Relation Between Resilient Modulus and Stress Conditions for Cohesive Subgrade Soils

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The relation between stress conditions and resilient modulus, which is a necessary input parameter in fatigue design of asphalt concrete pavements, is established. For a cohesive subgrade soil there is a relation between resilient modulus and deviator stress, confining pressure, and matrix suction. A proposed constitutive relation was experimentally checked by using samples of compacted glacial till from the Qu'Appelle Moraine in Saskatchewan, Canada. Four series of repeated triaxial tests were performed on the repeated-load triaxial system developed at the University of Saskatchewan. Matrix suctions were measured on a pressure-plate device immediately after each repeated-load test. Experimental data indicate a good correlation between the resilient modulus and the stress variables. The stress variables of most significance with respect to changes in resilient modulus are deviator stress and matrix suction. An equation is proposed by which the resilient modulus of a compacted subgrade soil can be linked to these stress variables.

The necessity of developing a complete fatigue design program for asphalt concrete pavements has become increasingly evident in recent years. One of the important input parameters to such a design program is the resilient modulus of the subgrade. Because fatigue prediction is highly sensitive to changes in subgrade resilient modulus, it is not enough to assume one resilient-modulus value for the year; a relation must be established between stress conditions and resilient modulus (1). Previous attempts to develop realistic fatigue simulation may have failed because of inadequate characterization of the subgrade soils.

The research presented here includes a theory that establishes the relation between stress conditions and resilient modulus. Results of laboratory tests on a subgrade soil are also presented to compliment the developed theory.

THEORY

Previous research has shown typical relations between the volume and weight, the method of sample preparation, the deviator stress, and the resilient modulus of compacted soils (7). However, the authors are not aware of any unique relations having been established among these variables. Establishing a relation between the resilient modulus and the stress conditions in a soil is imperative in the fatigue design of asphalt concrete pavements.

Fredlund, Bergan, and Sauer (5) showed from a stress analysis standpoint that the resilient modulus is a function of three stress variables.

$$M_R = f[(\sigma_3 - u_a), (\sigma_1 - \sigma_3), (u_a - u_w)] \tag{1}$$

where

M_R = resilient modulus,
σ_3 = confining pressure,
σ_1 = major (vertical) principal stress during the application of the repeated load,
u_a = pore air pressure (approximately atmospheric),
u_w = pore water pressure,
$(\sigma_3 - u_a)$ = net confining pressure,
$(\sigma_1 - \sigma_3)$ = deviator stress, and
$(u_a - u_w)$ = matrix suction.

In other words, if the above three stress variables were known during a repeated-load test, it would be reasonable to attempt to relate resilient modulus to them. Unfortunately, there are serious technical problems associated with measuring air and water pressure under dynamic loading conditions. Relating the resilient modulus to the stresses before or after the repeated-load test may be sufficient.

Under repeated-load conditions, the first 100 repetitions of load have been found to be sufficient to ensure proper seating of the sample in the testing apparatus (2, 3, 6). Continuing to load the sample up to 100 000 repetitions produces a further change in resilient modulus, and this change is probably related to changes in the stress variables. However, because the stresses cannot readily be monitored, it is proposed that the number of repetitions (N) be designated as a further state variable. This paper considers only the effect of the first 100 repetitions.

Figure 1 shows the anticipated linear relation between resilient modulus and confining pressure for samples compacted at various water contents. The normal range of confining pressure of interest in the field is approximately 20.7 to 41.4 kPa (3 to 6 lbf/in^2) and linearity is anticipated in this range (8). At water contents above optimum (i.e., low matrix suction), the voids are largely filled with water and an increase in confining pressure produces little change in the resilient modulus. At low water contents (i.e., high matrix suction), confining-pressure increases produce more substantial increases in resilient modulus.

Figure 2 shows typical variations in resilient modulus for various deviator stresses. Dry of optimum, the resilient modulus does not vary as much with deviator stress as it does when wet of optimum water content. The results from previous investigations show relations that are curved. At high deviator stresses an increase in resilient modulus has sometimes been observed. The practical range of deviator stress is 0 to 83 kPa (0 to 12 lbf/in^2). In Figure 3 the relation between resilient modulus and deviator stress is linearized over the above stress range by plotting resilient modulus on a logarithm scale.

In extending the log resilient modulus versus deviator stress back to a deviator stress of zero, two variables can be used to define each line: the slope of the line on the semilogplot (m_{1d}) and the intercept on the ordinate (c_{1d}). Each line is therefore described by

$$\log M_R = c_{1d} - m_{1d}(\sigma_1 - \sigma_3) \tag{2}$$

where c_{1d} and m_{1d} are functions of matrix suction. In this way, the resilient modulus is also related to the third stress variable $(u_a - u_w)$.

Because resilient modulus is expected to be more highly affected by deviator stress and matrix suction than by net confining pressure, the effect of confining pressure could either be ignored or a correction could be applied for confinement. The correction equation would take the following form (Figure 1):

$$\Delta M_R = m_c \times \Delta(\sigma_3 - u_a) \qquad (3)$$

where

ΔM_R = change in resilient modulus,
m_c = slope of the plot for confining pressure versus resilient modulus, and
$\Delta(\sigma_3 - u_a)$ = change in confining pressure from that used to define the plot for resilient modulus versus deviator stress.

The relation between c_{1d} and m_{1d} and matrix suction must be experimentally determined. The form is not yet definite but should become better established with further testing. The degree of uniqueness of the proposed equations must be established experimentally by subjecting samples to varying stress paths or methods of sample preparation and comparing the results by using the proposed equation. The relation between resilient modulus and matrix suction (for a particular deviator stress) can also be obtained by cross-plotting for resilient modulus versus water content and matrix suction versus water content (5).

Figure 1. Anticipated relation between resilient modulus and confining pressure.

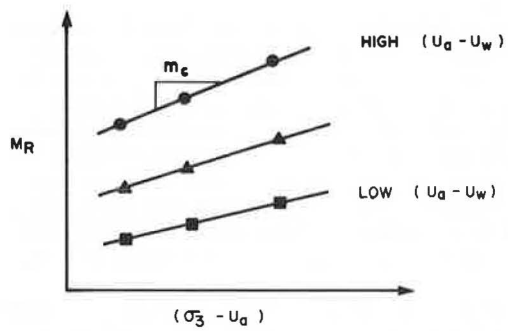


Figure 2. Anticipated resilient modulus versus deviator stress.

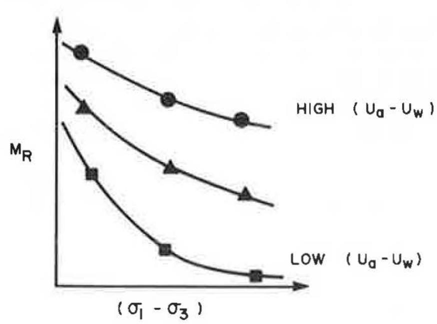
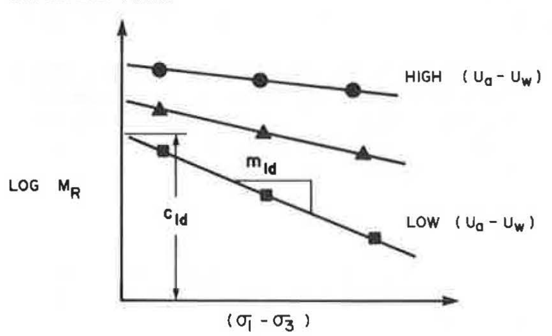


Figure 3. Linearization of relation between resilient modulus and deviator stress.



LABORATORY EQUIPMENT

The repeated-load apparatus (Figure 4) consists of a reinforced triaxial cell with a bellofram operated on compressed air to apply the deviator load. The cell was filled with air. The loading frequency was 20 repetitions/min with a load duration of 0.1 s. The load applied to the sample was measured by a load cell in the base plate of the triaxial cell. The vertical and lateral displacements of the sample were measured by linear variable differential transducers. The matrix suctions were measured by placing the samples on a high-air-entry disc [i.e., either 0.5 or 1.5 MPa (5 or 15 bars)] and using the axis-translation procedure to nullify the negative water pressures.

SOIL SAMPLES

The soil used in the study was a glacial till obtained from the Qu'Appelle Moraine in Saskatchewan. Its properties are summarized below (1 kg/m^3 = 0.06 lb/ft^3):

Property	Measurement
Liquid limit, %	33.9
Plastic limit, %	17.0
Sand, %	31.8
Silt, %	38.5
Clay, %	29.7
Specific gravity	2.77
Maximum standard density, kg/m^3	1767
Optimum water content, %	16.5
Modified AASHO density, kg/m^3	1967
Optimum AASHO water content, %	11.9

The soil samples were prepared by air drying, pulverizing, sorting on a 2-mm (No. 10) sieve, and then mixing with the appropriate amount of distilled water. The wet soil was placed in a plastic bag and stored in a high-humidity room for 24 h. The specimens were 15.2 cm (6 in) in length and 7.1 cm (2.8 in) in diameter and were formed by static compaction in three layers. The specimens were wrapped in plastic, waxed, and stored for at least 7 d before testing.

TEST PROGRAM

The test program was designed to evaluate the relation between resilient modulus (M_R) and deviator stress ($\sigma_1 - \sigma_3$), confining pressure ($\sigma_3 - u_a$), and matrix suction ($u_a - u_w$). The resilient modulus was calculated after 100 load repetitions; the effect of larger numbers of repetitions was not evaluated.

The test program consisted of four test series; data for dry density (γ_d) and water content are given in Table 1 and shown in Figure 5 (9). For all specimens, an attempt was made to measure the matrix suction at the top, middle, and bottom of the specimen (in some cases only two measurements were possible).

Series 1 samples were prepared at maximum standard density and water contents ranging from 7 to 19 percent. Each specimen was tested for deviator stresses (σ_d) of 20.6, 48.2, 82.7, and 103.4 kPa (3, 7, 12, and 15 lbf/in^2).

The confining pressure (σ_3 - u_a) was kept at 20.7 kPa (3 lbf/in^2) in all cases. The results from series 1 allowed a study of the resilient modulus versus deviator stress and matrix-suction relations when dry density is kept constant.

Series 2 was the same as the first series except that the dry density varied with water content in accordance with the standard compaction curve. The results allow a study of the resilient modulus (M_R) versus deviator stress and matrix-suction relation when dry density varies.

Figure 4. Repeated-load triaxial system.

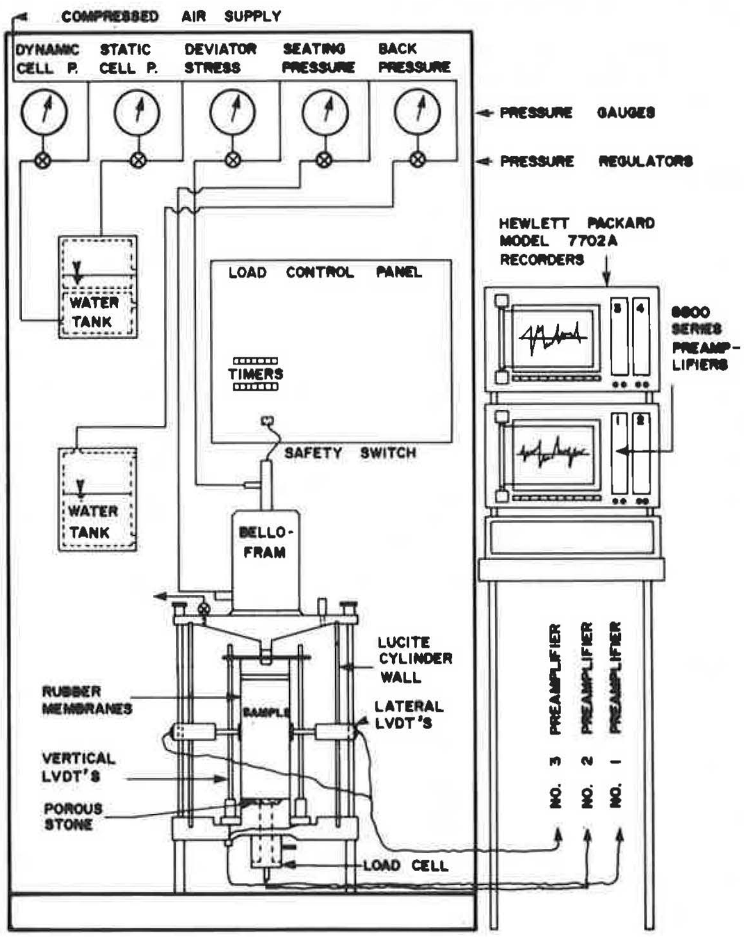
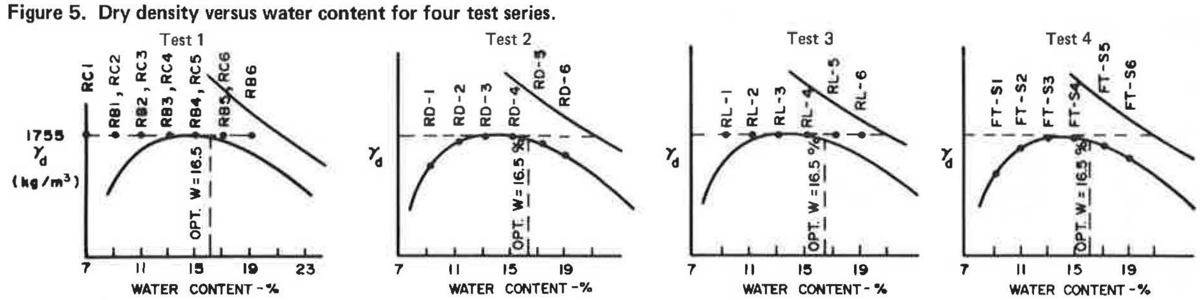


Table 1. Dry densities and water contents for four test series.

Test 1			Test 2			Test 3			Test 4		
Sample	Water Content (%)	γ_d (kg/m^3)	Sample	Water Content (%)	γ_d (kg/m^3)	Sample	Water Content (%)	γ_d (kg/m^3)	Sample	Water Content (%)	γ_d (kg/m^3)
RC-1	7	109.6	RD-1	9	90.0	RL-1	9	109.6	FT-S1	9	90.0
RB-1 and RC-2	9	109.6	RD-2	11	97.2	RL-2	11	109.6	FT-S2	11	97.2
RB-2 and RC-3	11	109.6	RD-3	13	102.8	RL-3	13	109.6	FT-S3	13	102.8
RB-3 and RC-4	13	109.6	RD-4	15	108.0	RL-4	15	109.6	FT-S4	15	108.0
RB-4 and RC-5	15	109.6	RD-5	17	109.4	RL-5	17	109.6	FT-S5	17	109.4
RB-5 and RC-6	17	109.6	RD-6	19	104.4	RL-6	19	109.6	FT-S6	19	104.4
RB-6	19	109.6									

Note: 1 kg/m^3 = 0.06 lb/ft^3.

Figure 5. Dry density versus water content for four test series.



Note: 1 kg/m^3 = 0.06 lb/ft^3

Series 3 samples were prepared at maximum standard density. Tests were run at deviator stresses of 48 and 69 kPa (7 and 10 lbf/in^2). The confining pressures on each specimen were 20.7, 68.9, 137.9, and 275.8 kPa (3, 10, 20, and 40 lbf/in^2). Each confining pressure was allowed 8 h for equalization. The results allow a study of the resilient modulus versus confining pressure and matrix-suction relations.

Series 4 samples were prepared at a constant dry density and varying water contents and then subjected to three freeze-thaw cycles. The purpose of freeze-thaw cycles was to check the consistency of the resilient modulus versus stress-variable relations when the soil structure was modified or disturbed. The confining pressure was 21 kPa (3 lbf/in^2) and the deviator stresses were 20.7, 34.5, 48.3, and 82.7 kPa (3, 5, 7, and 12 lbf/in^2).

PRESENTATION AND DISCUSSION OF DATA

The resilient-modulus values for series 1, 2, 3, and 4 are summarized in Tables 2, 3, 4, and 5 respectively.

Table 2. Results of test series 1.

Sample	Water Content (%)	γ_d (kg/m^3)	S[a] (%)	$(\sigma_3 - u_a)$ (kPa)	$(u_a - u_w)$[b] (kPa)	M_R (kPa) σ_d = 20.6 kPa	σ_d = 48.2 kPa	σ_d = 82.7 kPa	σ_d = 103.4 kPa
RB-1	11.4	1751	55.4	20.7	469	32 476	28 476	25 443	23 443
RB-2	13.5	1752	65.5	20.7	345	61 021	43 301	22 616	28 270
RB-3	15.2	1772	76	20.7	269	52 057	47 713	33 027	28 339
RB-4	17.7	1749	85.6	20.7	207	61 917	39 991	15 376	6 619
RB-5	20.8	1703	93.2	20.7	186	41 715	12 066	10 687	5 902
RB-6	21.9	1740	104.5	20.7	172	3 068	3 254	3 052	—
RC-1	9	1693	40	20.7	896	124 041	109 424	100 391	89 635
RC-2	11	1664	46.6	20.7	558	99 564	129 626	90 531	93 358
RC-3	13.1	1732	61.6	20.7	355	54 677	39 026	34 958	32 131
RC-4	15.3	1700	68.5	20.7	293	80 465	46 472	28 683	19 720
RC-5	17	1728	79.4	20.7	217	32 613	18 134	7 495	6 268
RC-6	19.4	1703	87.1	20.7	205	31 579	8 481	6 019	6 392

Note: 1 kg/m^3 = 0.06 lb/ft^3; 1 kPa = 0.145 lbf/in^2.
[a]Degree of saturation. [b]Values estimated from matrix suction versus water content plot.

Table 3. Results of test series 2.

Sample	Water Content (%)	γ_d (kg/m^3)	S[a] (%)	$(\sigma_3 - u_a)$ (kPa)	$(u_a - u_w)$ (kPa)	M_R (kPa) σ_d = 20.7 kPa	σ_d = 48.3 kPa	σ_d = 82.7 kPa	σ_d = 103.4 kPa
RD-1	11.3	1414	33.1	20.7	751	37 785	—	—	—
RD-2	13.1	1530	45.7	20.7	530	46 334	36 337	23 167	—
RD-3	15	1586	56.5	20.7	262	34 475	31 441	21 099	17 375
RD-4	17.3	1727	80.6	20.7	188	70 329	38 129	15 790	12 273
RD-5	19	1735	90	20.7	131	24 408	13 170	7 240	—
RD-6	21.2	1653	88.1	20.7	93	—	—	—	—

Note: 1 kg/m^3 = 0.06 lb/ft^3; 1 kPa = 0.145 lbf/in^2.
[a]Degree of saturation.

Table 4. Results of test series 3.

Sample	Water Content (%)	γ_d (kg/m^3)	S[a] (%)	$(u_a - u_w)$ (kPa)	$(\sigma_1 - \sigma_3)$ (kPa)	M_R (kPa) $(\sigma_3 - u_a)$ = 20.7 kPa	$(\sigma_3 - u_a)$ = 68.9 kPa	$(\sigma_3 - u_a)$ = 137.9 kPa	$(\sigma_3 - u_a)$ = 275.8 kPa
RL-1	11.7	1711	51.2	792	48	97 564	112 871	115 078	143 899
RL-2	12.1	1749	58.3	800	48	65 916	106 666	117 284	156 448
RL-3	14.3	1725	66.5	778	69	116 457	116 526	95 978	162 998
RL-4	15.1	1767	74.9	734	69	53 092	66 744	72 811	88 049
RL-5	17.4	1764	86.2	469	69	26 684	29 580	28 270	32 544
RL-6	19.4	1759	95.2	262	69	14 273	20 340	22 823	27 097

Note: 1 kg/m^3 = 0.06 lb/ft^3; 1 kPa = 0.145 lbf/in^2.
[a]Degree of saturation.

Table 5. Results of test series 4.

Sample	Water Content (%)	γ_d (kg/m^3)	S[a] (%)	$(\sigma_3 - u_a)$ (kPa)	$(u_a - u_w)$ (kPa)	M_R (kPa) σ_d = 20.7 kPa	σ_d = 34.5 kPa	σ_d = 48.3 kPa	σ_d = 82.7 kPa
FT-S1	11.4	1296	33.9	21	731	14 342	—	—	—
FT-S2	13.2	1506	44	21	483	42 473	—	21 237	11 101
FT-S3	15.2	1624	57.8	21	272	29 511	—	10 412	—
FT-S4	17.5	1724	81.4	21	169	9 239	4 013	5 364	9 998
FT-S5	19.5	1719	89.9	21	97	3 186	—	3 944	—
FT-S6	19.9	1680	86.4	21	66	8 412	15 721	11 101	—

Note: 1 kg/m^3 = 0.06 lb/ft^3; 1 kPa = 0.145 lbf/in^2.
[a]Degree of saturation.

Figure 6 shows the changes in resilient modulus versus confining pressure (σ_3 - u_a) for a wide range of water contents (series 3). The changes in resilient modulus with confining pressure are linear and more pronounced for water contents below optimum. The slopes of the resilient modulus versus confining pressure relation are plotted versus matrix suction in Figure 7. The slopes decrease to a relatively low value as the water content is increased. It should be noted that the confining pressure has been varied over a wide range and that field water contents will generally be in the vicinity of (or above) optimum conditions.

The results confirm that the confining pressure is relatively insignificant. Therefore, the proposed procedure of applying a correction for the confining pressure appears justifiable. The authors recommend that a constant slope (m_c) corresponding to the optimum water-content conditions be used in the correction equation.

The resilient modulus versus deviator stress (σ_1 - σ_3) can be plotted from series 1, 2, and 4. Figure 8 shows an arithmetic plot of the tests on the RC samples from series 1. They exhibit a characteristic decrease in resilient modulus with increasing deviator stress. At water contents above optimum there is some strain-hardening effect at deviator stresses greater than 83 kPa (12 lbf/in^2). The curves for resilient modulus versus deviator stress can be linearized on a semilogarithmic plot. Figures 9, 10, and 11 show the semilog plots from series 1 (RB and RC samples) and series 2. Test series 4 was not plotted because of the erratic results following freeze-thaw cycles.

The slopes and intercepts of the semilog plots of resilient modulus versus deviator stress are given in Table 6 and are shown plotted versus matrix suction in Figures

Figure 6. Resilient modulus versus confining pressure for test series 3.

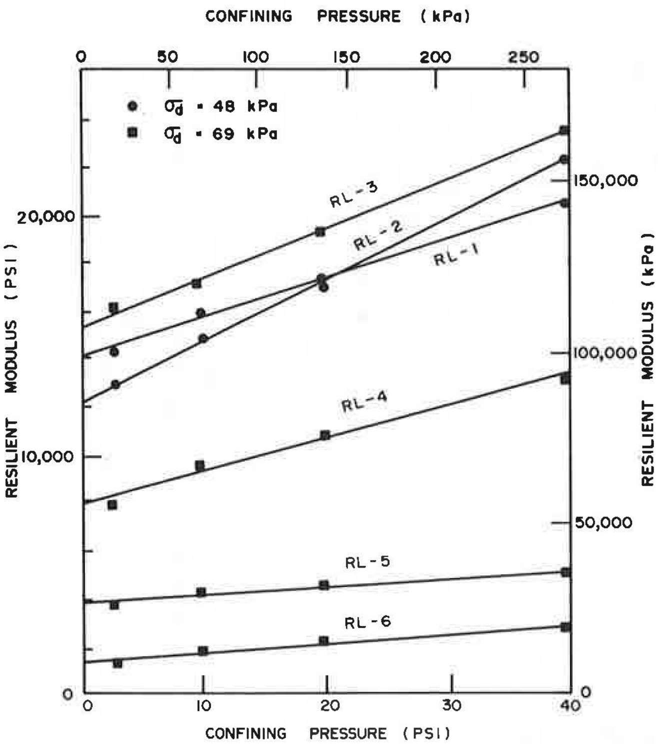


Figure 7. Slope of confining pressure versus resilient modulus for various matrix suctions.

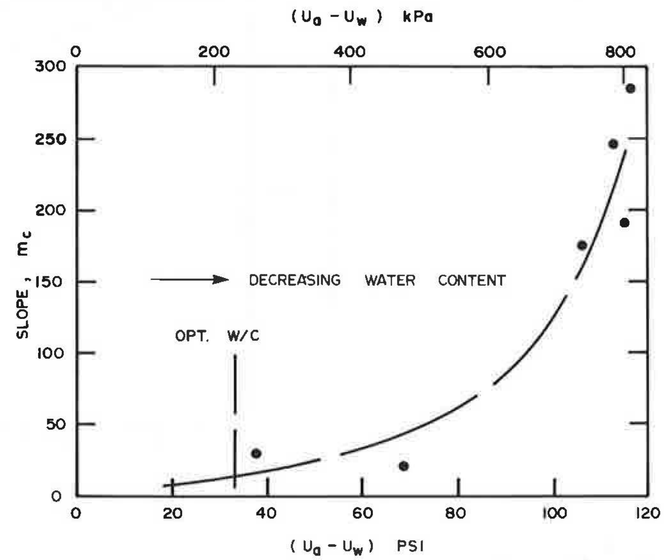
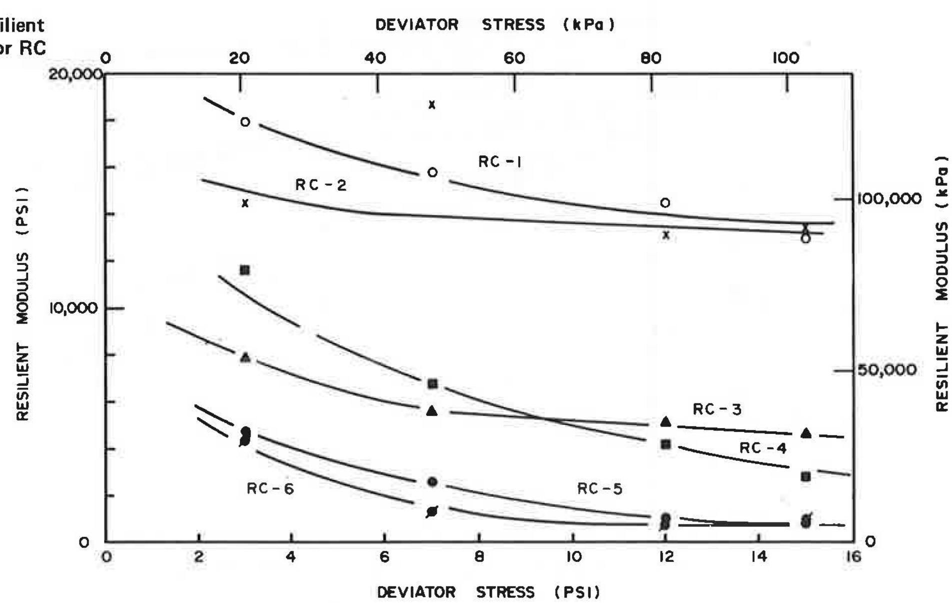


Figure 8. Arithmetic plot of resilient modulus versus deviator stress for RC samples of test series 1.



12 and 13 respectively. The slope (m_{1d}) is shown to increase as matrix suction decreases. The scatter within an individual series shows that it is not possible to differentiate between the samples prepared at constant dry densities and those with dry densities that vary according to the standard compaction curve. One result from the freeze-thaw samples indicates an increased slope (m_{1d}).

The logarithm of the intercept corresponding to zero deviator stress (c_{1d}) shows a decrease as matrix suction decreases (Figure 13). Again, the scatter within a test series is greater than are the variations produced by varying the dry density.

The best fit lines (dashed portion) from Figures 12 and 13 were used to obtain the intercept (c_{1d}) and slope (m_{1d}) values to be substituted into Equation 2. By assuming various deviator stresses, a family of curves of resilient modulus versus matrix suction was derived (Figure 14). The trend of the plots is similar to that presented in the cross-plotting technique of Fredlund, Bergan, and Sauer (5).

Figure 15 shows the relation between matrix suction and water content, and Figure 16 shows the relation between resilient modulus and water content for the samples tested. The best fit lines through each set of data were cross-plotted, and the results are superimposed on Figure 13. The resilient-modulus values used in cross-plotting correspond to a deviator stress of 48 kPa (7 lbf/in^2). The results from Equation 2 show good agreement with the results obtained by the cross-plotting technique.

The results from the proposed Equation 2 show that the plot of resilient modulus versus matrix suction can be highly nonlinear in the region of low matrix suction. That nonlinearity grows more pronounced as the deviator

Figure 9. Resilient modulus versus deviator stress for RB samples of test series 1.

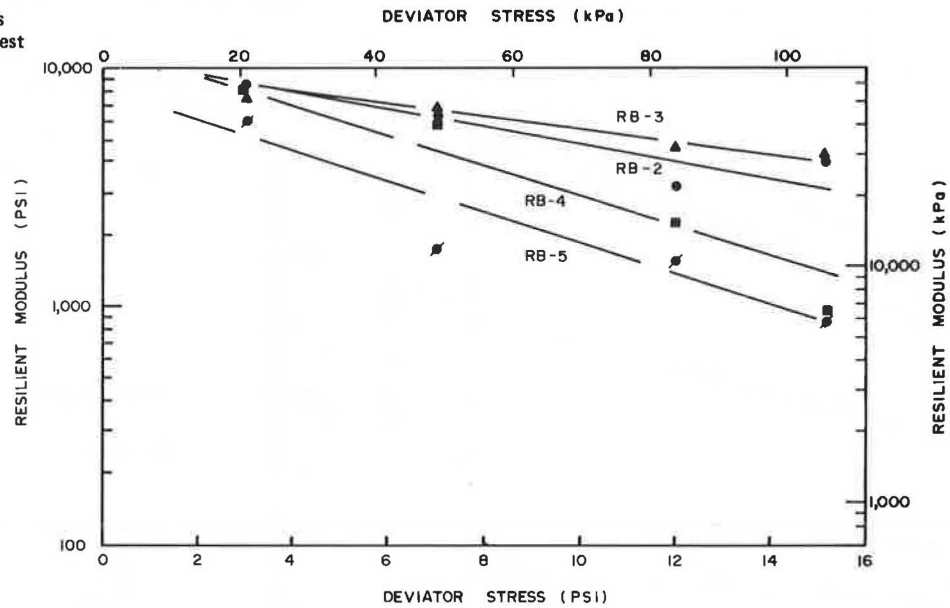


Figure 10. Resilient modulus versus deviator stress for RC samples of test series 1.

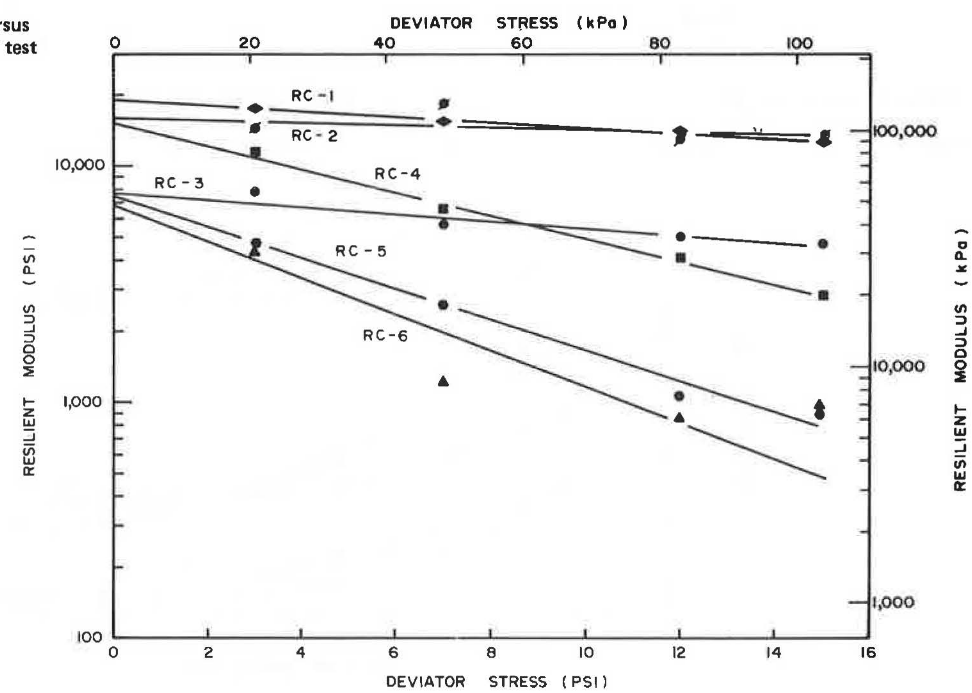


Figure 11. Resilient modulus versus deviator stress for test series 2.

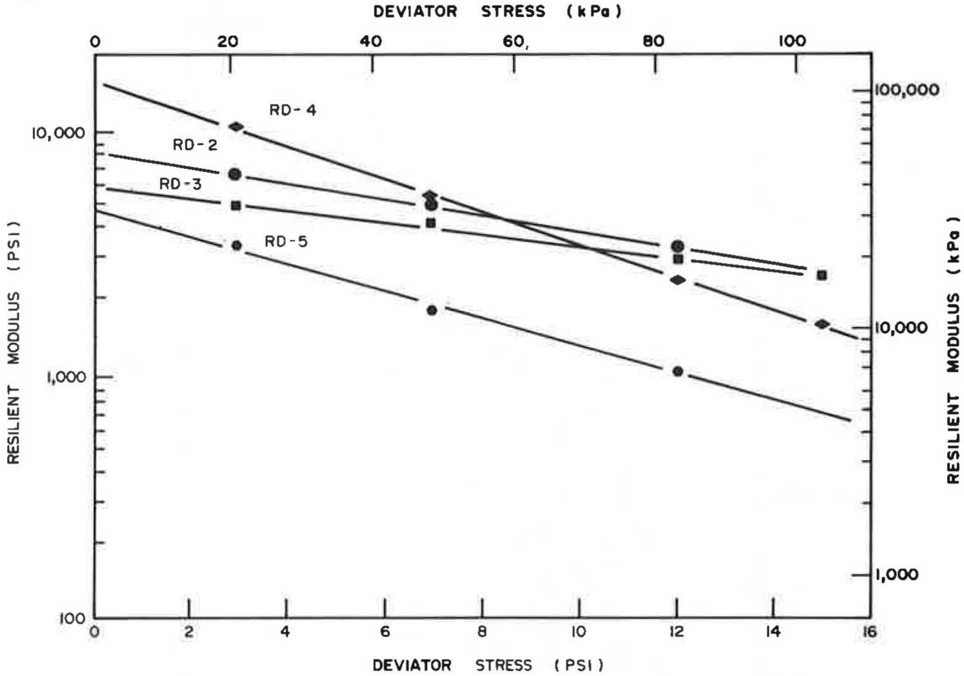


Table 6. Slopes and intercepts of resilient modulus versus log of deviator stress plots.

Sample	$(u_a - u_w)^a$ (kPa)	m_{1d}	M_R Intercept (kPa)	c_{1d}	Sample	$(u_a - u_w)^a$ (kPa)	m_{1d}	M_R Intercept (kPa)	c_{1d}
RB-2	345	0.0360	75 845	4.041	RC-5	217	0.0649	51 023	3.869
RB-3	269	0.0272	71 019	4.013	RC-6	205	0.0764	46 886	3.832
RB-4	207	0.0624	84 119	4.086	RD-2	530	0.0312	56 539	3.914
RB-5	186	0.0641	55 850	3.908	RD-3	262	0.0234	41 370	3.778
RC-1	896	0.0108	131 005	4.279	RD-4	188	0.0668	112 389	4.212
RC-2	559	0.0052	110 320	4.204	RD-5	131	0.0578	34 475	3.699
RC-3	355	0.0140	52 402	3.881	FT-S2	483	0.0854	77 914	4.053
RC-4	293	0.0477	103 425	4.176	FT-S3	272	0.0989	53 781	3.892

Note: 1 kPa = 0.145 lbf/in².
[a]Matrix suction value is in doubt.

Figure 12. Slopes versus matrix suction.

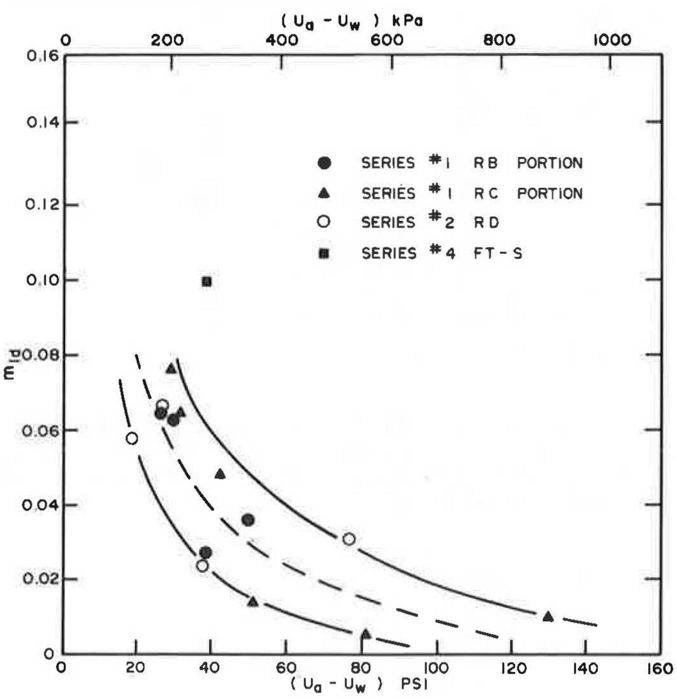


Figure 13. Log of resilient modulus for zero deviator stress versus matrix suction.

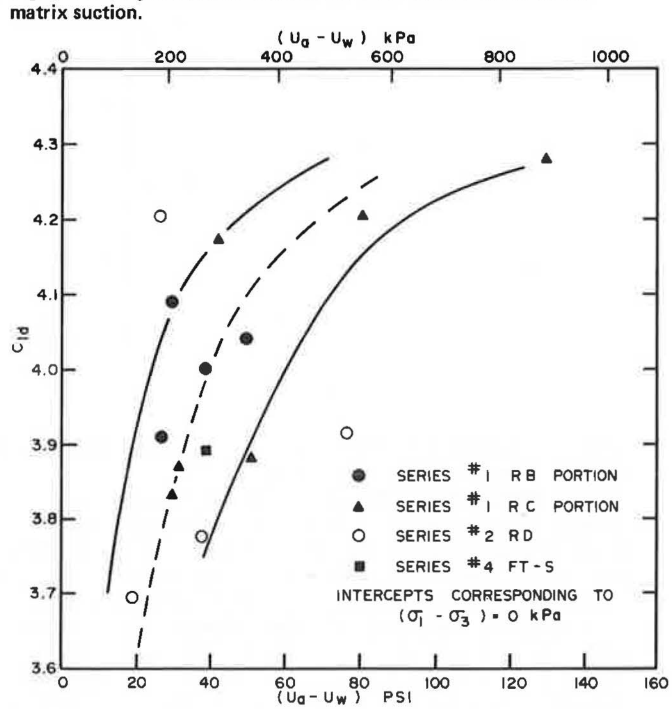


Figure 14. Cross-plotted relation for resilient modulus versus matrix suction.

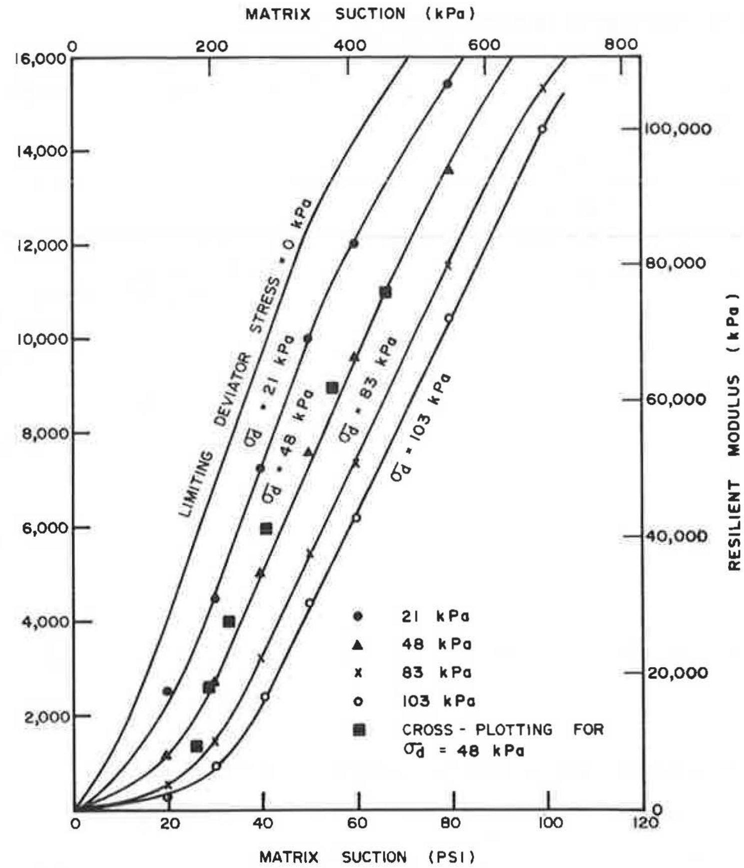
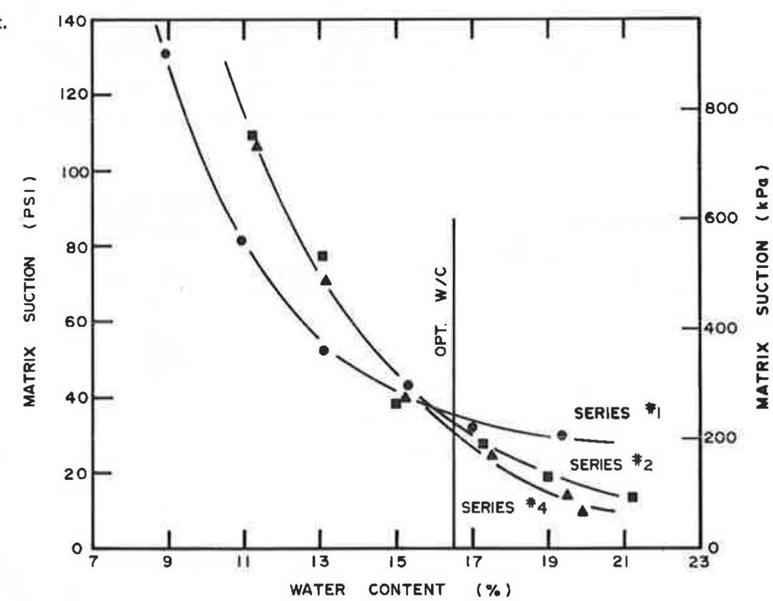


Figure 15. Matrix suction versus water content.



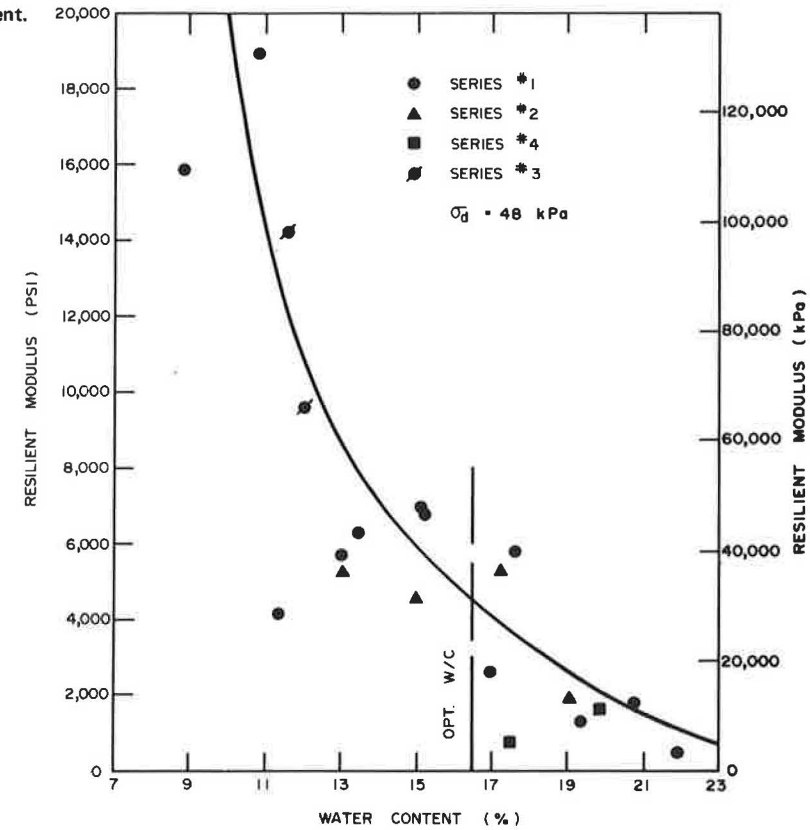
stress is increased. There is also a reversed nonlinearity in the high matrix-suction range.

The slopes (m_{1d}) (Figure 12) and intercepts (c_{1d}) (Figure 13) showed that the scatter within one series of tests was similar to that experienced between the different series. Therefore, Equation 2 appears to be unique in its accuracy in measuring resilient modulus.

Considering the typical ranges for the stress variables, it is possible to assess the significance of each stress in terms of corresponding changes in resilient modulus. As given in the following table, at a water content near optimum the deviator stress is the most significant stress variable, the matrix suction is also significant, and the confining pressure has little significance (1 kPa = 0.145 lbf/in^2):

Stress Variable	Approximate Change in Field (kPa)	Change in Resilient Modulus (kPa)
$(\sigma_1 - \sigma_3)$	0 to 83	43 439
$(u_a - u_w)$	227 to 0	24 132
$(\sigma_3 - u_a)$	21 to 41	69

Figure 16. Resilient modulus versus water content.



SUMMARY

The resilient modulus of a compacted subgrade soil can be linked to the stress variables by Equation 2, which appears to be unique within the limits of accuracy of the resilient-modulus measurements. The effect of confining pressure appears to be negligible for the soil tested.

The recommended testing program to evaluate c_{1d} and m_{1d} for Equation 2 is as follows:

1. Samples should be compacted at various water contents and densities and a compactive-energy input comparable to field placement conditions should be used.
2. Each sample should be subjected to at least 100 repetitions of deviator stresses ranging from 21 to 83 kPa (3 to 12 lbf/in^2).
3. After the completion of the repeated-load test, two or three matrix-suction tests should be performed on smaller samples cut from the tested sample.

Because of the difficulty of obtaining reproducibility in the measurements of resilient modulus, the procedure should be repeated on three carefully prepared specimens at each chosen water content and density. The testing program showed that it was extremely difficult to get reproducibility of resilient modulus on samples in cases in which the structure had been modified by freeze-thaw cycles.

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