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# Comparison of Diametral and Triaxial Repeated Load Testing Techniques for Untreated Soils

**JOSE R. MONTALVO, CHRIS A. BELL, and JAMES E. WILSON**

## ABSTRACT

The techniques involved in, and the results from, resilient modulus testing of subgrade soils typically found in Oregon are described in this paper. In addition, two methods of testing, the triaxial and diametral repeated load procedures, were investigated. Subgrade soils obtained from two projects were tested. One project was a new alignment construction project in the Willamette Valley (Salem Parkway) for which there were two distinct subgrade soils (AASHTO classifications A-7-6 and A-4); the other was an overlay project in central Oregon (US-97) with a pumiceous subgrade soil (AASHTO classification A-1-b). It was found that the diametral testing procedure was adequate for use with cohesive soils, typical of those occurring in the Willamette Valley, but it is not recommended for use with the noncohesive volcanic soils occurring in eastern Oregon. For such soils, the triaxial testing mode is recommended. The major advantage of the diametral test for treated materials is its simplicity compared to the triaxial test. However, the necessity to consider the effects of confining pressure for untreated soils diminishes this advantage, and with cohesionless soils, the test is no simpler than the triaxial test, which is preferable for modeling the in situ stress regime.

Highways in Oregon, as well as in other states, are constructed using a wide variety of subgrade materials, and pavement structural sections designed using standard procedures, such as the Hveem or CBR methods, often do not perform satisfactorily. To attempt to more accurately predict pavement performance, analytical procedures based on multilayer elastic theory in conjunction with suitable failure criteria can be employed. This approach requires a knowledge of the mechanical properties of each pavement component under repeated load test conditions, typically the dynamic Young's modulus (resilient modulus, $M_R$) and Poisson's ratio ($\nu$).

## OBJECTIVES

The specific objectives of this study were to (a) compare the diametral and triaxial repeated load testing techniques for untreated soils, and (b) recommend procedures for routine use of the diametral test for soils evaluation and pavement design.

## STUDY APPROACH

The results of a study to examine the use of two repeated load testing procedures, the diametral and triaxial devices, are presented. Soils typical of those occurring as subgrades in Oregon were selected for testing to achieve the objectives of this study. The soils used were obtained from Oregon highways, the Salem Parkway in the Willamette Valley, and the US-97 highway in central Oregon, and represent typical soils for those areas (Figure 1). The testing program undertaken is shown in Figure 2 and is discussed later in this paper. The test equipment and procedure associated with repeated load triaxial and diametral resilient modulus are also presented. Test results for both subgrade soils are summarized and analyzed. Comparison of the resilient properties determined with repeated load triaxial and diametral test is presented. Also, comparison of testing equipment and the procedure associated with the repeated load diametral and triaxial resilient modulus test is presented. Finally, conclusions and recommendations for the use of both test methods are presented.

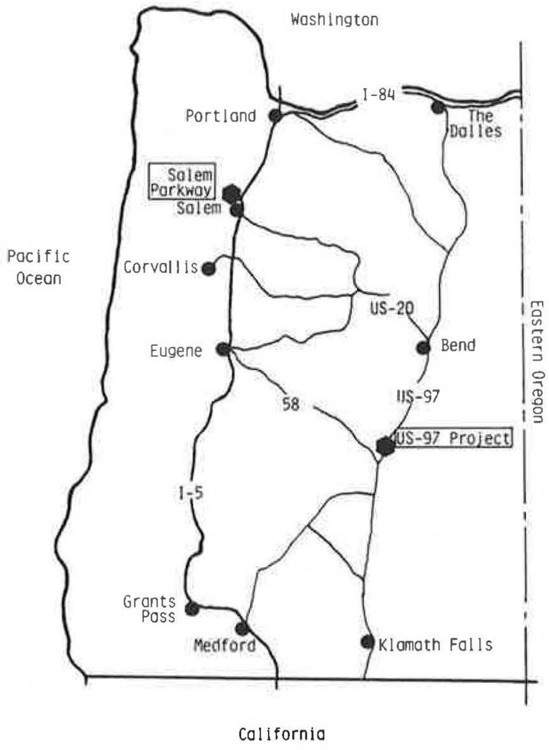

FIGURE 1 Location map—Salem Parkway and US-97 projects.

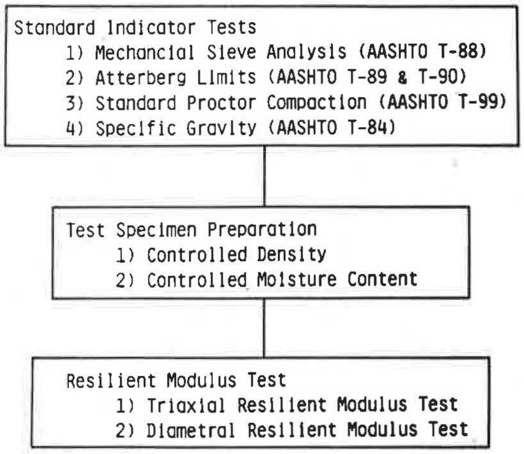

FIGURE 2 Flow chart of test program for subgrade materials.

## EXPERIMENTAL PROGRAM

### Project Locations and Descriptions

The subgrades from two project sites were selected for this study. The first site was a new alignment construction project in the Willamette Valley, which will be referred to as the Salem Parkway project, and the second was an asphalt concrete overlay project east of the Cascades, which will be referred to as the US-97 project. The precise location of both the projects is shown in Figure 1.

### Test Program

The test program undertaken in the study for the subgrade materials is shown in Figure 2. The program consisted of four major phases:

1. Standard indicator tests and in situ properties,
2. Test specimen preparation,
3. Repeated load diametral modulus tests, and
4. Repeated load triaxial modulus tests.

The standard indicator tests were performed for basic identification of subgrade materials. In situ properties, that is, density and moisture content, of subgrade materials were also determined using the sand cone method (AASHTO T-191).

The resilient modulus ($M_R$) of the subgrade materials was determined for a range of density and moisture content close to those obtained in the field. Each phase of the test program is discussed in the paragraphs that follow.

### Standard Indicator Tests and In Situ Properties

The standard indicator tests were performed at the Materials Section, Highway Division, Oregon Department of Transportation, Salem. These included Atterberg limits (AASHTO T-89 and T-90), sieve analysis (AASHTO T-88), specific gravity (AASHTO T-84), and standard Proctor compaction (AASHTO T-99).

Results of standard indicator tests, summarized in Table 1, show that the subgrades occurring along the Salem Parkway project were a clay and a silty sand material, which classified as A-7-6 and A-4 (AASHTO soil classification), respectively. These soils will be referred to as subgrade 1 and subgrade 2. A volcanic pumiceous material, which classified as A-1-b, occurred as the subgrade for the second project (US-97). The results of the standard Proctor compaction test for this material are variable. This is due to the nature of the pumice-type volcanic material, which absorbs moisture and retains a high moisture content. On the basis of the tests performed on this material and experience in the use of the pumice material (3,6), a maximum density of 45 pcf and 60 percent optimum water content was used for testing. Results of in situ material properties are summarized in Table 2. The in situ density of the US-97 subgrade material was not determined.

### Specimen Preparation

The desired water contents and densities for the subgrade materials used in the repeated load tests were determined by choosing moisture contents above and below optimum and at a maximum dry density obtained from the standard AASHTO compaction test (T-99), and at 100 percent and 95 percent of the AASHTO T-99 maximum dry density such that the range

TABLE 1 Material Properties, Standard Indicator Test

| | % Passing | | |
|---|---|---|---|
| | Salem - New Parkway Subgrade* | | US - 97 |
| Particle Size | 1 | 2 | Subgrade |
| 38.1 mm (1-1½") | | | |
| 25.4 mm (1") | | | 100.0 |
| 19.0 mm (3/4") | | | 99.8 |
| 12.7 mm (1/2") | | | 98.2 |
| 9.5 mm (3/8") | | | 95.8 |
| 6.4 mm (1/4") | | | 91.1 |
| 4.75 mm (No.4) | 100 | 100 | 87.6 |
| 2.00 mm (No.10) | 99.9 | 99.9 | 66.1 |
| 0.425 mm (No.40) | 98.9 | 99.7 | 32.1 |
| 0.175 mm (No.60) | 96.2 | 99.5 | 26.4 |
| 0.074 mm (NO.200) | 73.1 | 33.1 | 17.3 |
| Liquid Limit, % (AASHTO T-89) | 48 | 23 | NP |
| Plasticity Index % (AASHTO T-90) | 20 | NP | NP |
| Specific Gravity | 2.70 | 2.72 | 2.20 |
| AASHTO Soil Classification | A-7-6 | A-4 | A-1-b |
| Maximum Density (pcf) (AASHTO T-99) | 90.45 | 107 | 45** |
| Optimum Water Content, % (AASHTO T-99) | 25 | 18 | 60** |

1 KN/m$^3$ = 6.369 pcf

* subgrade:
1 - Clayey soil (AASHTO classification A-7-6)
2 - Silty soil (AASHTO classification A-4)
** used for testing

TABLE 2 In-Place Material Properties

| | IN PLACE | | | |
|---|---|---|---|---|
| | Water Content, (%) | | Density, pcf | |
| | Subgrade* | | Subgrade* | |
| Location and Material | 1 | 2 | 1 | 2 |
| Salem - New Parkway | | | | |
| - Subgrade | 23.5 | 14.2 | 83.1 | 103.9 |
| US - 97 | | | | |
| - Subgrade | 76.1 | | + | |

+ No in-place tests were conducted.

Subgrade*:
1 = clayey soil (AASHTO classification A-7-6)
2 = silty soil (AASHTO classification A-4)

of test conditions encompassed those occurring in each project. Figure 3 summarizes the combination of moisture and density for which resilient modulus tests ($M_R$) were conducted. Due to the limited time available for this study, the comparison between the diametral and triaxial testing modes was possible for only subgrade 2 from the Salem Parkway project and for the subgrade from the US-97 project. In addition, due to the high level of saturation at 100 percent relative compaction and wet of optimum condition, tests were not successful at this combination. For similar reasons, tests at 95 percent relative compaction and wet of optimum were not successful for the Salem Parkway subgrade 2 soil. In the interest of brevity, only those results at 95 percent relative compaction are presented here. In summary, duplicate samples were tested by using the repeated load triaxial and diametral test devices at five different combinations of moisture content and density.

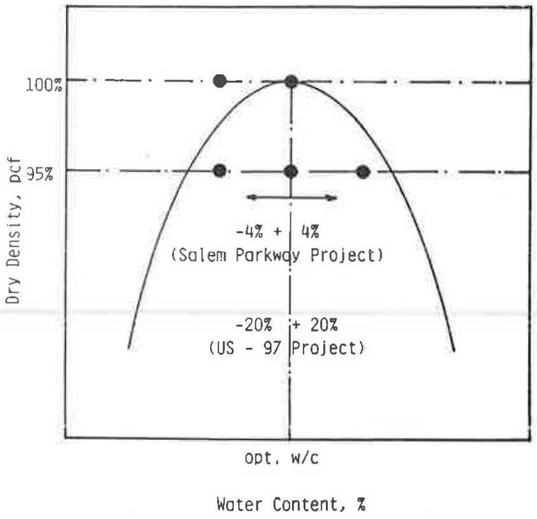

FIGURE 3 Combination of moisture and density for resilient modulus subgrade testing program.

The triaxial test specimen preparation was based on procedures used by Filz (1); Hull, et al. (2); and Kidwai (3). The test specimens were prepared by adding a predetermined amount of water to the sample and allowing equilibrium to be reached (24-hr waiting period). The appropriate soil weight was proportioned to give the desired specimen density in a mold of known volume. The test specimens were compacted in seven lifts (triaxial modulus specimen) and two lifts (diametral modulus specimen). A 2.5-kg (5.5-lb) hammer dropped 30.5 cm (12 in.) was used in compacting the specimens. Trial-and-error procedures were used to determine the number of blows per lift to reach the desired density. This procedure is different from AASHTO T-99, which uses 25 blows per layer and 3 layers establishing an unknown density.

## Repeated Load Triaxial Resilient Modulus Test Equipment and Procedures

The repeated load triaxial test device consists of:

1. Triaxial cell,
2. Loading system,
3. Timing device, and
4. Suitable readout equipment for the type of loading and deformation monitoring devices that are incorporated.

The test procedures employed were essentially the same as those used in previous studies (1-4). The load on the test specimen is measured by a load cell and vertical displacements are measured by two linear-variable differential transformers (LVDTs). The output from the load cell and LVDTs are input to a strip chart recorder.

The results from repeated load triaxial tests are expressed in terms of a resilient modulus, $M_R$. The resilient modulus is defined as:

$$M_R = \sigma_d/\epsilon_a \quad (1)$$

where

$\sigma_d$ = cyclic deviator stress ($\sigma_d = P/A$),
$\varepsilon_a$ = recoverable axial strain,
$P$ = axial load, and
$A$ = horizontal specimen area.

The test specimen, 10.4 cm (4 in.) in diameter by 25.4 cm (10 in.) high, was enclosed in a rubber membrane, achieved by fitting the rubber membrane in the split mold before compaction. After the mold was removed, LVDT clamps were attached to the specimen-rubber membrane. A 10.4-cm (4-in.) gauge length was set between the clamps, the triaxial cell was assembled, placed in the load frame, and the cyclic load was applied. A load duration of 0.10 seconds at a rate of 30 repetitions per minute was chosen in this study.

The resilient modulus for the subgrade materials was evaluated over a range of stresses. The stress level, sequences, and stress ratios used in the test program are given in Table 3. These are in accordance with recommendations made by Kalcheff and Hicks (4) and were chosen to encompass those likely to occur in the field.

TABLE 3 Stress Level Sequence and Stress Ratio Used for Repeated Load Testing of Untreated Soils

| | | DEVIATOR STRESS, PSI* | | | |
|---|---|---|---|---|---|
| Confining Pressure, psi | | 2 | 4 | 6 | 8 |
| Stress Ratio, $\sigma_1/\sigma_3$ | 1.5 | 1.0 | 2.0 | 3.0 | 4.0 |
| | 2.0 | 2.0 | 4.0 | 6.0 | 8.0 |
| | 2.5 | 3.0 | 6.0 | 9.0 | 12.0 |
| | 3.0 | 4.0 | 8.0 | 12.0 | 16.0 |
| | 3.5 | 5.0 | 10.0 | 15.0 | 20.0 |

1 psi = 6.9 KN/m$^2$.

* $\sigma_d = \sigma_1 . \sigma_3$.

Before the resilient modulus was measured, the sample was preconditioned (1-3) to eliminate the effects of the interval between compaction and loading and initial loading versus reloading. The specimens were preconditioned with 1,000 load repetitions at a combination of confining pressure and deviator stress which produces the greatest deformation of the sample to ensure removal of any permanent deformation. The conditioning starts by applying 200 repetitions at maximum confining pressure and minimum deviator stress, then increasing the deviator stress every 200 repetitions keeping constant the confining pressure until 1,000 repetitions and maximum deviator stress was achieved. After the sample had been conditioned, it was only necessary to subject the sample to 100 to 150 stress repetitions at each combination of confining pressure and deviator stress before measuring the resilient modulus.

### Repeated Load Diametral Resilient Modulus Test Equipment and Procedures

This type of test equipment and procedures have been used extensively at Oregon State University for bituminous mixture characterization (5), and the diametral test system used in this study is the same as the system employed by Hsu et al. (6) for soils. This system and the procedures used are similar to those described in ASTM D 4123-82 for bituminous mixtures.

The repeated load diametral test unit includes the same type of loading and deformation monitoring devices as the repeated load triaxial test unit. The vertical diametral load is measured with a load cell and horizontal deformations are measured with two horizontally mounted transducers. The vertical deformation was measured with a guage head LVDT. The output from the load cell, transducers, and LVDT are recorded with a two-channel strip chart recorder.

The results from repeated load diametral tests are expressed in terms of Poisson's ratio ($\nu_{RI}$) and resilient modulus ($M_R$). Equations developed by Kennedy (7) provide the formulas that permit the calculation of Poisson's ratio and modulus, as follows.

Instantaneous resilient Poisson's ratio:

$$\nu_{RI} = DR\ (0.0673) - 0.8954/DR\ (-0.2494) - 0.0156 \quad (2)$$

Instantaneous resilient modulus:

$$M_R = P/H_{RI} \times t\ (0.2692 + 0.9974\ \nu_{RI}) \quad (3)$$

where

$DR = V_{RI}/H_{RI}$ = deformation ratio,
$H_{RI}$ = instantaneous resilient horizontal deformation,
$V_{RI}$ = instantaneous resilient vertical deformation,
$P$ = diametral load ($P = \sigma_d \cdot t \cdot \pi \cdot d/6$),
$t$ = thickness,
$\sigma_d$ = deviator stress, and
$d$ = diameter of specimen.

The test specimen, 10.4 cm (4 in.) in diameter by 6.4 cm (2.5 in.) high, was compacted and transferred to a split mold and fitted with a rubber membrane. The specimen was enclosed between two aluminum plates, two teflon sheets and the rubber membrane. A vacuum was applied to confine the specimen. The specimen was preconditioned following the same pattern used with the repeated load triaxial test. Also, the resilient modulus was evaluated for the same range of stresses used in the repeated load triaxial tests.

## TEST RESULTS

A summary of the repeated load triaxial and diametral resilient modulus tests is presented in this section. For the Salem Parkway project, the results for 95 percent of maximum density at optimum and -4 percent of optimum water content are presented for the subgrade 2 soil. For the subgrade 1 soil from the Salem Parkway project, only the triaxial test results for 95 percent of maximum density and optimum moisture content are presented. For the US-97 project, results for 95 percent of maximum density and 40, 60, and 80 percent moisture contents are presented.

Although the results obtained at 100 percent of maximum density are not presented here, it was found that the resilient moduli were consistently higher for both testing modes at this higher level of compaction.

### Triaxial Resilient Modulus

Subgrade material from both projects were tested using the repeated load triaxial system. The results for the Salem Parkway project for both subgrade soils are given in Figures 4-6, which show the effect of the confining pressure ($\sigma_3$) and deviator stress ($\sigma_d$) on the triaxial resilient modulus. Both soils exhibited the usual behavior found with fine-grained soils--the triaxial resilient modulus increased with an increase in the confining pressure and decreased to a minimum with an increase of the deviator stress. For the subgrade 2 soil from the Salem Parkway, further increase in deviator stress resulted in a slight increase in modulus.

The triaxial resilient modulus results for the US-97 subgrade are shown in Figures 7-9. These figures show the effect of the confining pressure ($\sigma_3$) and sum of principal stresses ($\theta$) on the triaxial resilient modulus. For this soil, the triaxial resilient modulus increased with an increase in the confining pressure and increased with an increase of the sum of the principal stresses. These results are typical for a coarse-grained soil.

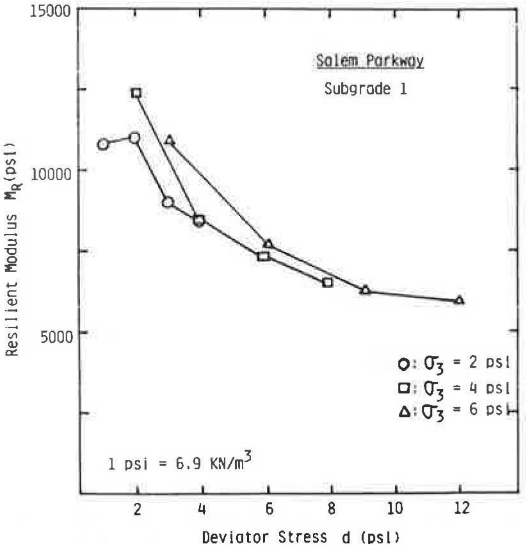

FIGURE 4 Triaxial resilient modulus versus deviator stress, Salem Parkway project, subgrade 1, 95 percent compaction, 25 percent water content.

### Diametral Resilient Modulus

Subgrade material from both projects were tested using the repeated load diametral test equipment; however, only the subgrade 2 soil (AASHTO A-7-6) was tested for the Salem Parkway project. The results for this soil are shown in Figures 5 and 6, which show the effect of the confining pressure, $\sigma_3$, and deviator stress, $\sigma_d$, on the diametral resilient modulus. Diametral resilient modulus test results for the US-97 subgrade soil are shown in Figures 7-9, which show the effect of the confining pressure, $\sigma_3$, and principal stress, $\theta$, on the diametral resilient modulus. The diametral resilient modulus increased with an increase in the confining pressure and increased with an increase of the deviator stress, as shown in Figures 5 and 6. Also, the diametral resilient modulus increased with an increase of the principal stress, as shown in Figures 7-9.

## COMPARISON OF TRIAXIAL AND DIAMETRAL RESILIENT MODULUS TEST RESULTS

### General

The comparison of the triaxial and diametral resilient modulus test procedures is based on the results for subgrade materials from both projects and previous work by Hsu et al. (6).

The resilient modulus for a homogeneous, isotropic, linear elastic material, whether determined with a triaxial system or determined with a diametral test system should be identical. Soils are generally recognized as highly nonlinear, anisotropic, heterogeneous materials. The diametral loading response undoubtedly differs from the triaxial loading response owing to these factors alone.

The comparison between resilient moduli determined with triaxial and diametral test systems may be examined assuming (6):

1. The initial state of stress of the test specimens are identical both in the triaxial and diametral test systems, and

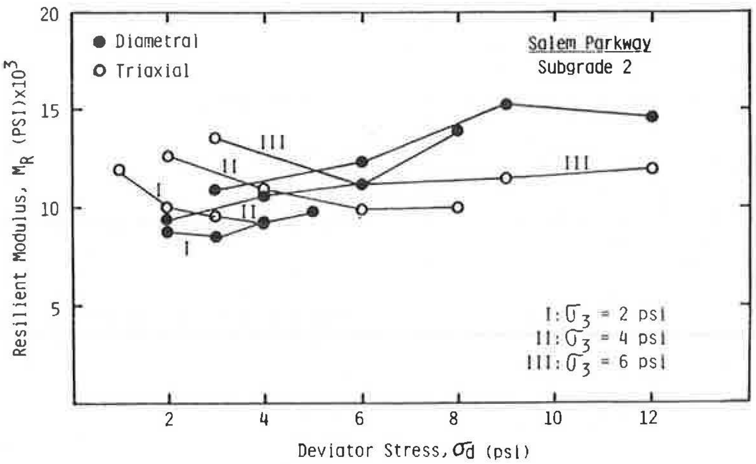

FIGURE 5 Comparison of triaxial and diametral resilient modulus results, Salem Parkway project, subgrade 2, 95 percent compaction, 14 percent water content.

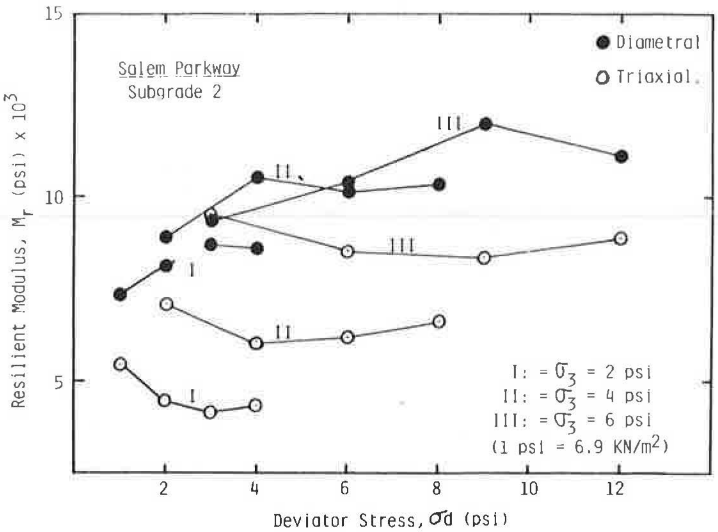

FIGURE 6 Comparison of triaxial and diametral resilient modulus results, Salem Parkway project, subgrade 2, 95 percent compaction, 18 percent water content.

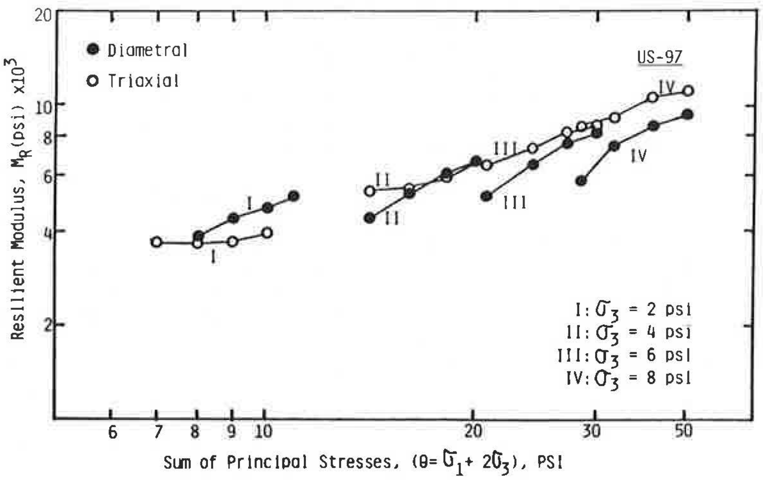

FIGURE 7 Comparison of triaxial and diametral resilient modulus results, US-97 project, subgrade soil, 95 percent compaction, 40 percent water content.

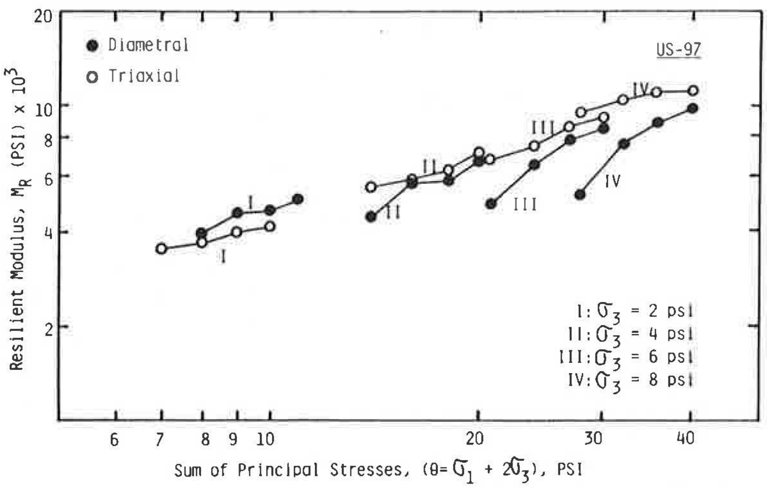

FIGURE 8 Comparison of triaxial and diametral resilient modulus results, US-97 project, subgrade soil, 95 percent compaction, 60 percent water content.

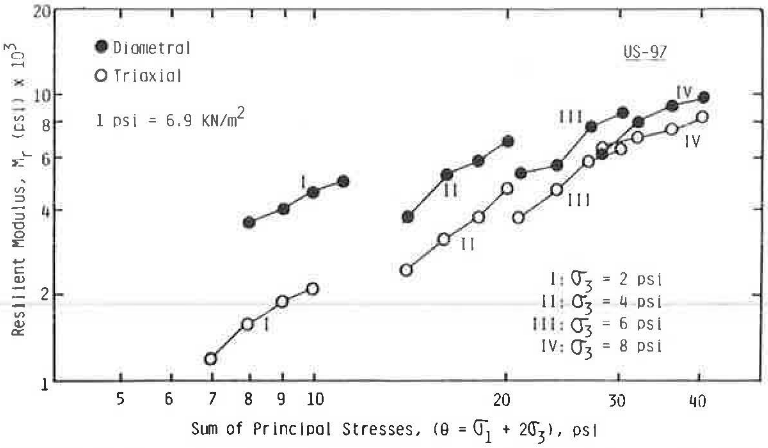

**FIGURE 9** Comparison of triaxial and diametral resilient modulus results, US-97 project, subgrade soil, 95 percent compaction, 80 percent water content.

2. The state of biaxial deviator stress of the diametral test specimen does not affect the resilient modulus and Poisson's ratio, that is, assuming the diametral test specimen is an idealized homogeneous, isotropic, and linear elastic material.

Based on these assumptions, the comparisons between triaxial resilient modulus and diametral resilient modulus may be examined in terms of comparable states of stress. Specifically, the triaxial test results are assessed in terms of the axial compressive deviator stress ($\sigma_d = P/A$), and the diametral test results are assessed in terms of the compressive deviator stress at the center of the specimen ($\sigma_d = 6P/t\pi d$).

Hsu et al. (6) stated that in the diametral resilient modulus test, the deviator stresses are not distributed uniformly either along the vertical or horizontal diameter of the specimen. Equations 2 and 3 used in this study to compute resilient modulus and Poisson's ratio are based on linear elasticity for an idealized material (7). The values of resilient modulus and Poisson's ratio should be constant for a homogeneous, isotropic, and linear elastic material; but the values of resilient modulus and Poisson's ratio for unbound materials would not be constant owing, in part, to the nonlinear and heterogeneous properties associated with unbound materials. Therefore, Hsu et al. (6) suggested that the diametral test results should be termed equivalent diametral resilient modulus and equivalent diametral Poisson's ratio to emphasize that these values are determined and computed based on linear elasticity and do not take account of nonlinear and heterogeneous properties associated with unbound materials.

## Comparison of Test Procedures

The triaxial test equipment and procedure is a straightforward test. The compaction of the triaxial test specimen is done on the test equipment base, which avoids the disturbance of the specimen after compaction is completed. Data obtained using this equipment can be reproduced, if the same testing conditions are used, and can be used for routine determination of the soil properties required for implementation of improved design methods.

The diametral test equipment and procedure for unbound materials is in the preliminary development stages. The test is very simple, but skill and knowledge of the testing equipment are required. After compaction of the specimen is completed, it is transferred to the split mold-rubber membrane, which may produce disturbance and loss of particles from the specimen. The reproduction of the data were not constant even though the same testing conditions were used.

## Comparison of Test Results

Comparison of triaxial and diametral test results for two subgrade soils are shown in Figures 5-9. The effect of the deviator stress ($\sigma_d$) and confining pressure ($\sigma_3$) on the triaxial and diametral resilient modulus for the subgrade 2 material from the Salem Parkway project are shown in Figures 5 and 6. The triaxial resilient modulus increased with an increase in the confining pressure, decreased to a minimum, and then increased with an increase in the deviator stress. The confining pressure and deviator stress effects on the diametral resilient modulus are about the same as for the triaxial test results. In general, the diametral resilient modulus increased with increasing confining pressure and increased slightly with increasing deviator stress.

The effect of the sum of principal stresses ($\theta$) on the triaxial and diametral resilient modulus for the subgrade from the US-97 project is shown in Figures 7-9. As shown, the triaxial and diametral resilient modulus increases with increasing sum of the principal stresses. Judging from Figures 7-9, it can be deduced that at low levels of stress, the diametral resilient modulus is higher than the triaxial resilient modulus but at high levels of stress, there is no particular trend.

In summary, because of the differences and inconsistency of the resilient modulus values ($M_R$), no general statement can be made about the triaxial and diametral resilient modulus. Results obtained with diametral equipment were more variable, but average values were not consistently higher nor lower than results obtained with triaxial equipment. From the results obtained in this study, it appears that the relationship between moduli obtained using both devices is a function of soil type in addition to differences in equipment and testing procedures.

# CONCLUSIONS AND RECOMMENDATIONS

## Conclusions

Repeated load diametral and triaxial tests were conducted to determine the resilient moduli of subgrade materials for two projects, one new alignment project in the Willamette Valley (Salem Parkway), and one overlay project in central Oregon (US-97).

The resilient moduli were measured over a range of density, moisture content, and level of stress. However, for the purpose of comparing the diametral and triaxial test procedures, only the results corresponding to the 95 percent of the maximum density were used. A summary of the significant findings follows.

For subgrade 1 soil from the Salem Parkway project, the triaxial resilient modulus increased with an increase in the confining pressure and decreased to a minimum for the range of deviator stress considered. For subgrade 2 soil, the diametral resilient modulus increased with increasing confining pressure, decreased to a minimum, and then increased slightly with increasing deviator stress. For the US-97 subgrade soil, the triaxial and diametral resilient modulus increased greatly with an increase in the sum of the principal stresses ($\theta$). For all subgrade soils, the resilient modulus increased with an increase in the level of compaction, but decreased with an increase in the water content.

The diametral resilient modulus results tended to be higher, at low stress levels, than the triaxial resilient modulus results, but at high stress levels there was no particular trend. The equations employed in the diametral resilient modulus and Poisson's ratio calculation are based on linear elasticity for an idealized material. The value of resilient modulus and Poisson's ratio should be constant for a homogeneous, isotropic, and linear elastic material, but the values obtained are not constant due to the nonlinear and heterogeneous properties associated with the unbound material tested.

The repeated load triaxial test is straightforward to conduct, and it produces repeatable results for all pavement materials. The repeated load diametral test is well-established for treated materials, but for untreated materials, particularly cohesionless soils, the results obtained tend to be variable. To conduct the test requires high skill and knowledge of the equipment being used.

## Recommendations

On the basis of the results of this study and a previous study conducted by Hsu et al. (6), it is recommended that for cohesive soils, the repeated load diametral test can be used for determination of the resilient properties. However, the results of this study show that the repeated load triaxial procedure is preferable. For untreated cohesionless material, the repeated load triaxial test should be used for routine determination of the soil properties required for implementation of improved design methods.

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