the mix is not the primary factor increasing the permanent shear resistance of the SGC specimens also comes from the Arizona DOT project. Texas gyratory specimens were reheated following the same procedure as the SGC specimens, yet had considerably less shear resistance to permanent deformation resistance than the field cores, as can be seen in Table 5.3 and Figure 5.6. This indicates that, at least at higher test temperatures, differences in permanent shear resistance are imparted to the specimen primarily by the laboratory compaction method, and not by binder aging from reheating of the mix.

In addition to aggregate orientation and distribution, different compaction methods produce different stress states in the mix during compaction. The 1.25 degree angle of the SGC

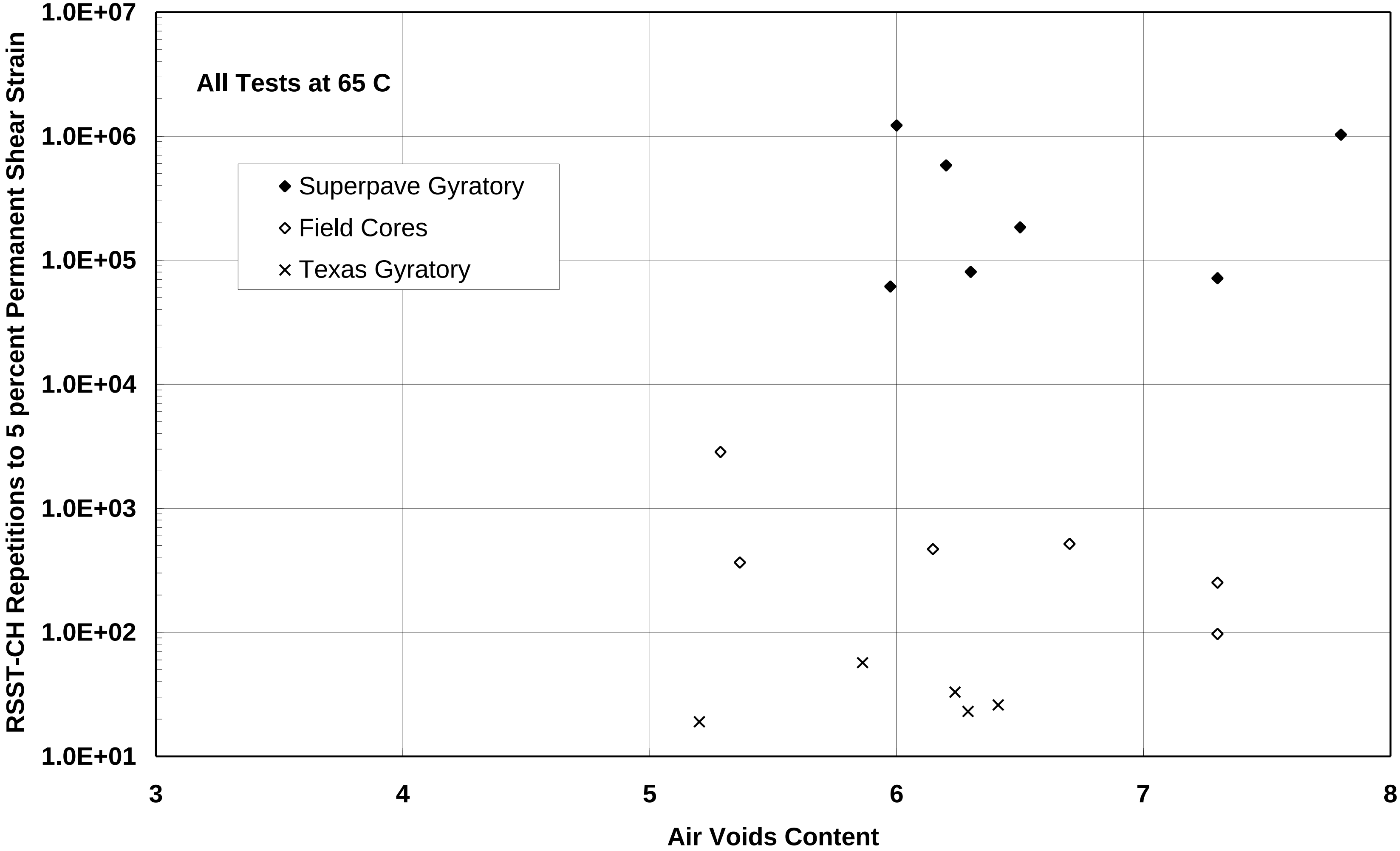

Figure 5.6. Results of RSST-CH Tests at 65°C for Arizona Study.

is likely to produce larger hydrostatic compressive forces and smaller shear forces than does the 5.5 degree angle of the large Texas gyratory device used for the Arizona DOT project. The larger hydrostatic compressive forces of the SGC would be expected to push aggregate together without allowing them to reorient, rather than the forces produced in the mix by the Texas gyratory which allow more aggregate reorientation and movement.

Aggregate distributions, and potentially the asphalt aggregate interfaces, can be evaluated through newly available methods for non-destructive mapping the three dimensional distribution of particles within specimens to evaluate void content and aggregate orientation and contact. The same specimens can then be modeled using three-dimensional finite element techniques, and tested in the laboratory for validation. These results, with binder stiffness tests, will provide a better understanding of the factors responsible for the large difference in permanent shear resistance between SGC specimens and field cores.

5.3.2 Variability of Results

The mean and standard deviation of the number of repetitions to selected permanent shear strains are included in Tables A-2 and A-4. These tables show that the standard deviations are typically of the same order of magnitude as the averages. This is confirmed by the coefficients of variation (ratio of standard deviation over the mean), also shown in Tables 5.2 and 5.3, which range between 0.45 and 1.73. Slightly less variance exists in the air-voids content data for the SGC specimens (0.26 average standard deviation) than for the field cores (0.37 average standard deviation). Observation of the results in Tables 5.2 and 5.3 leads to the conclusion that the coefficients of variation for SGC specimens and field cores are very similar.

Table 5.3 Average and Coefficient Variation of RSST-CH at 65° C from Arizona Project.

	AIR-VOIDS (%)	RSST-CH Repetitions to 2% Permanent Shear Strain
Superpave Gyratory at 65 C		
Average	6.6	4.611E+05
Coeff. of Variation		0.94
Field Core at 65 C		
Average	6.3	7.577E+02
Coeff. of Variation		0.73

Table 5.3 shows that the coefficient of variation of results is typically somewhat constant for permanent shear strains of one, two, and five percent for a given set of replicate specimens. Table 5.3 also shows that the coefficient of variation decreases with increased temperature, and is less for field cores than for SGC specimens. The average coefficient of variation for SGC specimens is 1.40 at 40 C and 1.27 at 50 C. For the field cores, the average coefficient of variation is 1.33 at 40 C and 0.63 at 50 C. Much of this difference can be attributed to the need to extrapolate results at 40 C because the binder is very stiff, and for SGC specimens because of their large permanent shear resistance. A test temperature of 40 C is not likely to be selected for a mix containing a relatively stiff AR-4000 asphalt and designed by the Hveem procedure to be rut resistant.

The coefficients of variation from the Arizona project are greater for the field cores than for the SGC specimens. However, there is less variability in air-void contents for the SGC specimens than for the field cores in this set of data (Table A-3), as well as in other sets (Table A-2).

Besides the need to extrapolate at low test temperatures and for SGC specimens, another likely cause of the apparently random variance across specimen sets is that the specimens are not larger than the Representative Volume Element (RVE). Definitions and theoretical evaluations of RVE are presented in detail in the report by Symplectic Engineering Corporation. *(2)*

5.4 Findings

The findings from the results presented in this chapter are:

- Laboratory specimens compacted from reheated field mix using the Superpave Gyratory Compactor (SGC) have much greater resistance to permanent shear deformation than do field cores taken from the locations where the field mix was sampled. This was found to be true at test temperatures of 40 C and 50 C for one mix, and at 65 C for a second mix.
- The differences in permanent shear deformation resistance between SGC specimens and field cores are less at test temperatures of 65 C and 50 C than at 40 C.
- Extrapolation was required to obtain the repetitions to a permanent shear strains of two and five percent for SGC specimens at 40 C, 50 C and 65 C, because of their large resistance to permanent shear deformation.
- At 40 C, extrapolation was required for the field cores as well. However, at 50 C and 65 C, most field core results did not require extrapolation to obtain the repetitions to two and five percent permanent shear strains.
- The variance of the test results is much greater for the SGC specimens than for the field cores because the SGC specimens have greater mean permanent shear deformation resistance.

- The standard deviation is of the same order of magnitude as the mean number of repetitions to a given permanent shear strain for the specimens tested.

6.0 CONCLUSIONS AND RECOMMENDATIONS

Three experiments were included in the work for this project. The main conclusion of the experiment that evaluated the non-linearity of the complex shear modulus with respect to temperature, frequency and shear strain, was that the material was highly non-linear with respect to all three variables. The test temperatures were 20°, 40°, and 57° C, the frequencies were between 0.01 and 10 Hz, and the shear strains included 0.01, 0.05, and 0.1 percent shear strain. The extent of the non-linearity with respect to strain rate was larger, and more complicated, than expected. The complex shear modulus is a shape distortion property of the material, which is measured directly by the shear frequency sweep test. The non-linearity of shape distortion properties of asphalt concrete with respect to temperature, frequency, and strain makes the extraction of G* or other shape distortion material properties from indirect test methods and other measured properties difficult because linear elasticity is not an applicable constitutive relation for such a non-linear material.

In particular, the use of a linear elastic relation to extract shear properties from indirect tests, such as axial tests that provide a quasi-Young's modulus (E), will be very difficult. Because of the non-linearities, and plastic as well as elastic and viscoelastic behavior, there is no acceptable constitutive relation for asphalt concrete mixes at high temperatures that permits easy calculation of shape distortion properties from other material properties. The use of an assumed linear elastic constitutive relation will likely result in prediction of material properties that are not consistently reliable.

The second experiment was intended to evaluate the benefits of larger specimen size to reduce test results variability and a more prismatic specimen shape to obtain a more uniform stress state in simple shear tests. The results were inconclusive. This is likely due to an insufficient number of replicate specimens included within the limited budget for this project and because specimen height relative to aggregate size was not increased. It could also mean that more prismatic specimens do not behave much differently in the SST than cylindrical specimens.

It was found that standard deviations of RSST-CH repetitions are about as large as the mean number of repetitions, resulting in coefficients of variation typically between about 0.5 and 1.5. Differences between the mean number of repetitions to a given permanent shear strain of two or five percent for different mixes were on the order of 10 to several hundred. The exponential sensitivity of results to mix variables and performance criteria should be considered when evaluating the variance of results.

Lateral bulging of RSST-CH specimens was found to be similar for both 150 mm and 200 mm diameter cylindrical specimens, and for the same size specimens after being trimmed to 100 mm width. In all cases, the width of the specimens only changed about 0.7 percent.

The third experiment compared Repeated Simple Shear Test at Constant Height (RSST-CH) results of field cores and specimens prepared using the same field mix and the Superpave Gyratory compactor (SGC). The primary conclusion of the comparison of the permanent shear strain resistance SGC specimens and field cores is that field cores have considerably less resistance to permanent shear deformation than do specimens prepared using the SGC. This conclusion is drawn from test results from specimens of the same mix, compacted to the same air-voids contents. The difference is much larger at 40° C than at 50° and 65°. It was also observed that the standard deviation of RSST-CH results is approximately the same magnitude as the average number of repetitions to a given permanent shear strain for both SGC specimens and field cores. Because SGC specimens require more repetitions to reach a given permanent shear strain than do field cores, the standard deviations of SGC specimen results are considerably larger than are those from field cores. The coefficients of variation were typically somewhat less for field cores than for SGC specimens. This is due in part to the need to extrapolate SGC specimen results to obtain the repetitions to two and five percent permanent shear strains. The coefficients of variation were typically somewhat less at 50 C and 65 C than at 40 C, again due in part to the need to extrapolate results at lower test temperatures.

Based on the results of this project, included in this report and the results included in the report by Symplectic Engineering Corporation insight into some of the requirements for simple performance test equipment has been obtained. *(2)* In particular:

- The permanent shear deformation resistance of most mixes is a useful property to measure at test temperatures that are greater than about 30 C. Therefore, only heating is required for the test apparatus, and no cooling capability is required.
- The tests performed by the simple performance tester should include purely shear kinematics, in order to obtain direct measures of shape distortion properties.
- To be able to reduce variance in test results, the equipment should be capable of testing larger specimens than the current 150 mm diameter by 50 mm tall specimens produced by field coring or the Superpave gyratory compactor. This will preserve the ability to test larger specimens in order to reduce the variance of the results by using specimen dimensions closer to those of the Representative Volume Element (RVE), although those dimensions have not yet been determined for typical paving mixes.
- It is possible to reduce the variance of test results from the Repeated Simple Shear Test at Constant Height (RSST-CH) by increasing the size of the specimens and by

testing at higher temperatures. However, it must be kept in mind that the test is extremely sensitive to mix variables. It has been demonstrated that that the response of the mix varies exponentially, and it is not reasonable to expect variance to be as small as for tests (such as the Marshall and Hveem tests) where response to mix variables changes linearly.

Recommendations for future work are :

- ***Perform a larger experiment to determine RVE for typical paving mixes***. The RVE will be primarily dependent on aggregate size and shape as well as temperature and rate of loading. An adequate number of replicate specimens is needed in the experiment to evaluate variance, on the order to 10 to 20 replicates. The experiment should include specimens that are definitely larger than the RVE in order to establish variances for RVE specimens as a baseline. Several different aggregate sizes and shapes should also be included in the experiment. The test used to evaluate RVE should be a shape distortion test primarily, and include different temperatures and frequencies. Once the RVE dimensions are determined for the material, exploration of the effects of specimen shape to reduce imperfections will be more fruitful than the results produced by the study included in this report.
- ***Evaluate whether the variance of results from the RSST-CH can be assumed to be constant when results are evaluated on an exponential basis.*** It is apparent from the results included in this report, and results from tests performed at FHWA by Dr. Pedro Romero, that the variance of the mix increases with the mean. *(7)* It is possible that a log transform of the results may produce a test result variable that has a

constant variance regardless of the mean. This, and other similar possibilities to make better use of test results should be explored.

7.0 REFERENCES

1. Bukowski, J. 1997. Federal Highways Administration. Letter to Carl Monismith at the University of California, Berkeley Pavement Research Center. 17 June, and follow-up letter 10 October.

2. Symplectic Engineering Corporation. 1997. *The Mechanics of Permanent Deformation in Asphalt-Aggregate Mixtures: A Guide to Laboratory Test Selection.* Report prepared for the Pavement Research Center, University of California, Berkeley. December.

3. Weissman, S. L., J. Harvey, and F. Long. 1998. Asphalt Concrete Laboratory Test and Specimen Dimensions Selection Based on Mechanical Constraints. *Proceedings of the 12th Engineering Mechanics Conference* ASCE. (LaJolla, California.) May.

4. Sousa, J. B., J. A. Deacon, S. L. Weissman, R. B. Leahy, J. T. Harvey, G. Paulsen, J. S. Coplantz, and C. L. Monismith. 1994. *Permanent Deformation Response of Asphalt Aggregate Mixes.* Strategic Highway Research Program, National Research Council, Washington, D.C., Report No. SHRP-A-415.

5. Federal Highways Administration, University of Maryland Models Contract Team, University of California, Berkeley/Symplectic Engineering Corporation Team. 1998. Notes from meeting to discuss models. 26-27 February. Washington, D. C.

6. Weissman, S. and J. Sackman. 1997. *Analysis of the Universal Testing System and Laboratory Test Procedures* Report prepared for the Pavement Research Center, University of California, Berkeley. February.

7. Federal Highways Administration, University of Maryland Models Contract Team, University of California, Berkeley/Symplectic Engineering Corporation Team. 1998. Notes from meeting to discuss models. 27-28 July. Washington, D. C.

8. University of California, Berkeley, Pavement Research Center. 1997. *Goal 3 Test Plan* Report prepared for the California Department of Transportation as part of the Caltrans Accelerated Pavement Testing (CAL/APT) Program. Institute of Transportation Studies, University of California, Berkeley.

9. SHRP Equipment Corporation, Inc. 1988-94. *Automated Testing System Software, Version 3.13* (Walnut Creek, California.)

10. Harvey, J., J. Deacon, B-W Tsai, and C. L. Monismith. 1996. *Fatigue Performance of Asphalt Concrete Mixes and its Relationship to Asphalt Concrete Pavement Performance in California* Report prepared for the California Department of Transportation. Institute of Transportation Studies, University of California, Berkeley, January.

11. California Department of Transportation. 1995. *Standard Specifications* July.

12. Harvey, J. and I. Guada. 1998. *Information to Accompany Simple Shear Test Results* Technical Memorandum Submitted to the Federal Highway Administration, Mix Expert Task Group, by the Pacific Coast SHRP Superpave Facility, University of California, Berkeley.

13. Harvey, J. and I. Guada. 1998. *Recommended Changes to AASHTO TP7 Specifications* Submitted to the Federal Highway Administration, Mix Expert Task Group, by the Pacific Coast SHRP Superpave Facility, University of California, Berkeley.

14. Harvey, J. T., C. L. Monismith, J. Sousa. 1994. “An Investigation of Field- and Laboratory-Compacted Asphalt-Rubber, SMA, Recycled and Conventional Asphalt-Concrete Mixes Using SHRP Project A-003A Equipment” *Asphalt Paving Technology, Journal of the Association of Asphalt Paving Technologists* vol. 63:511-560.

15. Harvey, J., K. Eriksen, J. Sousa and C. Monismith. 1994. “Effects of Laboratory Specimen Preparation on Aggregate-Asphalt Structure, Air-Void Content Measurement and Repeated Simple Shear Test-Constant Height Results,” *Transportation Research Record* (National Research Council, Washington D.C.) no. 1454:113-122

8.0 APPENDIX

Table A-1 Results from All Frequency Sweep Tests Performed.

0.0001 Shear Strain

	20 C			**40 C**			**57C**		
	Complex Shear Modulus (kPa)			Complex Shear Modulus (kPa)			Complex Shear Modulus (kPa)		
Frequency	**G-35CA**	G-33CA	G-31CA	**G-43BA**	G-40BA	G-25BA	G-42AA	G-39AA	**G-29AA**
10	**2.928E+06**	2.136E+06	1.805E+06	**2.623E+05**	2.829E+05	2.288E+05	5.681E+04	5.248E+04	**5.310E+04**
5	**2.337E+06**	1.869E+06	1.549E+06	**1.775E+05**	1.880E+05	1.604E+05	4.422E+04	4.199E+04	**4.099E+04**
2	**1.673E+06**	1.499E+06	1.222E+06	**1.034E+05**	1.111E+05	9.476E+04	3.242E+04	3.387E+04	**3.164E+04**
1	**1.265E+06**	1.205E+06	1.045E+06	**6.984E+04**	7.490E+04	6.406E+04	2.671E+04	2.904E+04	**2.651E+04**
0.5	**9.587E+05**	9.788E+05	8.262E+05	**4.788E+04**	5.216E+04	4.433E+04	2.380E+04	2.684E+04	**2.434E+04**
0.2	**6.309E+05**	6.935E+05	5.641E+05	**3.173E+04**	3.338E+04	3.089E+04	2.033E+04	2.564E+04	**2.154E+04**
0.1	**4.422E+05**	4.862E+05	4.080E+05	**2.573E+04**	2.556E+04	2.318E+04	1.818E+04	2.336E+04	**2.039E+04**
0.05	**2.607E+05**	3.167E+05	2.724E+05	**1.973E+04**	2.404E+04	1.873E+04	2.190E+04	2.468E+04	**1.844E+04**
0.02	**1.671E+05**	1.974E+05	1.639E+05	**1.874E+04**	2.013E+04	1.512E+04	2.155E+04	2.417E+04	**1.794E+04**
0.01	**1.071E+05**	1.102E+05	1.088E+05	**1.717E+04**	1.891E+04	1.244E+04	1.900E+04		**1.666E+04**

	Shear Phase Angle (degrees)			Shear Phase Angle (degrees)			Shear Phase Angle (degrees)		
10	**33.1**	24.9	23.7	**52.6**	53.1	58.6	58.5	52.8	**53.1**
5	**34.8**	27.4	25.8	**56.4**	56.5	57.4	50.6	45.9	**48.2**
2	**37.4**	31.5	27.1	**56.8**	57.0	56.9	43.9	38.3	**41.2**
1	**39.9**	34.0	30.7	**55.7**	55.6	54.3	40.7	35.7	**38.2**
0.5	**42.1**	37.5	35.3	**50.9**	52.0	51.1	36.2	34.2	**35.7**
0.2	**46.9**	43.0	40.5	**45.6**	46.3	45.0	33.4	31.1	**32.7**
0.1	**48.6**	46.5	44.5	**42.0**	39.7	34.6	31.1	30.7	**31.2**
0.05	**40.8**	33.9	40.5	**36.0**	39.4	33.3	23.0	27.6	**30.7**
0.02	**48.7**	40.5	45.8	**29.8**	41.3	38.9	25.6	32.4	**35.4**
0.01	**49.7**	40.2	47.0	**31.5**	41.1	34.7	25.5		**35.3**

0.0005 Shear Strain

	20 C			**40 C**			**57C**		
	Complex Shear Modulus (kPa)			Complex Shear Modulus (kPa)			Complex Shear Modulus (kPa)		
Frequency	G-35CB	G-33CB	**G-31CB**	G-43BB	G-40BB	**G-25BB**	**G-42AB**	G-39AB	G-29AB
10	3.517E+06	2.008E+06	**1.196E+06**	2.036E+05	2.039E+05	**1.922E+05**	**2.960E+04**	2.723E+04	2.681E+04
5	2.462E+06	1.506E+06	**1.030E+06**	1.340E+05	1.327E+05	**1.256E+05**	**2.119E+04**	1.853E+04	1.773E+04
2	1.626E+06	1.049E+06	**8.435E+05**	7.611E+04	7.454E+04	**7.138E+04**	**1.473E+04**	1.211E+04	1.170E+04
1	1.138E+06	8.520E+05	**6.858E+05**	4.995E+04	4.837E+04	**4.665E+04**	**1.198E+04**	9.802E+03	9.514E+03
0.5	8.346E+05	6.941E+05	**5.522E+05**	4.748E+04	3.181E+04	**3.117E+04**	**1.005E+04**	8.271E+03	7.606E+03
0.2	5.624E+05	4.773E+05	**3.999E+05**	2.913E+04	1.946E+04	**1.904E+04**	**8.920E+03**	7.209E+03	6.901E+03
0.1	4.114E+05	3.423E+05	**3.085E+05**	2.132E+04	1.464E+04	**1.450E+04**	**8.536E+03**	6.820E+03	5.536E+03
0.05	2.693E+05	2.122E+05	**2.148E+05**	1.658E+04	1.147E+04	**1.121E+04**	**7.360E+03**	6.405E+03	5.794E+03
0.02	1.724E+05	1.279E+05	**1.425E+05**	1.311E+04	9.525E+03	**9.166E+03**	**6.973E+03**	6.627E+03	5.808E+03
0.01	1.149E+05	8.538E+04	**1.010E+05**	1.110E+04	8.807E+03	**8.223E+03**	**6.250E+03**	6.284E+03	5.513E+03

	Shear Phase Angle (degrees)			Shear Phase Angle (degrees)			Shear Phase Angle (degrees)		
10	35.7	15.9	**9.4**	58.8	61.8	**60.8**	**57.0**	61.0	63.0
5	34.6	17.4	**15.1**	60.7	61.2	**60.2**	**51.3**	54.9	57.2
2	34.3	24.0	**23.0**	62.1	62.5	**61.2**	**43.6**	47.8	47.9
1	36.1	28.2	**28.5**	61.2	61.5	**60.5**	**38.5**	41.4	45.0
0.5	39.3	33.8	**32.6**	51.3	59.3	**58.0**	**34.4**	36.6	39.5
0.2	43.5	41.6	**37.7**	47.7	53.4	**52.4**	**27.9**	32.2	32.8
0.1	46.6	45.9	**41.1**	43.7	48.8	**47.9**	**27.2**	24.6	32.6
0.05	49.1	48.5	**43.8**	38.1	41.0	**41.9**	**23.7**	27.9	23.0
0.02	52.8	53.3	**47.7**	34.7	36.8	**34.7**	**24.7**	22.8	31.3
0.01	55.0	56.2	**50.2**	30.8	32.7	**31.5**	**24.6**	24.9	26.8

0.001 Shear Strain

	20 C			**40 C**			**57C**		
	Complex Shear Modulus (kPa)			Complex Shear Modulus (kPa)			Complex Shear Modulus (kPa)		
Frequency	G-35CC	**G-33CC**	G-31CC	G-43BC	**G-40BC**	G-25BC	G-42AC	**G-39AC**	G-29AC
10	1.134E+06	**1.062E+06**	6.718E+05	1.760E+05	**1.850E+05**	1.751E+05	2.333E+04	**2.345E+04**	2.430E+04
5	7.197E+05	**7.554E+05**	5.296E+05	1.109E+05	**1.167E+05**	1.117E+05	1.619E+04	**1.550E+04**	1.588E+04
2	5.252E+05	**5.929E+05**	4.088E+05	6.256E+04	**6.575E+04**	6.377E+04	1.076E+04	**9.819E+03**	9.816E+03
1	3.894E+05	**4.782E+05**	3.225E+05	4.012E+04	**4.216E+04**	4.128E+04	8.613E+03	**7.483E+03**	7.415E+03
0.5	2.965E+05	**3.892E+05**	2.567E+05	2.599E+04	**2.732E+04**	2.696E+04	7.452E+03	**6.355E+03**	6.117E+03
0.2	2.049E+05	**2.844E+05**	1.823E+05	1.527E+04	**1.604E+04**	1.606E+04	6.634E+03	**5.361E+03**	5.288E+03
0.1	1.526E+05	**2.135E+05**	1.370E+05	1.086E+04	**1.155E+04**	1.156E+04	6.096E+03	**5.233E+03**	5.019E+03
0.05	1.082E+05	**1.497E+05**	9.697E+04	8.116E+03	**8.583E+03**	8.775E+03	6.009E+03	**4.581E+03**	4.678E+03
0.02	7.068E+04	**9.517E+04**	6.308E+04	6.372E+03	**6.804E+03**	7.026E+03	5.540E+03	**4.571E+03**	4.605E+03
0.01		**6.388E+04**		5.651E+03	**6.000E+03**	6.194E+03	5.320E+03	**4.582E+03**	4.323E+03

	Shear Phase Angle (degrees)			Shear Phase Angle (degrees)			Shear Phase Angle (degrees)		
10	23.0	**6.1**	13.6	60.4	**60.5**	60.2	59.3	**62.7**	64.3
5	21.5	**8.4**	19.0	62.6	**62.8**	62.1	53.7	**58.1**	59.3
2	26.0	**13.7**	25.8	63.9	**64.1**	62.9	44.9	**47.9**	49.9
1	30.6	**20.8**	30.3	63.6	**63.7**	62.5	38.0	**42.8**	42.1
0.5	34.2	**26.0**	34.0	61.9	**61.9**	60.6	31.6	**34.1**	35.1
0.2	38.6	**31.9**	38.7	56.9	**56.9**	55.8	27.3	**29.1**	28.0
0.1	41.5	**36.6**	42.0	51.0	**51.4**	50.8	26.1	**26.4**	27.4
0.05	44.4	**39.8**	44.5	43.8	**44.5**	43.6	22.2	**20.2**	26.8
0.02	48.0	**45.4**	47.9	36.5	**36.5**	35.5	22.6	**21.7**	21.7
0.01		**49.1**		30.0	**31.9**	29.7	20.0	**21.0**	21.9

Table A-2 Summary of RSST-CH Testing for Comparison of Compaction Methods.

Compaction Method	Temperature (C)	Specimen	Air-Voids (%)	Repetitions to Permanent Shear Strain 1%	2%	5%
Specimens Tested at 40 C						
Superpave Gyratory	40	SGC12T	3.5	1.502E+07	3.148E+08	1.757E+10
Superpave Gyratory	40	SGC11T	3.7	3.401E+11	1.290E+14	3.311E+17
Superpave Gyratory	40	SGC13	3.7	1.102E+07	3.087E+08	2.529E+10
		AVG	**3.6**	**1.134E+11**	**4.301E+13**	**1.104E+17**
		StDev	**0.1**	**1.964E+11**	**7.449E+13**	**1.912E+17**
Field Core	40	FC45	3.1	1.489E+02	9.940E+02	8.516E+04
Field Core	40	FC63	3.6	3.268E+04	1.849E+06	3.836E+08
Field Core	40	FC12	3.7	1.779E+02	2.116E+03	5.697E+04
		AVG	**3.5**	**1.100E+04**	**6.175E+05**	**1.279E+08**
		StDev	**0.3**	**1.878E+04**	**1.067E+06**	**2.214E+08**
Superpave Gyratory	40	SGC16T	4.5	1.108E+12	6.282E+14	2.741E+18
Superpave Gyratory	40	SGC17T	4.8	1.097E+07	3.240E+08	2.847E+10
Superpave Gyratory	40	SGC18T	5.0	2.122E+07	2.960E+10	4.248E+14
		AVG	**4.8**	**3.695E+11**	**2.094E+14**	**9.137E+17**
		StDev	**0.3**	**6.400E+11**	**3.627E+14**	**1.582E+18**
Field Core	40	FC8	4.2	6.751E+01	7.493E+02	1.132E+04
Field Core	40	FC10	4.7	3.611E+02	1.532E+03	3.864E+04
Field Core	40	FC3	4.9	3.703E+02	2.808E+03	9.078E+04
		AVG	**4.6**	**2.663E+02**	**1.696E+03**	**4.691E+04**
		StDev	**0.4**	**1.722E+02**	**1.039E+03**	**4.037E+04**
Addtional Specimens at 40 C						
Superpave Gyratory	40	SGC10B	4.0	7.118E+06	1.191E+08	4.939E+09
Superpave Gyratory	40	SGC14T	5.9	8.819E+04	9.718E+05	2.319E+07
Superpave Gyratory	40	SGC15T	6.3	1.040E+05	1.320E+06	3.796E+07
Field Core	40	FC9	5.5	2.131E+03	1.265E+04	1.176E+05
Field Core	40	FC28	5.6	3.181E+02	8.160E+03	5.295E+05
Field Core	40	FC27	6.1	1.129E+03	1.855E+04	7.665E+05
Specimens Tested at 50 C						
Superpave Gyratory	50	SGC5B	3.7	1.288E+03	2.552E+04	1.020E+06
Superpave Gyratory	50	SGC6B	3.8	2.696E+03	3.513E+04	6.706E+05
Superpave Gyratory	50	SGC1B	3.9	5.704E+03	1.834E+05	1.245E+07
		AVG	**3.8**	**3.229E+03**	**8.134E+04**	**4.713E+06**
		StDev	**0.1**	**2.256E+03**	**8.850E+04**	**6.701E+06**
Field Core	50	FC49	3.3	1.971E+01	6.664E+01	4.618E+02
Field Core	50	FC48	3.5	1.967E+01	8.872E+01	1.231E+03
Field Core	50	FC61	3.6	1.026E+02	4.803E+02	2.422E+03
		AVG	**3.5**	**4.734E+01**	**2.119E+02**	**1.372E+03**
		StDev	**0.2**	**4.789E+01**	**2.327E+02**	**9.874E+02**
Superpave Gyratory	50	SGC2T	4.8	8.619E+03	1.431E+05	4.489E+06
Superpave Gyratory	50	SGC8T	5.0	4.747E+02	6.519E+03	2.671E+05
Superpave Gyratory	50	SGC2B	5.1	7.287E+03	1.415E+05	4.704E+06
		AVG	**5.0**	**5.460E+03**	**9.703E+04**	**3.153E+06**
		StDev	**0.1**	**4.369E+03**	**7.839E+04**	**2.502E+06**
Field Core	50	FC5	4.5	3.133E+01	1.135E+02	7.778E+02
Field Core	50	FC15	4.6	2.163E+01	8.883E+01	9.019E+02
Field Core	50	FC30	4.8	5.292E+01	2.662E+02	2.210E+03
		AVG	**4.6**	**3.529E+01**	**1.562E+02**	**1.297E+03**
		StDev	**0.1**	**1.602E+01**	**9.610E+01**	**7.937E+02**
Additional Specimens at 50 C						
Superpave Gyratory	50	SGC4B	5.2	3.906E+04	6.748E+05	2.917E+07
Superpave Gyratory	50	SGC7T	7.2	3.956E+02	4.489E+03	2.042E+05
Field Core	50	FC32	6.3	1.345E+01	5.183E+01	6.828E+02
Field Core	50	FC36	7.4	2.596E+01	1.613E+02	2.998E+03

Table A-3 Summary of RSST-CH tests at 65°C from Arizona Project.

Compaction Method	Temperature (C)	Specimen	Air-Voids (%)	RSST-CH Repetitions to Permanent Shear Strain 1%	2%	5%
Superpave Gyratory	65	AZ4b	6.0		6.127E+04	
Superpave Gyratory	65	AZ5a	6.0		1.223E+06	
Superpave Gyratory	65	AZ3a	6.2		5.818E+05	
Superpave Gyratory	65	AZ4a	6.3		8.043E+04	
Superpave Gyratory	65	AZ3b	6.5		1.837E+05	
Superpave Gyratory	65	AZ6a	7.3		7.151E+04	
Superpave Gyratory	65	AZ5b	7.8		1.026E+06	
		AVG	**6.6**		**4.611E+05**	
		StDev	**0.7**		**4.912E+05**	
Field Core	65	SH41	5.3		2.847E+03	
Field Core	65	SH43	5.4		3.650E+02	
Field Core	65	SH42	6.1		4.690E+02	
Field Core	65	SH211	6.7		5.160E+02	
Field Core	65	SH212	7.3		2.520E+02	
Field Core	65	H32	7.3		9.700E+01	
		AVG	**6.3**		**7.577E+02**	
		StDev	**0.9**		**1.035E+03**	
Texas Gyratory	65	AZFG5	5.2		1.9E+01	
Texas Gyratory	65	AZFG6	5.9		5.7E+01	
Texas Gyratory	65	AZFG3	6.2		3.3E+01	
Texas Gyratory	65	AZFG2	6.3		2.3E+01	
Texas Gyratory	65	AZFG1	6.4		2.6E+01	
		AVG	**6.0**		**3.2E+01**	
		StDev	**0.5**		**1.5E+01**	