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Type I Unbound Granular Base Synthetic Reference Sample Program

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Abstract

All laboratories conducting tests for the LTPP program were required to be accredited by the AASHTO Accreditation Program (AAP). AAP includes site inspections of equipment and procedures, and participation in applicable proficiency sample testing. A few critical LTPP tests were not addressed fully by the AAP, and LTPP decided to conduct supplemental testing. The Type 1 Unbound Granular Base Synthetic Reference Sample Program was approved for implementation as one such supplemental testing program.

SHRP Protocol P46 was the specified test procedure for laboratories performing resilient modulus tests on samples of unbound granular base material obtained from LTPP field sites. P46 requires a test system which includes a triaxial pressure cell component, a closed loop electro-hydraulic repeated load component, and certain load and specimen response control, measurement, and recording components.

In view of the complexity of P46, two elements of the supplemental testing were specially important:

- verification that the system is calibrated and yielding reasonable results, and
- a practical means of performing quality checks on a daily or more frequent basis.

Worksheets, supporting data, analyses, final comments, and conclusions are presented. A complete set of proficiency sample statements in AASHTO/ASTM format are provided.

PART I INTRODUCTION

SHRP Protocol P46, "Resilient Modulus of Unbound Granular Base/Subbase Materials and Subgrade Soils", was the specified test procedure for laboratories performing resilient modulus tests on research samples of unbound granular base obtained from long term pavement performance (LTPP) field sites.

P46 requires a test system which includes a triaxial pressure cell component, a closed loop electro-hydraulic repeated loading component, and certain load and specimen response measurement, control, and recording components.

All laboratories providing LTPP testing services were required to be accredited by the American Association of State Highway and Transportation Officials (AASHTO) accreditation program (AAP).

Many of the laboratory tests on LTPP field samples were addressed by the AAP, which includes on site inspections of equipment and procedures, and participation in applicable proficiency sample series. However, a few critical tests in the SHRP LTPP studies, such as the resilient modulus test, were not fully addressed. After extensive consultation and careful study, it was determined that supplemental programs should be designed to provide assurance of quality for these tests. Two important elements, particularly in view of the complexity of the test system required by P46, are:

- verification that the test system is calibrated and yielding a reasonable response, and

- a practical means for the performance of quality checks on a daily or more frequent basis to provide assurance that the test system is stable and continuing to yield reasonable results.

The Type I Unbound Granular Base Synthetic Reference Sample Program was approved for implementation as a supplemental program to cover the above noted needs.

The Type I Unbound Granular Base Synthetic Reference Sample research was designed, and synthetic specimens were obtained and prepared for shipment to participants, by the Vulcan Materials Research Laboratory in Birmingham, Alabama. Management and oversight of the research was performed by Steele Engineering, Inc.(SEI), Tornado, West Virginia. The raw data from this research was collated and analyzed by Charles E. Antle, Consulting Statistician of State College, Pennsylvania and the report was reviewed by David A. Anderson, Consulting Engineer.

In the Type I Unbound Granular Base Synthetic Reference Sample Program, a set of three synthetic reference specimens (Nylon-1, Teflon-1, and Low Density Polyethylene-1) was rotated to all participating laboratories for testing in accordance with certain specified parameters. The initial reference specimen tests by each participant were blind, that is, the participant did not know the reference values. In subsequent testing by the same participant (which has universally occurred) the acceptable range of reference values was revealed. The intent of this procedure was to provide participants with an opportunity to verify the calibration of their triaxial resilient modulus testing system by testing the set of three synthetic reference specimens using standardized parameters. When the measured response was not within the anticipated range, recalibration or maintenance of the system was indicated. When the measured response was within the anticipated range, successful verification of system calibration was deemed to have been accomplished.

A copy of the initiating letter, instructions to the participants, SHRP protocol P46, and worksheets for this program are included in Appendix A. The reduced data reported by each laboratory are given in Appendix B and a report on the work done at Vulcan Materials is given in Appendix C.

Appendix C contains references and data concerning five Teflon synthetic specimens. Teflon-1 is the specimen included in the above noted reference set. Teflon-2, Teflon-3, and Teflon-4 were quality control specimens used by each laboratory under contract to SHRP. Teflon-5 was an uncirculated control tested only by Vulcan at the beginning of the program and subsequent to the completion of the program. The five Teflon specimens were cut from the same stock.

Thirteen laboratories participated in the program. All participants made significant contributions to the success of the LTPP research effort. A list of participants is in Part II of this report.

The final comments, analyses, and conclusions for the Type I Unbound Granular Base Synthetic Reference Sample Program are contained in Part III.

A set of precision statements in AASHTO/ASTM format is contained in Part IV.

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PART III RESEARCH ANALYSES, OBSERVATIONS, AND CONCLUSIONS

1. Background

This experiment was designed with the following objectives:

- To evaluate the ability of certain selected laboratories to perform the resilient modulus testing of Type I unbound granular base synthetic reference specimens.

- To assist the participating laboratories in the calibration of their measuring process in the event their results indicated the need for such.

- To evaluate the performance of the participating laboratories as a group and to provide estimates of the within laboratory and among laboratories standard deviations and coefficients of variation in AASHTO/ASTM format.

A total of 13 laboratories participated in this experiment. Data from 10 of these were available for statistical analyses at the time this report was written. Sufficient repeated testing was done to allow an evaluation of the individual laboratories performance as well as to evaluate the performance of the laboratories as a group. Thus the objectives for this experiment were achieved and the laboratories have been advised of their performance.

It was observed in a preliminary analysis of the data then available that the measured resilient modulus as reported for the synthetic specimens was sometimes increasing with the level of the deviator stress. This behavior is addressed in this report and the preliminary finding is supported, that is, for the three synthetic specimens the measured M_R values increase with increasing deviator stress levels.

It was also observed in the preliminary analysis that, as expected for the synthetic specimens, the measured M_R values depend very little upon the value of the confining stress. That preliminary observation is supported in the final analyses. No generalization to soil samples should be implied where the effect of both deviator stress and confining pressure for granular materials would be expected to be different than for the homogeneous reference samples tested in this study.

2. Design of the Experiment

The experiment as considered in this part of the report required each laboratory in the study to measure the resilient modulus of the three synthetic specimens with selected values of the confining pressure (sometimes noted as CONF) and the deviator stress (sometimes noted as DEVSTR) as described in Appendix A. The participants were to report the results at each combination of the levels for two tests. These two tests provide the means for the evaluation of a within laboratory component of error.

The levels of the confining pressure were 0 and 10 psi. The levels for the deviator stress were 3, 20, and 37 psi. The tests for a given specimen at the six combinations of these factors were carried out in a sequence without removing the specimen and remounting it as is typically done when a soil specimen is tested. A second set of measurements (replicate measurements) were then obtained by repeating the sequence of confining pressures and deviator stresses, once again *without* removing the specimen or remounting the instrumentation. Thus, the replicate measurements do not include testing errors caused by mounting the specimen, installing the instrumentation or other factors that effect the results of truly independent testing. However, by eliminating these effects from the replicate measurements in this study a more precise estimate of the effect of the confining pressure and deviator stress on the measured M_R value was obtained.

3. Observations

It is helpful to look at the graphs of the measured M_R as given in Figures 1 to 3. The data reported in Figures 1 to 3 represent overall averages for each laboratory averaged over the different levels of confining pressure and deviator stress. In Figures 1 to 3:

- There is considerable variation in the measured M_R values among the different laboratories. This should result in a rather large coefficient of variation for the laboratory component in the statistical analysis.

- Laboratory G has the highest values for the L-POLY and NYLON specimens, but laboratory C has the highest values for the TEFLON specimen. Based on these values, laboratories C and G could be regarded as outliers. However, values for the other two materials reported by laboratories C and G were close to the mean values and, therefore, laboratories C and G were included in the analysis. In the analysis that follows, two data points were omitted from the data for laboratory J because they were for the same specimen under the same measuring conditions and differed by a very large amount. These data points are not included in the mean values shown in Figures 1 to 3.

It is useful to consider the within laboratory coefficient of variation in order to evaluate the repeatability for an individual laboratory. The average coefficients of variation for the within laboratory errors for the individual laboratories are presented in Figure 4. (Laboratory E provided insufficient data for the evaluation of their coefficient of variation.) These coefficients of variation seem to be quite reasonable and indeed indicate that the laboratories are capable of repeating the measurements for the synthetic specimens. This suggests that reference specimens such as these could be used in the future as an aid in validating the testing procedures in individual laboratories and the calibration of the measuring process.

As noted above, the test specimens were not remounted in the testing machine between replicate sets of measurements. Therefore, effects such as mounting the test sample and installing the instrumentation is not included in the replicate measurements. In a previous experiment with reference-type specimens it was found that for the synthetic specimens the major source of error in independent measurements was in the measurement process itself and not in the other contributions to measurement error such as mounting the test specimen

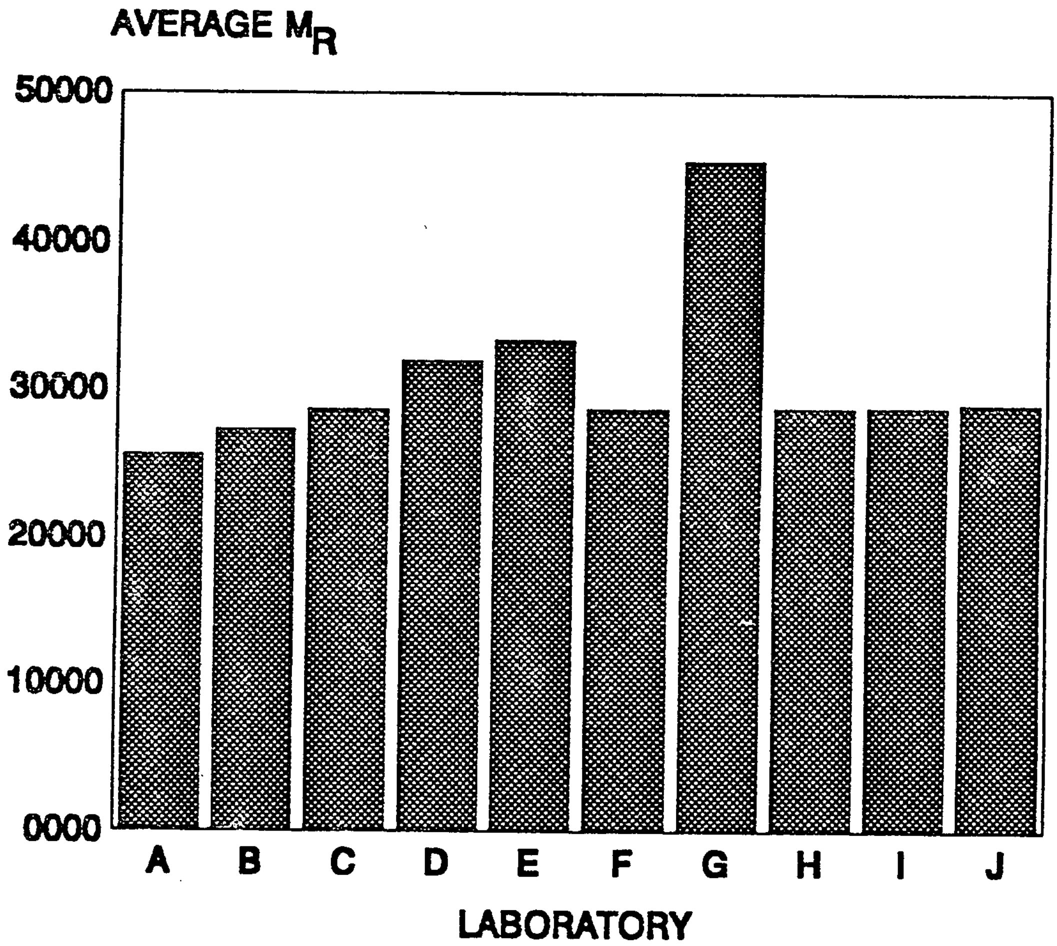

Figure 1. Average M_R Measurements by Laboratory for Type I Synthetic Specimen L- POLY.

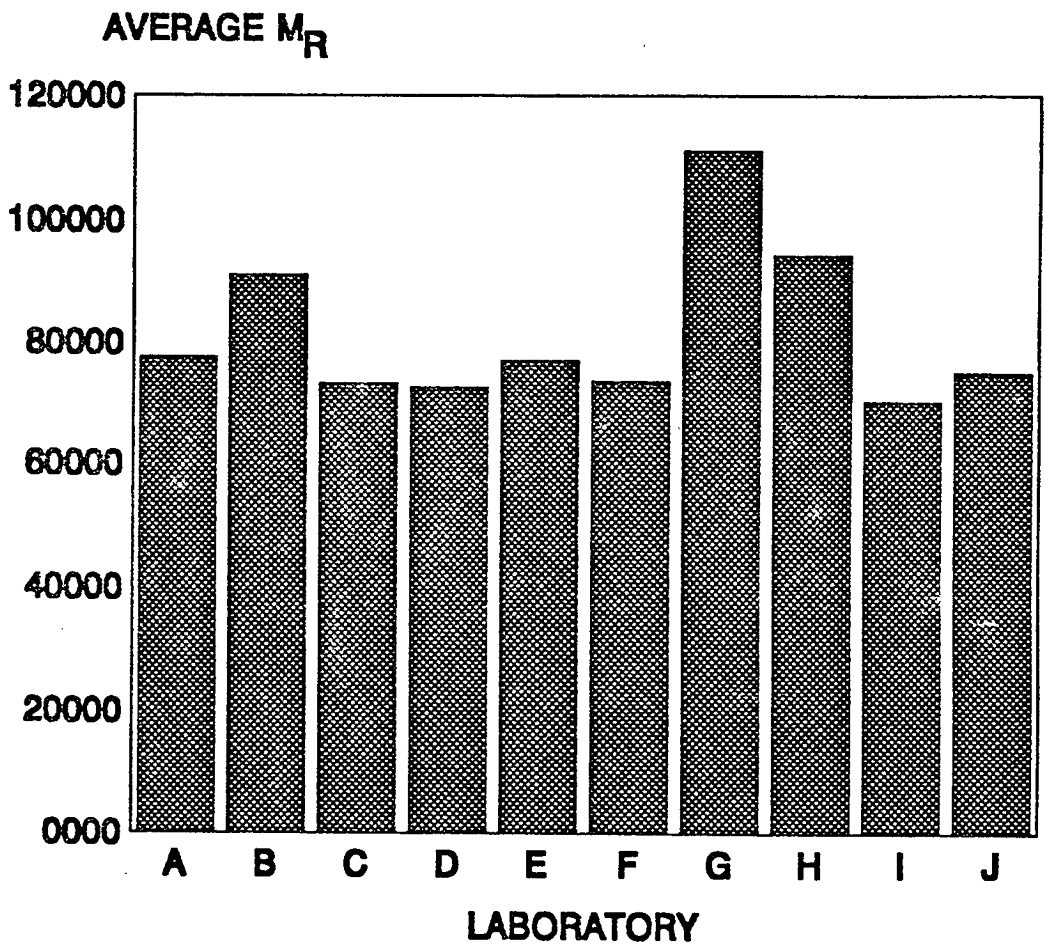

Figure 2. Average M_R Measurements by Laboratory for Type I Synthetic Specimen NYLON.

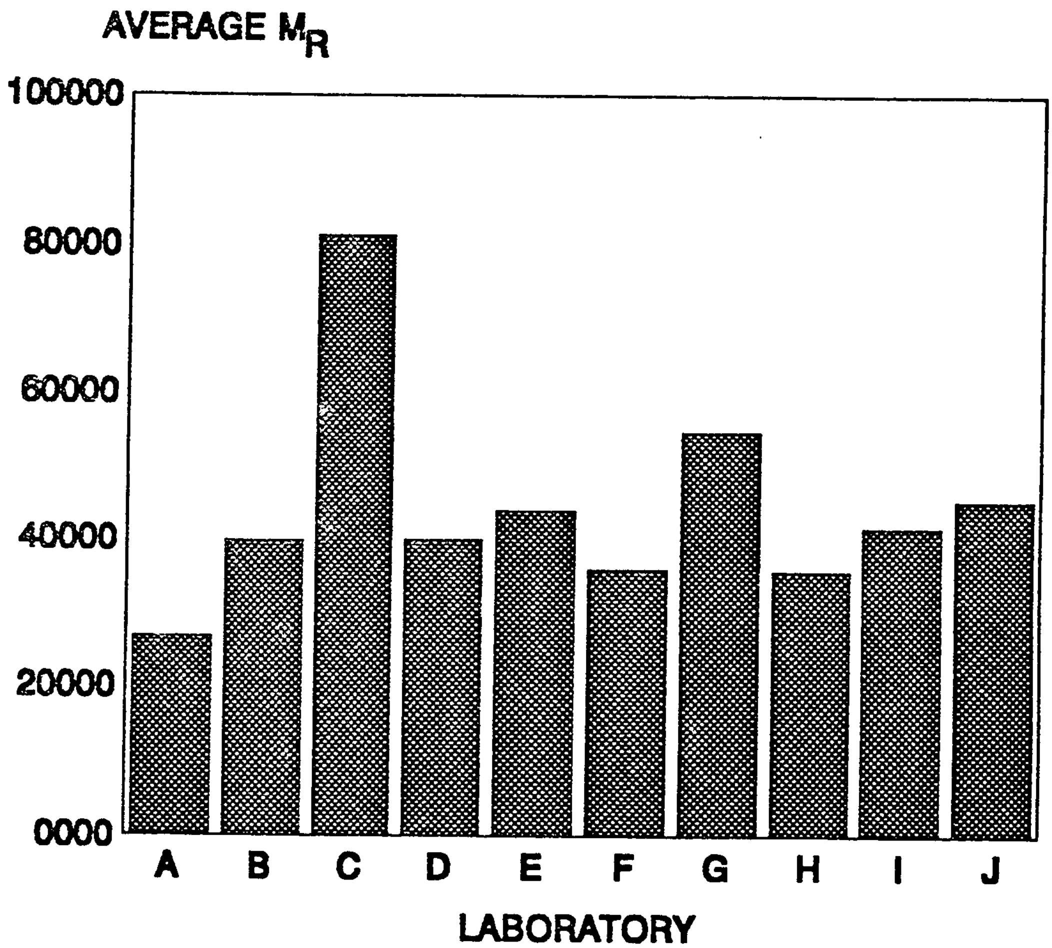

Figure 3. Average M_R Measurements by Laboratory for Type I Synthetic Specimen TEFLON.

and installing the instrumentation[1] . Thus, it seems reasonable in this experiment to regard the testing error as the within laboratory component of variance with the understanding that the reported testing error does not include effects such as mounting the test specimen and installing the instrumentation. To this extent the testing error given in the report may under estimate the true laboratory component of variance.

The effect of the confining pressure may be observed in Figure 5 where the averaged M_R at each level of the confining pressure for each of the specimens is given. As may be expected for the synthetic specimens, there is no apparent effect of the confining pressure on the measured values of M_R. As a consequence, in the preparation of the results for Part IV the data for the two levels of the confining pressure were pooled.

There was a large effect due to the deviator stress as may be observed in Figure 6 where the averaged values of M_R for the specimens are graphed versus the deviator stress. Appropriate t tests for the observed increases in measured values with increased levels of deviator stress make it clear that this is a real effect. The data from which the above analyses were developed are contained in Appendix B.

In the next section the statistical model needed for the identification of the sources of variation in the measured values for the modulus will be presented. The resulting analysis

[1]Steele, G. W., C. E. Antle, and D. A. Anderson, "Type II Unbound Cohesive Subgrade Soil Synthetic Reference Sample Program", Final Research Report prepared for Pavement Consultancy Services, FHWA Contract No. DTFH-61-92-C-00134, October, 1993.

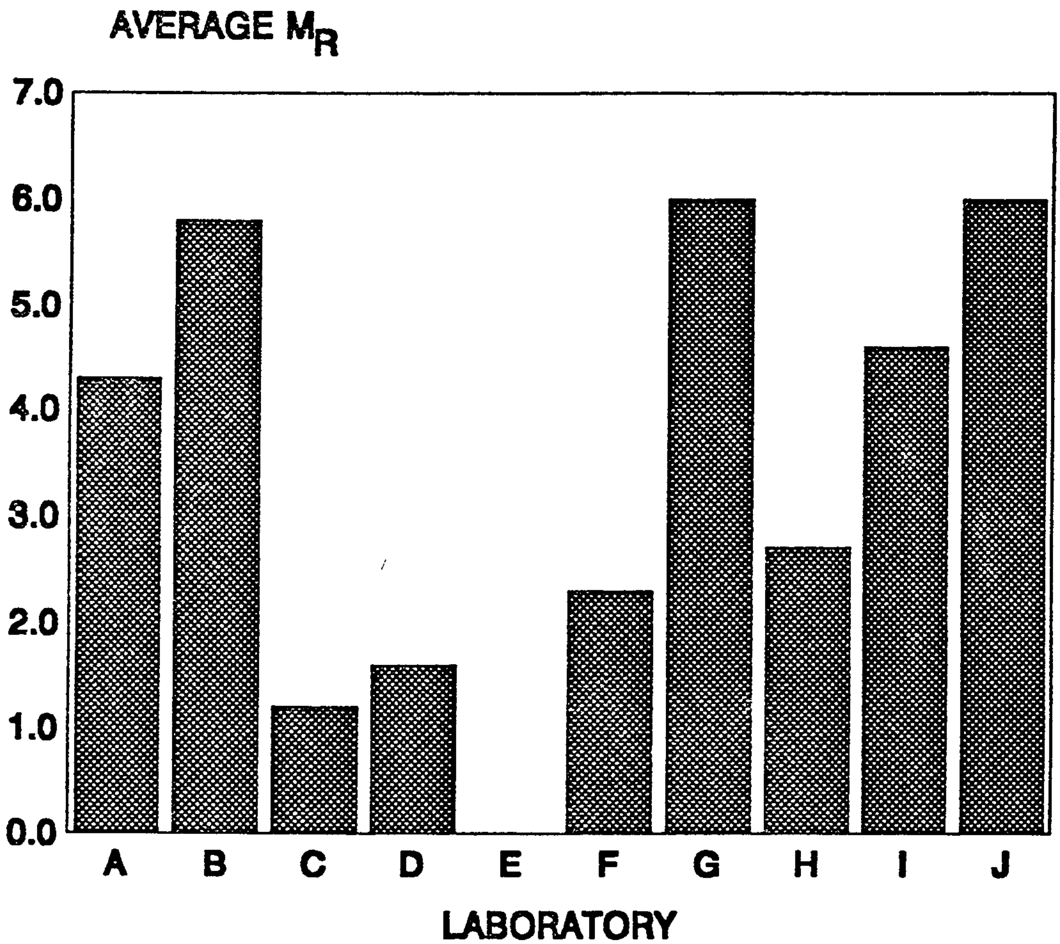

Figure 4. Average Coefficient of Variation for Within Laboratory Errors.

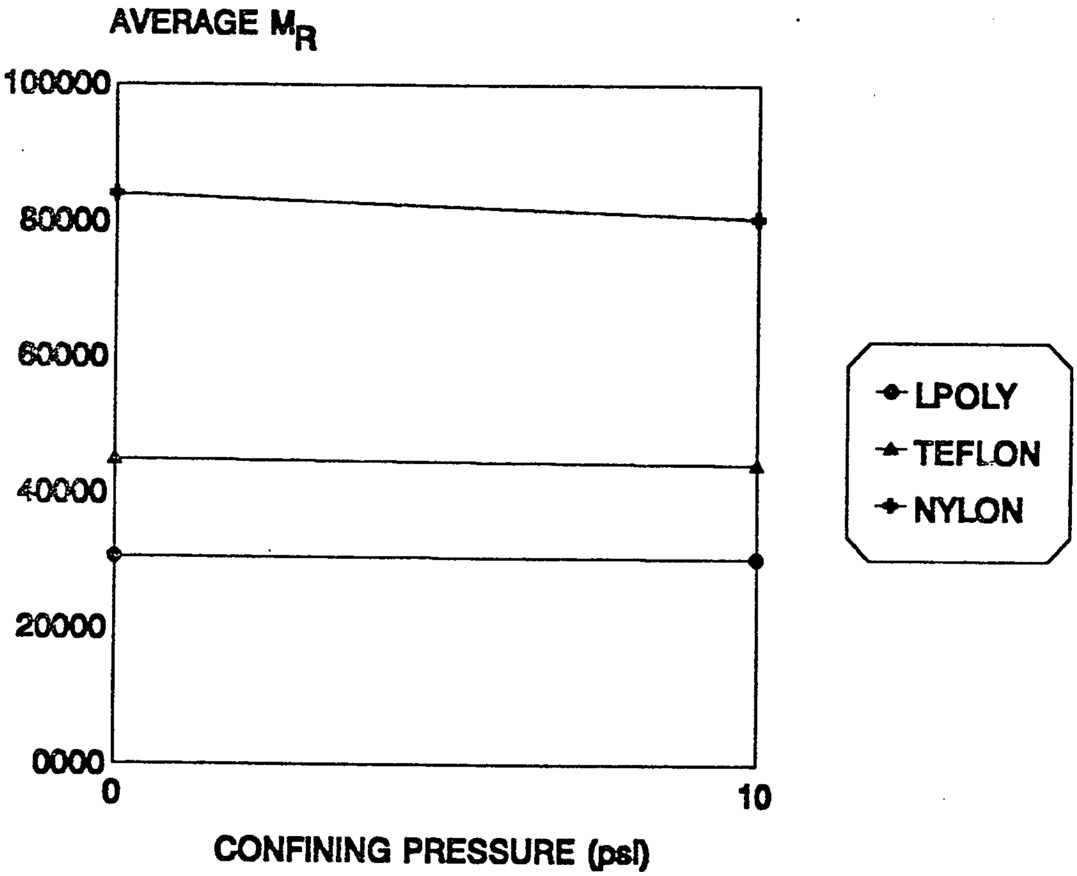

Figure 5. Average Values of M_R by Confining Pressure.

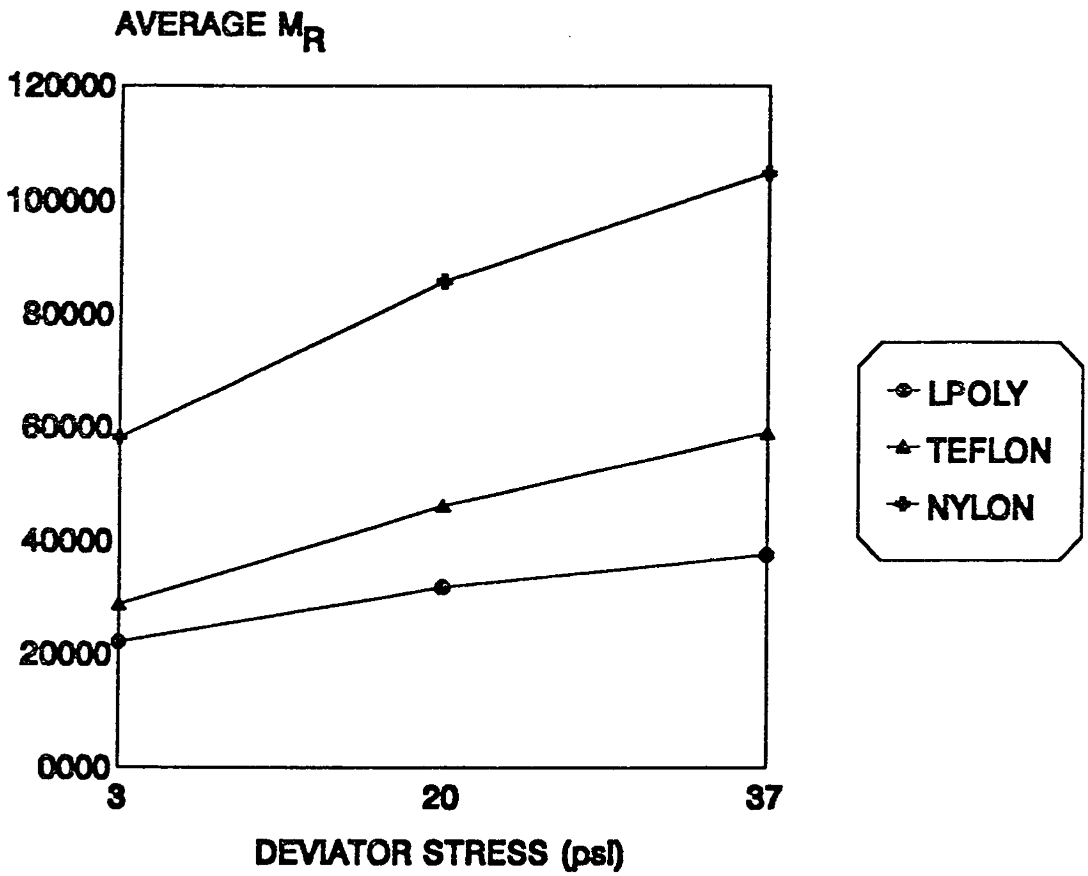

Figure 6. Average Values of M_R by Deviator Stress.

will allow for the assignment of the observed variation in the measurements of the modulus to the *within laboratory* and the *among laboratory* components. It will be seen that the among laboratory component is quite large compared to the within laboratory component. This should be expected as the synthetic components are convenient to mount, apply the instrumentation, etc.

4. The Statistical Analyses

The measured modulus, M_R, for a given specimen at laboratory I on test J, may be represented as:

$$M_R = MU + LAB(I) + TEST(I,J)$$

where it is assumed that MU is the true but unknown value for the modulus, LAB(I) is a normal random variable with mean of zero and standard deviation of STD(LAB), TEST(I,J) is a normal random variable with mean of zero and standard deviation of STD(TEST). It is the estimation of these standard deviations that is important in the analysis of the experimental data and in the development of the precision statements given in Part IV.

The estimates for the standard deviations for each of the combinations of confining pressure and deviator stress are given in Table 1. Since there was no apparent effect due to the confining pressure, the standard deviations were pooled across the levels of confining pressure. The results are given in Table 2. The values given in Table 2 form the basis for the values reported in the tables in Part IV of this report.

It is especially useful to consider the coefficient of variation when evaluating the precision of measurements over a range of values for the measurements. This is true here and these coefficients of variation (CV) are also given in Table 2, along with their averages over the levels of the specimens and the deviator stress levels. It may be useful to simply summarize the analysis of the components of variance by considering that the Laboratory CV is about

Table 1. Standard Deviations for Model Components.

Material	Confining Pressure, psi	Deviator Stress	M_R	Lab	STD
LPOLY	0	3	22,462	5,512	1,408
LPOLY	0	20	31,770	5,723	1,170
LPOLY	0	37	37,638	7,921	1,423
LPOLY	10	3	21,812	5,117	2,783
LPOLY	10	20	31,851	6,555	718
LPOLY	10	37	37,496	8,388	1,253
NYLON	0	3	60,247	16,150	7,331
NYLON	0	20	87,389	10,737	2,671
NYLON	0	37	104,561	14,605	1,356
NYLON	10	3	56,249	14,642	4,142
NYLON	10	20	84,393	13,404	3,280
NYLON	10	37	105,007	19,471	3,793
TEFLON	0	3	28,783	13,138	2,047
TEFLON	0	20	46,675	14,852	2,085
TEFLON	0	37	59,611	19,998	2,012
TEFLON	10	3	28,756	14,448	1,609
TEFLON	10	20	45,689	17,739	3,462
TEFLON	10	37	58,398	22,921	3,522

Table 2. Pooled Values for Standard Deviations and Coefficients of Variation.

Material	Deviator Stress, psi	Average M_R	STDLAB	CVLAB	STD Test	CV Test
LPOLY	3	22,137	5,318	24	2,205	10
LPOLY	20	31,811	6,153	19	971	3
LPOLY	37	37,567	8,158	22	1,341	4
NYLON	3	58,248	15,414	26	5,954	10
NYLON	20	85,891	12,144	14	2,991	3
NYLON	37	104,784	17,211	16	2,848	3
TEFLON	3	28,770	13,809	48	1,841	6
TEFLON	20	46,182	16,359	35	2,858	6
TEFLON	37	59,005	21,509	36	2,868	5
AVERAGE	3			32.8		8.9
AVERAGE	20			23.0		4.2
AVERAGE	37			24.9		3.7
AVERAGE ALL DEVIATOR STRESS				26.9		5.6

27% and the Test CV is about 5-6%. It should be noted that if one or two of the laboratories had been regarded as outliers the Laboratory CV would have decreased somewhat, but it would have still been quite large. Some regular means for assuring that the laboratories are in better agreement is needed in order to reduce this component to a more acceptable level.

Pooled values for the standard deviation and coefficients of variation for each laboratory are given in Table 2. Both the laboratory and testing coefficient of variation are considerably larger for the M_R values obtained at 3 psi than at 20 or 27 psi. This suggests that there may be some difficulty associated with the test procedure when low values of deviator stress are used. This is discussed in the report prepared by Vulcan Materials and included as Appendix C of this report. Consideration should be given improving the test method so that the testing variability is improved at low deviator stresses. Alternatively, consideration should be given to the continued use of 3 psi in the testing sequence. Perhaps a larger value for the minimum deviator stress than 3 psi will still allow the development of an adequate model for M_R and increase the reliability of the coefficients in the model where the model for M_R.

The data in Table 2 also reflect a very large laboratory coefficient of variation for the teflon sample. The cause of these seemingly large coefficients of variation for the teflon sample merits further investigation and suggests that, even though the teflon can be measured repeatedly within a laboratory, it is difficult to reproduce at different laboratories. This raises serious questions regarding further use of teflon as a reference material.

The lack of reproducibility of the results in this experiment has been studied by the Vulcan Materials Company and they have prepared a report which is included as Appendix C to this report. It should be noted in this regard that all of the calculations for the M_R in this report were based upon Method 1 in their report. The computer files which they refer to will be made available to interested researchers.

The within laboratory means for each material are shown in Table 3 where they are compared to the overall (among laboratory) mean for each material. Ideally, the differences, when present, should be consistent for a given laboratory for all of the materials. When this is the case, as general "adjustment" of the calibration factors for that laboratory can be applied. When the differences are inconsistent, as, for example, with laboratory H and, in the extreme for laboratory C, a simple adjustment of the calibration factor cannot be justified. Differences in calibration between different laboratories should not be material dependent. Laboratory A appears to have both a systematic difference from the other laboratories as well as excessive variability. In any future reference testing more than one sample with a range in moduli should be included in any reference testing program. Basing a "correction" factor on a sample specimen would be a risky procedure.

5. Experiments Performed by the Vulcan Laboratory

The report, "Resilient Modulus Testing of SHRP LTPP Type I Synthetic Specimens", by the Vulcan Materials Company is included in this report as Appendix C. Attention is given in their report to the possibility of three methods for the calculation of the resilient modulus for the Type I synthetic specimens. It should be noted that their Method 1 was used in all calculations in this report. It is clear from their examples that, as expected, the estimated resilient modulus will have a large dependence upon the choice of the method for the calculation, especially for low deviator stress levels.

It may be observed from the results given in the Vulcan report that there is a very large variation in the estimated values for the resilient modulus when the deviator stress is low. There are not enough replications in the Vulcan experiments to allow for a good estimate of this variation. However, this is in agreement with the results as given in this report.

The results presented in the Vulcan report do not provide very much information regarding other questions of interest. Some concern was expressed in regard to the possible changes that might have occurred during the repeated experimentation with the synthetic specimens in the various laboratories. The Teflon 1 specimen was used in all of the laboratories included in this report. In addition it was tested by the Vulcan Laboratory three different times during

Table 3. Comparison of Laboratory Means with Overall Means.

Lab	L Poly		Nylon		Teflon	
	Lab Mean, psi	Difference from Overall Mean, %	Lab Mean, psi	Difference from Overall Mean, %	Lab Mean, psi	Difference from Overall Mean, %
A	25,525	-16	77,592	-6	26,708	-40
B	27,284	-11	91,026	10	39,704	-11
C	28,604	-6	73,134	-12	81,152	82
D	31,894	5	72,535	-13	39,821	-11
E	33,274	9	77,013	-7	43,782	-2
F	28,645	-6	73,597	11	35,783	-20
G	45,383	49	111,049	34	54,652	22
H	28,700	-6	94,322	14	35,566	-20
I	28,736	-6	70,157	-15	41,495	-7
J	28,978	-5	75,080	-10	45,193	1
Overall Mean	30,505		82,974		44,652	

this experimental program. The results are presented in Tables 9-12 in the Vulcan report. The differences in the measured resilient modulus as reported in those tables do not suggestthat there were any changes in the true modulus that could not be explained as due to either the conditions of the experiment or the usual lack of repeatability in the measurements of the resilient modulus.

The observed increases in measured resilient modulus with seating load as given in the Vulcan report appear to be a very important effect, especially at the low levels for the deviator stress. This is also true for the observed differences in the measured resilient modulus depending upon whether the small or the large triaxial cell is used. There is not sufficient data with which to evaluate these effects, but these are the observed effects which provided the motivation for the development of the two additional methods for the calculation of the resilient modulus.

It is interesting to observe from Tables 10, 14 and 15 that when the three different Teflon specimens were tested under the same conditions during the first session, there was very good agreement in the reported values. This would suggest that these specimens may be very good indeed as an aid in the calibration of the laboratories. However, as is the case for all of the observations regarding the testing at the Vulcan Laboratory, no strong conclusions should be stated from the limited experiments which were carried out at this laboratory.

6. Conclusions

The following conclusions are based upon the analysis of the data as described in this part of the report:

- The within laboratory single operator average coefficient of variation for all specimens was approximately 6%, indicating that the within laboratory repeatability, when measuring the synthetic specimens, appears to be at an acceptable level.

This finding indicates that, for the homogeneous synthetic specimens, a properly maintained and operated triaxial M_R test system for 6-inch diameter by 12-inch length specimens can be stabilized and tests performed for reasonable time periods with good repeatability.

- There is a large laboratory bias in the measurements as reported in this study. The between laboratories (multi-laboratory) average coefficient of variation was about 22%.

  The between laboratories coefficients of variation, which are several times larger than that found for within laboratories, demonstrate that different test systems operated in different laboratories for 6 inch diameter by 12 inch length specimens yield responses that vary significantly when tests are performed on the same specimens.

  An effort to improve upon the calibration and testing procedure should be made to reduce this bias. Another means for accounting for the laboratory bias would be the continued use of the synthetic specimens so that the results from any given laboratory could be "adjusted" to the mean values. This procedure may not be applicable to measurements obtained with aggregate specimens because it is not known if the "adjustments" for the synthetic specimens will be equally valid for aggregate specimens. In other words, the "adjustments may be material-type dependent.

- The between laboratories coefficient of variation was approximately 22% for all specimens except the teflon which was about 40%. Based on this finding, teflon may not be a suitable reference material for multi-laboratory testing.

- The effect of confining pressure on the measurements for the synthetic specimens was negligible. The lack of a confining pressure effect is unique to the synthetic materials--granular materials will exhibit a definite confining pressure effect.

- There was a considerable effect on the measured M_R due to the level of the deviator stress. This must be accounted for in any statistical calibration studies and specific levels of deviator stress should be specified when these or similar specimens are used for verification of test systems.

- An appropriately designed and operated reference testing program using synthetic reference specimens on a continuous basis would provide the means for preserving a good within laboratory single operator coefficient of variation and may eventually improve the between laboratory coefficients of variation of the test procedure followed in this study.

- Based on the results of this research, consideration should be given to the establishment of a two tiered reference specimen program, similar to that recommended in the Final Report on the Type II Unbound Cohesive Subgrade Soil Synthetic Reference Sample Program (see reference 1).

  The first tier or primary reference samples would be rotated on a frequent basis. Participating laboratories would be expected to verify calibration of their test system based on expected test values with the set of primary reference samples. If expected values were not obtained, further calibration or maintenance of their test system would be performed prior to further use of the system.

  The second tier or secondary reference sets would be rented or loaned to participating laboratories for quality control checks of the M_R test system prior to testing each specimen. When anticipated values are obtained from a quality control test, the stability (e.g. change in calibration with time) of the test system would be verified and the laboratory would proceed with confidence in performing scheduled tests. If expected values were not obtained from a quality control test, maintenance on the test system would be performed prior to proceeding with scheduled tests.

PART IV AASHTO/ASTM FORMAT PRECISION STATEMENTS

Two concepts of precision that are described in ASTM documents are the repeatability and the reproducibility measures. The repeatability measure will indicate the within laboratory precision and will be given by the within laboratory standard deviation for the measured modulus. Alternatively, it may be given as a coefficient of variation for the within laboratory errors. The basis for the tables in Part IV for the entries regarding the within laboratory results is the estimated standard deviations as given in the tables for the within laboratory standard deviations. These within laboratory standard deviations are designated as 1s for the Single Operator Precision entries in Part IV.

The 1s% for the Single Operator Precision statements are the 1s values divided by the average value for the measurements multiplied by 100, i.e., the coefficient of variation. The d2s entries given in Part IV for the Single Operator Precision statements are 2.8 x 1s and this represents the limits (±) within which we would expect to find the difference between *two observations at the same laboratory for the same specimen* with probability of 0.95. When two such measurements differ by more than this at the same laboratory, a check should be made to determine if it is a chance event or if there has been a mistake in the measurements.

The 1s values given in the tables in Part IV for the Multi-Laboratory Precision entries are the standard deviation one would have in the measured M_R values *if a specimen is sent to a random laboratory and a measured value is reported.* Thus, this standard deviation includes the variation among laboratories and the variation within the laboratories. The d2s entries in the tables in Part IV are simply 2.8 times the value for 1s in the respective table.

The value for the 1s entries in the Multi-Laboratory Precision part of the tables are given by

$$[(STDLAB)^2 + (STDTEST^2)]^{0.5}$$

that is, the square root of the sum of the squares of the standard deviations for the

Laboratory and the Test (or Error) components of the model. The d2s limits in the Multi-Laboratory Precision entries represent the limits (±) within which the difference in the measurements of the same specimen at two different laboratories should occur with probability of 0.95. When observed differences are outside this range for the same specimen as measured at two laboratories one should make an inquiry into the correctness of the experiment and the data.

Table 4. Precision Statements for Type I Synthetic Reference Samples, 3 psi Deviator Stress.

Specimen & Type of Index	Mean Total M_R (psi) at 3 psi deviator stress	1s[1]	1s%[1]	d2s[1]
Single Operator Precision				
low density polyethylene	22,137	2,205	10%	6,174
teflon	28,770	1,841	6%	5,154
nylon	58,248	5,954	10%	16,671
Multi-laboratory Precision				
low density polyethylene	22,137	5,757	26%	16,120
teflon	28,770	13,931	48%	39,007
nylon	58,248	16,524	28%	46,267

[1] These numbers represent, respectively, the (1s), (1s%), and (d2s) limits described in ASTM C670, Preparing Precision Statements for Test Methods for Construction Materials.

Table 5. Precision Statements for Type I Synthetic Reference Samples, 20 psi Deviator Stress.

Specimen & Type of Index	Mean Total M_R (psi) at 20 psi deviator stress	1s[1]	1s%[1]	d2s[1]
Single Operator Precision				
low density polyethylene	31,811	971	3%	2,719
teflon	46,182	2,858	6%	8,002
nylon	85,891	2,991	3%	8,375
Multi-laboratory Precision				
low density polyethylene	31,811	6,229	20%	17,442
teflon	46,182	16,607	36%	46,499
nylon	85,891	12,507	15%	35,019

[1] These numbers represent, respectively, the (1s), (1s%), and (d2s) limits described in ASTM C670, Preparing Precision Statements for Test Methods for Construction Materials.

Table 6. Precision Statements for Type I Synthetic Reference Samples, 37 psi Deviator Stress.

Specimen & Type of Index	Mean Total M_R (psi) at 37 psi deviator stress	1s[1]	1s%[1]	d2s[1]
Single Operator Precision				
low density polyethylene	37,567	1,341	4%	3,755
teflon	59,005	2,868	5%	8,030
nylon	104,784	2,848	3%	7,974
Multi-laboratory Precision				
low density polyethylene	37,567	8,268	22%	23,149
teflon	59,005	21,699	37%	60,758
nylon	104,784	17,445	17%	48,846

[1] These numbers represent, respectively, the (1s), (1s%), and (d2s) limits described in ASTM C670, Preparing Precision Statements for Test Methods for Construction Materials.

APPENDIX A

Vulcan

Materials Company

August 30, 1990

Name

Dear :

Thank you for agreeing to participate in this proficiency sample series. This series of experiments is absolutely critical to the highest and best use of the Resilient Modulus data gathered as part of the SHRP Long Term Pavement Performance (LTPP) research. As a proficiency sample cooperator, your organization will be participating in the development of data required to determine the precision of SHRP protocol P-46, the Resilient Modulus of Unbound Granular Base/Subbase Materials.

Briefly, P-46 requires a closed-loop electro-hydraulic loading device capable of providing varying, haversine-shaped, repeated loads in fixed cycles of load and rest period. Test samples are encased in a membrane and subjected to varying confining pressure during test. Loads are measured using a load cell located inside the triaxial cell. Deformations are measured using two spring-loaded LVDT's mounted outside the triaxial cell. Suitable signal excitation, conditioning and recording equipment are required for simultaneous recording of axial load and deformations. Attached is a copy of SHRP protocol P-46 further defining these equipment requirements.

The first step in assuring the reliability of the data obtained from P-46 testing is calibration of the test systems. Attached is a copy of the calibration procedure to be used for calibrating your system. We realize that not all systems are the same and some variation of this procedure may be required for your equipment. We ask that you follow this procedure as closely as possible and notify us of any deviations that you make.

A set of synthetic reference specimens (as indicated in the procedure) will be rotated through your laboratory on a loan basis for use in verifying your system. These specimens are to be tested after calibration of your system as set forth in the attachment and the data recorded on the form under SYNTHETIC SPECIMEN TEST DATA ON CALIBRATED EQUIPMENT.

In order to minimize the time required for equipment verification, you should call Garland Steele at 304/727-8719 or me at 205/877-3108 to determine whether the results are in the expected range. If so, the forms should be returned to **Steele Engineering, Inc., Box 173, Tornado, West Virginia 25202**. If not, the system should be recalibrated and the specimens tested again. It is anticipated that each laboratory will:

P.O. BOX 530187 • BIRMINGHAM, ALABAMA 35253-0187

- Carefully unpack the reference specimens when received
- Retain the reference specimens no more than three workdays
- Cross off your address before re-enclosing the shipping list
- Repack the reference specimens in the same or equivalent packaging
- Ship by overnight air express to the next laboratory on the shipping list enclosed with the specimens

After a laboratory has completed the above indicated calibration and verification procedure, that laboratory may proceed with testing of the SHRP Type I Soil Proficiency samples that we will send to you along with forms and instructions. Please note that Round I of the Type I Soil Proficiency samples may arrive at your laboratory before the synthetic reference specimens. Do <u>NOT</u> test them before:

1) Your equipment has been calibrated and verified
2) A Notice-To-Proceed has been issued from this office.

Please let me know if you have any questions or comments.

Sincerely,

Richard S. Phillips, P.E.
Laboratory Manager/Research Engineer

RSP:nb

Encl

RESILIENT MODULUS TESTING EQUIPMENT
GUIDE FOR CALIBRATION
SHRP TYPE I SOIL SAMPLES

1. SCOPE

This procedure is a guide for calibrating testing equipment to be used in measuring the resilient modulus of SHRP Type I soils. Several sources for resilient modulus test equipment are available. This procedure describes several steps that should be followed, regardless of manufacturer. Some of the adjustments mentioned in this procedure may not be available on all models. In these cases, calibration should be performed by the manufacturer, either on site or at the factory.

2. REFERENCED DOCUMENTS

SHRP (Strategic Highway Research Program) Test Protocol P-46, Resilient Modulus of Unbound Granular Base/Subbase Materials and Subgrade Soils.

3. SUMMARY OF METHOD

The calibration procedure consists of the following steps:
- Measuring the laboratory temperature
- Calibrating the LVDT's
- Adjusting the load application timing control
- Calibrating the load cell
- Testing of synthetic reference specimens to verify test equipment calibration.

4. APPARATUS

4.1 Thermometer - suitable for measuring temperatures of approximately 20-30 C with an accuracy of 0.5 C and traceable to a National Bureau of Standards calibrated thermometer.

4.2 Resilient Modulus Testing Apparatus - Suitable for performing SHRP (Strategic Highway Research Project) Protocol P-46, Resilient Modulus of Unbound Granular Base/Subbase Materials and Subgrade Soils.

4.3 LVDT Transducer Calibrator - Accurate to 0.0005 inch. May be available from the manufacturer of the resilient modulus apparatus. Should be accompanied by a calibration certificate. The device should be of a configuration such that the device and LVDT will not be held and warmed by the hand. Some configurations of resilient modulus equipment requires that the LVDT's be calibrated at the same time. These configurations will require 2 LVDT transducer calibrators.

4.4 Machinist's Gage Block (Optional) - Size to be equal to the full range of the LVDT to be calibrated, accurate to ± .0005 inches, calibration certificates required.

4.5 Oscilloscope.

4.6 Load cell calibration stand and weights - Stand must be suitable for applying compression loads to the load cell by use of weights. Weights shall be accurate to 0.01 lb and shall be accompanied by a calibration certificate. Weights must be available for the range of the load cell.

4.7 Proving Ring (Optional) - Capacity to be equal to or greater than the largest load applied during the resilient modulus test. Accurate to 0.01 lb, calibration certificate required.

4.8 Small hand tools (screwdriver, etc.)

5. PROCEDURE

5.1 Measure and record the temperature of the sample storage and sample test rooms. The temperature of the rooms should be 25±1 C. If the temperature of the sample storage and sample test rooms is outside this range, adjust the temperature.

5.2 Calibration of the LVDT's - The resilient modulus testing equipment measures the vertical deformation of a sample which occurs during an applied load by use of very sensitive transducers. Assuring accurate response of the transducers and the display to known deformation is a key step in calibrating the modulus test equipment.

Calibrate the LVDT's in accordance with the resilient modulus equipment manufacturer's instructions. The LVDT's must be calibrated using a standard for which calibration certificates are available.

If no procedure is available, calibrate the LVDT's in accordance with the following procedure. This procedure assumes a resilient modulus apparatus configuration which allows calibration of each LVDT separately. Modifications to this section may be made for equipment configurations that require simultaneous calibration.

5.2.1 Turn on the Resilient Modulus Apparatus (RMA) and allow the electronic equipment to warm up for at least 15 minutes or as directed by the manufacturer.

5.2.2 Mount one LVDT form the RMA in the LVDT transducer calibrator. Connect the LVDT to the RMA and set up the RMA for calibration.

5.2.3 Set the LVDT transducer calibrator to a convenient zero position, one that will allow the movement of the LVDT through its full linear range (the exact midpoint of the calibrator is suggested). Record the value displayed on the LVDT calibrator.

5.2.4 Position the LVDT in the LVDT transducer calibrator so that the LVDT is at its electronic center.

5.2.5 Adjust the RMA "Zero" potentiometer until the RMA readout indicates 0.000 in.

5.2.6 Advance the LVDT calibrator the full linear range of the LVDT in the "compression" direction. The RMA readout should display the value of the full linear range of the transducer. Record the RMA readout.

5.2.7 Return the LVDT transducer calibrator to its zero position. The RMA readout should read zero.

5.2.8 Repeat steps 5.2.5 through 5.2.7 four times. Compute the average RMA readout at the full linear range of the LVDT. This should be the same as the full linear range.

5.2.9 If the average RMA readout and the LVDT calibrator display do not agree, adjust the "Gain" on the appropriate potentiometer on the RMA (see manufacturer's instructions).

5.2.10 Repeat Steps 5.2.5 through 5.2.9 until the transducer displacement is accurately indicated on the RMA.

5.2.11 Repeat for the second transducer (if required).

NOTE: An alternate acceptable method of LVDT calibration would be to use a rigid frame to hold the LVDT and move it through its full linear range by use of a machinist's gage block.

5.3 ADJUSTING THE LOAD APPLICATION TIMING CONTROL - The load application sequence must be checked for precise timing.

5.3.1 Connect an oscilloscope to the appropriate terminals on the RMA (refer to the manufacturer's manual for your RMA).

5.3.2 The trigger pulse must be set for 0.10 seconds "ON"; 0.9 seconds "OFF"; 1.00 seconds per cycle.

5.3.3 Adjust the timing if necessary. Timing controllers are usually found on a circuit board inside the RMA housing.

5.4 CALIBRATING THE LOAD CELL - An electronic load cell is used to indicate the instantaneous force which is applied onto the test specimen during the resilient modulus test. Accurate load application is important in determining the resilient modulus. The load cell must be calibrated. Calibrate the load cell in accordance with the resilient modulus equipment manufacturer's instructions. The load cell must be calibrated using a standard for which calibration certificates are available.

If no procedure is available, calibrate the load cell in accordance with the following procedure.

5.4.1 Turn on the Resilient Modulus Apparatus (RMA) and allow the electronic equipment to warm up for at least 15 minutes or as directed by the manufacturer.

5.4.2 Connect the load cell to the RMA.

5.4.3 Place the load cell under a suitable stand. The loading stand provides a stable platform for applying known weights onto the center of the load cell.

5.4.4 The RMA display must read 0.00 lb for the unloaded load cell. If the display is not 0.00 lb, then zero the readout by adjusting the appropriate potentiometer (refer to the manufacturer's instructions).

5.4.5 Lower the loading platform shaft carefully onto the center of the load cell. Record the tare weight.

5.4.6 Place known weights on the loading platform. The weights should bracket the range load which will be applied during the resilient modulus test. Record the readout on the RMA display for each applied load. The RMA display should indicate the applied load (including tare) over the full range of loads that are applied. If not, calibrate the readout by adjusting the appropriate potentiometer (see manufacturer's instructions).

5.4.7 Repeat Steps 5.4.5 and 5.4.6 until the correct loads are displayed on the RMA.

NOTE: An alternate, acceptable method of load cell calibration would be to place the load and proving ring in a load frame. The loads measured by the proving ring must equal the loads measured by the load cell and displayed by the RMA.

6. TESTING THE SYNTHETIC REFERENCE SAMPLES

Synthetic reference samples will be loaned to you for round robin testing.

6.1 Determine the resilient moduli of the synthetic reference samples which have been temperature conditioned to 25±1C, in accordance with the following.

6.1.1 Make several measurements of the diameter and height of the specimen.

6.1.2 Clean the triaxial base pedestal. Center the synthetic reference specimen on the triaxial cell pedestal. Do not use porous stones or membrane.

6.1.3 Using commercially available glue (e.g., Superglue), confine the sample to the pedestal base with four equally spaced spots of glue along the sides of sample at the pedestal base. Do not put glue between the pedestal base and the specimen, use the sides.

6.1.4 In a similar manner, attach the top cap to the sample.

6.1.5 Assemble the triaxial chamber and connect all transducers and zero out the LVDT's.

6.1.6 With a confining pressure at zero, apply a static load of between 0.5 and 1.0 psi to the specimen (seating load).

6.1.7 Using a frequency of 1 Hz with a load duration of 0.1 second and a no-load duration of 0.9 second, apply a dynamic load of 3 psi.

6.1.8 Apply 50 repetitions of the 3 psi load and record the recovered deformations and loads of the last five cycles. Repeat another 50 load repetitions and record the last five recovered deformations and loads.

6.1.9 Repeat Step 6.1.8 for dynamic loads of 20 psi and 37 psi.

6.1.10 Increase the confining pressure to 10 psi and repeat Steps 6.1.8 and 6.1.9.

6.1.11 Calculate the resilient modulus for each set of measurements. Stresses and strains should be corrected based on permanent strain accumulation.

6.1.12 Record all data and the resilient moduli on the attached form.

RESILIENT MODULUS TESTING EQUIPMENT
SHRP TYPE I SOIL
SYNTHETIC SPECIMEN TEST DATA ON CALIBRATED EQUIPMENT

TESTING LABORATORY:______________________________________

DATE:____________ TIME:__________ TEMPERATURE:____________

SAMPLE ID:________OPERATOR:________________

Sample Height ______
Sample Diameter _____

		Confining Pressure = 0 psi						Confining Pressure = 10 psi					
		Test 1			Test 2			Test 1			Test 2		
Dynamic Load	Cycle	LVDT 1	LVDT 2	Load	LVDT 1	LVDT 2	Load	LVDT 1	LVDT 2	Load	LVDT 1	LVDT 2	Load
3 psi	46	___	___	___	___	___	___	___	___	___	___	___	___
	47	___	___	___	___	___	___	___	___	___	___	___	___
	48	___	___	___	___	___	___	___	___	___	___	___	___
	49	___	___	___	___	___	___	___	___	___	___	___	___
	50	___	___	___	___	___	___	___	___	___	___	___	___
	MR	___			___			___			___		
20 psi	46	___	___	___	___	___	___	___	___	___	___	___	___
	47	___	___	___	___	___	___	___	___	___	___	___	___
	48	___	___	___	___	___	___	___	___	___	___	___	___
	49	___	___	___	___	___	___	___	___	___	___	___	___
	50	___	___	___	___	___	___	___	___	___	___	___	___
	MR	___			___			___			___		
37 psi	46	___	___	___	___	___	___	___	___	___	___	___	___
	47	___	___	___	___	___	___	___	___	___	___	___	___
	48	___	___	___	___	___	___	___	___	___	___	___	___
	49	___	___	___	___	___	___	___	___	___	___	___	___
	50	___	___	___	___	___	___	___	___	___	___	___	___
	MR	___			___			___			___		

NOTE CONCERNING P46

An earlier draft of SHRP Protocol P46 supplemented by several additional procedural directions was supplied to all participants in this Program. The initiating letter with attachments and the P46 draft included in the appendix for information contains all the procedural requirements, including the supplemental procedural directions, that were conveyed to participants.

SHRP PROTOCOL: P46

For SHRP Test Designation: UG07, SS07

RESILIENT MODULUS OF UNBOUND GRANULAR BASE/SUBBASE MATERIALS AND SUBGRADE SOILS

This SHRP protocol describes the laboratory testing procedure for the determination of the Resilient Modulus (M_r) of unbound granular base and subbase materials and subgrade soils. This protocol is based partially on the test standard AASHTO T292-91I, Resilient Modulus of Subgrade Soils and Untreated Base/Subbase Materials. The test shall be carried out in accordance with the following protocol procedure.

Resilient modulus testing for unbound materials shall commence only after approval by the SHRP Regional Engineer to begin testing.

Definitions

The following definitions, associated with LTPP pavement sample handling and testing, will be used throughout this protocol:

(a) Layer: That part of the pavement produced with similar material and placed with similar equipment and techniques. The material within a particular layer is assumed to be homogeneous. The layer thickness of unbound granular base and subbase materials is determined from field exploration logs (borehole logs and/or test pit log).

(b) Sample: A representative portion of material from one or more pavement layers received from the field. A sample can be a core, block, chunk, pieces, bulk, thin-walled tube or jar sample.

(c) Bulk Sample: That part of the pavement material that is removed from an unbound base or subbase layer or from the subgrade. Bulk samples are retrieved from the borehole(s) and the test pit at the designated locations. The bulk sample of each layer is shipped in one or more bag(s) to the Regional Laboratory Material Testing Contractor. The material from one layer should never be mixed with the material from another layer - even if there is less than the desired amount to perform the specified tests.

(d) Test Sample: That part of the bulk sample of an unbound base or subbase layer or subgrade which is prepared and used for the specified test. The quantity of the test sample may be the same but will usually be less than the bulk sample.

(e) Test Specimen: For the purpose of this protocol, a test specimen is defined as (i) that part of the thin-walled tube sample of the subgrade which is used for the specified tests and (ii) that part of the test sample of unbound granular base or subbase materials or untreated subgrade soils which is remolded to the specified moisture and density condition by recompaction in the laboratory.

(f) Unbound Granular Base and Subbase Materials: These include soil-aggregate mixtures and naturally occurring materials used in each layer of base or subbase. No binding or stabilizing agent is used to prepare unbound granular base or subbase layers.

(g) Subgrade: Subgrade soils are prepared and compacted before the placement of subbase and/or base layers.

(i) A treated subgrade layer (for example cement- or lime-treated soils) is considered a treated subbase layer in the GPS study of the LTPP program. Treated subgrade materials and bound or stabilized layers of subgrade soils are considered treated subbase materials and should be tested using Protocol P31.

(ii) Untreated subgrade soils include all cohesive and non-cohesive (granular) soils present in the sampling zone.

For the GPS material Sampling and Testing Program: the thin-walled tube sample of the subgrade is considered to be representative of the subgrade soils within the top five feet of the subgrade; and the bulk sample of the subgrade retrieved from 12 inch diameter boreholes or the test pit is considered to be representative of the subgrade soils within 12 inches below the top of the subgrade, unless otherwise indicated on field exploration logs (borehole logs and/or test pit logs).

(h) Material Type 1: For the purposes of this protocol (resilient modulus tests), Material Type 1 includes; (i) all unbound granular base and subbase material, and (ii) all untreated subgrade soils which meet the criteria of less than 70% passing the No. 10 sieve and 20% maximum passing No. 200 sieve. Testing parameters used for Type 1 unbound materials are different from those specified for Material Type 2.

(j) Material Type 2: For the purpose of this protocol (resilient modulus tests), Material Type 2 includes all untreated subgrade soils not meeting the criteria given above in (h) (ii). Generally, thin-walled tube samples of untreated subgrade soils fall in this Type 2 category.

(k) Resilient Modulus of Unbound Materials: The modulus of an unbound material is determined by repeated load triaxial compression tests on test specimens of the unbound material samples. Resilient modulus (M_r) is the ratio of the amplitude of the repeated axial stress to the amplitude of the resultant recoverable axial strain.

Sample Locations for GPS Pavement Sections

(a) The test shall be performed on the test specimens prepared from bulk samples of the unbound granular base and subbase materials retrieved from boreholes BA1, BA2, BA3, etc. and from the test pit (or bulk samples retrieved from boreholes BA4, BA5, BA6, etc. in the absence of the test pit samples).

(b) For the subgrade soils, the test shall be carried out on undisturbed thin-walled tube samples retrieved from boreholes A1 and A2; if available. If the thin-walled tube samples are unavailable or unsuitable for testing, or if directed by SHRP, then bulk samples of subgrade soils shall be used to remold test specimens for resilient modulus tests. Bulk samples of subgrade soils are retrieved from boreholes BA1, BA2, BA3, etc. and from the test pit (or bulk samples from boreholes BA4, BA5, BA6, etc. in the absence of the test pit samples).

Assignment of SHRP Laboratory Numbers

For each layer, SHRP requires a representative test sample to be taken from the bulk samples to perform the designated tests. The test results shall be reported separately for test samples obtained from the bulk samples collected at the beginning and end of the section as follows:

(a) Beginning of the Section (Stations 0-):

Bulk samples of each layer are retrieved from BA1, BA2, BA3, etc. type 12 inch diameter boreholes. These bulk samples are combined, prepared and reduced to a representative test size in accordance with AASHTO T87-86 and AASHTO T248-83. The results of each test determined from a representative portion of this bulk sample shall be assigned SHRP Laboratory Test Number '1'.

The results of each test determined from a representative portion of the thin-walled tube sample of subgrade soils from borehole A1 shall be assigned SHRP Laboratory Test Number '1'.

(b) End of the Section (Stations 5+):

If there is no test pit, then bulk samples of each layer are retrieved from one or more BA type 12 inch diameter boreholes generally designated as BA4, BA5, BA6, etc. When there is a test pit, the bulk samples are retrieved from the test pit. These bulk samples are combined, prepared and reduced to a representative test size in accordance with AASHTO T87-86 and AASHTO T248-83. The results of each test determined for the end of the section location shall be assigned SHRP Laboratory Test Number '2'.

The results of each test determined from a representative portion of the thin-walled tube sample of subgrade soils from borehole A2 shall be assigned SHRP Laboratory Test Number '2'.

Laboratory Testing Sequence of Unbound Granular Base and Subbase Materials

Bulk samples of each layer of unbound granular base and subbase materials from LTPP-GPS pavement sections shall be used for the laboratory tests in the following sequence:

- Natural Moisture Content (SHRP Test Designation UG10, Protocol P49)
- Particle Size Analysis (SHRP Test Designations UG01 and UG02, Protocol P41)
- Atterberg Limits (SHRP Test Designation UG04, Protocol P43)
- Classification and Description (SHRP Test Designation UG08, Protocol P47)
- Moisture-Density Relations (SHRP Test Designation UG05, Protocol P44)
- Resilient Modulus (SHRP Test Designation UG07, Protocol P46)

The Resilient Modulus Test shall be the last test performed in the above testing sequence. If the available bulk sample is insufficient in size and a sample from one test is reused for other test(s) and/or the resilient modulus, then the appropriate comment code shall be used in reporting the test results for P46.

Laboratory Testing Sequence of Untreated Subgrade Soils

(a) Bulk samples of untreated subgrade soils from LTPP-GPS pavement sections shall be used for the laboratory tests in the following sequence:

- Natural Moisture Content (SHRP Test Designation SS09, Protocol P49)
- Sieve Analysis (SHRP Test Designation SS01, Protocol P51)
- Hydrometer Analysis (SHRP Test Designation SS02, Protocol P42)
- Atterberg Limits (SHRP Test Designation SS03, Protocol P43)
- Classification and Description (SHRP Test Designation SS04, Protocol P52)
- Moisture-Density Relations (SHRP Test Designation SS05, Protocol P55)

- Resilient Modulus (SHRP Test Designation SS07, Protocol P46)

The resilient modulus test shall be the last test performed in the above testing sequence when thin-walled tube samples are unavailable or unsuitable for testing as explained in (b) below. If the available bulk sample is insufficient in size and a test sample from one test is reused for other test(s) and/or the resilient modulus test, then appropriate comment codes shall be used in reporting the test results for P46.

(b) If the thin-walled tube samples are not available, then follow the test sequence described in (a) above for the resilient modulus test. The test specimen however is reconstituted from a representative portion of the bulk sample. The comment code 89 shall be used in reporting the test results for P46.

(c) Instructions for undisturbed thin-walled tube samples of subgrade soils:

- If the thin-walled tubes are available and acceptable for the resilient modulus test then no bulk sample is needed to reconstitute the test sample for Protocol P46. The "undisturbed" thin-walled tube sample is used in the resilient modulus testing (Protocol P46). The comment code 87 shall be used in reporting the test results for P46.
- The resilient modulus testing of the "undisturbed" thin-walled tube sample can be done without waiting for the entire sequence of testing shown in (a) above provided that the thin-walled tube sample is suitable for testing. The comment code 87 shall be used in reporting the test results for P46.
- If the thin-walled tube sample is not acceptable then use bulk samples as described in (a) above to reconstitute the test specimen for the resilient modulus testing (Protocol P46). The comment code 88 shall be used in reporting the test results for P46.
- If available, properly mark the untested thin-walled tube sample and store for possible future use by SHRP. The comment code 90 shall be used in reporting the test results for P46.

1. SCOPE

1.1 These methods cover procedures for preparing and testing unbound granular base/subbase materials and subgrade soils for determination of resilient modulus under specified conditions representing stress states beneath flexible and rigid pavements subjected to moving wheel loads.

1.2 The methods described are applicable to: undisturbed samples of natural and compacted subgrade soils, and to disturbed samples of unbound base and subbase and subgrade soils prepared for testing by compaction in the laboratory.

1.3 The value of resilient modulus (M_r) determined from this protocol procedure is a measure of the elastic modulus of unbound base and subbase materials and subgrade soils recognizing certain nonlinear characteristics.

1.4 Resilient modulus (M_r) values can be used with structural response analysis models to calculate pavement structural response to wheel loads, and with pavement design procedures to design pavement structures.

2. APPLICABLE DOCUMENTS

2.1 AASHTO Standards

T88-86 Particle Size Analysis of Soils

T99-86 The Moisture-Density Relations of Soils Using a 5.5 lb. Rammer and 12-Inch Drop

T100-86 Specific Gravity of Soils

T233-86 Density of Soil-in-Place by Block, Chunk or Core Sampling

T234-85 Strength parameters of soils by Triaxial Compression

T265-86 Laboratory Determination of Moisture Content of Soils

T292-91I Resilient Modulus of Subgrade Soils and Untreated Base/Subbase Materials

2.2 SHRP Protocols

P41 - Gradation of Unbound Granular Base and Subbase Materials

P42 - Hydrometer Analysis of Subgrade Soils

P43 - Determination of Atterberg Limits of Unbound Granular Base and Subbase Materials and Subgrade Soils

P44 - Moisture-Density Relations of Unbound Granular Base and Subbase Materials

P47 - Classification and Description of Unbound Granular Base and Subbase Materials

P49 - Determination of Natural Moisture Content

P51 - Sieve Analysis of Subgrade Soils

P52 - Classification and Description of Subgrade Soils

P55 - Moisture-Density Relations of Subgrade Soils

3. SUMMARY OF TEST METHOD

3.1 A repeated axial deviator stress of fixed magnitude, load duration (0.1 second), and cycle duration (1 second) is applied to a cylindrical test specimen. During testing, the specimen is subjected to a dynamic deviator stress and a static confining stress provided by means of a triaxial pressure chamber. The total resilient (recoverable) axial deformation response of the specimen is measured and used to calculate the resilient modulus.

4. SIGNIFICANCE AND USE

4.1 The resilient modulus test provides a basic constitutive relationship between stress and deformation of pavement construction materials for use in structural analysis of layered pavement systems.

4.2 The resilient modulus test provides a means of characterizing pavement construction materials, including subgrade soils under a variety of conditions (i.e. moisture, density, etc.) and stress states that simulate the conditions in pavements subjected to moving wheel loads.

5. BASIC DEFINITIONS

5.1 S_1 is the total axial stress (major principal stress).

5.2 S_3 is the total radial stress; that is, the applied confining pressure in the triaxial chamber (minor principal stress).

5.3 $S_d = S_1 - S_3$ is the repeated axial deviator stress for this procedure, and is the difference between the major and minor principal stresses in a triaxial test.

5.4 e_1 is the total axial deformation due to S_d.

5.5 e_r is the resilient (recovered) axial deformation due to S_d.

5.6 $M_r = S_d/e_r$ is defined as the resilient modulus.

5.7 Load duration is the time interval the specimen is subjected to a deviator stress.

5.8 Cycle duration is the time interval between successive applications of a deviator stress.

5.9 $Y_d = GY_w/[1+ (wG/S)]$

where Y_d = unit weight of dry soil, pounds per cubic foot

G = specific gravity of soil solids, dimensionless,

w = moisture content of soil, (%),

S = degree of saturation, (%), and

Y_w = unit weight of water, pounds per cubic foot and may be assumed to be 62.4 pounds per cubic foot (pcf).

NOTE 1: Both w and S must be expressed as numbers; (e.g., 20% is 20), and shall be reported as numbers for SHRP test results.

5.10 Material Definitions - For the purpose of this testing protocol unbound granular base and subbase materials and subgrade soil are categorized as one of two types using the following criteria.

5.10.1 Material Type 1 - all unbound granular base and subbase material, and all untreated subgrade soils which meet the criteria of less than 70% passing the No. 10 sieve and 20% maximum passing the No. 200 sieve.

5.10.2 Material Type 2 - all the untreated subgrade soils not meeting the criteria in 5.10.1. Generally, thin-walled samples of untreated subgrade soils fall in this Type 2 category.

5.10.3 Testing parameters used for Type 1 unbound materials are different from those specified for unbound material Type 2. Type 1 will always include AASHTO classification A-1-a soils, and Type 2 will always include A-4, A-5, A-6, and A-7 soils. A-1-b, A-2 and A-3 soils may fall into either category.

5.10.4 Use the test results of gradation tests (Protocols P41 or P51) and classification tests (Protocols P47 or P52) to establish the material category according to the above criteria.

6. APPARATUS

6.1 Triaxial Pressure Chamber - The pressure chamber is used to contain the test specimen and the confining fluid during the test. A triaxial chamber suitable for use in resilient testing of soils is shown in Figure 1. The deformation is measured externally with two spring loaded LVDT's as shown in Figure 1.

6.1.1 Air shall be used in the triaxial chamber as the confining fluid for all SHRP testing.

6.2 Loading Device:

6.2.1 The external loading device must be capable of providing variable magnitude of repeated loads for fixed cycles of load and rest period. A closed-loop electro-hydraulic system is required by SHRP.

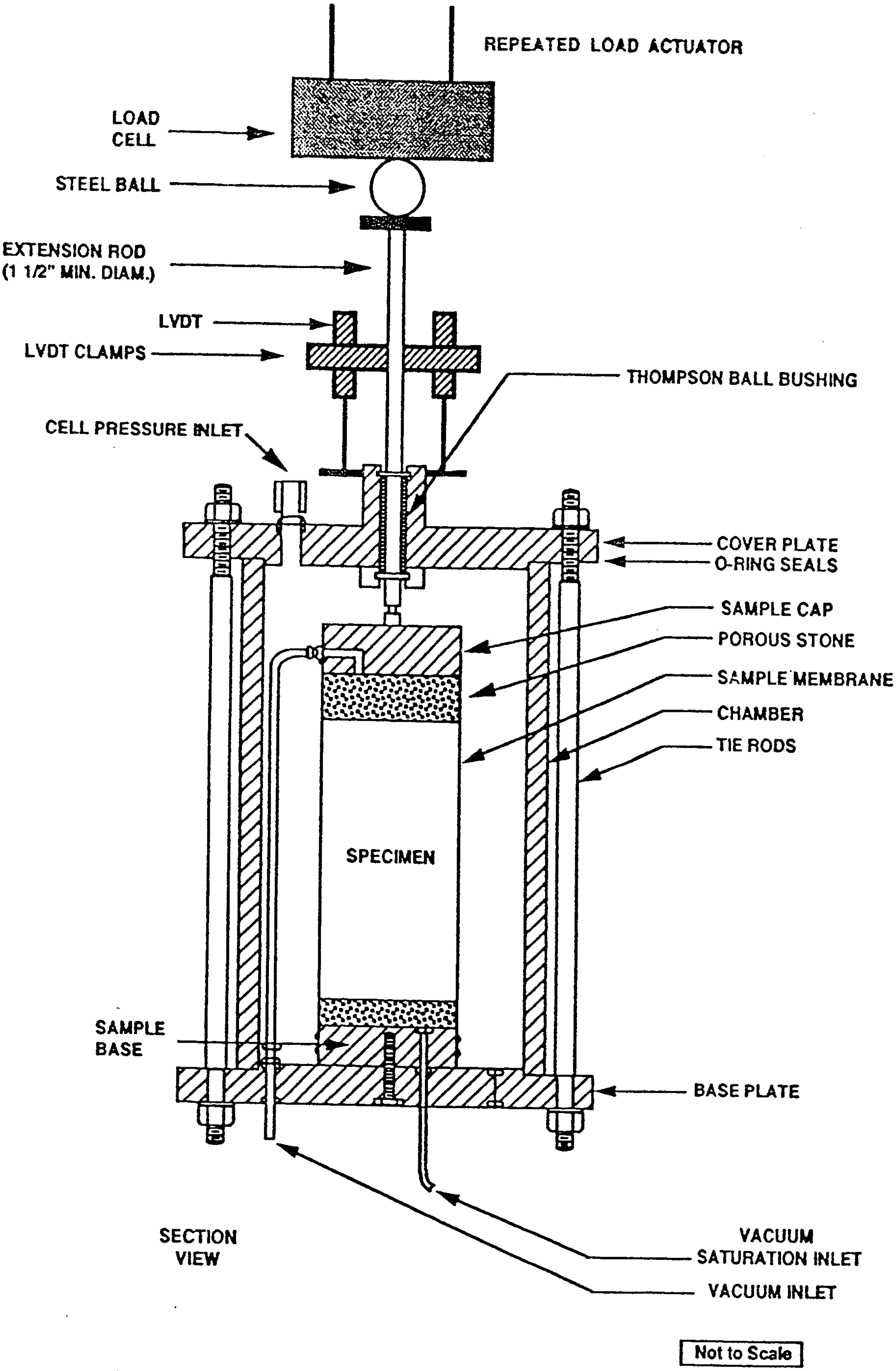

Figure 1. Triaxial chamber with external LVDT's and load cell.

6.2.2 A load duration of 0.1 seconds and cycle duration of 1 second is required. A haversine shaped stress pulse form shall be used.

6.3 Load and Specimen Response Measuring Equipment:

6.3.1 The axial load measuring device should be an electronic load cell and will be located between the specimen cap and the loading piston as shown in Figure 1. The following load cell capacities are recommended:

Sample Diameter In Inches	Maximum Load Capacity
2.8	100 lb.
6.0	1400 lb.

6.3.2 Test chamber pressures shall be monitored with conventional pressure gages, manometers or pressure transducers accurate to 0.1 psi.

6.3.3 Axial Deformation - Measuring equipment for all materials shall consist of 2 Linear Variable Differential Transducers (LVDT's) clamped to the piston rod outside the test chamber as shown in Figure 1. Spring-loaded LVDT's are required. The following LVDT ranges are recommended:

Sample Diameter In Inches	Range
2.8	±0.05 inch
6.0	±0.25 inch

All the LVDT's shall meet the following specifications:

Linearity	± 25% of full scale
Repeatability	± 1% of full scale
Minimum Sensitivity	2mv/v(AC) or 5mv/v(DC)

6.3.4 Suitable signal excitation, conditioning, and recording equipment are required for simultaneous recording of axial load and deformations. The signal shall be clean and free of noise (use shield cables for connections). If a filter is used, it should have a frequency which cannot attenuate the signal. The LVDT's should be wired separately so each LVDT signal can be monitored independently.

6.3.5 In order to minimize errors in testing specimens, LVDT's shall be calibrated daily and load cells should be calibrated once a week using a suitable proving ring. The load cell shall be calibrated semi-annually by an external agency.

6.4 Specimen Preparation Equipment - A variety of equipment is required to prepare undisturbed samples for testing and to obtain compacted specimens that are representative of field conditions. Use of different materials and different methods of compaction in the field requires the use of varying compaction techniques in the laboratory. See Attachment A and Attachment B of this procedure for specimen compaction equipment.

6.5 Equipment for trimming test specimen from undisturbed thin-walled tube samples of subgrade soils shall be as described in AASHTO T234-85. Strength Parameters of Soils by Triaxial Compression.

6.6 Miscellaneous Apparatus - This includes calipers, micrometer gauge, steel rule (calibrated to 0.02 inch), rubber membranes from 0.01 to 0.031 inch thickness, rubber O-rings, vacuum source with bubble chamber and regulator, membrane expander, porous stones, scales, moisture content cans and data sheets, as required.

6.7 System Calibration and Periodic Checks - The entire system (transducer, conditioning and recording devices) will be calibrated using synthetic samples of known modulus. Periodic checks of the system shall be performed using reference samples provided by SHRP. This is done in order to calibrate the systems used by all the laboratories participating in the SHRP material testing program.

7. PREPARATION OF TEST SPECIMENS

7.1 Specimen Size - Specimen length should not be less than two times the diameter. Minimum specimen diameter is 2.8 inches or five times the nominal particle size. (Nominal particle size is the sieve opening for which 95 percent of the material passes during the sieve analysis. See Form P41 or P51 as appropriate for the sieve analysis test results).

Unless otherwise directed by SHRP, the following guidelines, based on the sieve analysis test results (See Form T41 or T51 as appropriate), shall be used to determine the test specimen size.

7.1.1 Use the 2.8-inch diameter undisturbed specimen from the thin-walled tube samples for cohesive subgrade soils (Material Type 2). The specimen length shall be at least two times the diameter (5.6 inches) and the specimen shall be prepared as described in Section 7.2. If undisturbed subgrade samples are unavailable or unsuitable for testing, then 2.8-inch diameter molds shall be used to reconstitute Type 2 test specimens.

7.1.2 Use 6.0 inch diameter split molds to prepare 12 inch high test specimens for all Type 1 materials with nominal particle sizes 1 1/4 inch, without removing any coarse aggregate.

7.1.3 If more than 5 percent of a sample is retained on the 1 1/4-inch sieve remove the particles retained on the 1 1/4-inch sieve prior to specimen preparation. If more than 10 percent of the sample is plus 1 1/4 inch material, the specimen shall be stored and the RCOC contacted for further instructions.

7.2 Undisturbed Specimens - Undisturbed subgrade soil specimens are trimmed and prepared as described in AASHTO T234-85, Strength Parameters of Soils by Triaxial Compression, using the thin-walled tube samples of the subgrade soil. Determine the natural moisture content (w) of the tube sample following the procedure outlined in SHRP Protocol P49 (AASHTO T265-86) and record in the test report. Determine the in situ density of the subgrade soil as specified in AASHTO T233-86.

The following procedure shall be followed for the thin-walled tube samples:

7.2.1 Examine the thin-walled tube samples from each end of the test section separately. For both ends of a test section, select a sample suitable for testing (see NOTE 2) giving priority to samples extracted near the surface of the subgrade. That is, the sample should be taken from the top of the first tube pushed, if it is suitable for testing. If not, examine samples from increasing depths in the subgrade, selecting the first sample suitable for testing.

NOTE 2: To be suitable for testing, a specimen of sufficient length (generally twice the diameter of the specimen after preparation) must be cut from the tube sample, and must be free from defects that would result in unacceptable or biased test results. Such defects include cracks in the specimen, edges sheared off that cannot be repaired during preparation, presence of particles much larger than that typical for the material (example, 1-inch gravel in a fine-grained soil), presence of "foreign objects" such as large roots, wood particles, organic material and gouges due to gravel hanging on the edge of the tube.

7.2.2 If a good undisturbed subgrade sample is unavailable from a particular location, a reconstituted specimen shall be prepared as described in Sections 7.3, 7.4 and 7.5. Select a sample for reconstitution, again giving priority to samples extracted near the surface of the subgrade. Determine the in situ moisture content (w) of material that is representative of the sample to be reconstituted, (about 200 grams of the sample for moisture content determination), following the procedure outlined in SHRP Protocol P49 (AASHTO T265-86), and record on the test report. Assume the in-place density measured in the test pit (for asphalt concrete pavements) as the basis for reconstitution. In the absence of a test pit and if in-place densities are not measured, select the optimum moisture content and 95 percent of the maximum dry density (determined for the same layer using SHRP Protocol P55, Moisture Density Relations of Subgrade Soils, for reconstitution of the test specimen.

The moisture content of the laboratory compacted specimen should not vary more than ± 1/2 percentage point from the in situ moisture content obtained for that layer. The dry density of the laboratory compacted specimens should not vary by more than ± 5 percent of the in-place dry density for that layer.

Where subgrade samples were not retrieved in either of the two thin-wall tubes or the thin-walled tube samples are unsuitable for testing, than a representative test sample from the bulk samples of subgrade shall be used to prepare reconstituted specimens according to Sections 7.3, 7.4 and 7.5.

7.3 Laboratory Compacted Specimens - Reconstituted test specimens shall be prepared to approximate the in situ dry density (Y_d) and moisture content (w), (see NOTE 3). These laboratory compacted specimens shall be prepared for all unbound granular base and subbase material and for all subgrade soils for which undisturbed tube specimens could not be obtained.

NOTE 3: In general, in situ densities for unbound bases, subbases and subgrade soils are measured directly using nuclear moisture/density testing equipment in test pits near the end of a GPS section (after Station 5+00) for asphalt concrete pavements. For PCC pavements, in situ density measurements are generally not made for bases, subbases and subgrade soils because test pit excavations are usually not performed on PCC pavements. In situ moisture contents will generally be available from laboratory measurements of samples taken in the field (see Section 7.4). The same applies for subgrade samples if undisturbed thin-walled tube samples suitable for testing are not available. See Section 7.2.2 for guidance on selecting densities and moisture contents for reconstitution of subgrade materials.

7.3.1 The moisture content of the laboratory compacted specimen should not vary more than ±1/2 percentage point from the in situ moisture content obtained for that layer.

The dry density of the laboratory compacted specimens should not vary by more than ± 5 percent of the in-place dry density for that layer. The desired in-place density shall be taken from the first available option of the following: (a) the average in-place density determined in the field, or (b) from the moisture-density relations as described in Section 7.4.

7.3.2 If the sample is damp when received from the field, dry it until it becomes friable. Drying may be in air or by use of a drying apparatus such that the temperature does not exceed 60°C (140°F). Then thoroughly break up the aggregations in such a manner as to avoid reducing the natural size of individual particles.

7.3.3 Determine the moisture content (w_1) of the air-dried sample. The sample for moisture content shall weigh not less than 200 g for samples with a maximum particle size smaller than the No. 4 sieve (4.75 mm) and not less than 500 g for samples with a maximum particle size greater than the No. 4 sieve (4.75 mm).

7.3.4 Determine the appropriate total volume (V) of the compacted specimen to be prepared. The total volume must be based on a height of the compacted specimen slightly greater than that required for resilient testing to allow for trimming of the specimen ends. An excess of 0.5-inch (13 mm) is generally adequate for this purpose.

7.3.5 Determine the weight of oven-dry soil solids (W_s) and water (W_w) required to obtain the desired dry density (Y_d) and moisture content (w) as follows:

W_s (pounds) = Y_d (pounds per cubic foot) x V (cubic feet)

W_s (grams) = W_s (pounds) x 454

W_w (pounds) = W_s (pounds) x w (%/100)

W_w (grams) = W_w (pounds) x 454

7.3.6 Determine the total weight of the prepared material sample (W_t) required to obtain W_s to produce the desired specimen of volume V at dry density

Y_d and moisture content w.

W_t (grams) = W_s x (1 + w/100)

7.3.7 Determine the weight of the dried sample (W_{ad}), with the moisture content (w_1), required to obtain W_s, including an additional amount W_{as} of at least 500 grams to provide material for the determination of moisture content at the time of compaction.

W_{ad} (grams) = (W_s + W_{as}) x (1 + w_1/100)

7.3.8 Determine the weight of water (W_{aw}) required to increase the weight from the existing dried weight of water (W_1) to the weight of water (W_w) corresponding to the desired compaction moisture content (w).

W_1 (grams) = (W_s + W_{as}) x (w_1/100)

W_2 (grams) = (W_s + W_{as}) x (w/100)

W_{aw} (grams) = W_2 - W_1

7.3.9 Place the mass of the sample (W_{ad}) determined in 7.3.7 into a mixing pan.

7.3.10 Add the water (W_{aw}) to the sample in small amounts and mix thoroughly after each addition.

7.3.11 Place the mixture in a plastic bag. Seal the bag and place it in a second bag and seal it.

7.3.12 After mixing and storage, weigh the wet soil and container to the nearest gram and record this value on the appropriate form (see Worksheet T46).

7.4 Compaction Methods and Equipment for Reconstituting Specimens

7.4.1 Compacting Specimens for Type 1 Materials - The general method of compaction for these soils will be those of Attachment A of this protocol.

7.4.2 Compacting Specimens for Type 2 Materials - The general method of compaction for Type 2 materials will be that of Attachment B of this protocol.

7.4.3 Moisture and Density for Compaction - When the in situ density and moisture content are known from the field data (see Section 7.2.2) the sample should be compacted to this in situ dry density and moisture content.

7.4.4 Moisture and Density for Compaction when Field Data is not Available - In the absence of the test pit, the in situ density and moisture contents are not known; therefore one of the following procedures is used.

(a) Unbound Granular Base and Subbase Materials (Type 1): Use the results of the UG05 test (Protocol P44) on Form T44 to establish the maximum dry density and the optimum moisture content based on AASHTO T180-85. Select the optimum moisture content and 95 percent of the maximum dry density for sample compaction.

(b) Subgrade Soils (Type 1): Subgrade soils may be categorized as Type 1 or as Type 2 according to the criteria of Section 5.10. In the case of Type 1 subgrade soils, use the results of SS05 (Protocol P55) on Form T55 to establish the maximum dry density and the optimum moisture content based on AASHTO T99-86. Select the optimum moisture content and 95% of the maximum dry density for sample compaction.

(c) Unbound Material Type 2: Generally subgrade soils (fine-grained) are included in the unbound material Type 2 category. Select the optimum moisture content and 95% maximum dry density for sample compaction as described in Section 7.4.4.

The sample dry density and moisture content should not differ by more than 3 percent of the in situ dry density and 1 percentage point of the in situ moisture content respectively for Type 1 materials, and 2 percent of the in situ dry density and 1/2% of the in situ moisture content for Type 2 materials respectively (See NOTE 4). If the remolded sample does not meet this criteria, it should be discarded.

NOTE 4: Example: if the desired dry density is 120 pcf and desired moisture content is 8.0 percent for a Type 1 soil, a dry density between 116.4 and 123.6 pcf and a moisture content between 7.2 and 8.8 percent would be acceptable.

7.4.5 The specimen should be protected from moisture change and tested the same day it is compacted.

7.5 Specific Gravity - Determine the specific gravity of solids following AASHTO T100-86.

8. TEST PROCEDURE

8.1 Resilient Modulus Test for Type 2 Soils - The procedure described in this section is used for undisturbed or laboratory compacted specimens of Type 2 soils as defined in Section 5.10.2. Compacted specimens should be tested on the same day after preparation.

8.1.1 Assembly of Triaxial Chamber - Specimens trimmed from undisturbed samples and laboratory compacted specimens are placed in the triaxial chamber and loading apparatus in the following steps.

8.1.1.1 Place the triaxial chamber base assembly on a table close to the loading frame. If the chamber has a removable bottom platen (sample base) tighten it firmly to obtain an air tight seal.

8.1.1.2 Place a porous stone on the top of the pedestal or bottom and plate of the triaxial chamber.

8.1.1.3 Carefully place the specimen on the porous stone. Place the membrane on a membrane expander, apply vacuum to the membrane expander, then carefully place the membrane on the sample and remove the vacuum and the membrane expander. Seal the membrane to the pedestal (or bottom plate) with an O-ring or other pressure seals.

8.1.1.4 Place the top platen (with load cell included) on the specimen, fold up the membrane, and seal it to the top platen with an O-ring or some pressure seal.

8.1.1.5 If the specimen has been compacted inside a rubber membrane and the porous stones and sample are already attached to the rubber membrane in place, steps 8.1.1.2, 8.1.1.3, and 8.1.1.4 are omitted. Instead, the "specimen assembly" is placed on the top of the pedestal or bottom end plate of the triaxial chamber.

8.1.1.6 Connect the specimen's bottom drainage line to the vacuum source through the medium of a bubble chamber. Apply a vacuum of 1 psi. If bubbles are present, check for leakage caused by poor connections, holes in the membrane, or imperfect seals at the cap and base. The existence of an airtight seal ensures that the membrane will remain firmly in contact with the specimen. Leakage through holes in the membrane can frequently be eliminated by coating the surface of the membrane with liquid rubber latex or by using a second membrane.

8.1.1.7 When leakage has been eliminated, disconnect the vacuum supply and place the chamber on the base plate, the load cell on the porous stone, and the cover plate on the chamber. Insert the loading piston and obtain a firm connection with the load cell. Tighten the chamber tie rods firmly.

8.1.1.8 Slide the assembly apparatus into position under the axial loading device. Bring the loading device down and couple it to the triaxial chamber piston and apply a seating pressure to the sample of 2 psi in order to obtain full contact of the piston with the top platen.

8.1.2 Conduct the Resilient Modulus Test - The following steps are required to conduct the resilient modulus test on a specimen of Type 2 soil which has been installed in the triaxial chamber and placed under the loading frame.

8.1.2.1 Open all drainage valves loading into the specimen.

8.1.2.2 If it is not already connected, connect the air pressure supply line to the triaxial chamber and apply a confining pressure of 6 psi to the test specimen. A contact load of 10% (±.5 lbs.) (.1S_d) of the maximum applied load during each sequence number shall be maintained during all repeated load applications.

8.1.2.3 Conducting - Begin the test by applying 1000 repetitions of a deviator stress of 4 psi using a haversine shaped load pulse consisting of a 0.1 second load followed by a 0.9 second rest period. The foregoing stress sequence constitutes sample conditioning, that is, the elimination of the effects of the interval between compaction and loading and the elimination of initial loading versus reloading. This conditioning also aids in minimizing the effects of initially imperfect contact between the end platens and the test specimen.

8.1.2.4 Testing Specimen - The testing is performed following the loading sequence shown in Table 1. Begin by decreasing the deviator stress to 2 psi (Sequence No. 1, Table 1). Apply 100 repetitions of deviator stress using a haversine shaped load pulse consisting of a 0.1 second load followed by a 0.9 second rest period and record the average of the recovered deformations of the last five cycles on Worksheet T46.

Sequence No.	Confining Pressure S_3 psi.	Dev. Stress S_d psi.	Contact Load $.1S_d$ psi.	Number of Load Applications
0 (preconditioning)	6	4		1000
1	6	2		100
2	6	4		100
3	6	6		100
4	6	8		100
5	6	10		100
6	4	2		100
7	4	4		100
8	4	6		100
9	4	8		100
10	4	10		100
11	2	2		100
12	2	4		100
13	2	6		100
14	2	8		100
15	2	10		100

Table 1. Testing Sequence for Type 2 Soils.

8.1.2.5 Increase the deviator stress to 4 psi (Sequence No. 3) and repeat step 8.1.2.4 at this new stress level.

8.1.2.6 Increase the deviator stress to 6 psi (Sequence No. 3) and repeat step 8.1.2.4 at this new stress level.

8.1.2.7 Continue the test for the remaining load sequences in Table 1 (4 to 15) recording the vertical recovered deformation. If at any time the permanent strain of the sample exceeds 5 percent, stop the test and report the result on the appropriate worksheet (See Worksheet T46).

8.1.2.8 After completion of the resilient modulus test procedure, check the total vertical permanent strain that the specimen was subjected to during the resilient modulus portion of the test procedure. If the total vertical permanent strain did not exceed 5 percent, continue with the quick shear test procedure. (Section 8.1.2.9 - 8.1.2.10). If the total vertical permanent strain exceeds 5 percent, the test is completed. No additional testing is to be conducted on the specimen.

8.1.2.9 Apply a confining pressure of 4 psi. to the specimen. Apply a load so as to produce an axial strain at a rate of 1 percent per minute. Continue loading until (1) the load values decrease with increasing strain, (2) 5 percent strain is reached, or (3) the capacity of the load cell is reached. The internally mounted deformation transducer in the actuator shaft shall be used to monitor specimen deformation.

8.1.2.10 Plot the stress-strain curve for the specimen for the quick shear test procedure.

8.1.2.11 At the completion of the loading sequences, disassemble the triaxial cell.

8.1.2.12 Remove the membrane from the specimen and use the entire specimen to determine moisture content. Record this value on the appropriate form (See Worksheet T46).

8.2 Resilient Modulus Test for Type 1 Materials - The procedure described in this section applies to all unbound granular base and subbase materials and all unbound subgrade soils which meet the following criteria.
Less than 70% passing the #10 sieve and a
maximum of 20% passing the #200 sieve

8.2.1 Assembly of the Triaxial Chamber - Follow Steps 8.1.1.1 through 8.1.1.8. When compaction is completed, place the porous stone and top sample cap on the surface of the specimen. Roll the rubber membrane off the rim of the mold and over the sample cap. If the sample cap projects above the rim of the mold, the membrane should be sealed tightly against the cap with the O-ring seal. If it does not, the seal can be applied later.

8.2.1.1 through 8.2.1.8 are the same as steps 8.1.1.1 through 8.1.1.8.

8.2.1.9 Connect the chamber pressure supply line and apply a confining pressure of 15 psi.

8.2.1.10 Remove the vacuum supply from the vacuum saturation inlet and close this line.

8.2.2 Conduct the Resilient Modulus Test - After the test specimen has been prepared and placed in the loading device as described in 8.2.1, the following steps are necessary to conduct the resilient modulus testing:

8.2.2.1 If not already done, adjust the position of the axial loading device or triaxial chamber base support as necessary to couple the load-generation device piston and the triaxial chamber piston. The triaxial chamber piston should bear firmly on the load cell. This can be done by applying a seating pressure of 2 psi. A minimum contact load of 10 percent ($.1S_d$) of the maximum applied load shall be maintained during all repeated load determination.

8.2.2.2 Adjust the recording devices for the LVDT's and load cell as needed.

8.2.2.3 Set the confining pressure to 15 psi and apply 1000 repetitions of an axial deviator stress of 15 psi using a haversine shaped load pulse consisting of a 0.1 second load followed by a 0.9 second rest period. The drainage valve should be open throughout the resilient testing. This stress sequence constitutes the sample conditioning.

8.2.2.4 Testing the Sample. The testing is performed following the loading sequences in Table 2 using a haversine shaped load pulse consisting of a 0.1 second load followed by a 0.9 second rest period. Decrease the deviator stress to 3 psi and set the confining pressure to 3 psi (Sequence No. 1, Table 2). Apply 100 repetitions of deviator stress and record the average of the deformations of the last five load cycles on the appropriate testing form as shown on Worksheet T46.

8.2.2.5 Continue with Sequence No. 2 increasing the deviator stress to 6 psi and repeat 8.2.2.4 at this new stress level.

8.2.2.6 Continue the test for the remaining load sequences in Table 2 (3 to 15) recording the vertical recovered deformation. If, at any time the total vertical permanent strain deformation exceeds 5 percent, stop the test and report the results on Worksheet T46.

8.2.2.7 After completion of the resilient modulus test procedure, check the total vertical permanent strain that the specimen was subjected to during the resilient modulus portion of the test procedure. If the total vertical permanent strain did not exceed 5 percent, continue with the quick shear test procedure (Section 8.2.2.8 - 8.2.2.9). If the total vertical permanent strain exceeds 5 percent, the test is completed. No additional testing is to be conducted on the specimen.

8.2.2.8 Apply the load so as to produce an axial strain at a rate of 1 percent per minute. Continue loading until (1) the load values decrease with increasing strain, (2) 5 percent strain is reached, or (3) the capacity of the load cell is reached. The internally mounted deformation transducer in the actuator shaft shall be used to monitor specimen deformation.

8.2.2.9 Plot the stress-strain curve for the specimen for the quick shear test procedure.

8.2.2.10 At the completion of the quick shear test, reduce the confining pressure to zero and disassemble the triaxial cell.

8.2.2.11 Remove the membrane from the specimen and use the entire sample to determine the moisture content. Record this value on the form shown in Worksheet T46.

Sequence No.	Confining Pressure S_3 psi.	Dev. Stress S_d psi.	Contact Load $.1S_d$ psi.	Number of Load Applications
0 (preconditioning)	15	15		1000
1	3	3		100
2	3	6		100
3	3	9		100
4	5	5		100
5	5	10		100
6	5	15		100
7	10	10		100
8	10	20		100
9	10	30		100
10	15	10		100
11	15	15		100
12	15	30		100
13	20	15		100
14	20	20		100
15	20	40		100

Table 2. Testing Sequence for Type 1 Soils.

9. CALCULATIONS

9.1 Perform calculations using the tabular arrangement shown on Worksheet T46.

9.1.1 Calculate the mean and standard deviation of the load and recoverable deformation. The mean values are used to calculate the deviator stress and the resilient strain.

10. REPORT

The following information is to be recorded on Form T46.

10.1 The specimen identification shall include: Laboratory Identification Code, State Code, SHRP Section ID, Layer Number, Field Set Number, Sample Location Number and SHRP Sample Number.

10.2 The test identification shall include: SHRP Test Designation, SHRP Protocol Number, SHRP Laboratory Test Number, and Test Date.

10.3 Test Results

(a) Worksheet: Record the test data for each specimen on Worksheet T46 and attach with Form T46.

(b) M_r Relationships and Plots: Plot Log M_r versus Log S_d and attach the appropriate plots to Form T46. Determine the appropriate coefficients (k_1 and k_2 and k_5) using least squares regression.

- Simple relationship for Type 1 Material (Figure T46A)

  $M_r = k_1(1 + S_3)k_2(S_d)^{k5}$

  Where S_d = deviator stress and

  S_3 = confining pressure

- Simple relationship for Type 2 Material (Figure T46B)

  $M_r = k_1 (S_d)^{k2}(1 + S_3)^{k5}$

  Where S_d = deviator stress and

  S_3 = confining pressure

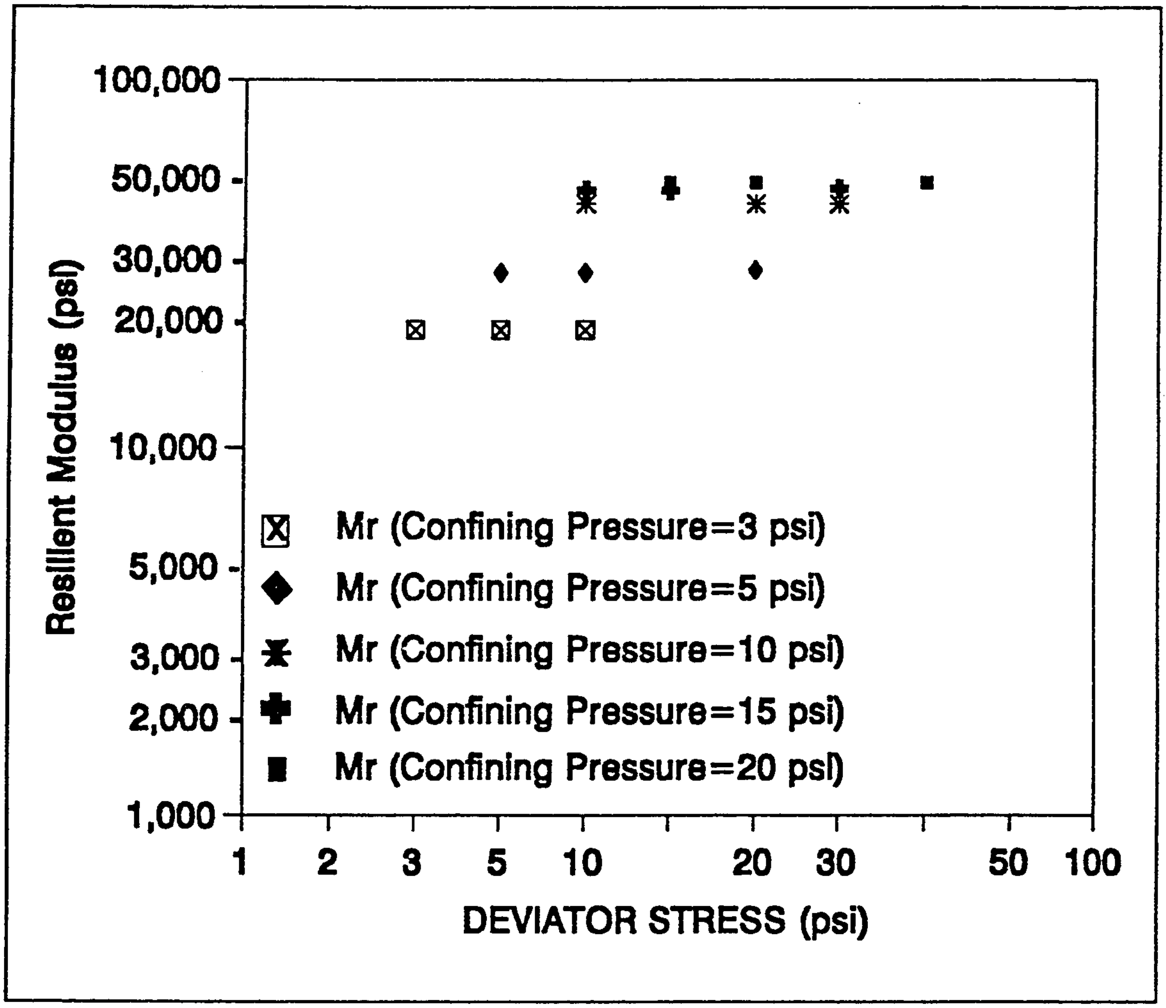

Figure T46A. Logarithmic plot of resilient modulus vs. deviator stress for type 1 materials.

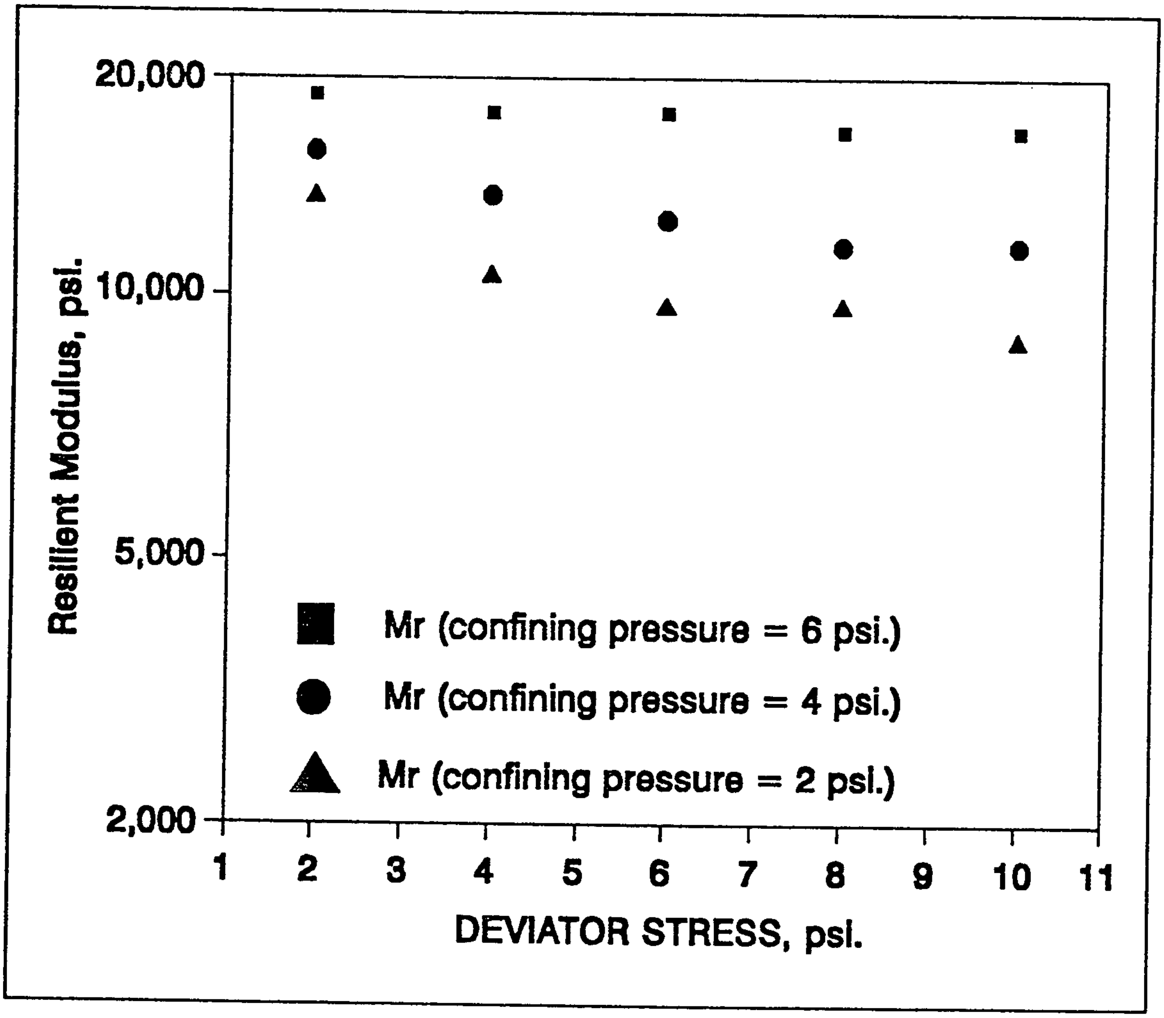

Figure T46B. Logarithmic plot of resilient modulus vs. deviator stress for type 2 materials.

(c) Specimen Data: moisture content (After the test), w, % Dry Density, Y_d, pcf

(d) Constants for M_r Relationships: Values of regression constants and related stress parameters used in the M_r relationship.

(e) M_r for Material Type 1 at a confining pressure of 15 psi and deviator stress of 15 psi.

(f) M_r for Material Type 2 at a confining pressure of 6 psi and deviator stress of 4 psi.

10.4 Comments shall include SHRP standard comment code(s), as shown on Page E.1-3 of the SHRP Laboratory Material Testing Guide and any other note as needed. Additional codes associated with resilient modulus testing are:

Code	Comment
80	Due to the insufficient size of the bulk sample, the test sample used for the last test (Protocol P46, if the sample was reconstituted) was saved and stored for possible future use by SHRP.
81	A separate test sample was used for classification and description tests (Protocol P47 or P52).
82	Due to the insufficient size of the bulk sample, the test sample for the gradation test (Protocol P41 or P51) was also used to complete the classification and description tests (Protocol P47 or P52).
83	Due to the insufficient size of the bulk sample, the test sample for the moisture-density test (Protocol P44 or P55) was saved after the test and reused for the resilient modulus testing (Protocol P46).
85	Due to the insufficient size of the bulk sample, only dry sieving was used for the gradation test (Protocol P41 or P51). The test sample after the gradation test was saved and reused to reconstitute the test sample for the resilient modulus testing (Protocol P46).

86 Due to the insufficient size of the bulk sample, only dry sieving was used for the gradation test (Protocol P41 or P51). This test sample was reused for other designated tests and the remnant of the samples was saved and stored for possible future use by SHRP.

87 The "undisturbed" thin-walled tube sample was used for the resilient modulus testing (Protocol P46).

88 The thin-walled tube sample was not suitable, therefore, a reconstituted sample from the bulk samples was used for the resilient modulus testing.

89 The thin-walled tube sample was not available. The test sample for the resilient modulus testing (Protocol P46) was reconstituted from the bulk sample.

90 An excess portion of the thin-walled tube sample was saved and stored for possible future use by SHRP.

94 The test was not performed because of the oversize aggregates; sample was stored until further instructions from SHRP.

10.5 Use Form T46, Worksheet T46 and Figure T46A or T46B to report the results of the resilient modulus test to the SHRP Regional Engineer.

NOTE 5: Item 5(d) of Form T46 contains six constants for the M_r relationship, k_1, k_2, k_3, k_4, k_5 and k_6. Constants k_3 and k_4 and k_6 are for future use and will not be required at this time. In addition, stress parameters S_4, S_5 and S_6 are for future use and will not be required at this time.

ATTACHMENT A TO SHRP PROTOCOL P46
COMPACTION OF TYPE 1 SOILS

Type 1 soils will be recompacted using a 6.0 inch split mold and vibratory compaction. Six inch diameter split molds shall be used to prepare 12 inch high test samples for all Type 1 materials with nominal particle sizes less than or equal to 1 1/4 inches. If samples contain more than 5 percent by volume of plus 1 1/4 inch material, the plus 1 1/4 inch material shall be removed prior to sample preparation and this condition shall be noted in the data reporting for this test.

Cohesionless soils are compacted readily by use of a split mold mounted on the base of the triaxial cell as shown in Figure 2. Compaction forces are generated by a small hand-held air hammer.

1. SCOPE

   This method covers the compaction of Type 1 soils for use in resilient modulus testing.

2. APPARATUS

   2.1 Six inch diameter split mold.

   2.2 Vibratory compaction device.

3. PROCEDURE

   3.1 Tighten the bottom platen into place on the triaxial cell base. It is essential that an airtight seal is obtained.

   3.2 Place the two porous stones and the top platen on the bottom platen. Determine the total height of the top and bottom platens and stones to the nearest 0.01 inch.

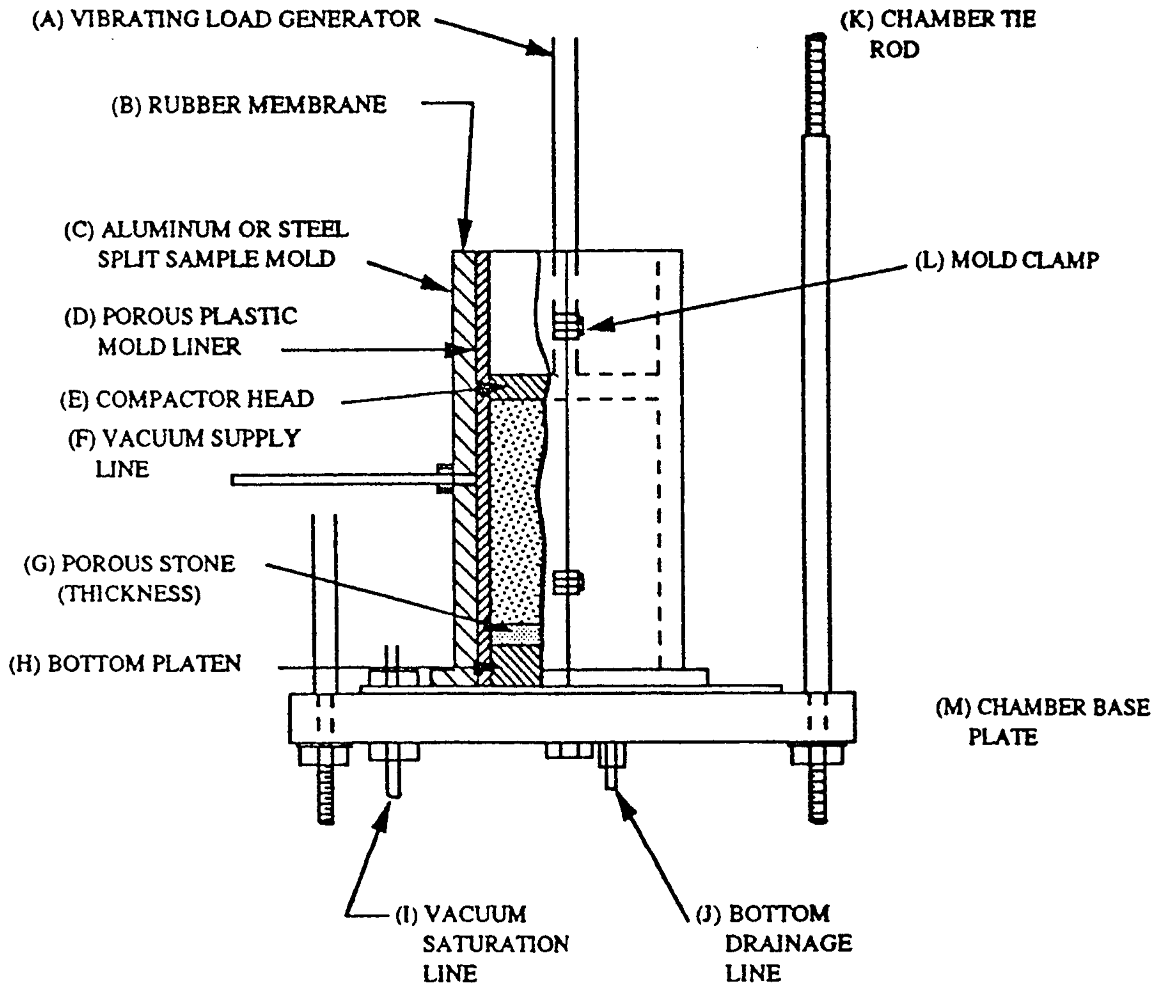

TABLE OF MEASUREMENTS (TYPICAL)

DIMENSION	A	B	D	C	E	F	G	H	I	J	K	L	M
METRIC, mm	Note 1	Note 2	Note 2	Note 2	Note 3	6.4	6.4	38.1	6.4	6.4	12.7	Note 1	25.4
ENGLISH, in.						0.25	0.25	1.50	0.25	0.25	0.50		1.00

NOTE:

1. Dimension varies with manufacturer
2. Dimension varies with specimen size
3. Diameter should be 0.25 ± 0.02 inch (6.35 ± 0.5 mm) smaller then specimen diameter

Figure 2. Apparatus for vibratory compaction of Type 1 unbound materials.

3.3 Remove the top platen and upper porous stone if used. Measure the thickness of the rubber membrane with a micrometer.

3.4 Place the rubber membrane over the bottom platen and lower porous stone. Secure the membrane to the bottom platen using an O-ring or other means to obtain an airtight seal.

3.5 Place the split mold around the bottom platen and draw the membrane up through the mold. Tighten the split mold firmly in place. Exercise care to avoid pinching the membrane.

3.6 Stretch the membrane tightly over the rim of the mold. Apply a vacuum to the mold to draw the membrane in contact. If wrinkles are present in the membrane, release the vacuum, adjust the membrane and reapply the vacuum. The use of a porous plastic forming jacket line helps to ensure that the membrane fits smoothly inside the mold. The vacuum is maintained throughout the compaction procedure.

3.7 Measure, to the nearest 0.01 inch, the inside diameter of the membrane lined mold and the distance between the top of the lower porous stone and the top of the mold.

3.8 Determine the volume, V, of the specimen to be prepared using the diameter determined in step 3.7 and a value of height between 5.6 inches and the height measured in step 3.7.

3.9 Determine the weight of material, at the desired water content, to be compacted into the volume, V, to obtain the desired density.

3.10 For six inch diameter specimens (specimen height of 12 inches) 5 layers of two inches per layer are required for the compaction process. Determine the weight of wet soil, W_L required for each layer.

$W_L = W_t/N$

where:

W_t = total weight of test specimen to produce appropriate density,

N = number of layers to be compacted.

3.11 Place the total required mass of soil, W_{ad} into a mixing pan. Add the required amount of water, W_{aw} and mix thoroughly.

3.12 Determine the weight of wet soil and the mixing pan.

3.13 Place the amount of wet soil, W_L, into the mold. Avoid spillage. Using a spatula, draw soil away from the inside edge of the mold to form a small mound at the center.

3.14 Insert the vibrator head and vibrate the soil until the distance from the surface of the compacted layer to the rim of the mold is equal to the distance measured in step 3.7 minus the thickness of the layer selected in step 3.10. This may require removal and reinsertion of the vibrator several times until experience is gained in gaging the vibration time which is required.

3.15 Repeat steps 3.13 and 3.14 for each new layer. The measured distance from the surface of the compacted layer to the rim of the mold is successively reduced by the layer thickness selected in step 3.10. The fine surface shall be a smooth horizontal plane.

3.16 When the compaction process is completed, weigh the mixing pan and the excess soil. This weight subtracted from the weight determined in step 3.12 is the weight of the wet soil used (weight of specimen). Verify the compaction water, W_c of the excess soil. The moisture content of this sample shall be using SHRP Protocol P49.

Proceed with section 8.2 of this protocol.

ATTACHMENT B TO SHRP PROTOCOL P46
COMPACTION OF TYPE 2 SOILS

The general method of compaction of Type 2 soils will be that of static loading (also known as the double plunger method). If testable thin-walled tubes are available, specimens shall not be recompacted.

Specimens shall be recompacted in a 2.8 inch diameter mold. The process is one of compacting a known weight of soil to a volume that is fixed by the dimensions of the mold assembly (mold shall be of a sufficient size to produce specimens 2.8 inches in diameter and 5.6 inches in height). A typical mold assembly is shown in Figure 3. Several steps are required for static compaction as follows in the Procedures section of this attachment.

1. SCOPE

This method covers the compaction of Type 2 soils for use in resilient modulus testing.

2. APPARATUS

As shown in Figure 3.

3. PROCEDURE

3.1 Five layers of equal mass shall be used to compact the specimens using this procedure. Determine the mass of wet soil, W_L to be used per layer where $W_L = W_t/5$.

3.2 Place one of the loading rams into the specimen mold.

3.3 Place the mass of soil, W_L determined in Step 3.1 into the specimen mold. Using a spatula, draw the soil away from the edge of the mold to form a slight mound in the center.

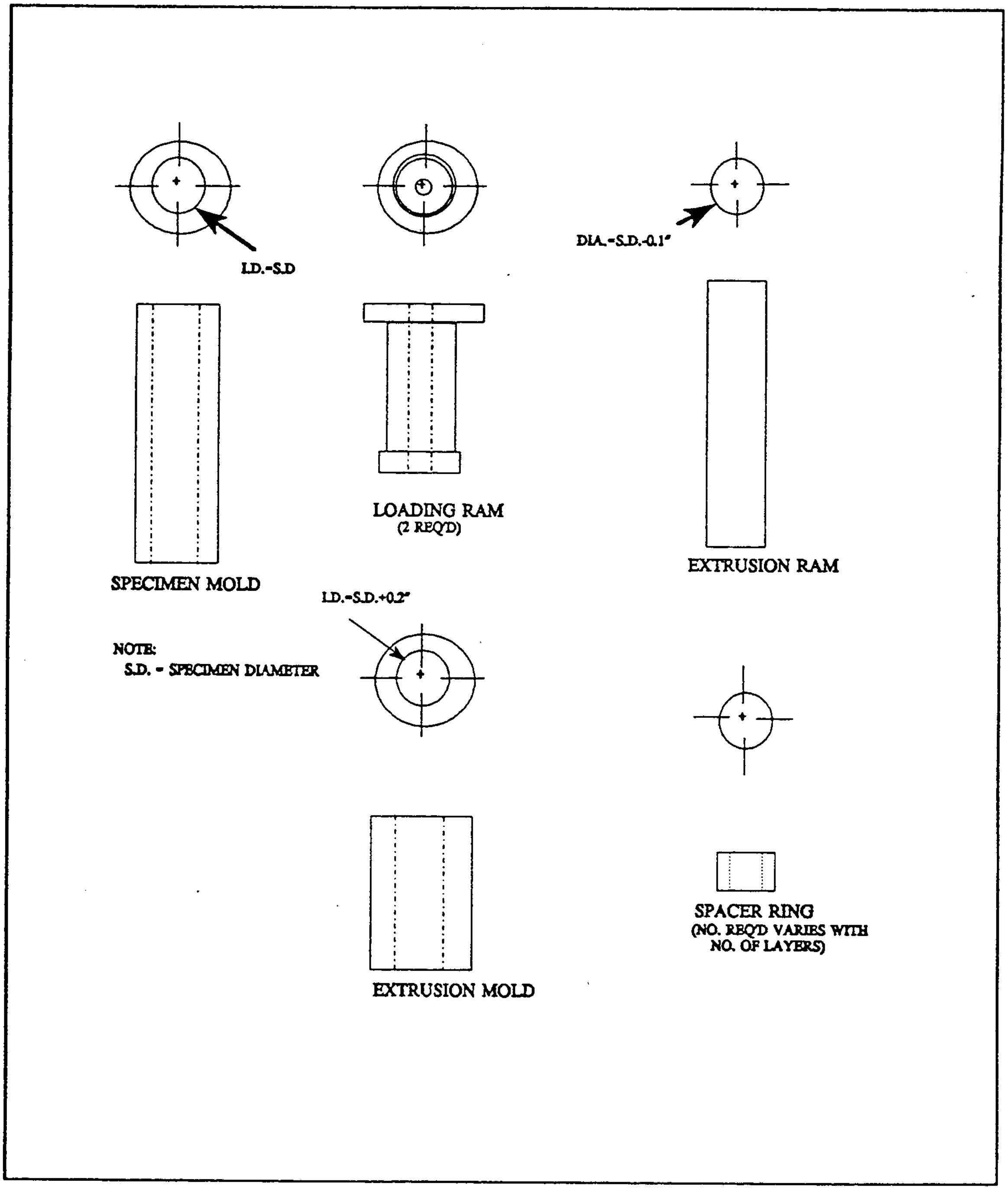

Figure 3. Apparatus for static compaction of Type 2 unbound materials.

3.4 Insert the second ram and place the assembly in the static loading machine. Apply a small load. Adjust the position of the mold with respect to the soil mass, so that the distances from the mold ends to the respective load ram caps are equal. Soil pressure developed by the initial loading will serve to hold the mold in place. By having both loading rams reach the zero volume change simultaneously, more uniform layer densities are obtained.

3.5 Slowly increase the load until the loading caps rest firmly against the mold. Maintain this load for a period of not less than one minute. The amount of soil rebound depends on the rate of loading and load duration. The slower the rate of loading and the longer the load is maintained, the less the rebound.
NOTE 6: To obtain uniform densities, extreme care must be taken to center the first soil layer exactly between the ends of the specimen mold. Checks and any necessary adjustments should be made after completion of steps 4 and 5.

3.6 Decrease the load to zero and remove the assembly from the loading machine.

3.7 Remove the loading ram. Scarify the surfaces of the compacted layer and put the weight of wet soil W_L for the second layer in place and form a mound. Add a spacer ring and insert the loading ram.

3.8 Invert the assembly and repeat step 3.7.

3.9 Place the assembly in the machine. Increase the load slowly until the spacer rings firmly contact the ends of the specimen mold. Maintain this load for a period of not less than one minute.

3.10 Repeat steps 3.7, 3.8 and 3.9 to compact the remaining two layers.

3.11 After completion is completed, determine the moisture content of the remaining soil using SHRP Protocol P49. Record this value on SHRP Worksheet T46.

3.12 Using the extrusion ram, press the compacted soil out of the specimen mold and into the extrusion mold. Extrusion should be done slowly to avoid impact loading the specimen.

3.13 Using the extrusion mold, carefully slide the specimen off the ram, onto a solid end platen. The platen should be circular with a diameter equal to that of the specimen and have a minimum thickness of 0.5 in. (13 mm.). Platens shall be of a material which will not absorb soil moisture.

3.14 Determine the weight of the compacted specimen to the nearest gram. Measure the height and diameter to the nearest 0.01 inch. Record these values on Worksheet T46.

3.15 Place a platen similar to the one used in step 3.13 on top of the specimen.

3.16 Using a vacuum membrane expander, place the membrane over the specimen. Carefully pull the ends of the membrane over the end platens. Secure the membrane to each platen using O-rings or other means to provide an airtight seal.

Proceed with Section 8.1 of this protocol.

LABORATORY MATERIAL HANDLING AND TESTING
LABORATORY MATERIAL TEST DATA
RESILIENT MODULUS OF UNBOUND GRANULAR BASE/SUBBASE
WORKSHEET T46 - PAGE 1

SHEET NO __ OF __

UNBOUND GRANULAR BASE, SUBBASE AND SUBGRADE SOILS
SHRP TEST DESIGNATION UG07, SS07/SHRP PROTOCOL P46

LABORATORY PERFORMING TEST: ____________________
LABORATORY IDENTIFICATION CODE: ___ ___ ___ ___

STATE CODE: ___ ___
SHRP SECTION ID.: ___ ___ ___ ___ ___ ___
FIELD SET NO.: ___

1. LAYER NUMBER (FROM LAB SHEET L04) ___

2. SHRP LABORATORY TEST NUMBER ___

3. LOCATION NUMBER (enter an asterisk as the third digit if the specimen is recompacted from a combined bulk sample) ___ ___ ___

4. SHRP SAMPLE NUMBER (enter an asterisk as the third and fourth digit if the specimen is recompacted from a combined bulk sample) ___ ___ ___ ___

5. MATERIAL TYPE (TYPE 1 OR TYPE 2) ___

6. SPECIMEN INFORMATION:
   SPECIFIC GRAVITY ___ . ___ ___ ___
   SPECIMEN DIAMETER; inches
   TOP ___ . ___ ___
   MIDDLE ___ . ___ ___
   BOTTOM ___ . ___ ___
   AVERAGE ___ . ___ ___
   MEMBRANE THICKNESS, inches ___ . ___ ___
   NET DIAMETER, inches ___ . ___ ___
   HEIGHT OF SPEC. + CAP + BASE, inches ___ . ___ ___
   HEIGHT OF CAP + BASE, inches ___ ___ . ___ ___
   INITIAL LENGTH, L_o, inches ___ ___ . ___ ___
   INSIDE DIAMETER OF MOLD, inches ___ ___ . ___ ___
   ___ . ___ ___

7. SOIL SPECIMEN WEIGHT:
   INITIAL WEIGHT OF CONTAINER AND WET SOIL, grams * ___ ___ ___ ___ ___ . ___ ___
   FINAL WEIGHT OF CONTAINER AND WET SOIL, grams * ___ ___ ___ ___ ___ . ___ ___
   WEIGHT OF WET SOIL USED, grams * ___ ___ ___ ___ ___ . ___ ___

8. SOIL SPECIMEN VOLUME:
   INITIAL AREA, A_o, in.^{2} ___ ___ . ___ ___
   INITIAL VOLUME, $A_o * L_o$, in.^{3} ___ ___ ___ . ___ ___

9. SOIL PROPERTIES:
   WET DENSITY, pcf. ___ ___ ___ . ___
   COMPACTION MOISTURE CONTENT ___ ___ . ___
   SATURATION, S, % ___ ___ . ___
   DRY DENSITY, Y_d, pcf. ___ ___ ___ . ___
   MOISTURE CONTENT AFTER M_r TESTING, % ___ ___ ___ . ___

10. COMMENTS (20 characters or less)
____
____
____

Notes: * If a thin-walled tube is used for resilient modulus testing, these items do not need to be reported.
** If a thin-walled tube is used for resilient modulus testing, record the moisture content of the pavement layer being tested.

Worksheet T46 - Page 1, March 1992

LABORATORY MATERIAL HANDLING AND TESTING
LABORATORY MATERIAL TEST DATA
RESILIENT MODULUS OF UNBOUND GRANULAR BASE/SUBBASE
MATERIALS AND SUBGRADE SOILS
LAB DATA SHEET T46

SHEET NO __ OF __

UNBOUND GRANULAR BASE, SUBBASE AND SUBGRADE SOILS
SHRP TEST DESIGNATION UG07, SS07/SHRP PROTOCOL P46

LABORATORY PERFORMING TEST: ______________________
LABORATORY IDENTIFICATION CODE: ___ ___ ___ ___

SAMPLES FROM: SHRP REGION ______ STATE _____ STATE CODE: ___ ___
LTPP EXPT. NO.: ____________ SHRP SECTION ID.: ___ ___ ___ ___ ___ ___
SAMPLED BY: ______________________ FIELD SET NO.: ___
DRILLING AND SAMPLING CONTRACTOR/AGENCY

SAMPLING DATE: ___ ___ ___ ___-19___ ___

1. LAYER NUMBER (FROM LAB SHEET L04)
   LAYER MATERIAL (CIRCLE ONE): BASE/SUBBASE/SUBGRADE
2. SHRP LABORATORY TEST NUMBER . . . . ___
3. LOCATION NUMBER (Enter an asterisk as the third digit) . . . . ___ ___ ___
4. SHRP SAMPLE NUMBER (Enter an asterisk as third and fourth digit) . . . . ___ ___ ___ ___
5. MATERIAL TYPE — TYPE ___
6. TEST RESULTS (Section 10.3 of Protocol P46)
   (a) PLOTS (FIGURE T46A or T46B).: (Record the attached Figure No.) — T46 ___
   (b) CONSTANTS FOR Mr RELATIONSHIP

k^2 = _ . _ _ _ _ _ _

k_1 _ _ _ _ _ _ _ _ . k_2 _ . _ _ _ _ _ _
k_3 _ _ _ _ _ _ _ _ . k_4 _ . _ _ _ _ _ _
k_5 _ _ _ _ _ _ _ _ . k_6 _ . _ _ _ _ _ _

STRESS PARAMETERS (Specify one or more from Sd, S4, S5, S6)

_ _ _ . _ _ _ . _ _ _ . _ _
S_d S_4 S_5 S_6

   (c) Mr FOR MATERIAL TYPE 1;
   AT CONFINING (CHAMBER) PRESSURE = 15 psi, DEVIATOR STRESS = 15 psi _ _ _ _ _ _ .
   (d) Mr FOR MATERIAL TYPE 2;
   AT CONFINING (CHAMBER) PRESSURE = 6 psi, DEVIATOR STRESS = 4 psi _ _ _ _ _ _ .

7. STRESS-STRAIN PLOT ATTACHED (YES OR NO) ___ ___ ___

8. COMMENTS (Section 10.4 of Protocol P46)
   (a) CODE — _ _ _ _ _ _
   (b) NOTE — _ _ _ _ _ _

9. TEST DATE — _ _ . _ _ . _ _

NOTE: * RESULTS OF CLASSIFICATION AND DESCRIPTION (FORM T47 FOR UNBOUND BASE/SUBBASE OR FORM T52 FOR SUBGRADE) SHALL BE USED TO CATEGORIZE MATERIAL TYPE 1 OR 2.

GENERAL REMARKS: ______________________

SUBMITTED BY, DATE

____
LABORATORY CHIEF
Affiliation ________

CHECKED AND APPROVED, DATE

____
Affiliation ________

Form T46, March 1992

SHRP SECTION NUMBER ________
SHRP SAMPLE NUMBER ________
SHRP LABORATORY TEST NUMBER __
LAYER NUMBER ____________
MATERIAL TYPE ____________
10. RESILIENT MODULUS TESTING.

A Chamber Confining Pressure, S_3 (psi)	B Nominal Deviator Stress, S_d (psi)	C Mean Deviator Load (lb)*	D Standard Deviation of Load (lb)*	E Mean Applied Dev. Stress (psi)*	F Mean Applied Contact Stress (psi)*	G Mean Recov. Del. LVDT #1 Reading (in.)*	H Mean Recov. Del. LVDT #2 Reading (in.)*	I Mean Recoverable Deformation (in.)*	J Std. Dev. of Recoverable Deformation (in.)*	K Mean of Resilient Strain (in/in.)*	L Mean of M_r (psi.)*	M Standard Dev. of M_r (psi.)*

* obtained from the last five load cycles

SUBMITTED BY, DATE

____

LABORATORY CHIEF
Affiliation ________

CHECKED AND APPROVED, DATE

____

Affiliation ____________

APPENDIX B

DATA FOR TYPE I SYNTHETIC SPECIMEN EXPERIMENT

OBS	MATERIAL	LAB	CONF	DEVSTR	MR
1	LPOLY	A	00	03	17300
2	LPOLY	A	00	03	20600
3	LPOLY	A	00	20	27000
4	LPOLY	A	00	20	27400
5	LPOLY	A	00	37	30700
6	LPOLY	A	00	37	30700
7	LPOLY	A	10	03	18000
8	LPOLY	A	10	03	18400
9	LPOLY	A	10	20	27400
10	LPOLY	A	10	20	27400
11	LPOLY	A	10	37	30700
12	LPOLY	A	10	37	30700
13	LPOLY	B	00	03	13500
14	LPOLY	B	00	03	12742
15	LPOLY	B	00	20	30894
16	LPOLY	B	00	20	29697
17	LPOLY	B	00	37	36337
18	LPOLY	B	00	37	34736
19	LPOLY	B	10	03	14882
20	LPOLY	B	10	03	15867
21	LPOLY	B	10	20	31336
22	LPOLY	B	10	20	33291
23	LPOLY	B	10	37	35315
24	LPOLY	B	10	37	38812
25	LPOLY	C	00	03	19007
26	LPOLY	C	00	03	20442
27	LPOLY	C	00	20	29661
28	LPOLY	C	00	20	29720
29	LPOLY	C	00	37	34394
30	LPOLY	C	00	37	34657
31	LPOLY	C	10	03	19857
33	LPOLY	C	10	20	29706
34	LPOLY	C	10	20	30003
35	LPOLY	C	10	37	39466
36	LPOLY	C	10	37	36478
37	LPOLY	D	00	03	24747
38	LPOLY	D	00	03	25223
39	LPOLY	D	00	20	34167
40	LPOLY	D	00	20	32848
41	LPOLY	D	00	37	37399
42	LPOLY	D	00	37	36982
49	LPOLY	E	00	03	23516

OBS	MATERIAL	LAB	CONF	DEVSTR	MR
51	LPOLY	E	00	20	34751
53	LPOLY	E	00	37	40792
55	LPOLY	E	10	03	25531
57	LPOLY	E	10	20	35207
59	LPOLY	E	10	37	39844
61	LPOLY	F	00	03	28826
62	LPOLY	F	00	03	28768
63	LPOLY	F	00	20	28955
64	LPOLY	F	00	20	29086
65	LPOLY	F	00	37	33819
66	LPOLY	F	00	37	34383
67	LPOLY	F	10	03	20125
68	LPOLY	F	10	03	22909
69	LPOLY	F	10	20	26300
70	LPOLY	F	10	20	26553
71	LPOLY	F	10	37	31623
72	LPOLY	F	10	37	32397
73	LPOLY	G	00	03	32073
74	LPOLY	G	00	03	28835
75	LPOLY	G	00	20	45715
76	LPOLY	G	00	20	47809
77	LPOLY	G	00	37	55720
78	LPOLY	G	00	37	61435
79	LPOLY	G	10	03	26802
80	LPOLY	G	10	03	36723
81	LPOLY	G	10	20	47308
82	LPOLY	G	10	20	47555
83	LPOLY	G	10	37	56517
84	LPOLY	G	10	37	58105
85	LPOLY	H	00	03	17067
86	LPOLY	H	00	03	17693
87	LPOLY	H	00	20	27109
88	LPOLY	H	00	20	30978
89	LPOLY	H	00	37	37672
90	LPOLY	H	00	37	37846
91	LPOLY	H	10	03	16996
92	LPOLY	H	10	03	17613
93	LPOLY	H	10	20	31716
94	LPOLY	H	10	20	33391
95	LPOLY	H	10	37	38025
96	LPOLY	H	10	37	38299
97	LPOLY	I	00	03	21818
98	LPOLY	I	00	03	20282
99	LPOLY	I	00	20	30476

OBS	MATERIAL	LAB	CONF	DEVSTR	MR
100	LPOLY	I	00	20	29091
101	LPOLY	I	00	37	35520
102	LPOLY	I	00	37	36245
103	LPOLY	I	10	03	20282
104	LPOLY	I	10	03	20282
105	LPOLY	I	10	20	29538
106	LPOLY	I	10	20	29538
107	LPOLY	I	10	37	35520
108	LPOLY	I	10	37	36245
109	LPOLY	J	00	03	28640
110	LPOLY	J	00	03	25690
111	LPOLY	J	00	20	29060
112	LPOLY	J	00	20	29220
113	LPOLY	J	00	37	32710
114	LPOLY	J	00	37	33070
115	LPOLY	J	10	03	26930
116	LPOLY	J	10	03	27800
117	LPOLY	J	10	20	28210
118	LPOLY	J	10	20	27020
119	LPOLY	J	10	37	29940
120	LPOLY	J	10	37	29440

OBS	MATERIAL	LAB	CONF	DEVSTR	MR
1	NYLON	A	00	03	62500
2	NYLON	A	00	03	67600
3	NYLON	A	00	20	80000
4	NYLON	A	00	20	80000
5	NYLON	A	00	37	91000
6	NYLON	A	00	37	91000
7	NYLON	A	10	03	56500
8	NYLON	A	10	03	60500
9	NYLON	A	10	20	80000
10	NYLON	A	10	20	80000
11	NYLON	A	10	37	91000
13	NYLON	B	00	03	67237
14	NYLON	B	00	03	61441
15	NYLON	B	00	20	106341
16	NYLON	B	00	20	101538
17	NYLON	B	00	37	103780
18	NYLON	B	00	37	100659
19	NYLON	B	10	03	67775
20	NYLON	B	10	03	57944
21	NYLON	B	10	20	91947
22	NYLON	B	10	20	103409
23	NYLON	B	10	37	121130
24	NYLON	B	10	37	109106
25	NYLON	C	00	03	52910
26	NYLON	C	00	03	53366
27	NYLON	C	00	20	78403
28	NYLON	C	00	20	77037
29	NYLON	C	00	37	102543
30	NYLON	C	00	37	102230
31	NYLON	C	10	03	44848
32	NYLON	C	10	03	45075
33	NYLON	C	10	20	69450
34	NYLON	C	10	20	68721
35	NYLON	C	10	37	92477
36	NYLON	C	10	37	90552
37	NYLON	D	00	03	37672
38	NYLON	D	00	03	36320
39	NYLON	D	00	20	85755
40	NYLON	D	00	20	84492
41	NYLON	D	00	37	95634
42	NYLON	D	00	37	95338
49	NYLON	E	00	03	42965

OBS	MATERIAL	LAB	CONF	DEVSTR	MR
51	NYLON	E	00	20	78249
53	NYLON	E	00	37	102675
55	NYLON	E	10	03	46103
57	NYLON	E	10	20	82359
59	NYLON	E	10	37	109725
61	NYLON	F	00	03	56517
62	NYLON	F	00	03	57990
63	NYLON	F	00	20	84352
64	NYLON	F	00	20	84428
65	NYLON	F	00	37	98113
66	NYLON	F	00	37	98924
67	NYLON	F	10	03	36858
68	NYLON	F	10	03	41357
69	NYLON	F	10	20	72022
70	NYLON	F	10	20	74120
71	NYLON	F	10	37	89370
72	NYLON	F	10	37	89116
73	NYLON	G	00	03	85391
74	NYLON	G	00	03	115280
75	NYLON	G	00	20	101602
76	NYLON	G	00	20	103893
77	NYLON	G	00	37	134507
78	NYLON	G	00	37	135637
79	NYLON	G	10	03	92225
80	NYLON	G	10	03	83955
81	NYLON	G	10	20	104799
82	NYLON	G	10	20	102089
83	NYLON	G	10	37	135270
84	NYLON	G	10	37	137937
85	NYLON	H	00	03	63210
86	NYLON	H	00	03	64470
87	NYLON	H	00	20	98712
88	NYLON	H	00	20	100661
89	NYLON	H	00	37	119087
90	NYLON	H	00	37	119348
91	NYLON	H	10	03	60612
92	NYLON	H	10	03	64290
93	NYLON	H	10	20	99836
94	NYLON	H	10	20	102516
95	NYLON	H	10	37	118787
96	NYLON	H	10	37	120334
97	NYLON	I	00	03	55385
98	NYLON	I	00	03	55385
99	NYLON	I	00	20	83478

OBS	MATERIAL	LAB	CONF	DEVSTR	MR	
100	NYLON	I	00	20	73846	
101	NYLON	I	00	37	88800	
102	NYLON	I	00	37	84571	
103	NYLON	I	10	03	46452	
104	NYLON	I	10	03	46452	
105	NYLON	I	10	20	71111	
106	NYLON	I	10	20	71111	
107	NYLON	I	10	37	80727	
108	NYLON	I	10	37	84571	
109	NYLON	J	00	03	53060	
110	NYLON	J	00	03	56000	
111	NYLON	J	00	20	78750	
112	NYLON	J	00	20	78850	
113	NYLON	J	00	37	112310	
114	NYLON	J	00	37	110500	
115	NYLON	J	10	03	56500	
116	NYLON	J	10	03	48780	
117	NYLON	J	10	20	82900	
118	NYLON	J	10	20	78290	
119	NYLON	J	10	37	14900	outlier?
120	NYLON	J	10	37	30120	outlier?

OBS	MATERIAL	LAB	CONF	DEVSTR	MR
1	TEFLON	A	00	03	18800
2	TEFLON	A	00	03	19200
3	TEFLON	A	00	20	27900
4	TEFLON	A	00	20	27900
5	TEFLON	A	00	37	36200
6	TEFLON	A	00	37	33000
7	TEFLON	A	10	03	19200
8	TEFLON	A	10	03	19700
9	TEFLON	A	10	20	26100
10	TEFLON	A	10	20	27900
11	TEFLON	A	10	37	33000
12	TEFLON	A	10	37	31600
13	TEFLON	B	00	03	19985
14	TEFLON	B	00	03	23837
15	TEFLON	B	00	20	43892
16	TEFLON	B	00	20	45252
17	TEFLON	B	00	37	52885
18	TEFLON	B	00	37	51216
19	TEFLON	B	10	03	19187
20	TEFLON	B	10	03	24809
21	TEFLON	B	10	20	42798
22	TEFLON	B	10	20	44960
23	TEFLON	B	10	37	54844
24	TEFLON	B	10	37	52777
25	TEFLON	C	00	03	60536
26	TEFLON	C	00	03	60636
27	TEFLON	C	00	20	82685
28	TEFLON	C	00	20	82376
29	TEFLON	C	00	37	95661
30	TEFLON	C	00	37	93934
31	TEFLON	C	10	03	61166
32	TEFLON	C	10	03	62108
33	TEFLON	C	10	20	88107
34	TEFLON	C	10	20	87763
35	TEFLON	C	10	37	99509
36	TEFLON	C	10	37	99337
37	TEFLON	D	00	03	25597
38	TEFLON	D	00	03	26231
39	TEFLON	D	00	20	41485
40	TEFLON	D	00	20	42934

OBS	MATERIAL	LAB	CONF	DEVSTR	MR
41	TEFLON	D	00	37	51996
42	TEFLON	D	00	37	50681
43	TEFLON	E	00	03	26744
44	TEFLON	E	00	20	44112
45	TEFLON	E	00	37	57422
46	TEFLON	E	10	03	27705
47	TEFLON	E	10	20	46739
48	TEFLON	E	10	37	59972
49	TEFLON	F	00	03	22488
50	TEFLON	F	00	03	21671
51	TEFLON	F	00	20	38470
52	TEFLON	F	00	20	38009
53	TEFLON	F	00	37	51521
54	TEFLON	F	00	37	50936
55	TEFLON	F	10	03	25109
56	TEFLON	F	10	03	25777
57	TEFLON	F	10	20	31365
58	TEFLON	F	10	20	33880
59	TEFLON	F	10	37	43932
60	TEFLON	F	10	37	46233
61	TEFLON	G	00	03	18082
62	TEFLON	G	00	03	22339
63	TEFLON	G	00	20	52119
64	TEFLON	G	00	20	59400
65	TEFLON	G	00	37	93167
66	TEFLON	G	00	37	94417
67	TEFLON	G	10	03	15675
68	TEFLON	G	10	03	14909
69	TEFLON	G	10	20	50144
70	TEFLON	G	10	20	52575
71	TEFLON	G	10	37	91228
72	TEFLON	G	10	37	91764
73	TEFLON	H	00	03	17193
74	TEFLON	H	00	03	20648
75	TEFLON	H	00	20	37623
76	TEFLON	H	00	20	38073
77	TEFLON	H	00	37	46798
78	TEFLON	H	00	37	47017
79	TEFLON	H	10	03	22306
80	TEFLON	H	10	03	22733

OBS	MATERIAL	LAB	CONF	DEVSTR	MR
81	TEFLON	H	10	20	38868
82	TEFLON	H	10	20	40259
83	TEFLON	H	10	37	47274
84	TEFLON	H	10	37	47998
85	TEFLON	I	00	03	34977
86	TEFLON	I	00	03	31174
87	TEFLON	I	00	20	46634
88	TEFLON	I	00	20	43455
89	TEFLON	I	00	37	53594
90	TEFLON	I	00	37	53594
91	TEFLON	I	10	03	25607
92	TEFLON	I	10	03	23508
93	TEFLON	I	10	20	40681
94	TEFLON	I	10	20	40681
95	TEFLON	I	10	37	52018
96	TEFLON	I	10	37	52018
97	TEFLON	J	00	03	40290
98	TEFLON	J	00	03	36440
99	TEFLON	J	00	20	45620
100	TEFLON	J	00	20	48890
101	TEFLON	J	00	37	55640
102	TEFLON	J	00	37	62930
103	TEFLON	J	10	03	38800
104	TEFLON	J	10	03	40550
105	TEFLON	J	10	20	35440
106	TEFLON	J	10	20	48460
107	TEFLON	J	10	37	37810
108	TEFLON	J	10	37	51450

APPENDIX C

RESILIENT MODULUS TESTING OF

SHRP LTPP TYPE I SYNTHETIC SPECIMENS

JUNE 1993
REVISED SEPTEMBER 1993

Vulcan Materials Company
Construction Materials Group
Research and Development Laboratory
Birmingham, Alabama

INTRODUCTION

The SHRP LTPP TYPE I 6" diameter x 12" height synthetic specimens were tested by the VMC Research and Development Laboratory at three different times throughout the duration of the SHRP Round Robin study. During each individual test session, the specimens underwent repeated testing with one or more separate mountings and repetitions. A test mount constituted complete removal of the specimen and disassembly of the triaxial cell, then reassembly for the next test specimen or sequence. A repetition constituted the number of times testing was conducted on a synthetic specimen (or a test sequence on a specimen) during each mount.

All data were collected at 0 and 10 psi confining pressure for target deviator stresses of 3, 20, and 37 psi and seat loads of 0.5 or 1.0 psi. A fourth test session, on TEFLON-5 only, was undertaken in order to further define the effect of the seat loads actually encountered due to the testing equipment used in the first and second sessions (large triaxial cell with 12" diameter platen) versus the third test session (small triaxial cell with 6" diameter platen). The test sessions, mounts and repetitions performed by the R&D laboratory are shown on the following page.

Due to the differences between testing organizations in the interpretation of the SHRP TYPE I synthetic specimen test protocol, involving the calculation of the deviator stress used to determine resilient modulus, the data for each SHRP synthetic specimen is presented in three different formats. The testing protocol as used by the VMC R&D Lab is described and sample calculations for each of the three methods are detailed. A comparison of each deviator and confining stress state using the sample calculation data is shown in Table 1.

SHRP LTPP TYPE I SYNTHETIC SPECIMEN TESTING

Vulcan Materials Company
Construction Materials Group
Research & Development Laboratory
Birmingham, Alabama

Test Session	Session Date	Test Specimens	Mounts/Repetitions
First	September 1990	LDPE-1, NYLON-1 TEFLON-1, TEFLON-2, TEFLON-3, TEFLON-4, TEFLON-5	2 mounts with 2 repetitions each
Second	March 1991	LDPE-1 NYLON-1 TEFLON-1, TEFLON-4	2 mounts with 1 repetition each
Third	December 1992	LDPE-1 NYLON-1 TEFLON-1	3 to 5 mounts with 1 repetition each
Fourth	May 1993 June 1993	TEFLON-5	1 mount with 1 repetition each

DEFINITIONS

H_s = Specimen height (in)
H_r = Specimen recoverable deformation (in)
D_s = Specimen diameter (in)
D_r = Rod diameter (in)
A_s = Cross-sectional area of specimen (in^2)
A_r = Cross-sectional area of rod (in^2)

$L = L_{dyn} + L_s + L_p$ = Axial load (lb)

L_{dyn} = Dynamic load (lb)
L_s = Applied static seat load (lb)
L_p = Static load due to mass of platen, rod, and/or ball bearing (lb)

$\sigma_d = \sigma_1 - \sigma_3$ = Deviator stress (psi)

$\sigma_1 = \sigma_{dyn} + \sigma_s + \sigma_p + \sigma_u + \sigma_3$ = Total axial stress (psi)

$\sigma_{dyn} = L_{dyn}/A_s$ = Axial stress from dynamic portion of deviator stress (psi)
$\sigma_s = L_s/A_s$ = Axial stress from static seat load (psi)
$\sigma_p = L_p/A_s$ = Axial stress from static load of platen, rod, and/or ball bearing (psi)
$\sigma_u = A_r\sigma_3/A_s$ = Upward axial stress on load rod due to confining pressure (psi)

σ_3 = Confining stress (psi)

$\varepsilon_r = H_r/H_s$ = Recoverable strain (in/in)

$M_r = \sigma_d/\varepsilon_r$ = Resilient modulus (psi)

DEVIATOR STRESS INTERPRETATION

Method 1: $\sigma_{d1} = \sigma_{dyn}$

Method 2: $\sigma_{d2} = \sigma_{dyn} + \sigma_s$

Method 3: $\sigma_{d3} = \sigma_{dyn} + \sigma_s + \sigma_p$

LARGE TRIAXIAL CELL CONFIGURATION
(12 Inch Diameter Platen)

Figure 1 is a diagram of the VMC R&D Lab large triaxial cell equipment which was available for use in the initial SHRP 6" dia. x 12" synthetic specimen study at the onset of the round robin program. The first and second testing sessions were accomplished using the large triaxial cell which normally accommodates a sample 12" diameter x 24" height. The load cell was internal to the triaxial cell and located between the load piston and the load rod. The rod contacted the ball bearing and transferred the load to the platen. The mass of the 12" diameter platen and the ball bearing rested on the 6" diameter specimen, exerting a static load (L_p = 79.5 lb) and an axial stress (σ_p = 2.8 psi) on the specimen. In addition, any upward force exerted on the load piston and rod upon introduction of the 10 psi confining pressure was counteracted through the zeroing of the load cell (σ_u = 0 psi). After the seat load (L_s = 15 or 30 lb) was applied to the specimen, the LVDTs were zeroed. Testing was conducted by cycling the load between the applied seat load stress (σ_s = 0.5 or 1.0 psi) and the target deviator stress of 3, 20, or 37 psi (σ_d) at confining pressures of either 0 or 10 psi (σ_3).

SMALL TRIAXIAL CELL CONFIGURATION
(6 Inch Diameter Platen)

Figure 2 is a diagram of the VMC R&D Lab small triaxial cell equipment which became available for use in the SHRP 6" dia. x 12" synthetic specimen study just prior to the testing of the TYPE I samples (Fall 1991). The third and fourth test sessions were accomplished using the small triaxial cell which accommodates a sample 6" dia. x 12" ht. Both the load cell and load piston were located external to the triaxial cell. The load piston contacted the ball bearing which transferred the load through the rod to the platen. In this configuration, the mass of the 6" diameter platen, the rod and the steel ball bearing rested on the specimen. The load cell was zeroed and a seat load (L_s = 15 lb), was applied to the specimen. The LVDTs were zeroed and testing was conducted by cycling between the applied seat load stress (σ_s = 0.5 psi) and a target deviator stress of 3, 20, or 37 psi (σ_d). At a confining pressure of 0 psi (σ_3), the platen, the rod and the ball bearing were a static load (L_p = 11.5 lb) and exerted an axial stress (σ_p = 0.4 psi) on the specimen. Due to zero confining pressure, there was no upward force exerted on the load rod and ball bearing (σ_u = 0 psi).

At a confining pressure of 10 psi, the platen only was a static load (L_p = 10.7 lb) and exerted an axial stress (σ_p = 0.38 psi) on the specimen. The 10 psi confining pressure forced the rod and ball bearing upward off the platen and against the load piston. The rod and ball bearing moved dynamically with the load piston and the zeroing of the load cell served to counteract any load indicated by this contact (σ_u = 0 psi). The remainder of the test was conducted as indicated above.

DEVIATOR STRESS CALCULATION - METHOD #1

This interpretation of the SHRP synthetic specimen test protocol for Method #1 is based on the assumption that the deviator stress, σ_{d1}, is the dynamic or cycled stress only, σ_{dyn}. In the M_r testing conducted on the synthetic specimens in all sessions, the dynamic load was cycled between the applied seat load of either 0.5 or 1.0 psi and the target deviator load of 3, 20, or 37 psi. Therefore, the dynamic stresses, as defined by Method #1, were 2.5, 19.5, and 36.5 psi for an applied seat load of 0.5 psi and 2, 19, and 36 psi for a seat load of 1.0 psi. The axial stress due to the mass of the platen, ball bearing and/or rod, σ_p, was not taken into consideration in this calculation method nor was the upward lift of the rod, σ_u, from the introduction of the 10 psi confining pressure to the triaxial chamber, σ_3. If the Method #1 interpretation of the test protocol was the desired interpretation by the SHRP LTPP personnel, then testing should have been accomplished by cycling the dynamic load between the 0.5 psi applied seat load and 3.5, 20.5, or 37.5 psi or the 1.0 psi seat load and 4, 21, or 38 psi in order to achieve dynamic stresses equal to 3, 20, or 37 psi. The sample calculation for Method #1 was the same when testing was conducted using either the large or small triaxial cell and at either confining pressure.

<u>Method #1 Sample Calculation:</u> $\sigma_{d1} = \sigma_{dyn}$

All Test Sessions
Large and **Small** Triaxial Cells
σ_3 = **0** or **10** psi

H_s = Specimen height (in)	12.0 in
H_r = Specimen recoverable deformation (in)	0.005 in
D_s = Specimen diameter (in)	6.0 in
A_s = Cross-sectional area of specimen (in^2)	28.27 in^2
L_{dyn} = Dynamic load (lb)	70 lb
$\sigma_{dyn} = L_{dyn}/A_s$ = Dynamic axial stress (psi)	2.5 psi
$\sigma_{d1} = \sigma_{dyn}$ = Deviator Stress (psi)	2.5 psi
σ_3 = Confining stress (psi)	0 or 10 psi
$\varepsilon_r = H_r/H_s$ = Recoverable strain (in/in)	0.00042 in/in
$M_r = \sigma_d/\varepsilon_r$ = Resilient modulus (psi)	5952 psi

DEVIATOR STRESS CALCULATION - METHOD #2

This method for the calculation of the deviator stress, used to determine the resilient modulus of the SHRP synthetic specimens was used by the VMC R&D Lab when the specimens were tested in September 1990, prior to circulation of the specimens to the other participating laboratories. **All data submitted to you in correspondence dated December 20, 1990 was calculated using Method #2.** In order to remain consistent when comparing M_r data, this method was also used by the VMC Lab in all following test sessions.

The interpretation of the SHRP synthetic specimen test protocol for Method #2 is based on the assumption that the applied seat load, σ_s, is a component of the deviator stress, σ_{d2}, along with the dynamic or cycled stress, σ_{dyn}. The basis for this assumption was the equipment configuration and applies for both the large and small triaxial cells. Due to the inherent design of our particular instrumentation, the load cell was not re-zeroed after the application of the seat load because of zero drift (i.e. control and accuracy is maintained when the electronics are reading a load, in this case 15 or 30 lbs, versus a reading of zero load). After the static seat load had been applied and the LVDTs zeroed, dynamic loading could then not be accomplished (without electronic interference) by cycling between loads or stresses less than the applied seat load stress and the target deviator stress. To have cycled between (or back to) zero load and the target deviator load, rather than between the applied seat load and the target deviator load, would have "removed" then "re-applied" the seat load (*Other laboratories may have referred to this effect as "clattering" or "chattering" of the ball bearing if they attempted to run the test in this manner*). Since dynamic loading could only be conducted in this manner, by cycling the instrument between the applied seat stress and the target deviator stress, i.e. 0.5 or 1.0 psi and 3, 20, or 37 psi, it lead to the assumption that the seat load was to be treated as a component of the deviator load. The axial stress due to the mass of the platen, ball bearing and/or rod, σ_p, was not considered in this calculation method nor was the upward lift of the rod, σ_u, from the introduction of the 10 psi confining pressure to the triaxial chamber, σ_3. Therefore, the sample calculation Method #2 is the same when testing was accomplished using either the large or small triaxial cell and at either confining pressure.

Method #2 Sample Calculation: $\sigma_{d2} = \sigma_{dyn} + \sigma_s$

All Test Sessions
Large and **Small** Triaxial Cells
σ_3 = **0** or **10** psi

H_s = Specimen height (in)	12.0 in
H_r = Specimen recoverable deformation (in)	0.005 in
D_s = Specimen diameter (in)	6.0 in

A_s = Cross-sectional area of specimen (in^2)	28.27 in^2
L_{dyn} = Dynamic load (lb)	70 lb
L_s = Applied static seat load (lb)	15 lb
$L = L_{dyn} + L_s$ = Axial load (lb)	85 lb
$\sigma_{dyn} = L_{dyn}/A_s$ = Axial stress from dynamic portion of deviator stress (psi)	2.5 psi
$\sigma_s = L_s/A_s$ = Axial stress from static seat load (psi)	0.5 psi
$\sigma_{d2} = \sigma_{dyn} + \sigma_s$ = Deviator Stress (psi)	3.0 psi
σ_3 = Confining stress (psi)	0 or 10 psi
$\varepsilon_r = H_r/H_s$ = Recoverable strain (in/in)	0.00042 in/in
$M_r = \sigma_d/\varepsilon_r$ = Resilient modulus (psi)	7143 psi

DEVIATOR STRESS CALCULATION - METHOD #3

The interpretation of the SHRP synthetic specimen test protocol for Method #3 is based on the assumption that the seat load is defined as the sum of the applied seat load, L_s, and the load due to the mass of the platen, ball bearing and/or rod, L_p. The axial stress that this static load exerts on the specimen is in turn a component of the deviator stress, σ_{d3}, along with the dynamic or cycled stress, σ_{dyn}. The rational behind this assumption was again due to the equipment configuration and was undertaken in an attempt to explain the differences between the M_r values of the synthetic specimens when tested in the large triaxial cell in the first and second sessions versus the small triaxial cell used in the third session. The axial stress due to the mass of the platen, ball bearing and/or rod, σ_p, was accounted for in this method as was the upward lift of the rod, σ_u, from the introduction of the 10 psi confining pressure to the triaxial chamber, σ_3. Therefore, sample calculations for Method #3 are dependent upon the triaxial cell (large vs. small) and confining pressure (0 vs. 10 psi) used during testing.

<u>Method #3 Sample Calculation:</u> $\sigma_{d3} = \sigma_{dyn} + \sigma_s + \sigma_p$

First and **Second** Test Sessions
Large Triaxial Cell
σ_3 = **0** or **10** psi

H_s = Specimen height (in)	12.0 in
H_r = Specimen recoverable deformation (in)	0.005 in
D_s = Specimen diameter (in)	6.0 in
A_s = Cross-sectional area of specimen (in^2)	28.27 in^2
L_{dyn} = Dynamic load (lb)	70 lb
L_s = Applied static seat load (lb)	15 lb
L_p = Static load due to mass of platen, rod, and/or ball bearing (lb)	79.5 lb
$L = L_{dyn} + L_s + L_p$ = Axial load (lb)	164.5 lb
$\sigma_{dyn} = L_{dyn}/A_s$ = Axial stress from dynamic portion of deviator stress (psi)	2.5 psi
$\sigma_s = L_s/A_s$ = Axial stress from static seat load (psi)	0.5 psi
$\sigma_p = L_p/A_s$ = Axial stress from static load of platen, rod, and/or ball bearing (psi)	2.8 psi
$\sigma_u = A_r\sigma_3/A_s$ = Upward axial stress on load rod due to confining pressure (psi)	0 psi
$\sigma_{d3} = \sigma_{dyn} + \sigma_s + \sigma_p$ = Deviator Stress (psi)	5.8 psi
σ_3 = Confining stress (psi)	0 or 10 psi
$\varepsilon_r = H_r/H_s$ = Recoverable strain (in/in)	0.00042 in/in

$M_r = \sigma_d/\varepsilon_r$ = Resilient modulus (psi) 13810 psi

Method #3 Sample Calculation: $\sigma_{d3} = \sigma_{dyn} + \sigma_s + \sigma_p$

Third and **Fourth** Test Sessions
Small Triaxial Cell
σ_3 = **0** psi

H_s = Specimen height (in)	12.0 in
H_r = Specimen recoverable deformation (in)	0.005 in
D_s = Specimen diameter (in)	6.0 in
A_s = Cross-sectional area of specimen (in^2)	28.27 in^2

L_{dyn} = Dynamic load (lb)	70 lb
L_s = Applied static seat load (lb)	15 lb
L_p = Static load due to mass of platen, rod, and/or ball bearing (lb)	11.5 lb
$L = L_{dyn} + L_s + L_p$ = Axial load (lb)	96.5 lb

$\sigma_{dyn} = L_{dyn}/A_s$ = Axial stress from dynamic portion of deviator stress (psi)	2.5 psi
$\sigma_s = L_s/A_s$ = Axial stress from static seat load (psi)	0.5 psi
$\sigma_p = L_p/A_s$ = Axial stress from static load of platen, rod, and/or ball bearing (psi)	0.4 psi
$\sigma_u = A_r\sigma_3/A_s$ = Upward axial stress on load rod due to confining pressure (psi)	0 psi
$\sigma_{d3} = \sigma_{dyn} + \sigma_s + \sigma_p$ = Deviator Stress (psi)	3.4 psi
σ_3 = Confining stress (psi)	0 psi

$\varepsilon_r = H_r/H_s$ = Recoverable strain (in/in) 0.00042 in/in

$M_r = \sigma_d/\varepsilon_r$ = Resilient modulus (psi) 8095 psi

Method #3 Sample Calculation: $\sigma_{d3} = \sigma_{dyn} + \sigma_s + \sigma_p$

Third and **Fourth** Test Sessions
Small Triaxial Cell
σ_3 = **10** psi

H_s = Specimen height (in)	12.0 in
H_r = Specimen recoverable deformation (in)	0.005 in

D_s = Specimen diameter (in) 6.0 in
A_s = Cross-sectional area of specimen (in^2) 28.27 in^2

L_{dyn} = Dynamic load (lb)70 lb
L_s = Applied static seat load (lb) 15 lb
L_p = Static load due to mass of platen, rod, and/or ball bearing (lb) 10.7 lb
$L = L_{dyn} + L_s + L_p$ = Axial load (lb) 95.7 lb

$\sigma_{dyn} = L_{dyn}/A_s$ = Axial stress from dynamic portion of deviator stress (psi)2.5 psi
$\sigma_s = L_s/A_s$ = Axial stress from static seat load (psi) 0.5 psi
$\sigma_p = L_p/A_s$ = Axial stress from static load of platen, rod, and/or ball bearing (psi) 0.38 psi
$\sigma_u = A_r\sigma_3/A_s$ = Upward axial stress on load rod due to confining pressure (psi) 0 psi
$\sigma_{d3} = \sigma_{dyn} + \sigma_s + \sigma_p$ = Deviator Stress (psi) 3.38 psi
σ_3 = Confining stress (psi) 10 psi

$\varepsilon_r = H_r/H_s$ = Recoverable strain (in/in) 0.00042 in/in

$M_r = \sigma_d/\varepsilon_r$ = Resilient modulus (psi) 8048 psi

COMMENTS

Standard Deviation

The standard deviation of population as presented for the M_r data contained in this report was calculated by the (biased) formula as defined in LOTUS SYMPHONY 2.2 whereby:

$$@STD = @SQRT\ [\Sigma(v_i - @AVG)^2/n]$$

or

$$@STD = @SQRT(@VAR)$$

Sample Calculations

The effect of the interpretation of the deviator stress definition on the M_r for the example calculations is shown in Table I. The data for each deviator and confining stress state is calculated using the three methods for both the large and small triaxial cell configurations. For comparison purposes, the recoverable deformation was the same for all conditions shown (H_r = 0.005 in). Relative to Method #1, the resilient modulus increases as the applied seat load (σ_s) then the platen load (σ_p) are accounted for in the deviator stress. The difference in the resilient modulus is significant for a low deviator stress of 3 psi as compared to the higher 20 and 37 psi M_r data. The applied seat load of 0.5 psi represents 17%, 2.5%, and 1.4% of the deviator stress for the 3, 20, and 37 psi conditions, respectively. The increased platen mass of the large triaxial cell, as compared to the small cell platen, contributes to the differences in the M_r results at all deviator stresses in Method #3 shown in Table I.

First Test Session

Tables 2, 6, 10, 14, 15, 16, and 19 summarize the first test session data as originally reported in December 1990 (Method #2) for the LDPE-1, NYLON-1, and TEFLON-1 through TEFLON-5 synthetic specimens, and include the M_r as calculated by Methods #1 and #3.

Second Test Session

During the second test session, the effect of the magnitude of the applied seat load was investigated by comparing the 0.5 versus 1.0 psi conditions on the LDPE-1 (Tables 3 & 4), NYLON-1 (Tables 7 & 8), TEFLON-1 (Tables 11 & 12), and TEFLON-4 (Tables 17 &

18) synthetic specimens. As indicated in the example calculations shown in Table I, the effect of the seat load on the M_r value appears to be greatest at the low 3 psi deviator stress, where it constitutes a greater percentage of the axial stress.

Third Test Session

The attempt to define the differences in the resilient modulus data of the same synthetic specimens (LDPE-1, NYLON-1, and TEFLON-1) between the first and second test sessions conducted in the large triaxial cell and the third session tested in the small triaxial cell, led to the consideration of the platen, rod and/or ball bearing mass as a component of the deviator stress in Method #3. A cursory examination of the data using Method #2, as originally used by the R&D Lab, shows general agreement between the first and second test sessions for all three specimens, especially at the higher deviator stresses of 20 and 37 psi. However, the values for the third set of M_r data (Tables 5, 9, and 13) are generally lower when compared to sessions one and two. Based on the data provided by this and other laboratories, the statistician may be able to provide a correction factor, if required, between the data derived in the large versus small triaxial cell.

Fourth Test Session

The testing of the TEFLON-5 specimen in the fourth session had a dual purpose. This specimen had been tested originally in the R&D Lab (Table 19) but was not circulated in the round robin and therefore not been exposed to numerous repeated stresses and handling as had the other synthetics. Testing of TEFLON-5 in the small triaxial cell was conducted to determine if a deviator stress, $\sigma_{d1} = \sigma_{dyn}$ in Method #1 (Tables 21 & 23), is equivalent to $\sigma_{d2} = \sigma_{dyn} + \sigma_s$ in Method #2 (Tables 20 & 22) when the dynamic loading is accomplished such that both σ_{d1} and σ_{d2} are 3.0, 20.0 or 37.0 psi. In addition, an effort was made to mimic the axial load of the large cell platen on the specimen but in the small triaxial cell (Tables 22 & 23). Retesting of TEFLON-5 in the large triaxial cell (Tables 24 & 25) was conducted in order to help determine whether or not possible damage to the LDPE-1, NYLON-1, and TEFLON-1 specimens could account for the differences in the first two versus third test sessions.

FIGURE 1

Vulcan Materials Company Research & Development Laboratory
Large Triaxial Cell Configuration

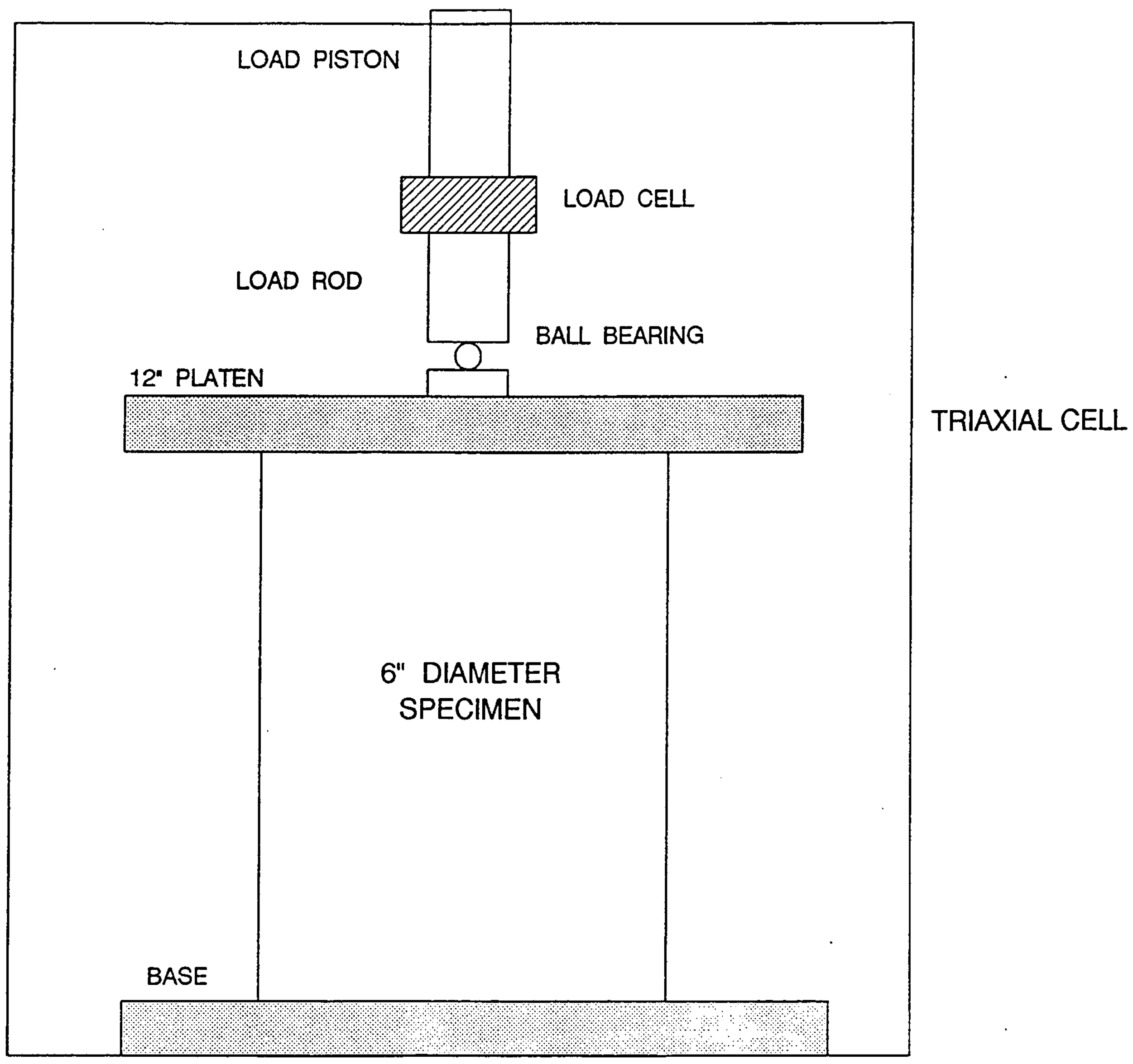

FIGURE 2

Vulcan Materials Company Research & Development Laboratory
Small Triaxial Cell Configuration

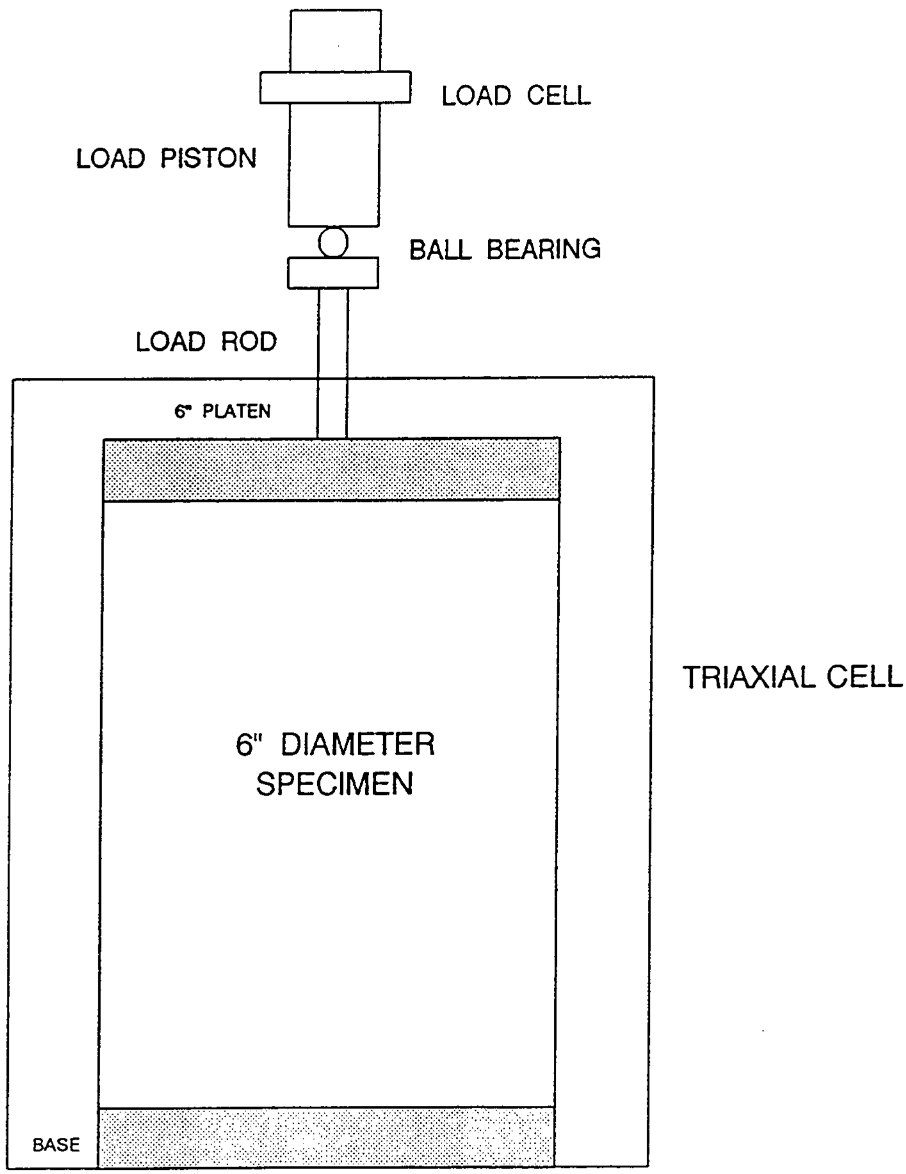

TABLE 1

Example Calculations Showing the Effect of the Definition of Deviator Stress on Resilient Modulus Using an Assumed Constant Recoverable Deformation and Seat Load

Deviator Stress Calculation Comparison - Effect on M_r $H_r = 0.005"$			Method 1 $\sigma_{d1} = \sigma_{dyn}$		Method 2 $\sigma_{d2} = \sigma_{dyn} + \sigma_s$		Method 3 $\sigma_{d3} = \sigma_{dyn} + \sigma_s + \sigma_p$	
Confining Stress psi	Target Deviator Stress psi	Applied Seat Load psi	Large Cell M_r psi	Small Cell M_r psi	Large Cell M_r psi	Small Cell M_r psi	Large Cell M_r psi	Small Cell M_r psi
0	3	0.5	5952	5952	7143	7143	13810	8095
10	3	0.5	5952	5952	7143	7143	13810	8048
0	20	0.5	46429	46429	47619	47619	54289	48571
10	20	0.5	46429	46429	47619	47619	54289	48524
0	37	0.5	86905	86905	88095	88095	94762	89048
10	37	0.5	86905	86905	88095	88095	94762	89000

σ_d = Target deviator stress
σ_{dyn} = Dynamic portion of deviator stress
σ_s = Stress due to manually applied seat load
σ_p = Stress due to mass of platen, rod, and/or ball bearing

TABLE 2

Effect of the Definition of Deviator Stress on the Resilient Modulus of LDPE-1 from the First Test Session at σ_s = 0.5 psi and σ_{dyn} = 2.5, 19.5, & 36.5 psi

LDPE-1 First Session Large Triaxial Cell			Method 1 $\sigma_{d1} = \sigma_{dyn}$	Method 2 $\sigma_{d2} = \sigma_{dyn} + \sigma_s$	Method 3 $\sigma_{d3} = \sigma_{dyn} + \sigma_s + \sigma_p$
Confining Stress psi	Target Deviator Stress psi	Seat/Dynamic Load psi	M_r psi	M_r psi	M_r psi
0	3	0.5 / 2.5	10621	13023	25749
10	3	0.5 / 2.5	12674	15602	31119
0	20	0.5 / 19.5	29580	30434	34961
10	20	0.5 / 19.5	31343	32246	37034
0	37	0.5 / 36.5	35441	35986	38873
10	37	0.5 / 36.5	36641	37205	40196

σ_d = Target deviator stress
σ_{dyn} = Dynamic portion of deviator stress
σ_s = Stress due to manually applied seat load
σ_p = Stress due to mass of platen, rod, and/or ball bearing

TABLE 3

Effect of the Definition of Deviator Stress on the Resilient Modulus of LDPE-1 from the Second Session at σ_s = 0.5 psi and σ_{dyn} = 2.5, 19.5, & 36.5 psi

LDPE-1 Second Session Large Triaxial Cell			Method 1 $\sigma_{d1} = \sigma_{dyn}$	Method 2 $\sigma_{d2} = \sigma_{dyn} + \sigma_s$	Method 3 $\sigma_{d3} = \sigma_{dyn} + \sigma_s + \sigma_p$
Confining Stress psi	Target Deviator Stress psi	Seat/Dynamic Load psi	M_r psi	M_r psi	M_r psi
0	3	0.5 / 2.5	24025	29325	57413
10	3	0.5 / 2.5	20389	24822	48314
0	20	0.5 / 19.5	34599	35562	40666
10	20	0.5 / 19.5	33892	34835	39834
0	37	0.5 / 36.5	40021	40615	43765
10	37	0.5 / 36.5	39625	40214	43333

σ_d = Target deviator stress
σ_{dyn} = Dynamic portion of deviator stress
σ_s = Stress due to manually applied seat load
σ_p = Stress due to mass of platen, rod, and/or ball bearing

TABLE 4

Effect of the Definition of Deviator Stress on the Resilient Modulus of LDPE-1 from the Second Session at σ_s = 1.0 psi and σ_{dyn} = 2.0, 19.0, & 36.0 psi

LDPE-1 Second Session Large Triaxial Cell			Method 1 $\sigma_{d1} = \sigma_{dyn}$	Method 2 $\sigma_{d2} = \sigma_{dyn} + \sigma_s$	Method 3 $\sigma_{d3} = \sigma_{dyn} + \sigma_s + \sigma_p$
Confining Stress psi	Target Deviator Stress psi	Seat/Dynamic Load psi	M_r psi	M_r psi	M_r psi
0	3	1.0 / 2.0	27483	43039	84263
10	3	1.0 / 2.0	23809	37286	73000
0	20	1.0 / 19.0	36263	38339	43840
10	20	1.0 / 19.0	36385	38472	44003
0	37	1.0 / 36.0	39990	41196	44391
10	37	1.0 / 36.0	41935	43201	46555

σ_d = Target deviator stress
σ_{dyn} = Dynamic portion of deviator stress
σ_s = Stress due to manually applied seat load
σ_p = Stress due to mass of platen, rod, and/or ball bearing

TABLE 5

Effect of the Definition of Deviator Stress on the Resilient Modulus of LDPE-1 from the Third Session at σ_s = 0.5 psi and σ_{dyn} = 2.5, 19.5, & 36.5 psi

LDPE-1 Third Session Small Triaxial Cell			Method 1 $\sigma_{d1} = \sigma_{dyn}$	Method 2 $\sigma_{d2} = \sigma_{dyn} + \sigma_s$	Method 3 $\sigma_{d3} = \sigma_{dyn} + \sigma_s + \sigma_p$
Confining Stress psi	Target Deviator Stress psi	Seat/Dynamic Load psi	M_r psi	M_r psi	M_r psi
0	3	0.5 / 2.5	23754	29149	33286
10	3	0.5 / 2.5	26112	32163	36479
0	20	0.5 / 19.5	27630	28400	28991
10	20	0.5 / 19.5	27669	28448	29004
0	37	0.5 / 36.5	31341	31811	32172
10	37	0.5 / 36.5	32659	33151	33502

σ_d = Target deviator stress
σ_{dyn} = Dynamic portion of deviator stress
σ_s = Stress due to manually applied seat load
σ_p = Stress due to mass of platen, rod, and/or ball bearing

TABLE 6

Effect of the Definition of Deviator Stress on the Resilient Modulus of NYLON-1 from the First Session at σ_s = 0.5 psi and σ_{dyn} = 2.5, 19.5, & 36.5 psi

NYLON-1 First Session Large Triaxial Cell			Method 1 $\sigma_{d1} = \sigma_{dyn}$	Method 2 $\sigma_{d2} = \sigma_{dyn} + \sigma_s$	Method 3 $\sigma_{d3} = \sigma_{dyn} + \sigma_s + \sigma_p$
Confining Stress psi	Target Deviator Stress psi	Seat/Dynamic Load psi	M_r psi	M_r psi	M_r psi
0	3	0.5 / 2.5	51946	62716	119798
10	3	0.5 / 2.5	52360	63201	120657
0	20	0.5 / 19.5	95686	98197	111502
10	20	0.5 / 19.5	94635	97121	110294
0	37	0.5 / 36.5	100504	101913	109378
10	37	0.5 / 36.5	112032	113601	121918

σ_d = Target deviator stress
σ_{dyn} = Dynamic portion of deviator stress
σ_s = Stress due to manually applied seat load
σ_p = Stress due to mass of platen, rod, and/or ball bearing

TABLE 7

Effect of the Definition of Deviator Stress on the Resilient Modulus of NYLON-1 from the Second Session at σ_s = 0.5 psi and σ_{dyn} = 2.5, 19.5, & 36.5 psi

NYLON-1 Second Session Large Triaxial Cell			Method 1 $\sigma_{d1} = \sigma_{dyn}$	Method 2 $\sigma_{d2} = \sigma_{dyn} + \sigma_s$	Method 3 $\sigma_{d3} = \sigma_{dyn} + \sigma_s + \sigma_p$
Confining Stress psi	Target Deviator Stress psi	Seat/Dynamic Load psi	M_r psi	M_r psi	M_r psi
0	3	0.5 / 2.5	69154	83363	158674
10	3	0.5 / 2.5	68653*	82759*	157525*
0	20	0.5 / 19.5	97027	99587	113155
10	20	0.5 / 19.5	99809	102442	116399
0	37	0.5 / 36.5	104650	106126	113945
10	37	0.5 / 36.5	106840	108347	116329

* = Resilient modulus value shown has been derived from a data file edited due to LVDT malfunction during testing.
σ_d = Target deviator stress
σ_{dyn} = Dynamic portion of deviator stress
σ_s = Stress due to manually applied seat load
σ_p = Stress due to mass of platen, rod, and/or ball bearing

TABLE 8

Effect of the Definition of Deviator Stress on the Resilient Modulus of NYLON-1 from the Second Session at σ_s = 1.0 psi and σ_{dyn} = 2.0, 19.0, & 36.0 psi

NYLON-1 Second Session Large Triaxial Cell			Method 1 $\sigma_{d1} = \sigma_{dyn}$	Method 2 $\sigma_{d2} = \sigma_{dyn} + \sigma_s$	Method 3 $\sigma_{d3} = \sigma_{dyn} + \sigma_s + \sigma_p$
Confining Stress psi	Target Deviator Stress psi	Seat/Dynamic Load psi	M_r psi	M_r psi	M_r psi
0	3	1.0 / 2.0	88588	134410	255836
10	3	1.0 / 2.0	101351*	153773*	292694*
0	20	1.0 / 19.0	97891	103192	117239
10	20	1.0 / 19.0	100485	105936	120382
0	37	1.0 / 36.0	113009	116241	124805
10	37	1.0 / 36.0	110402	113560	121927

* = Resilient modulus value shown has been derived from a data file edited due to LVDT malfunction during testing.
σ_d = Target deviator stress
σ_{dyn} = Dynamic portion of deviator stress
σ_s = Stress due to manually applied seat load
σ_p = Stress due to mass of platen, rod, and/or ball bearing

TABLE 9

Effect of the Definition of Deviator Stress on the Resilient Modulus of NYLON-1 from the Third Session at σ_s = 0.5 psi and σ_{dyn} = 2.5, 19.5, & 36.5 psi

NYLON-1 Third Session Small Triaxial Cell			Method 1 $\sigma_{d1} = \sigma_{dyn}$	Method 2 $\sigma_{d2} = \sigma_{dyn} + \sigma_s$	Method 3 $\sigma_{d3} = \sigma_{dyn} + \sigma_s + \sigma_p$
Confining Stress psi	Target Deviator Stress psi	Seat/Dynamic Load psi	M_r psi	M_r psi	M_r psi
0	3	0.5 / 2.5	62667*	75790*	85851*
10	3	0.5 / 2.5	45506*	55076*	61903*
0	20	0.5 / 19.5	85690	87936	89657
10	20	0.5 / 19.5	71160	73049	74397
0	37	0.5 / 36.5	95416	96749	97772
10	37	0.5 / 36.5	85813	87016	87874

* = Resilient modulus value shown has been derived from a data file edited due to LVDT malfunction during testing.
σ_d = Target deviator stress
σ_{dyn} = Dynamic portion of deviator stress
σ_s = Stress due to manually applied seat load
σ_p = Stress due to mass of platen, rod, and/or ball bearing

TABLE 10

Effect of the Definition of Deviator Stress on the Resilient Modulus of TEFLON-1 from the First Session at σ_s = 0.5 psi and σ_{dyn} = 2.5, 19.5, & 36.5 psi

TEFLON-1 First Session Large Triaxial Cell			Method 1 $\sigma_{d1} = \sigma_{dyn}$	Method 2 $\sigma_{d2} = \sigma_{dyn} + \sigma_s$	Method 3 $\sigma_{d3} = \sigma_{dyn} + \sigma_s + \sigma_p$
Confining Stress psi	Target Deviator Stress psi	Seat/Dynamic Load psi	M_r psi	M_r psi	M_r psi
0	3	0.5 / 2.5	15178	18696	37345
10	3	0.5 / 2.5	15064	18561	37093
0	20	0.5 / 19.5	36048	37091	42618
10	20	0.5 / 19.5	36447	37500	43080
0	37	0.5 / 36.5	47230	47957	51811
10	37	0.5 / 36.5	47313	48041	51903

σ_d = Target deviator stress
σ_{dyn} = Dynamic portion of deviator stress
σ_s = Stress due to manually applied seat load
σ_p = Stress due to mass of platen, rod, and/or ball bearing

TABLE 11

Effect of the Definition of Deviator Stress on the Resilient Modulus of TEFLON-1 from the Second Session at σ_s = 0.5 psi and σ_{dyn} = 2.5, 19.5, & 36.5 psi

TEFLON-1 Second Session Large Triaxial Cell			Method 1 $\sigma_{d1} = \sigma_{dyn}$	Method 2 $\sigma_{d2} = \sigma_{dyn} + \sigma_s$	Method 3 $\sigma_{d3} = \sigma_{dyn} + \sigma_s + \sigma_p$
Confining Stress psi	Target Deviator Stress psi	Seat/Dynamic Load psi	M_r psi	M_r psi	M_r psi
0	3	0.5 / 2.5	29137	35759	70856
10	3	0.5 / 2.5	29907	36704	72728
0	20	0.5 / 19.5	42041	43242	49608
10	20	0.5 / 19.5	44197	45462	52168
0	37	0.5 / 36.5	53562	54379	58711
10	37	0.5 / 36.5	55677	56527	61030

σ_d = Target deviator stress
σ_{dyn} = Dynamic portion of deviator stress
σ_s = Stress due to manually applied seat load
σ_p = Stress due to mass of platen, rod, and/or ball bearing

TABLE 12

Effect of the Definition of Deviator Stress on the Resilient Modulus of TEFLON-1 from the Second Session at σ_s = 1.0 psi and σ_{dyn} = 2.0, 19.0, & 36.0 psi

TEFLON-1 Second Session Large Triaxial Cell			Method 1 $\sigma_{d1} = \sigma_{dyn}$	Method 2 $\sigma_{d2} = \sigma_{dyn} + \sigma_s$	Method 3 $\sigma_{d3} = \sigma_{dyn} + \sigma_s + \sigma_p$
Confining Stress psi	Target Deviator Stress psi	Seat/Dynamic Load psi	M_r psi	M_r psi	M_r psi
0	3	1.0 / 2.0	32201	51143	101339
10	3	1.0 / 2.0	34323	54513	108017
0	20	1.0 / 19.0	45202	47861	54907
10	20	1.0 / 19.0	44950	47594	54601
0	37	1.0 / 36.0	57704	59492	64231
10	37	1.0 / 36.0	57727	59516	64257

σ_d = Target deviator stress
σ_{dyn} = Dynamic portion of deviator stress
σ_s = Stress due to manually applied seat load
σ_p = Stress due to mass of platen, rod, and/or ball bearing

TABLE 13

Effect of the Definition of Deviator Stress on the Resilient Modulus of TEFLON-1 from the Third Session at σ_s = 0.5 psi and σ_{dyn} = 2.5, 19.5, & 36.5 psi

TEFLON-1 Third Session Small Triaxial Cell			Method 1 $\sigma_{d1} = \sigma_{dyn}$	Method 2 $\sigma_{d2} = \sigma_{dyn} + \sigma_s$	Method 3 $\sigma_{d3} = \sigma_{dyn} + \sigma_s + \sigma_p$
Confining Stress psi	Target Deviator Stress psi	Seat/Dynamic Load psi	M_r psi	M_r psi	M_r psi
0	3	0.5 / 2.5	21784	27039	31068
10	3	0.5 / 2.5	27141	33448	37948
0	20	0.5 / 19.5	42693	43913	44848
10	20	0.5 / 19.5	50137	51576	52602
0	37	0.5 / 36.5	48553	49293	49859
10	37	0.5 / 36.5	56268	57127	57739

σ_d = Target deviator stress
σ_{dyn} = Dynamic portion of deviator stress
σ_s = Stress due to manually applied seat load
σ_p = Stress due to mass of platen, rod, and/or ball bearing

TABLE 14

Effect of the Definition of Deviator Stress on the Resilient Modulus of TEFLON-2 from the First Session at σ_s = 0.5 psi and σ_{dyn} = 2.5, 19.5, & 36.5 psi

TEFLON-2 First Session Large Triaxial Cell			Method 1 $\sigma_{d1} = \sigma_{dyn}$	Method 2 $\sigma_{d2} = \sigma_{dyn} + \sigma_s$	Method 3 $\sigma_{d3} = \sigma_{dyn} + \sigma_s + \sigma_p$
Confining Stress psi	Target Deviator Stress psi	Seat/Dynamic Load psi	M_r psi	M_r psi	M_r psi
0	3	0.5 / 2.5	18405	22468	44007
10	3	0.5 / 2.5	18045	22037	43193
0	20	0.5 / 19.5	43099	44294	50629
10	20	0.5 / 19.5	42634	43821	50109
0	37	0.5 / 36.5	51757	52523	56353
10	37	0.5 / 36.5	52039	52811	54237

σ_d = Target deviator stress
σ_{dyn} = Dynamic portion of deviator stress
σ_s = Stress due to manually applied seat load
σ_p = Stress due to mass of platen, rod, and/or ball bearing

TABLE 15

Effect of the Definition of Deviator Stress on the Resilient Modulus of TEFLON-3 from the First Session at σ_s = 0.5 psi and σ_{dyn} = 2.5, 19.5, & 36.5 psi

TEFLON-3 First Session Large Triaxial Cell			Method 1 $\sigma_{d1} = \sigma_{dyn}$	Method 2 $\sigma_{d2} = \sigma_{dyn} + \sigma_s$	Method 3 $\sigma_{d3} = \sigma_{dyn} + \sigma_s + \sigma_p$
Confining Stress psi	Target Deviator Stress psi	Seat/Dynamic Load psi	M_r psi	M_r psi	M_r psi
0	3	0.5 / 2.5	18782	23192	46567
10	3	0.5 / 2.5	18593	22970	46167
0	20	0.5 / 19.5	42552	43799	50403
10	20	0.5 / 19.5	43428	44698	51428
0	37	0.5 / 36.5	51042	51835	56039
10	37	0.5 / 36.5	52817	53640	57999

σ_d = Target deviator stress
σ_{dyn} = Dynamic portion of deviator stress
σ_s = Stress due to manually applied seat load
σ_p = Stress due to mass of platen, rod, and/or ball bearing

TABLE 16

Effect of the Definition of Deviator Stress on the Resilient Modulus of TEFLON-4 from the First Session at σ_s = 0.5 psi and σ_{dyn} = 2.5, 19.5, & 36.5 psi

TEFLON-4 First Session Large Triaxial Cell			Method 1 $\sigma_{d1} = \sigma_{dyn}$	Method 2 $\sigma_{d2} = \sigma_{dyn} + \sigma_s$	Method 3 $\sigma_{d3} = \sigma_{dyn} + \sigma_s + \sigma_p$
Confining Stress psi	Target Deviator Stress psi	Seat/Dynamic Load psi	M_r psi	M_r psi	M_r psi
0	3	0.5 / 2.5	23362	28510	55791
10	3	0.5 / 2.5	20623	25174	49295
0	20	0.5 / 19.5	39561	40659	46478
10	20	0.5 / 19.5	39690	40789	46617
0	37	0.5 / 36.5	47922	48629	52379
10	37	0.5 / 36.5	47822	48530	52281

σ_d = Target deviator stress
σ_{dyn} = Dynamic portion of deviator stress
σ_s = Stress due to manually applied seat load
σ_p = Stress due to mass of platen, rod, and/or ball bearing

TABLE 17

Effect of the Definition of Deviator Stress on the Resilient Modulus of TEFLON-4 from the Second Session at σ_s = 0.5 psi and σ_{dyn} = 2.5, 19.5, & 36.5 psi

TEFLON-4 Second Session Large Triaxial Cell			Method 1 $\sigma_{d1} = \sigma_{dyn}$	Method 2 $\sigma_{d2} = \sigma_{dyn} + \sigma_s$	Method 3 $\sigma_{d3} = \sigma_{dyn} + \sigma_s + \sigma_p$
Confining Stress psi	Target Deviator Stress psi	Seat/Dynamic Load psi	M_r psi	M_r psi	M_r psi
0	3	0.5 / 2.5	34475*	83830*	162700*
10	3	0.5 / 2.5	35596	43279	83996
0	20	0.5 / 19.5	54323	55808	63682
10	20	0.5 / 19.5	53160	54614	62319
0	37	0.5 / 36.5	62254	63163	67980
10	37	0.5 / 36.5	62925	63844	68713

* = Resilient modulus value shown has been derived from a data file edited due to LVDT malfunction during testing.
σ_d = Target deviator stress
σ_{dyn} = Dynamic portion of deviator stress
σ_s = Stress due to manually applied seat load
σ_p = Stress due to mass of platen, rod, and/or ball bearing

TABLE 18

Effect of the Definition of Deviator Stress on the Resilient Modulus of TEFLON-4 from the Second Session at σ_s = 1.0 psi and σ_{dyn} = 2.0, 19.0, & 36.0 psi

TEFLON-4 Second Session Large Triaxial Cell			Method 1 $\sigma_{d1} = \sigma_{dyn}$	Method 2 $\sigma_{d2} = \sigma_{dyn} + \sigma_s$	Method 3 $\sigma_{d3} = \sigma_{dyn} + \sigma_s + \sigma_p$
Confining Stress psi	Target Deviator Stress psi	Seat/Dynamic Load psi	M_r psi	M_r psi	M_r psi
0	3	1.0 / 2.0	41956	65051	126252
10	3	1.0 / 2.0	45179	70048	135952
0	20	1.0 / 19.0	55171	58274	66495
10	20	1.0 / 19.0	55875	59017	67344
0	37	1.0 / 36.0	66112	68071	73262
10	37	1.0 / 36.0	65659	67604	72760

σ_d = Target deviator stress
σ_{dyn} = Dynamic portion of deviator stress
σ_s = Stress due to manually applied seat load
σ_p = Stress due to mass of platen, rod, and/or ball bearing

TABLE 19

Effect of the Definition of Deviator Stress on the Resilient Modulus of TEFLON-5 from the First Session at σ_s = 0.5 psi and σ_{dyn} = 2.5, 19.5, & 36.5 psi

TEFLON-5 First Session Large Triaxial Cell			Method 1 $\sigma_{d1} = \sigma_{dyn}$	Method 2 $\sigma_{d2} = \sigma_{dyn} + \sigma_s$	Method 3 $\sigma_{d3} = \sigma_{dyn} + \sigma_s + \sigma_p$
Confining Stress psi	Target Deviator Stress psi	Seat/Dynamic Load psi	M_r psi	M_r psi	M_r psi
0	3	0.5 / 2.5	25962	31667	61906
10	3	0.5 / 2.5	25791	31480	61633
0	20	0.5 / 19.5	49228	50593	57831
10	20	0.5 / 19.5	52256	53705	61385
0	37	0.5 / 36.5	58893	59762	64372
10	37	0.5 / 36.5	61789	62702	67540

σ_d = Target deviator stress
σ_{dyn} = Dynamic portion of deviator stress
σ_s = Stress due to manually applied seat load
σ_p = Stress due to mass of platen, rod, and/or ball bearing

TABLE 20

Effect of the Definition of Deviator Stress on the Resilient Modulus of TEFLON-5 from the Fourth Session at σ_s = 0.5 psi and σ_{dyn} = 2.5, 19.5, & 36.5 psi

TEFLON-5 Fourth Session Small Triaxial Cell			Method 1 $\sigma_{d1} = \sigma_{dyn}$	Method 2 $\sigma_{d2} = \sigma_{dyn} + \sigma_s$	Method 3 $\sigma_{d3} = \sigma_{dyn} + \sigma_s + \sigma_p$
Confining Stress psi	Target Deviator Stress psi	Seat/Dynamic Load psi	M_r psi	M_r psi	M_r psi
0	3	0.5 / 2.5	6658	8209	9398
10	3	0.5 / 2.5	6509	7889	8874
0	20	0.5 / 19.5	28220	29004	29606
10	20	0.5 / 19.5	29195	29985	30548
0	37	0.5 / 36.5	39115	39682	40113
10	37	0.5 / 36.5	40603	41191	41611

σ_d = Target deviator stress
σ_{dyn} = Dynamic portion of deviator stress
σ_s = Stress due to manually applied seat load
σ_p = Stress due to mass of platen, rod, and/or ball bearing

TABLE 21

Effect of the Definition of Deviator Stress on the Resilient Modulus of TEFLON-5 from the Fourth Session at σ_s = 0.5 psi and σ_{dyn} = 3.0, 20.0, & 37.0 psi

TEFLON-5 Fourth Session Small Triaxial Cell			Method 1 $\sigma_{d1} = \sigma_{dyn}$	Method 2 $\sigma_{d2} = \sigma_{dyn} + \sigma_s$	Method 3 $\sigma_{d3} = \sigma_{dyn} + \sigma_s + \sigma_p$
Confining Stress psi	Target Deviator Stress psi	Seat/Dynamic Load psi	M_r psi	M_r psi	M_r psi
0	3	0.5 / 3.0	5818	6874	7684
10	3	0.5 / 3.0	12454	14692	16289
0	20	0.5 / 20.0	26791	27503	28048
10	20	0.5 / 20.0	38554	39570	40295
0	37	0.5 / 37.0	38694	39245	39669
10	37	0.5 / 37.0	51203	51922	52435

σ_d = Target deviator stress
σ_{dyn} = Dynamic portion of deviator stress
σ_s = Stress due to manually applied seat load
σ_p = Stress due to mass of platen, rod, and/or ball bearing

TABLE 22

Effect of the Definition of Deviator Stress on the Resilient Modulus of TEFLON-5 from the Fourth Session at σ_s = 2.93 psi and σ_{dyn} = 2.5, 19.5, & 36.5 psi

TEFLON-5 Fourth Session Small Triaxial Cell			Method 1 $\sigma_{d1} = \sigma_{dyn}$	Method 2 $\sigma_{d2} = \sigma_{dyn} + \sigma_s$	Method 3 $\sigma_{d3} = \sigma_{dyn} + \sigma_s + \sigma_p$
Confining Stress psi	Target Deviator Stress psi	Seat/Dynamic Load* psi	M_r psi	M_r psi	M_r psi
0	3	2.93 / 2.5	62041	NA	135952
10	3	2.93 / 2.5	59919	NA	131996
0	20	2.93 / 19.5	67862	NA	78231
10	20	2.93 / 19.5	68678	NA	79145
0	37	2.93 / 36.5	73133	NA	79095
10	37	2.93 / 36.5	72415	NA	78277

* = This seat load pressure mimics the mass of the 12" diameter platen from the large triaxial cell and includes the 0.5 psi manually applied seat load.
σ_d = Target deviator stress
σ_{dyn} = Dynamic portion of deviator stress
σ_s = Stress due to manually applied seat load
σ_p = Stress due to mass of platen, rod, and/or ball bearing
NA = Due to the procedure for testing, M_r values for this method could not be determined

TABLE 23

Effect of the Definition of Deviator Stress on the Resilient Modulus of TEFLON-5 from the Fourth Session at σ_s = 2.93 psi and σ_{dyn} = 3.0, 20.0, & 37.0 psi

TEFLON-5 Fourth Session Small Triaxial Cell			Method 1 $\sigma_{d1} = \sigma_{dyn}$	Method 2 $\sigma_{d2} = \sigma_{dyn} + \sigma_s$	Method 3 $\sigma_{d3} = \sigma_{dyn} + \sigma_s + \sigma_p$
Confining Stress psi	Target Deviator Stress psi	Seat/Dynamic Load* psi	M_r psi	M_r psi	M_r psi
0	3	2.93 / 3.0	74942	NA	147811
10	3	2.93 / 3.0	73849	NA	147851
0	20	2.93 / 20.0	72133	NA	82733
10	20	2.93 / 20.0	70941	NA	81256
0	37	2.93 / 37.0	74532	NA	80478
10	37	2.93 / 37.0	75897	NA	81887

* = This seat load pressure mimics the mass of the 12" diameter platen from the large triaxial cell and includes the 0.5 psi manually applied seat load.
σ_d = Target deviator stress
σ_{dyn} = Dynamic portion of deviator stress
σ_s = Stress due to manually applied seat load
σ_p = Stress due to mass of platen, rod, and/or ball bearing
NA = Due to the procedure for testing, M_r values for this method could not be determined

TABLE 24

Effect of the Definition of Deviator Stress on the Resilient Modulus of TEFLON-5 from the Fourth Session at σ_s = 0.5 psi and σ_{dyn} = 2.5, 19.5, & 36.5 psi

TEFLON-5 Fourth Session Large Triaxial Cell			Method 1 $\sigma_{d1} = \sigma_{dyn}$	Method 2 $\sigma_{d2} = \sigma_{dyn} + \sigma_s$	Method 3 $\sigma_{d3} = \sigma_{dyn} + \sigma_s + \sigma_p$
Confining Stress psi	Target Deviator Stress psi	Seat/Dynamic Load psi	M_r psi	M_r psi	M_r psi
0	3	0.5 / 2.5	62478	118686	150251
10	3	0.5 / 2.5	63648	77246	149321
0	20	0.5 / 19.5	51071	52450	59757
10	20	0.5 / 19.5	51996	53390	59940
0	37	0.5 / 36.5	53376	54144	58209
10	37	0.5 / 36.5	54463	55251	59426

σ_d = Target deviator stress
σ_{dyn} = Dynamic portion of deviator stress
σ_s = Stress due to manually applied seat load
σ_p = Stress due to mass of platen, rod, and/or ball bearing

TABLE 25

Effect of the Definition of Deviator Stress on the Resilient Modulus of TEFLON-5 from the Fourth Session at σ_s = 1.0 psi and σ_{dyn} = 2.0, 19.0, & 36.0 psi

TEFLON-5 Fourth Session Large Triaxial Cell			Method 1 $\sigma_{d1} = \sigma_{dyn}$	Method 2 $\sigma_{d2} = \sigma_{dyn} + \sigma_s$	Method 3 $\sigma_{d3} = \sigma_{dyn} + \sigma_s + \sigma_p$
Confining Stress psi	Target Deviator Stress psi	Seat/Dynamic Load psi	M_r psi	M_r psi	M_r psi
0	3	1.0 / 2.0	76401	76411	230742
10	3	1.0 / 2.0	61838	97435	94330
0	20	1.0 / 19.0	53797	56790	64719
10	20	1.0 / 19.0	56814	59978	68363
0	37	1.0 / 36.0	55487	57116	61462
10	37	1.0 / 36.0	55223	56831	61093

σ_d = Target deviator stress
σ_{dyn} = Dynamic portion of deviator stress
σ_s = Stress due to manually applied seat load
σ_p = Stress due to mass of platen, rod, and/or ball bearing

DATA FILE DIRECTORY

SHRP LTPP TYPE I 6" x 12" SYNTHETIC SPECIMENS

(Stored as LOTUS SYMPHONY *.WR1 Files)

Calculation Disk #	Test Session Directory	SubDirectory	No. Files	M_r Calculation Method	I.D. #
1	First	SYN1SHRP	42	$\sigma_{d1} = \sigma_{dyn}$	1
1	(large cell)	SYNSHRP1	42	$\sigma_{d2} = \sigma_{dyn} + \sigma_s$	2
1		SYNSHRPA	42	$\sigma_{d3} = \sigma_{dyn} + \sigma_s + \sigma_p$	3
1	Second	SYN2SHRP	26	$\sigma_{d1} = \sigma_{dyn}$	1
1	(large cell)	SYNSHRP2	26	$\sigma_{d2} = \sigma_{dyn} + \sigma_s$	2
2		SYNSHRPB	26	$\sigma_{d3} = \sigma_{dyn} + \sigma_s + \sigma_p$	3
2	Third	SYN3SHRP	20	$\sigma_{d1} = \sigma_{dyn}$	1
2	(small cell)	SYNSHRP3	20	$\sigma_{d2} = \sigma_{dyn} + \sigma_s$	2
2		SYNSHRPC	20	$\sigma_{d3} = \sigma_{dyn} + \sigma_s + \sigma_p$	3
2	Fourth	SYN4SHRP	12	$\sigma_{d1} = \sigma_{dyn}$	1
2	(small cell)	SYNSHRP4	6	$\sigma_{d2} = \sigma_{dyn} + \sigma_s$	2
2		SYNSHRPD	12	$\sigma_{d3} = \sigma_{dyn} + \sigma_s + \sigma_p$	3
3	Fourth	SYN4SHRP	8	$\sigma_{d1} = \sigma_{dyn}$	1
3	(large cell)	SYNSHRP4	8	$\sigma_{d2} = \sigma_{dyn} + \sigma_s$	2
3		SYNSHRPD	8	$\sigma_{d3} = \sigma_{dyn} + \sigma_s + \sigma_p$	3

NOTE: Several files among the subdirectories have identical file names and extreme caution must be used when transferring or storing data files.

DISK	TEST SESSION DIRECTORY	METHOD #1 SUBDIRECTORY	FILE NAME σ_d	σ_3	σ_s	
1	First	SYN1SHRP	L1-3-0	3	0	0.5
1	First	SYN1SHRP	L1-3-10	3	10	0.5
1	First	SYN1SHRP	L1-20-0	20	0	0.5
1	First	SYN1SHRP	L1-20-10	20	10	0.5
1	First	SYN1SHRP	L1-37-0	37	0	0.5
1	First	SYN1SHRP	L1-37-10	37	10	0.5
1	First	SYN1SHRP	T1-3-0	3	0	0.5
1	First	SYN1SHRP	T1-3-10	3	10	0.5
1	First	SYN1SHRP	T1-20-0	20	0	0.5
1	First	SYN1SHRP	T1-20-10	20	10	0.5
1	First	SYN1SHRP	T1-37-0	37	0	0.5
1	First	SYN1SHRP	T1-37-10	37	10	0.5
1	First	SYN1SHRP	T2-3-0	3	0	0.5
1	First	SYN1SHRP	T2-3-10	3	10	0.5
1	First	SYN1SHRP	T2-20-0	20	0	0.5
1	First	SYN1SHRP	T2-20-10	20	10	0.5
1	First	SYN1SHRP	T2-37-0	37	0	0.5
1	First	SYN1SHRP	T2-37-10	37	10	0.5
1	First	SYN1SHRP	T3-3-0	3	0	0.5
1	First	SYN1SHRP	T3-3-10	3	10	0.5
1	First	SYN1SHRP	T3-20-0	20	0	0.5
1	First	SYN1SHRP	T3-20-10	20	10	0.5
1	First	SYN1SHRP	T3-37-0	37	0	0.5
1	First	SYN1SHRP	T3-37-10	37	10	0.5
1	First	SYN1SHRP	T4-3-0	3	0	0.5
1	First	SYN1SHRP	T4-3-10	3	10	0.5
1	First	SYN1SHRP	T4-20-0	20	0	0.5
1	First	SYN1SHRP	T4-20-10	20	10	0.5
1	First	SYN1SHRP	T4-37-0	37	0	0.5
1	First	SYN1SHRP	T4-37-10	37	10	0.5
1	First	SYN1SHRP	T5-3-0	3	0	0.5
1	First	SYN1SHRP	T5-3-10	3	10	0.5
1	First	SYN1SHRP	T5-20-0	20	0	0.5
1	First	SYN1SHRP	T5-20-10	20	10	0.5
1	First	SYN1SHRP	T5-37-0	37	0	0.5
1	First	SYN1SHRP	T5-37-10	37	10	0.5
1	First	SYN1SHRP	N1-3-0	3	0	0.5
1	First	SYN1SHRP	N1-3-10	3	10	0.5
1	First	SYN1SHRP	N1-20-0	20	0	0.5
1	First	SYN1SHRP	N1-20-10	20	10	0.5
1	First	SYN1SHRP	N1-37-0	37	0	0.5
1	First	SYN1SHRP	N1-37-10	37	10	0.5

DISK	TEST SESSION DIRECTORY	METHOD #2 SUBDIRECTORY	FILE NAME	σ_d	σ_3	σ_s
1	First	SYNSHRP1	L1-3-0	3	0	0.5
1	First	SYNSHRP1	L1-3-10	3	10	0.5
1	First	SYNSHRP1	L1-20-0	20	0	0.5
1	First	SYNSHRP1	L1-20-10	20	10	0.5
1	First	SYNSHRP1	L1-37-0	37	0	0.5
1	First	SYNSHRP1	L1-37-10	37	10	0.5
1	First	SYNSHRP1	T1-3-0	3	0	0.5
1	First	SYNSHRP1	T1-3-10	3	10	0.5
1	First	SYNSHRP1	T1-20-0	20	0	0.5
1	First	SYNSHRP1	T1-20-10	20	10	0.5
1	First	SYNSHRP1	T1-37-0	37	0	0.5
1	First	SYNSHRP1	T1-37-10	37	10	0.5
1	First	SYNSHRP1	T2-3-0	3	0	0.5
1	First	SYNSHRP1	T2-3-10	3	10	0.5
1	First	SYNSHRP1	T2-20-0	20	0	0.5
1	First	SYNSHRP1	T2-20-10	20	10	0.5
1	First	SYNSHRP1	T2-37-0	37	0	0.5
1	First	SYNSHRP1	T2-37-10	37	10	0.5
1	First	SYNSHRP1	T3-3-0	3	0	0.5
1	First	SYNSHRP1	T3-3-10	3	10	0.5
1	First	SYNSHRP1	T3-20-0	20	0	0.5
1	First	SYNSHRP1	T3-20-10	20	10	0.5
1	First	SYNSHRP1	T3-37-0	37	0	0.5
1	First	SYNSHRP1	T3-37-10	37	10	0.5
1	First	SYNSHRP1	T4-3-0	3	0	0.5
1	First	SYNSHRP1	T4-3-10	3	10	0.5
1	First	SYNSHRP1	T4-20-0	20	0	0.5
1	First	SYNSHRP1	T4-20-10	20	10	0.5
1	First	SYNSHRP1	T4-37-0	37	0	0.5
1	First	SYNSHRP1	T4-37-10	37	10	0.5
1	First	SYNSHRP1	T5-3-0	3	0	0.5
1	First	SYNSHRP1	T5-3-10	3	10	0.5
1	First	SYNSHRP1	T5-20-0	20	0	0.5
1	First	SYNSHRP1	T5-20-10	20	10	0.5
1	First	SYNSHRP1	T5-37-0	37	0	0.5
1	First	SYNSHRP1	T5-37-10	37	10	0.5
1	First	SYNSHRP1	N1-3-0	3	0	0.5
1	First	SYNSHRP1	N1-3-10	3	10	0.5
1	First	SYNSHRP1	N1-20-0	20	0	0.5
1	First	SYNSHRP1	N1-20-10	20	10	0.5
1	First	SYNSHRP1	N1-37-0	37	0	0.5
1	First	SYNSHRP1	N1-37-10	37	10	0.5

DISK	TEST SESSION DIRECTORY	METHOD #3 SUBDIRECTORY	FILE NAME	σ_d	σ_3	σ_s
1	First	SYNSHRPA	L1-3-0	3	0	0.5
1	First	SYNSHRPA	L1-3-10	3	10	0.5
1	First	SYNSHRPA	L1-20-0	20	0	0.5
1	First	SYNSHRPA	L1-20-10	20	10	0.5
1	First	SYNSHRPA	L1-37-0	37	0	0.5
1	First	SYNSHRPA	L1-37-10	37	10	0.5
1	First	SYNSHRPA	T1-3-0	3	0	0.5
1	First	SYNSHRPA	T1-3-10	3	10	0.5
1	First	SYNSHRPA	T1-20-0	20	0	0.5
1	First	SYNSHRPA	T1-20-10	20	10	0.5
1	First	SYNSHRPA	T1-37-0	37	0	0.5
1	First	SYNSHRPA	T1-37-10	37	10	0.5
1	First	SYNSHRPA	T2-3-0	3	0	0.5
1	First	SYNSHRPA	T2-3-10	3	10	0.5
1	First	SYNSHRPA	T2-20-0	20	0	0.5
1	First	SYNSHRPA	T2-20-10	20	10	0.5
1	First	SYNSHRPA	T2-37-0	37	0	0.5
1	First	SYNSHRPA	T2-37-10	37	10	0.5
1	First	SYNSHRPA	T3-3-0	3	0	0.5
1	First	SYNSHRPA	T3-3-10	3	10	0.5
1	First	SYNSHRPA	T3-20-0	20	0	0.5
1	First	SYNSHRPA	T3-20-10	20	10	0.5
1	First	SYNSHRPA	T3-37-0	37	0	0.5
1	First	SYNSHRPA	T3-37-10	37	10	0.5
1	First	SYNSHRPA	T4-3-0	3	0	0.5
1	First	SYNSHRPA	T4-3-10	3	10	0.5
1	First	SYNSHRPA	T4-20-0	20	0	0.5
1	First	SYNSHRPA	T4-20-10	20	10	0.5
1	First	SYNSHRPA	T4-37-0	37	0	0.5
1	First	SYNSHRPA	T4-37-10	37	10	0.5
1	First	SYNSHRPA	T5-3-0	3	0	0.5
1	First	SYNSHRPA	T5-3-10	3	10	0.5
1	First	SYNSHRPA	T5-20-0	20	0	0.5
1	First	SYNSHRPA	T5-20-10	20	10	0.5
1	First	SYNSHRPA	T5-37-0	37	0	0.5
1	First	SYNSHRPA	T5-37-10	37	10	0.5
1	First	SYNSHRPA	N1-3-0	3	0	0.5
1	First	SYNSHRPA	N1-3-10	3	10	0.5
1	First	SYNSHRPA	N1-20-0	20	0	0.5
1	First	SYNSHRPA	N1-20-10	20	10	0.5
1	First	SYNSHRPA	N1-37-0	37	0	0.5
1	First	SYNSHRPA	N1-37-10	37	10	0.5

DISK	TEST SESSION DIRECTORY	METHOD #1 SUBDIRECTORY	FILE NAME σ_d	σ_3	σ_s	
1	Second	SYN2SHRP	3LDP-0	3	0	0.5 & 1.0
1	Second	SYN2SHRP	3LDP-10	3	10	0.5 & 1.0
1	Second	SYN2SHRP	20LDP-0	20	0	0.5 & 1.0
1	Second	SYN2SHRP	20LDP-10	20	10	0.5 & 1.0
1	Second	SYN2SHRP	37LDP-0	37	0	0.5 & 1.0
1	Second	SYN2SHRP	37LDP-10	37	10	0.5 & 1.0
1	Second	SYN2SHRP	3TEF-0	3	0	0.5 & 1.0
1	Second	SYN2SHRP	3TEF-10	3	10	0.5 & 1.0
1	Second	SYN2SHRP	20TEF-0	20	0	0.5 & 1.0
1	Second	SYN2SHRP	20TEF-10	20	10	0.5 & 1.0
1	Second	SYN2SHRP	37TEF-0	37	0	0.5 & 1.0
1	Second	SYN2SHRP	37TEF-10	37	10	0.5 & 1.0
1	Second	SYN2SHRP	3TEF4-0	3	0	0.5 & 1.0
1	Second	SYN2SHRP	3TEF4A-0*	3	0	0.5 & 1.0
1	Second	SYN2SHRP	3TEF4-10	3	10	0.5 & 1.0
1	Second	SYN2SHRP	20TEF4-0	20	0	0.5 & 1.0
1	Second	SYN2SHRP	20TEF410	20	10	0.5 & 1.0
1	Second	SYN2SHRP	37TEF4-0	37	0	0.5 & 1.0
1	Second	SYN2SHRP	37TEF410	37	10	0.5 & 1.0
1	Second	SYN2SHRP	3NYL-0	3	0	0.5 & 1.0
1	Second	SYN2SHRP	3NYL-10	3	10	0.5 & 1.0
1	Second	SYN2SHRP	3NYLA-10*	3	10	0.5 & 1.0
1	Second	SYN2SHRP	20NYL-0	20	0	0.5 & 1.0
1	Second	SYN2SHRP	20NYL-10	20	10	0.5 & 1.0
1	Second	SYN2SHRP	37NYL-0	37	0	0.5 & 1.0
1	Second	SYN2SHRP	37NYL-10	37	10	0.5 & 1.0

* = Data file edited due to LVDT malfunction during testing.

DISK	TEST SESSION DIRECTORY	METHOD #2 SUBDIRECTORY	FILE NAME	σ_d	σ_3	σ_s
1	Second	SYNSHRP2	LDP3-0	3	0	0.5 & 1.0
1	Second	SYNSHRP2	LDP3-10	3	10	0.5 & 1.0
1	Second	SYNSHRP2	LDP20-0	20	0	0.5 & 1.0
1	Second	SYNSHRP2	LDP20-10	20	10	0.5 & 1.0
1	Second	SYNSHRP2	LDP37-0	37	0	0.5 & 1.0
1	Second	SYNSHRP2	LDP37-10	37	10	0.5 & 1.0
1	Second	SYNSHRP2	TEF3-0	3	0	0.5 & 1.0
1	Second	SYNSHRP2	TEF3-10	3	10	0.5 & 1.0
1	Second	SYNSHRP2	TEF20-0	20	0	0.5 & 1.0
1	Second	SYNSHRP2	TEF20-10	20	10	0.5 & 1.0
1	Second	SYNSHRP2	TEF37-0	37	0	0.5 & 1.0
1	Second	SYNSHRP2	TEF37-10	37	10	0.5 & 1.0
1	Second	SYNSHRP2	TEF43-0	3	0	0.5 & 1.0
1	Second	SYNSHRP2	TEF43A-0*	3	0	0.5 & 1.0
1	Second	SYNSHRP2	TEF43-10	3	10	0.5 & 1.0
1	Second	SYNSHRP2	TEF420-0	20	0	0.5 & 1.0
1	Second	SYNSHRP2	TEF42010	20	10	0.5 & 1.0
1	Second	SYNSHRP2	TEF437-0	37	0	0.5 & 1.0
1	Second	SYNSHRP2	TEF43710	37	10	0.5 & 1.0
1	Second	SYNSHRP2	NYL3-0	3	0	0.5 & 1.0
1	Second	SYNSHRP2	NYL3-10	3	10	0.5 & 1.0
1	Second	SYNSHRP2	NYL3A-10*	3	10	0.5 & 1.0
1	Second	SYNSHRP2	NYL20-0	20	0	0.5 & 1.0
1	Second	SYNSHRP2	NYL20-10	20	10	0.5 & 1.0
1	Second	SYNSHRP2	NYL37-0	37	0	0.5 & 1.0
1	Second	SYNSHRP2	NYL37-10	37	10	0.5 & 1.0

* = Data file edited due to LVDT malfunction during testing.

DISK	TEST SESSION DIRECTORY	METHOD #3 SUBDIRECTORY	FILE NAME	σ_d	σ_3	σ_s
2	Second	SYNSHRPB	LDP3-0	3	0	0.5 & 1.0
2	Second	SYNSHRPB	LDP3-10	3	10	0.5 & 1.0
2	Second	SYNSHRPB	LDP20-0	20	0	0.5 & 1.0
2	Second	SYNSHRPB	LDP20-10	20	10	0.5 & 1.0
2	Second	SYNSHRPB	LDP37-0	37	0	0.5 & 1.0
2	Second	SYNSHRPB	LDP37-10	37	10	0.5 & 1.0
2	Second	SYNSHRPB	TEF3-0	3	0	0.5 & 1.0
2	Second	SYNSHRPB	TEF3-10	3	10	0.5 & 1.0
2	Second	SYNSHRPB	TEF20-0	20	0	0.5 & 1.0
2	Second	SYNSHRPB	TEF20-10	20	10	0.5 & 1.0
2	Second	SYNSHRPB	TEF37-0	37	0	0.5 & 1.0
2	Second	SYNSHRPB	TEF37-10	37	10	0.5 & 1.0
2	Second	SYNSHRPB	TEF43-0	3	0	0.5 & 1.0
2	Second	SYNSHRPB	TEF43A-0*	3	0	0.5 & 1.0
2	Second	SYNSHRPB	TEF43-10	3	10	0.5 & 1.0
2	Second	SYNSHRPB	TEF420-0	20	0	0.5 & 1.0
2	Second	SYNSHRPB	TEF42010	20	10	0.5 & 1.0
2	Second	SYNSHRPB	TEF437-0	37	0	0.5 & 1.0
2	Second	SYNSHRPB	TEF43710	37	10	0.5 & 1.0
2	Second	SYNSHRPB	NYL3-0	3	0	0.5 & 1.0
2	Second	SYNSHRPB	NYL3-10	3	10	0.5 & 1.0
2	Second	SYNSHRPB	NYL3A-10*	3	10	0.5 & 1.0
2	Second	SYNSHRPB	NYL20-0	20	0	0.5 & 1.0
2	Second	SYNSHRPB	NYL20-10	20	10	0.5 & 1.0
2	Second	SYNSHRPB	NYL37-0	37	0	0.5 & 1.0
2	Second	SYNSHRPB	NYL37-10	37	10	0.5 & 1.0

* = Data file edited due to LVDT malfunction during testing.

DISK	TEST SESSION DIRECTORY	METHOD #1 SUBDIRECTORY	FILE NAME	σ_d	σ_3	σ_s
2	Third	SYN3SHRP	3LDP-0	3	0	0.5
2	Third	SYN3SHRP	3LDP-10	3	10	0.5
2	Third	SYN3SHRP	20LDP-0	20	0	0.5
2	Third	SYN3SHRP	20LDP-10	20	10	0.5
2	Third	SYN3SHRP	37LDP-0	37	0	0.5
2	Third	SYN3SHRP	37LDP-10	37	10	0.5
2	Third	SYN3SHRP	3TEF-0	3	0	0.5
2	Third	SYN3SHRP	3TEF-10	3	10	0.5
2	Third	SYN3SHRP	20TEF-0	20	0	0.5
2	Third	SYN3SHRP	20TEF-10	20	10	0.5
2	Third	SYN3SHRP	37TEF-0	37	0	0.5
2	Third	SYN3SHRP	37TEF-10	37	10	0.5
2	Third	SYN3SHRP	3NYL-0	3	0	0.5
2	Third	SYN3SHRP	3NYLA-0*	3	0	0.5
2	Third	SYN3SHRP	3NYL-10	3	10	0.5
2	Third	SYN3SHRP	3NYLA-10*	3	10	0.5
2	Third	SYN3SHRP	20NYL-0	20	0	0.5
2	Third	SYN3SHRP	20NYL-10	20	10	0.5
2	Third	SYN3SHRP	37NYL-0	37	0	0.5
2	Third	SYN3SHRP	37NYL-10	37	10	0.5

* = Data file edited due to LVDT malfunction during testing.

DISK	TEST SESSION DIRECTORY	METHOD #2 SUBDIRECTORY	FILE NAME	σ_d	σ_3	σ_s
2	Third	SYNSHRP3	LDP3-0	3	0	0.5
2	Third	SYNSHRP3	LDP3-10	3	10	0.5
2	Third	SYNSHRP3	LDP20-0	20	0	0.5
2	Third	SYNSHRP3	LDP20-10	20	10	0.5
2	Third	SYNSHRP3	LDP37-0	37	0	0.5
2	Third	SYNSHRP3	LDP37-10	37	10	0.5
2	Third	SYNSHRP3	TEF3-0	3	0	0.5
2	Third	SYNSHRP3	TEF3-10	3	10	0.5
2	Third	SYNSHRP3	TEF20-0	20	0	0.5
2	Third	SYNSHRP3	TEF20-10	20	10	0.5
2	Third	SYNSHRP3	TEF37-0	37	0	0.5
2	Third	SYNSHRP3	TEF37-10	37	10	0.5
2	Third	SYNSHRP3	NYL3-0	3	0	0.5
2	Third	SYNSHRP3	NYL3A-0*	3	0	0.5
2	Third	SYNSHRP3	NYL3-10	3	10	0.5
2	Third	SYNSHRP3	NYL3A-10*	3	10	0.5
2	Third	SYNSHRP3	NYL20-0	20	0	0.5
2	Third	SYNSHRP3	NYL20-10	20	10	0.5
2	Third	SYNSHRP3	NYL37-0	37	0	0.5
2	Third	SYNSHRP3	NYL37-10	37	10	0.5

* = Data file edited due to LVDT malfunction during testing.

DISK	TEST SESSION DIRECTORY	METHOD #3 SUBDIRECTORY	FILE NAME	σ_d	σ_3	σ_s
2	Third	SYNSHRPC	LDP3-0	3	0	0.5
2	Third	SYNSHRPC	LDP3-10	3	10	0.5
2	Third	SYNSHRPC	LDP20-0	20	0	0.5
2	Third	SYNSHRPC	LDP20-10	20	10	0.5
2	Third	SYNSHRPC	LDP37-0	37	0	0.5
2	Third	SYNSHRPC	LDP37-10	37	10	0.5
2	Third	SYNSHRPC	TEF3-0	3	0	0.5
2	Third	SYNSHRPC	TEF3-10	3	10	0.5
2	Third	SYNSHRPC	TEF20-0	20	0	0.5
2	Third	SYNSHRPC	TEF20-10	20	10	0.5
2	Third	SYNSHRPC	TEF37-0	37	0	0.5
2	Third	SYNSHRPC	TEF37-10	37	10	0.5
2	Third	SYNSHRPC	NYL3-0	3	0	0.5
2	Third	SYNSHRPC	NYL3A-0*	3	0	0.5
2	Third	SYNSHRPC	NYL3-10	3	10	0.5
2	Third	SYNSHRPC	NYL3A-10*	3	10	0.5
2	Third	SYNSHRPC	NYL20-0	20	0	0.5
2	Third	SYNSHRPC	NYL20-10	20	10	0.5
2	Third	SYNSHRPC	NYL37-0	37	0	0.5
2	Third	SYNSHRPC	NYL37-10	37	10	0.5

* = Data file edited due to LVDT malfunction during testing.

DISK	TEST SESSION DIRECTORY	METHOD #1 SUBDIRECTORY	FILE NAME	σ_d	σ_3	σ_s
2	Fourth	SYN4SHRP	TEF5-3-0	3	0	0.5
2	Fourth	SYN4SHRP	TEF5-310	3	10	0.5
2	Fourth	SYN4SHRP	TEF520-0	20	0	0.5
2	Fourth	SYN4SHRP	TEF52010	20	10	0.5
2	Fourth	SYN4SHRP	TEF537-0	37	0	0.5
2	Fourth	SYN4SHRP	TEF53710	37	10	0.5
2	Fourth	SYN4SHRP	5TEF-3-0	3	0	2.93
2	Fourth	SYN4SHRP	5TEF-310	3	10	2.93
2	Fourth	SYN4SHRP	5TEF20-0	20	0	2.93
2	Fourth	SYN4SHRP	5TEF2010	20	10	2.93
2	Fourth	SYN4SHRP	5TEF37-0	37	0	2.93
2	Fourth	SYN4SHRP	5TEF3710	37	10	2.93

NEW DATA ADDED IN SEPTEMBER 1993 REVISION:

3	Fourth	SYN4SHRP	3-TEF5-0	3	0	0.5 & 1.0
3	Fourth	SYN4SHRP	3-TEF510	3	10	0.5 & 1.0
3	Fourth	SYN4SHRP	3ATEF5-0*	3	0	0.5 & 1.0
3	Fourth	SYN4SHRP	3ATEF510*	3	10	0.5 & 1.0
3	Fourth	SYN4SHRP	20TEF5-0	20	0	0.5 & 1.0
3	Fourth	SYN4SHRP	20TEF510	20	10	0.5 & 1.0
3	Fourth	SYN4SHRP	37TEF5-0	37	0	0.5 & 1.0
3	Fourth	SYN4SHRP	37TEF510	37	10	0.5 & 1.0

* = Data file edited due to LVDT malfunction during testing.

DISK	TEST SESSION DIRECTORY	METHOD #2 SUBDIRECTORY	FILE NAME	σ_d	σ_3	σ_s
2	Fourth	SYNSHRP4	TEF5-3-0	3	0	0.5
2	Fourth	SYNSHRP4	TEF5-310	3	10	0.5
2	Fourth	SYNSHRP4	TEF520-0	20	0	0.5
2	Fourth	SYNSHRP4	TEF52010	20	10	0.5
2	Fourth	SYNSHRP4	TEF537-0	37	0	0.5
2	Fourth	SYNSHRP4	TEF53710	37	10	0.5

NEW DATA ADDED IN SEPTEMBER 1993 REVISION:

3	Fourth	SYNSHRP4	3-TEF5-0	3	0	0.5 & 1.0
3	Fourth	SYNSHRP4	3-TEF510	3	10	0.5 & 1.0
3	Fourth	SYNSHRP4	3ATEF5-0*	3	0	0.5 & 1.0
3	Fourth	SYNSHRP4	3ATEF510*	3	10	0.5 & 1.0
3	Fourth	SYNSHRP4	20TEF5-0	20	0	0.5 & 1.0
3	Fourth	SYNSHRP4	20TEF510	20	10	0.5 & 1.0
3	Fourth	SYNSHRP4	37TEF5-0	37	0	0.5 & 1.0
3	Fourth	SYNSHRP4	37TEF510	37	10	0.5 & 1.0

* = Data file edited due to LVDT malfunction during testing.

DISK	TEST SESSION DIRECTORY	METHOD #3 SUBDIRECTORY	FILE NAME	σ_d	σ_3	σ_s
2	Fourth	SYNSHRPD	TEF5-3-0	3	0	0.5
2	Fourth	SYNSHRPD	TEF5-310	3	10	0.5
2	Fourth	SYNSHRPD	TEF520-0	20	0	0.5
2	Fourth	SYNSHRPD	TEF52010	20	10	0.5
2	Fourth	SYNSHRPD	TEF537-0	37	0	0.5
2	Fourth	SYNSHRPD	TEF53710	37	10	0.5
2	Fourth	SYNSHRPD	5TEF-3-0	3	0	2.93
2	Fourth	SYNSHRPD	5TEF-310	3	10	2.93
2	Fourth	SYNSHRPD	5TEF20-0	20	0	2.93
2	Fourth	SYNSHRPD	5TEF2010	20	10	2.93
2	Fourth	SYNSHRPD	5TEF37-0	37	0	2.93
2	Fourth	SYNSHRPD	5TEF3710	37	10	2.93

NEW DATA ADDED IN SEPTEMBER 1993 REVISION:

3	Fourth	SYNSHRPD	3-TEF5-0	3	0	0.5 & 1.0
3	Fourth	SYNSHRPD	3-TEF510	3	10	0.5 & 1.0
3	Fourth	SYNSHRPD	3ATEF5-0*	3	0	0.5 & 1.0
3	Fourth	SYNSHRPD	3ATEF510*	3	10	0.5 & 1.0
3	Fourth	SYNSHRPD	20TEF5-0	20	0	0.5 & 1.0
3	Fourth	SYNSHRPD	20TEF510	20	10	0.5 & 1.0
3	Fourth	SYNSHRPD	37TEF5-0	37	0	0.5 & 1.0
3	Fourth	SYNSHRPD	37TEF510	37	10	0.5 & 1.0

* = Data file edited due to LVDT malfunction during testing.