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RESILIENT PROPERTIES OF COLORADO SOILS

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16. Abstract

During the past 30 years, pavement engineers have increasingly used the elastic layered system theory to predict the physical response of pavement structures in order to determine a proper pavement thickness. The 1986 ASSHTO Guide for Design of Pavement Structures has adopted resilient properties in its pavement design. The committee for this Guide recognized that many state highway agencies do not have the proper equipment to determine the resilient modulus. In the Design Guide, correlation of the resilient modulus (M_r) with the California bearing ratio (CBR) and the R-value are given. However, these correlations are general in nature and can be used temporarily and only for certain types of soils. The committee has recommended that states develop their own correlations. During this research study, attempts were made to find a correlation between the resilient modulus and the R-value for Colorado soils. To accomplish this task, an extensive laboratory testing program was conducted and the following correlation was established: $M_r = 3500 + 125 \times (\text{R-value})$.

Implementation

Based on the results of this study, the above correlation was established for Colorado soils. Verification of this correlation by additional tests on high quality subgrade (i.e. A-1-b or better) will be needed. After verification, attempts will be made to incorporate this finding in the current CDOH Pavement Design Procedures.

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I. INTRODUCTION

During the past 30 years, pavement engineers have increasingly used elastic layered system theory for prediction of the physical response of pavement structures in order to determine proper pavement thickness. Use of such theory requires the estimation of both vertical and lateral stress-strain relationships in each layer of the pavement structure. The stress-strain relationships can generally be characterized by modulus of elasticity and Poisson's ratio.

Sufficient evidence has been found that the Poisson's ratio is relatively insensitive to minor variation of factors such as stress state, repetitive loading, moisture condition and density. However, variation of these factors can significantly affect the modulus of elasticity. Resilient modulus was therefore developed to account for repetitive loading under certain stress level and density conditions.

The 1986 AASHTO Guide for Design of Pavement Structures has adopted such resilient properties in the pavement design. The committee for this guide has recognized that many state highway agencies do not have the proper equipment to determine the resilient modulus. In the design guide, correlations of resilient modulus (M_r) with California Bearing Ratio (CBR) and Stabilometer R-value are given. However, these correlations are general in nature and can be used temporarily and only for certain types of soils. The committee has recommended that each state develop their own correlations.

The Colorado Department of Highways currently uses stabilometer R-value for design of pavement structures. Therefore, this research is designed to correlate the relationships, if any, between resilient modulus and R-value.

II. LITERATURE REVIEW

Resilient Modulus (M_r), by definition, is a dynamic response defined as the ratio of the repeated axial deviator stress simulating traffic loading to the recoverable axial strain as presented in Equation (a). In other words, it is the elastic stiffness of a material after many load repetitions have been applied.

$$M_r = \frac{\sigma_d}{\epsilon_R} \qquad \text{(a)}$$

where: M_r = Resilient Modulus
σ_d = Deviator Stress, psi
ϵ_R = Recoverable Strain, in/in

Figure 2.1 shows a typical relationship between stress and strain in a soil specimen when repetitive load is applied. The stress-strain relationship is essentially linear after many load repetitions. Therefore, resilient modulus is the slope of the stress-strain curve shown in the figure. Since the modulus varies with the load applied as well as the ambient stresses occurred in the subgrade, it is normally expressed by a series of curve plotted against those variables. Both arithmetical and log-log scales are used. Typical results are shown on Figure 2.2 (a)(b).

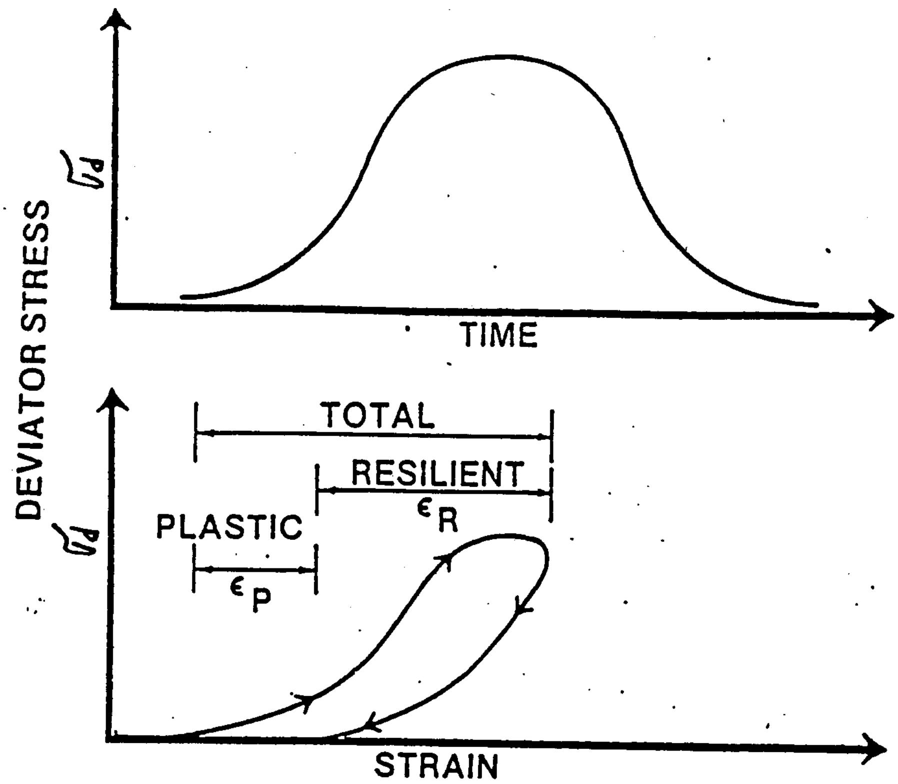


Figure 2.1: Typical stress-strain behavior of resilient modulus test

Many research studies have been conducted to investigate the sensitivities of various factors affecting the values of the resilient modulus (5)(7)(9)(15)(20). These factors include material type, sample preparation method, stress state, and the condition of samples. The importance of each of these factors is discussed below.

<u>Soil Properties</u> -- The grain size, plasticity (LL, PI), Group Index (G.I.), clay and silt content can influence the behavior of the resilient modulus (8)(11). A detailed study of these soil properties which control the behavior of Illinois soils was conducted by Thompson and Robnett (17). No correlation between the resilient modulus and any single soil property was found in their studies.

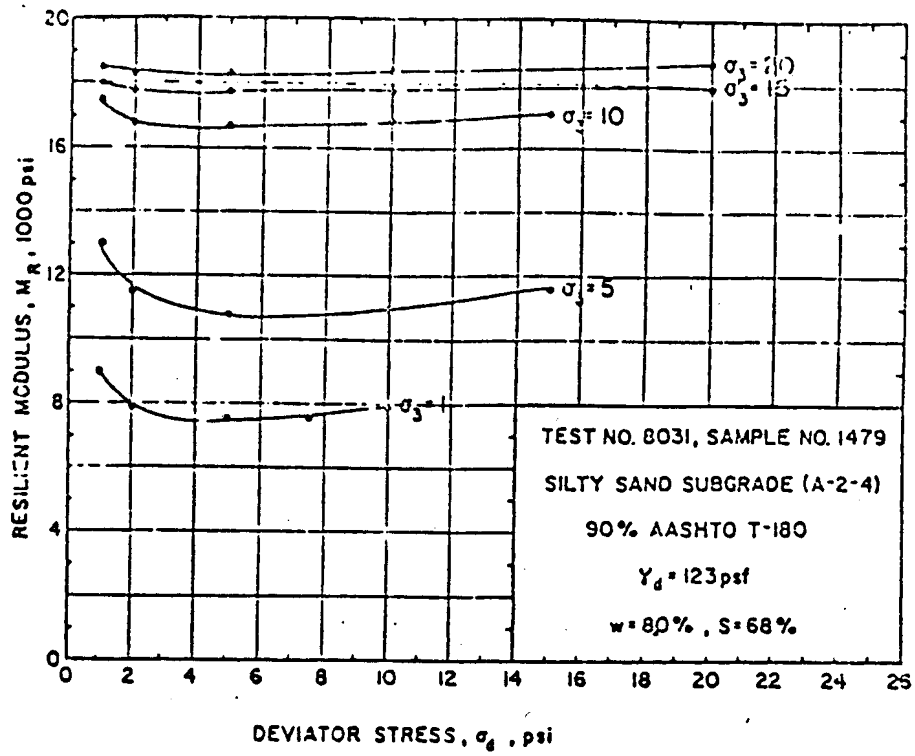


Figure 2.2(a): Arithmetic Plot of Resilient Modulus Test Results

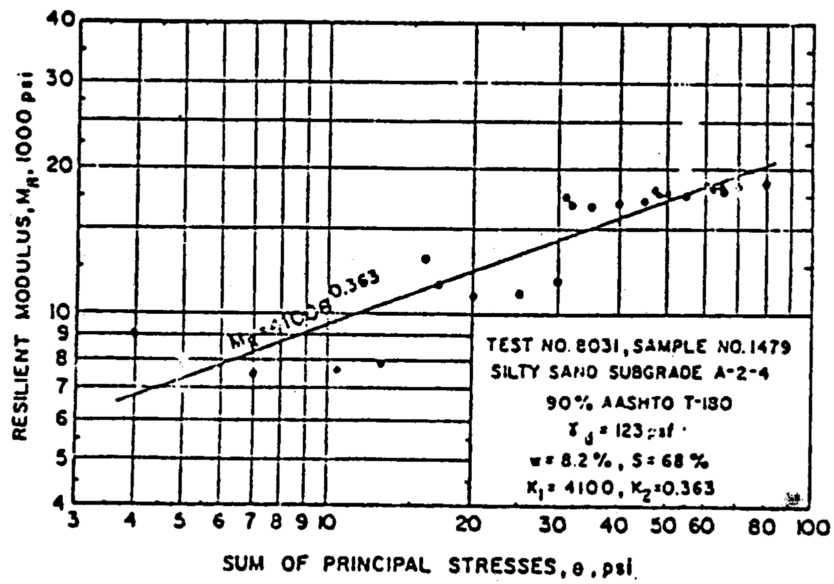
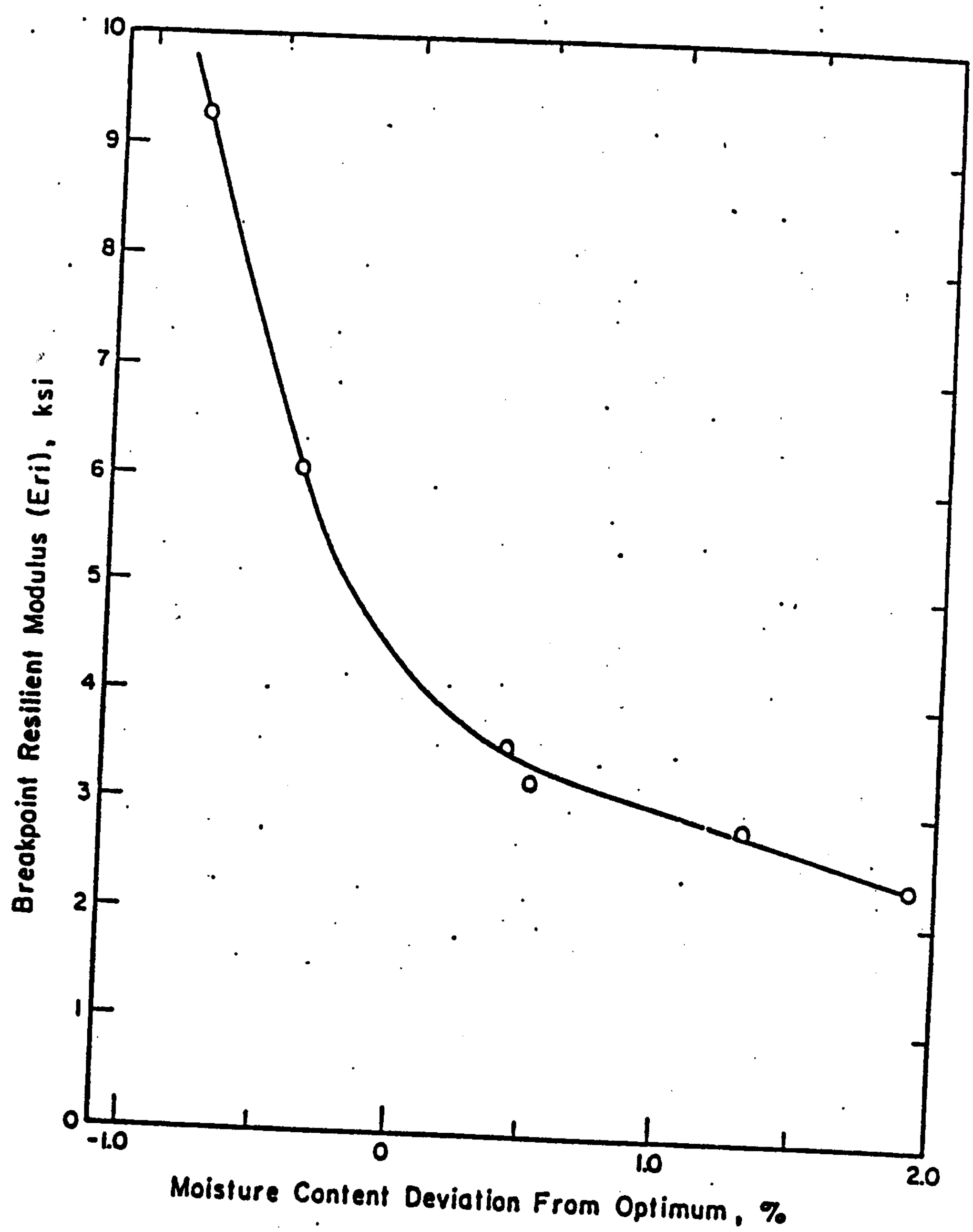


Figure 2.2(b): Logarithmic Plot of Resilient Modulus Test Results

Moisture and Density -- Moisture content and density have been found to influence the resilient modulus in some studies. Thompson and Robnett (17) reported that the effect of moisture content on the modulus appears to become smaller as water content increases relative to the optimum moisture content. The effect of moisture content on the resilient modulus is illustrated in Figure 2.3. It was concluded that moisture content is a critical factor affecting the behavior of resilient modulus. Robnett and Thompson (17) also found that the difference in modulus is small for soils tested at 95% and 100% of the standard Proctor density as shown in Figure 2.4.

Degree of Saturation -- The modulus of a pavement subgrade is strongly related to the degree of saturation, as concluded by Thompson and Robnett (17). The degree of saturation generally reflects the combined effect of density and moisture content. As shown in Figure 2.5, the values of the modulus decrease with the increase of soil saturation, particularly in fine-grained materials.

Confining Pressure -- The effect of confining pressure, especially for granular materials have been thoroughly studied (4)(5)(14) in the past decade. It was concluded that confining pressure greatly influences the resilient modulus of granular materials. Generally, resilient modulus increases with increasing confining pressure (Figure 2.6). However, a recent study of the effect of confining pressure to the resilient properties of cohesive soils indicated that it is relatively insignificant when compared with granular (cohesionless) soils.



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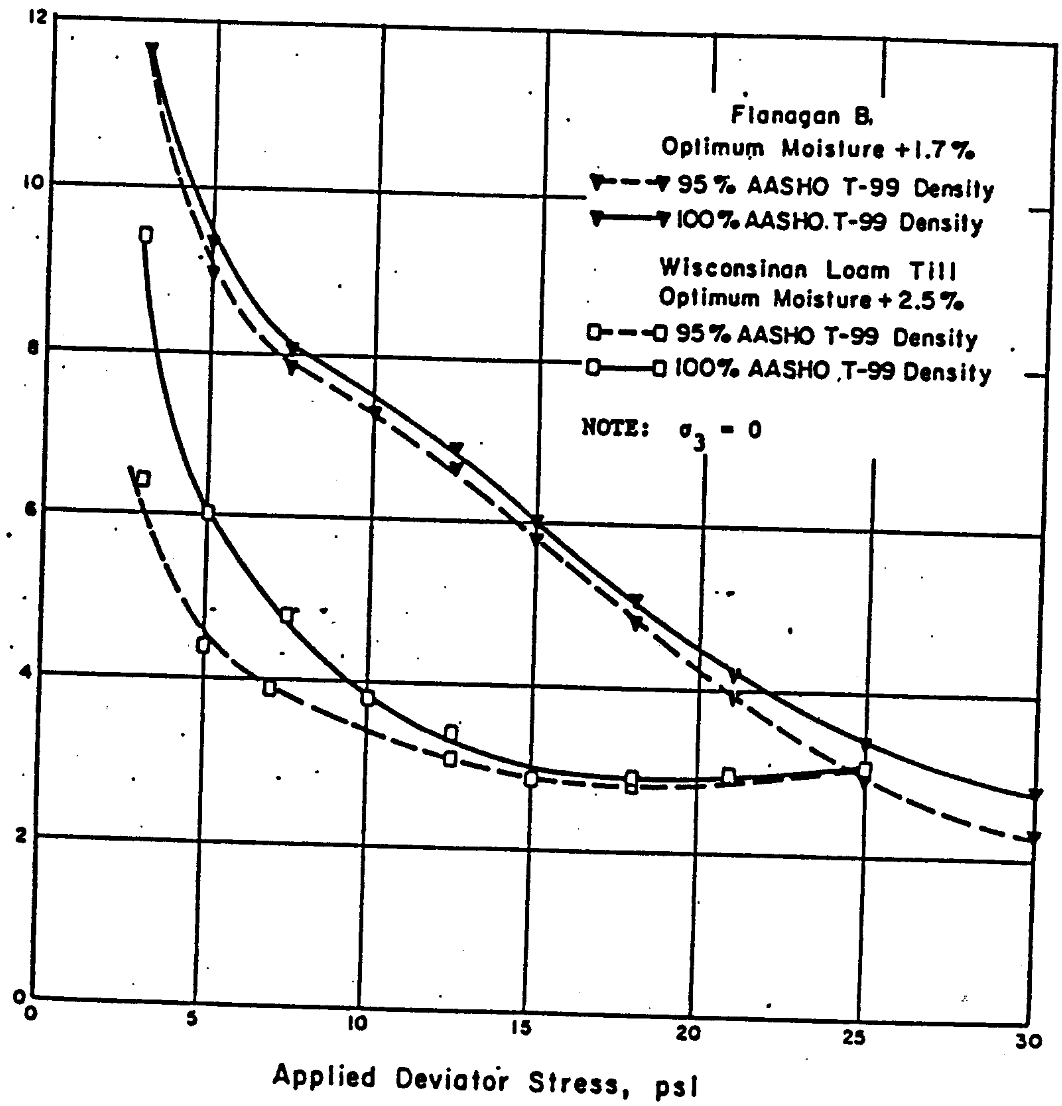

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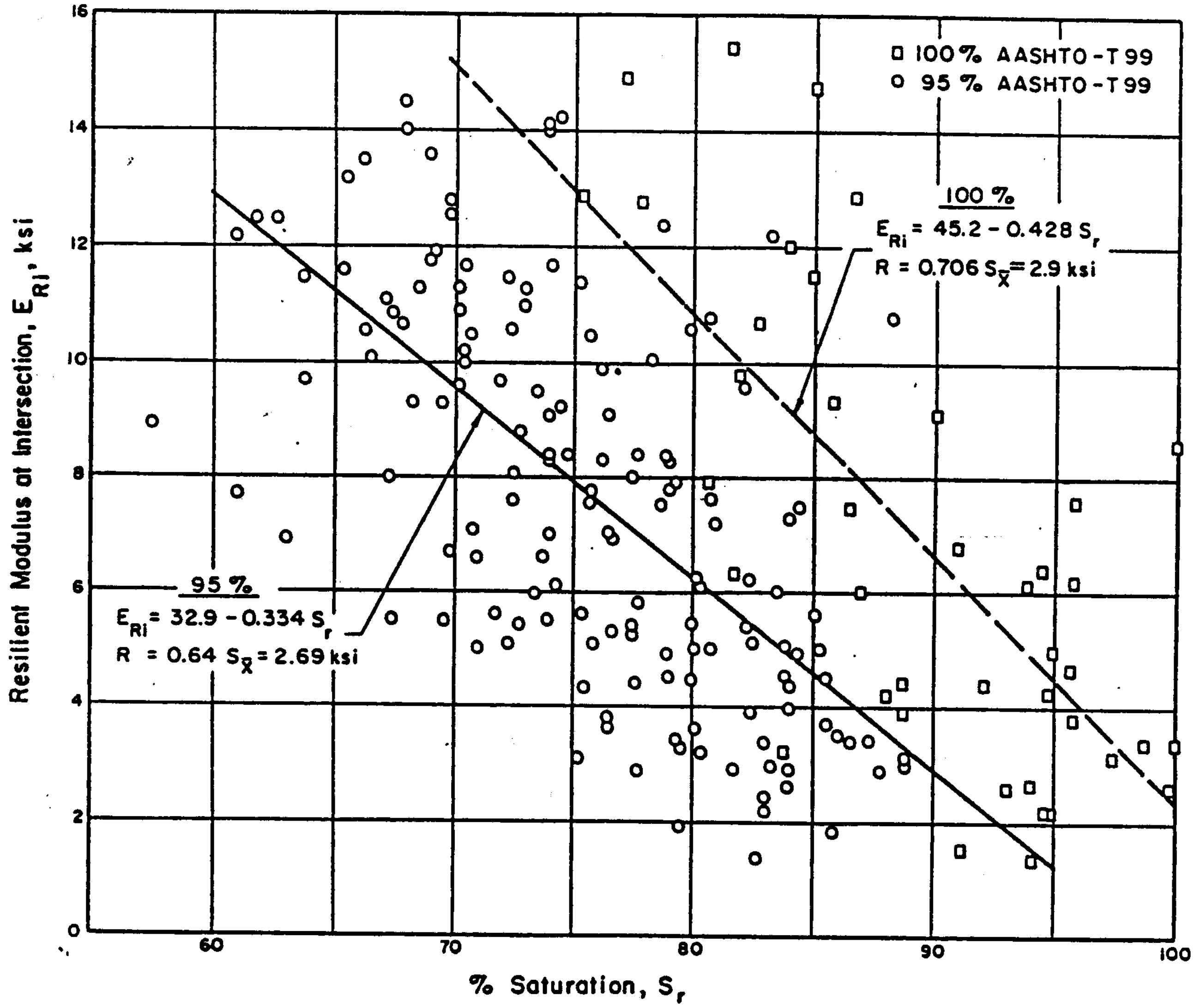


Figure 2.5: Resilient Modulus - % Saturation Relations for 95% and 100% of Compaction.

Deviator Stress -- Both cohesive and cohesionless soils are influenced by the amount of the repeated axial stress (deviator stress). In general, the modulus increases with the decrease of deviator stress as shown in Figure 2.7. A "break point" deviator stress was observed by Thompson and Robnett (1976). The break point is found at a deviator stress of 5 to 6 psi as the stress level is increased approximately 3 to 5 psi per increment (Figure 2.8)

Freeze-Thaw Cycles -- The deformation characteristics of subgrade will generally vary with the change of season during the year. The effect of freezing and thawing on compacted soils was reported by Hamilton (10). The freezing and thawing cycle of the subgrade will significantly influence the modulus of fine grained soils, particularly at the first freeze-thaw cycle (Figure 2.9) (13).

After examining the conclusions of the other researchers, it was determined that there is no significant correlation between the resilient modulus and the California Bearing Ratio (CBR) or Hveem Stabilometer R-value (11)(19). Howard and Lottman (1977) also indicated that the resilient modulus (M_r) value may not be directly related to the R-value. However, for more convenience, some correlations have been established in recent years to relate the M_r value to the standard CBR and the R-value (3)(6)(21). One of these correlations, which was developed by the Asphalt Institute (16), was used in the 1986 AASHTO

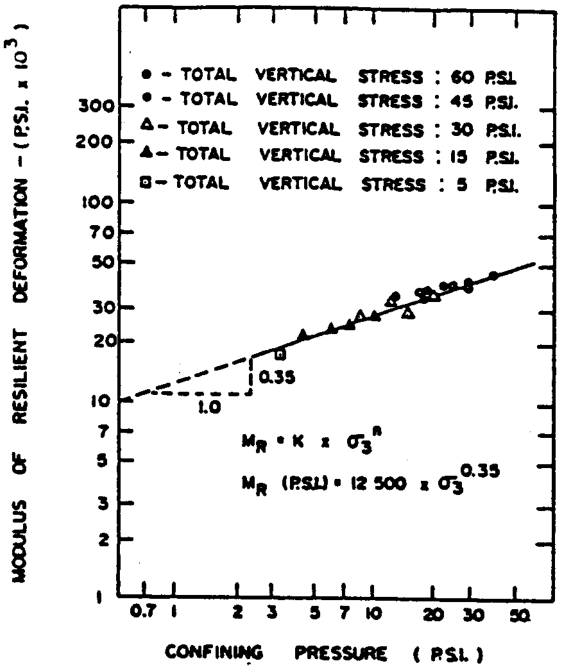


Figure 2.6: Effect of Confining Pressures on the Resilient Moduli of Sand (from Seed et al., 1967).

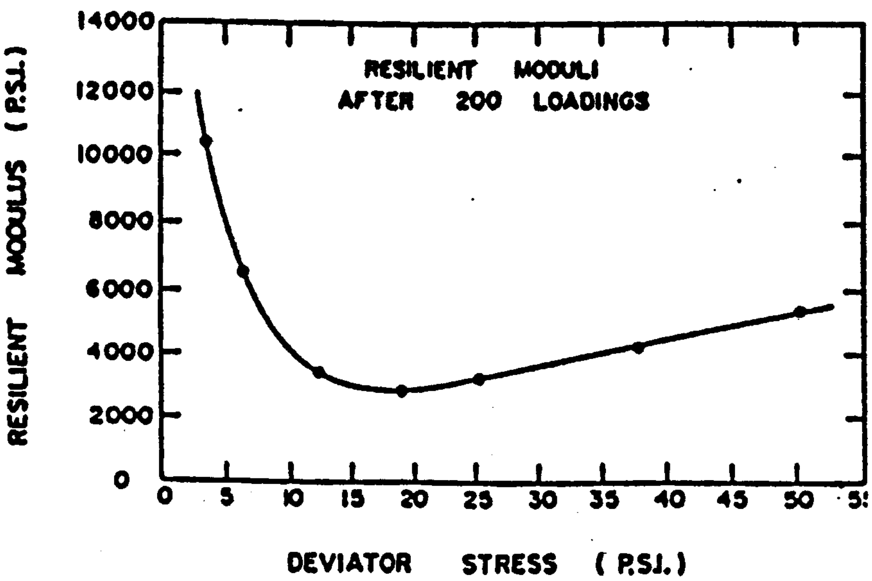
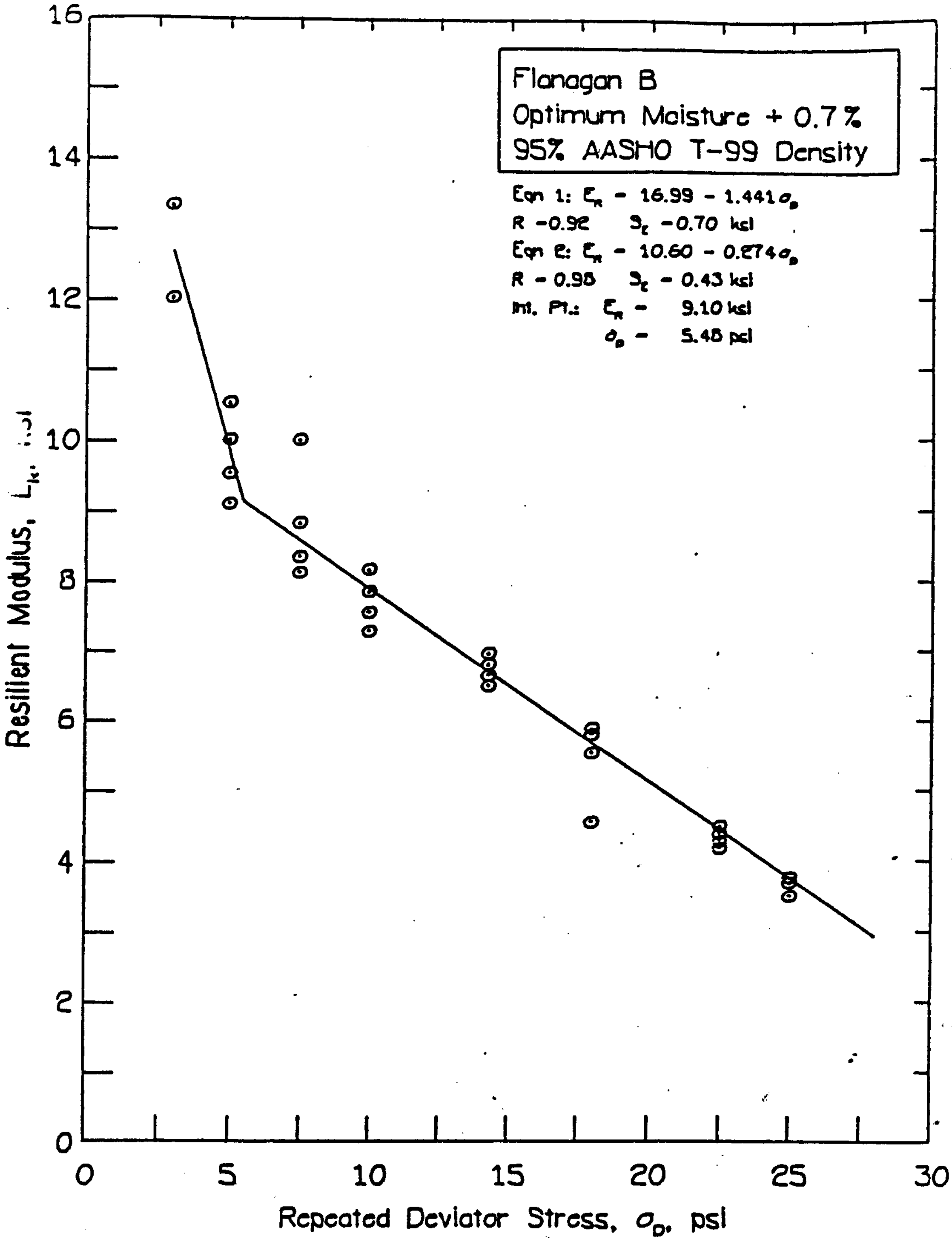


Figure 2.7: Effect of Deviator Stress on Resilient Characteristics of the AASHO Road Test Subgrade Soil (after Seed et al., 1967).



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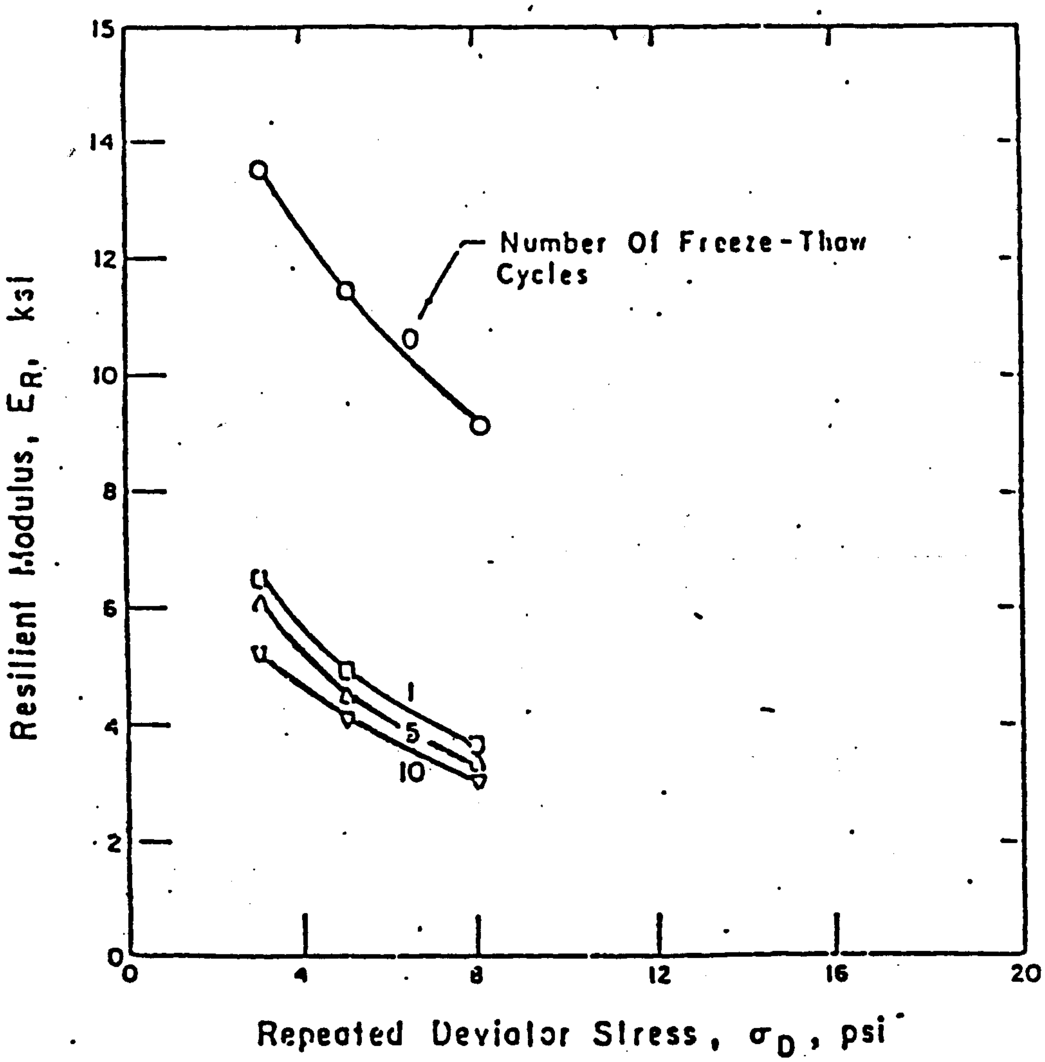


Figure 2.9: Effect of Freeze-Thaw on Resilient Modulus (from Robnett and Thompson, 1976)

guide for pavement design (1) and is plotted in Figure 2.10. The equations can be expressed as follows:

$$M_r(\text{psi}) = A + B \times (\text{R-value})$$

$$A = 772 \text{ to } 1155$$

$$B = 369 \text{ to } 555$$

The current correlation used by the CDOH is also plotted in this figure. This correlation is obtained through soil support value. It is an indirect method combining the following two equations:

$$M_r(\text{psi}) = 10^{(S1 + 18.72)/6.24}$$

$$S1 = [\,(R-5)/11.29\,] + 3 \qquad S1\text{: Soil Support Value}$$

Which yields an equation of:

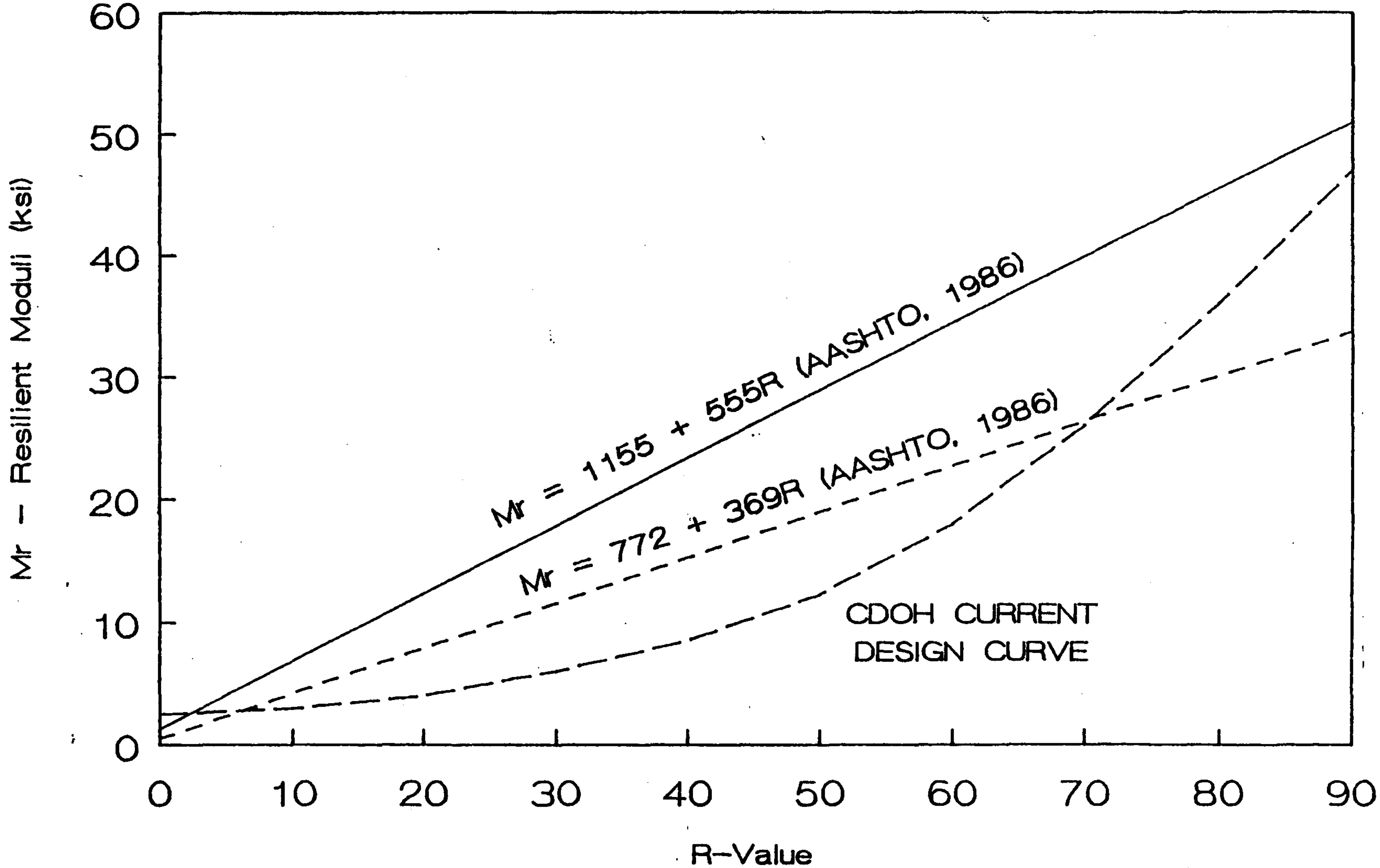
$$M_r(\text{psi}) = 10^{\{[(R-5)/11.29]+21.72\}/6.24}$$

Figures 2.11(a) and 2.11(b) present the relationship between the resilient modulus and the R-value of fine grained and coarse grained soils from Idaho Department of Transportation in 1980. The curves represent equations of:

$$M_r(\text{psi}) = 1455 + 57 \times (\text{R-value}) \qquad \text{for fine grained soils}$$

$$M_r(\text{psi}) = 1600 + 38 \times (\text{R-value}) \qquad \text{for coarse grained soils}$$

Correlation between Resilient Modulus and R-values
(from 1986 AASHTO Design Guide and CDOH Current Design Curve)



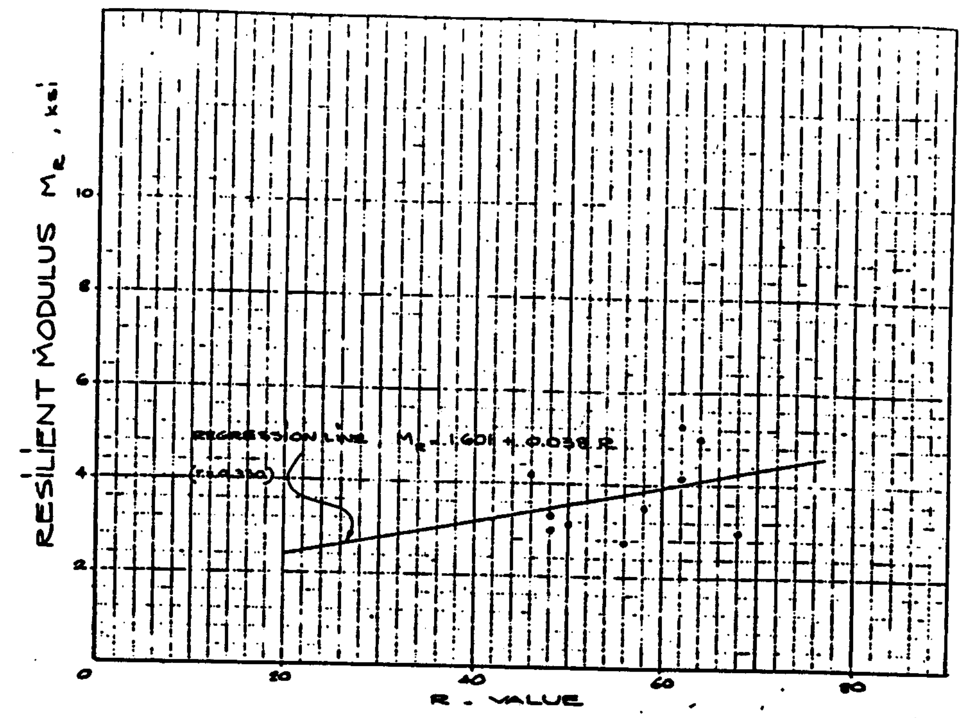


Figure 2.11(a): Resilient Modulus versus R-value of Fine Grained Soils (from Idaho Department of Transportation, 1980)

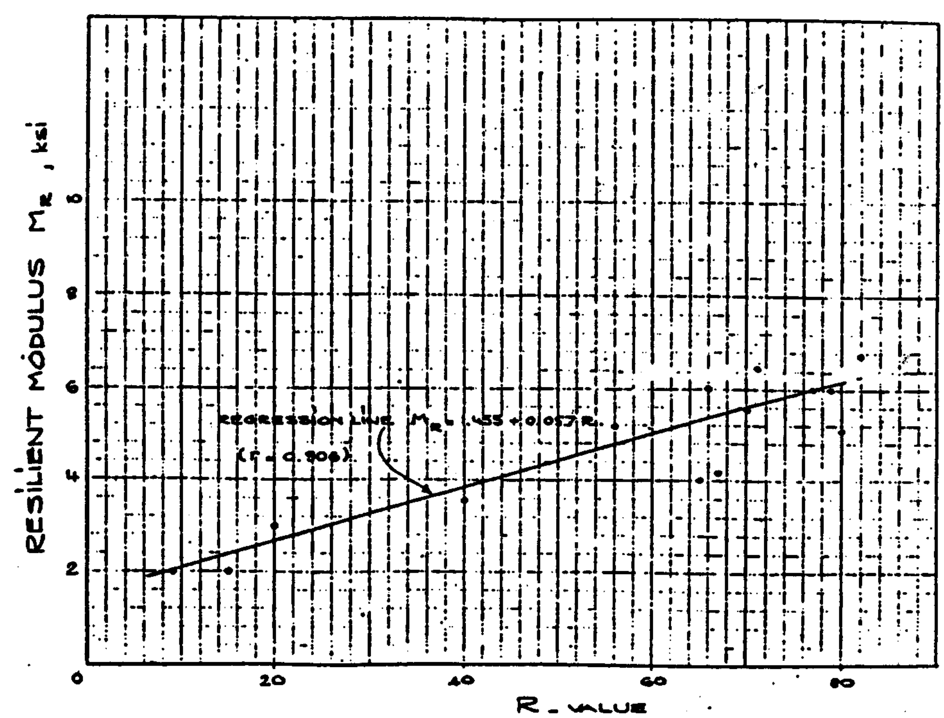


Figure 2.11(b): Resilient Modulus versus R-value of Coarse Grained Soils (from Idaho Department of Transportation, 1980)

It should be noted that an accurate determination of the resilient properties can only be obtained through resilient modulus test which requires a specialty test equipment.

III. TESTING PROGRAM

Early in 1985, a preliminary study to investigate the feasibility of correlations between the Hveem R-value and the resilient modulus of the Colorado soils was undertaken by the Soils Unit of the CDOH Central Laboratory. Six representative soils were selected for the study. These soils were all fine grained clay material having R-values from 5 to 40. The material properties of these soils are tabulated on Table 3.1.

The results of this study indicated that a correlation between the R-value and the subgrade resilient modulus is possible. Therefore, an extension of this study to cover coarse grained material was needed. Since the primary objective of this research was to find the direct relationship between R-value and resilient modulus over the entire range of soils, a wide spectrum of material types was selected. Samples of cohesive material were tested in the preliminary study. Therefore, an additional 13 soil samples, mostly granular material, were selected to cover the materials of higher R-values.

The selection of these 13 test samples was based on the R-values. The physical properties of all soil samples selected along with their respective R-values are shown on Table 3.1. These materials were randomly selected from ongoing state-wide construction projects. Soil

Table 3.1: Soil Properties for Resilient Modulus Test

Sample No.	L.L.	P.I.	% Passing No. 200	OMC (%)	Dry unit Wt. (pcf)	Class. and G.I.	R-value
Group 1	43	28	69	17.8	108.0	A-7-6(17)	6
Group 2	42	22	42	17.1	108.5	A-7-6(2)	15
Group 3	35	19	69	16.4	109.1	A-6(11)	11
Group 4	31	13	44	15.2	110.8	A-6(2)	30
Group 5	25	10	42	11.6	119.0	A-4(1)	26
Group 6	30	14	25	11.1	119.9	A-2-6(1)	39
Sample 1	28	10	20	12.1	116.2	A-2-4(0)	34
Sample 2	22	4	25	7.2	130.0	A-1-b(0)	42
Sample 3	27	9	23	13.5	115.4	A-2-4(0)	45
Sample 4	29	9	57	14.4	114.4	A-4(3)	50
Sample 5	24	8	34	12.8	116.7	A-2-4(0)	55
Sample 6	24	6	44	12.1	116.2	A-4(0)	58
Sample 7	23	9	36	16.0	117.9	A-4(0)	64
Sample 8	22	1	48	11.3	120.3	A-4(0)	70
Sample 9	NV	NP	16	10.9	119.9	A-2-4(0)	75
Sample 10	NV	NP	10	6.2	118.2	A-1-b(0)	80
Sample A	NV	NP	10	8.0	127.7*	A-1-b(0)	62
Sample B	22	3	17	11.3	120.9	A-1-b(0)	72
Sample C	NV	NP	9	8.5	129.9	A-1-b(0)	80

Note: NV: No Value
NP: None Plastic

specimens with R-values from 35 to 80 were used for the study.

The selected samples were tested in house for R-value determination, then sent to the Advanced Soils Lab of the University of Colorado at Denver. The resilient modulus of the specimens was carefully determined by the University Lab and the specimens were returned to the Department. A second R-value of each returned material was then determined and the physical properties were checked. The correlation of the resilient modulus and the various R-values was then made.

During the resilient modulus test, all samples were compacted to 95% standard proctor density(T-99). The majority of the samples were under 100% saturation condition when the modulus was determined. This simulates the worst in-situ condition the sample could experience during its entire service life. Three samples (A,B, and C) were tested at the optimum moisture content so that the effect of sample saturation could be evaluated.

IV. TEST PROCEDURES

A. Resilient Modulus

Standard procedures for determing the resilient properties of highway soils are included in Appendix A (AASHTO T274-82). Based on the AASHTO procedures, the testing time required to determine a modulus is approximately 2.5 hours for the cohesive material and 4.5 hours for the granular material. This time does not include the time needed for sample preparations, setting up the sample in the machine and making any necessary adjustment. Due to this relatively time consuming process, a large scale testing program to consider every aspect of the Colorado soils is not practical. The following describes a step by step procedure for the determination of the resilient modulus used by the University. Minor modifications on the testing procedures were made to shorten the testing time.

Soil Specimen Preparation

For groups 1 through 6, all specimens were prepared in a 4-inch diameter mold and compacted in 3-inch layers to a height of approximately 8 inches. The remainder of the samples were prepared in a 6-inch diameter mold and compacted in 4-inch lifts to a height of 12 inches. The specimens were compacted to at least 95% of the maximum dry density (AASHTO T-99) to represent the expected field conditions during construction. Figure 4.1 shows a prepared specimen being placed on the

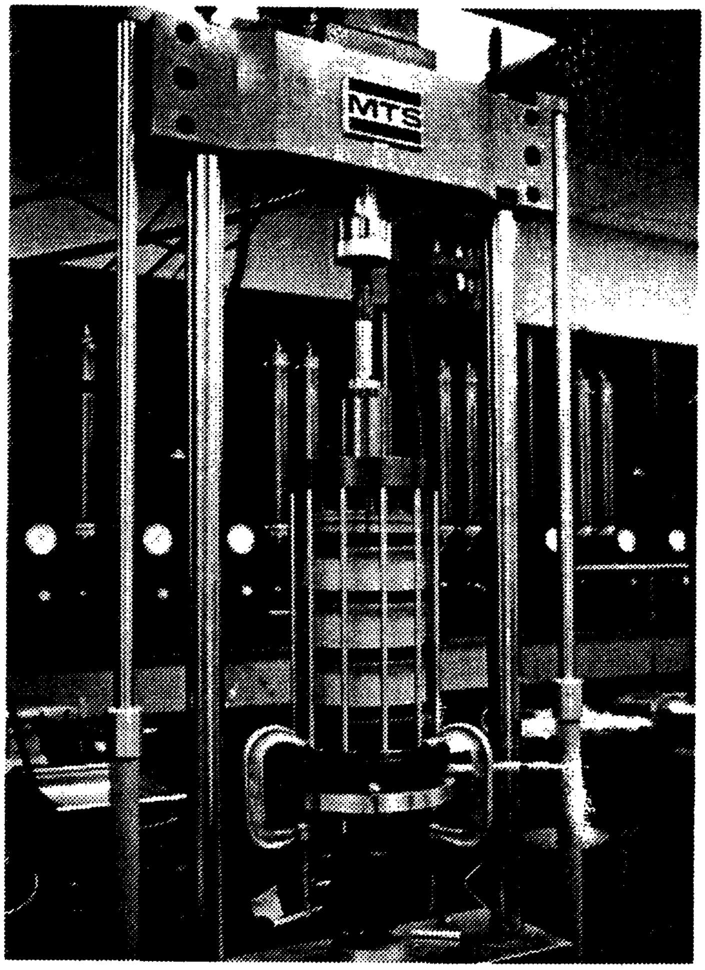


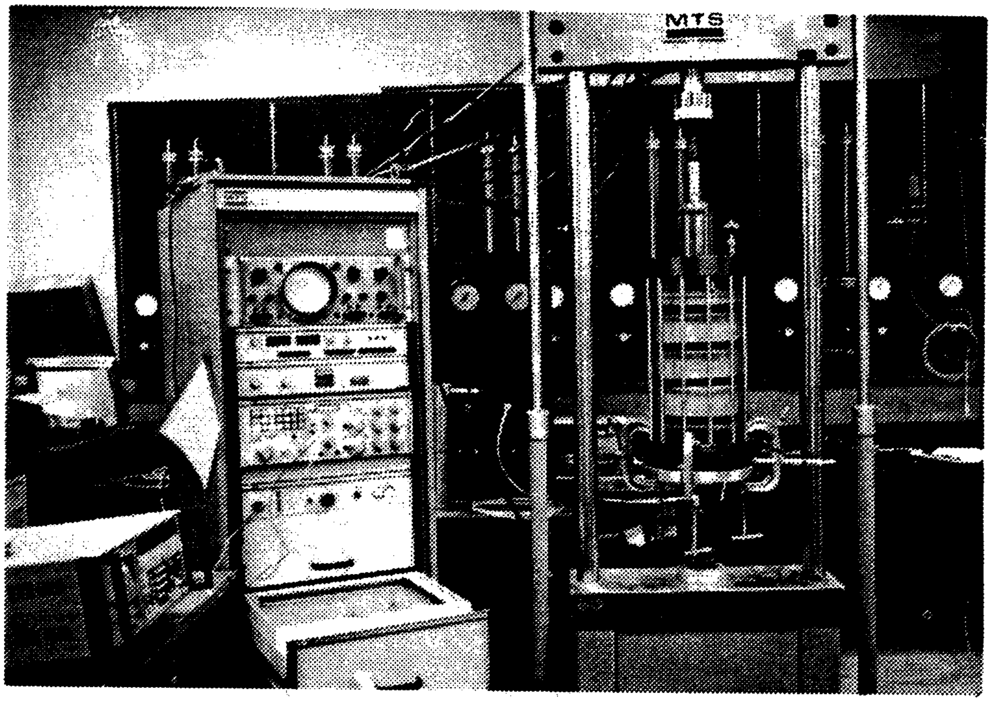
Figure 4.1: Triaxial Apparatus for Resilient Modulus Test

base of a triaxial assembly. Figure 4.2 shows a sample ready to receive loading from the MTS machine at the University of Colorado.

Test Procedures

The test procedure described in AASHTO T-274 includes loading cylindrical specimens for both fine grained and coarse grained soils. It should be noted that the behaviors of the resilient deformation of soils are greatly affected by the magnitude of the confining pressure and the deviator stress. Therefore, it is necessary to test soil samples over a range of deviator stress levels and at different confining pressures. Groups 1 through 6 were tested at deviator stresses of 2, 5, 7, and 10 psi and confining pressures of 0, 3, 6 psi. Samples 1 through 10 and A, B, C were tested at deviator stresses of 1, 2, 4, and 8 psi under 3 and 6 psi confining pressures. A summary of the confining pressures and deviator stresses for both sets is presented in Table 4.1 (a) and 4.1 (b).

All the laboratory tests were conducted at 100% saturation condition except for samples A, B, and C which were tested at optimum moisture content. A load duration of 0.1 seconds and a cycle duration of 2 seconds was used in the program. The samples were then subjected to cyclic loads of 200 repetitions and a frequency of 10 Hertz at various confining pressures.



Fugure 4.2: MTS Machine for Resilient Modulus Test in Progress

Table 4.1(a): Applied Stresses in Resilient Modulus Test for Samples Group 1 to 6

	Confining Pressure(psi)	Deviator Stress (psi)
Conditioning	6	2, 5, 7, 10
Testing	6, 3, 0	2
	6, 3, 0	5
	6, 3, 0	7
	6, 3, 0	10

Table 4.1(b): Applied Stresses in Resilient Modulus Test for Samples 1 to 10 and A, B, C

	Confining Pressure(psi)	Deviator Stress (psi)
Conditioning	6	1, 2, 4, 8
Testing	6	1, 2, 4, 8
	3	1, 2, 4, 8

This procedure is known as conditioning. Research has indicated that the load-deformation behavior of a sample generally stabilizes after 100 repetitions is applied. Detailed procedures for determining the resilient modulus of a soil sample is described as follows:

1. Install specimen in triaxial chamber and place in the loading apparatus.
2. Open the drainage valve from the base of the specimen to the back-pressure reservoir for saturated specimens.
3. Obtain 100% saturation of specimen before proceeding with following operations.
4. Apply a confining pressure of 6 psi to the test specimen.
5. Begin the test conditioning by applying 200 repetitions of a deviator stress of 2 psi for the confining pressure of 6 psi and then 200 repetitions each of 5, 7, and 10 psi.
6. Decrease the deviator stress to 2 psi. Apply 200 repetitions of deviator stress and record the recovered deformations at the 200th repetition.
7. Decrease the confining stress to 3 psi. Repeat Step 6.
8. Decrease the confining stress to zero. Repeat Step 6.
9. Increase the confining stress to 6 psi and deviator stress to 2 psi, apply 200 repetitions of load and record the vertical recovered deformations at the 200th repetition.
10. With the deviator stress at 2 psi, apply 200 repetitions of deviator stress and record vertical recovered deformations at successive

confining stresses of 3 psi and zero.

11 Continue recording vertical recovered deformations after 200 repetitions of the constant deviator stress - decreasing confining stress sequence for the constant stress values of 5, 7 and 10 psi.

The foregoing sample conditioning procedure is to eliminate or minimize the random behavior as a result of loading and reloading. This procedure also simulates the long term condition of a roadbed. The test procedures for the additional samples, i.e., samples 1 through 10 and samples A, B, and C, have been modified to reduce running time. The following sequence of stresses is used:

(1) Condition the samples with cyclic deviator stresses of 1, 2, 4, and 8 psi at a confining pressure of 6 psi.

(2) Apply 200 repetitions of deviator stress of 1 psi at the confining pressure of 6 psi and record the recovered deformations at the 200th repetition.

(3) Continue recording load-deformation of the sample at 200 repetitions of deviator stress for the stress levels of 2, 4, and 8 psi.

(4) Decrease the confining pressure to 3 psi and repeat step 3.

B. Hveem Stabilometer (R-Value)

The ability of soils to resist plastic deformation is measured in terms of R-value. All samples for R-value tests were prepared by kneading compaction. Each sample consisted of at least 3 specimens with different moisture contents. The R-value is obtained by extrapolation at exudation pressure of 300 psi. Figure 4.3 shows a typical R-value versus exudation pressure curve. The R-value test procedure used in the CDOH Materials Lab is similar to the AASHTO T-190, except the specimen is compacted on top surface of the mold. The test procedures of CDOH are presented in Appendix B.

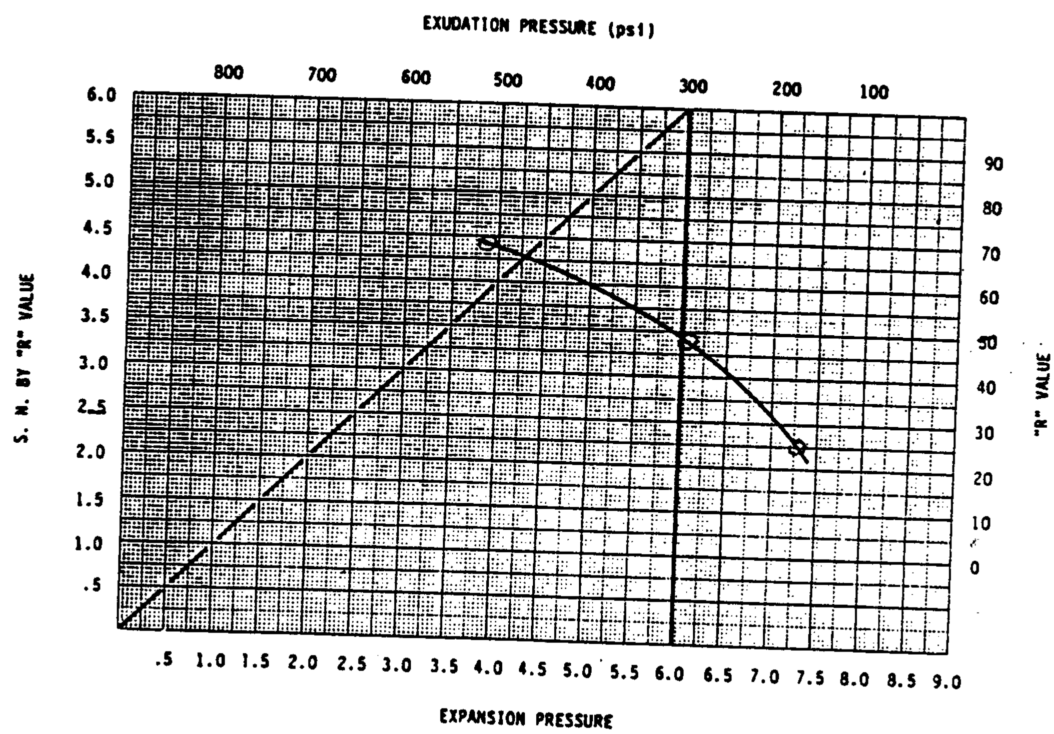


Figure 4.3: Typical R-value Test Result of a Specimen

V. RESULTS OF THE TEST AND ANALYSIS

A. Resilient Modulus Results

Since the resilient behavior of a soil sample is controlled by the applied confining pressure, the deviator stress and the degree of saturation of the sample, it is important to establish an appropriate stress level during modulus determination. The stress levels are determined based on the anticipated traffic loadings, the depths of the material and other factors. It was determined that a modulus measured under 3 and 6 psi confining pressures and deviator stresses of 4, 6, and 8 psi was the most common. Therefore, the modulus obtained at these stress levels are used for correlation purposes. Table 5.1 summarizes the results of the modulus tests at different stress conditions. These results are plotted under the various ambient stresses (confining stresses) using the arithmatic scale. All the results are presented in Appendix C.

Figure 5.1 illustrates a typical curve of the resilient modulus versus deviator stress at confining pressures of 0, 3, and 6 psi. It provides comprehensive information on the effect of variations in confining and deviator stresses. As illustrated in the figure, the resilient modulus decreases with increasing deviator stress. An increase of the applied confining pressure will result in an increase of the modulus of a fine grained soil.

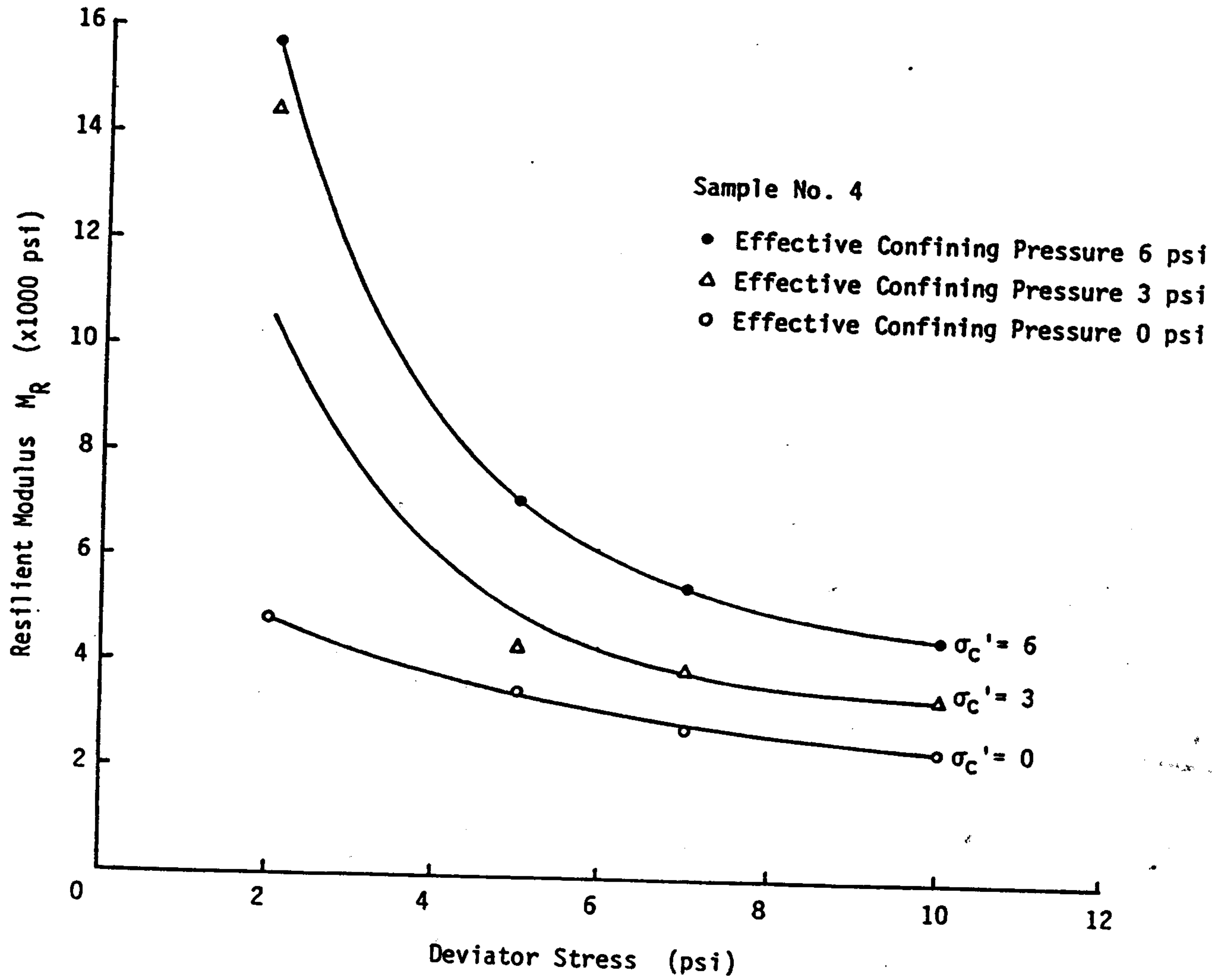


Figure 5.1: Typical curves of Resilient Modulus versus Deviator Stresses at Confining Pressures of 0, 3, and 6 psi.

Based on the test results, it can be seen that a substantial change in the magnitude of the resilient modulus occurs with increased applied deviator stress. It appears that the curves become flatter after a stress level of 6 psi is reached. A "break point" in this change is estimated at a deviator stress of 5 to 6 psi. It is also found that the deviator stress at 6 psi has a small deviation with regard to the changes in the confining pressure. Therefore, the use of a 6-psi deviator stress to simulate the repetitive nature of the traffic loading would seem to be appropriate for most practical purposes. This conclusion coincides with the recommendation made by the Asphalt Institute who also uses a deviatoric stress level of 6 psi (Soils Manual, MS-10) for normal pavement design. It should be noted that the stress conditions resulting from the daily traffic could vary from location to location. Adjustment of the deviatoric stress according to the traffic loading is required if substantially different loading conditions are anticipated.

To simulate the ambient soil stress in the field, all the tests were conducted at confining pressures of 0 to 6 psi. This confining pressure is normally obtained from its overburden and some from the traffic loads. The ambient stress resulting from these loads generally ranges from 1 to 5 psi (The Asphalt Institute recommends a value of 2 psi, Soils Manual, MS-10). A confining pressure of 3 psi, the median value, was selected in this study.

The physical properties of the test specimens from Sample 1 to 10, measured both before and after the resilient modulus determination, is tabulated in Table 5.2. Analysis of the results found that the percent passing No. 200 fine material was increased substantially for Samples No. 2 and 3, and increased slightly for the remaining samples. Because of this increase, the classification of Samples 2, 3, and 5, which are all granular materials, became A-4(0) and A-4(1), a fine grained material classification. It is believed that the soil particles in the specimen have disintegrated due to heavy remolding.

In general, an R-value is strongly affected by the change of the moisture content, especially for a cohesive material. An increase of moisture content will normally reduce the R-value if the material contains cohesive fines. R-value of a material is also strongly affected by the amount of fines in the samples. Table 5.2 summarizes the R-values of the test specimens before and after resilient modulus tests were taken. It is evident that the R-values of these samples are significantly decreased due to the increase of the fines. The reduction for silty soils, i.e., A-4(0), A-4(2), and A-4(3), materials which are the most sensitive to the moisture, was the greatest after the samples were remolded.

Table 5.2: Soil Properties Before and After Remolding for Samples 1 through 10

Sample No.	Initial % Passing No. 200	Post % Passing No. 200	Initial Class. and G.I.	Post Class. and G.I.	Initial R-value	Post R-value
Sample 1	20	25	A-2-4(0)	A-2-4(0)	34	49
Sample 2	25	41	A-1-b(0)	A-4(0)	42	25
Sample 3	23	50	A-2-4(0)	A-4(1)	45	30
Sample 4	57	58	A-4(3)	A-4(3)	50	24
Sample 5	34	38	A-2-4(0)	A-4(0)	55	30
Sample 6	44	46	A-4(0)	A-4(2)	58	20
Sample 7	36	36	A-4(0)	A-4(0)	64	17
Sample 8	48	48	A-4(0)	A-4(0)	70	70
Sample 9	16	20	A-2-4(0)	A-2-4(0)	75	79
Sample 10	10	13	A-1-b(0)	A-1-b(0)	80	78

B. Correlation of Resilient Modulus and R-values

The values of the resilient modulus are plotted against R-values based on all the test results obtained in the study. Figure 5.2 illustrates the results of the modulus at a confining pressure of 3 psi and a deviator stress of 6 psi versus the R-value obtained prior to the determination of the resilient modulus. The modulus at 6 psi confining pressure plotted against the R-value is shown in Figure 5.3. Since the R-value is greatly changed as a result of sample remolding, an average R-value obtained before and after the resilient modulus test, is most likely to give a representative correlation. The average R-values and

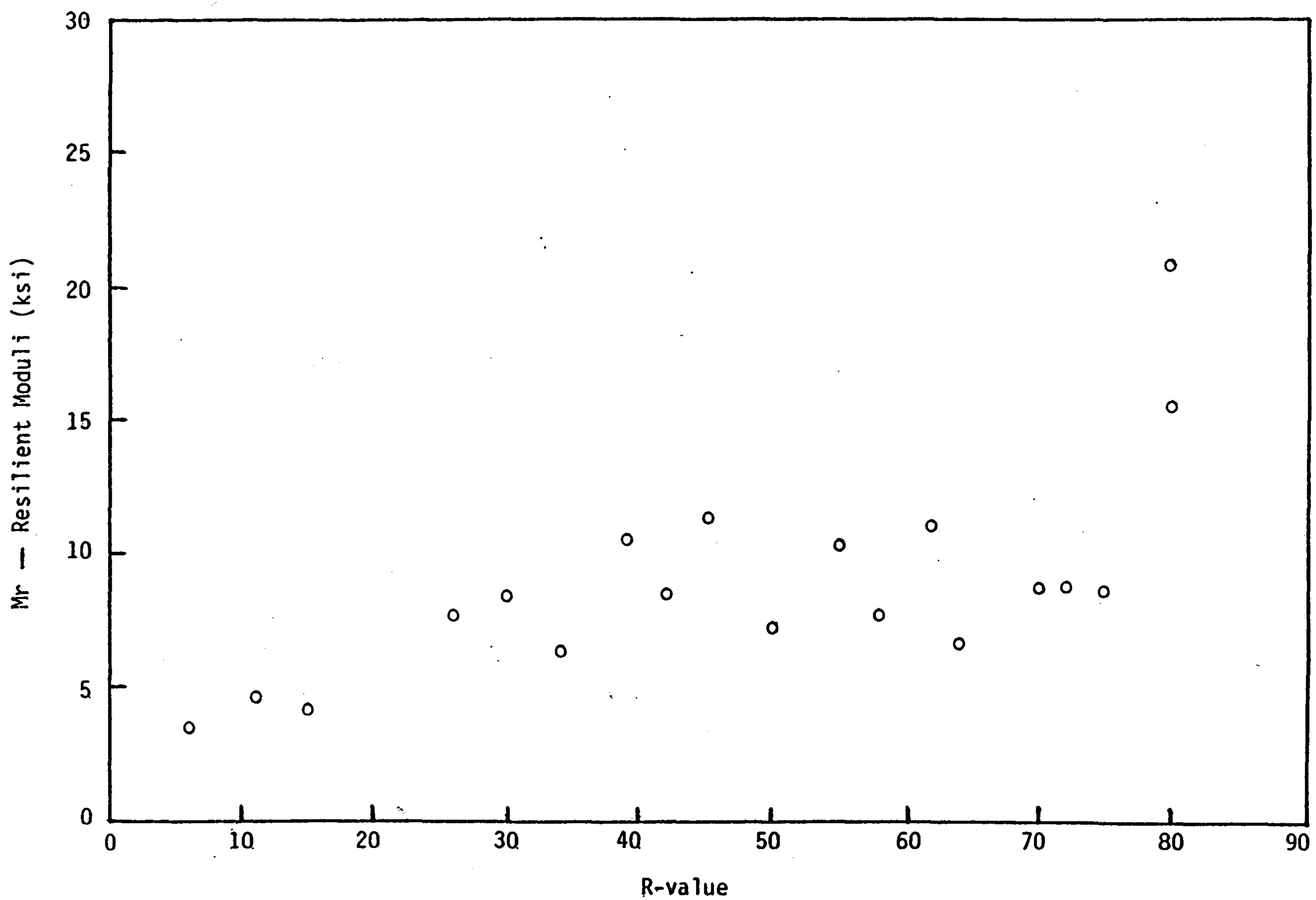


Figure 5.2: Correlations of Resilient Modulus and R-values
(Resilient Modulus at 3 psi Confining Pressure)

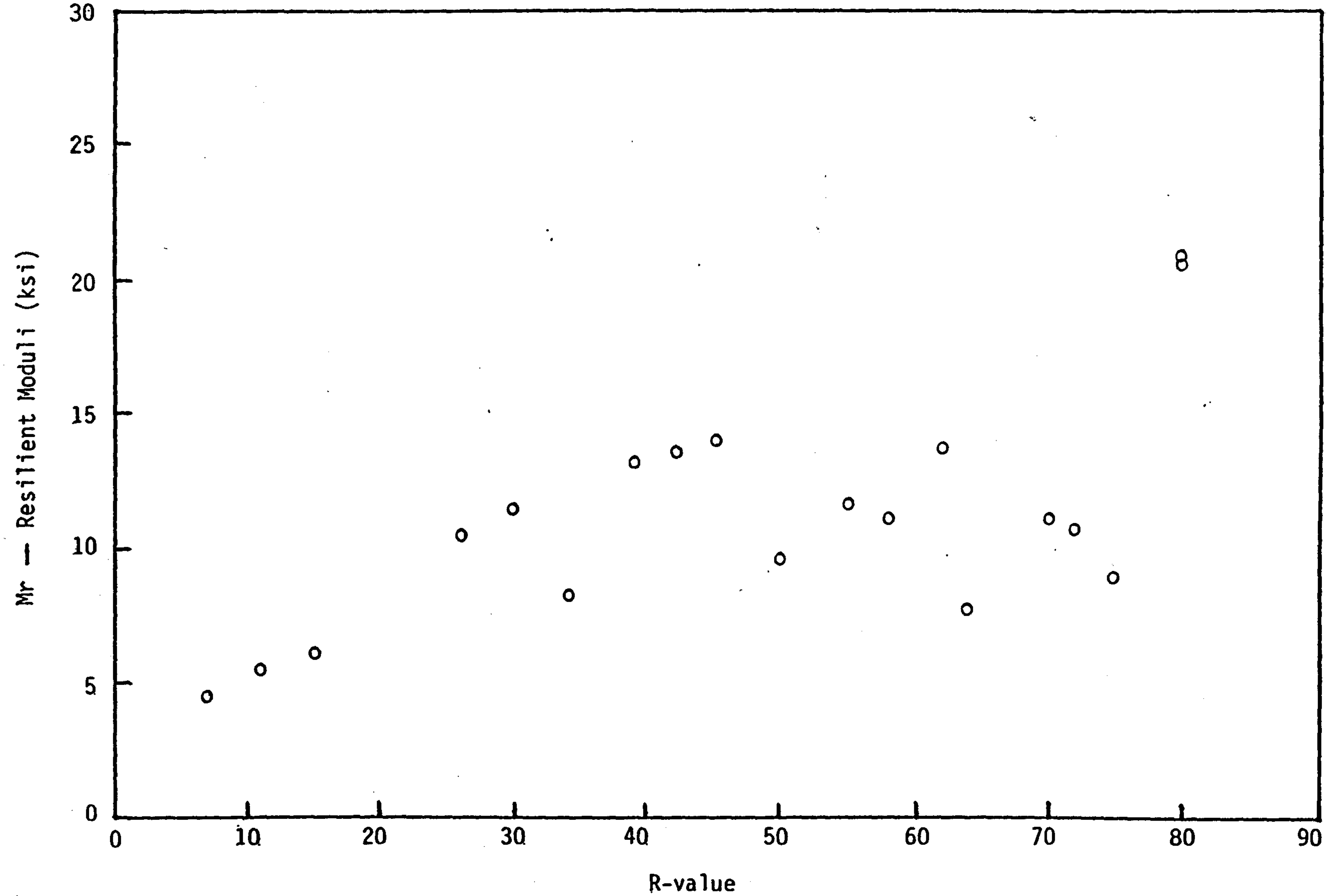


Figure 5.3: Correlations of Resilient Modulus and R-values
(Resilient Modulus at 6 psi Confining Pressure)

respective moduli (M_r) are presented in Table 5.3. Figure 5.4 shows the relationship between the resilient modulus and theaverage R-value. Regression analysis indicates the following correlation:

$$M_r(psi) = 3500 + 125 \times R$$

R = Stabilometer R-value

This correlation between the resilient modulus and the R-value shows a very good agreement with the current CDOH design for most of the fine grained soils with R-values less than 50. The modulus is substantially lower at higher R-value range. As can be seen on Figure 5.2 and Figure 5.3, wider scatter in modulus is observed,therefore, the correlation at the higher R-value range may need further investigation. In general, the resilient moduli obtained by this research are substantially higher than the values established by the Idaho DOT. However, they are lower than the correlation developed by the Asphalt Institute (1986, AASHTO Design Guide). These lower values will result in a thicker pavement section design, especially for granular soils.

A comparison of the normalized pavement thickness using resilient modulus values recommended by AASHTO, the current CDOH design ant the results of this research is presented in Figure 5.5. The differences of the pavement thickness are plotted against the R-value. In general, thinner pavement sections are required for Colorado fine grained soils and thicker sections are needed for coarse grained materials, if the results obtained from this research are used. A comparison is made based on the following parameters:

(1) The same total number of 18 kip single-axle loads,

Table 5.3: Resilient Modulus VS Corrected R-value

Sample No.	Soil Class. and G.I.	Resilient Modulus(psi)	R-value
Group 1	A-7-6(17)	3,500	6
Group 2	A-7-6(2)	4,200	15
Group 3	A-6(11)	4,600	11
Group 4	A-6(11)	8,400	30
Group 5	A-4(1)	7,800	26
Group 6	A-2-6(1)	10,500	39
Sample 1	A-2-4(0)	6,400	41
Sample 2	A-4(0)	8,500	34
Sample 3	A-4(1)	11,200	37
Sample 4	A-4(3)	7,200	37
Sample 5	A-4(0)	10,300	42
Sample 6	A-4(2)	7,700	39
Sample 7	A-4(0)	6,800	40
Sample 8	A-4(0)	8,700	70
Sample 9	A-2-4(0)	8,600	77
Sample 10	A-1-b(0)	15,500	79
Sample A	A-1-b(0)	11,000	62
Sample B	A-1-b(0)	8,700	72
Sample C	A-1-b(0)	21,900	80

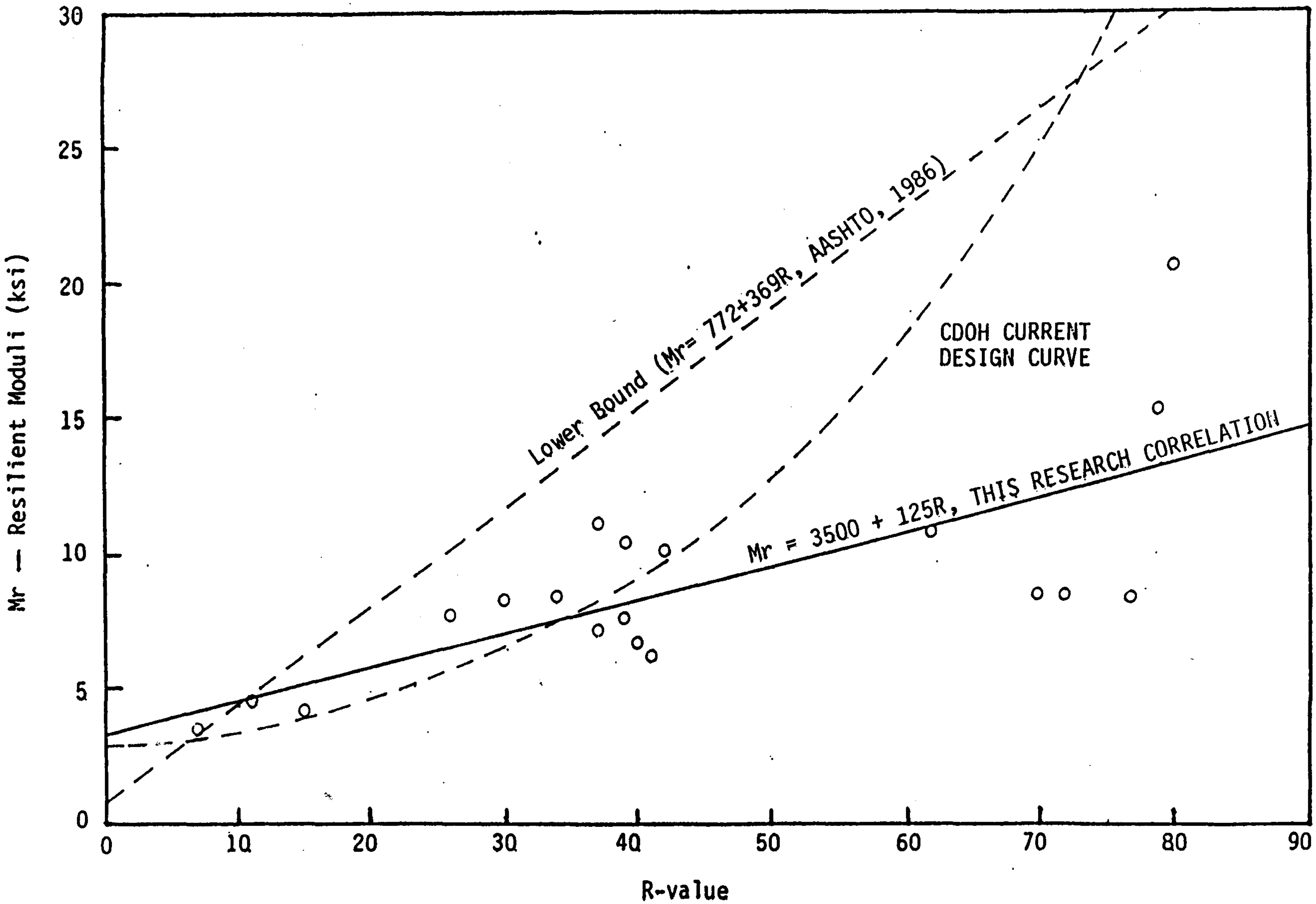


Figure 5.4: Correlations of Resilient Modulus and Corrected R- values

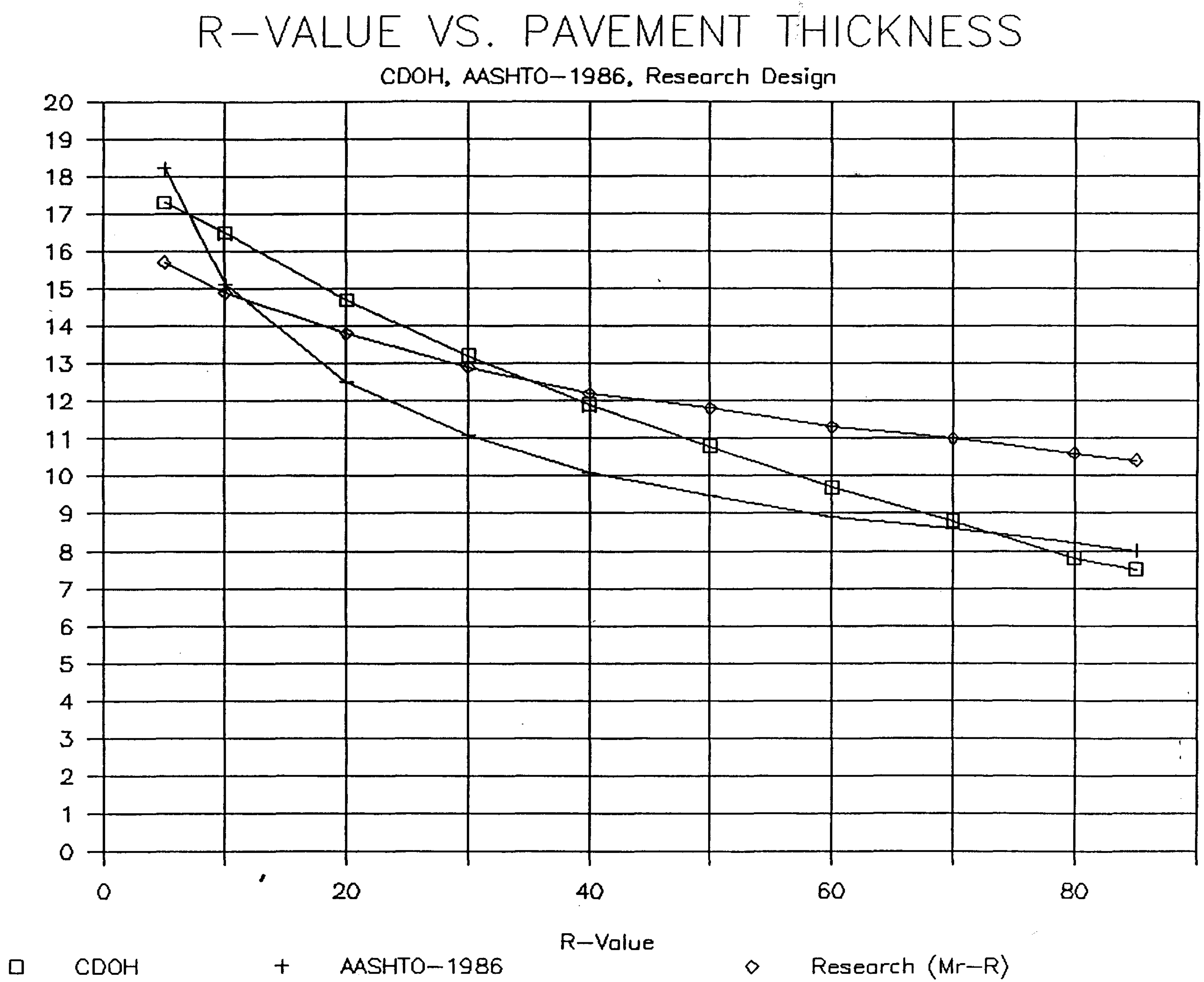


Figure 5.5: Comparison of the Pavement thickness using M_r Values Recommended by AAshTO, and Current CDOH Design

(2) A structural number of five and a resilient modulus of 5 ksi as base values,

(3) The structural numbers converted to equivalent full depth asphalt thickness are based on structural layer coefficients of 0.44 for asphalt and 0.30 for bituminous base.

VI. CONCLUSIONS AND IMPLEMENTATION

Summary

A comprehensive study to correlate the resilient properties and Hveem stabilometer R-value of soils was conducted in the Colorado Department of Highways (CDOH). A total of 19 soil samples were used to establish a relationship between these two parameters. The moduli were determined at different confining pressures subjected to various deviator stresses. The soil samples tested in this program have a wide range of R-values which represent subgrade soils that commonly occur under Colorado's highways.

Many factors affect the behavior of the resilient properties of a soil. Selection of proper values to represent field conditions for the highway pavement design can be complicated; but, it can be carefully determined. The modulus obtained at a confining pressure of 3 psi and deviator stress of 6 psi was considered adequate to simulate most of the field conditions.

Conclusions

Based on the results of this study, the following conclusions are made:

(1) The resilient behavior of materials, including both cohesive and cohesionless soils, are affected by the amount of confining pressure and deviator stress applied. Deviator stress has more effect on the resilient modulus of the fine grained than the coarse grained soils.

(2) The physical properties of a coarse grained soil are most likely to be changed due to sample remolding. In general, the effect of sample remolding on R-values decreased with the increase of the amount of fines for the same material.

(3) The linear relationship, M_r (psi) = 3500 + 125 x (R-value), has been established between the resilient modulus and the R-value for Colorado soils. For fine grained soils (R-value below 50), the moduli obtained by the current AASHTO guide and by the current CDOH design are similar. However, this modulus is lower for a coarse grained material when compared with the modulus obtained by these two methods. This implies that for a coarse grained subbase, a thicker pavement section is required.

(4) It should be noted that the correlation established between the resilient modulus and R-value in the granular soils range is based on a limited number of tests. Verification of this correlation for high quality subgrade (i.e. A-1-b or better) should be made.

Implementation

The finding of this research validates the correlation curve in the fine grain soils range (R<50) currently used by the CDOH design staff. Full implementation of the research results should be based on additional tests conducted on soils in the very high R-value range.

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APPENDIX A

DESCRIPTION OF RESILIENT MODULUS TEST

The resilient modulus test included loading cylindrical specimens of fine grained cohesive and granular cohesionless soils separately. The specimens were prepared at 95% of optimum moisture content (AASHTO T-99) to represent the expected field conditions. The load duration of 0.1 second and cycle duration of 3 seconds will satisfy most applications.

It is noted that behavior of resilient deformation of cohesive soils are greatly affected by the magnitude of the deviator stress. Therefore, it is necessary to test cohesive soils over a range of deviator stress levels. The foregoing sequence of sample conditioning and testing is used to eliminate or minimize the effects of initial loading versus reloading.

Test procedures of resilient modulus on cohesive soils are as follows:

1. Install specimen in triaxial chamber and place in the loading apparatus.

2. Obtain 100% saturation of specimen before proceeding with following operations.

3. Open all drainage valves leading into the specimens.

4. Apply a confining pressure of 6 psi to the test specimen.

*5. Begin the test by applying 200 repetitions of a deviator stress of 1 psi for the confining pressure of 6 psi and then 200 repetitions each of 2, 4, 8, and 10 psi.

6. Decrease the deviator stress to 1 psi. Apply 200 repetitions of deviator stress and record the recovered deformations at the 200th repetition.

7. Decrease the confining stress to 3 psi. Repeat Step 6.

8. Decrease the confining stress to zero. Repeat Step 6.

9. Increase the confining stress to 6 psi and deviator stress to 2 psi, apply 200 repetitions of load and record the vertical recovered deformations at the 200th repetition.

10. With the deviator stress at 2 psi, apply 200 deviator stress repetitions and record vertical recovered deformations at successive confining stress of 3 psi and zero.

11. Continue recording vertical recovered deformations after 200 repetitions of the constant deviator stress - decreasing confining stress sequence for the constant stress values of 4, 8 and 10 psi.

Since the modulus of resilient deformation on granular soils is greatly dependent on the magnitude of the confining pressure, similarly, the test on granular materials is required over a range of confining and deviator stresses. The effect of initial loading will be eliminated by the application of conditioning stress and sequence of the set confining pressures.

The procedures listed in this section are used for both saturated and unsaturated specimens of cohesionless soils.

1. Prepare test specimen and place in load device.

2. Open the drainage value from the base of the specimen to the back-pressure reservoir for saturated specimens.

3. Set a confining pressure to 5 psi and apply 200 repetitions of an axial deviator stress of 5 psi.

4. Apply 200 repetitions of an axial deviator stress of 10 psi.

5. Increase the confining pressure to 10 psi and apply 200 repetitions each of 10 and 15 psi axial deviator stresses.

6. Increase the confining pressure to 15 psi and apply 200 repetitions each of 15 and 20 psi axial deviator stresses.

7. Reduce the back-pressure to zero for saturated specimens.

8. Begin the recorded resilient modulus test by increasing the confining pressure to 20 psi and a deviator stress of 1 psi. Recorded the vertical recovered deformations at the 200th repetition of this load.

9. Continue to record vertical recovered deformations after 200 repetitions for deviator stress levels of 2, 5, 10, 15, and 20 psi.

10. Reduce the confining pressure to 15 psi and record vertical recovered deformations after application of 200 repetitions of each of the following deviator stress levels: 1, 2, 5, 10, 15, and 20 psi.

11. Reduce the confining pressure to 10 and 5 psi. Repeat Step 10 without the deviator stress of 20 psi.

12. Reduce the confining pressure to 1 psi. Repeat Step 10 by following the deviator stress level: 1, 2, 5, 7.5, and 10 psi.

APPENDIX B

DESCRIPTION OF THE R-VALUE TEST

(Modified AASHTO Designation T 190)

AASHTO T 190 will be used to determine the Resistance R-Value except for paragraphs 2.1.1, "Compaction of Specimens", and 4.2 through 4.4, "Preparation of Specimens".

COMPACTION OF SPECIMENS

2.1.1 The compactor shall include a counter or timer for measuring the number of tamps applied to a specimen and a mold holder for use in compacting specimens, that rotates equally between tamps to give 5 to 7 tamps per revolution of the mold. The holder shall firmly restrain the mold during compaction. The base of the mold holder shall have a metal plate 3-31/32 inches (100.8 mm) in diameter and 0.5 inches (12.7 mm) high. The plate shall be and integral part of the base of the mold holder. A steel disk shall be placed inside the mold on the base of the mold holder. The disk shall be approximately 2 inches (50.8 mm) in height and 3-15/16 inches (100 mm) in diameter with a rubber disk of the same diameter by 1/8 inch (3.2 mm) thick cemented to the disk. A mold collar as shown in Figure 1 shall be placed on the mold during compaction. The compactor shall include a trough for feeding the sample into the mold in 20 increments.

PREPARATION OF SPECIMENS

4.2 Weigh out enough material to fabricate a compacted sample 4 inches (101.6 mm) in diameter by approximately 2.5 inches (63 mm) high. Compact the soil into the mold by means of the kneading compactor as follows: Place the mold in the mold holder. Place inside the mold the steel and rubber disk combination with the rubber disk up. Adjust the mold for approximately 1/8 inch (3 mm) clearance between the lower edge of the mold and base of the mold holder. The space between the top of the rubber disk to the top edge of the mold should not exceed 2-5/8 inches (67 mm). Place the collar (Figure 1, page 95) on the mold. With the compactor-foot pressure set at 250 ± 25 psi (1720 ± 170 kPa), feed the balance of the soil into the mold in 20 equal increments with one application of the ram after each increment. Allow 10 additional tamps to level the soil, then place a rubber disk on top of the specimen. Apply 100 additional tamps with a foot pressure of 350 psi (2410 kPa). Stop compacting the soil at any time before 100 tamps if water appears around the bottom of the mold.

NOTE: Use lower compaction pressures when necessary to limit penetration of the ram into the soil to not greater than 1/4 inch (6 mm). The top of the 2.5 inches (63 mm) compacted specimen should not be more than 1/8 inch (3 mm) from the top of the mold.

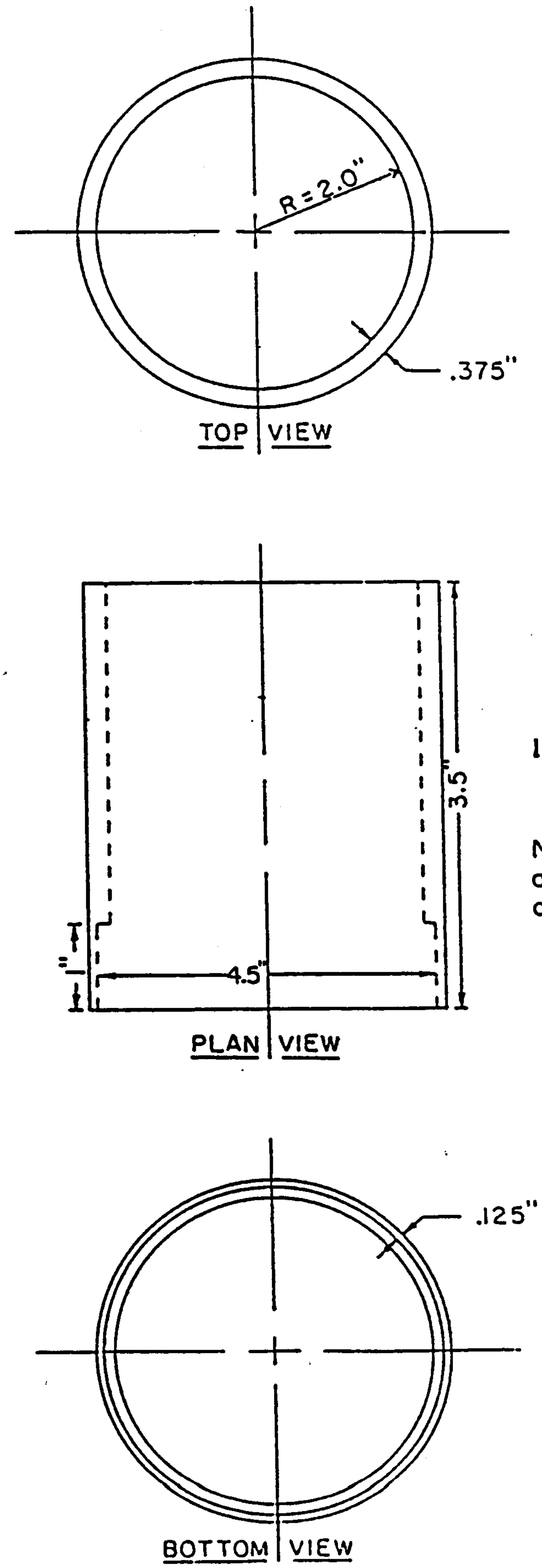
4.3 Place a steel disk 3-15/16 inches (100 mm) in diameter on the compacted soil and apply 12 additional tamps at a foot pressure sufficient to level the specimen. Remove the mold from the compactor. Place a phosphorbronze disk on the compacted surface of the soil and place a filter paper on top of the bronze disk. Invert the mold and place it one the exudation device so that the filter paper is on the bottom. Using the compression testing machine, apply a uniformly increasing pressure to the soil at the rate of 2000 lbs. (8900 N)/min. Water should be excluded from the soil between 100 (690) and 800 psi (5520 kPa). Stop loading and recording the exudation pressure when either five or six outer lights on the exudation device are lighted or three outer lights are lighted and free water is visible around the bottom of the mold.

4.4 Mold at least two more specimens with different amounts of moisture so that a range of exudation pressures from 100 to 800 psi (690 to 5520 kPa) (see note) is obtained which bracket the 300 psi (2070 kPa) value.

NOTE: Occasionally, material from very plastic, clay-test specimens will extrude from under the mold and around the follower ram during the loading operation. If this occurs when the 800 psi (5520 kPa) point is reached and fewer than five lights are lighted, the soil should be reported as less than 5 R-Value. Coarse granular materials and clean sands may require the use of paper baskets to permit testing.

Stabilometer Mold Collar

FIGURE I



MATERIALS

1). Steel Cylinder

NOTE: No machine tolerance are given as collar needs only to fit molds.

APPENDIX C

LIST OF RESILIENT MODULUS TEST CURVES

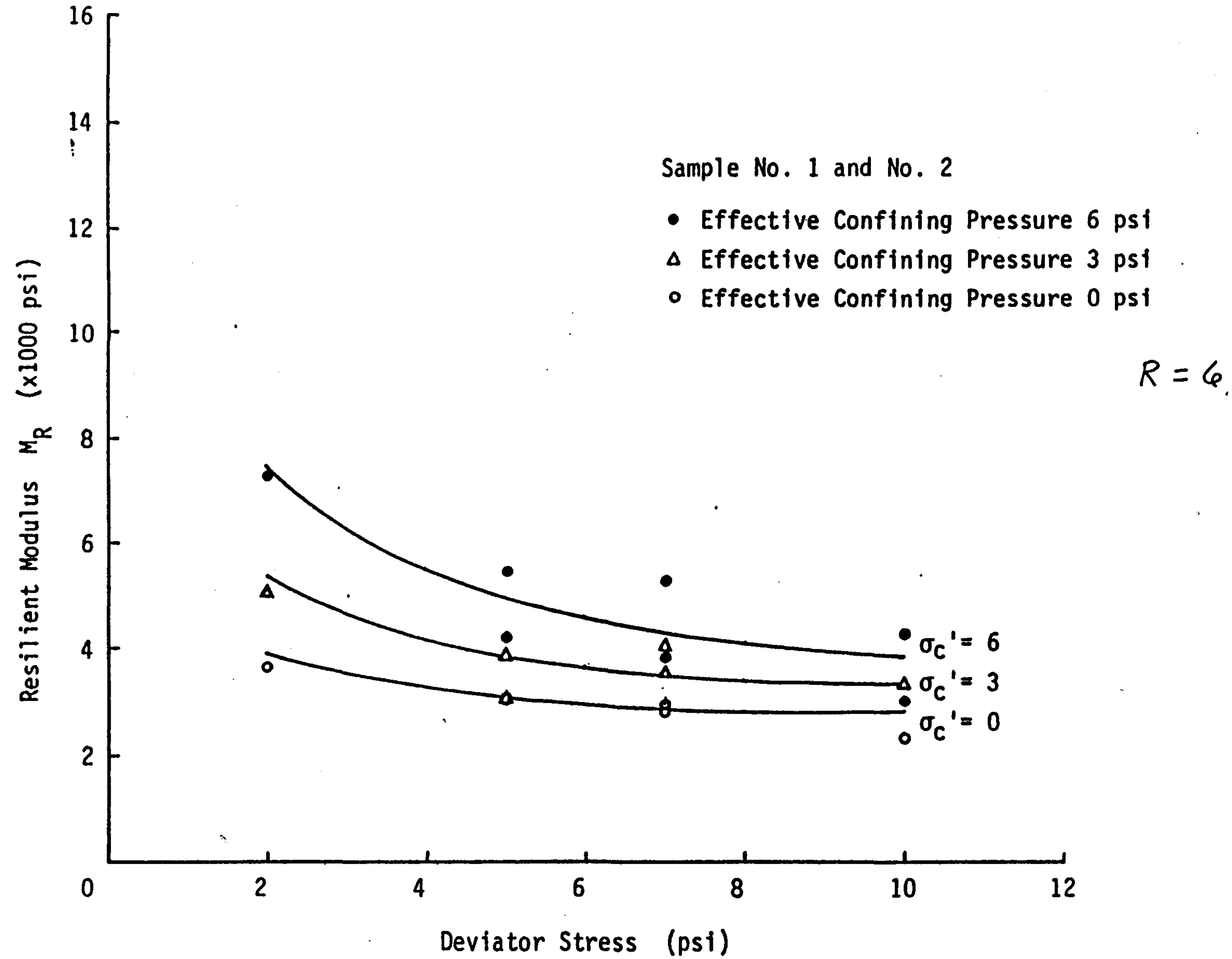


FIG. 13 Arithmetic Plot of Resilient Moduli of Sample No. 1 and No. 2

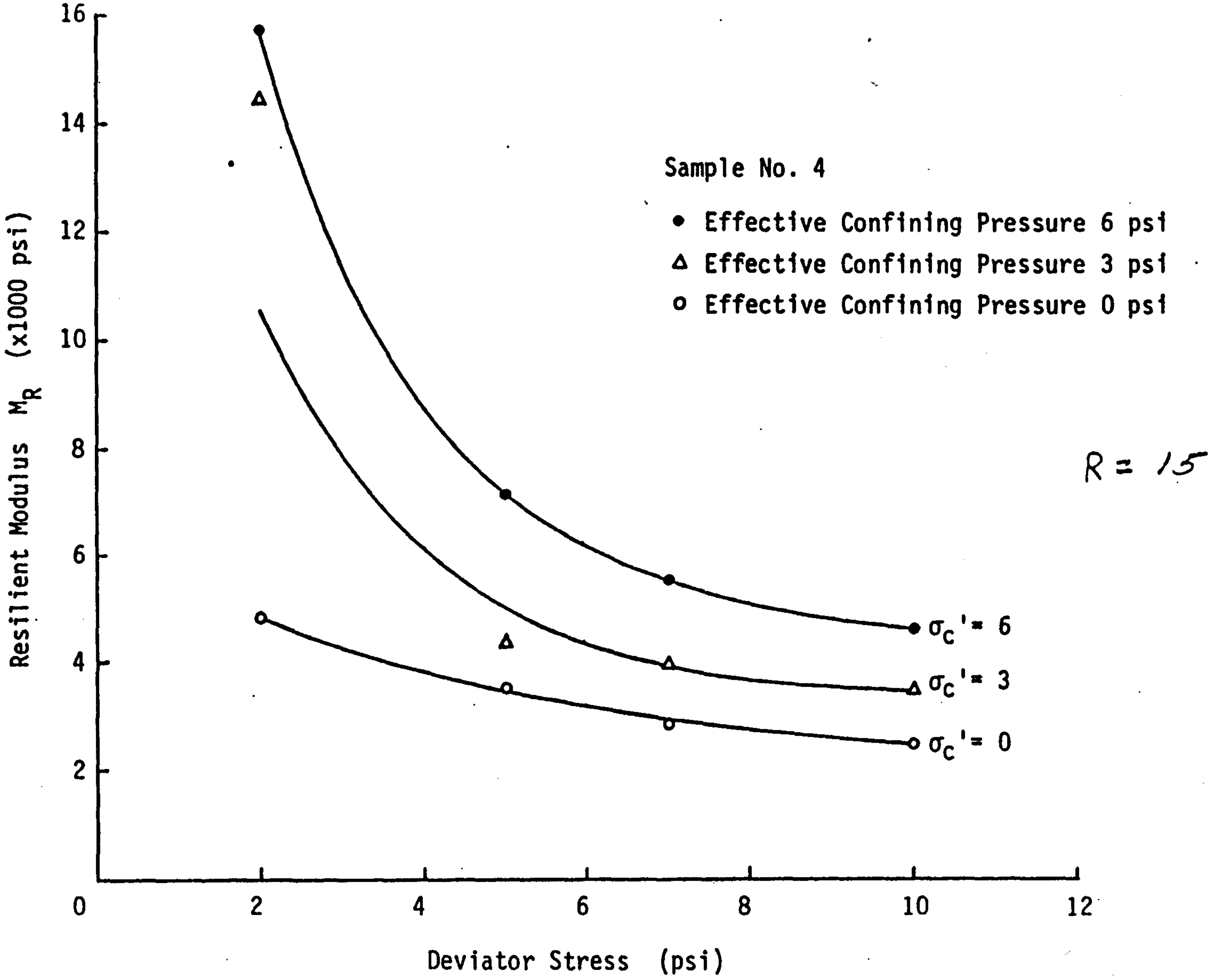


FIG. 14 Arithmetic Plot of Resilient Moduli of Sample No. 4

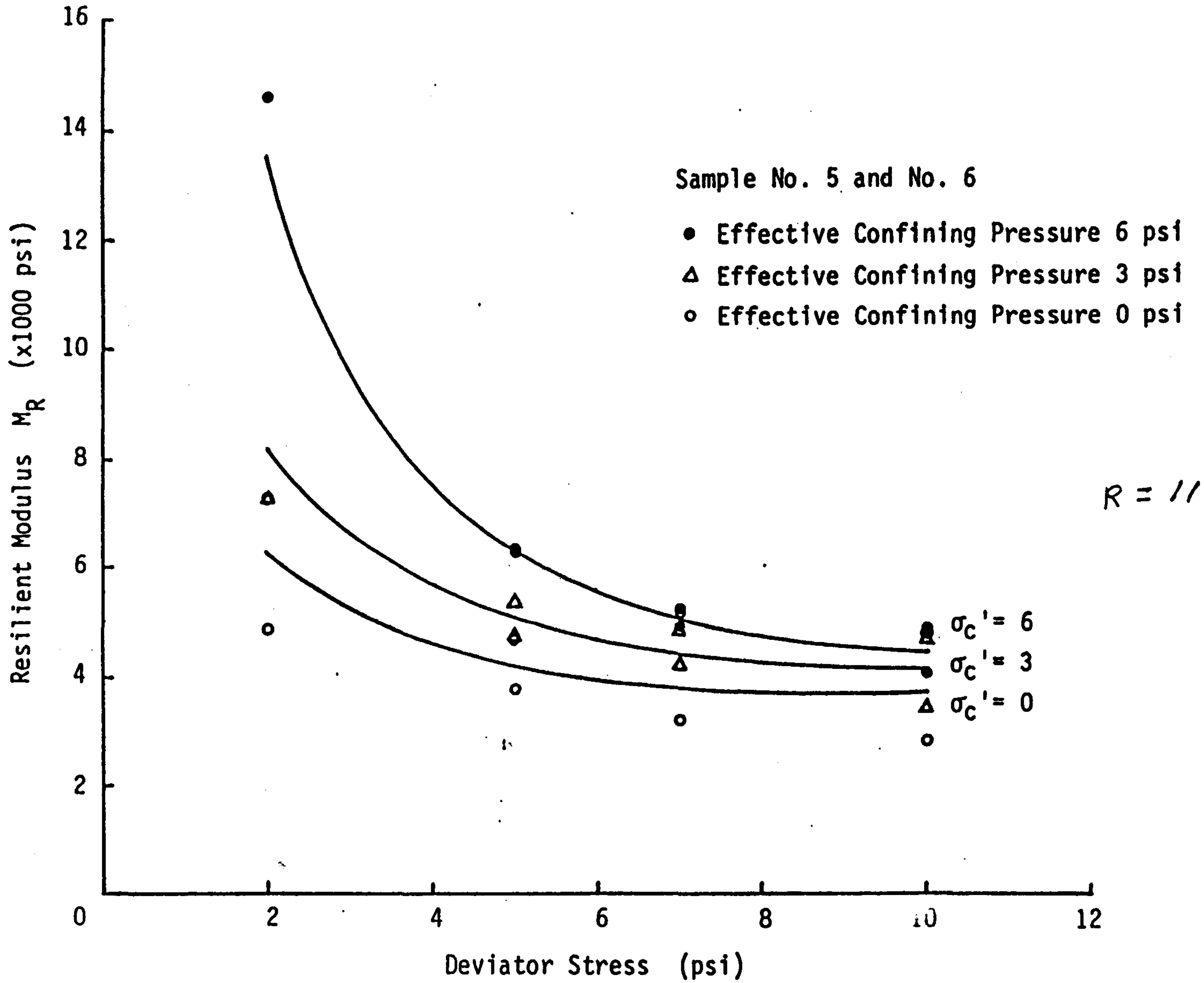
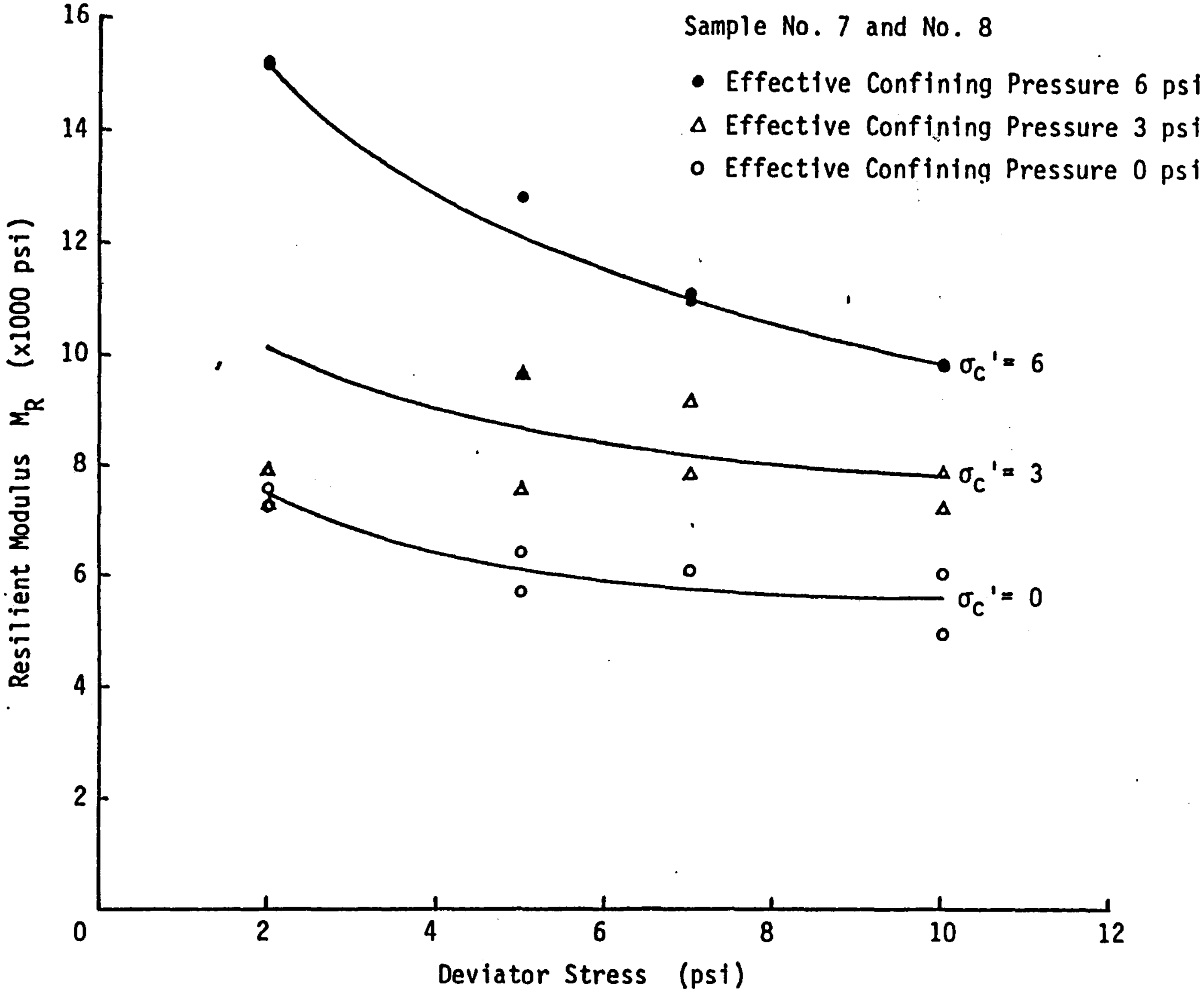
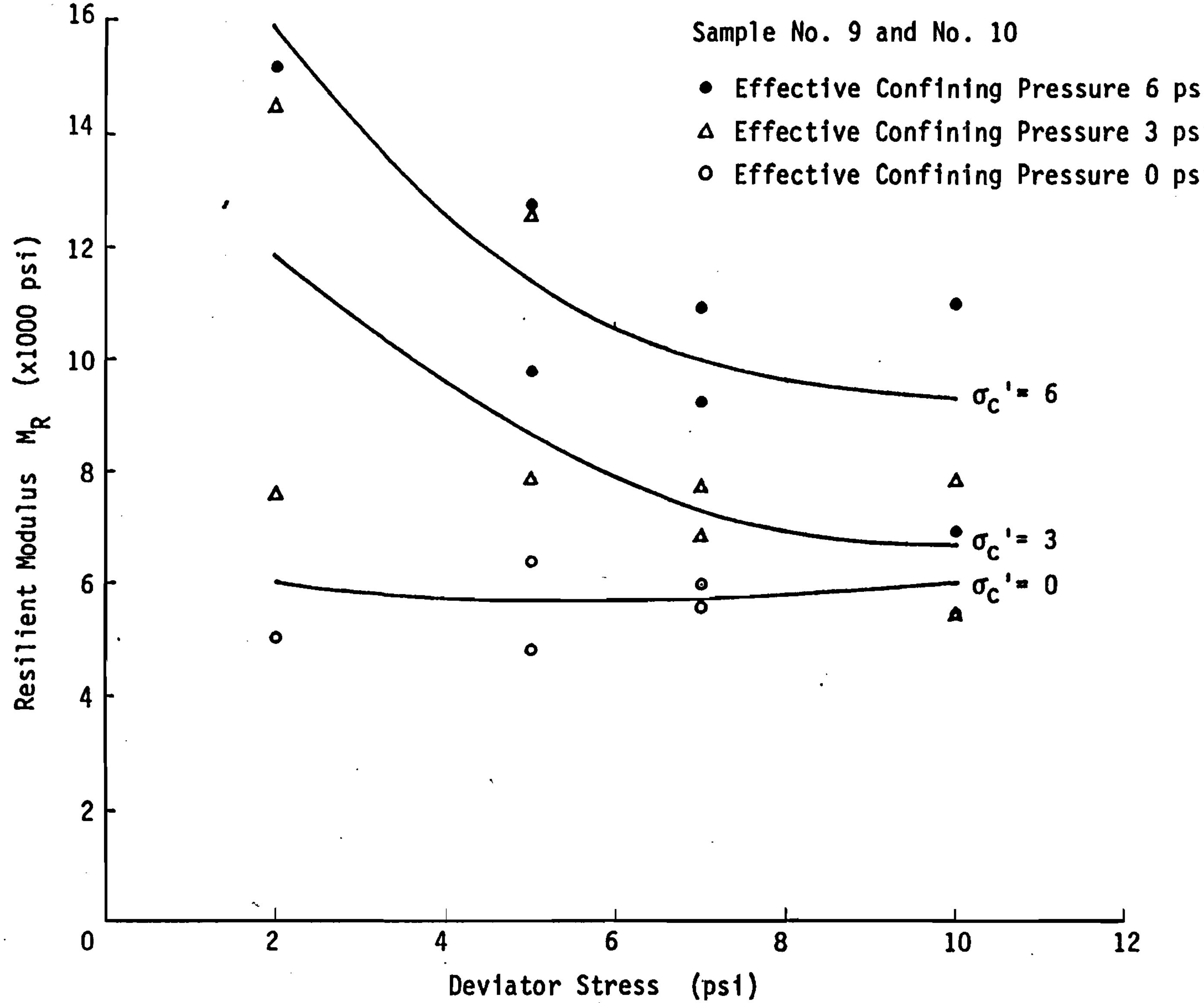


FIG. 15 Arithmetic Plot of Resilient Moduli of Sample No. 5 and No. 6



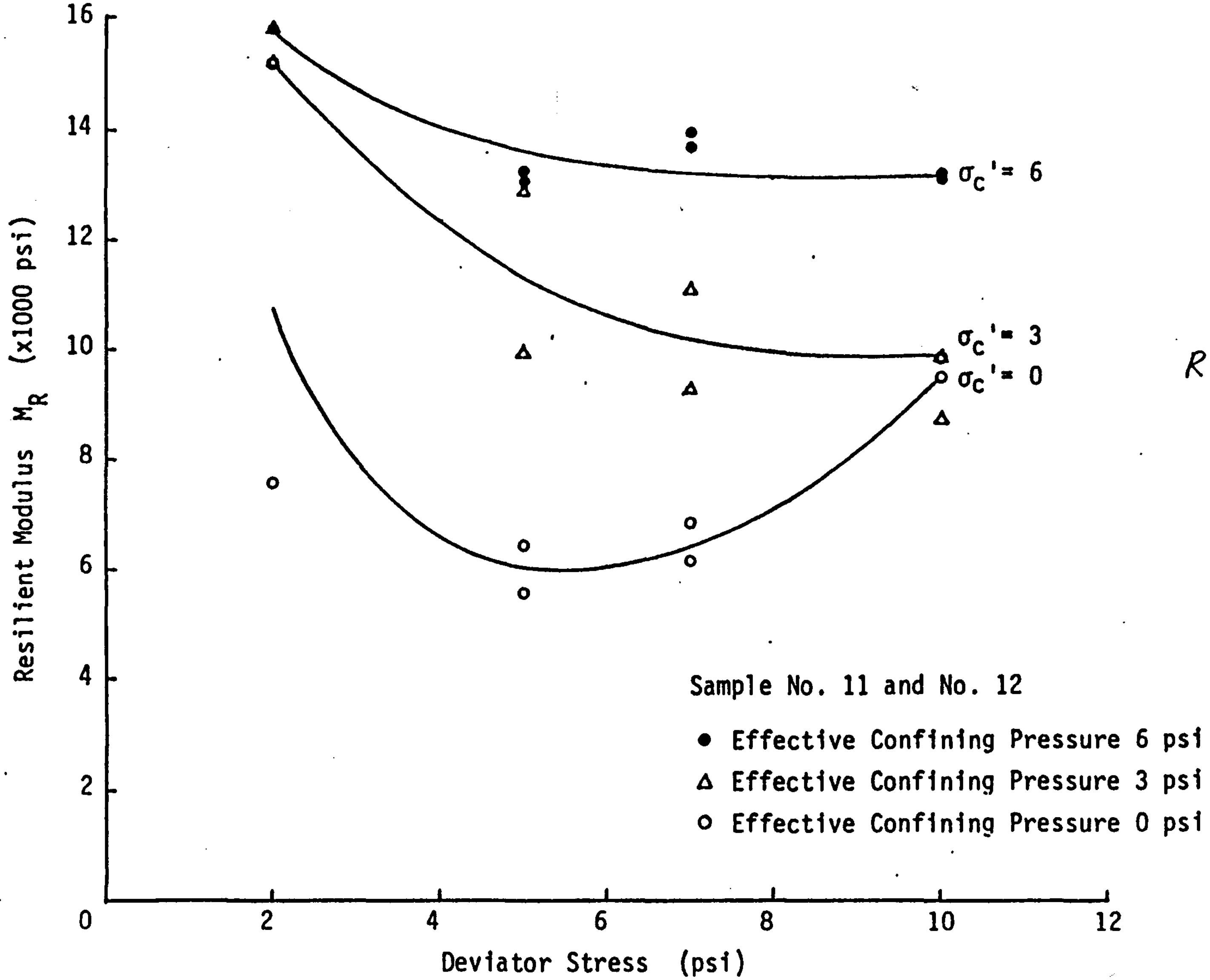
R = 30

FIG. 16 Arithmetic Plot of Resilient Moduli of Sample No. 7 and No. 8



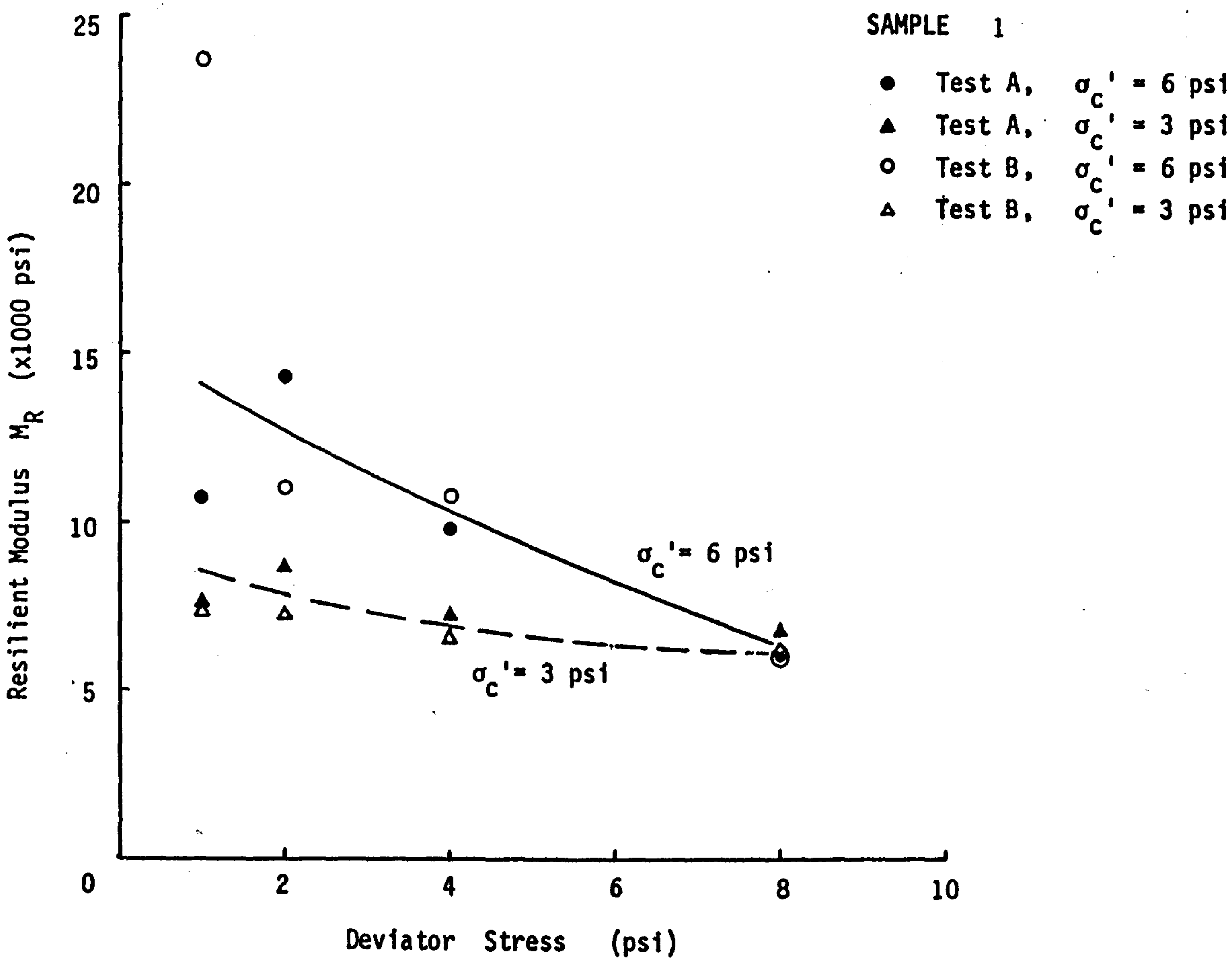
R = 26

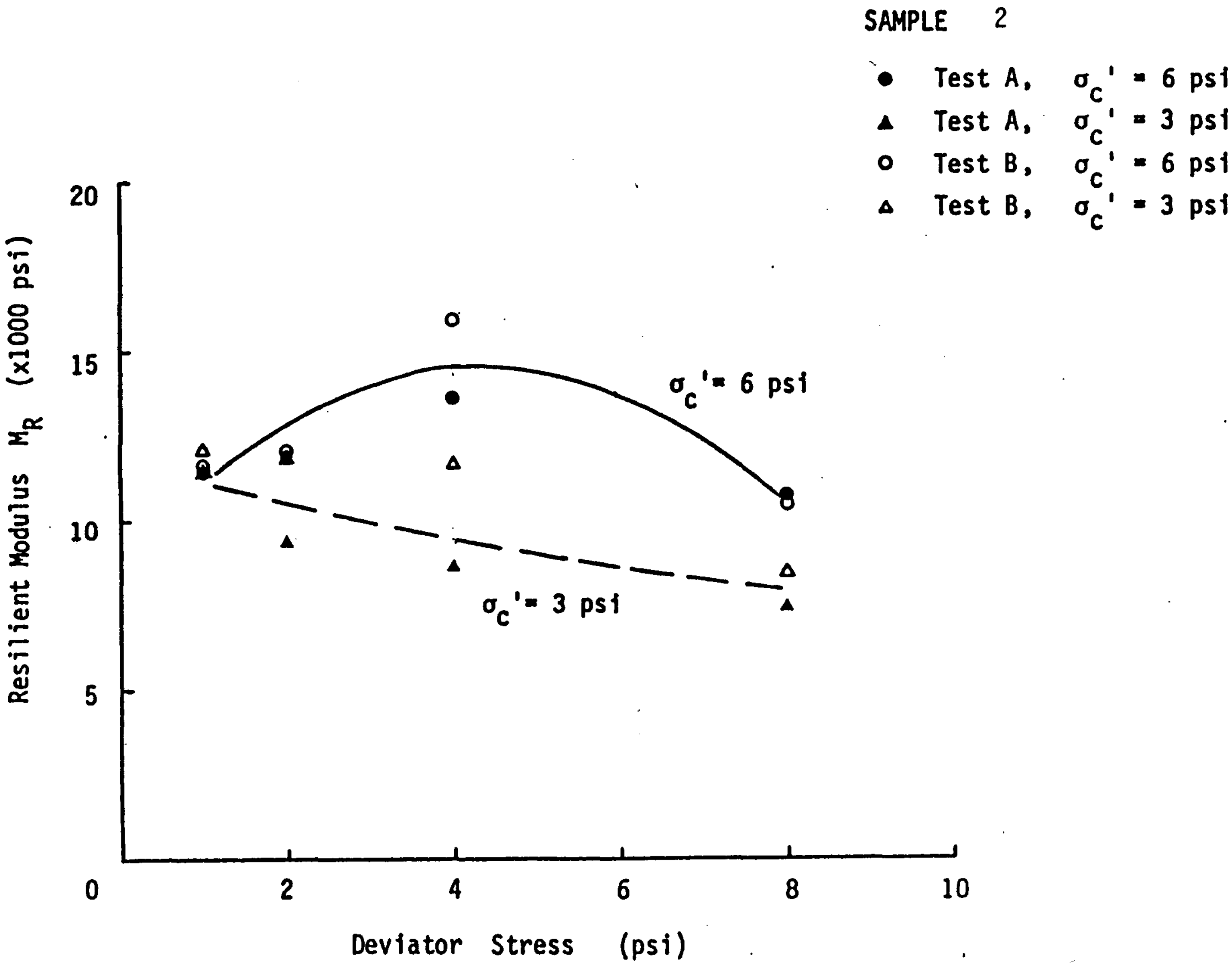
FIG. 17 Arithmetic Plot of Resilient Moduli of Sample No. 9 and No. 10

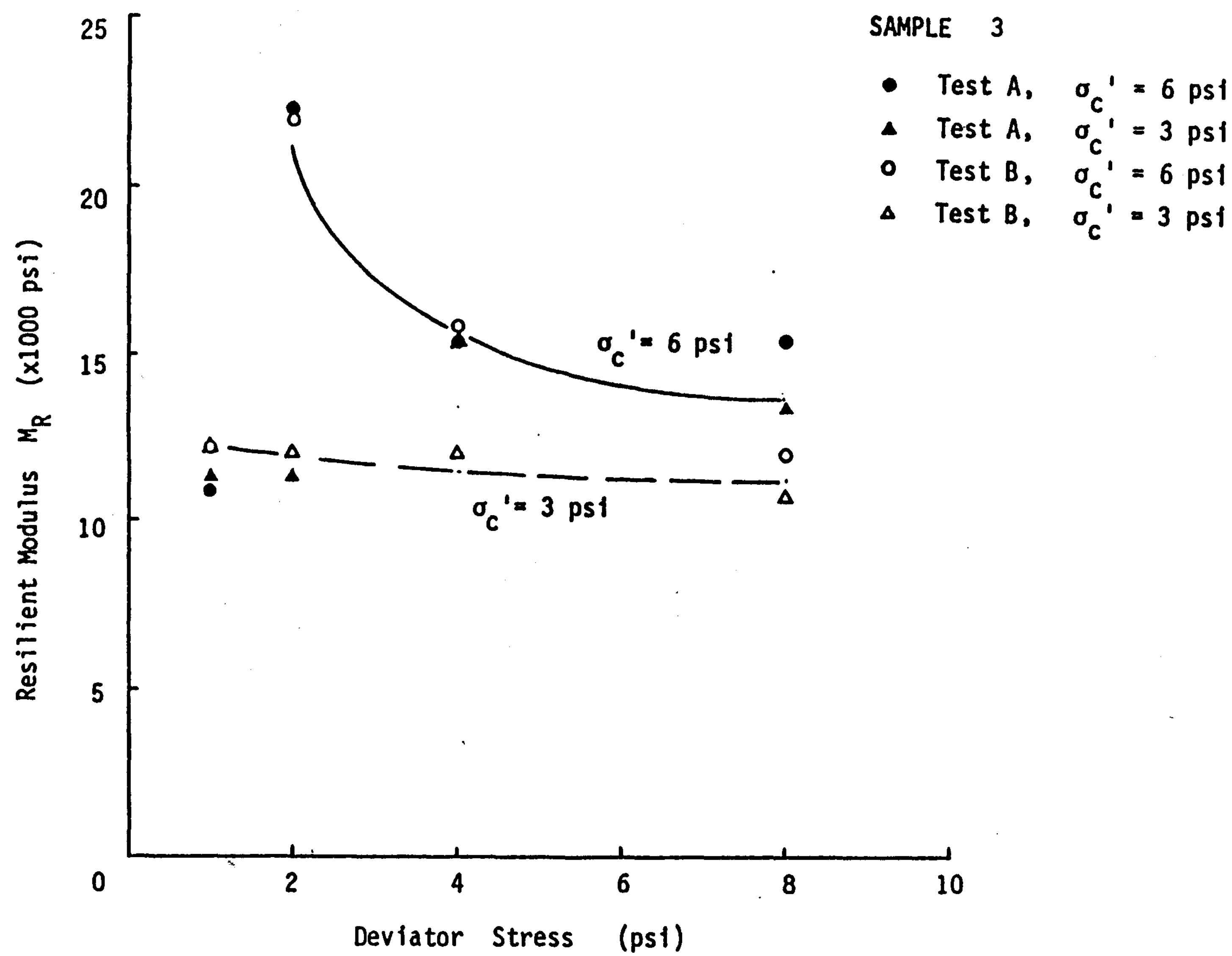


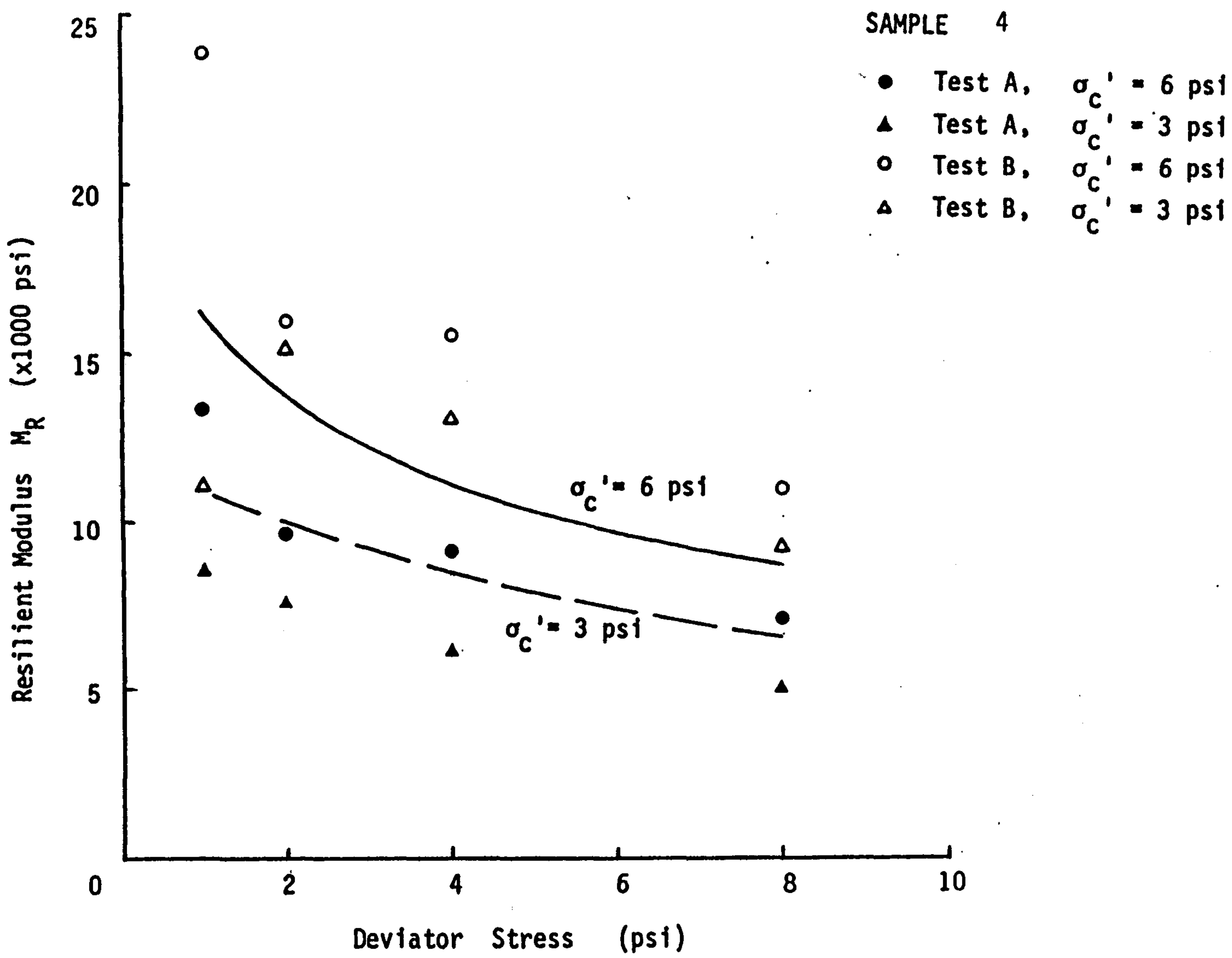
R=39

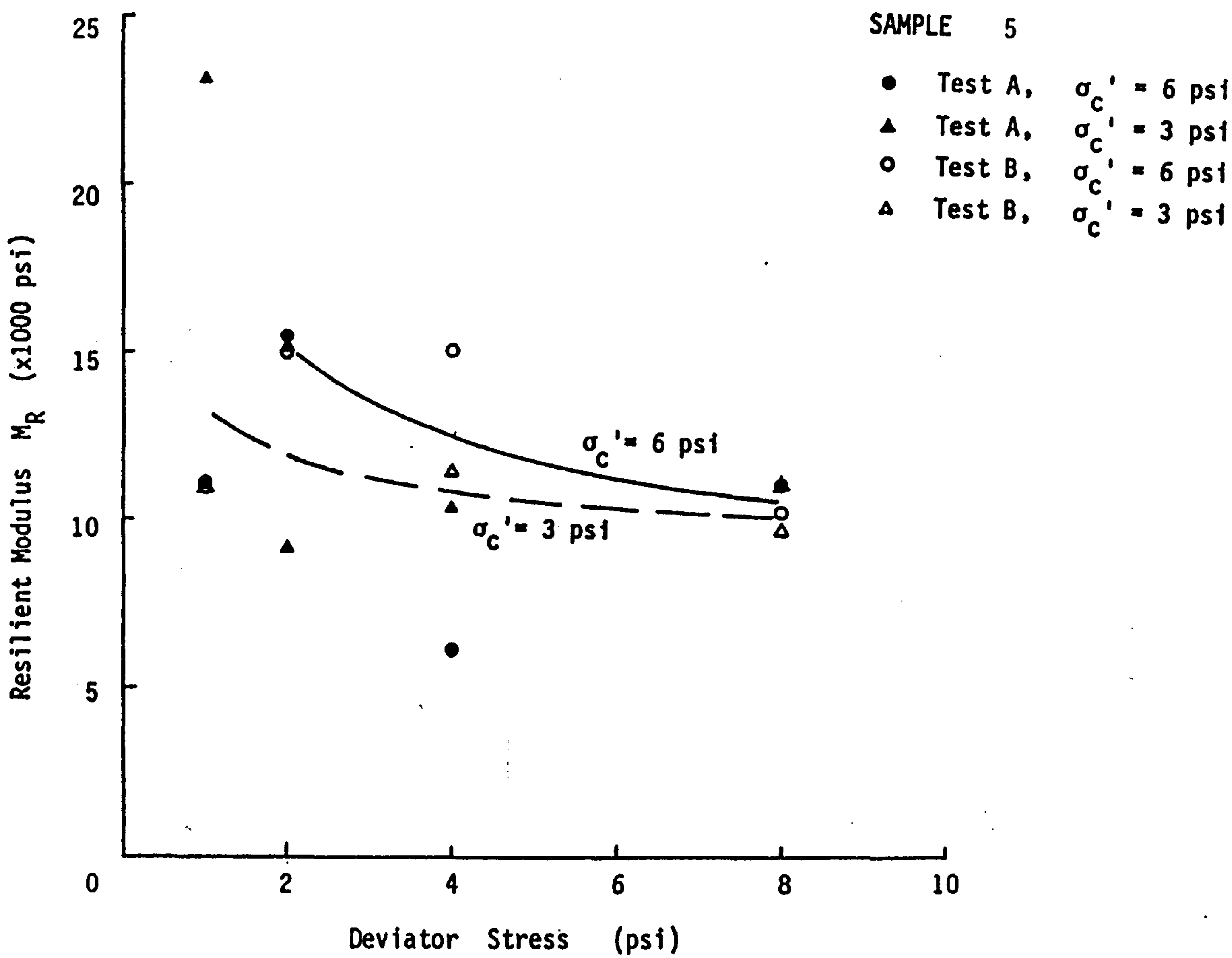
FIG. 18 Arithmetic Plot of Resilient Moduli of Sample No. 11 and No. 12

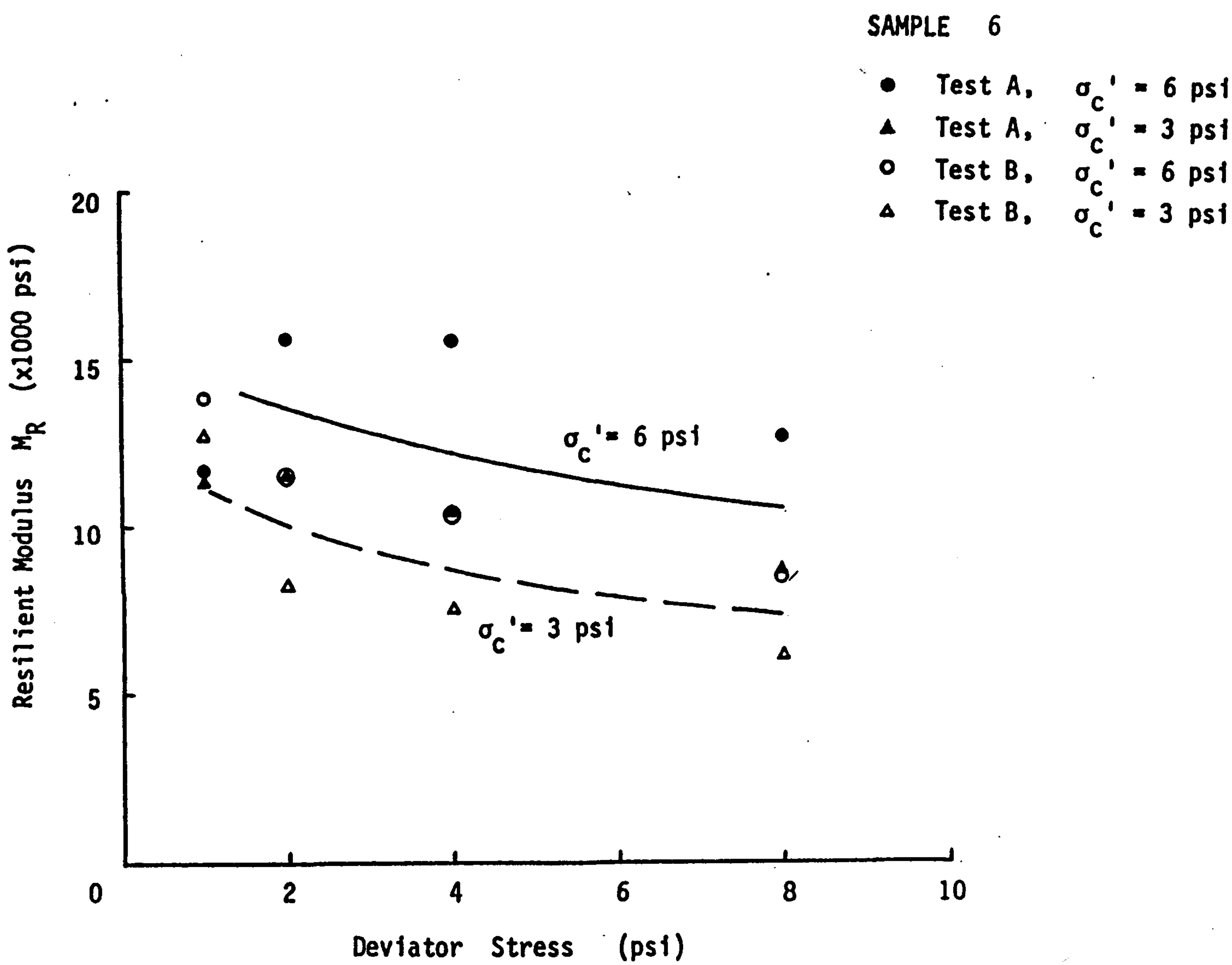

SAMPLE 1
Test A, σc' = 6 psi
Test A, σc' = 3 psi
Test B, σc' = 6 psi
Test B, σc' = 3 psi
σc' = 6 psi
σc' = 3 psi
Resilient Modulus MR (x1000 psi)
Deviator Stress (psi)
0
2
4
6
8
10
5
10
15
20
25

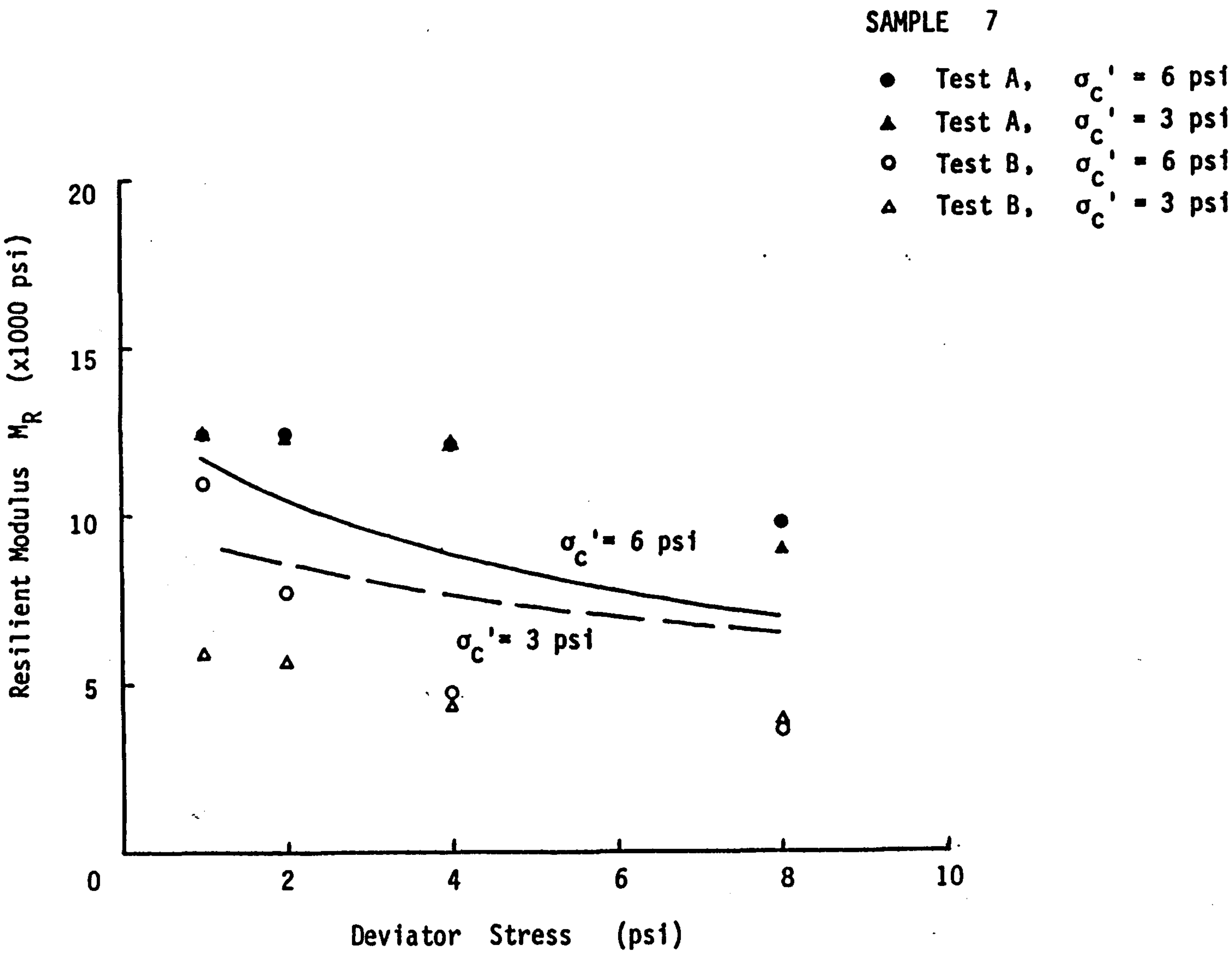

SAMPLE 2
● Test A, σ_c' = 6 psi
▲ Test A, σ_c' = 3 psi
○ Test B, σ_c' = 6 psi
△ Test B, σ_c' = 3 psi
σ_c'= 6 psi
σ_c'= 3 psi
Resilient Modulus M_R (x1000 psi)
20
15
10
5
0
2
4
6
8
10
Deviator Stress (psi)

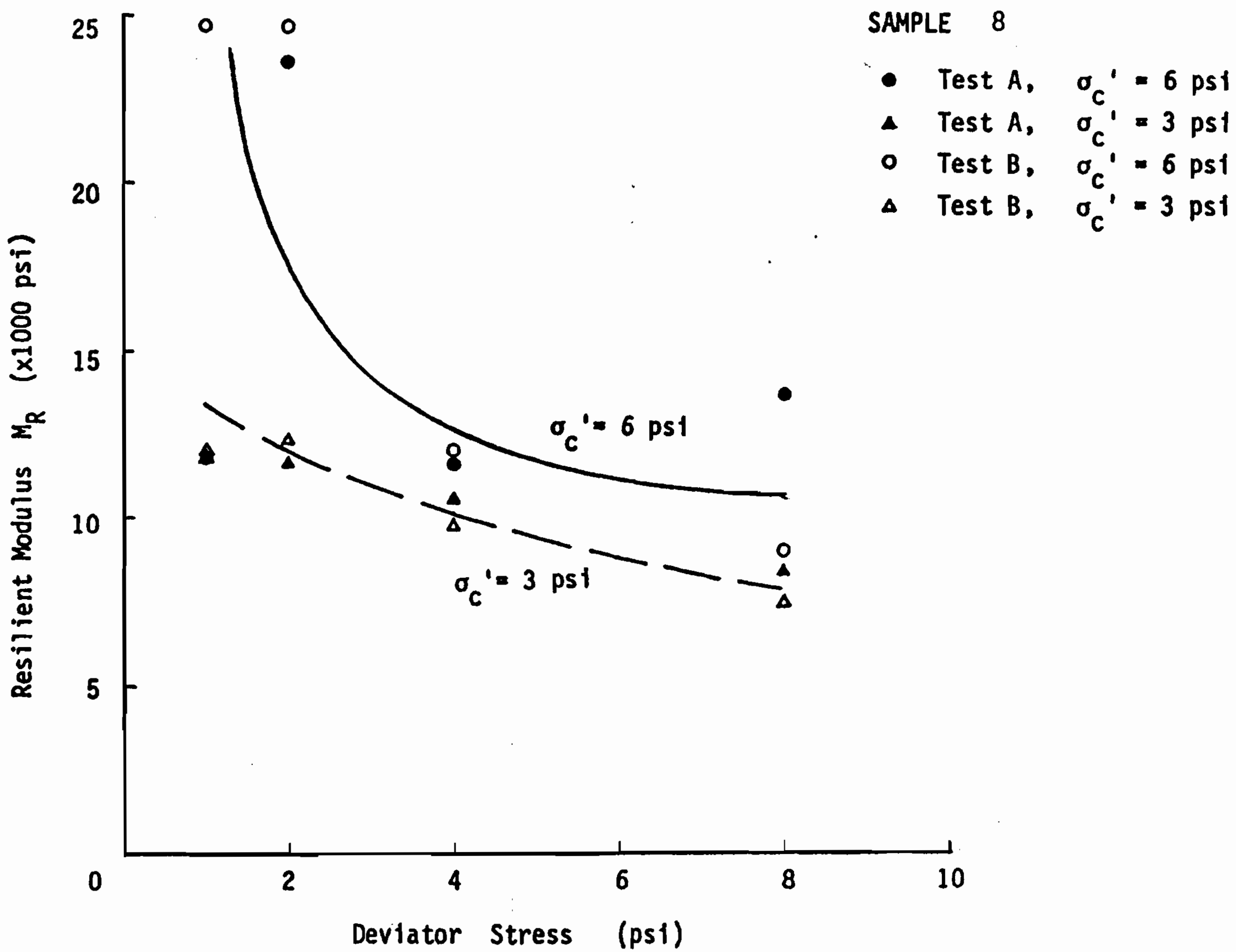

SAMPLE 3
● Test A, σc' = 6 psi
▲ Test A, σc' = 3 psi
○ Test B, σc' = 6 psi
△ Test B, σc' = 3 psi
σc'= 6 psi
σc'= 3 psi
Resilient Modulus MR (x1000 psi)
25
20
15
10
5
0
2
4
6
8
10
Deviator Stress (psi)

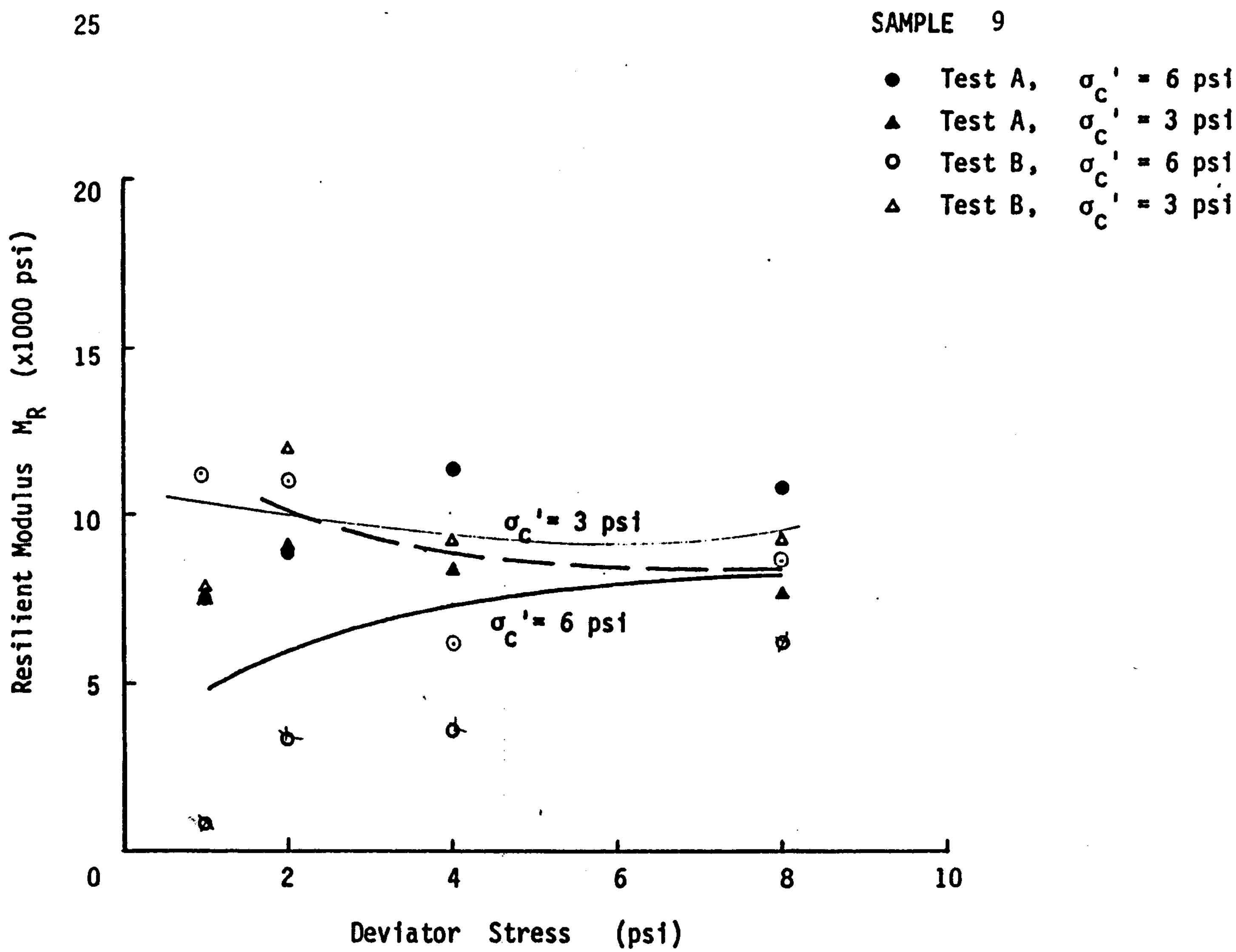

SAMPLE 4
Test A, σc' = 6 psi
Test A, σc' = 3 psi
Test B, σc' = 6 psi
Test B, σc' = 3 psi
σc' = 6 psi
σc' = 3 psi
Resilient Modulus MR (x1000 psi)
25
20
15
10
5
0
2
4
6
8
10
Deviator Stress (psi)

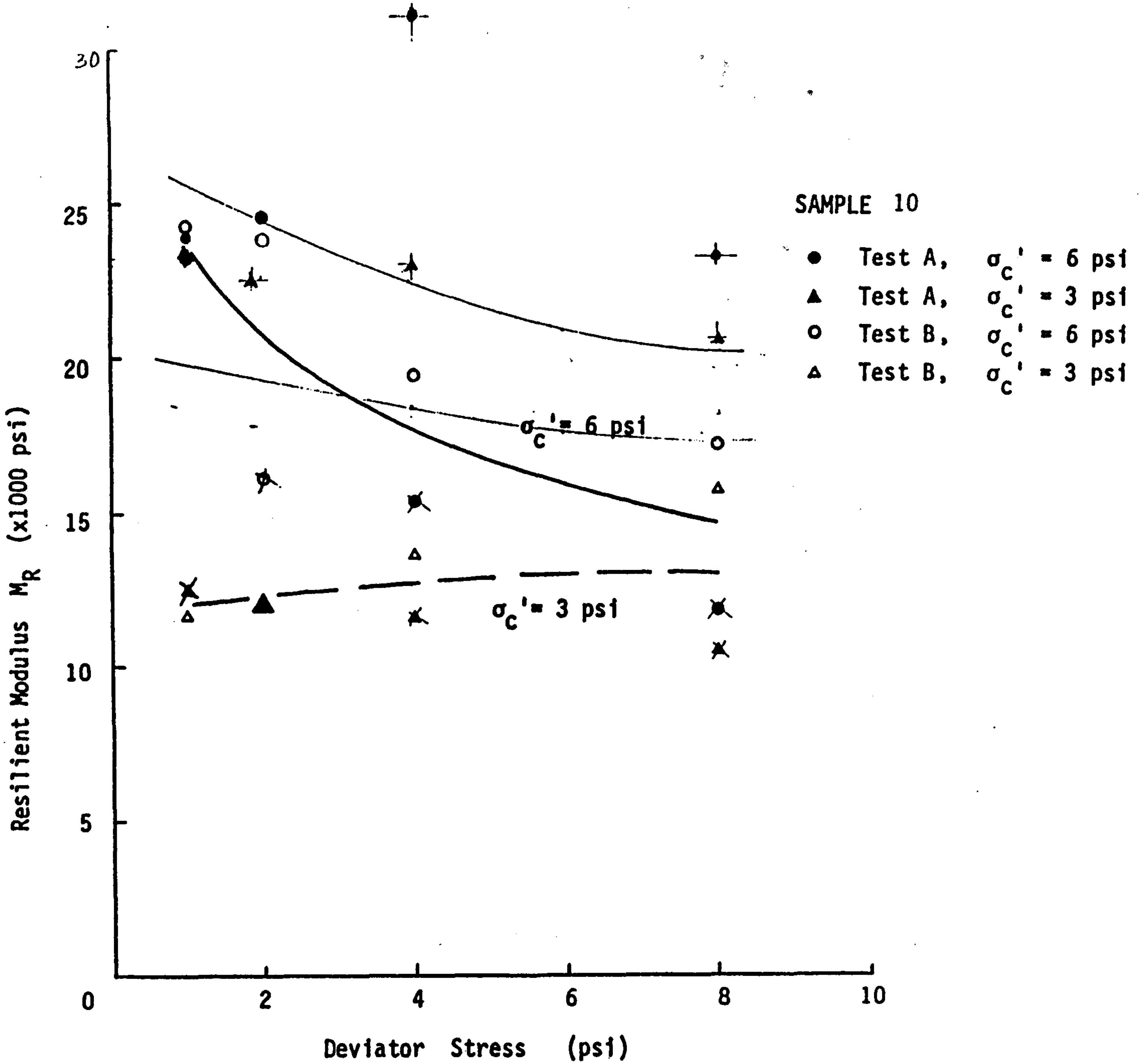

SAMPLE 5
Test A, $\sigma_c' = 6$ psi
Test A, $\sigma_c' = 3$ psi
Test B, $\sigma_c' = 6$ psi
Test B, $\sigma_c' = 3$ psi
$\sigma_c' = 6$ psi
$\sigma_c' = 3$ psi
Resilient Modulus M_R (x1000 psi)
25
20
15
10
5
0
2
4
6
8
10
Deviator Stress (psi)


SAMPLE 6
Test A, σ_c' = 6 psi
Test A, σ_c' = 3 psi
Test B, σ_c' = 6 psi
Test B, σ_c' = 3 psi
Resilient Modulus M_R (x1000 psi)
20
15
10
5
0
2
4
6
8
10
σ_c'= 6 psi
σ_c'= 3 psi
Deviator Stress (psi)


SAMPLE 7
Test A, σc' = 6 psi
Test A, σc' = 3 psi
Test B, σc' = 6 psi
Test B, σc' = 3 psi
Resilient Modulus MR (x1000 psi)
20
15
10
5
0
2
4
6
8
10
σc'= 6 psi
σc'= 3 psi
Deviator Stress (psi)


SAMPLE 8
Test A, σ_c' = 6 psi
Test A, σ_c' = 3 psi
Test B, σ_c' = 6 psi
Test B, σ_c' = 3 psi
σ_c'= 6 psi
σ_c'= 3 psi
Resilient Modulus M_R (x1000 psi)
25
20
15
10
5
0
2
4
6
8
10
Deviator Stress (psi)


SAMPLE 9
Test A, σ_c' = 6 psi
Test A, σ_c' = 3 psi
Test B, σ_c' = 6 psi
Test B, σ_c' = 3 psi
σ_c'= 3 psi
σ_c'= 6 psi
Resilient Modulus M_R (x1000 psi)
Deviator Stress (psi)
0
2
4
6
8
10
5
15
20
25



SAMPLE 10
Test A, σc' = 6 psi
Test A, σc' = 3 psi
Test B, σc' = 6 psi
Test B, σc' = 3 psi
σc' = 6 psi
σc' = 3 psi
Resilient Modulus MR (x1000 psi)
Deviator Stress (psi)
30
25
20
15
10
5
0
2
4
6
8
10

PUBLICATION
Department of Highways-State of Colorado
Division of Transportation Planning

89-1 Truck Tire Pressures in Colorado
89-2 Rockfall Modeling and Attenuator Testing
89-3 Frost Heave Control With Buried Insulation
89-4 Verglimit Evaluation (Boulder)
89-5 Use of Road Oils by Maintenance
89-6 Accelerated Rigid Paving Techniques
89-7 IBC Median Barrier Demonstration
89-8 *Monitoring of Nondurable Shale Fill in Semi-Arid Climate
89-9 Resilient Properties of Granular Soils
89-10 *Consolidation Testing Using Triaxial Apparatus
89-11 *Reactive Aggregate in Structures
89-12 *Five Inch Asphalt Overlay
89-13 *Avalanche - Interim Report
89-14 *Sawed Joints in AC Pavements
89-15 *Mirimat Erosion Control Fabric
89-16 *Use of Spirolite Plastic Pipe
89-17 *Reflective Sheeting - Interim Report
89-18 *Pavement Marking Materials - Interim Report

90-1 *Pretreatment of Aggregates
90-2 *Gravel Shoulders

*Reports soon to be published

PUBLICATION
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87-01 Finite Element Analysis of Twin-T Test Walls in Glenwood Canyon, CO
87-02 Flow Conflict Study
87-03 Epoxy Thermoplastic Pavement Marking Demonstration Project 60
87-04 Elastometric Concrete End Dams Used in Conjunction With Bridge Deck Expansion Devices
87-05 Colorado Reactive Aggregate
87-06 Bridge Approach Settlement
87-07
87-08 Third Party Construction Engineering
87-09 Preloading of Sanitary Landfills
87-10 Frost Heave Control With Buried Insulation (Interim)
87-11 AC Gauge "Between Operator" Precision Experiment
87-12 Long-Term Creep of Geotextile in the Confinement of Soils Under Sustained Loading - Phase I
87-13 Dynaflect Benkelman Beam Correlation
87-14 Cathodic Protection
87-15 Rubber Modified Asphalt Concrete
87-16 Concrete Pavement Repair Bennett to Strasburg

88-1 Pavement Profile Measurement Seminar Proceedings, Vol. I, Seminar Overview
88-2 Pavement Profile Measurement Seminar Proceedings, Vol. II, Data Collection Equipment
88-3 Pavement Profile Measurement Seminar Proceedings, Vol. III, Workshop Summaries
88-4 Micro Computers in Project Field Offices
88-5 Development of a Risk Cost Methodology for Detour Culvert Design
88-6 Concrete Pavement Restoration Demonstration
88-7 Inservice Evaluation of Highway Safety Appurtenances, FHWA Experimental Project No. 7
88-8 Embankment Settlement in Glenwood Canyon
88-8 Rehabilitation of Concrete Pavements Follow-Up Study
88-10 Effectiveness of Geogrids and Geotextiles in Embankment Reinforcement
88-11 Spring Breakup Study
88-12 Plastic Pipe Use Under Highways
88-13 Geothermal Space Heating
88-14
88-15 Tapered Asphalt Shoulders
88-16 Development of a Retrievable Test Rig for Drilled Pier Bridge Foundations
88-17 Flexible Roadside Delineator Post Evaluation
88-18 Long Term Pavement Monitoring
88-19 Expandable Membrane Ground Anchors in Talus
88-20 Research Status Report

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85-1	Literature Review On Frost Heaving
85-2	Nighttime Paving
85-3	In Service Evaluation of Highway Safety Appurtenances
85-4	Vail Pass Solar Heated Rest Area
85-5	Surface Sealers
85-6	A Field Test of a Grade Severity Rating System
85-7	Geothermal Heating of Bridges in Glenwood
85-8	not used
85-9	Stresses in Full Height Fascia Panels - Interim Report
85-10	Bridge Deck Expansion Devices
85-11	Rehabilitation of Bridge Decks Demonstration
85-12	Use of Road Oils by Maintenance
85-13	Flyash Use in Lean Concrete Bases
85-14	Compaction Grouting Operation in Talus Slopes of Glenwood Canyon
85-15	Monitoring the Two-phase Wall System
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86-2	Cathodic Protection of Bridge Deck
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86-5	Hot Bituminous Pavement Performance Study
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86-7	Retaining Wall Tiebacks in Talus Slopes
86-8	MOSS: An Interactive Three Dimensional Modeling System Evaluation
86-9	Explosive Treatment to Correct Swelling Shales Project I-70-1(61)
86-10	Load Distribution Under Retaining Walls
86-11	Reflection Cracking - Fabrics, Parker Rd., Mississippi Ave. to Iliff
86-12	The Use of Fly Ash in Structural Concrete, Demonstration Proj. No. 59
86-13	Acceptance Testing for Roadway Smoothness
86-14	Correlating Roadway Condition Data to Minor Reconstruction Projects
86-15	IBC Median Barrier Demonstration
86-16	Evaluation of Fabric Reinforced Earth Wall
86-17	Evaluation of Plastic Erosion Control Mat, Proj. RS 0133(11)
86-18	Cold Recycling of Asphalt Pavement
86-19	Reduced Freeway Lighting
86-20	Bridge Deck Repair And Protective Systems, Class DT Concrete With Waterproof Membrane and Asphalt Concrete Overlay
86-21	Stresses in Full Height Fascia Panels