LABORATORY TESTS FOR GRANULAR MATERIALS FOR FLEXIBLE AIRFIELD PAVEMENTS

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ABSTRACT

The U.S. Army Engineer Research and Development Center (ERDC) conducted a series of full-scale traffic experiments on flexible pavement test sections to evaluate design criteria for military pavements. The experimental research objectives were to evaluate the minimum thickness of asphalt surfacing for the F-15 and C-17 aircrafts, evaluate the performance of marginal base materials in flexible pavements, and evaluate the newly developed thickness criteria for flexible pavements. Standard triaxial and repeated-load triaxial tests were conducted on the 5 granular materials used in the test sections. These tests were also conducted on CH subgrade clay having California Bearing Ratio (CBR) values of 4, 10, and 15. By closely following the protocol described in the National Cooperative Highway Research Program Report 453 for the development of laboratory test procedures for evaluating the quality of granular materials, ERDC developed test protocols to evaluate the resilient modulus and shear strength of the materials being tested. This paper presents the test protocols, example material test results, and a proposed procedure for analysis of the material test data.

INTRODUCTION

Full-scale flexible pavement tests were conducted to evaluate the design criteria for military pavements. Three different test sections were designed to evaluate three objectives, which included the minimum thickness of asphalt surfacing for the F-15 and C-17 aircrafts, performance of marginal base materials in flexible pavements, and newly developed thickness criteria for flexible pavements. Each test section was constructed with instrumentation and trafficked using a load cart to simulate F-15 and C-17 loading patterns. In conjunction with these main three objectives, the granular materials and CH subgrade clay used in the test sections were further examined to develop test protocols for predicting pavement performance.

The current method used to design flexible pavements was developed by the U.S. Army Corps of Engineers at the start of World War II**.** Due to the increased tire loads and tire pressures of military vehicles and aircrafts, these design procedures have been increasingly challenged, particularly in the use of locally available materials for base and sub-base layers. The main structural elements to protect the subgrade of such pavements are the granular base and sub-base layers. Granular materials of increasing strength are used to protect the weaker natural subgrade.

Characterization of both subgrade and granular materials is necessary to predict the performance of flexible pavements. The performance of unbound, granular pavement layers is dependent on aggregate properties. Poor granular pavement layers perform poorly and lead to pavement distresses. Current procedures for characterizing granular and subgrade materials are not adequate for designing pavements. The current procedure for selecting granular materials is not based on a direct strength characterization, but rather indirectly by using gradation and fractured faces. Subgrade material has historically been characterized using the CBR test, which is not compatible with mechanistic design methodologies.

Strength and stiffness are important characteristics of pavement materials that influence pavement performance. According to the National Cooperative Highway Research Program (NCHRP) Report 453 [1], shear strength was judged to be the most important parameter to quantify the behavior of granular materials. The authors believe this same theory could be extended to subgrade materials as well. The Mohr-Coulomb strength theory is a methodology for measuring shear strength. The shear strength (τ_f) can be calculated using the Mohr-Coulomb failure criterion equation:

$$\tau_f = c + \sigma \tan \phi \qquad \text{Equation 1}$$

where c is the cohesion, ϕ is the angle of internal friction, and σ is the normal stress on the failure plane.

The resilient modulus is used in mechanistic design methodologies. The NCHRP Report 453 [1] recommends the repeated-load triaxial test for determining both resilient modulus and shear strength. Repeated-load tests were run on both granular and subgrade materials in conjunction with ongoing full-scale test sections.

TESTING PROCEDURE

The materials were tested using both quick/standard and repeated-load triaxial tests, and the cohesion and angle of internal friction values were estimated using these two tests. The behavior of resilient modulus was also examined using the results from the resilient modulus tests. The following sections describe sample preparation, testing protocols, and results.

Sample Preparation for Granular Materials

Prior to testing, each granular material sample was subjected to a rigorous preparation process. First, compaction curves were run on the samples to determine the optimum moisture content. The granular material was air dried until a constant moisture content was achieved before adding water to bring the sample to the optimum moisture content. A porous stone with a filter paper cover was placed in the bottom of a split mold prior to placing the material in the mold. The specimens were compacted in the split mold using a vacuum to keep the membrane expanded. For materials with maximum aggregate sizes of 0.5 in. or less, a mold that was 4 in. in diameter and 8 in. high was used. For materials with maximum aggregate sizes greater than 0.5 in., a mold that was 6 in. wide and 12 in. high was used. Each specimen was compacted in 8 lifts, using a 5.5-lb drop hammer at a height of 12 in. The heights of the second, fourth, and eighth lifts were measured to verify the sample density. After the eighth lift, the top was leveled, and if necessary, a small amount of sand was used on the surface to aid in obtaining a level top. A top filter paper, porous stone, and end cap were all placed on the specimen after compaction. The height and diameter of the specimens were then measured, and a second membrane was placed over the first membrane to prevent membrane leakage. After placing the specimen in the triaxial testing chamber, the chamber was sealed, and a low pressure (5 psi) was applied to the chamber. As the chamber pressure was applied, the vacuum on the specimen was released, and the drain to the specimen was opened to the atmosphere. The specimen was then ready to be placed on the test platform for loading.

Sample Preparation for Subgrade Materials

The subgrade sample specimens were taken from the test sections using 3-in.-diameter and 10-in.-length Shelby-tube samplers. Samples were wrapped with plastic wrap and aluminum foil, dipped in wax for moisture retention, and stored in a humid room until time for testing. At the time of testing, the samples were trimmed to a cylinder size of 2.8 in wide and 5.6 in. high. Samples were then covered with a rubber membrane and placed in the triaxial chamber for testing.

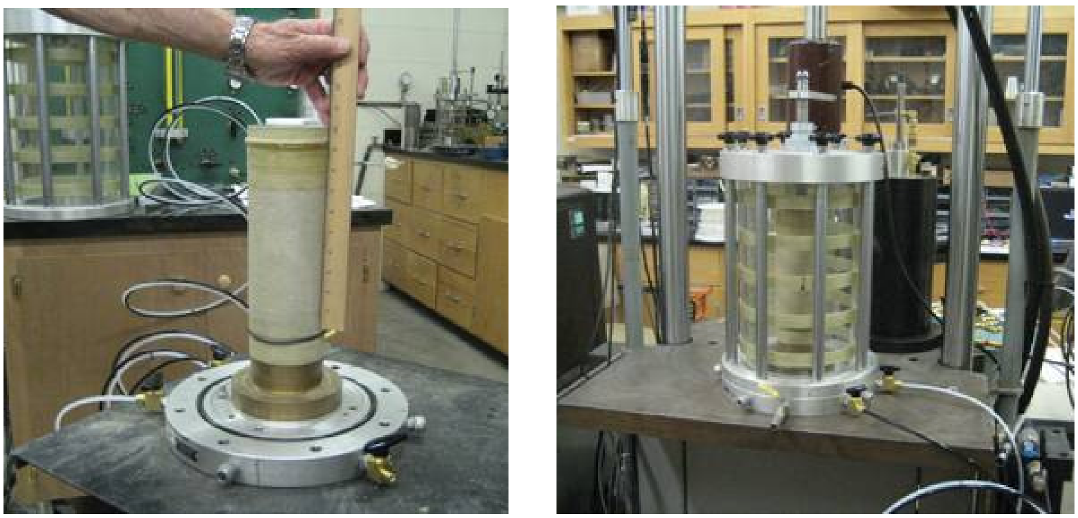

Figure 1. Specimen with membrane and the testing chamber.

Testing procedure

Three specimens were tested in both the standard and repeated-load triaxial tests under drained conditions at confining stresses of 5, 15, and 30 psi. Samples were not conditioned prior to testing. For the standard triaxial tests, the tests were conducted in a controlled rate of deformation (strain) mode. The rate of strain remained at 1% strain-per-minute until a total deformation of 0.85 in. was achieved. During testing, the cross-head movement, LVDT movement, and applied load were recorded. After testing, the water content and dry density were determined from the specimen.

For the repeated-load triaxial tests, the specimens were subjected to an array of increasing repeated increments of load instead of the constant strain rate loading used in standard triaxial testing. The load increments for a particular confining stress were determined by dividing the maximum strength, as determined from the standard triaxial tests, by 5 and rounding to the nearest 25 lb. The minimum load is 2-4 lb. Each load increment was applied for 1,001 cycles. For each load cycle, the load was applied for 1 second with a no-load duration of 2 seconds. The load waveform was an offset sine curve which was chosen to simulate the frequency of the load cart on the stress sensors within the full-scale test section. Although the pulse cycle estimated for the loading cycle of the load cart was approximately 6 seconds, the loading cycle for the laboratory testing was reduced by half so that one test could be run during an 8-hour day. A direct comparison of the laboratory testing and field testing was not done at this time, so the effect of the difference in loading cycles were not examined. Figure 2 shows an example of the load pulse and the corresponding response pulse. The load levels were increased until the specimen failed, which was at approximately 10% deformation. During testing, the time, load, crosshead movement, LVDT movement, chamber pressure, and cycle number were all recorded after the following cycles: 1-10, 20-100 in steps of 10, and 100-1,000 in steps of 100. Only these select cycles were recorded to keep the datasets manageable.

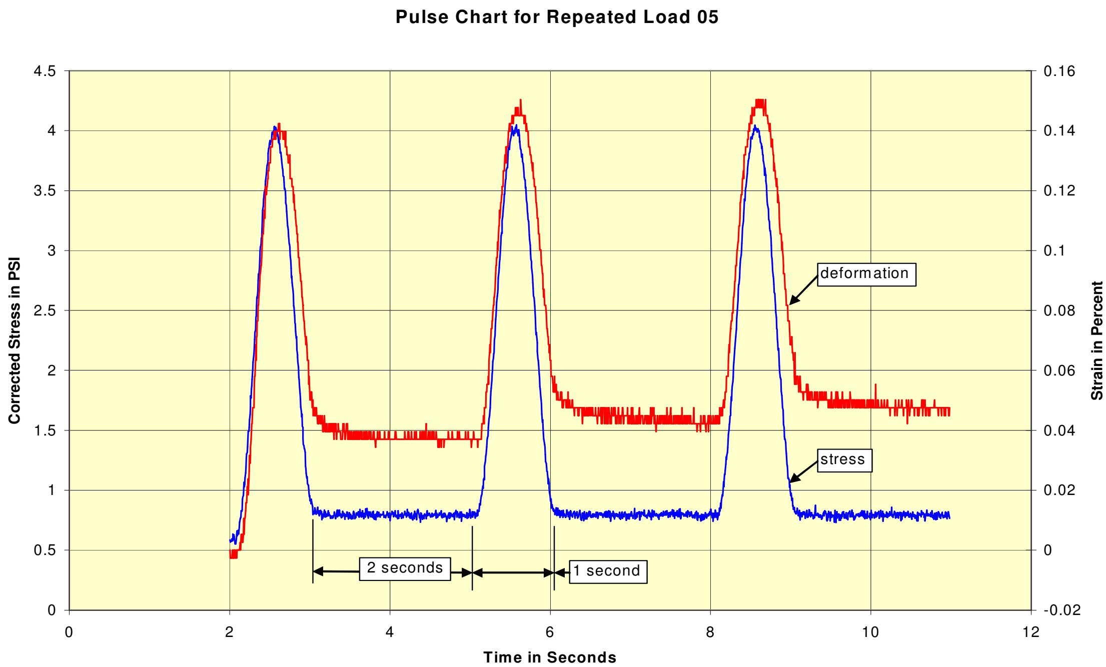

Figure 2. Example of the load pulse and corresponding response pulse.

TEST RESULTS AND DISCUSSION

Granular Materials

Figure 3 shows the stress-strain curves for the 3 confining stresses. This data was used to construct the Mohr Circle, which is shown in Figure 4, so that the cohesion and angle of internal friction values could be estimated. The maximum load from the standard triaxial tests was used to determine the load increment for the repeated-load triaxial tests, as noted earlier.

The repeated-load triaxial tests were run to determine the strength under repeated load and also to determine the resilient modulus. For the repeated-load triaxial tests, an example of stress-strain curves for one load increment can be seen in Figure 5. Figure 6 presents the permanent deformation as a function of the applied stress. Permanent deformation was defined as the deformation that occurs in the 900 load cycles between cycles 100 and 1,000. Deformation occurring in the first 100 cycles was not included because there was too much variability during these cycles. The stress applied during the load cycle is plotted on the x axis and permanent deformation on the y axis. Failure was defined as permanent deformation of 0.02 in./in. In this manner, the failure stress for the repeated triaxial tests for each confining stress was determined. From these data, the Mohr Circle was constructed for each material, as shown in Figure 7. Similar cohesion and angle of internal friction values were obtained from both the standard triaxial and repeated-load triaxial tests, as can be seen in Table 1. Using the values obtained from both sets of triaxial testing, the shear strength was calculated using the Mohr-Coulomb failure criterion equation and an assumed normal stress of 10 psi, as seen in Figure 8. The shear strength relationship among the different materials is easy to observe, and the values between the two tests yield similar results.

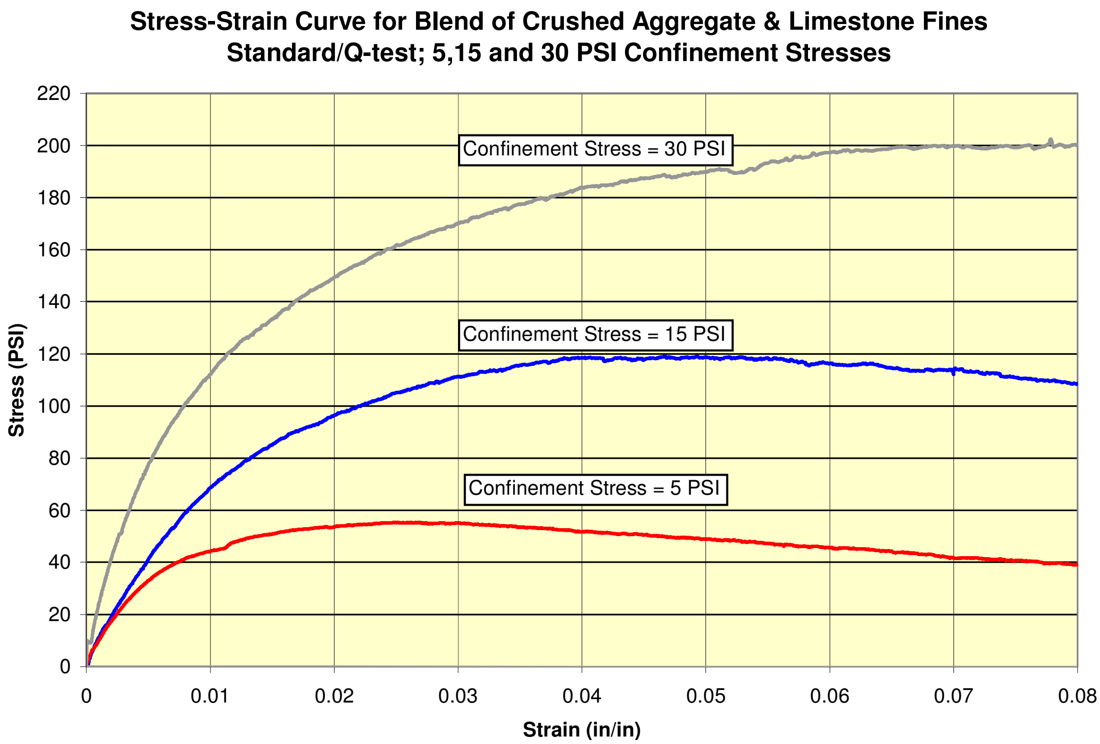

Figure 3. Example of a stress-strain curve from a standard/quick triaxial test.

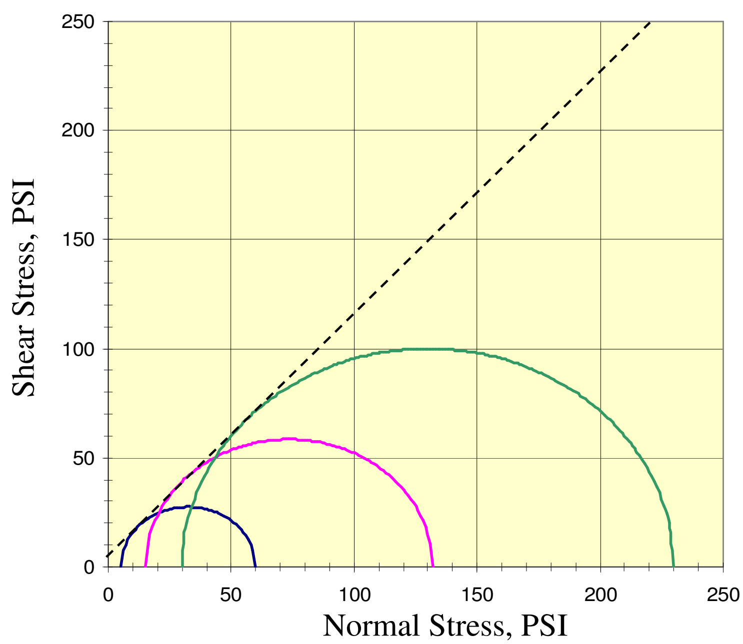

Figure 4. Example of the Mohr Circle diagram for the standard triaxial test.

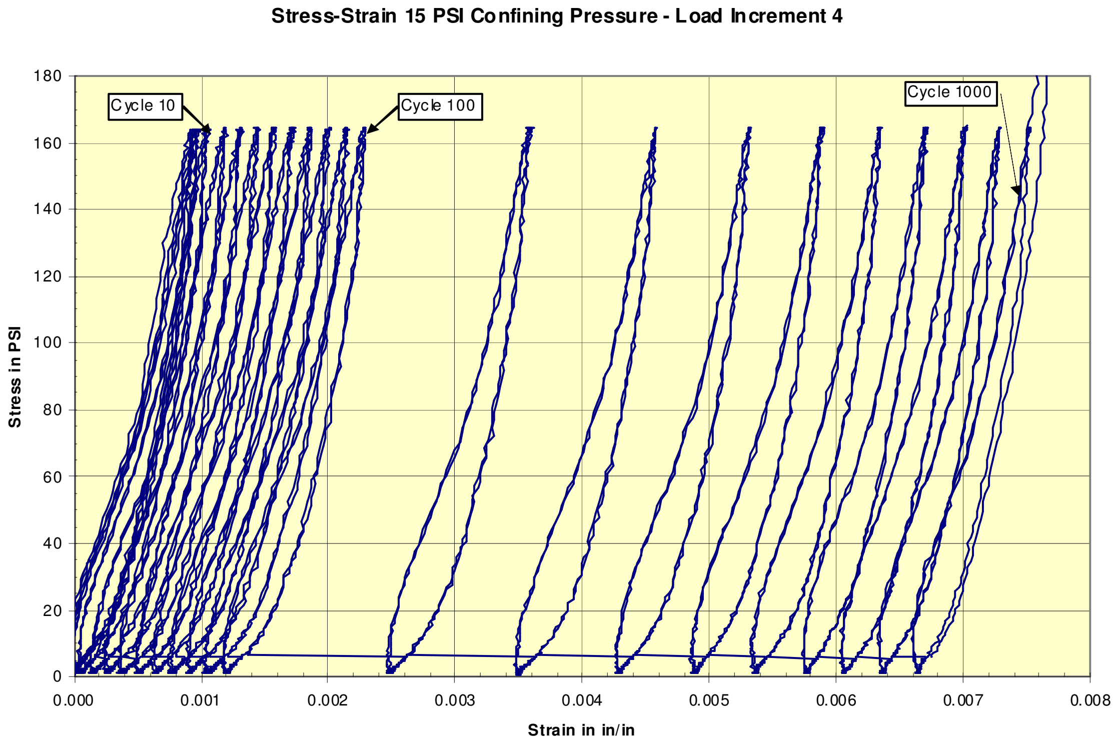

Figure 5. Example of stress-strain curve for a repeated load test.

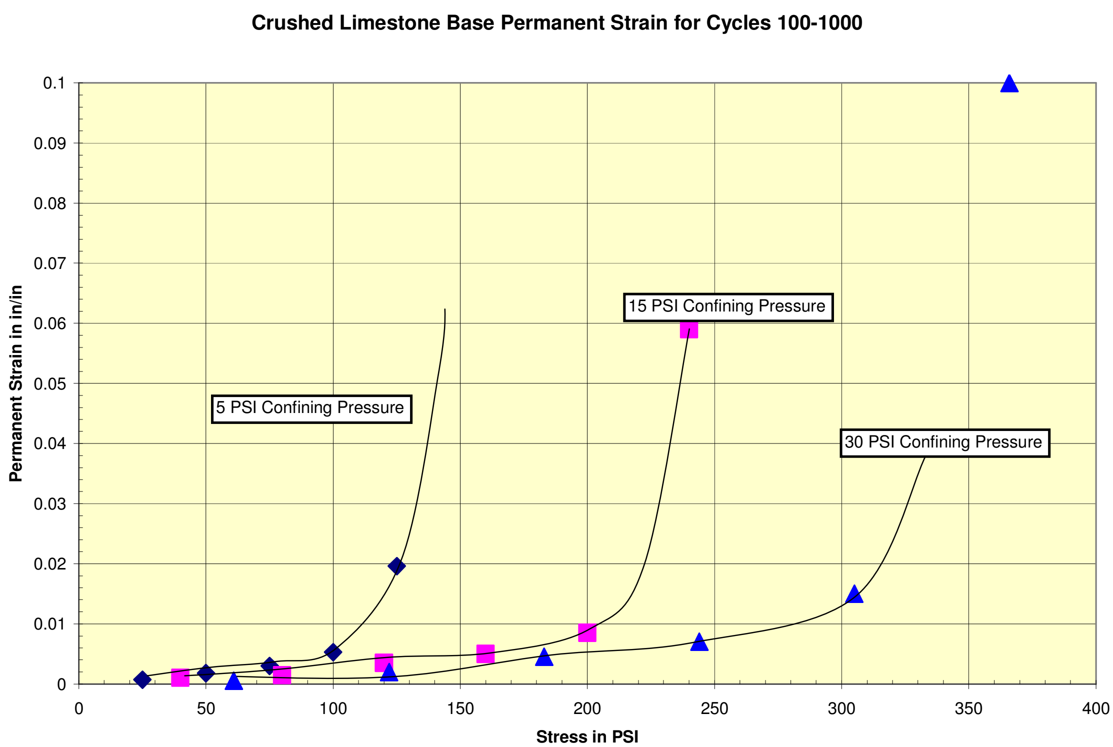

Figure 6. Permanent deformation/strain of crushed limestone.

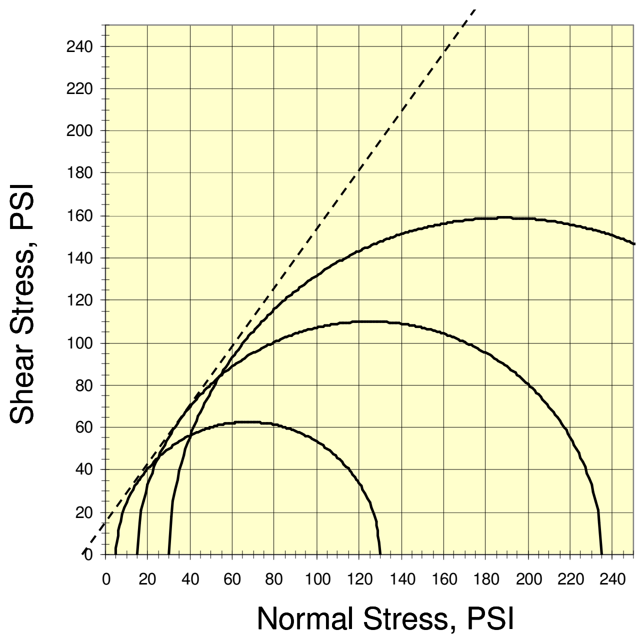

Figure 7. Example of the Mohr's Circle for a repeated-load triaxial test for crushed limestone.

Table 1.
Summary of Results.

Material	Quick-Drained / Standard			Repeated Load		
	Cohesion (psi)	**Angle of Internal Friction (Deg)**	**Shear Strength[a] (psi)**	**Cohesion (psi)**	**Angle of Internal Friction (Deg)**	**Shear Strength[a] (psi)**
Sand	2	43	11	8	40	16
Crushed Gravel	0	54	14	5	52	18
Crushed Limestone	17	53	30	14	55	28
Blend Crushed Gravel and Sand	2	54	16	0	54	14
Blend Crushed Gravel and Limestone Fines	8	49	20	5	51	17

[a] Based on an assumed normal stress of 10 psi

Figure 9 shows the behavior of the resilient modulus during a repeated-load triaxial test for a blend of crushed aggregate and limestone fines. The resilient modulus for granular materials remains relatively constant, staying within a narrow range during the load increments. However, as would be expected, an increase in resilient modulus is noted with increasing confinement stress.

Figure 10 depicts the stress-strain curves for the subbase material, CH clay, at 3 different CBR levels (4, 10, and 15 CBR). An example of the behavior of resilient modulus for clay can be seen in Figure 11. The resilient modulus for the clay materials is dependent on the load increments such that increasing load increments causes a decrease in resilient modulus. However, the resilient modulus appears to be independent of the confinement stress.

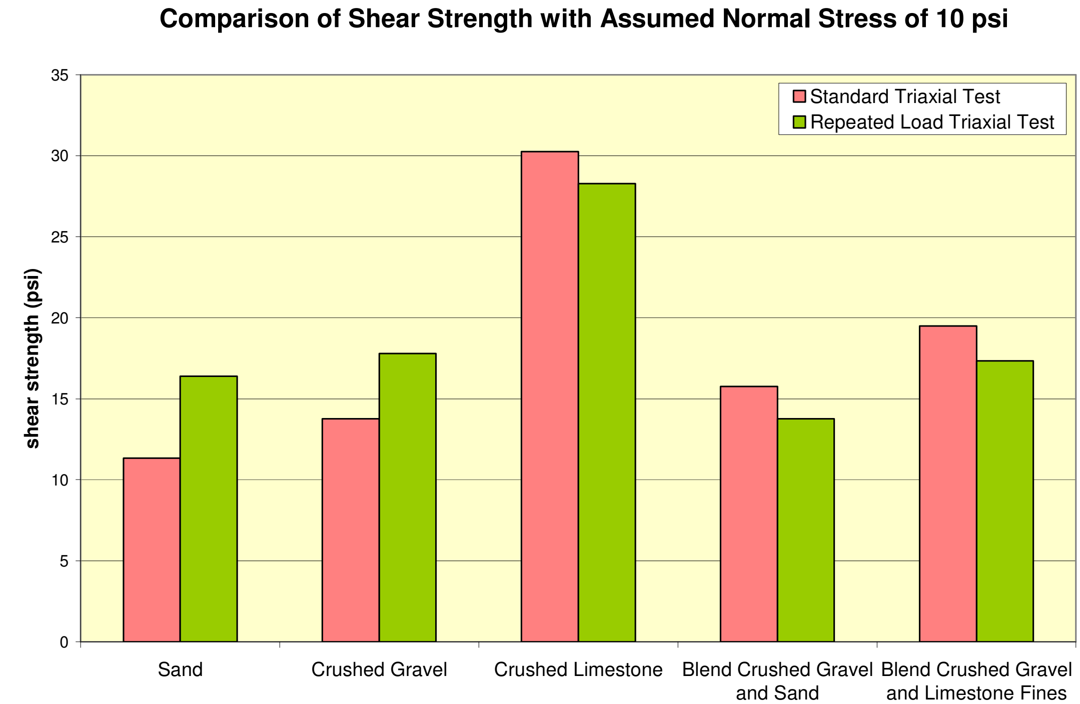

Figure 8. Plot of the shear strength resulting from the values extracted from the standard and repeated-load triaxial tests and an assumed normal stress of 10 psi.

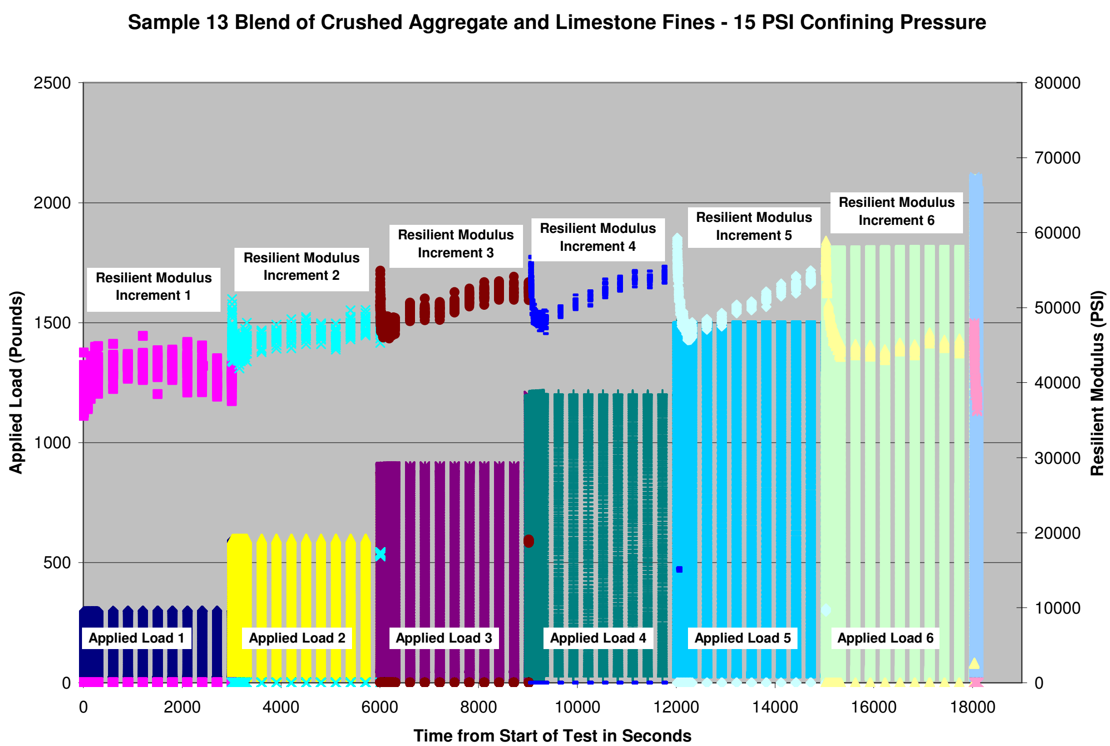

Figure 9. Applied load and corresponding resilient modulus values for the repeated-load triaxial test at a confining stress of 15 psi for the blend of crushed aggregates and limestone fines.

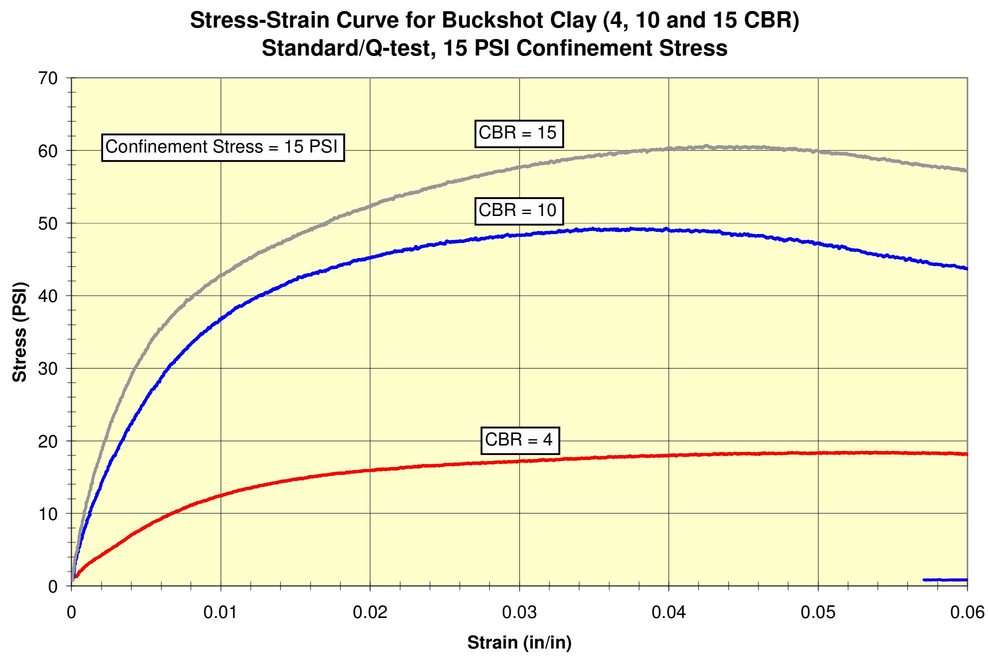

Figure 10. Example of stress strain curve for standard triaxial tests for the subgrade materials, CH clay at 4, 10, and 15 CBR.

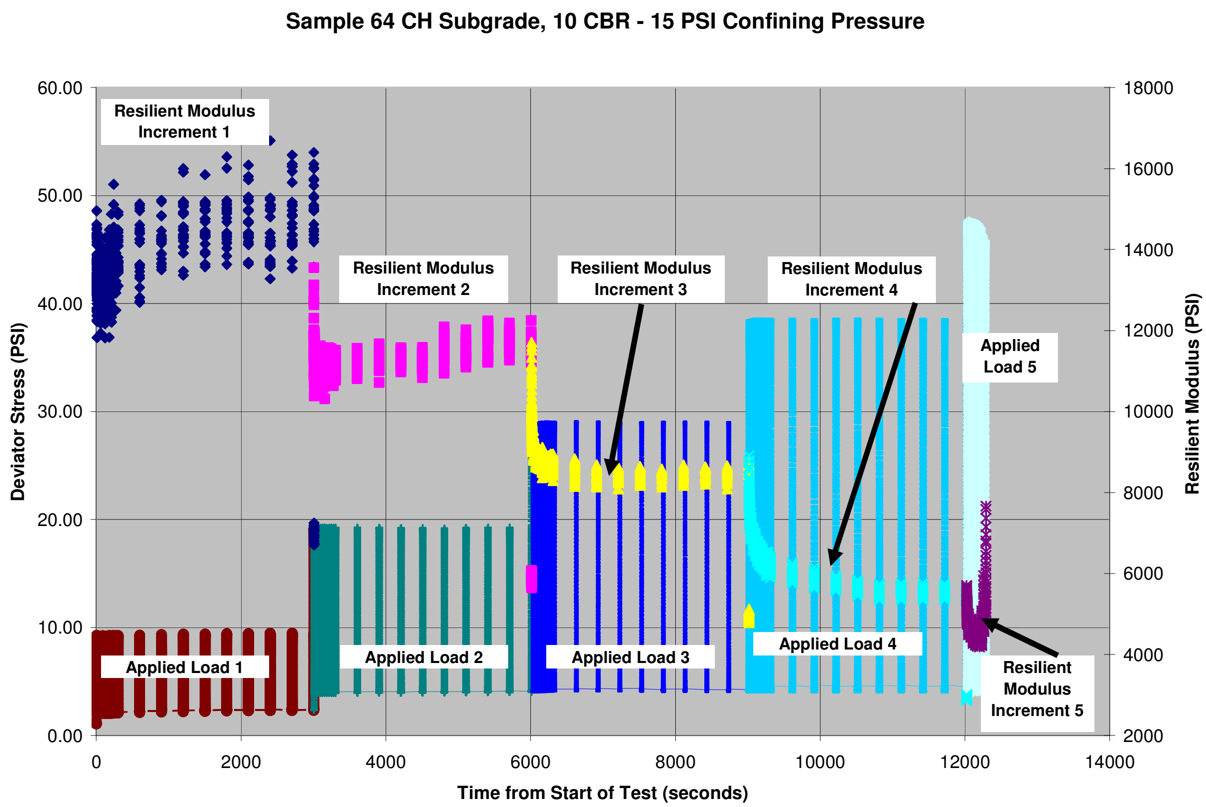

Figure 11. Example of stress strain curve for standard triaxial tests for the subgrade materials, CH clay at 4, 10, and 15 CBR.

CONCLUSIONS

Standard triaxial and repeated-load triaxial tests were used to determine the strength and resilient modulus of the materials. The results for the cohesion and angle of internal friction values were comparable for the standard and repeated triaxial load testing. The repeated-load triaxial test is an improvement over the standard triaxial test because it more accurately represents actual loading conditions, and the resilient modulus can be estimated from repeated load test results. Materials are also stressed to reach permanent deformation to provide a better understanding of the material behavior. However, the repeated-load triaxial test procedure as described in this paper is more complicated and time consuming to execute than the standard triaxial test.

REFERENCES

1. Saeed, Athar, Hall, Jim W., and Barker, Walter, "Performance-Related Tests of Aggregates for Use in Unbound Pavement Layers," National Cooperative Highway Research Program Report 453, Transportation Research Board, National Research Council, Washington, DC, 2001.