Final Research Report

for

RESILIENT MODULUS OF GRANULAR SOILS WITH FINES CONTENTS

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16. Abstract

This study examined the relationship of resilient modulus with the stabilometer R-values, and with the index properties of Colorado soils. A total of 39 resilient modulus tests were conducted, 20 in this test program and 19 in an earlier test program. Soil types ranged from A-1-a to A-7-6 with varying amounts of fines. Regression analyses were performed to formulate the functional relationship using the least square fit. Two regression equations were formulated to relate resilient modulus to R-value (one linear and one nonlinear), and four linear regression equations to relate resilient modulus to percent fines content, plasticity index, uniformity coefficient, and mean grain size. In general, the values of the Correlation coefficients are small and care should be taken when using these equations, particularly for granular soil samples with less than 30% of fines.

Implementation:

It is recommended to abandon the effort to formulate a relationship between resilinet modulus and R-value because of the inability of R-value in reflecting dynamic behavior of soils.

17. Key Words
Resilient Modulus,
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EXECUTIVE SUMMARY

After several decades of development, the design of pavement using theory of elastic layers has matured to an extent that its introduction for general acceptance by pavement engineers becomes feasible. This led to the adoption of the elastic layer theory in pavement design by the American Association of State Highway and Transportation Officials (AASHTO) in its "AASHTO Guide for Design of Pavement Structures - 1986." The use of elastic layer theory involves two elastic material parameters, namely resilient modulus and Poisson's ratio. The major difficulties in the implementation of the 1986 AASHTO Guide include: 1) the lack of proper/affordable testing equipment, 2) the lack of understanding of the physical meaning of resilient modulus, and 3) site (or soil type) dependency of resilient modulus. Thus, each state is advised to develop its own design curve and/or design equation.

Objectives of this research project are three fold: 1) to determine the resilient modulus and the stabilometer R value of soils of different index properties, 2) to formulate the functional relationship between the resilient modulus and R-value, and between the resilient modulus and different index properties of soils, and 3) to provide detailed test procedures for resilient modulus. Because of the recent nature of the implementation of resilient modulus in pavement design, its data base is extremely small compared to the data base for the

stabilometer R-value. Thus, the functional relationship between the resilient modulus and the R-value with a large data base would seem desirable. Once the equation is formulated, the resilient modulus of a subgrade soil can be evaluated for a R-value that can be easily determined. However, the R value does not reflect the dynamic property of soils that is required in the design of pavement. It would be extremely desirable to determine the resilient modulus of soils and then relate the resilient modulus to their index properties.

The resilient modulus is a dynamic property of soil. Previous studies indicate that the dynamic properties of soils are strongly related to the index properties of soils. These index properties include percent fines content, gradation characteristics and Atterberg's limits. Thus, the resilient modulus can be formulated as a function of index properties of soils. Given the functional relationship, a resilient modulus can be determined using the index properties that can be easily determined.

This study aims to provide the functional relationship where the resilient modulus is related to the stabilometer R value and/or index properties of Colorado soils. The statistical sample size is, however, too small to obtain a good functional relationship because of the large number of influencing factors involved. To form a bigger statistical data base, the results from the twenty resilient modulus tests from this research and the nineteen tests conducted earlier for the Colorado Department of Transportation are merged. Test results are found to be quite scatter, particularly for the granular soils. This is believed to be caused by a large number of factors affecting the dynamic behavior and properties of soils.

Both linear and nonlinear regression analyses were performed to relate the resilient modulus to the stabilometer R value. Both linear and nonlinear regression equations give nearly the same result as the one recommended by Yeh and Su (1989). The correlation relationship between the resilient modulus and the R value is weak. This weak correlation between M_R and R values could be because of the inability of the stabilometer R value in reflecting the dynamic properties of soils.

Linear regression analyses are also performed to relate the resilient modulus to each of the following index properties of soils: mean grain size D50, uniformity coefficient, Cu, percent fines content, FC (passing U.S. standard sieve #200), and plastic index, PI. The resilient modulus was found to be weakly correlated to these index properties in a descending order of the strength of correlation: % fines content, FC, plasticity index, PI, uniformity coefficient, Cu, and mean grain size, D50.

This study reveals the fact that the many factors affect the value of resilient modulus. These factors include density (or void ratio), moisture content, percent fines content, Atterberg's limits of fines, uniformity and mean grain size of coarse grain soils with grain size greater than US Standard Sieve #200, confining stress, and cyclic stress amplitude and the number of repetition, etc. To formulate an equation for an effective evaluation of the resilient modulus, it is recommended to conduct a systematic resilient modulus test program involving soils with a wide range of values for each index property. To facilitate technology transfer, it is recommended to hold resilient modulus training sessions for material and pavement design engineers throughout the state aiming at an eventual transfer the resilient modulus technology including the method of testing and the analysis of test results to the Colorado Department of Transportation.

I. INTRODUCTION

A highway pavement system includes pavement and subgrade materials, and, sometimes, base (and subbase) course. Its design naturally requires the mechanical properties of pavement materials and all base course and subgrade materials. Conventionally these mechanical properties are lumped in one single parameter, namely the stabilometer R-value or CBR. The continual distress of pavement designed using R-value indicates the shortcoming of using R-value in the pavement design. Besides, in the last three decades, the development of the elastic layer theory for pavement design has matured to an extent that its implementation in pavement design becomes feasible. This leads to the adoption of the 1986 AASHTO Guide for Design of Pavement Structures.

In the elastic layer theory, the material is assumed to be isotropic linear elastic with two independent material parameters, namely Poisson's ratio and Young's modulus. In the repetitive loading environment, the resilient Young's modulus (or resilient modulus) of subgrade varies with the number of repetition, amplitude of repetitive loading, confining pressure, and index properties of soils including density, void ratio, moisture content, gradation characteristics of soils, amount of fines passing #200 sieve and their Atterberg's limits. Major difficulties for the implementation of this design guideline in the State of Colorado include: 1) the lack of an appropriate test apparatus, 2) many factors influencing the resilient modulus of soils, and 3) the lack of a technology transfer program. To conduct cyclic triaxial tests for resilient modulus determination requires both a closed-loop hydro-electric universal testing machine and good analytical skills. In this study, twenty cyclic triaxial tests were conducted for different soils. Because of the variability of soils from one state to the other, AASHTO recommends each state to develop its own formula for resilient modulus. Many factors affect the resilient modulus of soils. This makes the task of formulating resilient modulus complex.

Objectives of this research project are three fold: 1) to determine the resilient modulus and the stabilometer R value of soils of different index properties, 2) to formulate the functional relationship between the resilient modulus and R-value, and between the resilient modulus and its influencing factors, and 3) to provide detailed test procedures for resilient modulus. These influencing factors include gradation characteristics (uniformity coefficient, effective and mean diameters and coefficient of curvature), fines content and plasticity, density, moisture content, cyclic stress amplitude and repetition and confining pressure, etc.

Regression equations were formulated to relate resilient modulus, individually, to R values, mean diameter, uniformity coefficient, %fines content and plasticity index. However, the number of resilient modulus tests is too small and the influencing factors too many to provide equations for effective evaluation of resilient modulus in terms of some easily determinable index properties of soils. Additional research is needed for accomplishing the effort in characterizing the resilient modulus of Colorado soils. This should involve a well designed experimental program to provide a sufficient data base for the statistical modeling.

II. LITERATURE REVIEW

II.1 AASHTO Pavement Design Guide

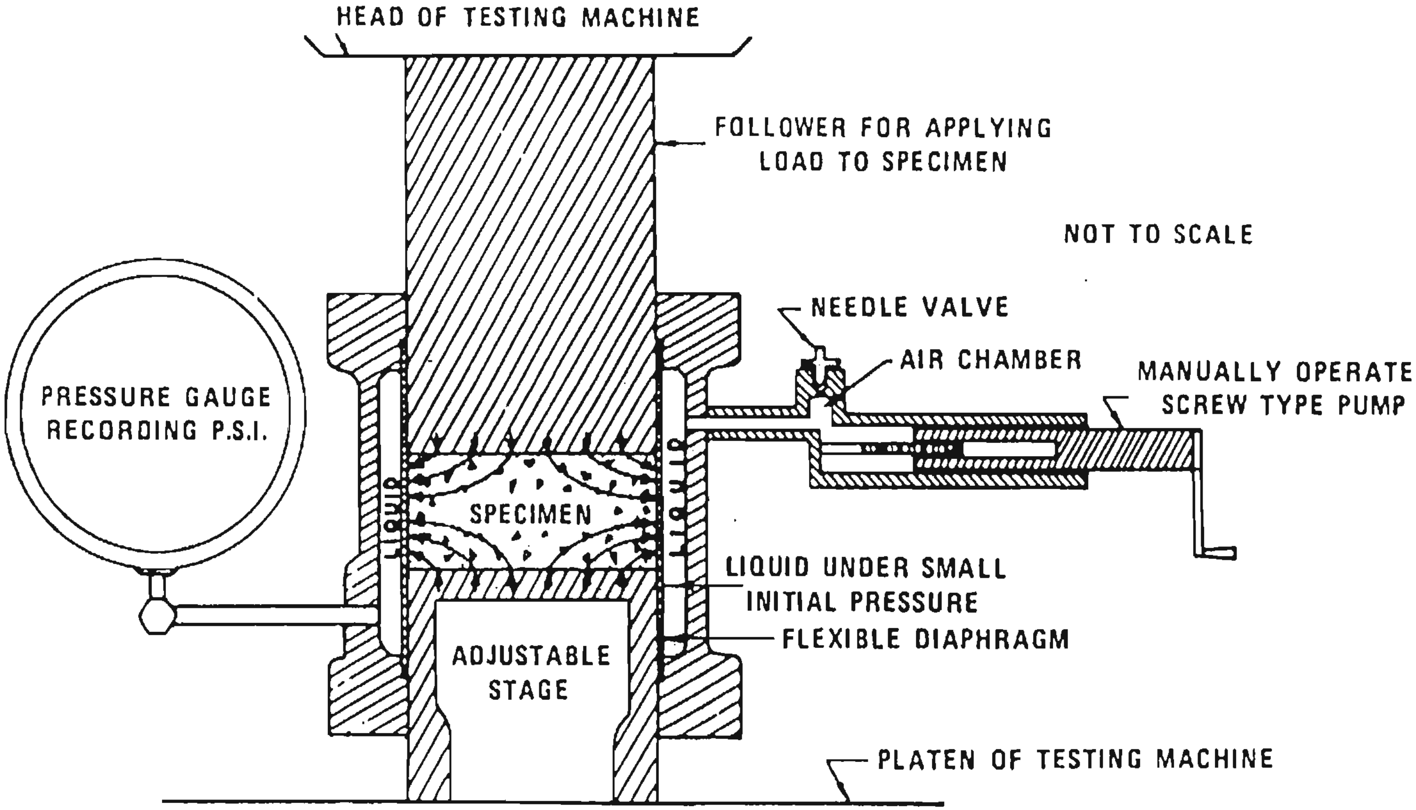
Based on the information provided by the AASHTO Road Test (AASHTO, 1962) conducted between 1958 and 1961, AASHTO published "AASHTO Interim Guide for Design of Pavement Structures - 1972" (AASHTO, 1972). This design guide takes into account of the soil support by incorporating the soil support value and strength coefficients in the design procedures. The soil support value and strength coefficients are determined from the California Bearing Ratio (CBR) and the stabilometer R-value, respectively. The Interim Guide had served its main objectives for many years without serious problems. The state highway agencies were generally satisfied with the Interim Guide but acknowledged that some improvements could be made.

After many years under the Interim Guide, the AASHTO Design Committee recommended that some revisions and additions were required to incorporate the information developed since 1972. This effort resulted in "AASHTO Guide for Design of Pavement Structures - 1986 (AASHTO, 1986)." This revised design guide, while retaining the basic algorithms developed from the AASHTO Road Test as used in the Interim Guide, adopts the resilient modulus of soils for characterizing soil support and assigning layer coefficients. The AASHTO test method T-274 was recommended as the definitive test for evaluating the resilient modulus of subgrade soils. Additionally, the concept of reliability was introduced to permit a designer to use the concept of risk analysis for various classes of roadways.

II.2 Stabilometer R-Value

The R-value (resistance value) is a parameter representing the resistance to the horizontal deformation of a soil under compression at a given density and moisture content. This parameter is an indication of the ability of soil to carry a load. The better can a subgrade soil resist horizontal deformation under a traffic load, the less surface pavement material is required to carry the design traffic load.

The R-value is derived from the result of a test (AASHTO T-190) conducted in a Hveem stabilometer as shown in Figure II.1. A cylindrical specimen with 4 inches (10.16 cm) in diameter and 2.5 inches (6.35 cm) in height is enclosed in a membrane. As a vertical load of 2000 lb (8896 N) is applied over the full face of the specimen to produce a pressure, P_v, the resulting horizontal pressure, P_h, is read. The vertical load is then reduced to 1000 lb (4448 N), and the horizontal pressure is adjusted to 5 psi (34.5 kPa) with a displacement pump. By turning the pump handle to raise the horizontal pressure from 5



NOTE–The specimen is given lateral support by the flexible sidewall, which transmits horizontal pressure to the liquid. The magnitude of the pressure can be read on the gauge.

Figure II.1 Schematic diagram of Hveem stabilometer.

to 100 psi (34.5 to 689.5 kPa), the number of turns is recorded as the turn displacement, D, of the specimen. The Stabilometer R-value is then determined using the equation below:

$$R = 100 - \frac{100}{\left(\frac{2.5}{D}\right)\left(\frac{P_v}{P_h} - 1\right) + 1}, \qquad (1)$$

where P_v is usually 160 psi (1103.2 kPa).

The R-value provides the information of relative quality of subgrade soils and empirically relates to the field performance of pavement materials. It has been correlated with CBR, soil classification, and other properties of different soil types. The R-value test, while being time and cost effective, does not have a sound theoretical base and it does not reflect the dynamic behavior and properties of soils. Its development and use are mainly based on trial and error, previous experience and observations, and engineering judgments. The R-value test is static in nature and irrespective of the dynamic load repetition under actual traffic.

II.3 Resilient Modulus

A pavement structure is designed to sustain millions of repeated wheel loads during its service life and it is more realistic to obtain and use in pavement design the repetitive load property of pavement materials. The resilient modulus, M_R, in AASHTO T292 and T294 is an elastic rebound stress-strain relationship. It measures the elastic rebound stiffness of flexible pavement materials, base courses and subgrades under repeated loading.

At a point under investigation, each moving wheel imparts a dynamic load pulse to all layers of a pavement system. It is followed by a period of zero dynamic load, relaxation period, before the next moving wheel arrives that causes the dynamic load cycle to be repeated. Therefore, the resilient modulus is determined from a repetitive pulse load triaxial compression test (AASHTO T-274) with a suggested pulse duration of 0.1 second followed by a 1.9 second rest period.

The test is conducted on a cylindrical specimen with 2.8 or 4 inches (7.11 or 10.16 cm) in diameter, depending on particle size, and at a desired density and moisture content. Before starting a test sequence, a series of axial load repetitions under various deviator stresses is applied for sample conditioning. The test is then conducted by varying the deviator stress and confining pressure, respectively, and by applying 200 repetitions under each load condition. The decreasing load and recovered deformation at the 200th repetition of each load condition are recorded for calculating the unloading stress and recovered strain. The resilient modulus at certain stress condition is defined as the secant modulus of the 200th unloading curve and is expressed as

$$M_R = \frac{\sigma_d}{E_r}, \tag{2}$$

where σ_d is deviator stress and E_r is recovered axial strain at the 200th repetition.

The resilient modulus test closely simulates the pavement materials at different depths under various traffic loads in field. It provides a fundamental dynamic stress-strain property of materials in a flexible pavement system that governs its response under a traffic load. However, the test needs sophisticated and expensive equipment, which many state highway agencies do not have. Based on the AASHTO procedure, the required testing time to determine a modulus is at least 2.5 hours for cohesive soils and 4.5 hours for granular materials, excluding the time for sample preparation and test setup. For lack of equipment and being very time consuming, Yeh and Su (1989) indicated that it would be impractical to attempt a large scale testing program for investigating every aspect of resilient modulus of all types of Colorado soils. The revised guide provided correlations of M_R with CBR, R-value, and other soil properties for some types of soil. Nevertheless, The AASHTO still recommended that each state should develop its own correlations due to the geographic dependency of resilient modulus.

II.4 Factors Affecting Resilient Modulus

A number of factors affect the resilient modulus of subgrade soils. Previous studies by Seed, et al. (1967), TRB (1975), Thompson and Robnett (1976), Thornton and Elliott (1986), Elliott and Thornton (1987), etc. have shown the influence of various factors on resilient modulus. Among these factors are grain size distribution, plasticity, density, moisture content, compaction method, freeze-thaw cycle, confining pressure, and deviator stress. The effect of these factors is discussed below.

II.4.1 Index Properties

The grain size distribution, fines content, liquid limit, plasticity index, and group index may influence the dynamic behavior of subgrade soils. Thompson and Robnett (1976) performed a detailed study on the effect of these properties of Illinois soils on their resilient moduli. However, this study did not find any significant correlation between resilient modulus and any single soil property.

II.4.2 Moisture Content and Density

The influence of moisture content has been found to be significant in some studies. As illustrated in Figure II.2, Thompson and Robnett (1976) presented the variations of resilient modulus of the AASHTO Road Test subgrade. With six different moisture contents ranging from 0.8% below to 1.9% above optimum, the resilient moduli decrease with the increase of moisture

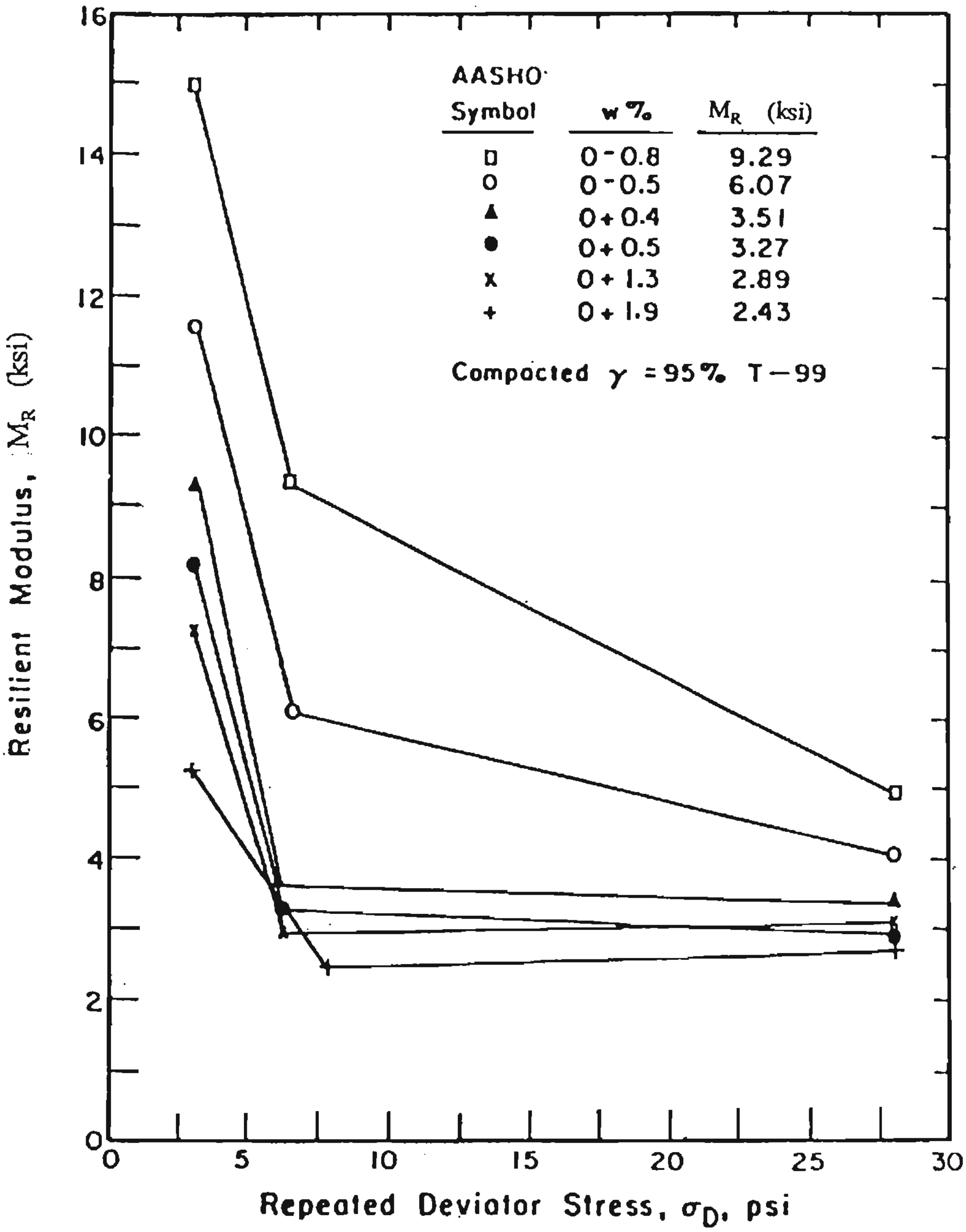


Figure II.2 Variation of resilient modulus with moisture contents ranging from 0.8% below to 1.9% above optimum (from Thompson and Robnett, 1976).

content. Robnett and Thompson (1976) studied the relationship between resilient modulus and moisture content of two fine-grained soils and AASHTO Road Test subgrade. Figure II.3 shows that the resilient modulus evidently decreases as the compaction moisture content increases. Thompson and Robnett (1976) also reported the influence of moisture content in terms of the degree of saturation. As plotted in Figure II.4, the general trend of resilient modulus decreases significantly with the increase of soil saturation. Therefore, the selection of an appropriate and representative moisture content for design, and the control of moisture content during sample preparation and field construction can be crucial.

Although Figure II.4 reveals the difference in the relationships between resilient modulus and soil saturation for 95% and 100% of compaction, the degree of saturation reflects the combined effect of moisture content and density. Robnett and Thompson (1973) conducted tests on two different cohesive soils at 1.7% and 2.5% over the optimum moisture content, respectively. Each sample was compacted to 95% and 100% of the standard proctor density. The results as presented in Figure II.5 indicates that the higher density results in higher resilient modulus but the difference in modulus is small. The investigation performed by Elliott and Thornton (1987) also concluded that resilient moduli of two Arkansas cohesive soils were not affected significantly by the variation of density.

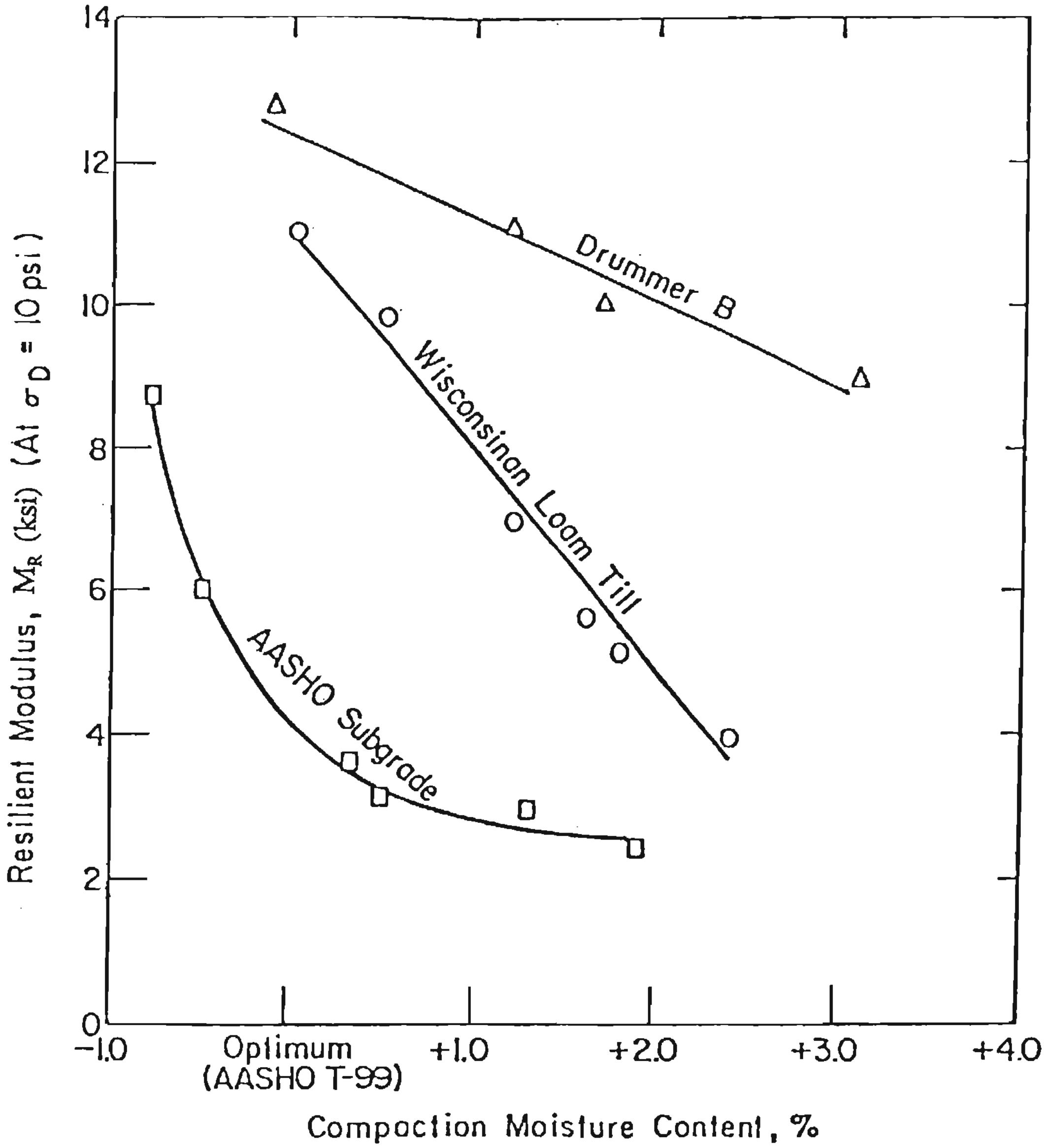


Figure II.3 Relationship between resilient modulus and moisture content of two fine-grained soils and AASHO Road Test subgrade (from Robnett and Thompson, 1976).

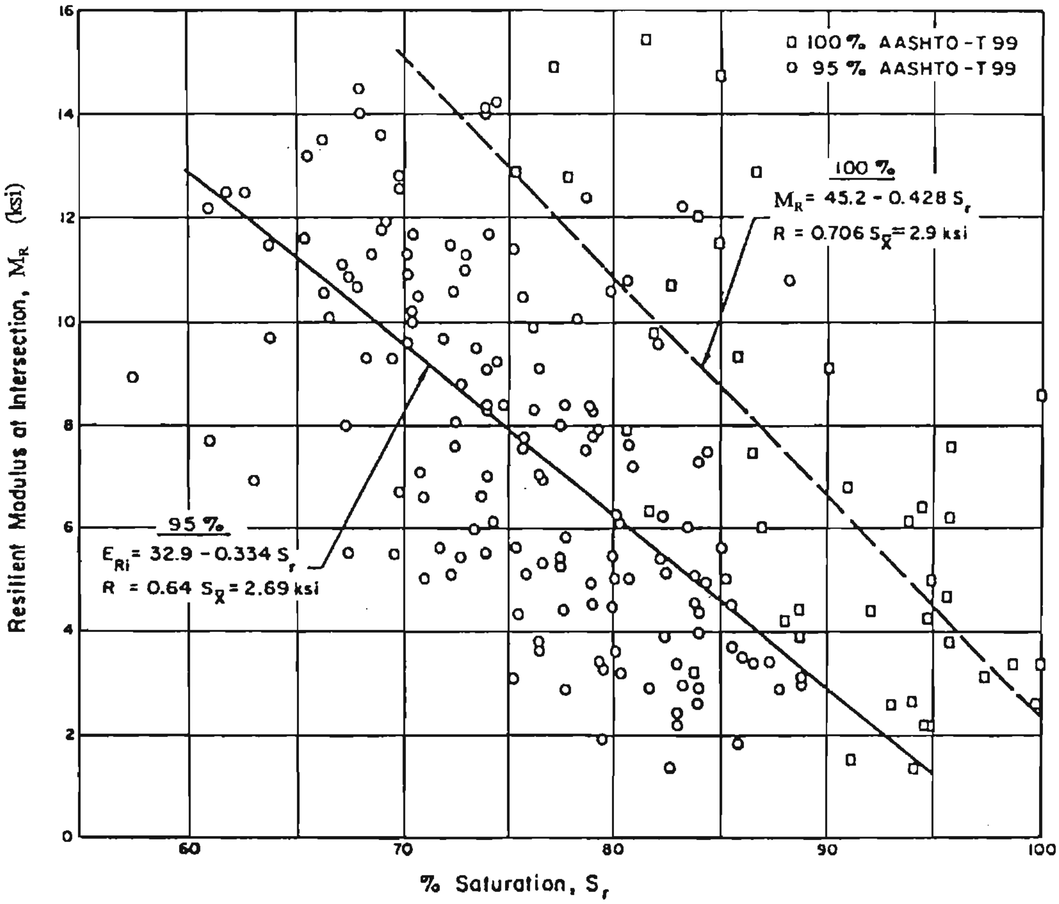


Figure II.4 Relationship between resilient modulus and degree of saturation at 95% and 100% of compaction (from Thompson and Robnett, 1976).

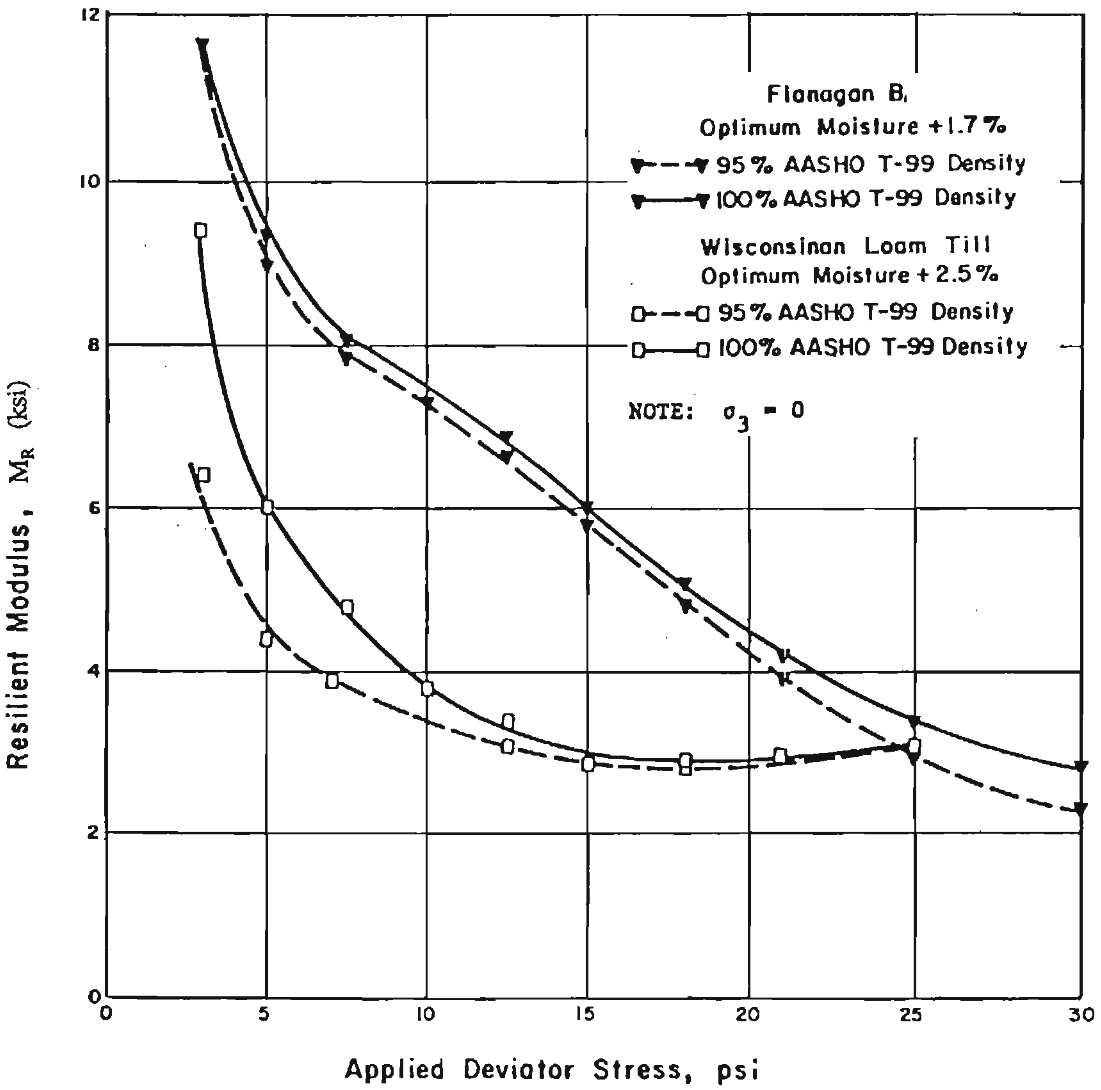


Figure II.5 Effect of density on resilient modulus of specimens compacted at 95% and 100% of AASHTO T-99 density (from Robnett and Thompson, 1973).

Some studies demonstrated that the method of compaction affects the resilient modulus as well, The results of test using static or kneading compaction method are compared in Figure II.6. Both Robnett and Thompson (1973) and Elliott and Thornton (1987) found that the specimen made by using static compaction has a higher resilient modulus than that using kneading compaction. Generally, the kneading compaction produces soil structures similar to that under field compaction, and generates more consistent test results. Thus, the standard resilient modulus test procedure (AASHTO T-274) specifies kneading compaction (AASHTO T-99) as the method for sample preparation.

II.4.3 Climate

The variation in resilient modulus throughout a year is expected because of the seasonal moisture changes of subgrade soil. Based on the analysis of deflection measurements taken during the AASHO Road Test, the seasonal variation in subgrade resilient modulus is shown in Figure II.7. The modulus has the lowest value in the spring and the highest value in the winter coinciding with freezing and thawing seasons. The spring thaw modulus of roadbed is typically 10% to 30% of the summer modulus while the frozen roadbed modulus is typically two orders of magnitude greater than the summer modulus. As a result, the roadbeds are softer in the spring than at other time of the year.

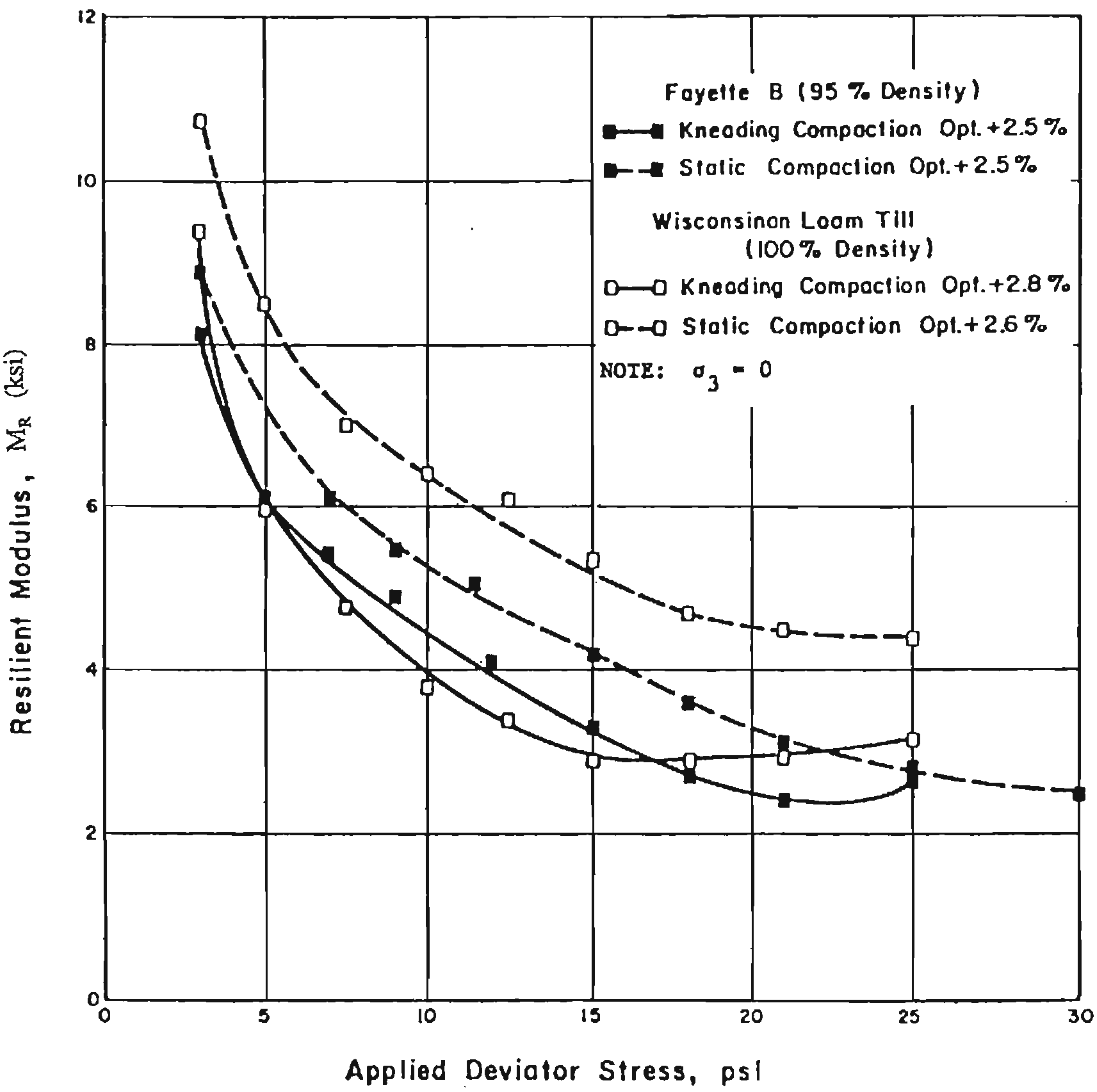


Figure II.6 Variation of resilient modulus of specimens made by using static and kneading compaction methods (from Robnett and Thompson, 1973).

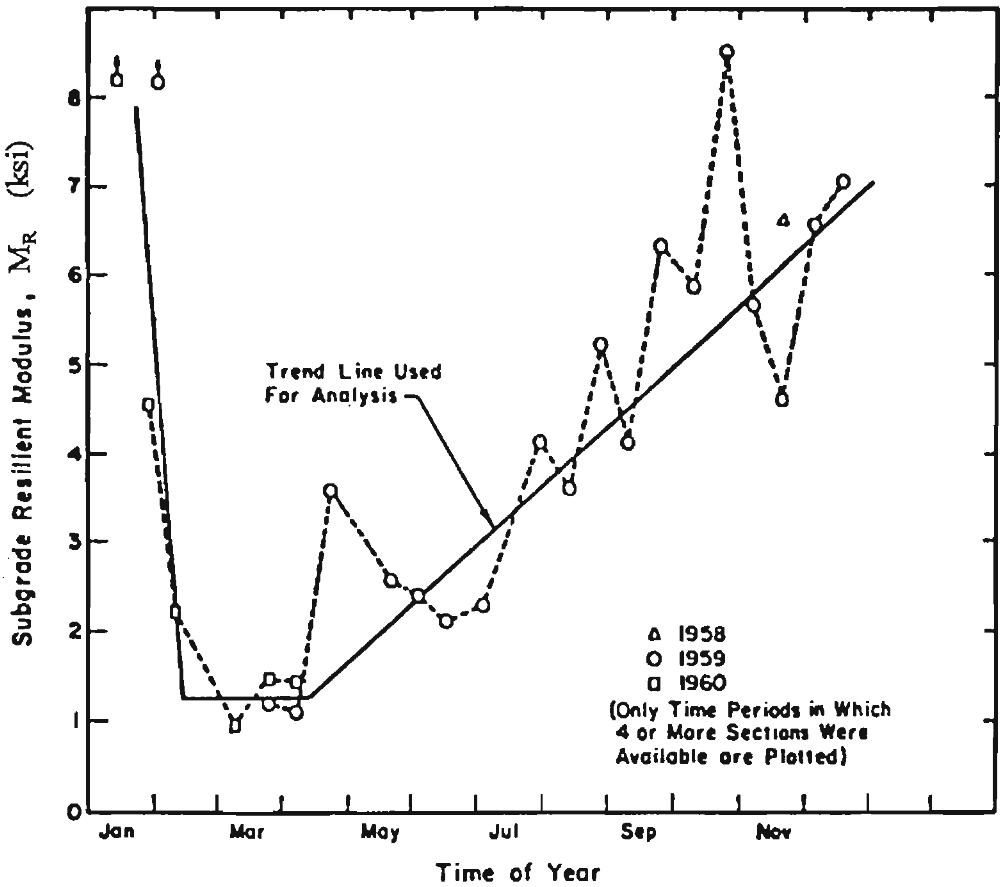


Figure II.7 Seasonal variation of subgrade resilient modulus during the AASHO Road Test.

It has been recognized that the freeze-thaw cycle has a major impact on the resilient modulus of subgrade soil. Robnett and Thompson (1976) investigated the effect of freeze-thaw cycles on the resilient modulus of fine-grained soils. Figure II.8 reveals that the first freeze-thaw cycle caused a dramatic reduction in the resilient modulus and the subsequent cycles caused additional minor reductions. Elliott and Thornton (1987) also reported that one freeze-thaw cycle significantly reduced the resilient modulus of three Arkansas soils.

II.4.4 Stress States

The effect of stress state on resilient modulus of subgrade soil has been studied extensively in the past two decades. Howard and Lottman (1977) conducted resilient modulus tests on four Idaho soils, including two fine sands, silt, and silty clay, under various stress conditions. The test results demonstrated that all four soils showed an increase in resilient modulus as deviator stress decreases, and resilient modulus exhibited a drastic increase for deviator stress less than 0.75 psi (5.17 kPa). It was also found that the resilient modulus of granular soils was predominantly dependent on confining pressure. The resilient modulus of soils, however, was not so sensitive to the variation of confining pressure, rather was more a function of deviator stress. Elliott and Thornton (1987) confirmed that in

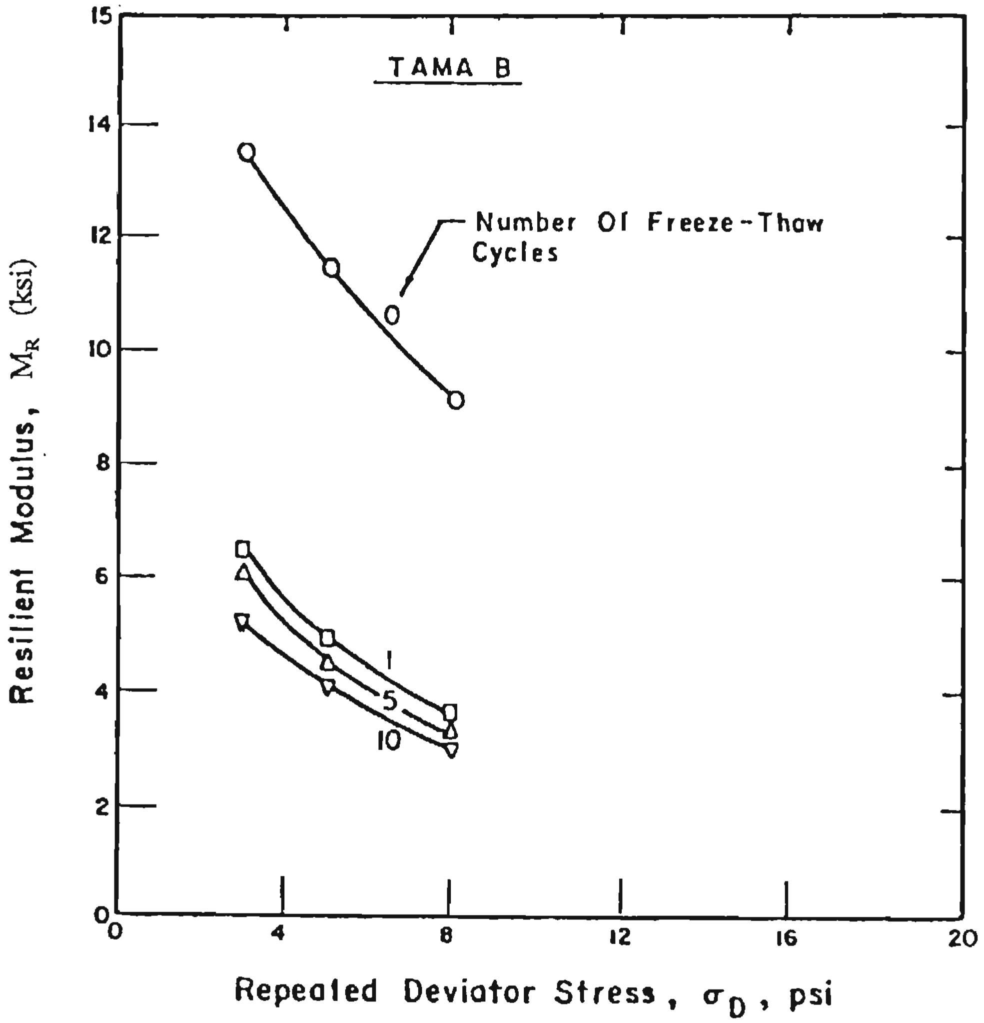


Figure II.8 Effect of number of freeze-thaw cycles on resilient modulus of fine-grained soil (from Robnett and Thompson, 1976).

no case was the effect of confining pressure of major significant for cohesive soils.

Because the resilient modulus varies with axial load and confining pressure, the resilient modulus has usually been plotted against deviator stress and confining pressure. Based on the results of early resilient modulus studies, Thornton and Elliott (1986) concluded that the modulus of granular base materials had a positive linear relationship with the sum of principal stresses on a log-log plot. As for cohesive soil, the test results are reported in an arithmetic plot of resilient modulus versus deviator stress at each confining pressure.

III. USE OF RESILIENT MODULUS IN PAVEMENT DESIGN

The surface deflection of a pavement results from the accumulation of load induced strain within the pavement and subgrade with the subgrade being a major contributor. In the AASHO Road Test (AASHO, 1962), 60% to 80% of the deflection measured at the surface was found to develop within the subgrade. Thus, the resilient modulus of subgrade is a major factor governing the surface deflection and the performance of flexible pavement and the procedure for its evaluation is included in the revised AASHTO pavement design procedure (AASHTO, 1986). In this procedure, resilient modulus is used in determining an effective resilient modulus as a direct input in pavement design and in selecting layer coefficients in determining layer thicknesses.

The effective resilient modulus of a roadbed soil is an average modulus weighted by relative damage and adjusted for seasonal variations. The following steps are involved in determining the effective resilient modulus:

1. Perform laboratory tests to develop a relationship between resilient modulus, M_R, and moisture content.

2. Estimate the seasonal variations of moisture content in subgrade.

3. Determine the monthly or bimonthly resilient modulus for a year from the above relationship.

4. Select a relative damage, u_f, value for each seasonal resilient modulus based on the M_R-u_f scale provided by the design guide.

5. Calculate the average of relative damage values for the year.

6. Select effective resilient modulus corresponding to the average relative damage from the M_R-u_f scale.

The effective resilient modulus which accounts for the combined effect of temperature, moisture, and seasonal damage is then used in design.

The revised guide provides a design chart as shown in Figure III.1 for the flexible pavement design. Reliability and overall standard deviation are introduced at the beginning of the design procedure. This uncertainty factor accounts for the combined effect of the variation in all the design variables so that the designer no longer need to use conservative estimates for the other input parameters. The traffic factor is then considered by entering the cumulative expected 18-kip equivalent single axle load (ESAL) during the design period. In terms of effective roadbed soil resilient modulus, the material properties and environmental effects are then included in the design. By incorporating the loss in design serviceability, which is the change between initial and terminal serviceability indexes, the nomograph leads to a structural number. "Structural number" is a parameter used in the design of layered pavement structure. It relates to the thickness of each layer by a layer coefficient.

NOMOGRAPH SOLVES:

$$\log_{10}W_{18} = Z_R{*}S_o + 9.36{*}\log_{10}(SN+1) - 0.20 + \frac{\log_{10}\left[\dfrac{\Delta PSI}{4.2 - 1.5}\right]}{0.40 + \dfrac{1094}{(SN+1)^{5.19}}} + 2.32{*}\log_{10}M_R - 8.07$$

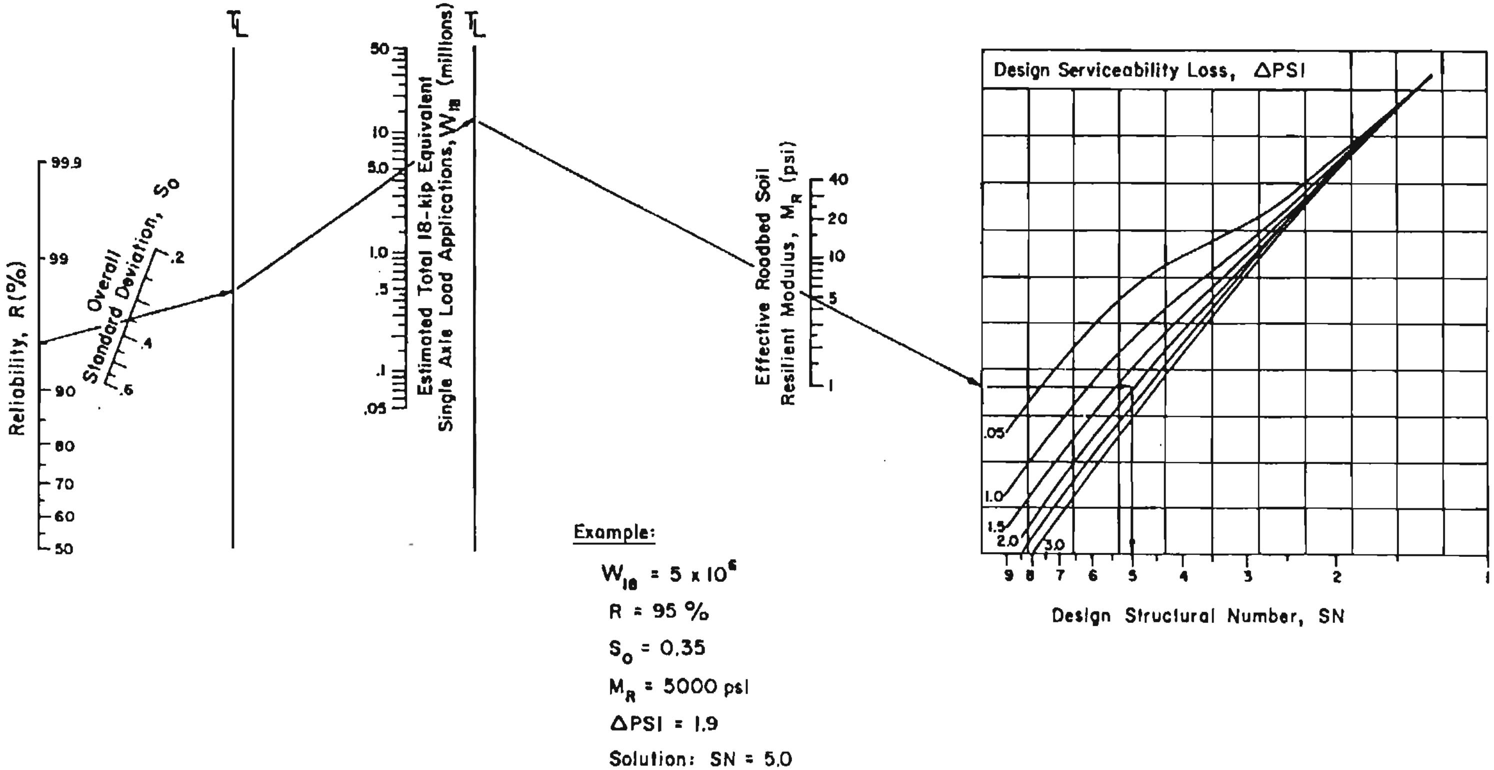


Figure III.1 Design chart for flexible pavements based on using mean values for each input (form AASHTO, 1986).

The revised guide employs layer coefficients, a_i, to express the empirical relationship between structural number and layer thicknesses, D_i, as formulated in the following equation:

$$SN = \sum_{i=1}^{n} a_i \cdot D_i \ . \qquad (3)$$

Based on the resilient modulus of each pavement material, the layer coefficients are individually estimated for asphalt concrete pavement, base course, and subbase layer. Once the structural number and layer coefficients are determined, the thickness of each layer can be calculated from the above equation. This equation does not provide a unique solution because many combinations of layer thicknesses all satisfy the design load-carrying capacity.

IV. TESTING PROGRAM, PROCEDURES, AND RESULTS

IV.1 Testing Program

Twenty resilient modulus tests were performed in this research program. Initially, twenty two bags of row soils were provided by the Materials Laboratory of Colorado Department of Transportation (CDOT). The bag soils were first sieved through a stack of sieves including U.S. standard sieves #4, #8, #20, #40, #60, #100, #200 and bottom pan. After sieving the soils, the amount of fines passing #200 sieve was found to be sufficient for preparing only eight samples, Nos. 1 to 8, of a desired gradation characteristics for this test program. With the CDOT's agreement, additional soils were carefully selected and delivered to the Geotechnical and Structural Laboratory at the University of Colorado at Denver (UCD) for preparing the other twelve samples, Nos. 9 to 20.

In order to test a broad spectrum of soil types for this research program, twenty soil samples were prepared of different gradation characteristics with the mean diameter (D50) ranging from 0.0053 inches (0.135 mm) to 0.187 inches (4.75 mm), and the coefficient of uniformity, C_u, from 6.3 to 75.4, and the percent fines content by weight from 6% to 32%. However, all samples except Nos. 17 and 19 do not have measurable plasticity index and their classification ranges from A-1-a to A-2-4 with the AASHTO classification. The gradation curves of twenty soil samples are reported in figures in Appendix A, and the AASHTO classification, gradation characteristics, and plasticity index, PI, of each sample are included in Table IV.1.

Soil samples were mixed for compaction in the Geotechnical and Structural Laboratory at the University of Colorado at Denver (UCD). The compaction (AASHTO T-99) and R-value test (AASHTO T-190) were carried out in the Materials Laboratory at the Colorado Department of Transportation (CDOT). A mechanical kneading compactor was used to compact all soil samples and the correction was then made for rock fraction. Results of the compaction test including maximum dry density, γ_d, and optimum moisture content, ω_{opt}, provided by the CDOT are summarized on Table IV.1. The R-value of tested samples ranges from 48 to 81, and are also listed on Table IV.1.

The cyclic triaxial test system at UCD was used in this resilient modulus test program. An MTS-810 series closed-loop electro-hydraulic universal testing machine with a capacity of 200 kips (890 kN). Figure IV.1 shows the test system, which consists of a stiff load frame, MicroConsole Model 458.20 providing the closed-loop control of the servo electro-hydraulic system, and data acquisition apparatus. Other system components include LVDT, load cell, actuator, servovalves, hydraulic pressure supply, and hydraulic service manifold.

Table IV.1 Soil classification, gradation characteristics, and laboratory test results of each soil sample.

No	Class. & G.I.	D_{50} (mm)	C_u	-#200 (%)	PI	γ_d (pcf)	ω_{opt} (%)	R	M_R (ksi)
1	A-2-4(0)	4.75	13.6	6	NP	132.6	5.7	78	13.6
2	A-1-a	4.75	22.8	6	NP	133.0	5.9	81	10.3
3	A-1-b	1.8	18.0	8	NP	128.0	8.0	72	28.8
4	A-1-b	1.6	25.5	8	NP	129.3	7.0	75	29.0
5	A-1-b	1.5	38.6	9	NP	130.6	6.6	78	13.0
6	A-1-b	1.3	57.7	13	NP	129.2	6.8	77	15.4
7	A-1-b	0.35	9.3	14	NP	122.7	9.6	78	10.0
8	A-1-b	0.54	16.0	14	NP	124.4	9.0	81	12.4
9	A-1-b(0)	1.9	41.3	10	NP	121.7	8.3	64	10.3
10	A-1-b(0)	1.68	11.2	2	NP	110.2	10.8	71	16.7
11	A-1-b(0)	0.63	11.1	9	NP	117.6	8.4	72	13.6
12	A-2-4(0)	0.14	7.0	28	NP	116.3	12.8	55	10.6
13	A-2-4(0)	0.135	9.3	32	NP	118.0	10.4	67	13.0
14	A-2-4(0)	0.25	9.5	18	NP	118.5	11.7	73	9.6
15	A-2-4(0)	0.24	6.3	15	NP	118.7	9.45	81	13.0
16	A-2-4(0)	0.4	25.0	22	NP	116.9	13.4	50	6.8
17	A-2-4(0)	0.147	11.5	32	4	123.5	10.1	62	20.0
18	A-1-a(0)	2.5	75.4	11	NP	133.3	6.1	77	11.0
19	A-2-4(0)	0.3	30.5	27	7	129.1	8.2	48	12.6
20	A-1-a(0)	2.24	55.4	8	NP	132.0	5.8	81	12.0

NP: Non-plastic

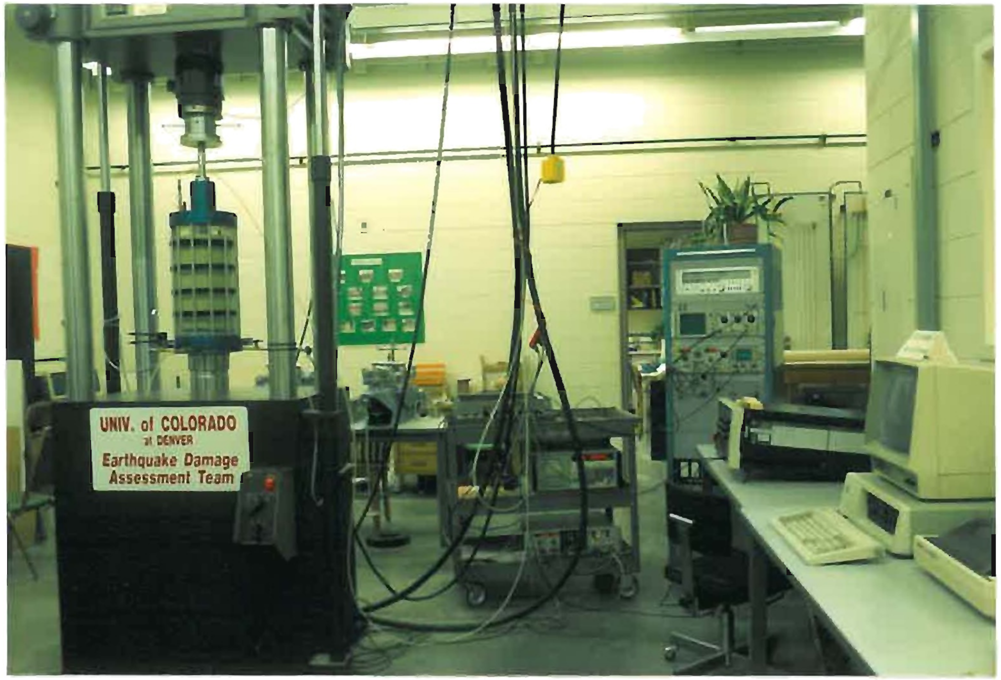


Figure IV.1 Cyclic triaxial test system MTS-801 at the UCD.

V.2 Procedures of Resilient Modulus Test

Twenty specimens for resilient modulus tests were prepared and compacted. A large size triaxial tests were used because samples contained large particles of over 1 inch (25.4 mm). The cylindrical sample dimensions were 6-inch (15.24-cm) in diameter and 12-inch (30.48-cm) in height. Soils samples were first cured at the optimum moisture content for 24 hours before testing. The specimen was then compacted in a 6-inch (15.24-cm) diameter mold by the standard Proctor method. To maintain the specimen uniformity and to achieve the maximum dry density, samples were compacted in eight 1.5-inch (3.81-cm) lifts. All specimens were consolidated in the triaxial chamber under a confining pressure for 24 hours. The procedure for sample preparation for resilient modulus test is detailed in Appendix B.

Because of the non-plastic nature of soils used in this research, the standard procedures for determining resilient modulus of granular soils as described in AASHTO T-274 were followed. During the test, 200 repetitions of axial load are applied under each load condition. Each axial load repetition comprises a 0.1-second load pulse followed by a 1.9-second zero load period.

The resilient modulus test for granular soils begins the sample conditioning under a cyclic load: 200 repetitions of each deviator stress, σ_d, of 5 and 10 psi (34.48 and 68.95 kPa) under a confining pressure, σ_c, of 5 psi (34.48 kPa), then, 200 repetitions of cyclic σ_d at 10 and 15 psi (68.95 and 103.43 kPa), respecitvely, under a σ_c of 10 psi (68.95 kPa), and, finally, another 200 repetitions of σ_d at 15 and 20 psi (103.43 and 137.90 kPa) are applied under a σ_c of 15 psi (103.43 kPa). This load conditioning eliminates the effects of the interval between compaction and loading, initial loading versus reloading, and initially imperfect contact between the end platens and the specimen.

In the resilient modulus test, each sample was tested under all combinations of σ_c of 20, 15, 10, 5, to 1 psi (137.90, 103.43, 68.95, 34.48, to 6.90 kPa), and σ_d from 1, 2, 5, 10, 15, to 20 psi (6.90, 13.79, 34.48, 68.95, 103.43, to 137.90 kPa). Load and deformation were recorded throughout the test. The recorded load and deformation for the 200th repetition of each load condition are used in determining the M_R under each stress condition. The confining pressures, deviator stresses, and the number of repetitions used during the sample conditioning and testing are summarized on Table IV.2. The detailed procedure for resilient modulus test is presented in Appendix C.

IV.3 Results of Resilient Modulus Test

The resilient modulus was calculated from the recorded axial load and recovered deformation after complete unloading under each load condition. Since the samples tested in this research were granular soils, the resilient moduli are reported in two forms:an arithmetic plot of resilient moduli versus deviator

Table IV.2 Confining pressures, deviator stresses, and number of repetitions used in resilient modulus test for granular soils.

	Confining Pressure (psi)	Deviator Stress (psi)	Repetitions at Each Load
Conditioning	5	5, 10	200
	10	10, 15	200
	15	15, 20	200
Testing	20	1, 2, 5, 10, 15, 20	199 + 1
	15	1, 2, 5, 10, 15, 20	199 + 1
	10	1, 2, 5, 10, 15	199 + 1
	5	1, 2, 5, 10, 15	199 + 1
	1	1, 2, 5, 10	199 + 1

stresses at various confining pressures, as presented in Appendix D and a log-log plot of resilient moduli versus the sum of principal stresses, θ, as presented in Appendix E.

The arithmetic plots exhibit an increase in M_R as σ_d increases from 5 psi (34.48 kPa), although the trend grows vaguer at σ_d below 5 psi (34.48 kPa). These plots illustrate the strong dependency of M_R on σ_c. This dependent relationship between the resilient modulus and confining pressure for granular soils agrees with the findings of previous research. The test results also demonstrate a strong linear relationship between M_R and θ on a log-log plot. The equation of least-square line relating M_R and θ for each sample is presented at the bottom of each log-log plot in Appendix E.

Yeh and Su (1989) concluded in their research report that the M_R under the stress condition of σ_d of 6 psi (41.37 kPa) and σ_c of 3 psi (20.69 kPa) is the most appropriate value for adoption in pavement design. From the arithmetic plots shown in Appendix D, the M_R under such stress condition was determined for each sample and was included in Table IV.1. These values of resilient modulus are used in developing the functional relationship between the M_R values and R values and index properties of soils. To enlarge the database for the statistical modeling of M_R, the results of the nineteen samples from the previous test program (Yeh and Su, 1989) with soil types ranging from A-1-b to A-7-6 per AASHTO classification are included in this study. The AASHTO classification, fines content, plasticity index, PI, maximum dry density, γ_d, and optimum moisture content, ω_{opt}, resilient modulus values and R values of these samples are included in Table IV.3.

Table IV.3 Soil classification of soil samples and laboratory test results from previous test program (From Yeh and Su, 1989).

No	Class. & G.I.	-#200 (%)	PI	γ_d (pcf)	ω_{opt} (%)	R	M_R (ksi)
21	A-7-6(17)	69	28	108.0	17.8	6	3.5
22	A-7-6(2)	42	22	108.5	17.1	15	4.2
23	A-6(11)	69	19	109.1	16.4	11	4.6
24	A-6(2)	44	13	110.8	15.2	30	8.4
25	A-4(1)	42	10	119.0	11.6	26	7.8
26	A-2-6(1)	25	14	119.9	11.1	39	10.5
27	A-2-4(0)	20	10	116.2	12.1	41	6.4
28	A-1-b(0)	25	4	130.0	7.2	34	8.5
29	A-2-4(0)	23	9	115.4	13.5	37	11.2
30	A-4(3)	57	9	114.4	14.4	37	7.2
31	A-2-4(0)	34	8	116.7	12.8	42	10.3
32	A-4(0)	44	6	116.2	12.1	39	7.7
33	A-4(0)	36	9	117.9	16.0	40	6.8
34	A-4(0)	48	1	120.3	11.3	70	8.7
35	A-2-4(0)	16	NP	119.9	10.9	77	8.6
36	A-1-b(0)	10	NP	118.2	6.2	79	15.5
37	A-1-b(0)	10	NP	127.7	8.0	62	11.0
38	A-1-b(0)	17	3	120.9	11.3	72	8.7
39	A-1-b(0)	9	NP	129.9	8.5	80	21.9

NP: Non-plastic

V.1 STATISTICAL MODELING

V.1 Introduction

Descriptive statistics and inferential statistics are the two major branches in statistics. The descriptive statistics deals with summary and description of data. The inferential statistics concerns with analysis of sample data to make inferences about a large set of data - a population, from which the sample is selected. Experimental research in engineering involves the use of experimental data - a statistical sample, to infer the nature of some conceptual population that characterizes a phenomenon of interest to the experimenter. One of the most important application of inferential statistics in engineering involves estimating the mean value of a response variable or predicting some future value of the response variable based on the knowledge of a set of related independent variables. A relationship used to relate a dependent (response) variable to a set of independent variables is generally referred to as a regression model or a statistical model (Mendenhall and Sincich, 1991). The regression modeling was used in this study to formulate the functionial relationship between the resilient modulus and their influencing parameters.

V.2 Regression Analysis

Regression equation relates a dependent variable, Y, to a set of independent variables, X_i, where i is a nonzero integer.

In this study, the dependent variable, resilient modulus, M_R, is related to the independent variable, stabilometer R-value and index properties of soils including uniformity coefficient, C_u, mean diameter, D_{50}, % fines content, FC, and plasticity index, PI. The least-squares approach is used to determine the best estimate of a regression equation. In general, the least-squares method chooses the best-fitting model which minimizes the sum of squares of the distances between the observed responses and those predicted by the fitted model. Once a regression model is obtained, it is desirable to test the contribution of each independent variable involved in predicting the response variable so that the model may be refined.

V.3 Regression Model between M_R and Stabilometer R-Value

Over a period of eight years, UCD has conducted resilient modulus tests on 39 different samples under the CDOT sponsorship. The data base from the results of the resilient modulus test on these samples is used in the statistical modeling. The type of soils tested ranges from clay to granular soils with various percentages of fines of minus #200 sieve. Besides the R-value, the gradation characteristics, including coefficient of uniformity, coefficient of curvature, and percent fines content by weight, are included as independent variables in the analysis. However, only 20 out of 39 samples have the information on gradation characteristics.

The regression analysis was performed to formulate the functional relationship between M_R and R-value and index properties. A commercially available statistical graphics system, "STATGRAPHICS" developed by Statistical Graphics Corporation was used. As shown in Figure V.1, data points of M_R versus R are quite scattered, particularly at the R-value above 60. Thus, it is extremely difficult to use one regression curve to represent the complete population of data points. After many experiments, the "best" regression equation is:

$$\log M_R = 0.118 + 0.517 \cdot \log R \,, \tag{4}$$

or

$$M_R = 1.312 \cdot R^{\,0.517}. \tag{5}$$

The above statistical formulation gives the intercept of 0.118, the slope of 0.517, the R^2 of 42.79% and the standard error of estimate of 0.155. The value of R^2 is much less than desired. This is mainly due to the scatter of data points. Figure V.1 shows the regression curve, upper and lower bound curves for one and two standard deviations, respectively. The predicted resilient modulus, M_{RP}, is plotted against M_R obtained the laboratory test in Figure V.2. The linear comparison between them has a R^2 value of 25.11%. Again this low R^2 value reflects the scatter of data points.

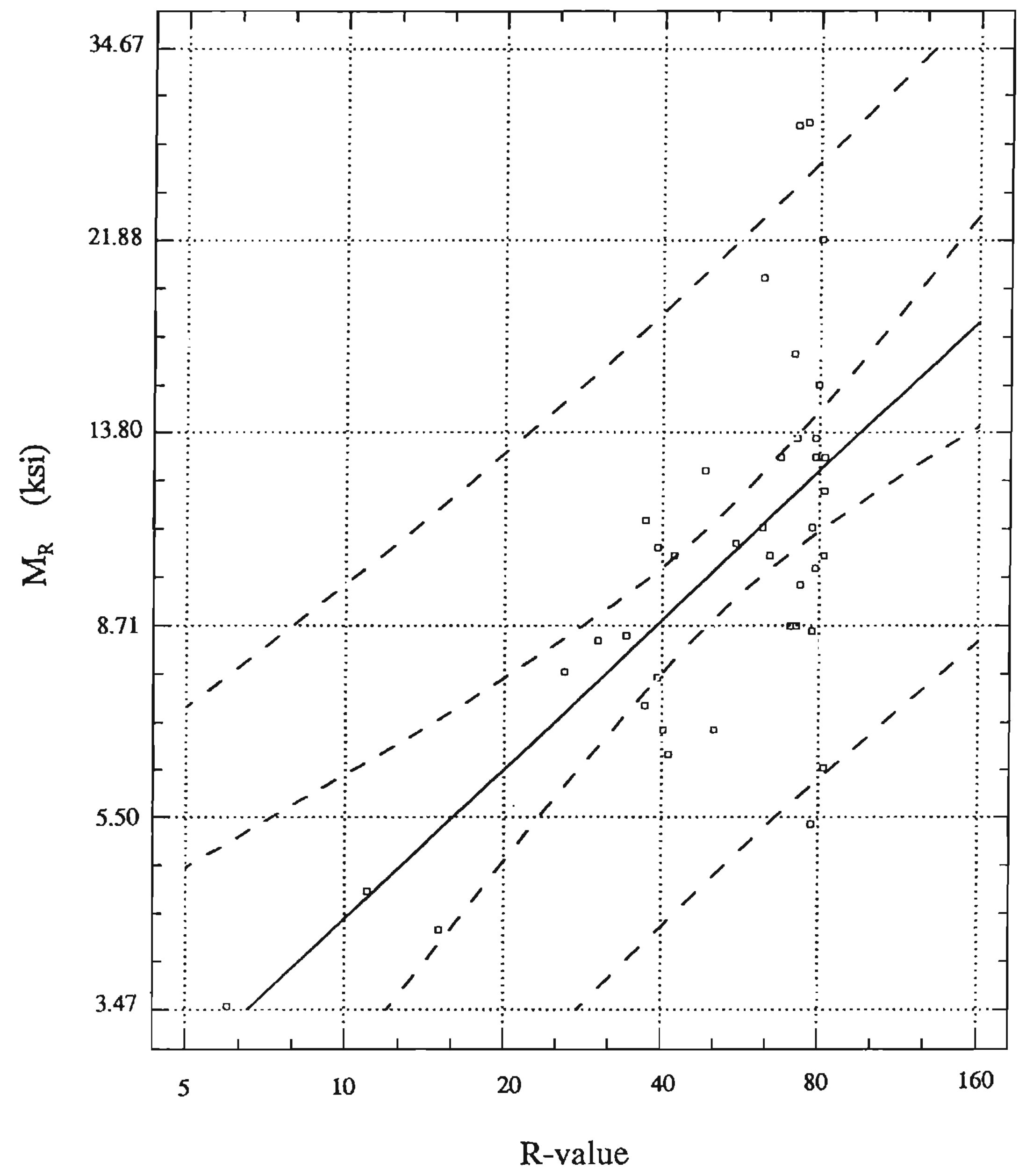


Figure V.1 Scatter plot of log M_R versus log R with regression curve, upper and lower bound curves for one and two standard deviations, respectively.

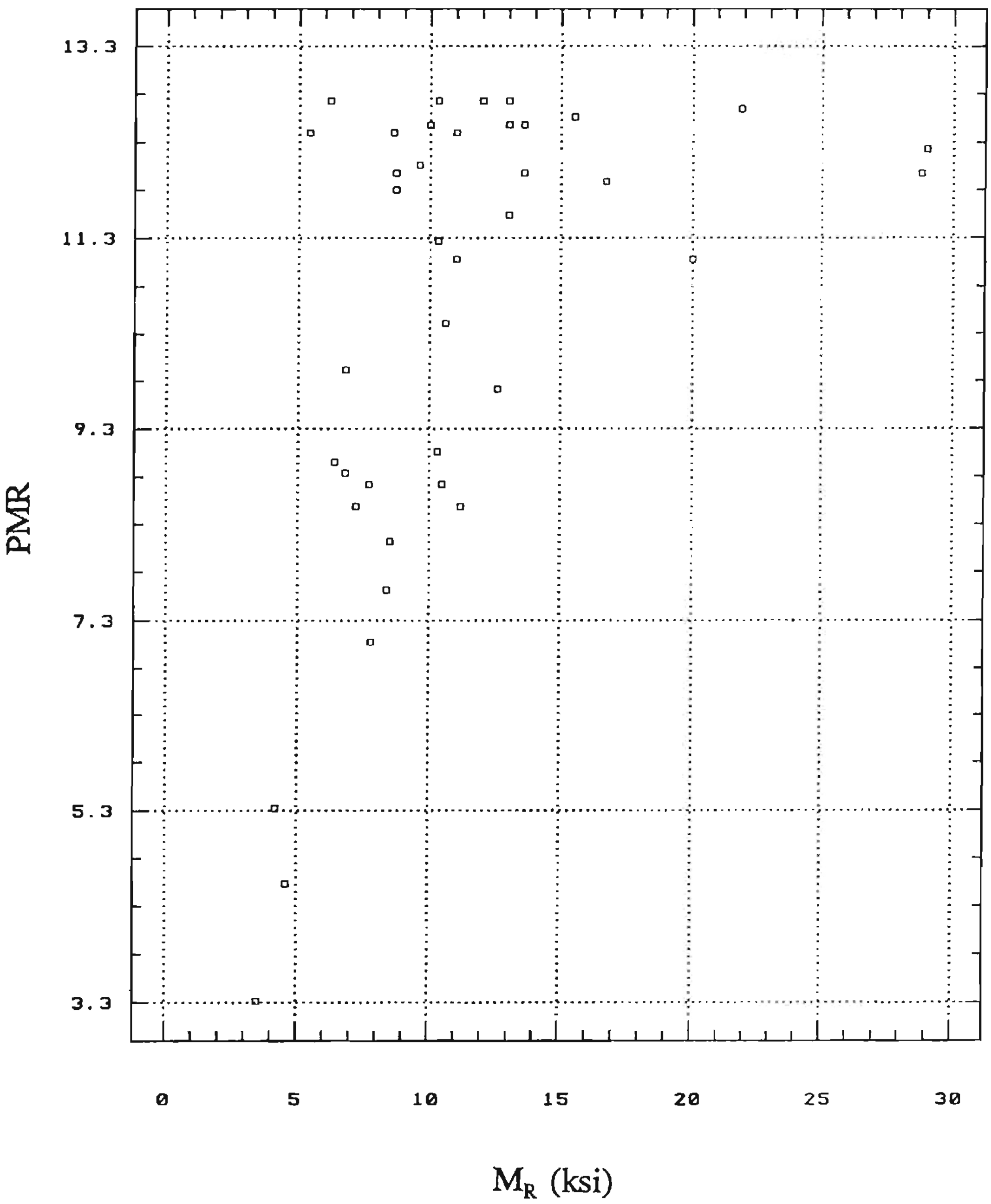


Figure V.2 Comparison of predicted M_R with M_R obtained from laboratory test.

Linear regreeeson analyses were performed to formulate the functional relationships between the resilient modulus and R-value and each of the following index properties: percent fines content, FC, plasticity index, PI, uniformity coefficient , C_u, and mean grain size, D_{50}. Results of these linear regression are shown in Figures V.3 to 7. Values of R^2 for these regression analyses are quite small.

The above-mentioned regression functions are less than ideal because of the scatter of data points. The scatterness of data points is caused by the fact that many factors can affect the value of resilient modulus and one single independent parameter is simply insufficient as a predictor. Instead, all significant influencing factors should be included in the formulation of the regression equation as independent parameters. These factors include gradation characteristics, liquid limit, plasticity index, confining pressure, deviator stress amplitude, number of loading cycles, etc. This will require additional tests with well documented index properties and test conditions.

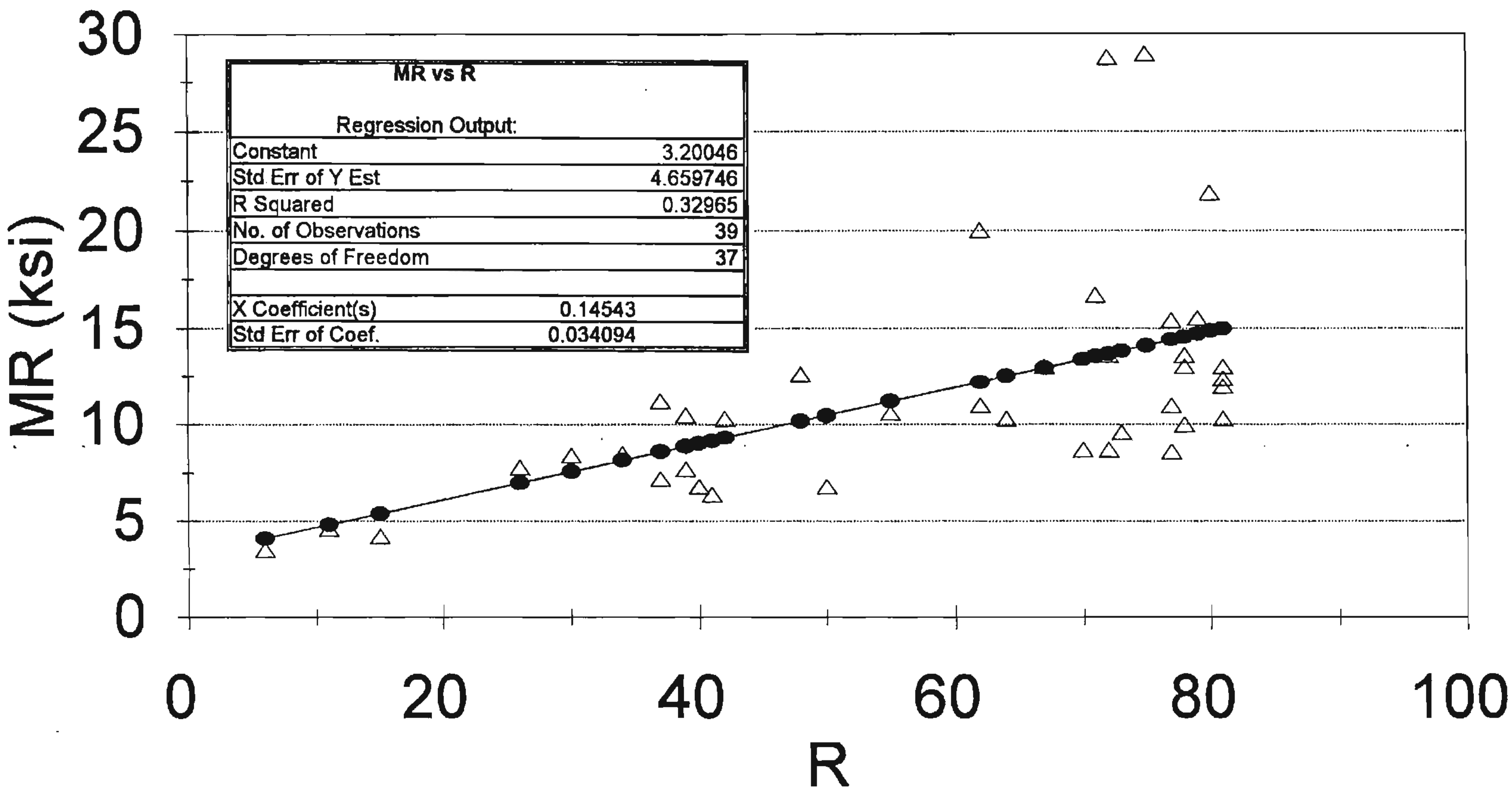


Figure V.3 Linear Regression Equation of M_r vs. R-value

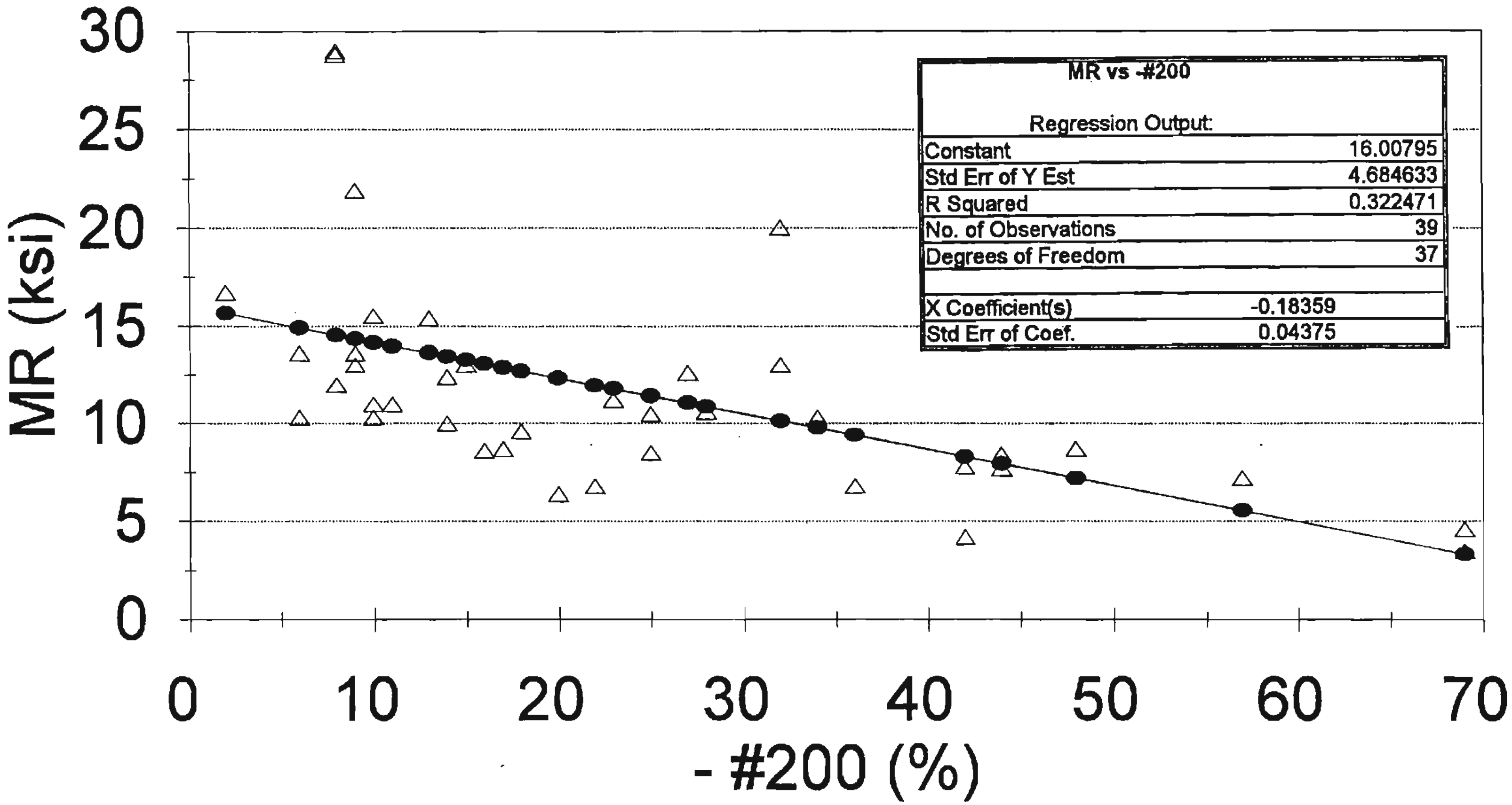


Figure V.4 Linear Regression Equation of M_r vs. Fines Content

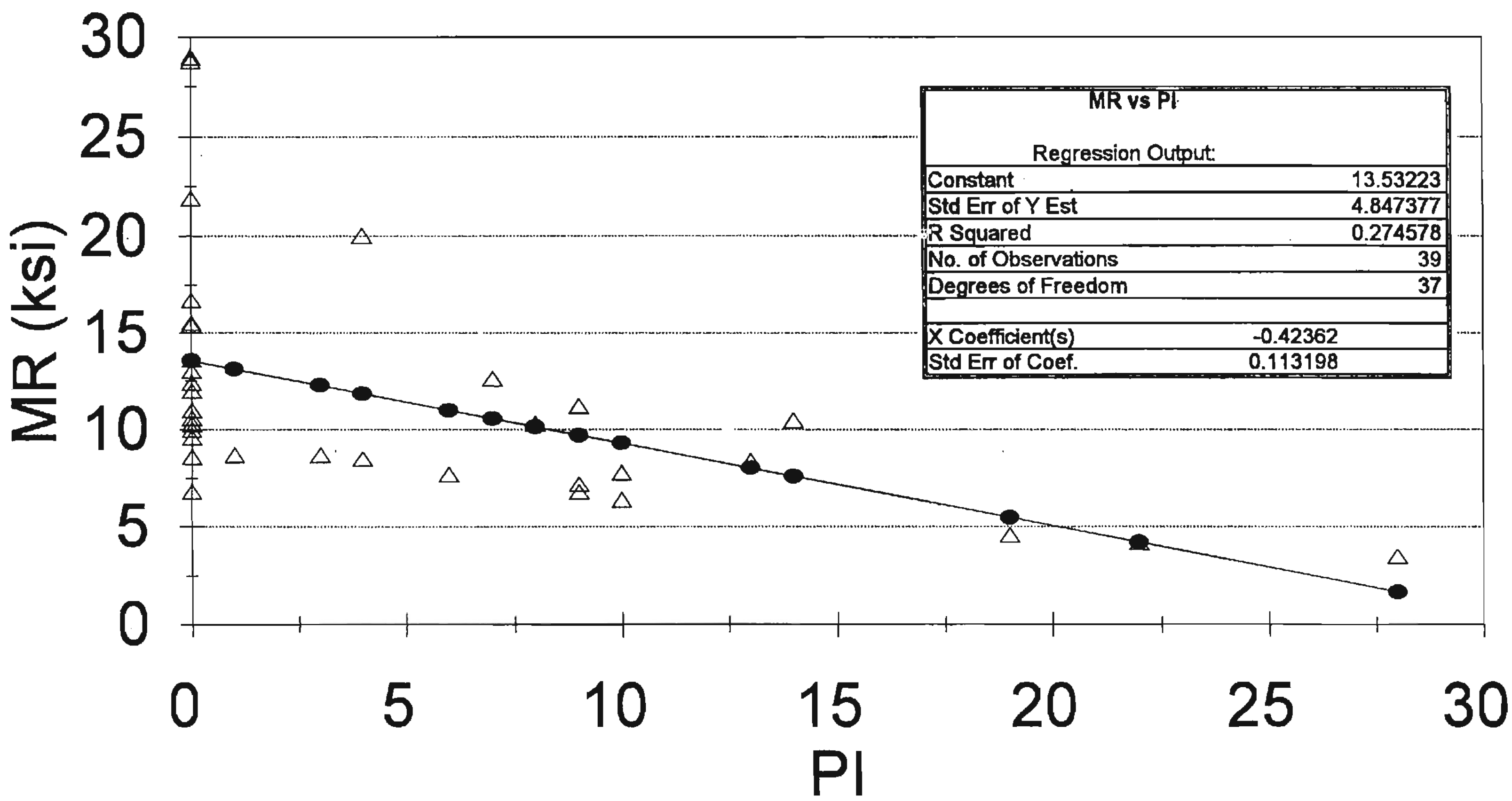


Figure V.5 Linear Regression Equation of M_r vs. Plasticity Index

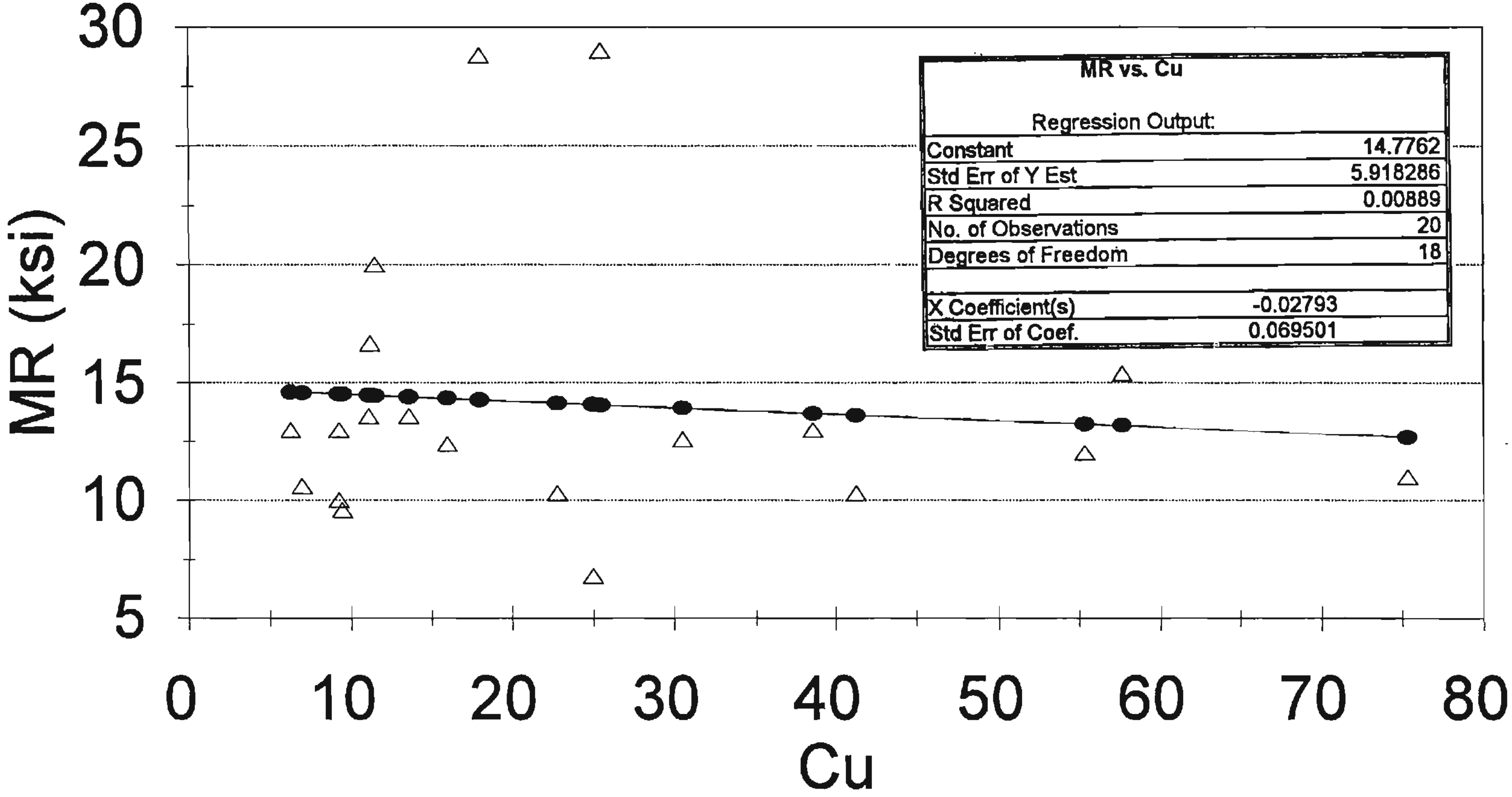


Figure V.6 Linear Regression Equation of M_r vs. C_u

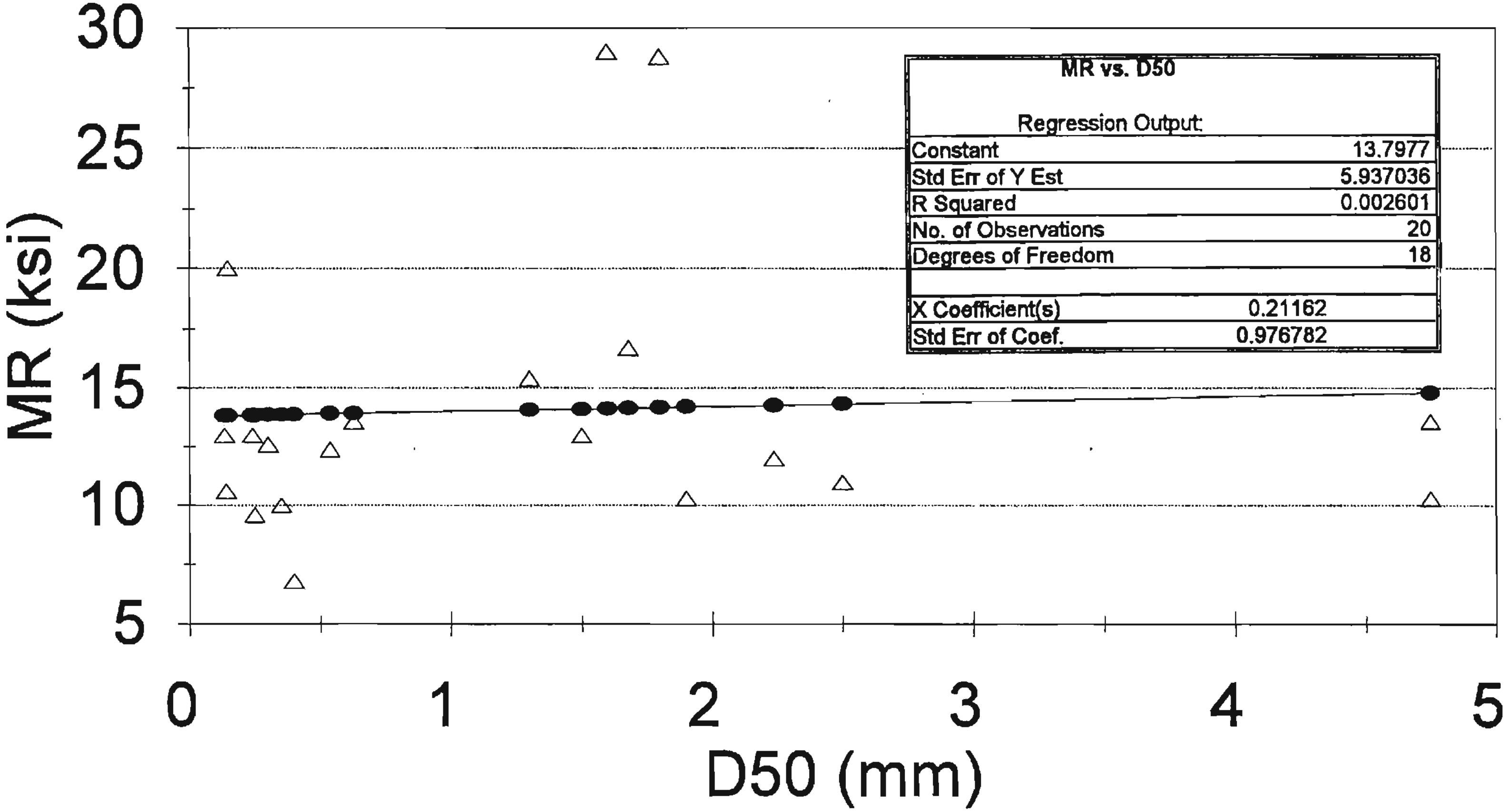


Figure V.7 Linear Regression Equation of M_r vs. D_{50}

VI. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

VI.1 Summary

The AASHTO Guide for Design of Pavement Structures - 1986 uses the theory of elastic layers in the design of pavement, which, in turn, requires the resilient modulus, M_R, of pavement materials, base course and subgrade. However, its implementation has met some technical difficulties resulted from 1) the lack of and the complexity of testing equipment, 2) the scarcity of resilient modulus data base, 3) the soil type dependency of resilient modulus, and 4) many influencing factors of resilient modulus.

Because of the recent nature of its implementation, the M_r data base is extremely small. Conversely, the Stabilometer R-value has been in use in the pavement design for decades and has a very large data base. To remove this shortcoming and to take the advantage of the large R-value data base, numerous attempts have been made to establish the correlation between M_r and R-value and to establish their functional relationship. The State of Colorado has also invested in this endeavor through the sponsorship of the resilient modulus research at the Univeristy of Coloradoat Denver by the Colorado Department of Transportation. A total of 39 resilient modulus tests were conducted, 20 in this test program and 19 in an earlier test program.

Regression analyses were performed to formulate the functional relationship using the least square fit. Two regression equations were formulated to relate the resilient modulus to R-value (one linear and one nonlinear) and four linear regression equations relate the resilient modulus to percent fines content, plasticity index, uniformity coefficient, and mean grain size. These equaitons , however, have small values of coefficient of representation called R square. The use of the equation relating the resilient modulus to the R-value can give the value of resilient modulus smaller than that obtained from the in-situ deflectometer test on subgrade and base course.

VI.2 Conclusions

From the data base of 39 samples with the soil type ranging from A-1-a to A-7-6, two regression equations, one linear and one nonlinear, were formulated in which the resilient modulus was written as a function of the stabilometer R-value. These equations do not represent significant improvement over the one provided in the study by Yeh and Su (1989).

Four linear equations were also formulated to express the resilient modulus in terms of fines content, plasticity index, uniformity coefficient and mean grain size. The values of the coefficients of representation are also small. This implies any one single independent parameter is ineffective as a predictor.

The correlation is weak for samples of granular soils containing varying amounts of fines of up to around 30%. For granular soils with less than 30% fines, the index properties of granular constituencies may have an important influence on the resilient modulus of soils. These influencing factors include gradation characteristics, relative density and grain shape of the granular soils and percent fines content and fines consistency. These factors are responsible for the scatter of M_R values at the stabilometer R-value greater than 60 and the poor functional relationship.

The inability of the Stabilometer R-value to realistically reflect the engineering properties of granular soils with less than 30% fines has also contributed to its poor functional relationship to resilient modulus.

To appropriately evaluate the resilient modulus of soils requires a sophisticated universal testing machine capable of simulating the pulsating load from traffic, and continual monitoring of lateral deformation, vertical deformation and the amplitude of pulsating load, etc.

To strengthen the equation, the multiple regressioin analysis is needed to formulate an equation expressing the resilient modulus in terms of a number of significant influencing factors.

VI.3 Recommendations

1. Use the M_R vs. R-value equations with caution, particularly for granular soil samples with less than 30% of fines.

2. Conduct a systematic research to study the influence of various factors affecting the resilient modulus of soils. For soils containing less than 30% fines of minus #200 sieve, the factors should include: gradation characteristics, relative density, grain shape, fines contents and plasticity, degree of saturation, confining pressure, cyclic stress amplitude, and number of cycles of repeated stress. For clayey soils, the effect of density, moisture content, liqid limit and plastic index should investigated.
3. When formulating the regression equation for M_R, it would be more reasonable to separate the granular (or nonplastic) soils from the clayey (or plastic) soils because of the different factors affecting the resilient modulus of these two types of soils, as discussed above.
4. Mutiple regression analysis should be performed to formulate the resilient modulus in terms of all significant influencing factors. With the combined effort of Items 2, 3 and 4, the authors of this report believe that a good set of regression equations can be formulated to effectively evaluate the resilient modulus in terms of factors that can be easily determined.
5. It is recommended to abandon the effort to formulate a functional relationship between resilient modulus and stabilometer R-value because of the inability of R-value in reflecting the dynamic behavior/properties of soils.

6. Develop design charts for the selection of resilient modulus with given index properties of soils.
7. Hold training sessions in different regions of CDOT, cities and counties in Colorado for the purpose of effective technology transfer.
8. To strengthen the equation, the multiple regressioin analysis is needed to formulate an equation expressing the resilient modulus in terms of a number of significant influencing factors.

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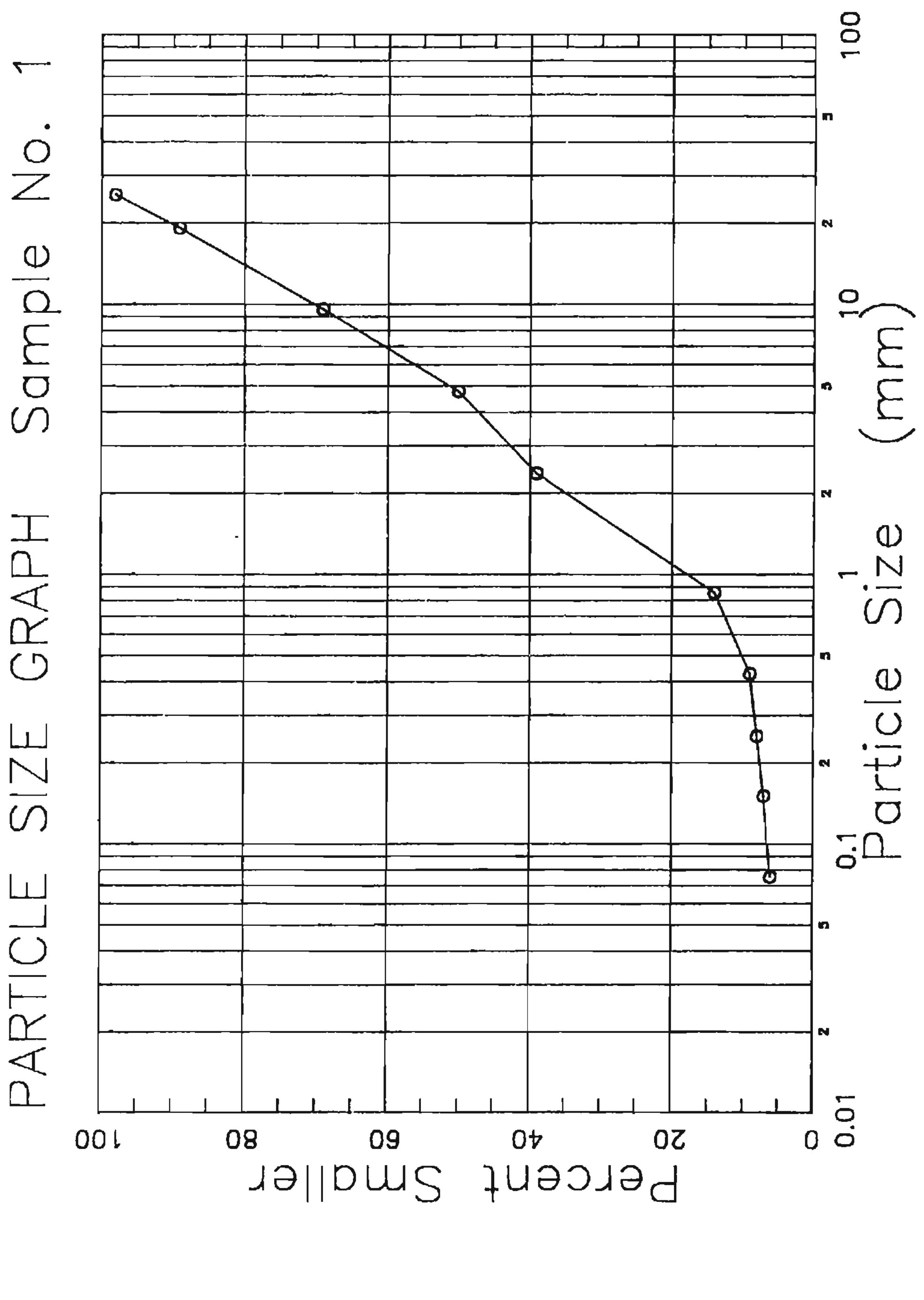
APPENDIX A

GRADATION CURVES OF SOIL SAMPLES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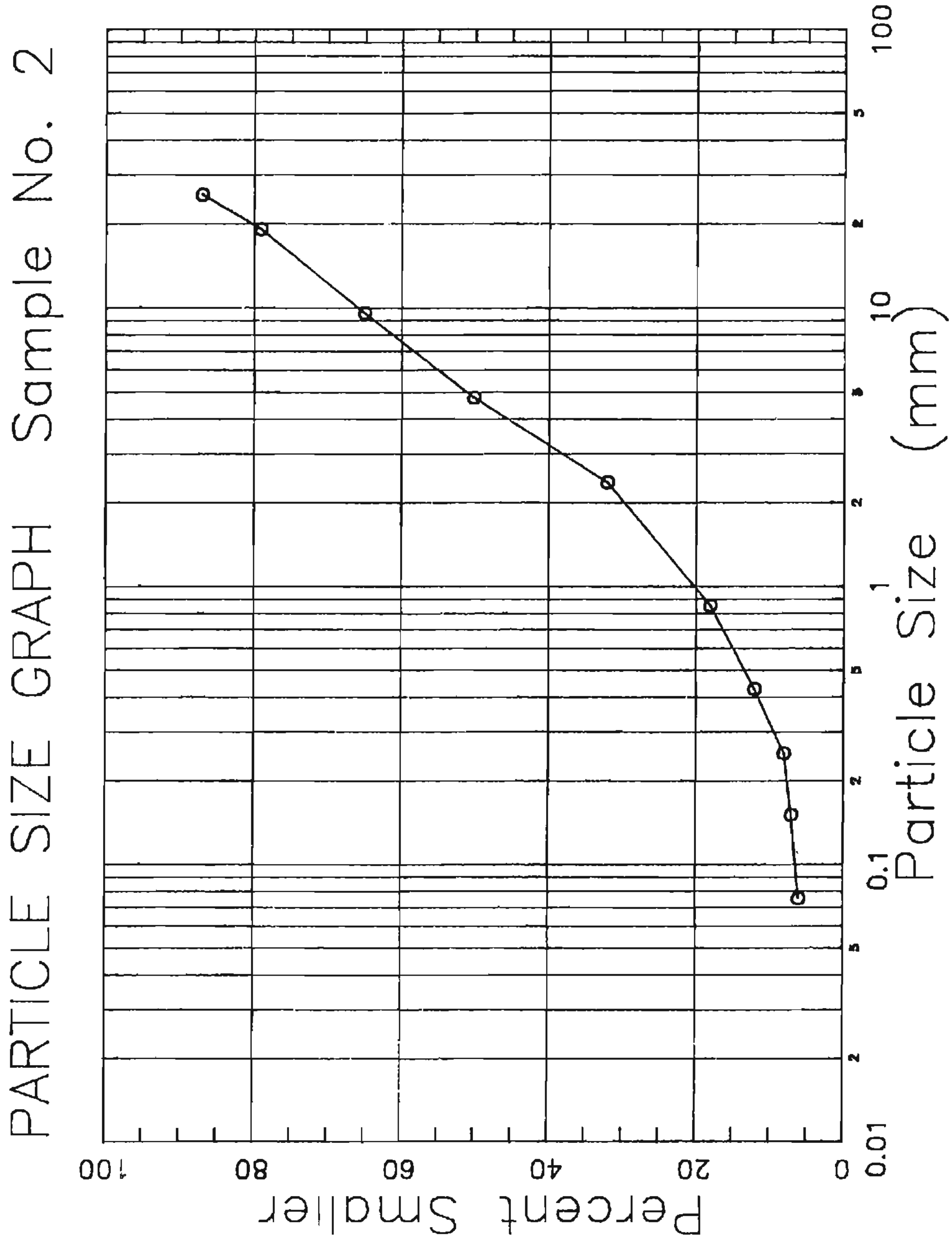
60
40
20
0
0.01
0.1
1
10
100
Particle Size (mm)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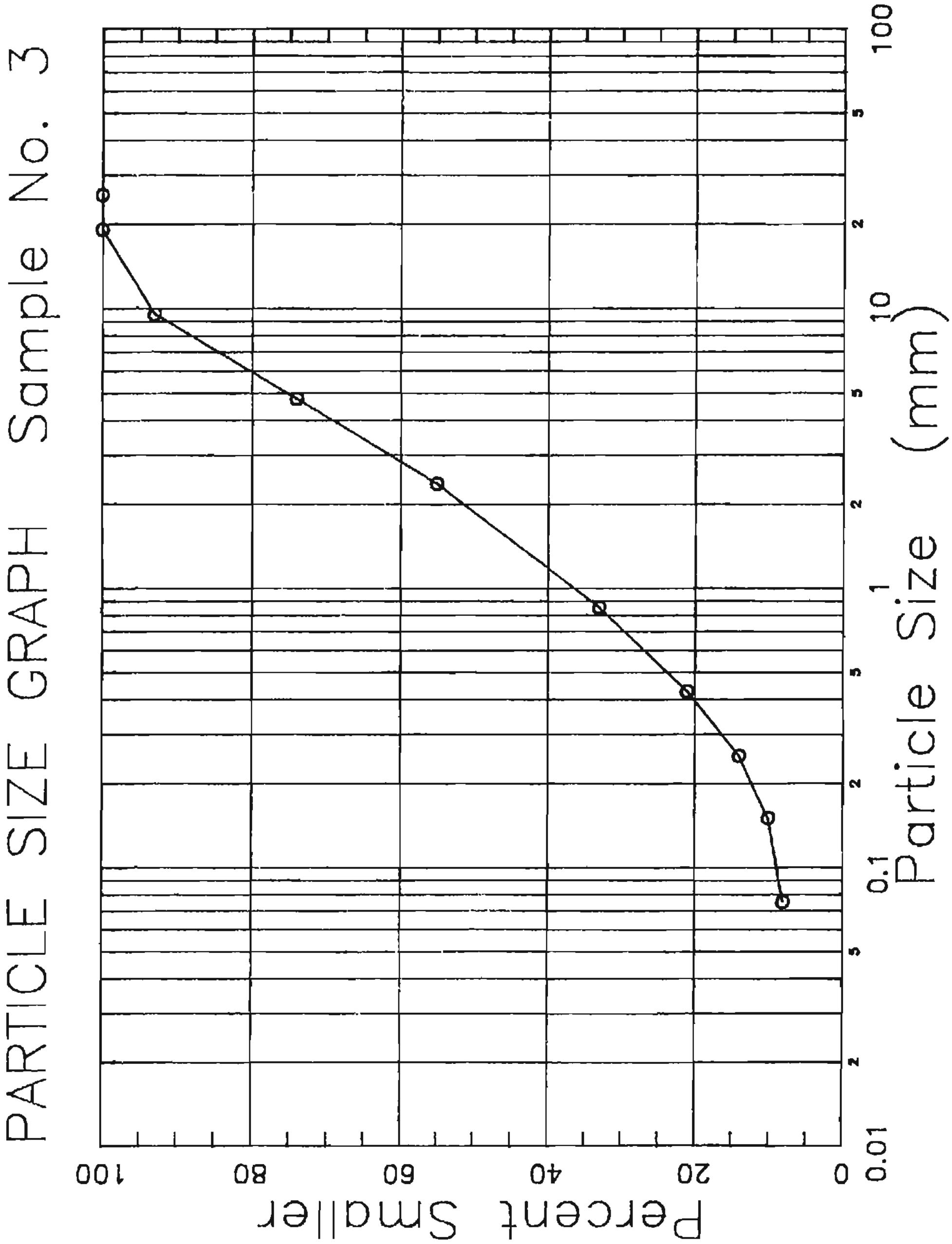
40
60
80
100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60
80
100
Particle Size (mm)
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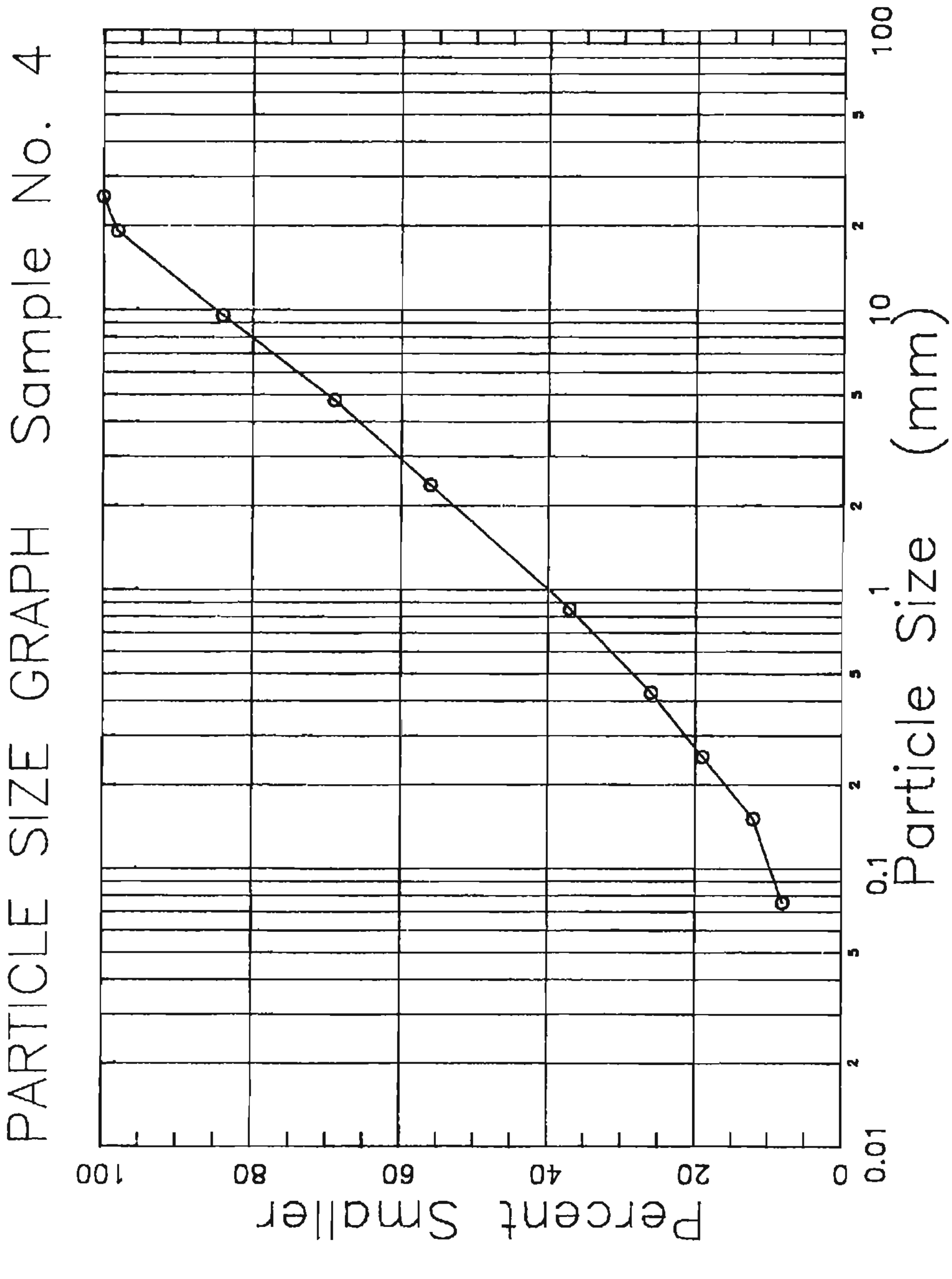
1
10
100
2
5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Percent Smaller
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0.01
2
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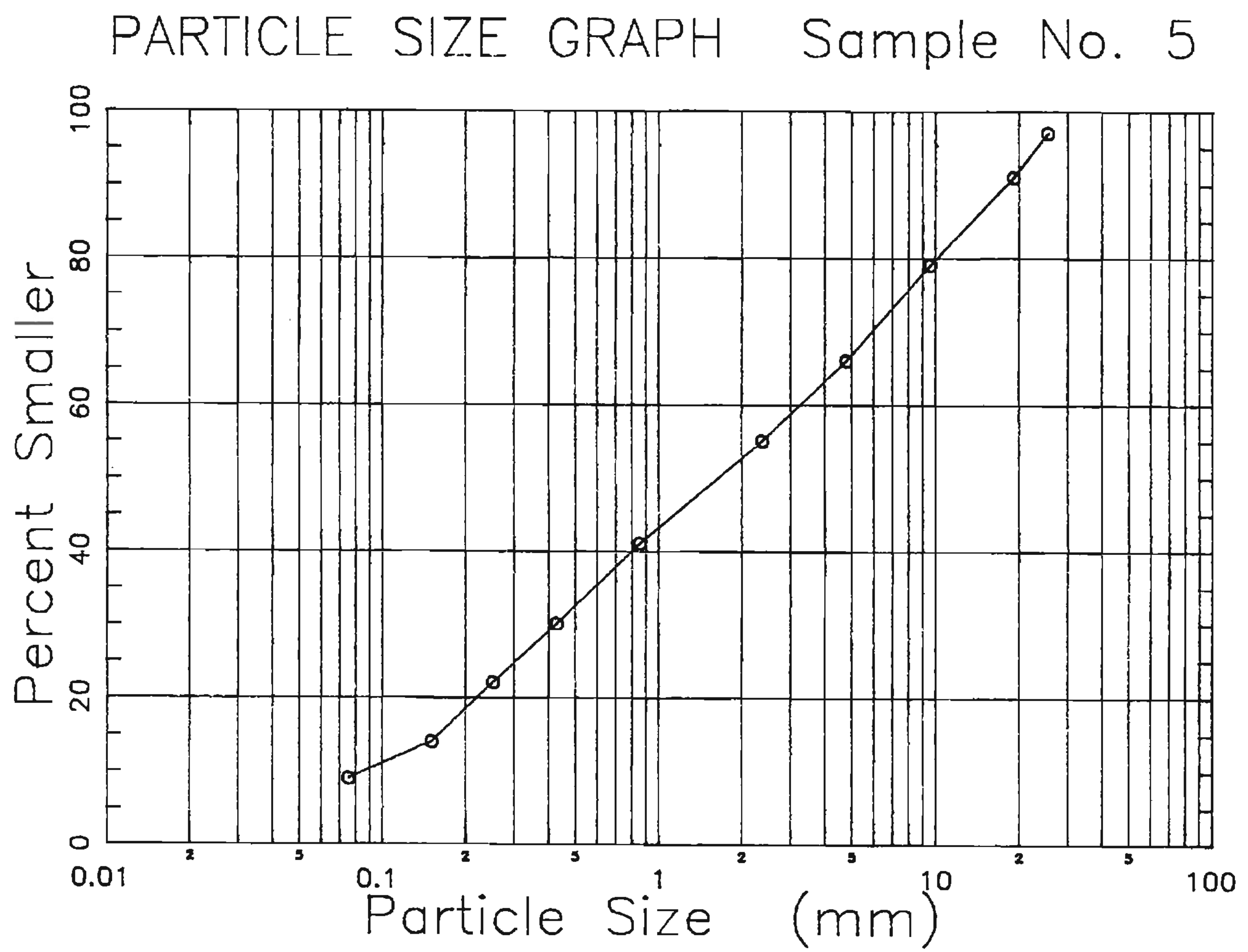
2
5
1
2
5
10
2
5
100
Particle Size (mm)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60
40
20
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Particle Size (mm)
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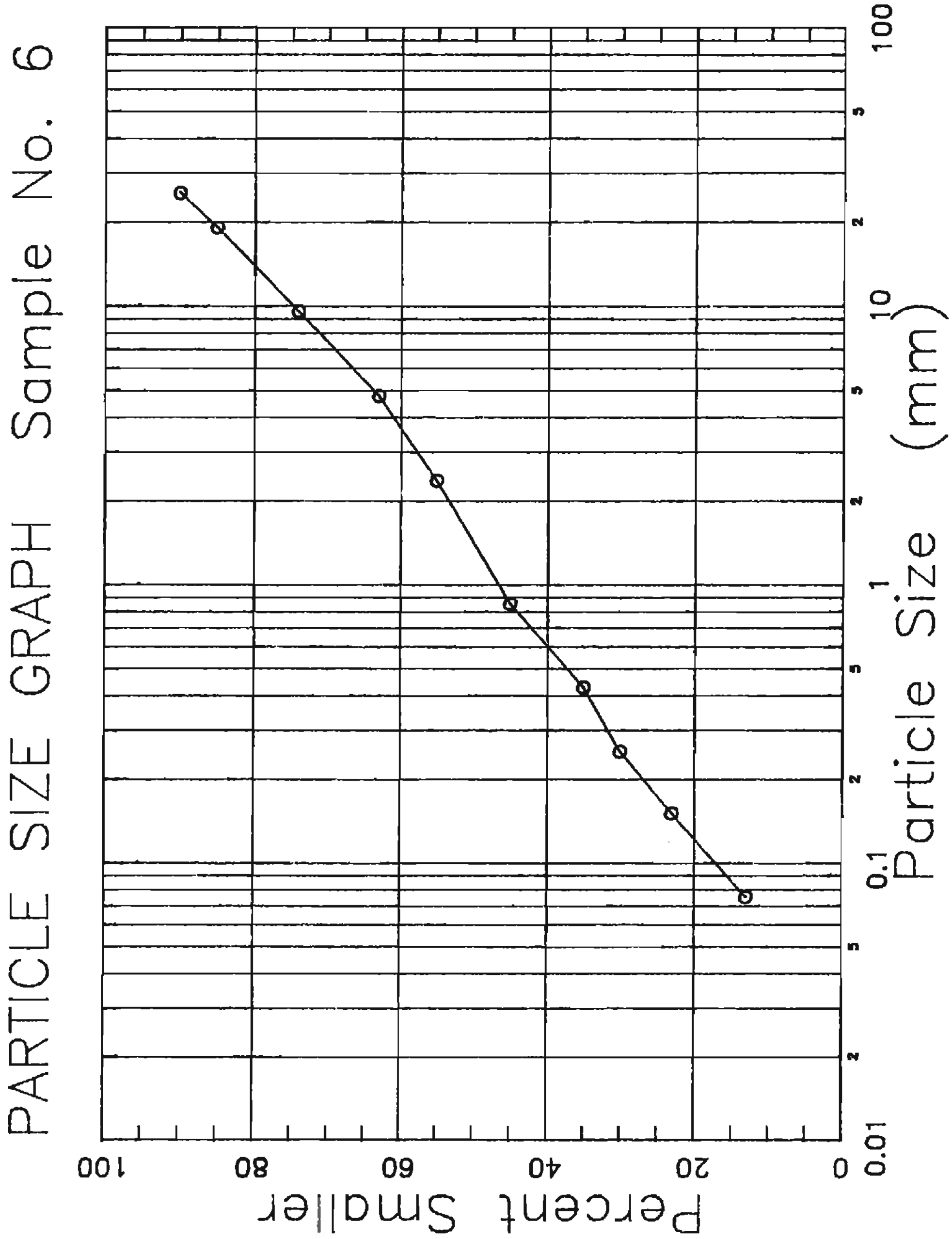
0.1
1
10
100


PARTICLE SIZE GRAPH Sample No. 6
Percent Smaller
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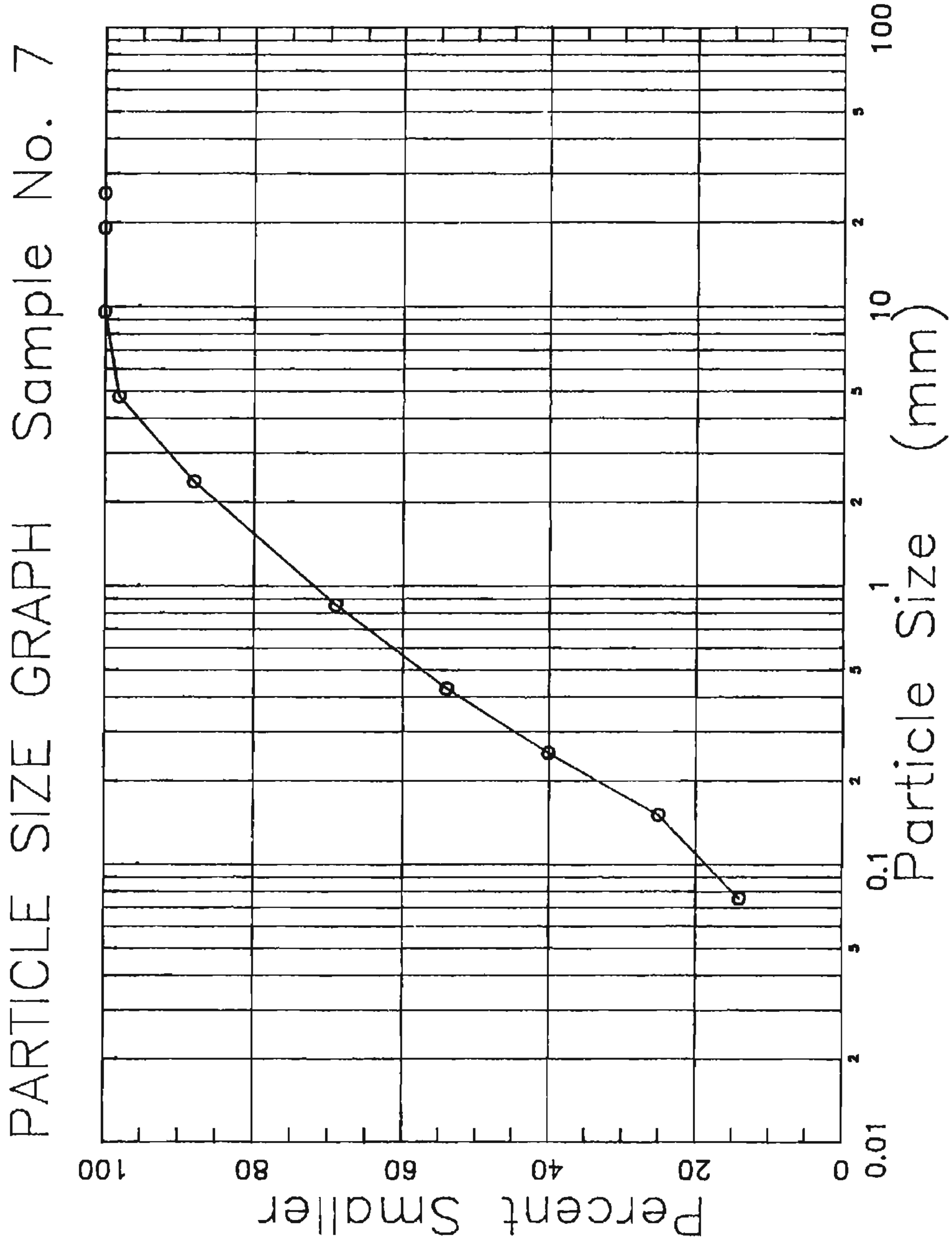
60
40
20
0
0.01
0.1
1
10
100
Particle Size (mm)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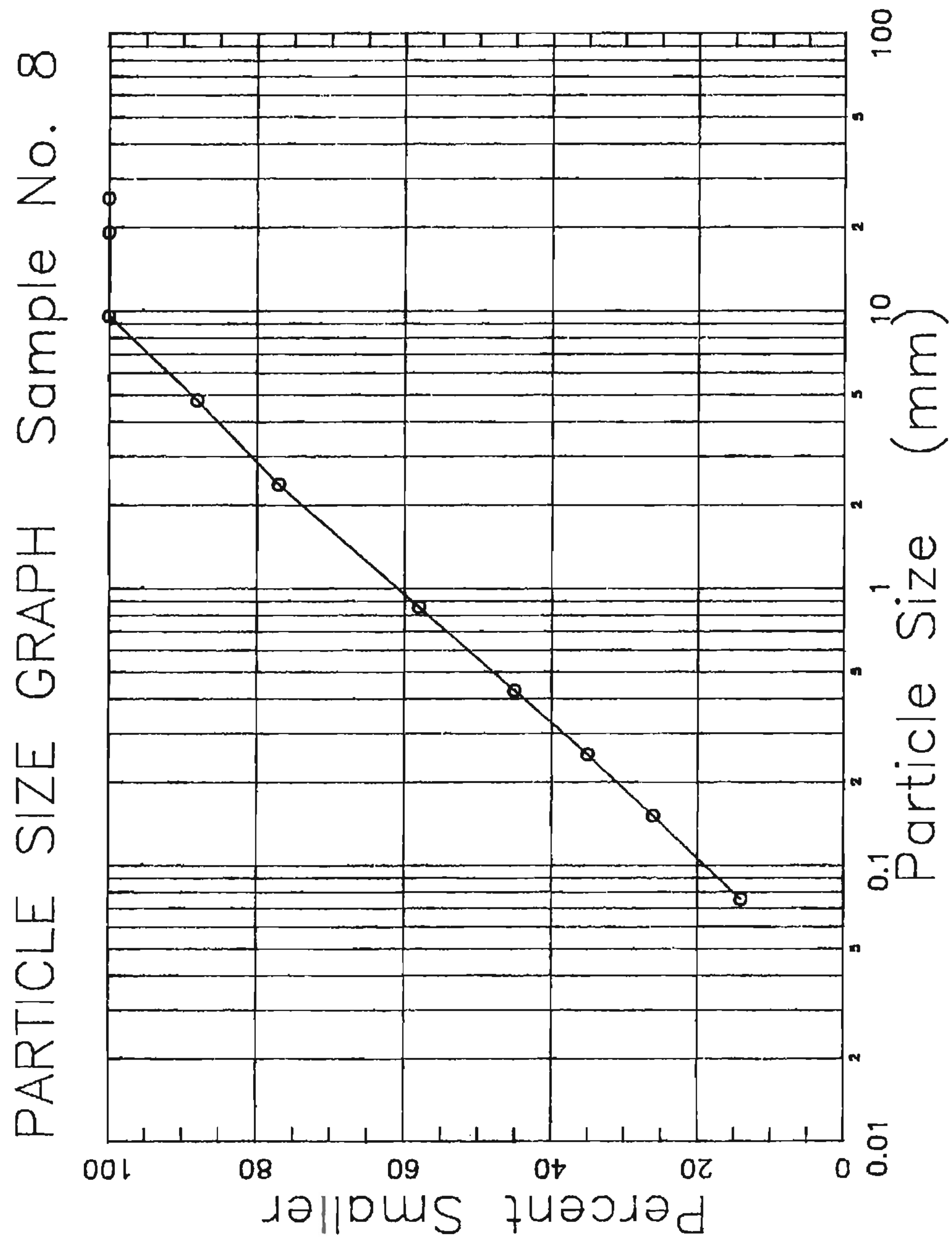
10
100
0
20
40
60
80
100


PARTICLE SIZE GRAPH Sample No. 8
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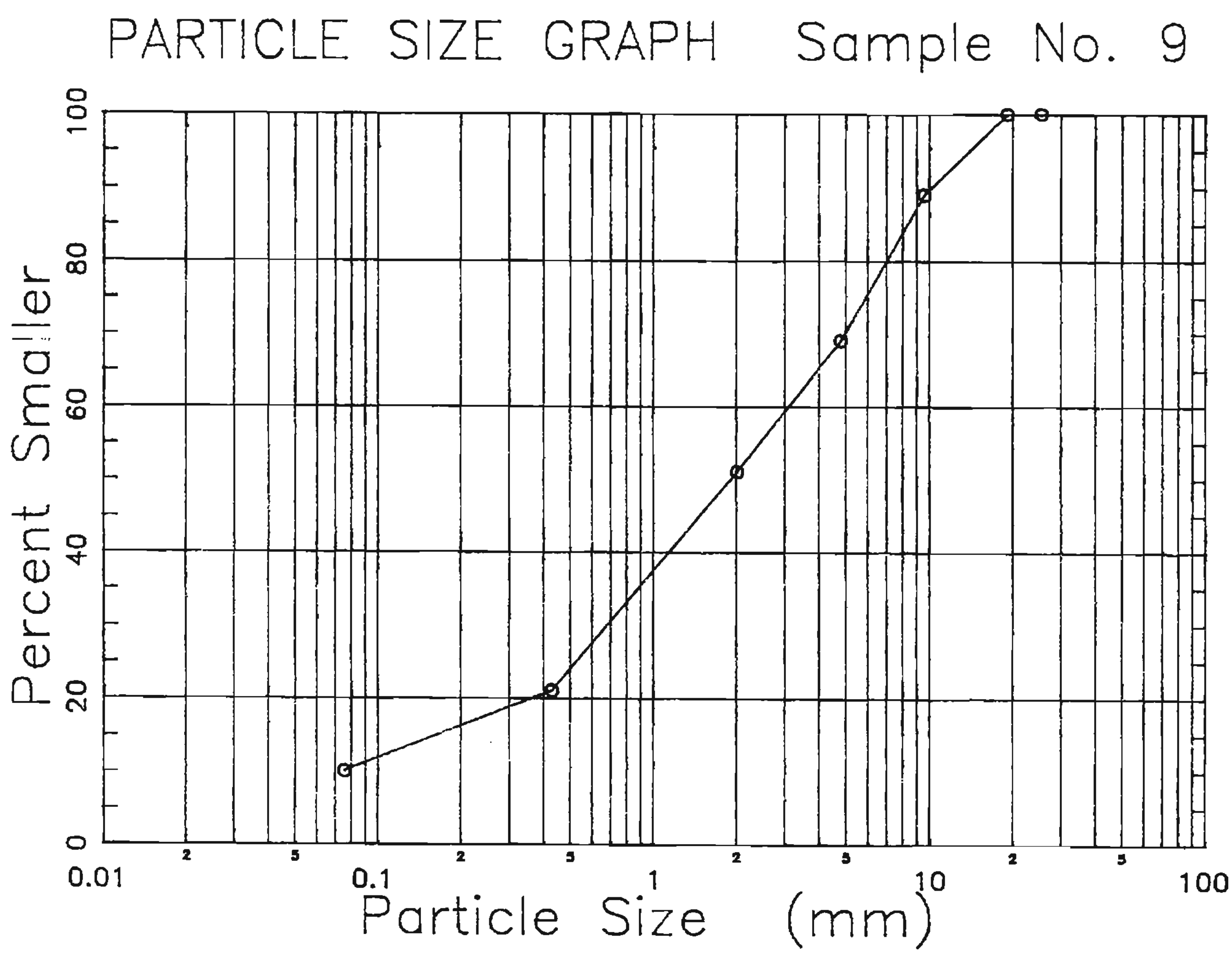
1
10
100
Particle Size (mm)



PARTICLE SIZE GRAPH Sample No. 9
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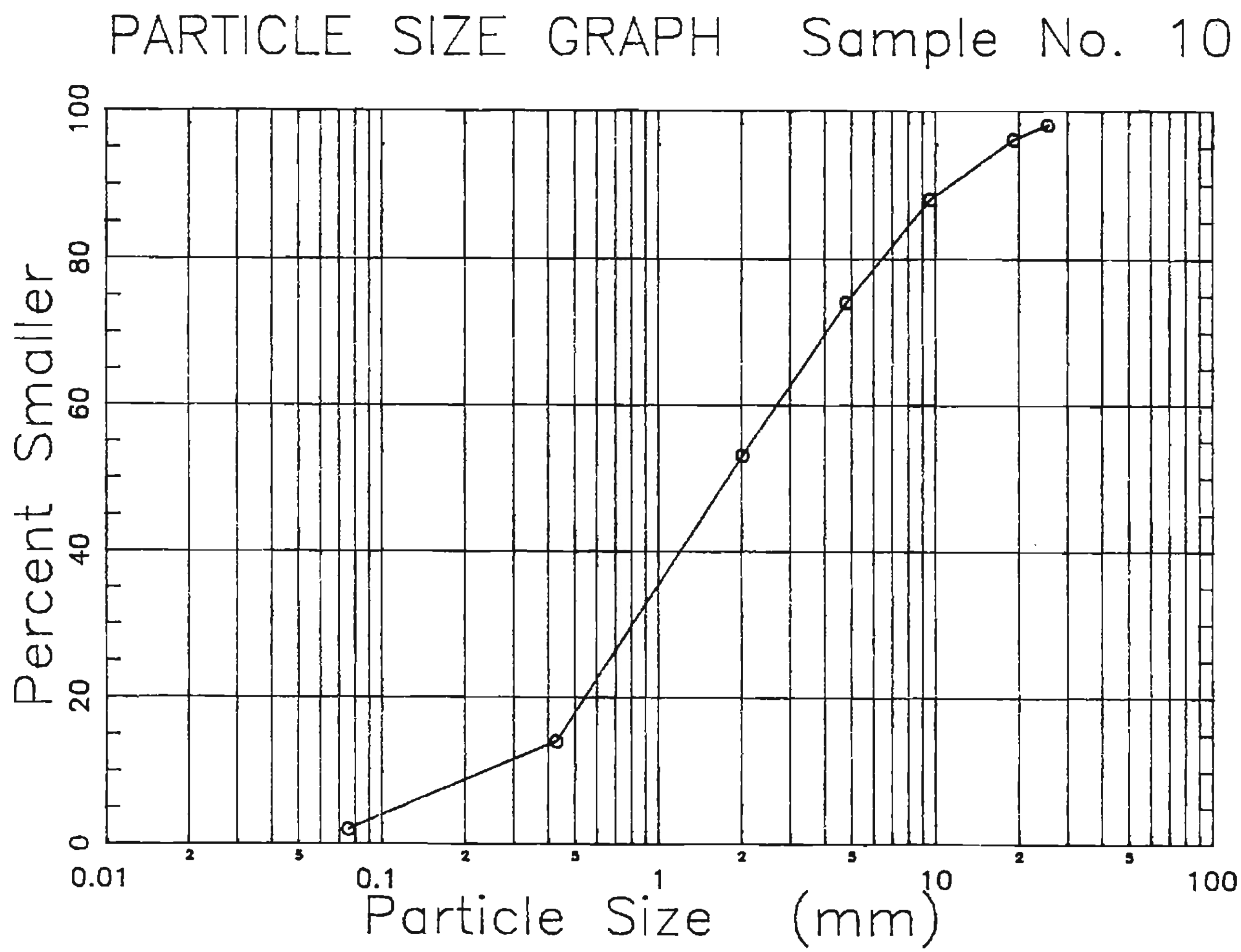
0.1
1
10
100
Particle Size (mm)


PARTICLE SIZE GRAPH Sample No. 10
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100
0.01
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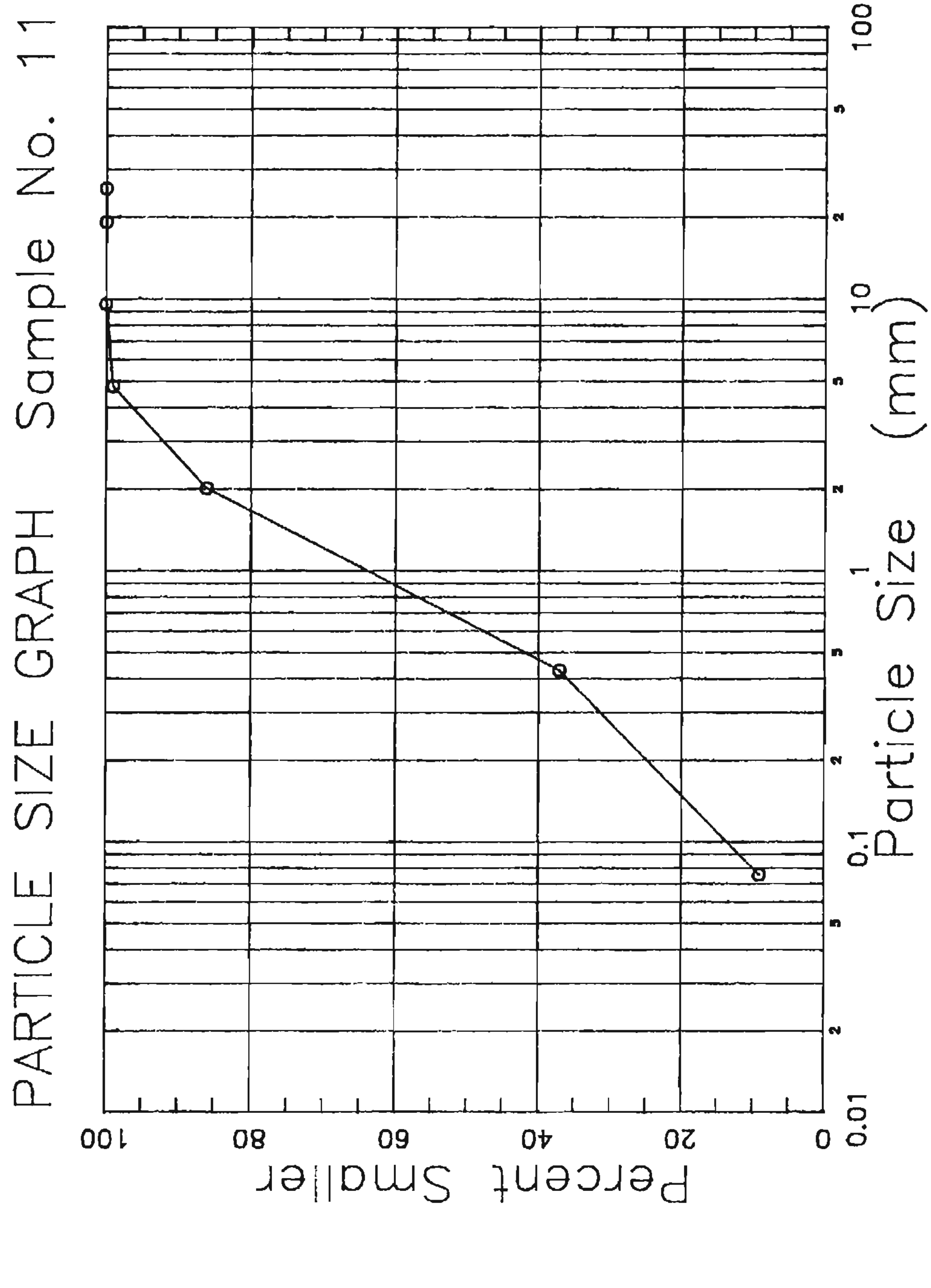
1
10
100
Particle Size (mm)



PARTICLE SIZE GRAPH Sample No. 11
Percent Smaller
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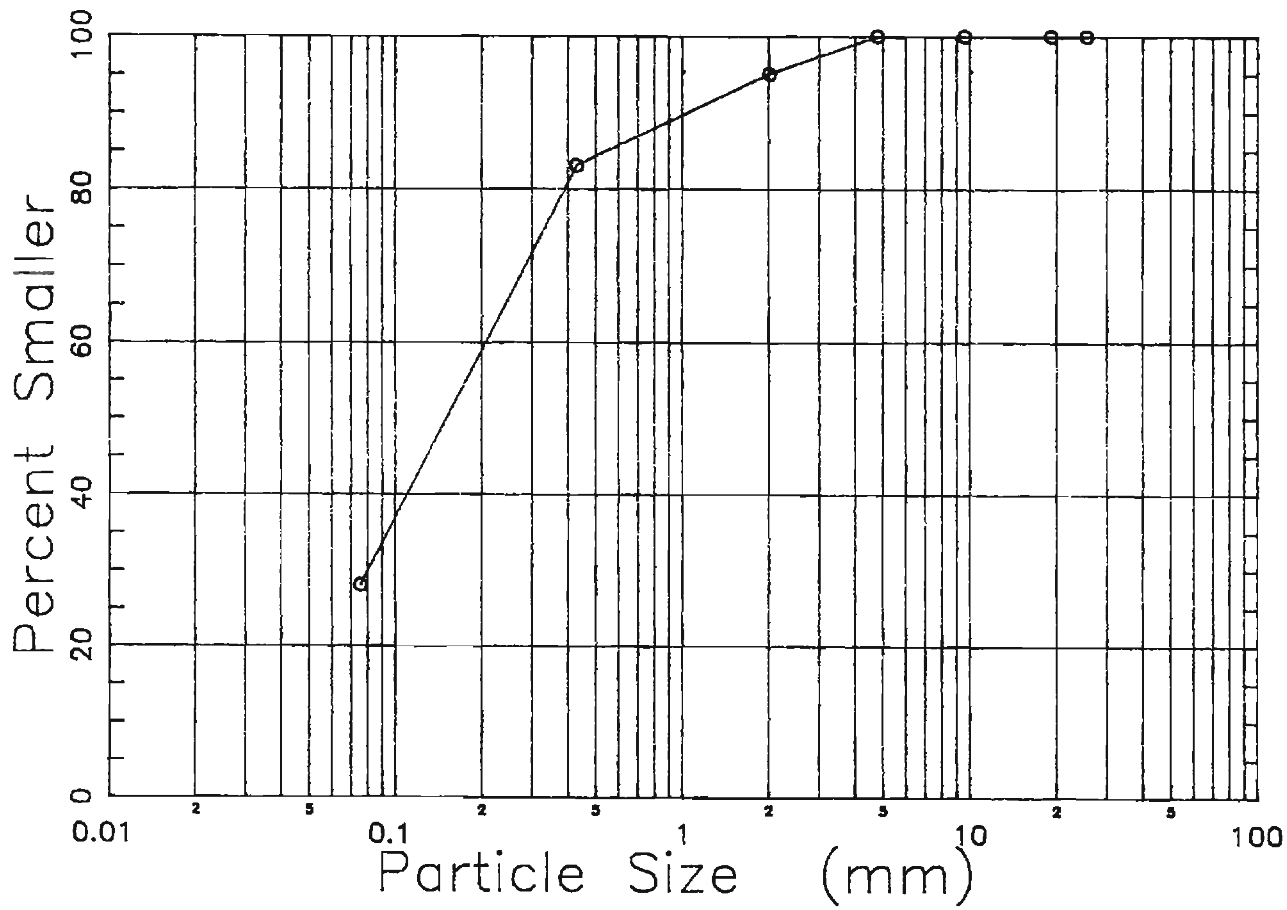
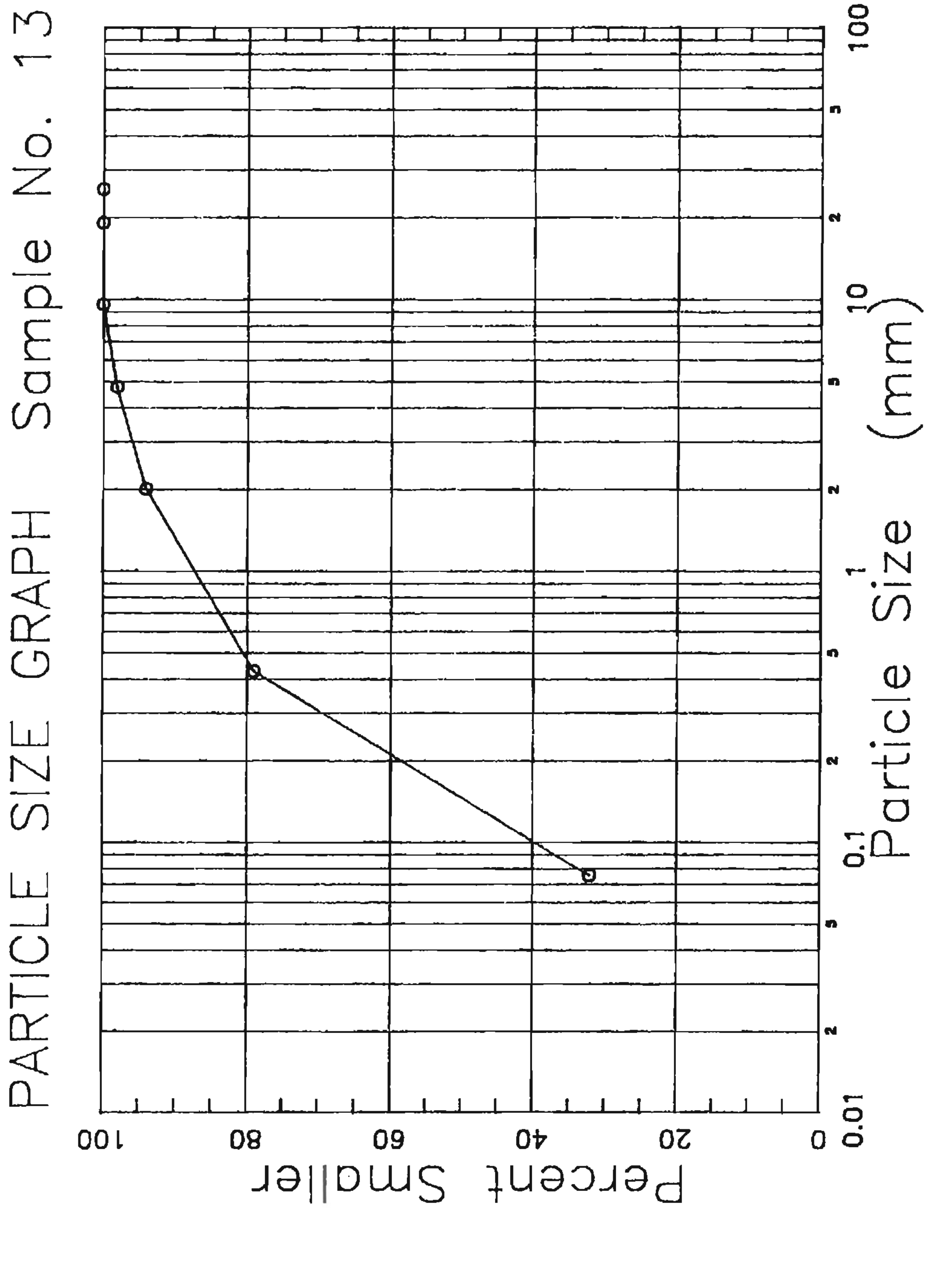
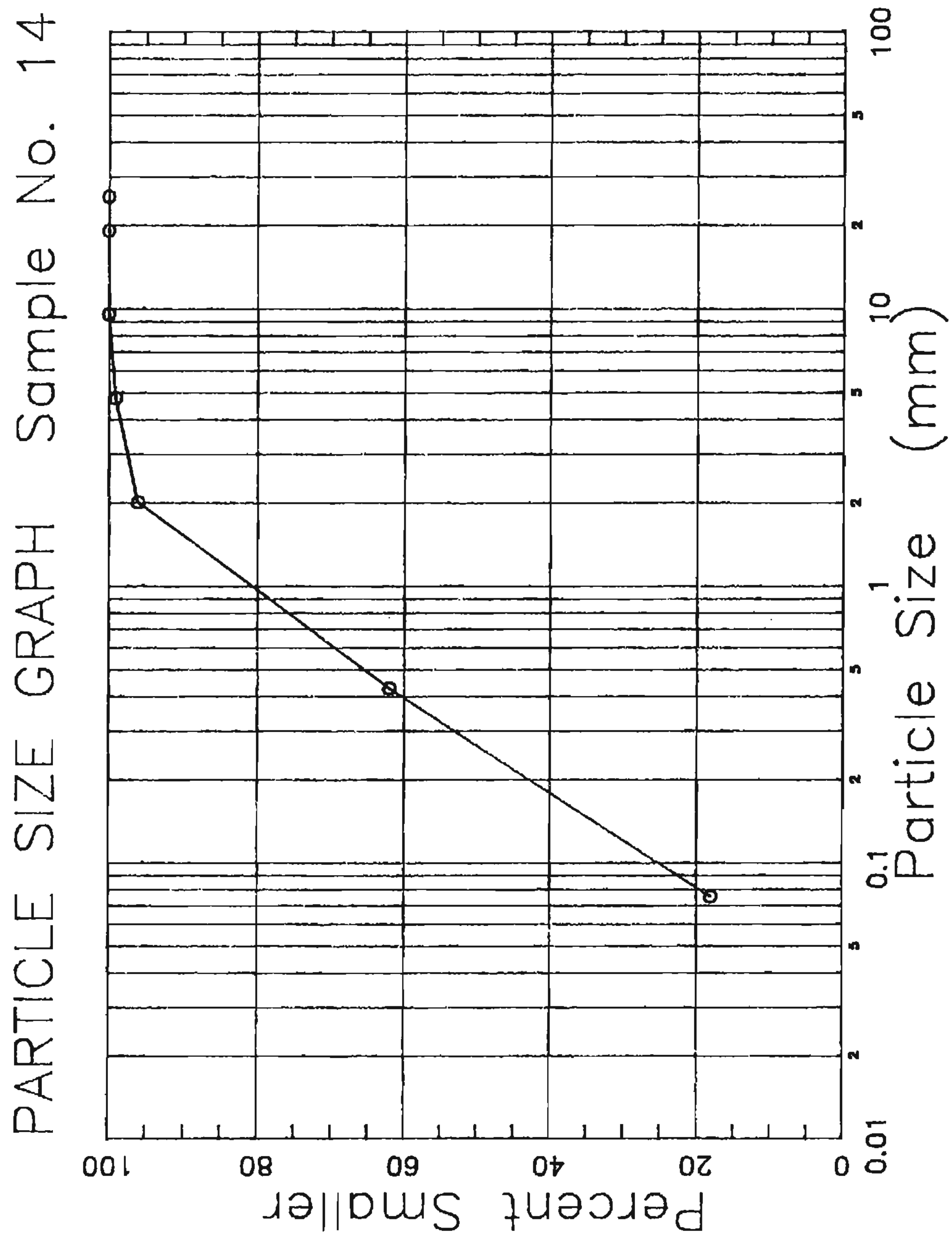
60
40
20
0
0.01
0.1
1
10
100
Particle Size (mm)

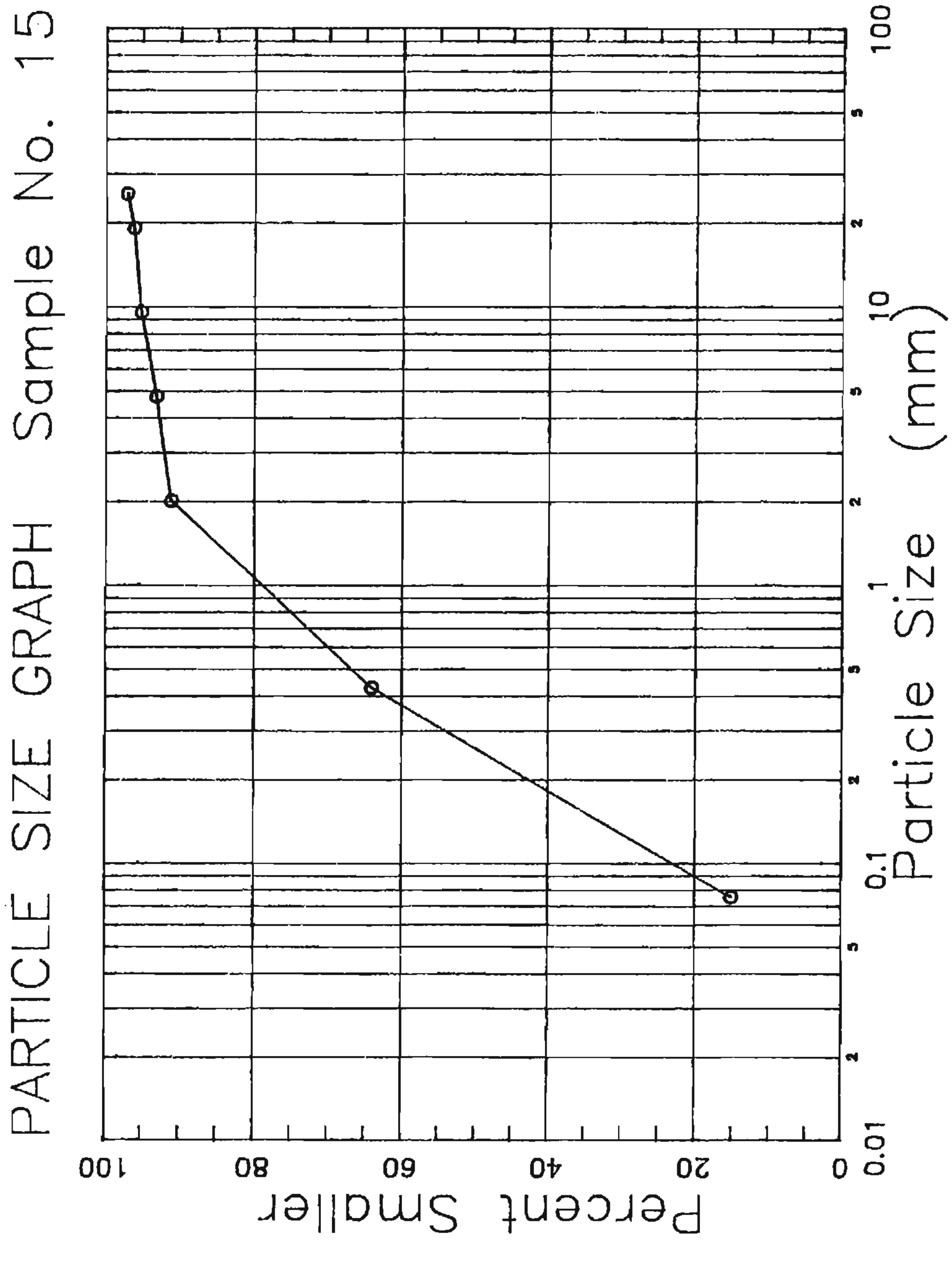
PARTICLE SIZE GRAPH Sample No. 12

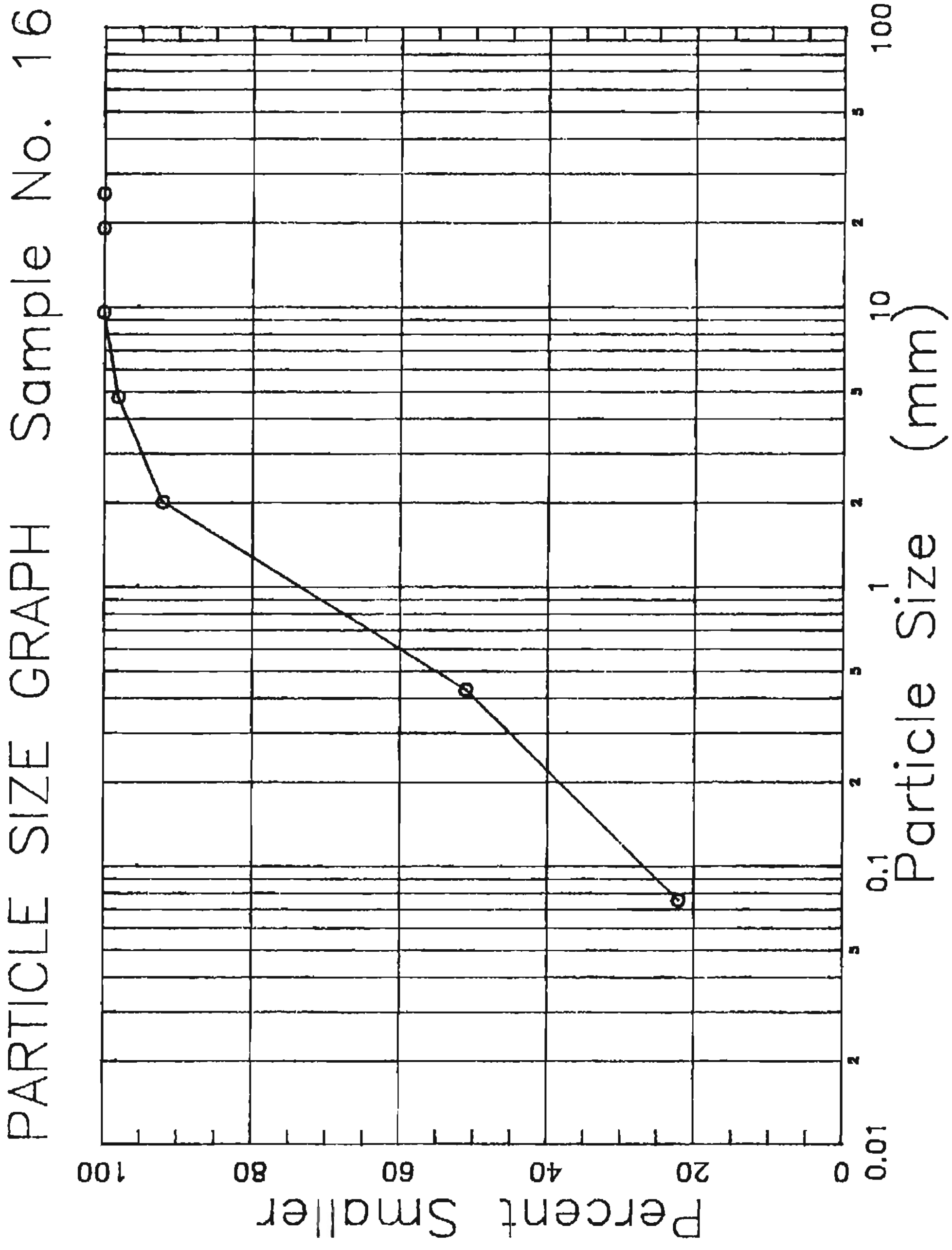


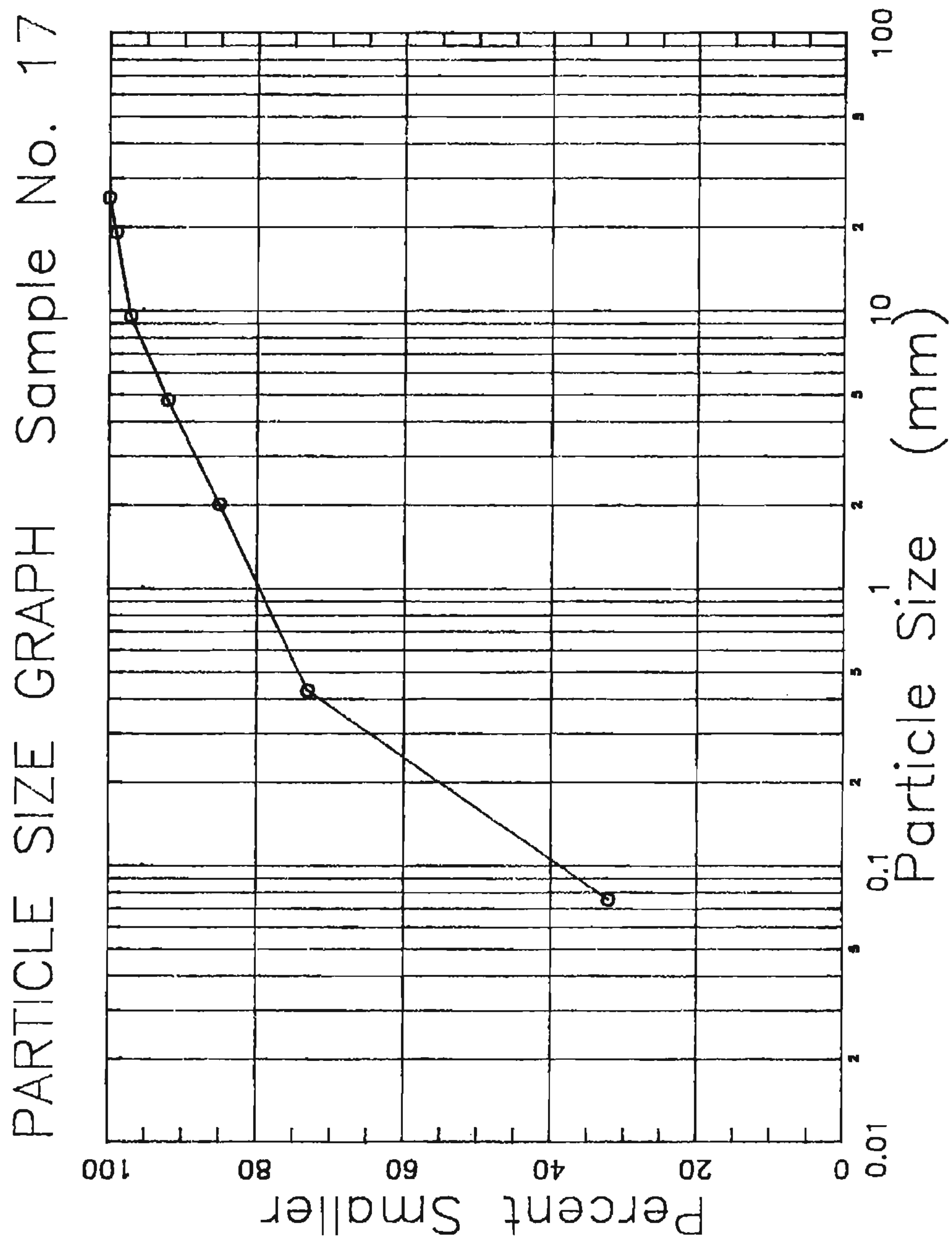


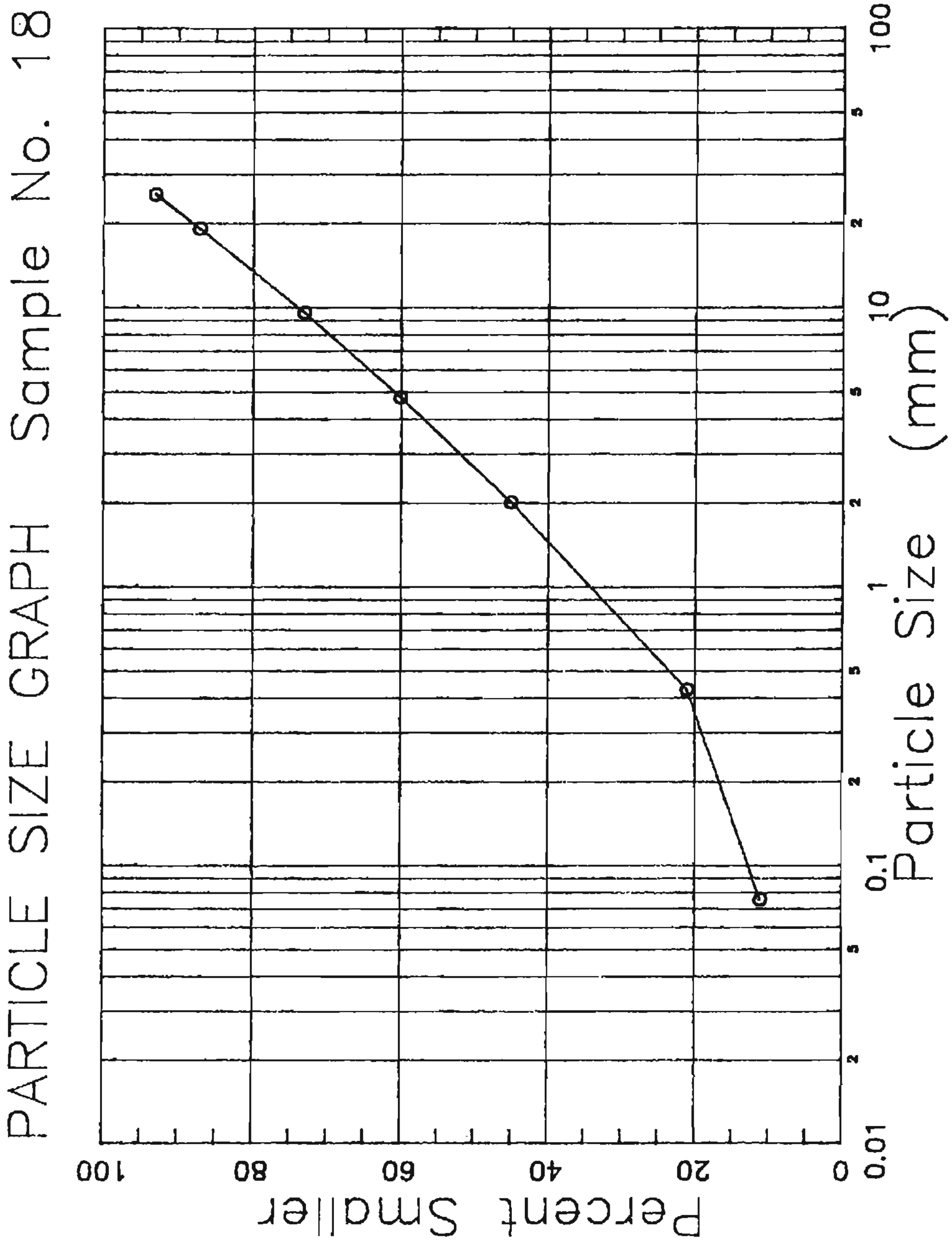
PARTICLE SIZE GRAPH Sample No. 13
Particle Size (mm)
Percent Smaller
0.01
0.1
1
10
100
0
20
40
60
80
100

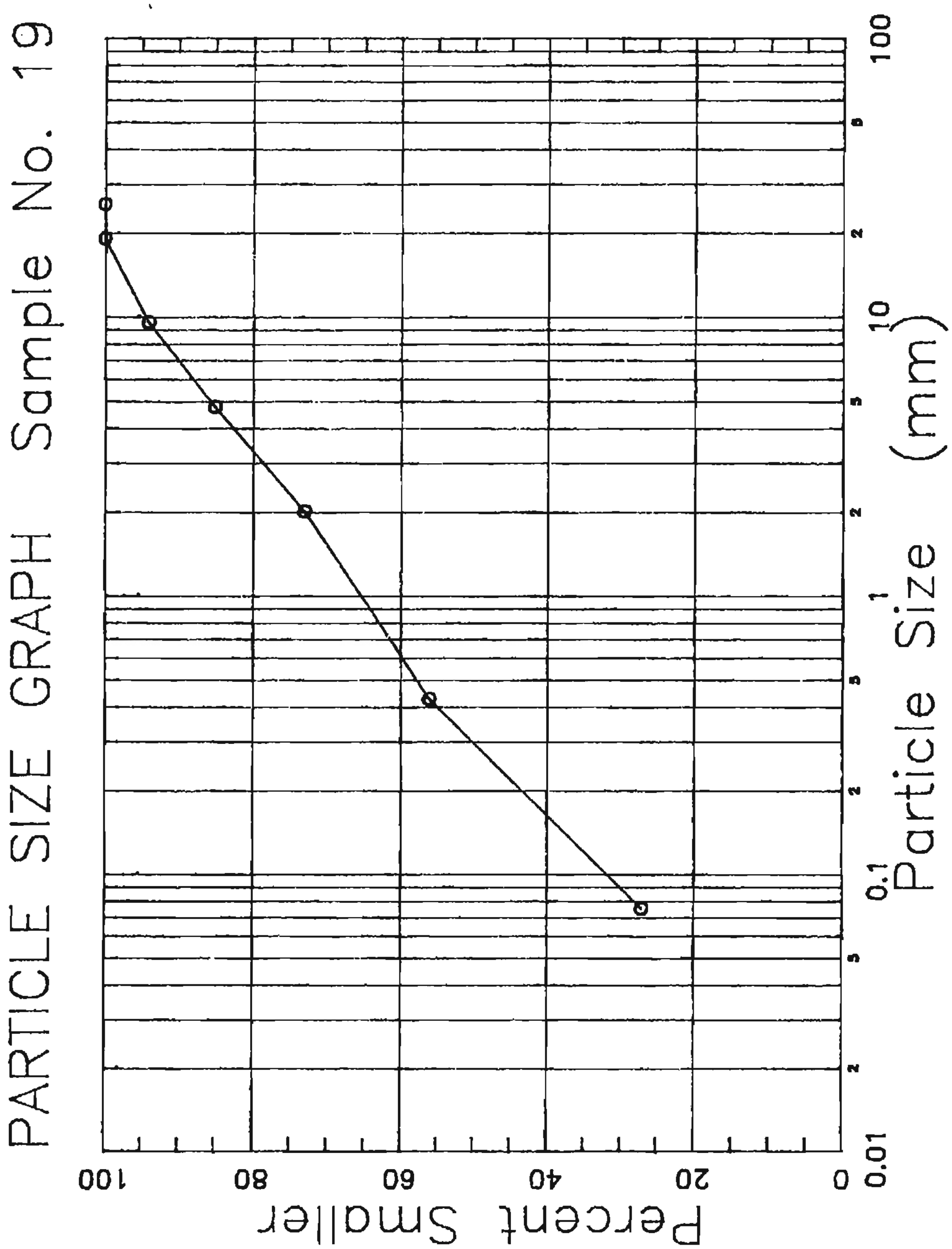

PARTICLE SIZE GRAPH Sample No. 14
Percent Smaller
0
20
40
60
80
100
Particle Size (mm)
0.01
2
5
0.1
2
5
1
2
5
10
2
5
100

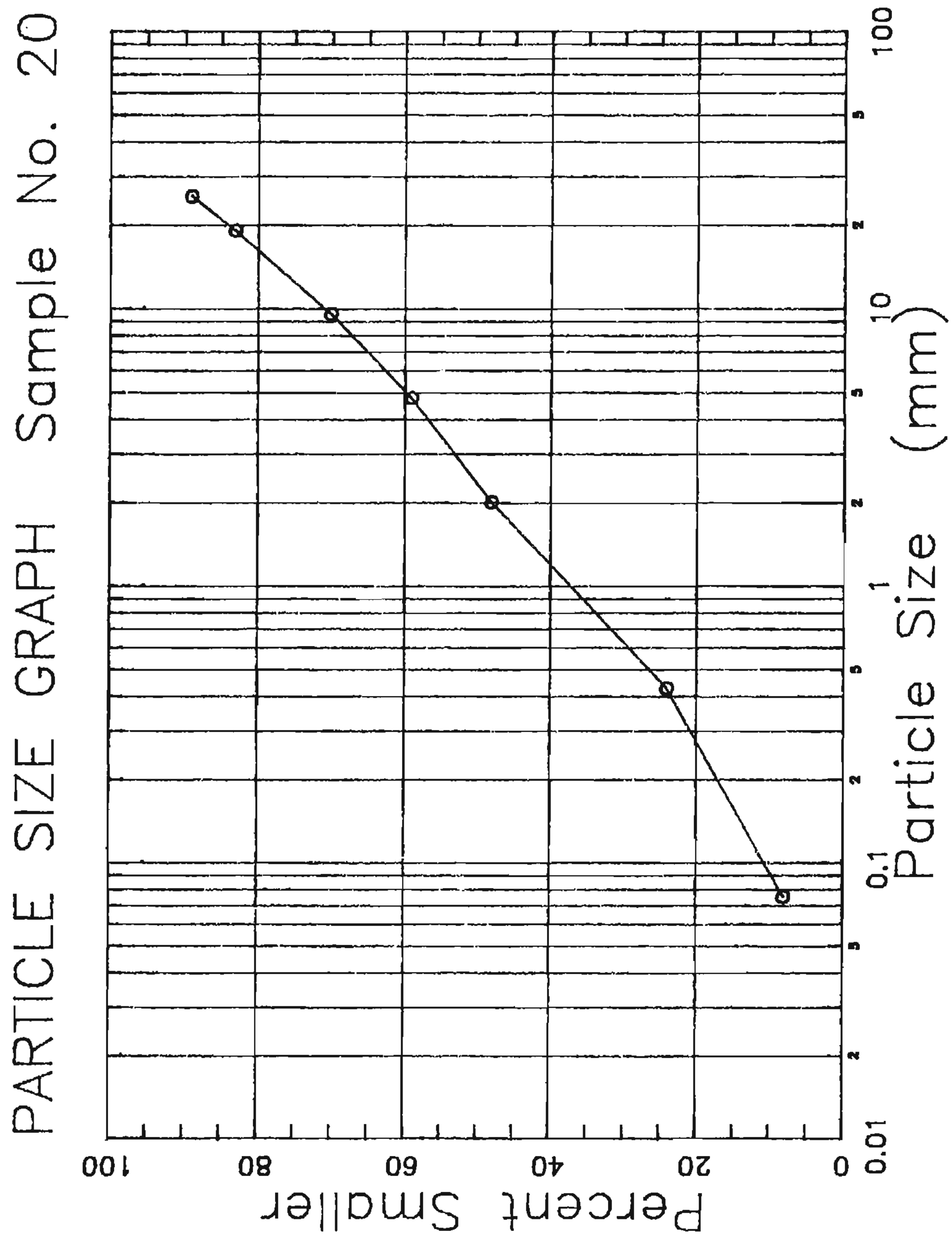

PARTICLE SIZE GRAPH Sample No. 15
Percent Smaller
100
80
60
40
20
0
Particle Size (mm)
0.01
0.1
1
10
100


PARTICLE SIZE GRAPH Sample No. 16
Percent Smaller
100
80
60
40
20
0
0.01
0.1
1
10
100
Particle Size (mm)


PARTICLE SIZE GRAPH Sample No. 17
Percent Smaller
100
80
60
40
20
0
0.01
0.1
1
10
100
Particle Size (mm)


PARTICLE SIZE GRAPH
Sample No. 18
Percent Smaller
100
80
60
40
20
0
Particle Size (mm)
0.01
0.1
1
10
100


PARTICLE SIZE GRAPH Sample No. 19
Percent Smaller
100
80
60
40
20
0
0.01
0.1
1
10
100
Particle Size (mm)


PARTICLE SIZE GRAPH Sample No. 20
Particle Size (mm)
Percent Smaller
0.01
0.1
1
10
100
0
20
40
60
80
100

APPENDIX B

SAMPLE PREPARATION PROCEDURES

B.1 Preparing Soil

1. Mix sieved soils with different particle sizes in designed amounts to obtain a designated gradation curve.

2. Prepare a soil mass not less than 30 pounds (13.6 kg), W_1, for a 6-inch diameter specimen, and determine its moisture content, ω_1.

3. Determine the weight of water, W_w, required to reach the optimum moisture content, ω_{opt}.

$$W_w = \frac{\omega_{opt} - \omega_1}{1 + \omega_1} \cdot W_1 . \tag{1}$$

4. Add the water W_w to the soil mass in small amounts and mix thoroughly after each addition.

5. Place the mixture in Ziploc plastic bags. Seal the bags and store them in a humidity room for 24 hours.

B.2 Initial Measurements

1. Carefully check the pressure system, triaxial cell, and rubber membrane under pressure for any possible leakage.

2. Measure the thickness of rubber membrane. Take four measurements, two at the top and two at the bottom. Take an average for double thickness, d_m.

3. Obtain two dry porous stones and two filter paper discs. The filter paper should not be larger than the porous stone.

4. Place two porous stones, two filter papers and loading cap on base pedestal. Measure the height of the stack at three different locations. Take an average as an initial height, h_i, without specimen.

5. Remove the loading cap, filter papers and porous stones.

B.3 Weighing Soil for Specimen

1. Obtain the soil prepared in Step B.1, and check the moisture content which should maintain at ω_{opt}. Adjust moisture content to ω_{opt} if it is necessary.

2. Measure the inner diameter of split compaction mold. The expected diameter of specimen, D_0, is subtracting the double thickness of membrane, d_m, determined in Step B.2.2 from this

measurement.

3. Measure the total height of mold sitting on triaxial cell base. The expected height of specimen, h_0, is subtracting the initial height, h_i, determined in Step B.2.4 from this measurement. The h_0 should be at least two times D.

4. Determine the expected volume of compacted specimen, V_0, to be prepared.

$$V_0 = \frac{1}{4} \cdot \pi \cdot D_0^2 \cdot h_0 . \tag{2}$$

5. Determine the total weight of the soil, W_t, to be compacted.

$$W_t = (1 + \omega_{opt}) \cdot \gamma_d \cdot V_0 , \tag{3}$$

where γ_d is the maximum dry density.

6. Specimen is to be compacted in eight layers. Divide the soil mass into eight equal portions. Seal each portion of soil in a Ziploc bag.

B.4 Mounting Split Compaction Mold

1. Apply a thin layer of grease sealant around the side of base pedestal.

2. Place a porous stone and a filter paper on the base pedestal.

3. Place the bottom of rubber membrane over the base pedestal, and smooth it around the side of base pedestal.

4. Fix the rubber membrane in place with three O-rings.

5. Apply a thin layer of grease sealant to the splitting surfaces of mold.

6. Tighten the split mold on base pedestal, and draw the rubber membrane up through the mold.

7. stretch the top of rubber membrane over the rim of mold.

8. Apply a vacuum of 10 psi (68.95 kPa) to the inside of mold, and remove membrane wrinkles.

9. Measure the distance from the bottom filter paper to the rim of mold.

B.5 Compacting Specimen

1. Carefully place a bag of soil prepared in Step B.3.6 in the mold, and level the surface of soil.

2. Compact the soil in the mold with a Proctor hammer until the thickness of the first layer is slightly over 1/8 of h_0 determined in Step B.3.3. The thickness of each layer compacted should be progressively smaller than the previous layer so that the compaction effort would be more uniform throughout the specimen. Thus, the thickness of each layer varies from slightly over $h_0/8$ for the first layer to $h_0/8$ for the top layer.

3. Scarify the surface of the compacted layer.

4. Carefully place the next bag of soil in the mold, and repeat Steps B.5.2 and B.5.3 for each new lift.

5. Level and smooth the final surface.

B.6 Removing Mold

1. Place a filter paper and a porous stone on the top of compacted specimen.

2. Apply a thin layer of grease sealant around the side of loading cap, and place it on top of the porous stone.

3. Check the level of the loading cap in two opposite directions. The maximum allowable tilt is 0.2% of D.

4. Carefully unfold the top of rubber membrane, and smooth it around the side of loading cap.

5. Fix the rubber membrane in place with three O-rings which already hung on the pressure line connecting to the loading cap.

6. With vacuum still in the mold, apply a vacuum of 5 psi (34.48 kPa) to the top of specimen.

7. Release the vacuum from the mold .

8. Carefully open and remove the split mold, and check the specimen for any irregularity on the surface.

B.7 Final Measurements

1. Measure the sample diameter including rubber membrane at

three different heights. Take an average as a final diameter, D_f. The actual diameter of specimen, D, is subtracting the double thickness of membrane, d_m, determined in Step B.2.2 from D_f.

2. Measure the total height to the top of loading cap at three different locations. Take an average as a final height, h_f, with specimen. The actual height of specimen, h, is subtracting the initial height, h_i, determined in Step B.2.4 from h_f.

3. Determine the actual volume of specimen, V,

$$V = \frac{1}{4} \cdot \pi \cdot D^2 \cdot h. \tag{4}$$

4. Determine the unit weight of specimen, γ_t,

$$\gamma_t = \frac{W_t}{V}, \tag{5}$$

   where W_t is total weight of soil determined in Step B.3.5.

5. Check any leakage around rubber membrane and fittings by spreading some water on them. If necessary, carefully install a second rubber membrane or reinstall fitting to stop leakage.

B.8 Mounting Triaxial Chamber

1. Clean the contact surface of triaxial cell base, and apply a thin layer of grease sealant.

2. Apply a thin layer of grease to the large O-ring, and place it on the triaxial cell base.

3. Assure the loading ram is fully lifted and locked in place.

4. Clean the bottom surface of the triaxial chamber, and apply a thin layer of grease sealant.

5. Open the valve at the top of chamber to the air.

6. Carefully place the chamber on the cell base, and lock it in place by a rim locking band.

7. Gently lower the loading ram to check if the specimen is properly centered. Then, raise and lock the loading ram back in place.

B.9 Applying Confining Pressure

1. With the chamber top valve open, fill the chamber with water, and leave about 0.5 inches short from the chamber top for an air pocket.

2. Turn off the water, disconnect the water supply line from the cell, and then close the chamber top valve.

3. With the pressure valves at the cell base closed, connect an empty confining pressure line at atmospheric pressure to the chamber top valve, and an empty drainage line at atmospheric pressure to the bottom of specimen.

4. Slowly release the vacuum from the specimen, and gradually raise the confining pressure to 5 psi (34.48 kPa) by slowly opening the chamber top valve.

5. Connect the transducer to the triaxial cell base.

6. Calibrate the transducer.

7. The specimen is ready for resilient modulus test after cured over night.

APPENDIX C

TEST PROCEDURES

C.1 Testing Setup

1. Turn on the material testing system MTS-810 and the hydraulic pressure system.

2. Setup the MicroConsole and data recording system as required.

3. With the drainage valve at the bottom of specimen closed and the confining pressure valve open, carefully place the triaxial cell on the platform of the loading machine.

4. Center the triaxial cell, and raise loading piston to couple the loading ram of triaxial cell with load cell. The testing setup at this step is shown in Figure C.1.

5. Apply an axial load about 5 psi (34.48 kPa) which slightly over compensates the chamber pressure to lower the loading ram slowly until it contacts the loading cap.

6. Open the drainage valve to dissipate the excess pore water pressure caused by possible disturbance in the Steps C.1.3 through C.1.5.

C.2 Conditioning

1. Set the confining pressure to 5 psi (34.48 kPa) and apply 200 repetitions of an axial deviator stress of 5 psi (34.48 kPa). Then, apply 200 repetitions of an axial deviator stress at 10 psi (68.95 kPa).

2. Set the confining pressure to 10 psi (68.95 kPa) and apply 200 repetitions of an axial deviator stress of 10 psi (68.95 kPa). Then, apply 200 repetitions of an axial deviator stress at 15 psi (103.43 kPa).

3. Set the confining pressure to 15 psi (103.43 kPa) and apply 200 repetitions of an axial deviator stress of 15 psi (103.43 kPa). Then, apply 200 repetitions of an axial deviator stress at 20 psi (137.90 kPa).

4. With the drainage valve open, let the specimen sit for a few minutes to fully dissipate any possible excess pore water pressure.

C.3 Recorded Resilient Modulus Test

1. Rebalancing the measuring devices and recording system.

2. Begin the recorded testing by increasing the confining pressure to 20 psi (137.90 kPa).

Figure C.1 Triaxial cell is on the loading machine and coupled with load cell ready for test.

3. Apply 200 repetitions of a deviator stress of 1 psi (6.895 kPa) and record the vertical recovered deformations for the 200th repetition.

4. Repeat Step C.3.3 for deviator stress levels of 2, 5, 10, 15, and 20 psi (13.79, 34.48, 68.95, 103.43, and 137.90 kPa) and continue to record vertical recovered deformations for each 200th repetition.

5. Reduce the confining pressure to 15 psi (103.43 kPa), and repeat Step C.3.3 for deviator stress levels of 1, 2, 5, 10, 15, and 20 psi (6.895, 13.79, 34.48, 68.95, 103.43, and 137.90 kPa).

6. Reduce the confining pressure to 10 psi (68.95 kPa), and repeat Step C.3.3 for deviator stress levels of 1, 2, 5, 10, and 15 psi (6.895, 13.79, 34.48, 68.95, and 103.43 kPa).

7. Reduce the confining pressure to 5 psi (34.48 kPa), and repeat Step C.3.3 for deviator stress levels of 1, 2, 5, 10, and 15 psi (6.895, 13.79, 34.48, 68.95, and 103.43 kPa).

8. Reduce the confining pressure to 1 psi (6.895 kPa), and repeat Step C.3.3 for deviator stress levels of 1, 2, 5, and 10 psi (6.895, 13.79, 34.48, and 68.95 kPa).

9. Stop the loading after 200 repetitions of the last deviator stress level or when specimen fails.

C.4 Post-Testing

1. Reduce the sitting load set in Step C.1.5, and slowly lower the loading piston to fully raise the loading ram.

2. Disconnect the loading ram from load cell, and lock the loading ram in place.

3. Reduce the chamber pressure to zero, and disconnect the transducer and pressure lines.

4. Remove the triaxial cell from the loading machine, and dismantle the cell.

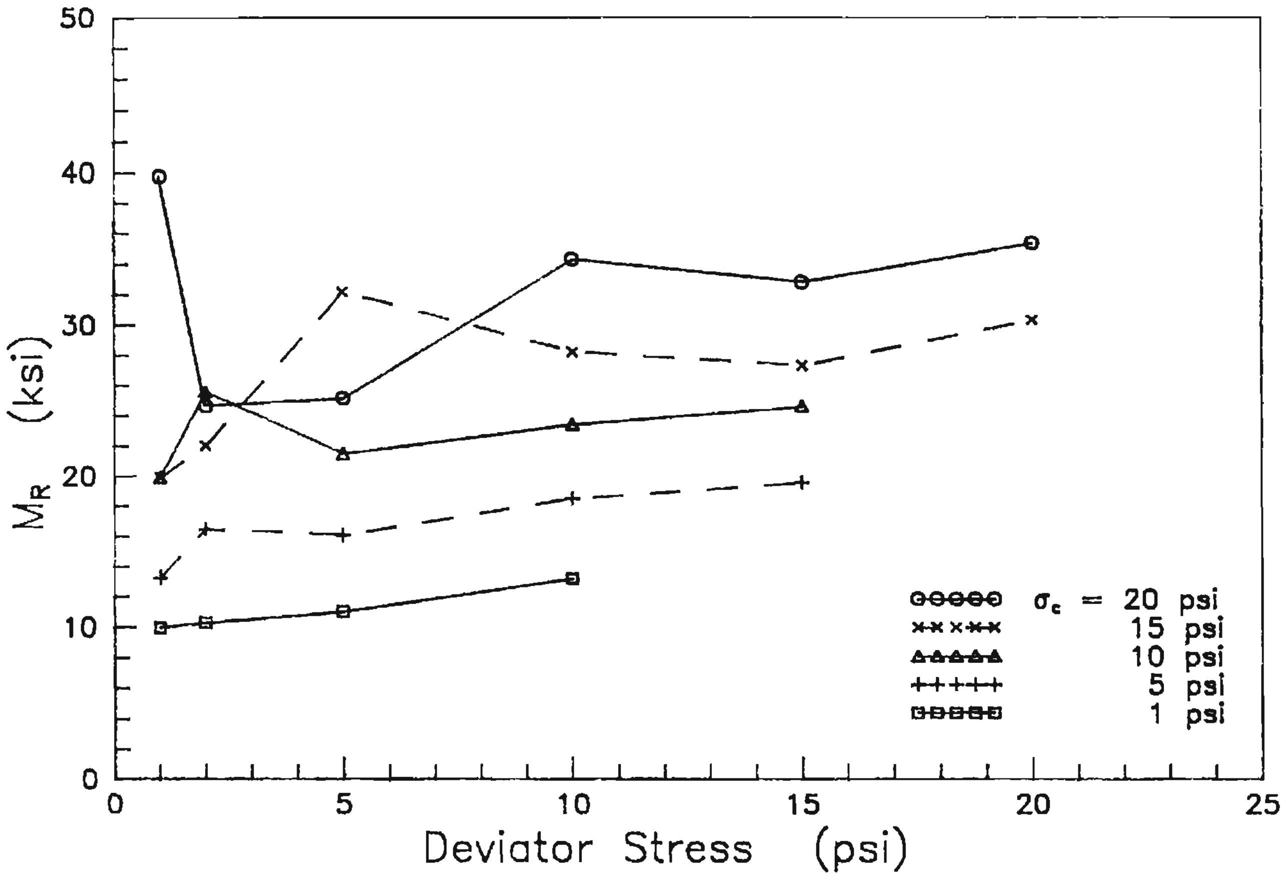
5. Turn off the hydraulic pressure system and the material testing system.

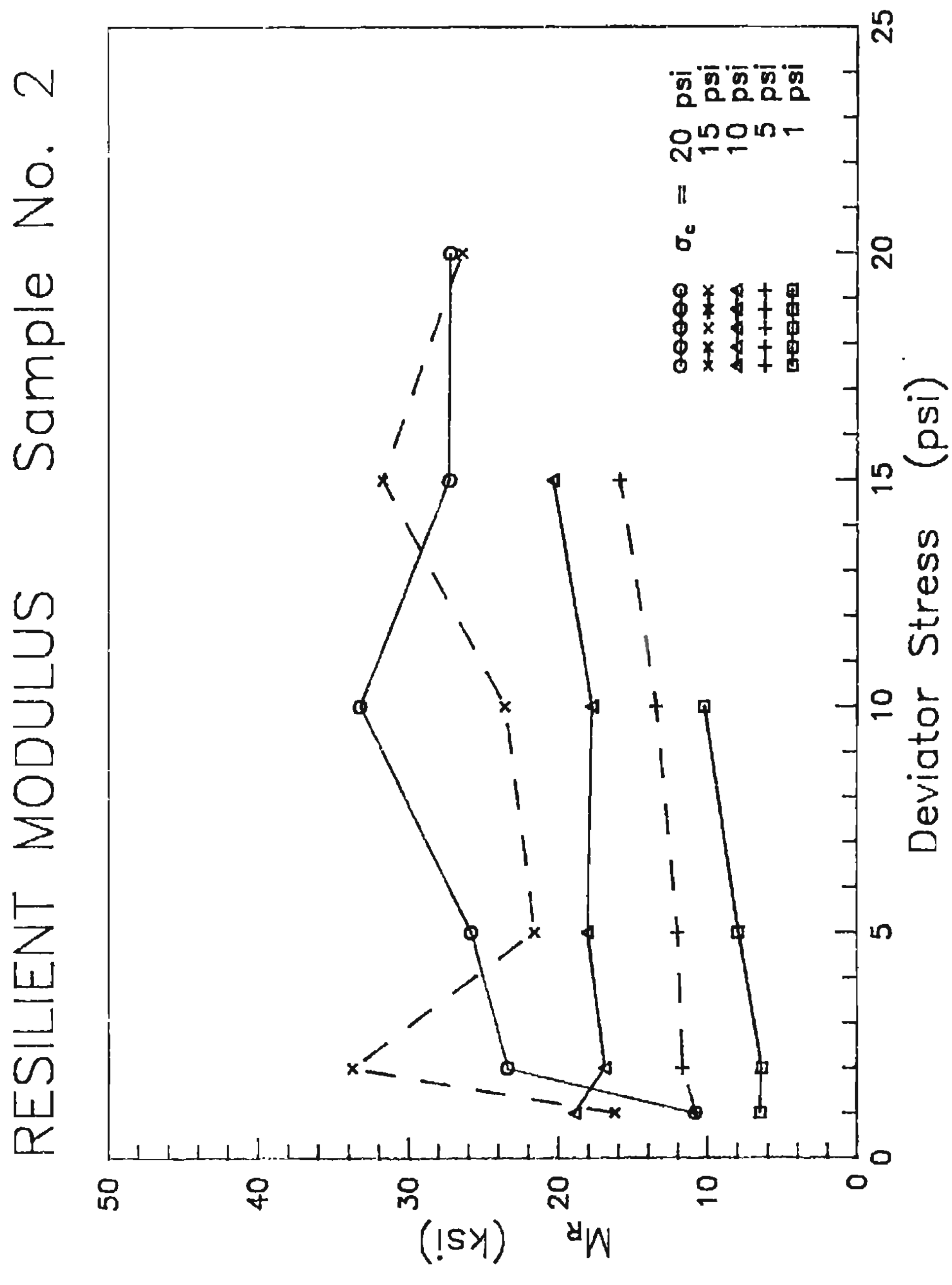
6. Use a part of specimen to determine the moisture content after test.

APPENDIX D

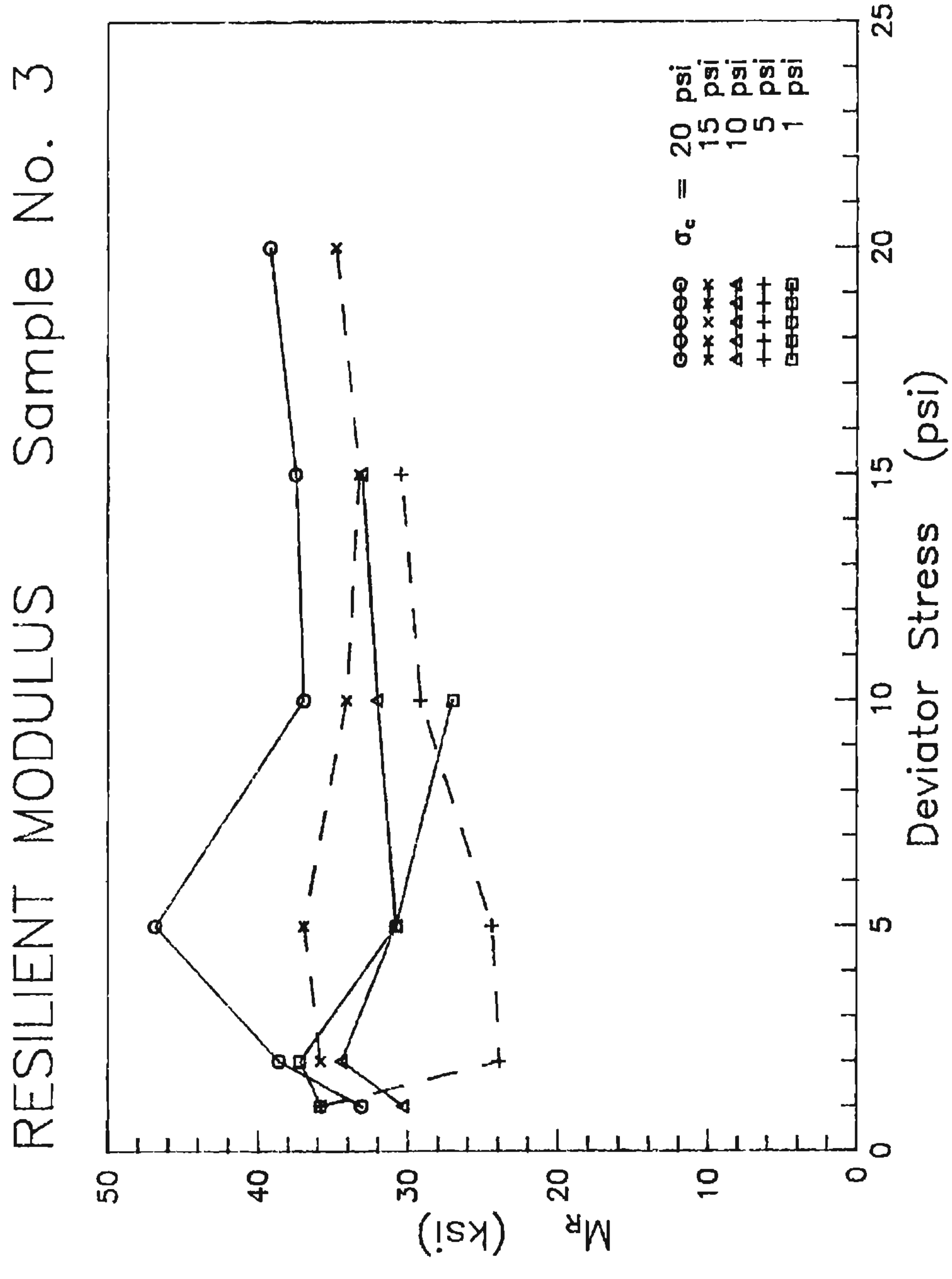
ARITHMETIC PLOT OF TEST RESULTS

RESILIENT MODULUS Sample No. 1

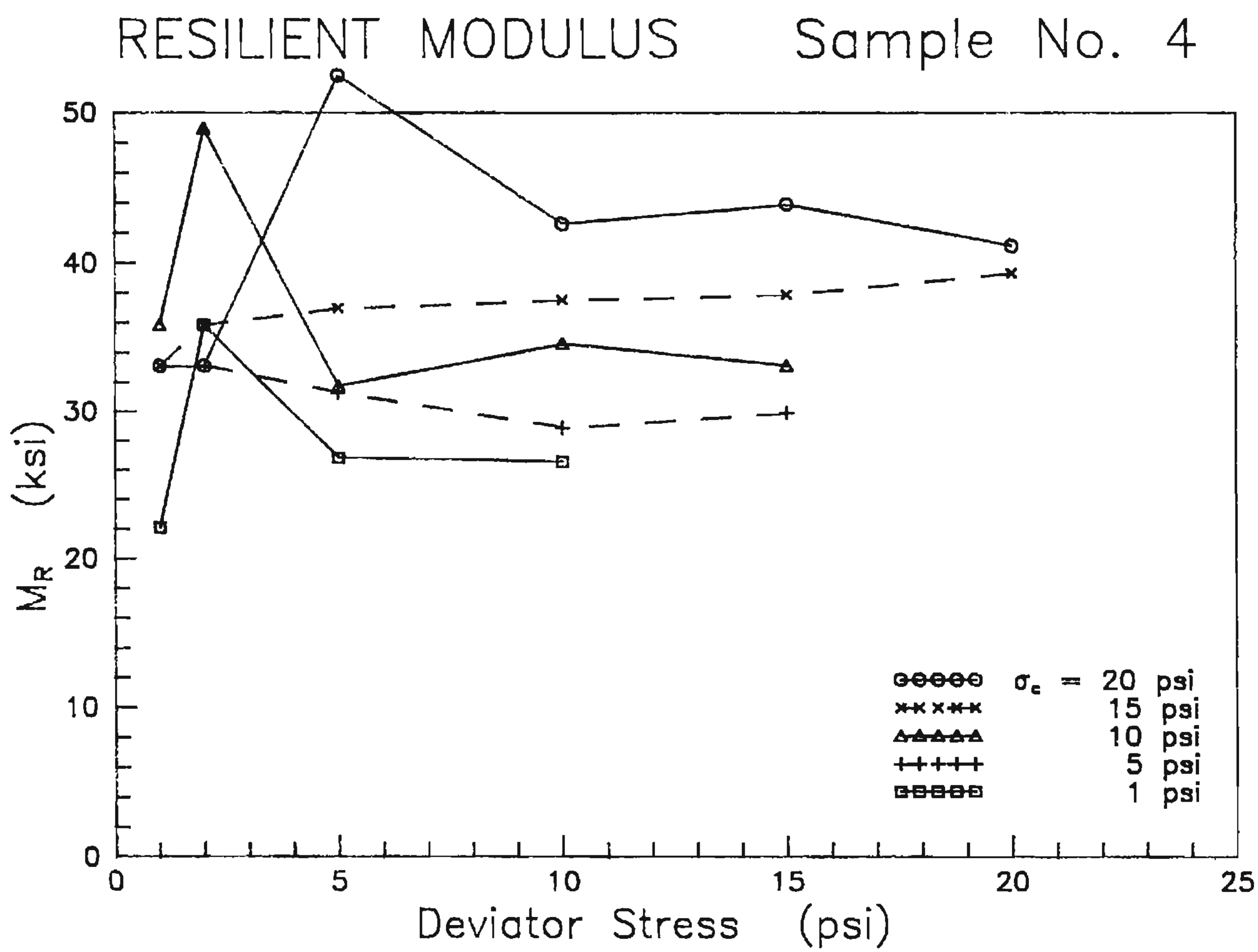




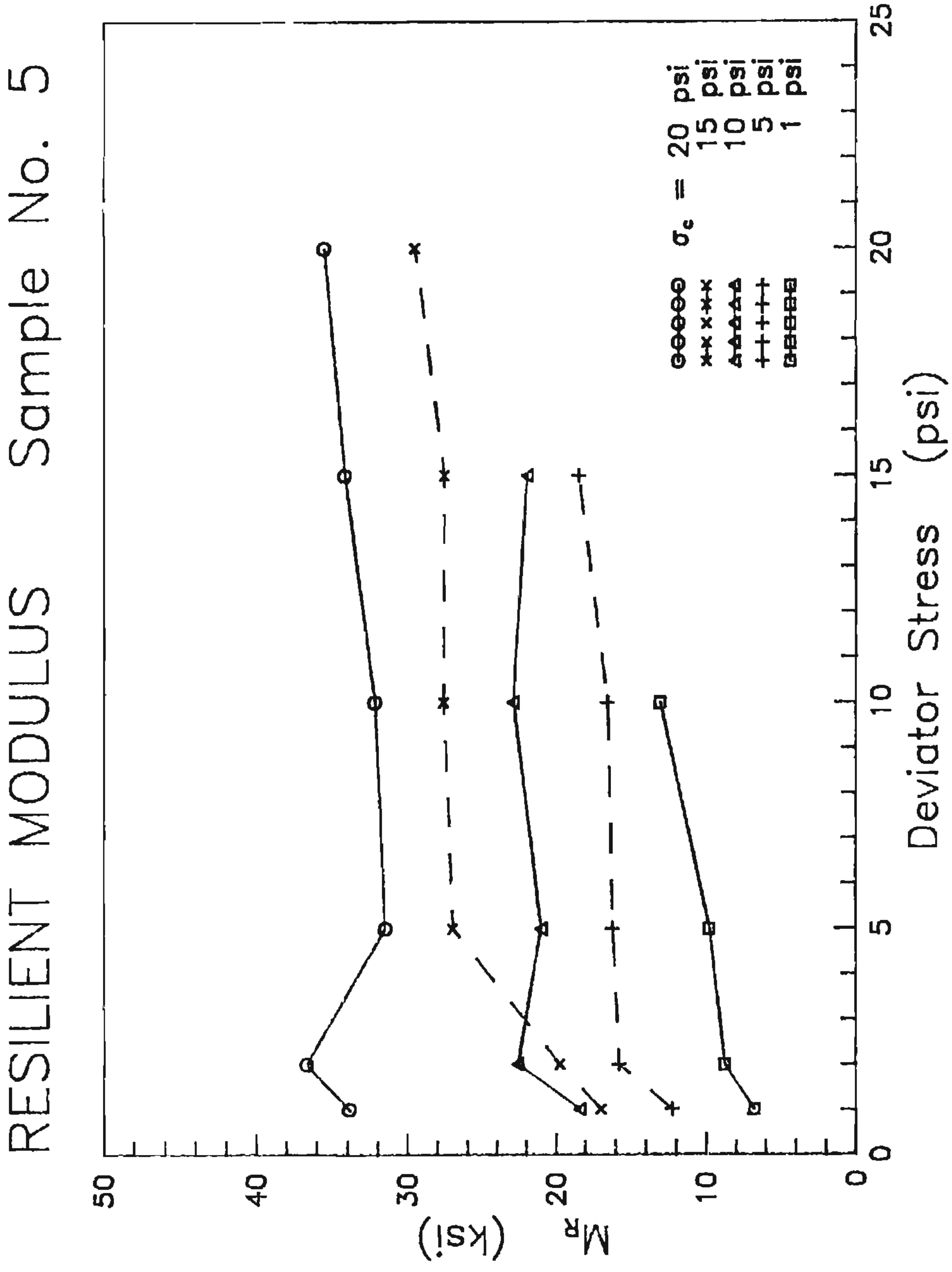
RESILIENT MODULUS Sample No. 2
Deviator Stress (psi)
M_R (ksi)
σ_c = 20 psi
15 psi
10 psi
5 psi
1 psi
0
5
10
15
20
25
0
10
20
30
40
50

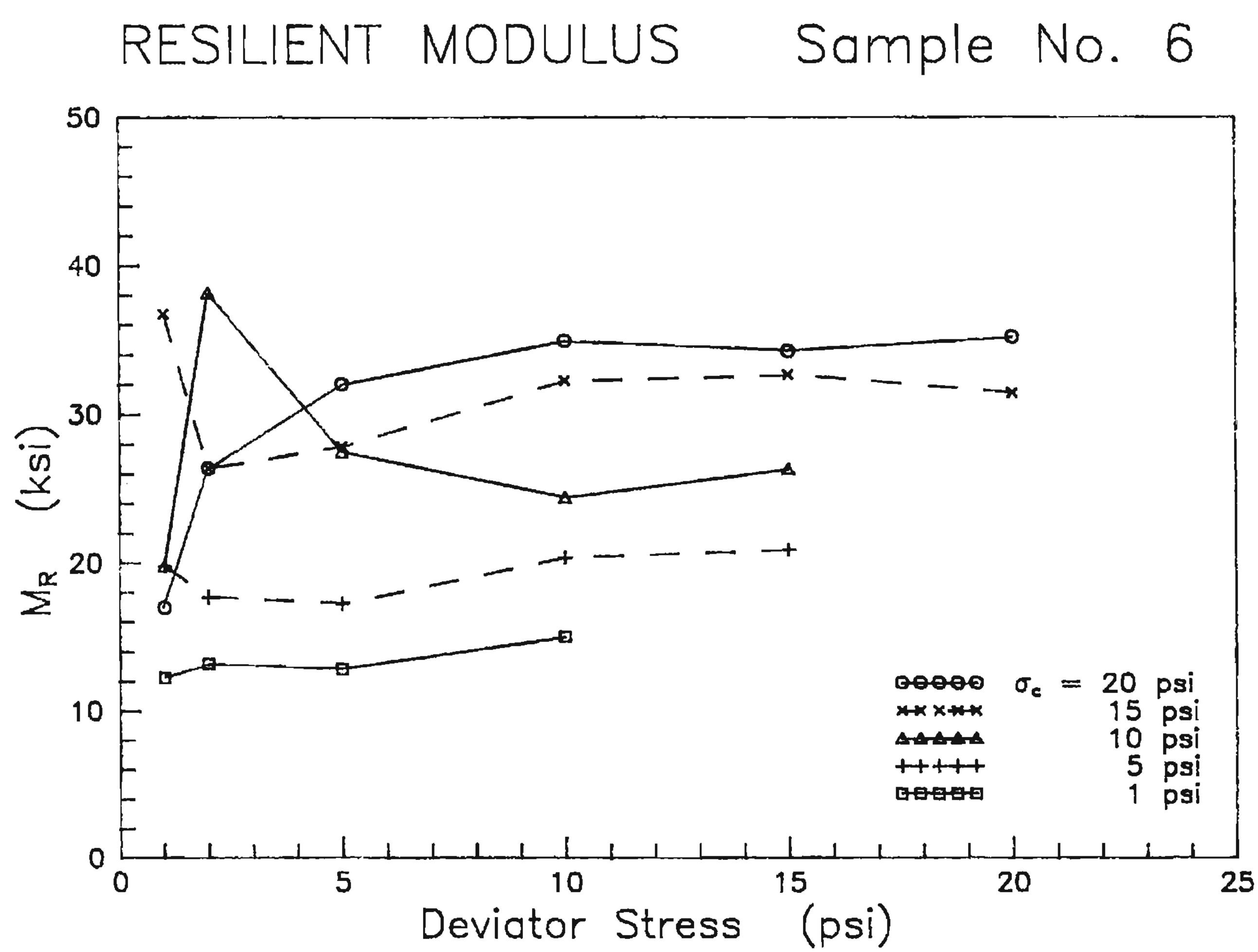


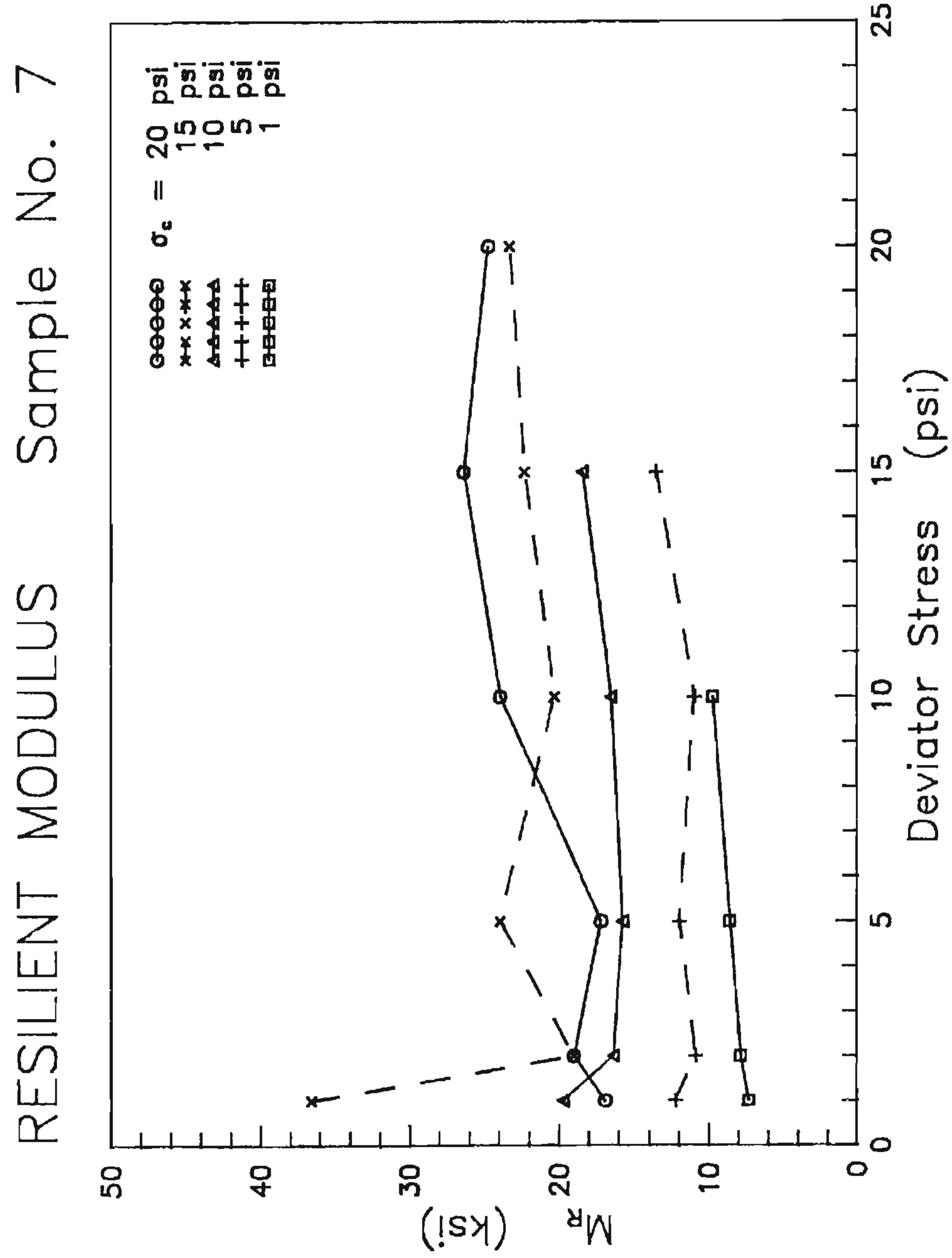
RESILIENT MODULUS Sample No. 3
M_R (ksi)
Deviator Stress (psi)
σ_c = 20 psi
15 psi
10 psi
5 psi
1 psi
0
10
20
30
40
50
0
5
10
15
20
25

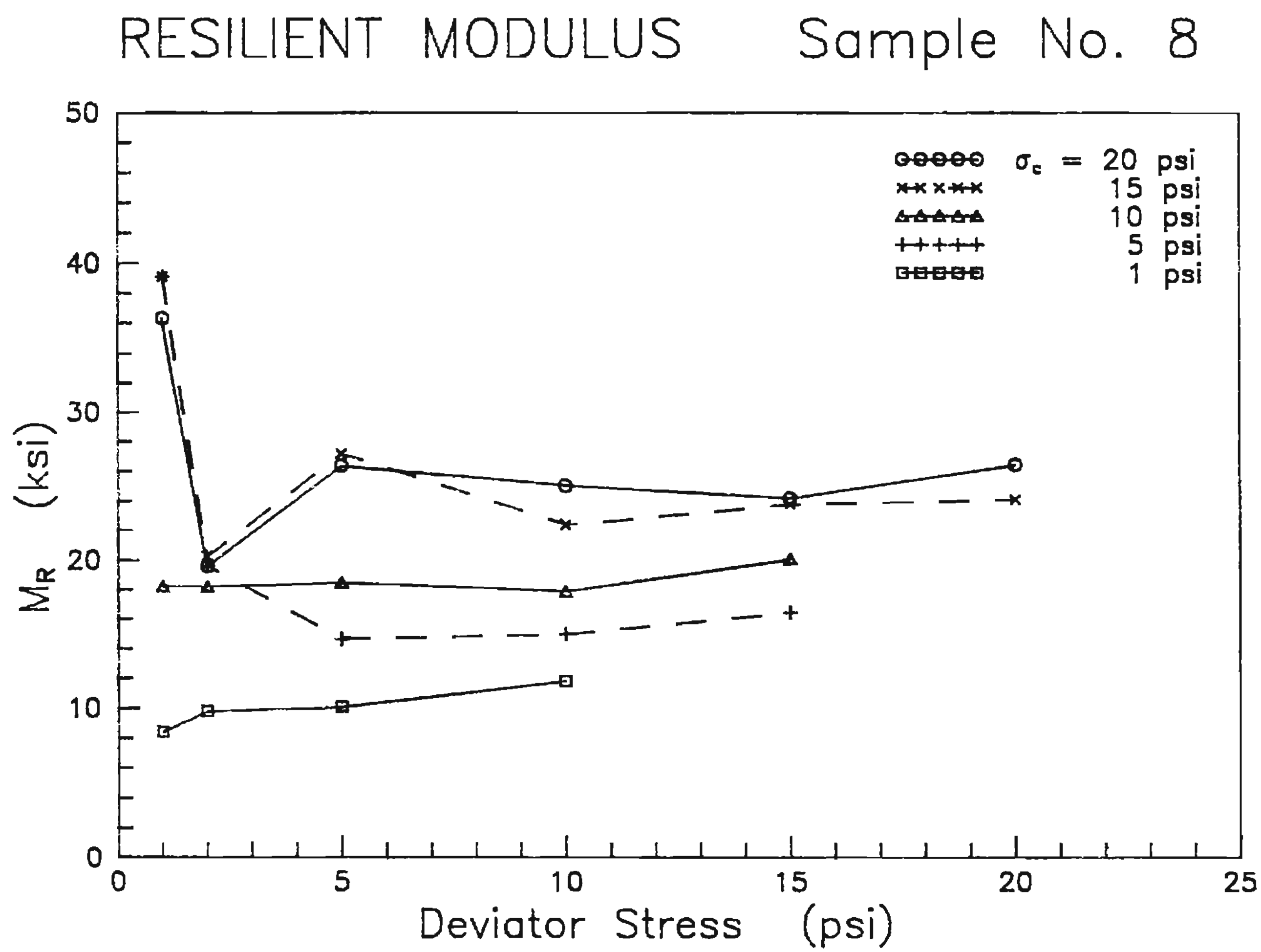


RESILIENT MODULUS Sample No. 4
M_R (ksi)
50
40
30
20
10
0
0
5
10
15
20
25
Deviator Stress (psi)
σ_c = 20 psi
15 psi
10 psi
5 psi
1 psi


RESILIENT MODULUS Sample No. 5
M_R (ksi)
Deviator Stress (psi)
σ_c = 20 psi
15 psi
10 psi
5 psi
1 psi
0
10
20
30
40
50
0
5
10
15
20
25

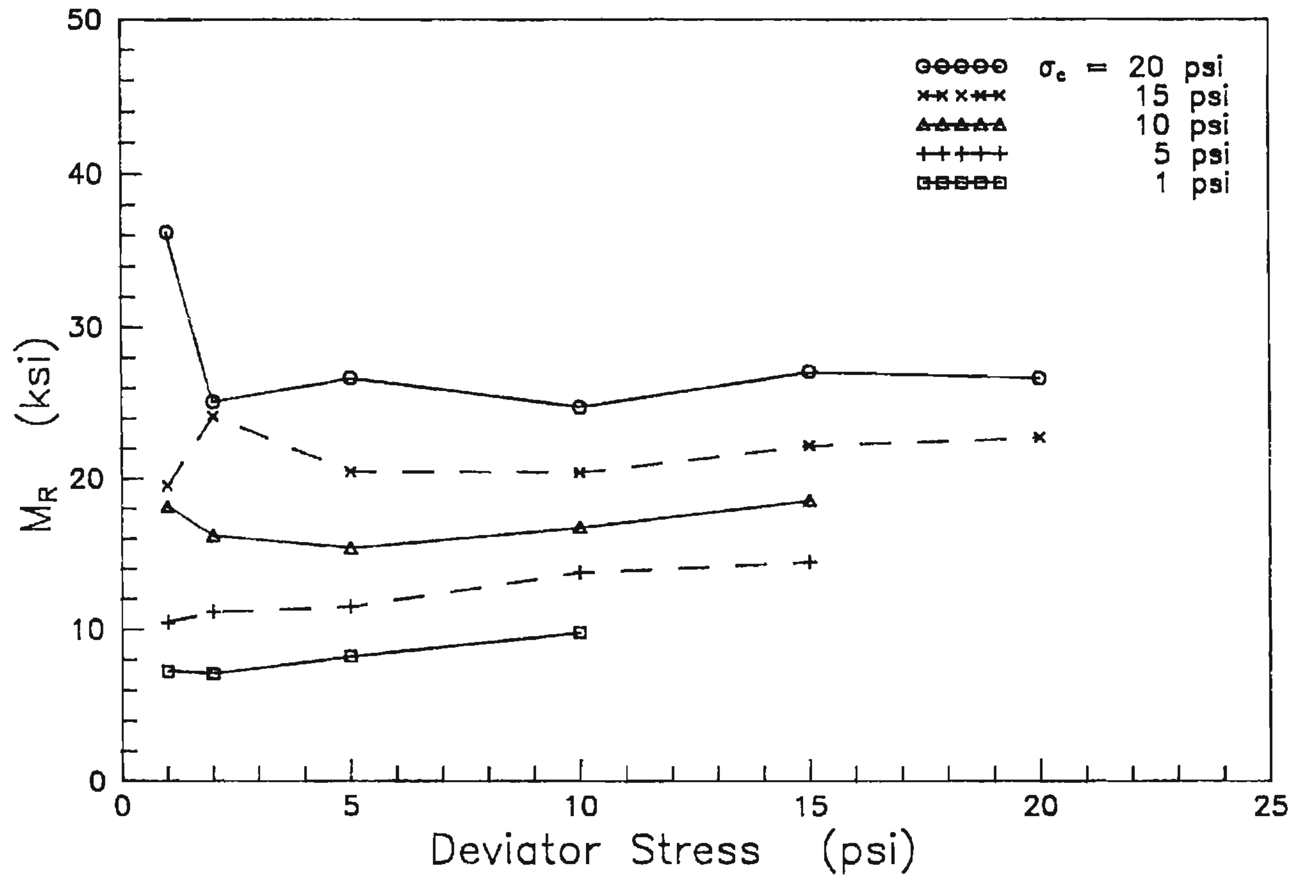

RESILIENT MODULUS Sample No. 6
M_R (ksi)
Deviator Stress (psi)
σ_c = 20 psi
15 psi
10 psi
5 psi
1 psi
0
10
20
30
40
50
0
5
10
15
20
25

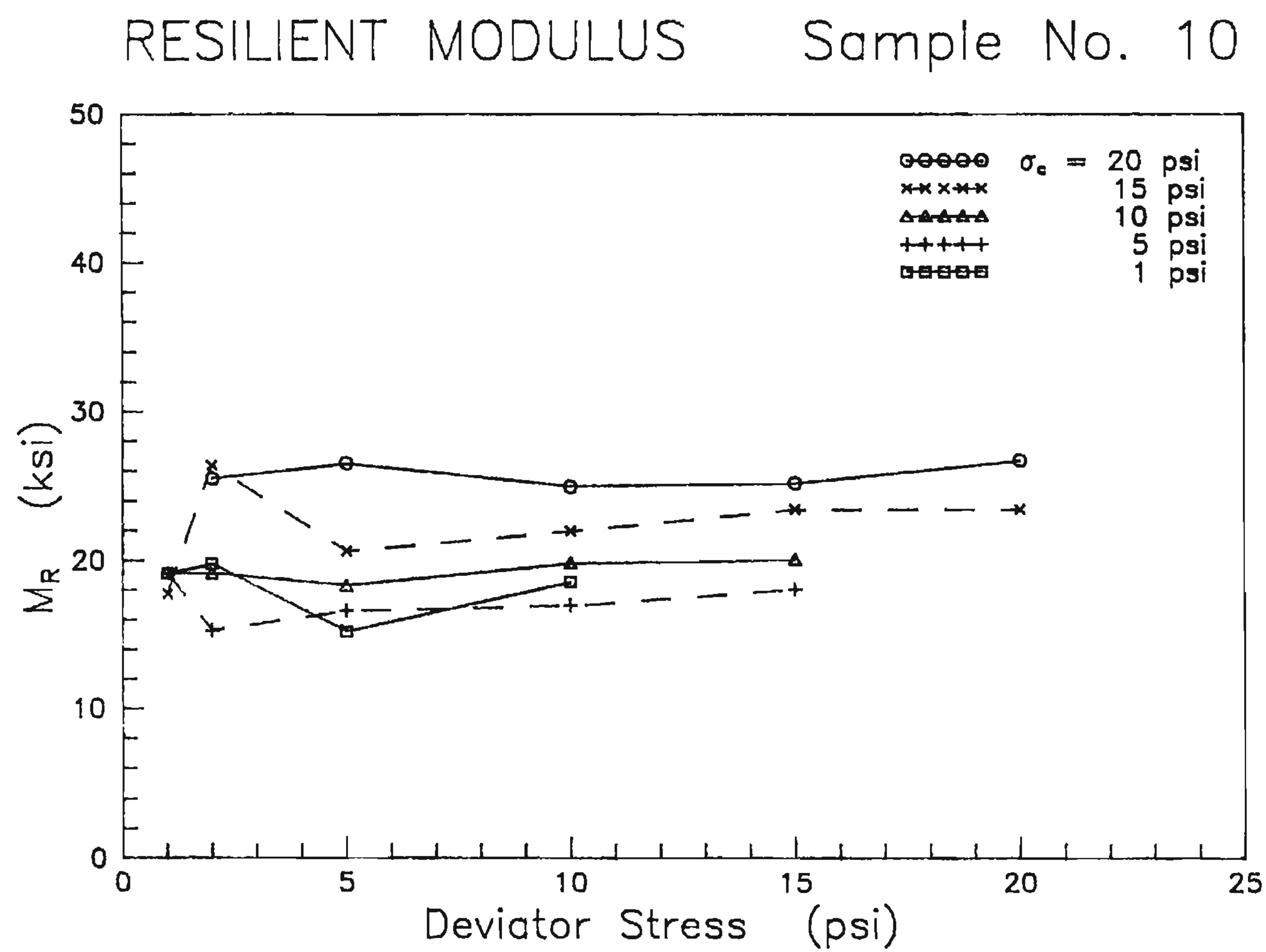

RESILIENT MODULUS Sample No. 7
σ_c = 20 psi
15 psi
10 psi
5 psi
1 psi
M_R (ksi)
0
10
20
30
40
50
0
5
10
15
20
25
Deviator Stress (psi)

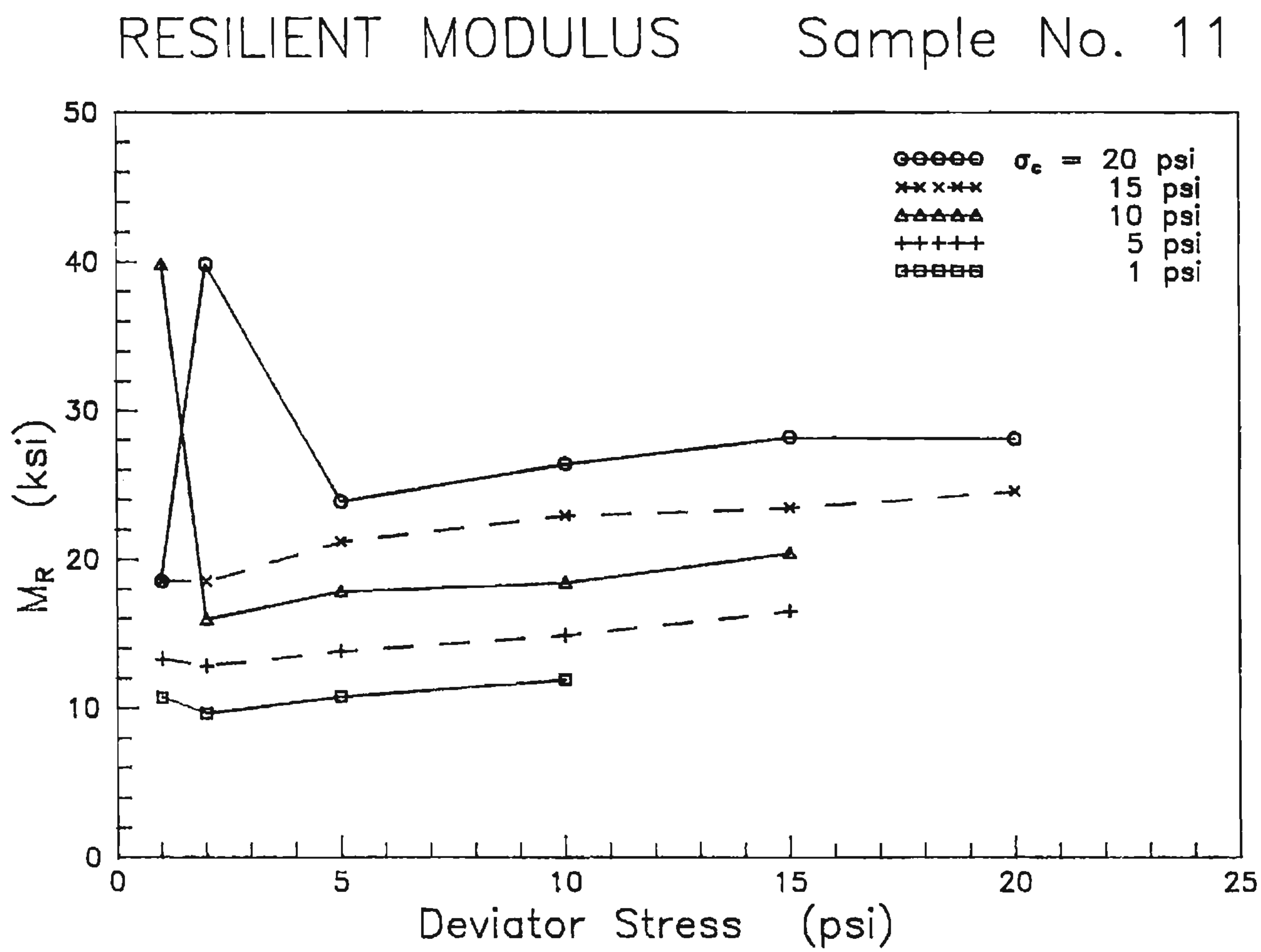


RESILIENT MODULUS Sample No. 8
σ_c = 20 psi
15 psi
10 psi
5 psi
1 psi
M_R (ksi)
0
10
20
30
40
50
0
5
10
15
20
25
Deviator Stress (psi)

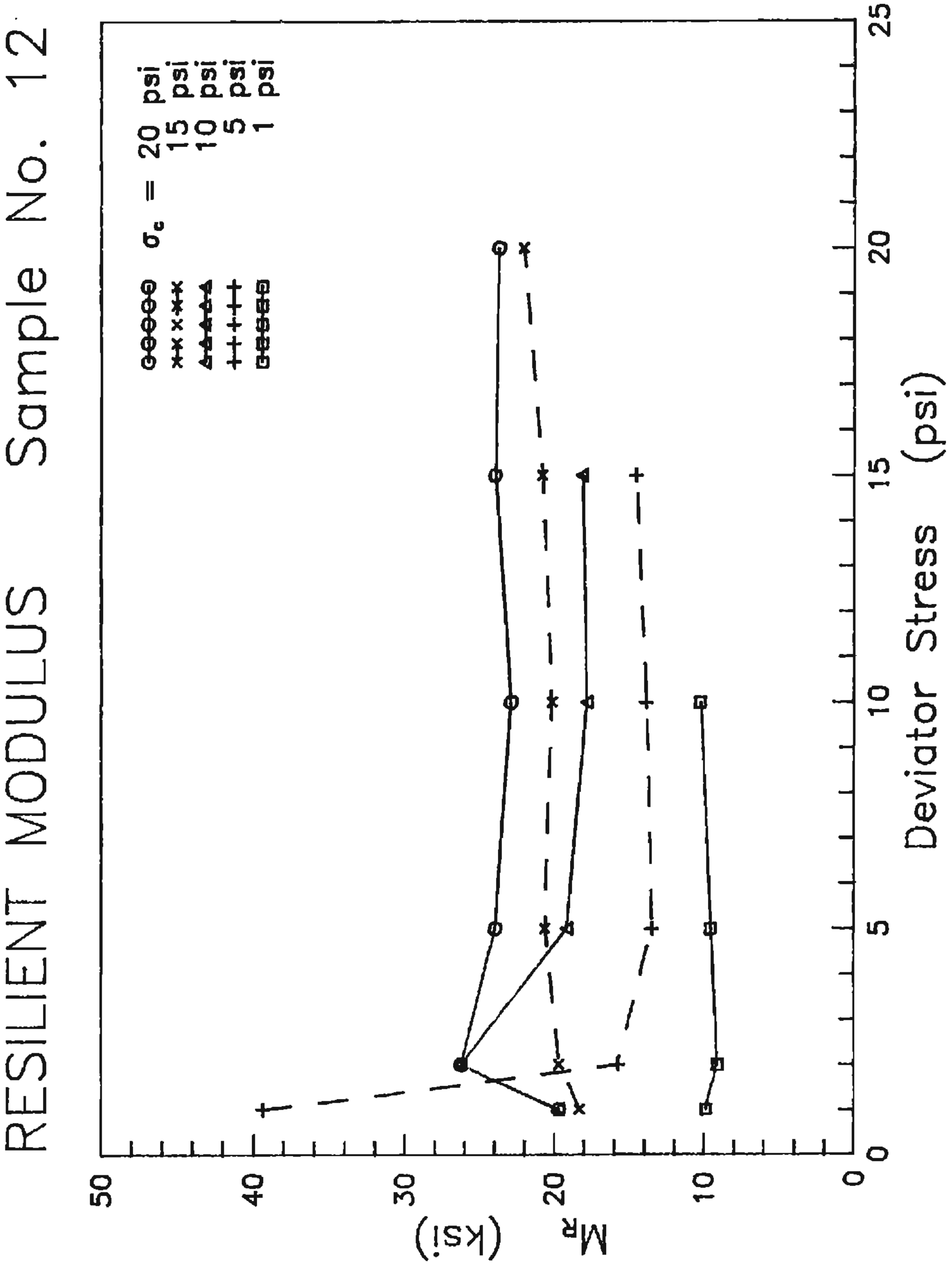
RESILIENT MODULUS   Sample No. 9



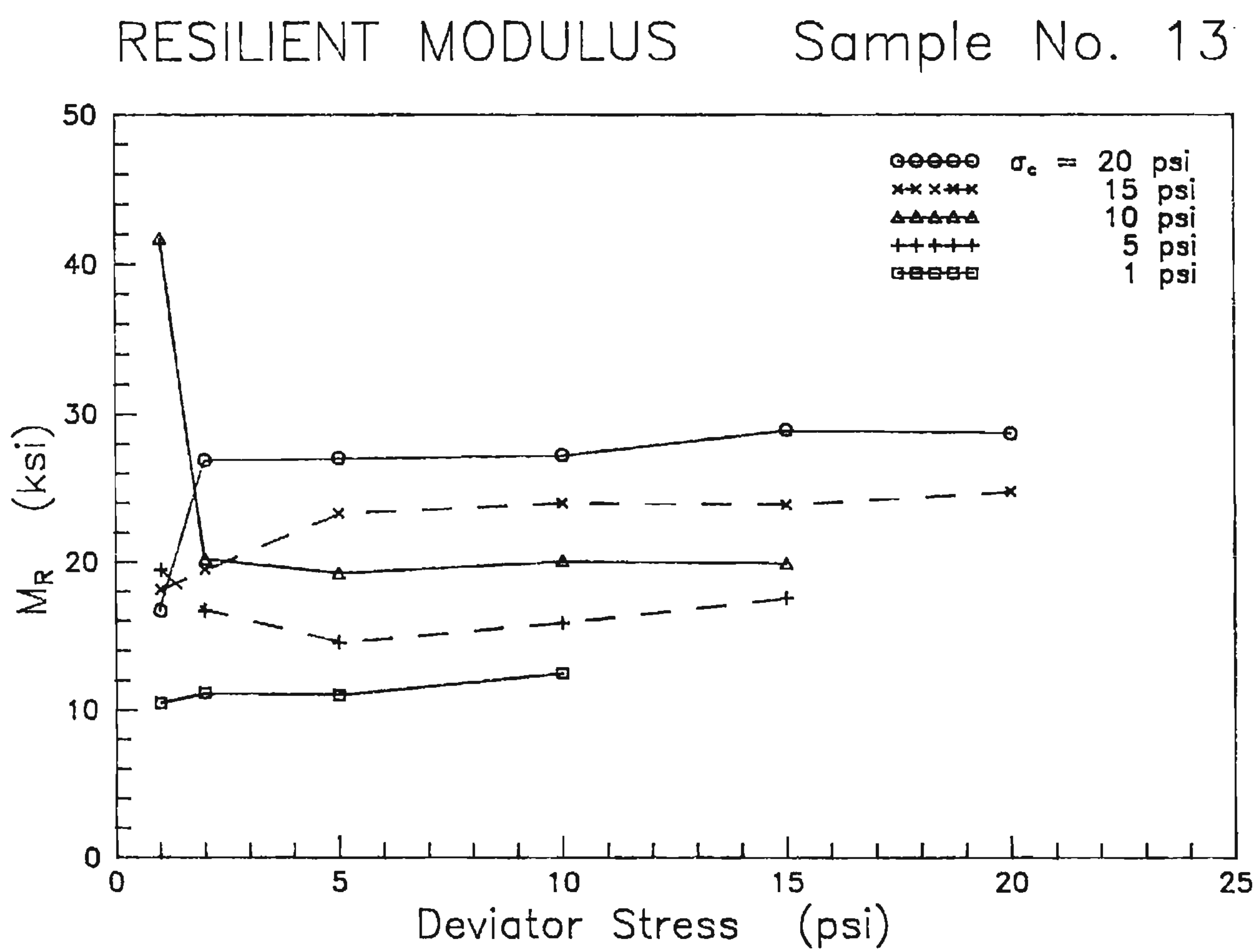

RESILIENT MODULUS Sample No. 10
σ_c = 20 psi
15 psi
10 psi
5 psi
1 psi
M_R (ksi)
0
10
20
30
40
50
0
5
10
15
20
25
Deviator Stress (psi)



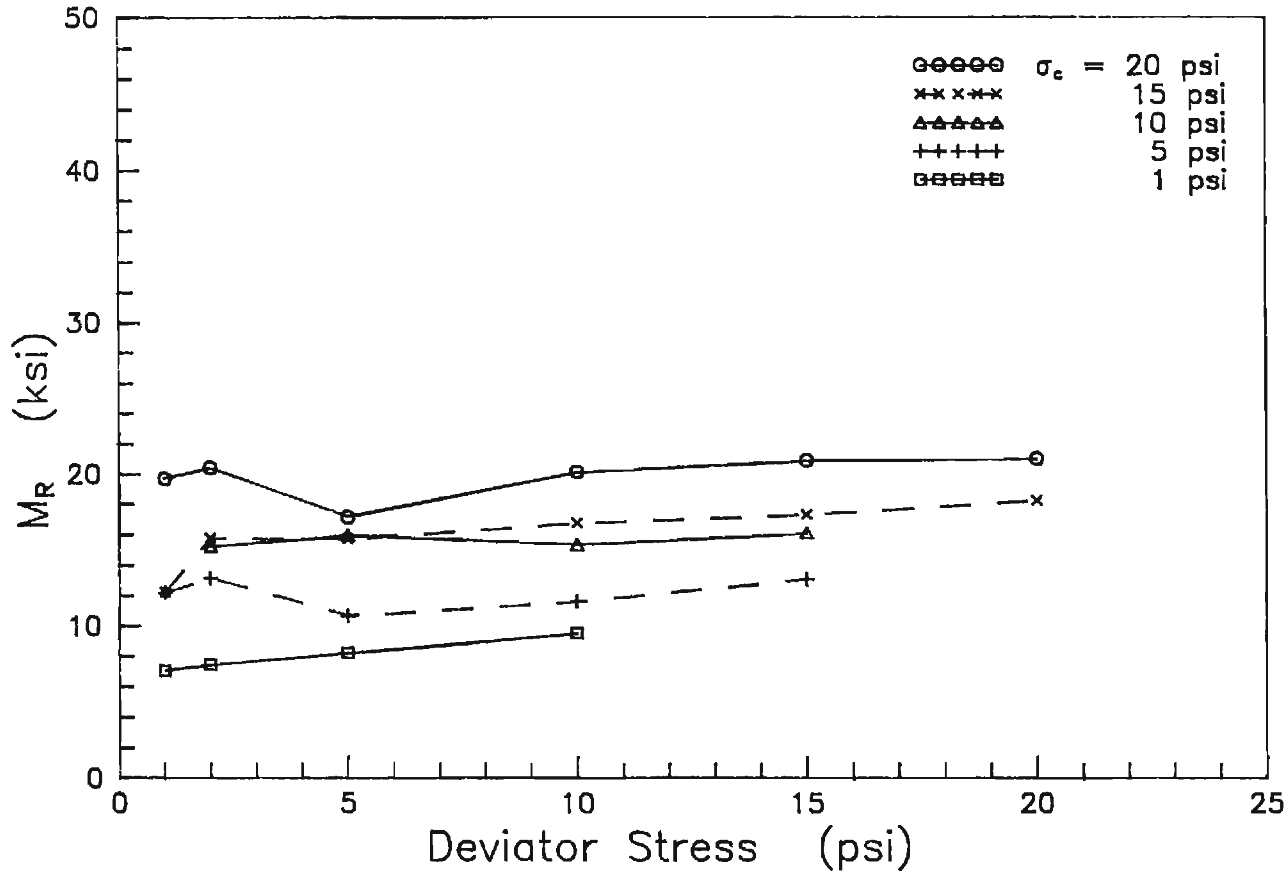
RESILIENT MODULUS Sample No. 11
σ_c = 20 psi
15 psi
10 psi
5 psi
1 psi
M_R (ksi)
Deviator Stress (psi)
0
10
20
30
40
50
0
5
10
15
20
25



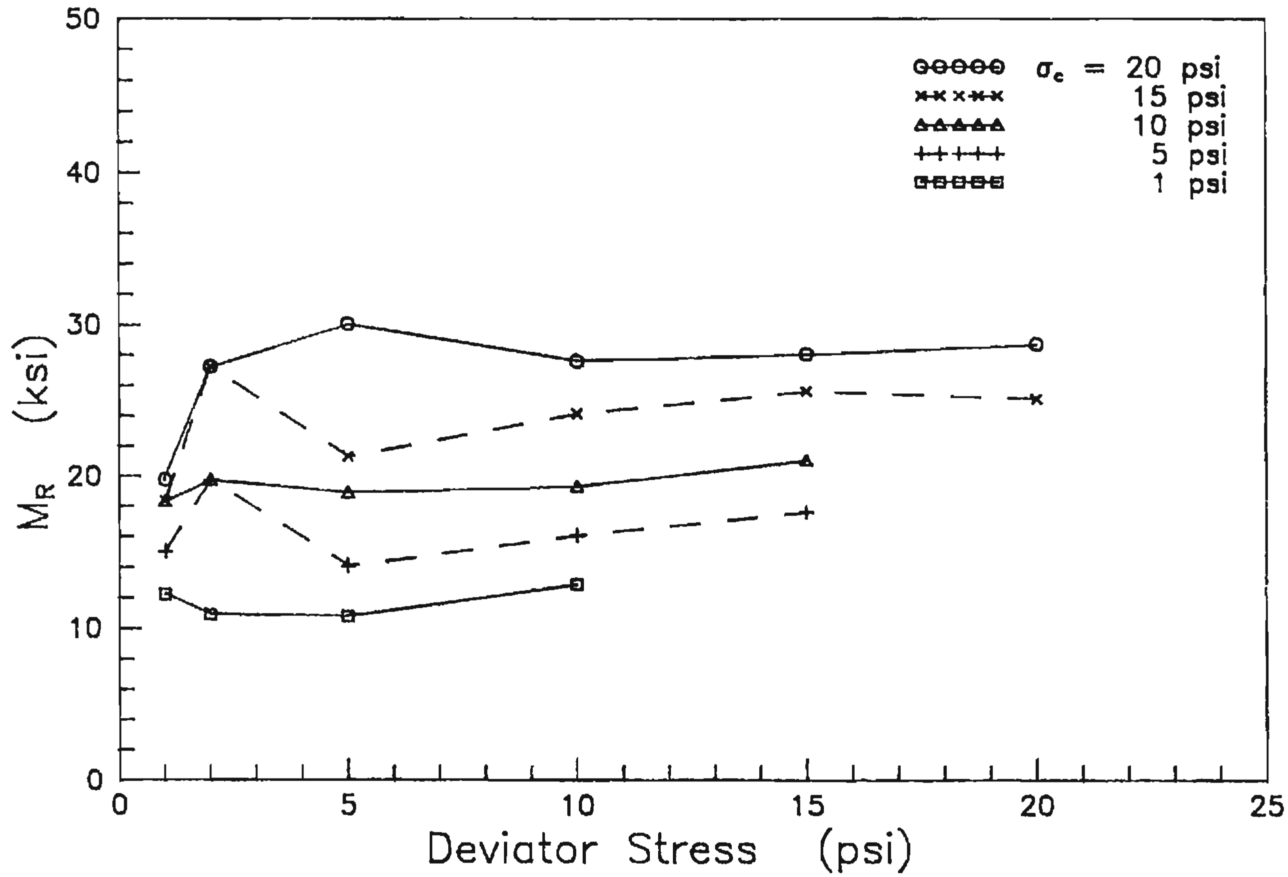
RESILIENT MODULUS Sample No. 12
σc = 20 psi
15 psi
10 psi
5 psi
1 psi
Deviator Stress (psi)
MR (ksi)
0
5
10
15
20
25
0
10
20
30
40
50

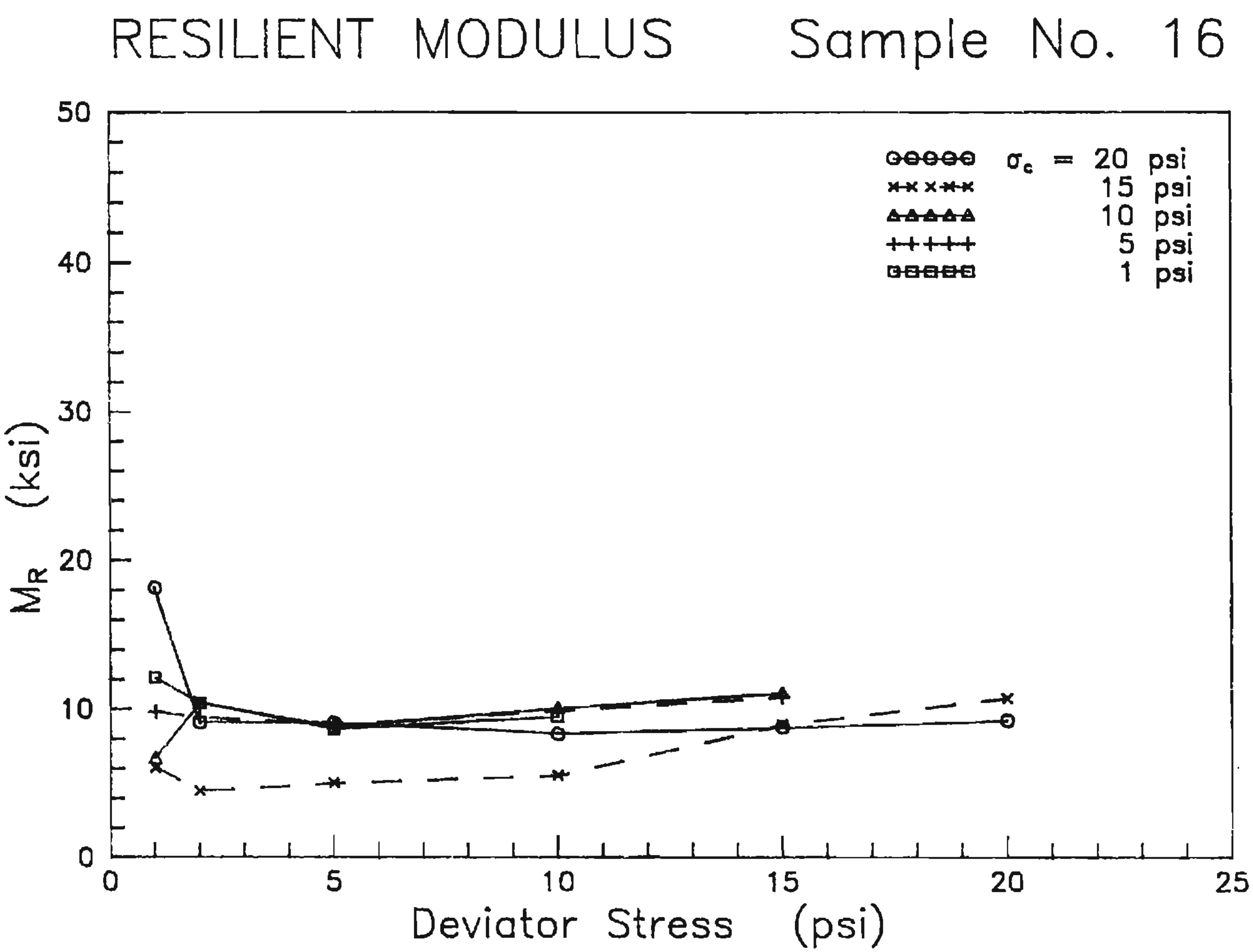

RESILIENT MODULUS Sample No. 13
σ_c = 20 psi
15 psi
10 psi
5 psi
1 psi
M_R (ksi)
Deviator Stress (psi)
0
10
20
30
40
50
0
5
10
15
20
25

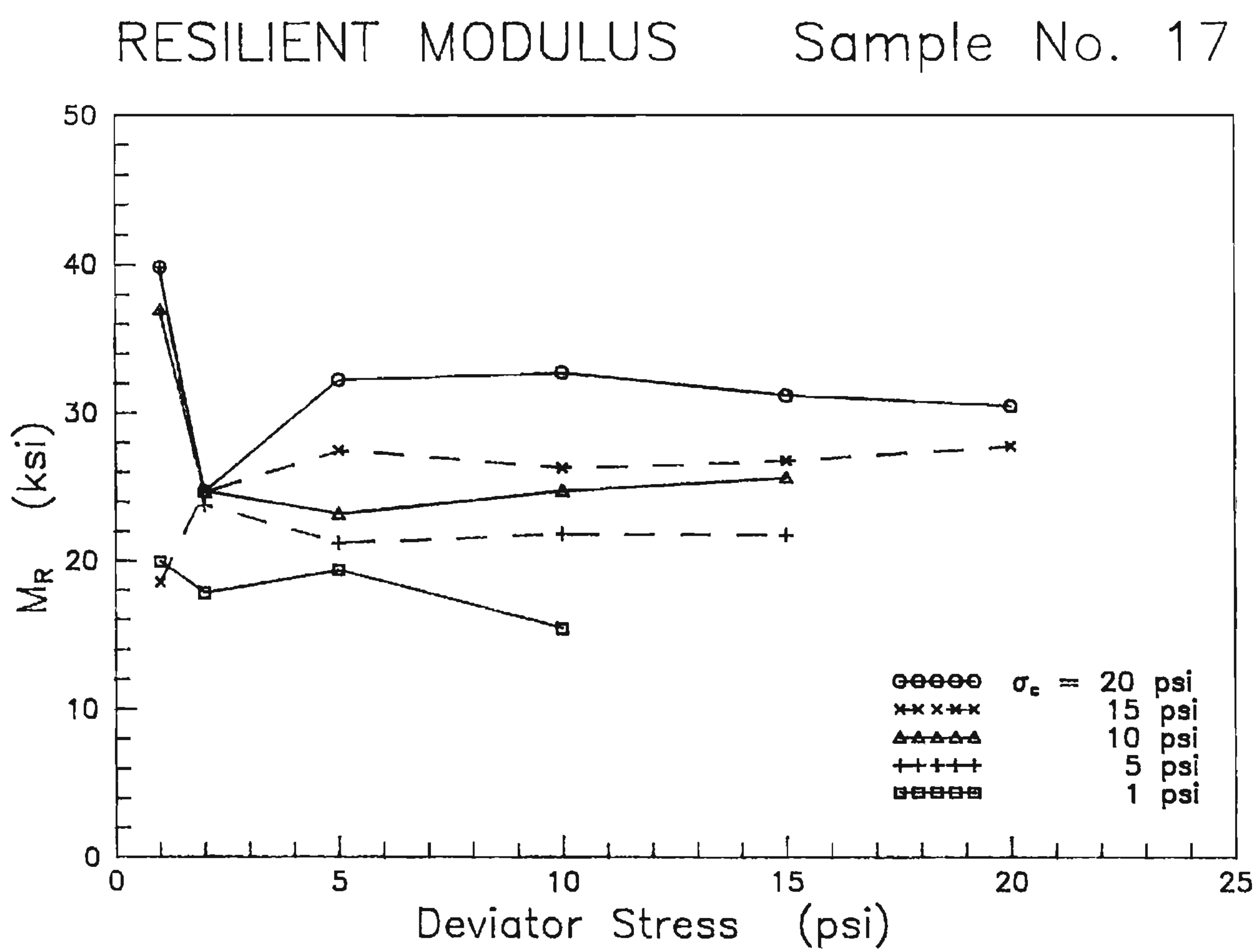
RESILIENT MODULUS Sample No. 14



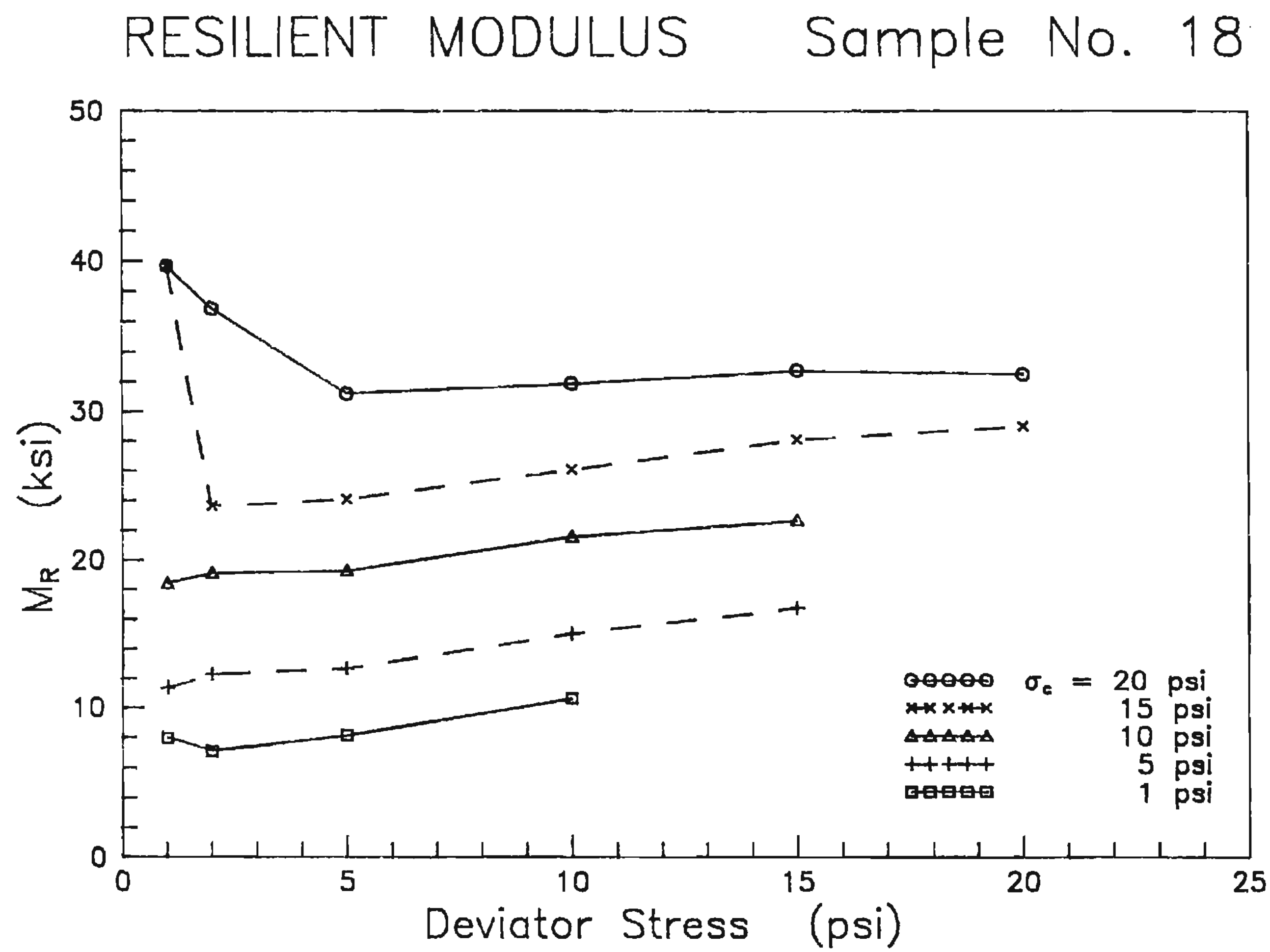
RESILIENT MODULUS   Sample No. 15




RESILIENT MODULUS Sample No. 16
σ_c = 20 psi
15 psi
10 psi
5 psi
1 psi
M_R (ksi)
Deviator Stress (psi)
0
10
20
30
40
50
0
5
10
15
20
25

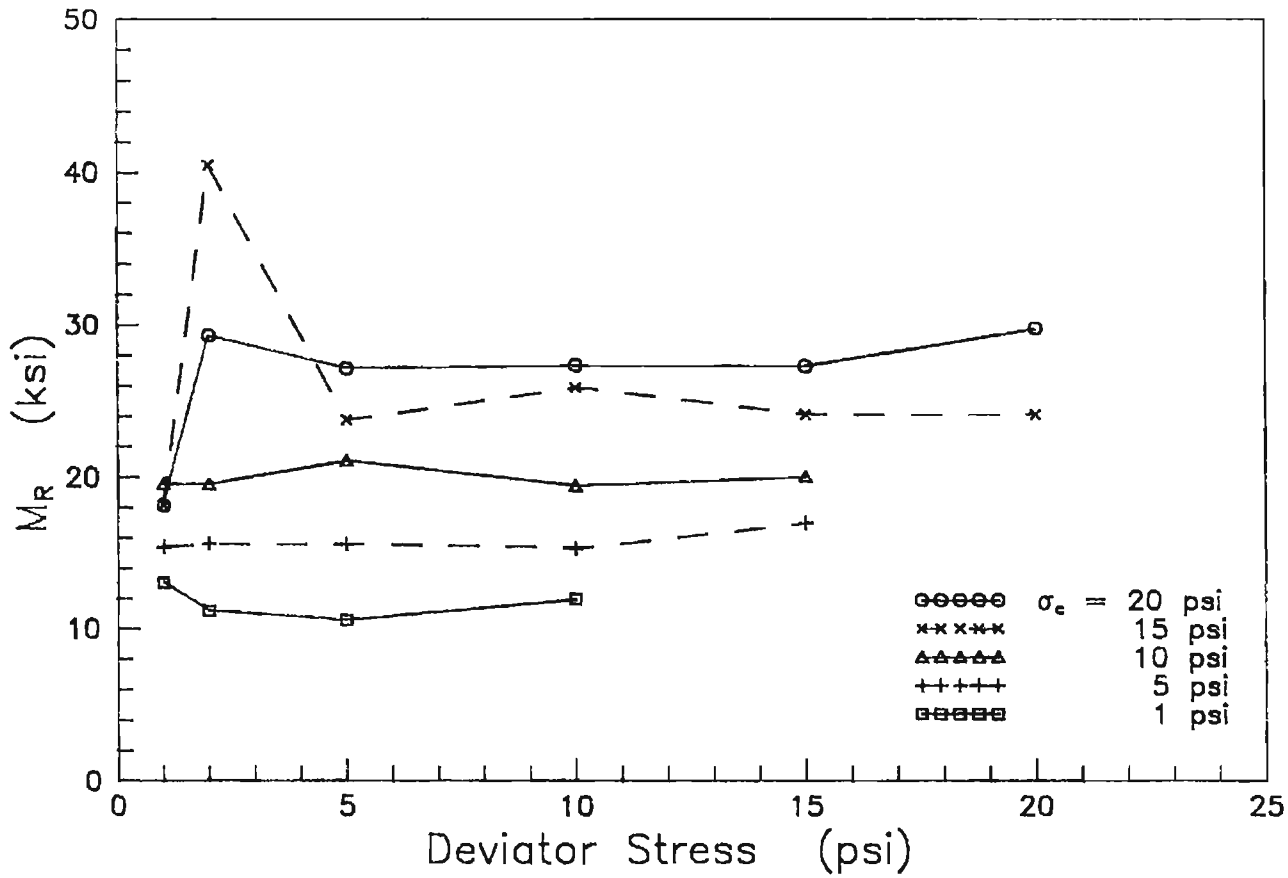


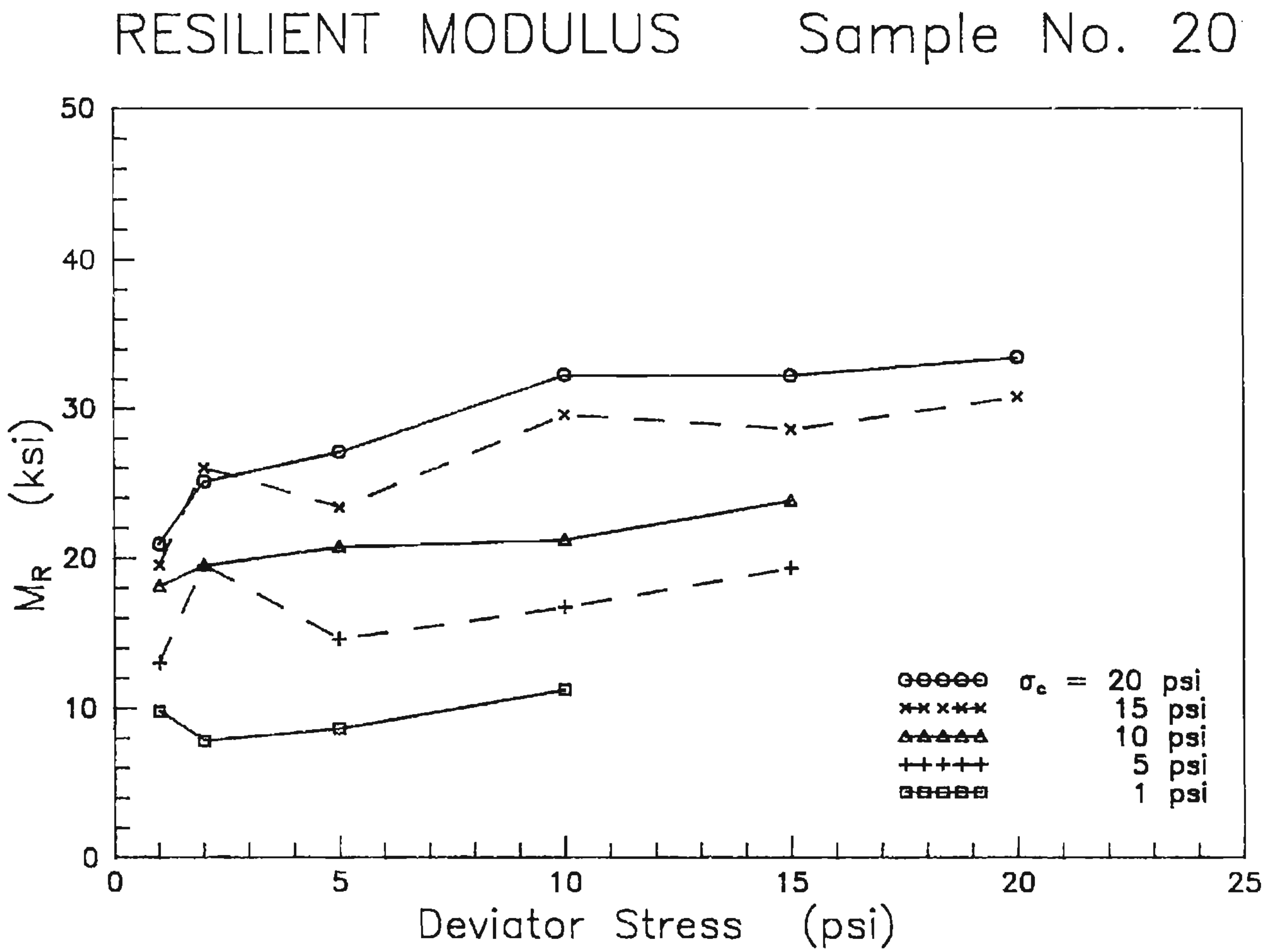
RESILIENT MODULUS Sample No. 17
M_R (ksi)
Deviator Stress (psi)
0
10
20
30
40
50
0
5
10
15
20
25
σ_c = 20 psi
15 psi
10 psi
5 psi
1 psi



RESILIENT MODULUS Sample No. 18
50
40
30
20
10
0
M_R (ksi)
0
5
10
15
20
25
Deviator Stress (psi)
σ_c = 20 psi
15 psi
10 psi
5 psi
1 psi

RESILIENT MODULUS Sample No. 19



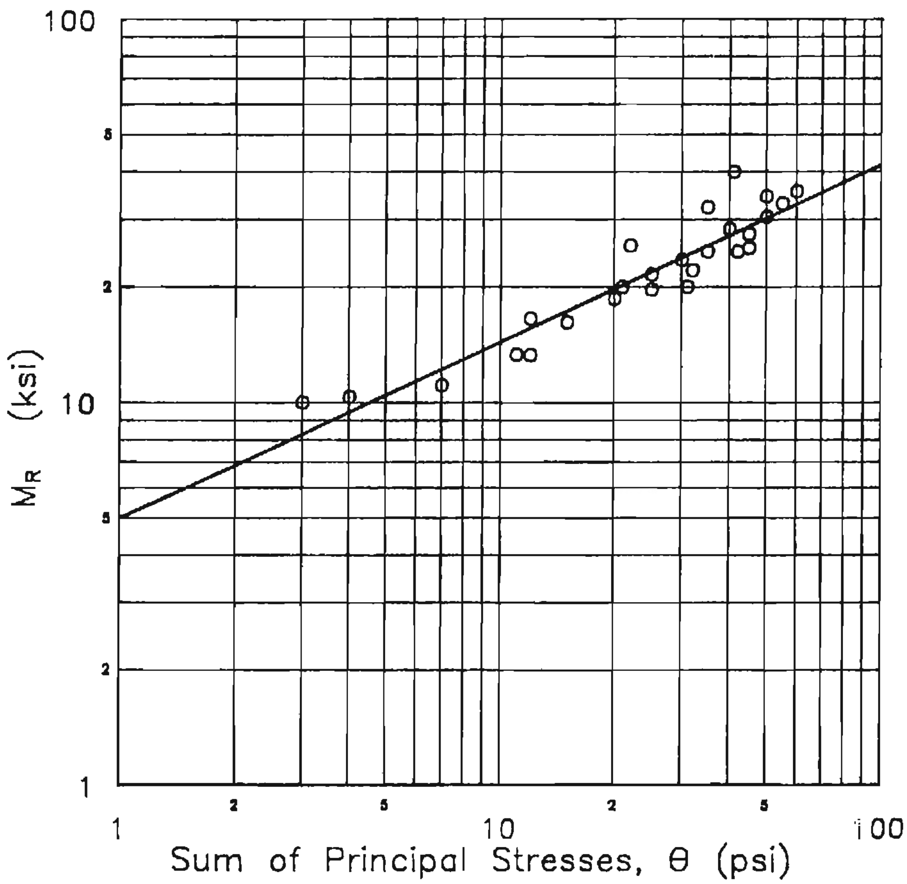


RESILIENT MODULUS Sample No. 20
M_R (ksi)
Deviator Stress (psi)
0
10
20
30
40
50
0
5
10
15
20
25
σ_c = 20 psi
15 psi
10 psi
5 psi
1 psi

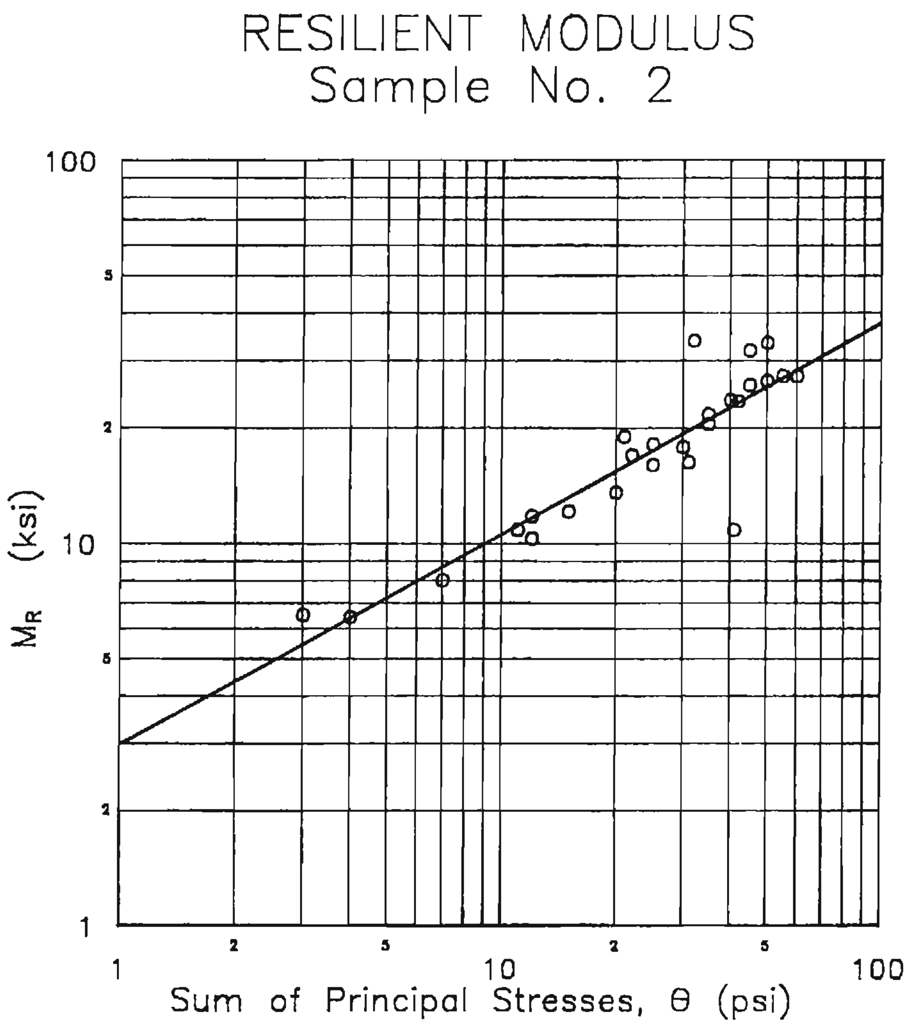
APPENDIX E

LOG-LOG PLOT OF TEST RESULTS

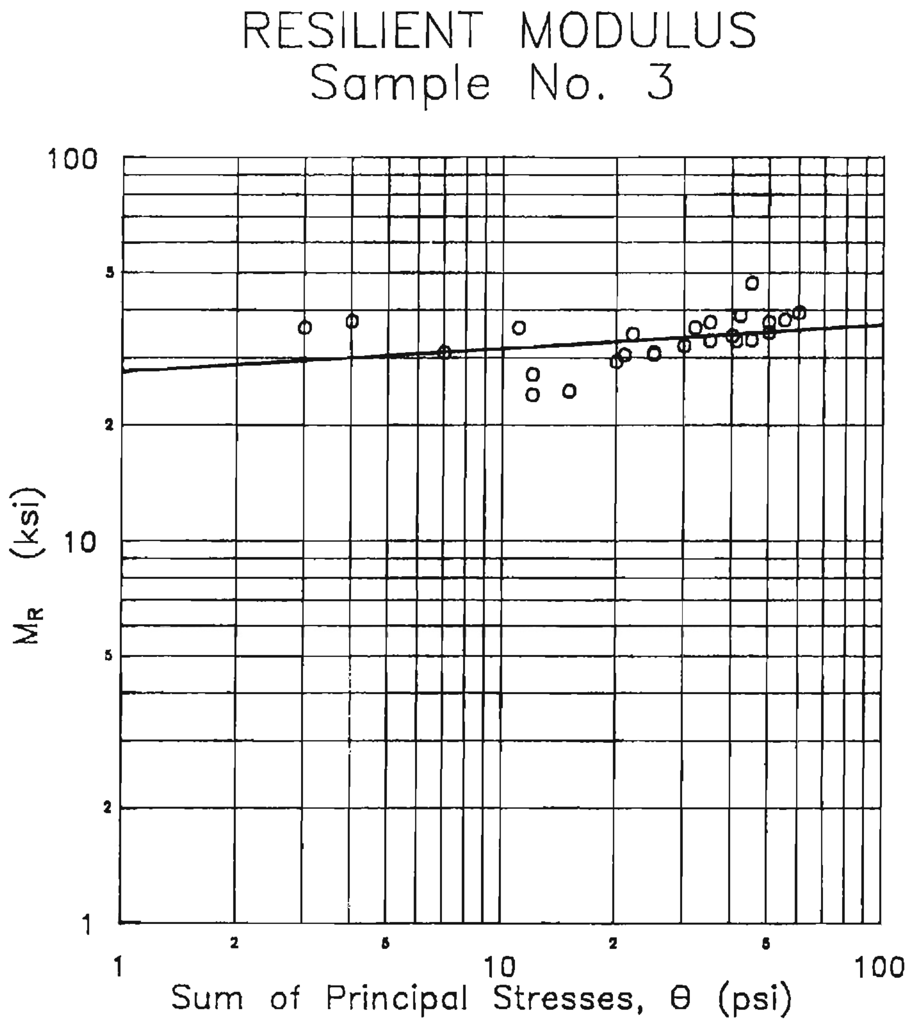
RESILIENT MODULUS
Sample No. 1



$$M_R = 4.988 \times \theta^{0.461}$$

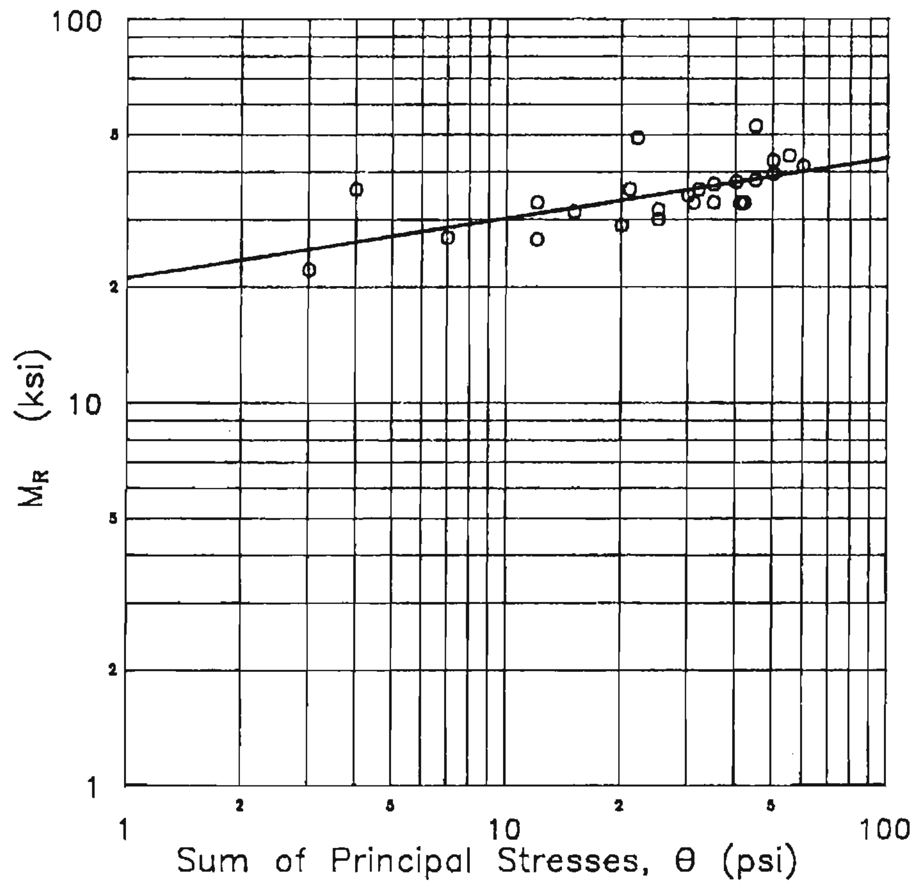


$$M_R = 2.977 \times \theta^{0.550}$$

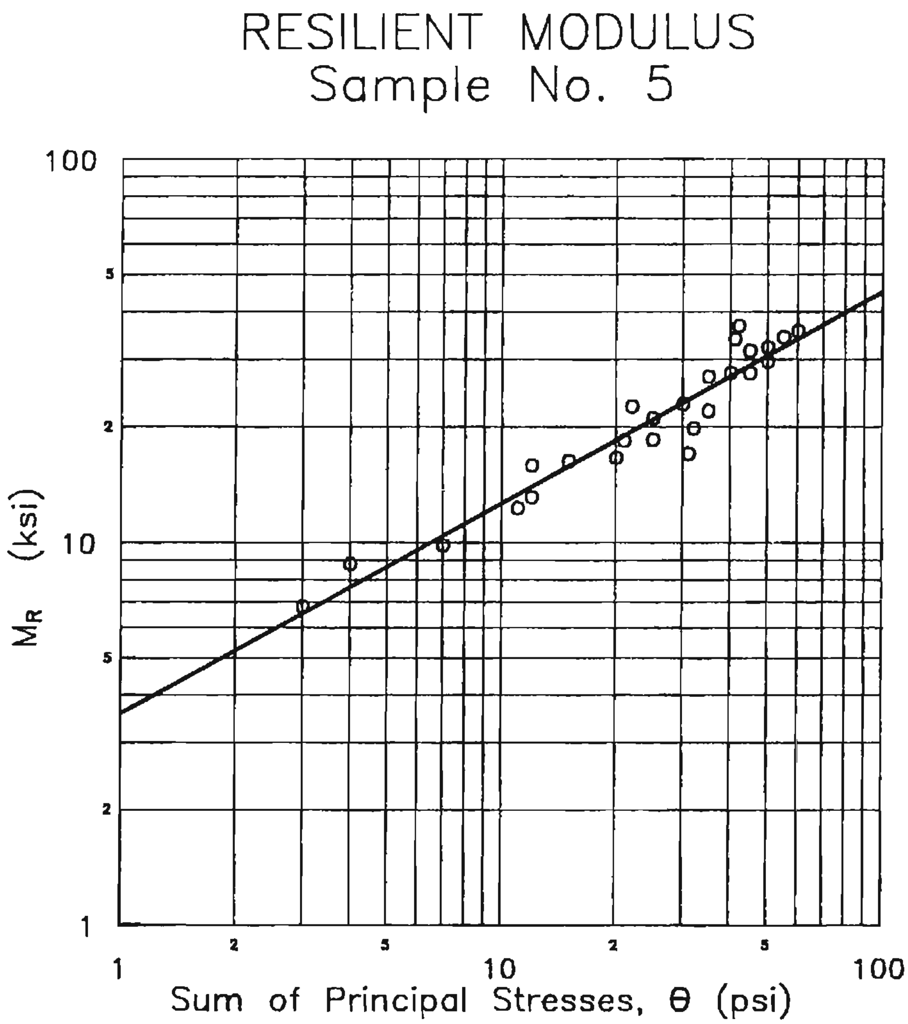


$$M_R = 27.502 \times \theta^{0.061}$$

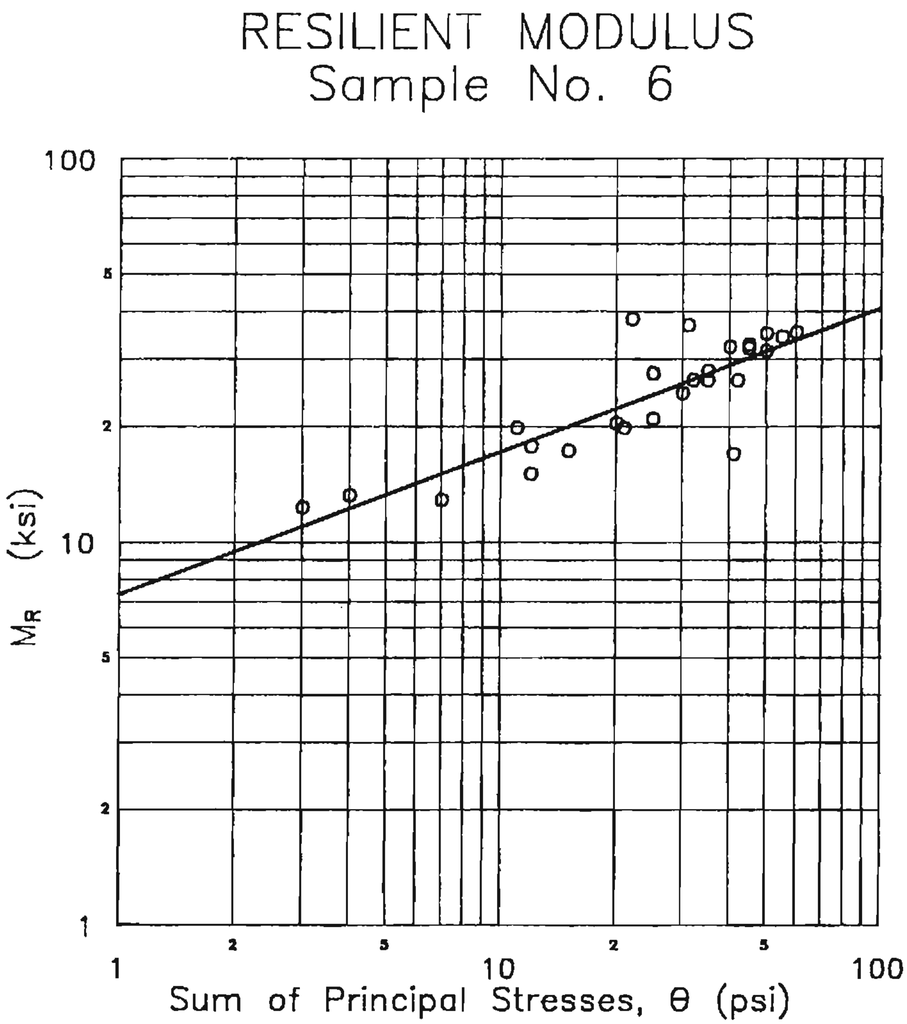
RESILIENT MODULUS
Sample No. 4



$$M_R = 21.089 \times \theta^{0.156}$$

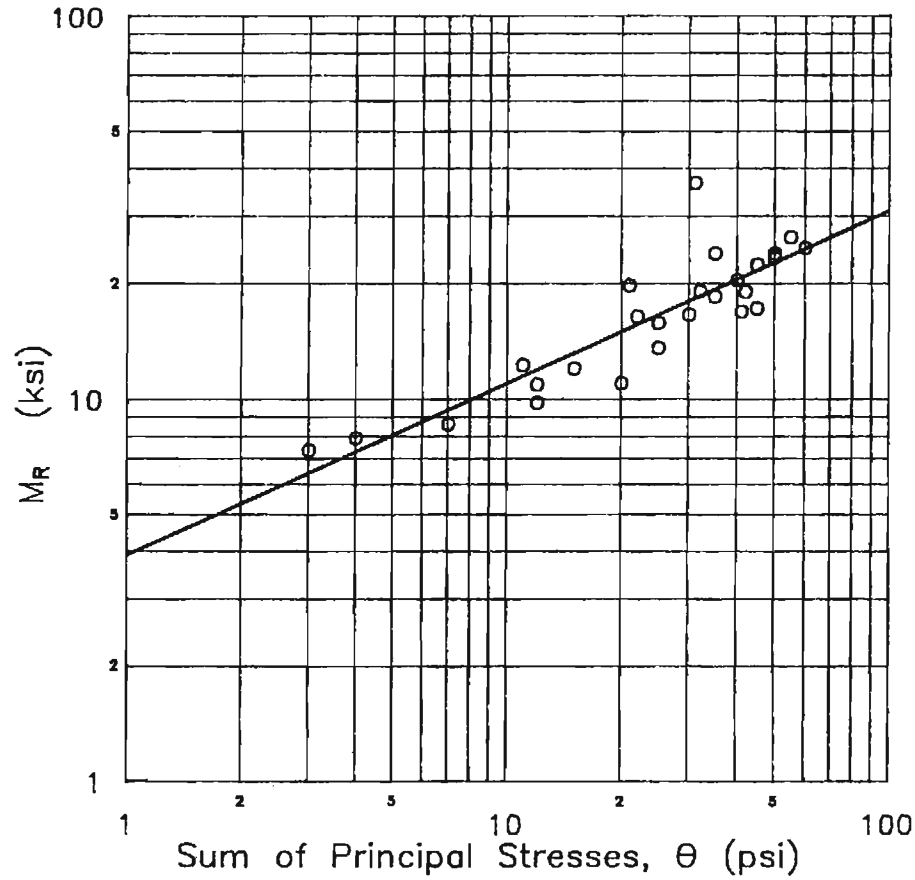


$$M_R = 3.568 \times \Theta^{0.550}$$

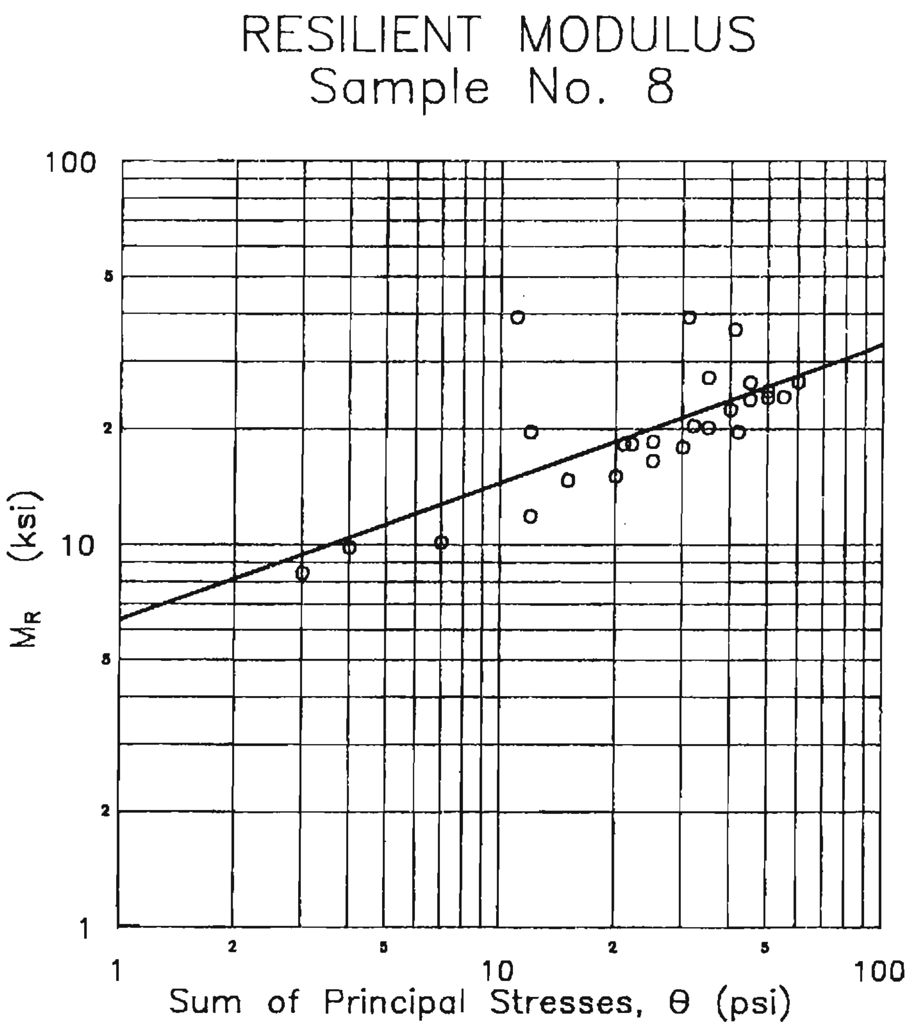


$$M_R = 7.278 \times \theta^{0.374}$$

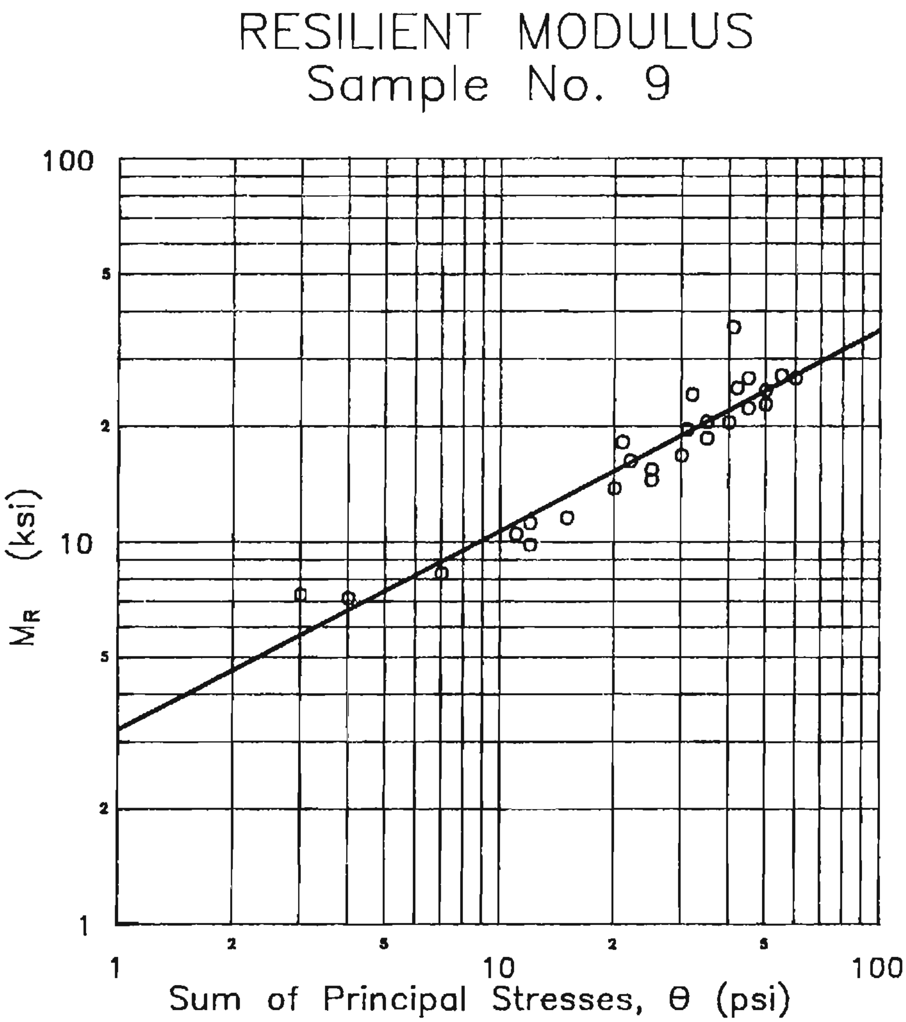
RESILIENT MODULUS
Sample No. 7



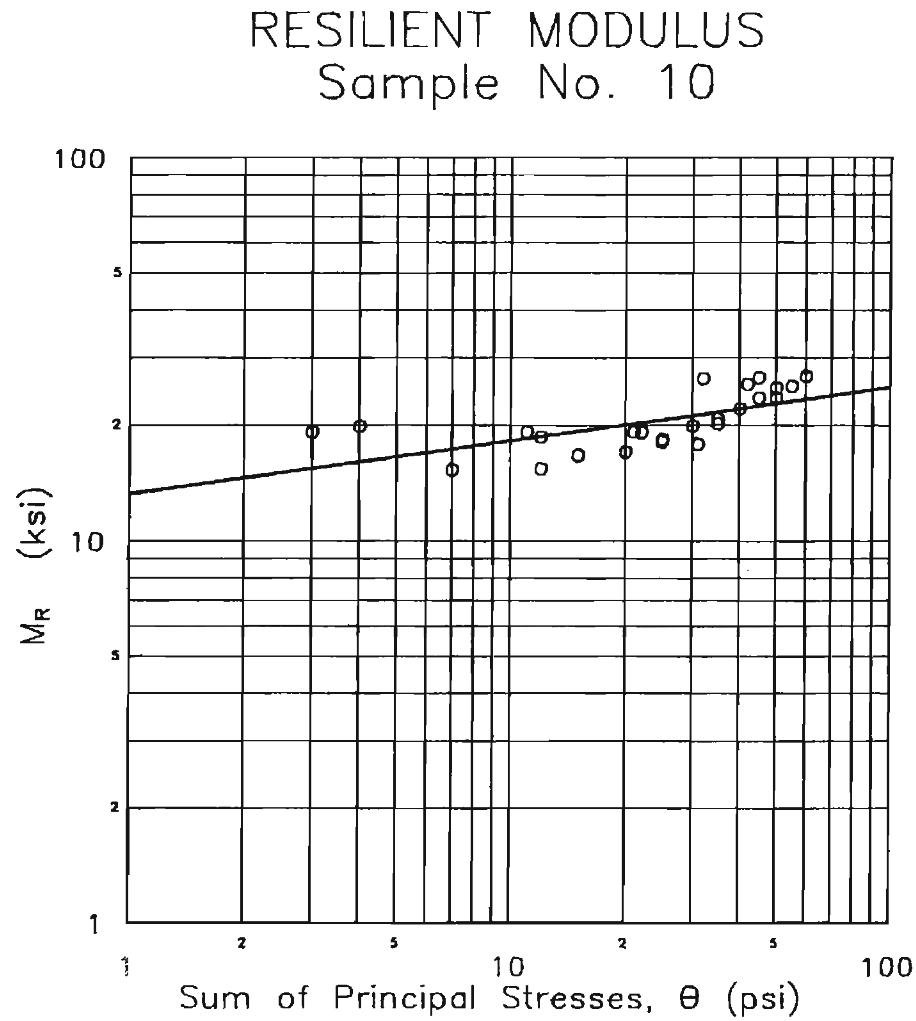
$$M_R = 3.910 \times \Theta^{0.449}$$



$$M_R = 6.345 \times \Theta^{0.359}$$

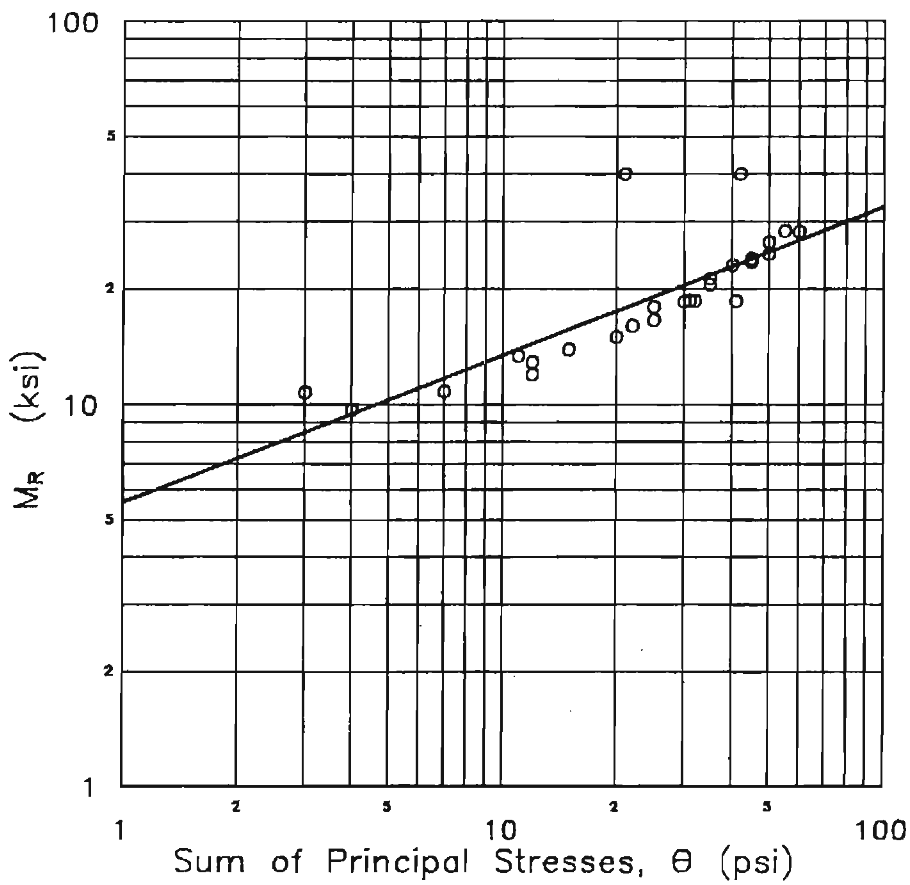


$$M_R = 3.208 \times \Theta^{0.523}$$

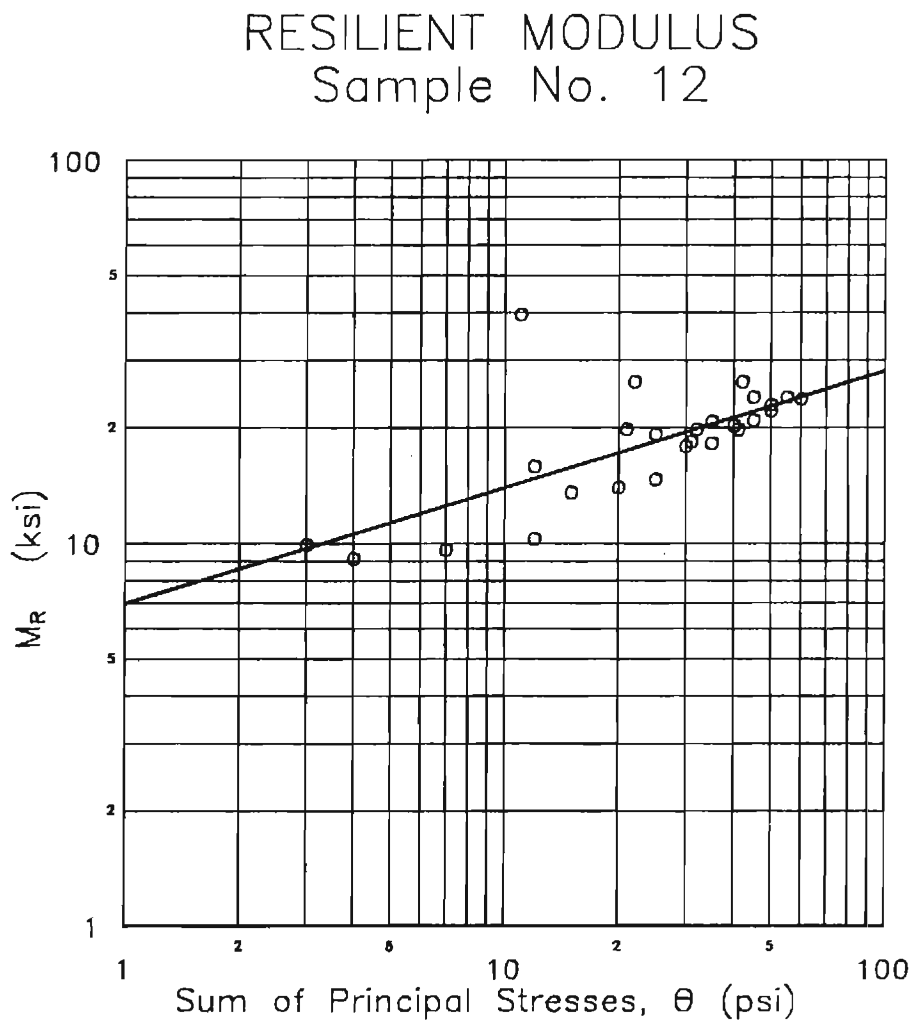


$$M_R = 13.207 \times \theta^{0.139}$$

RESILIENT MODULUS
Sample No. 11

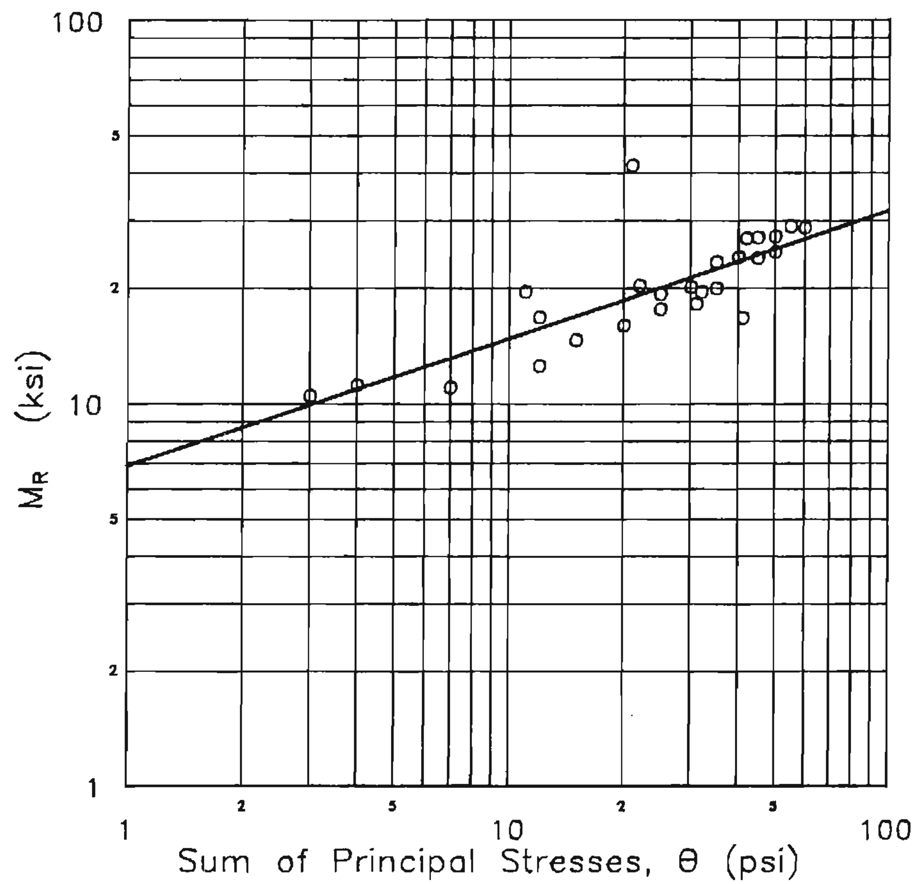


$$M_R = 5.524 \times \Theta^{0.385}$$

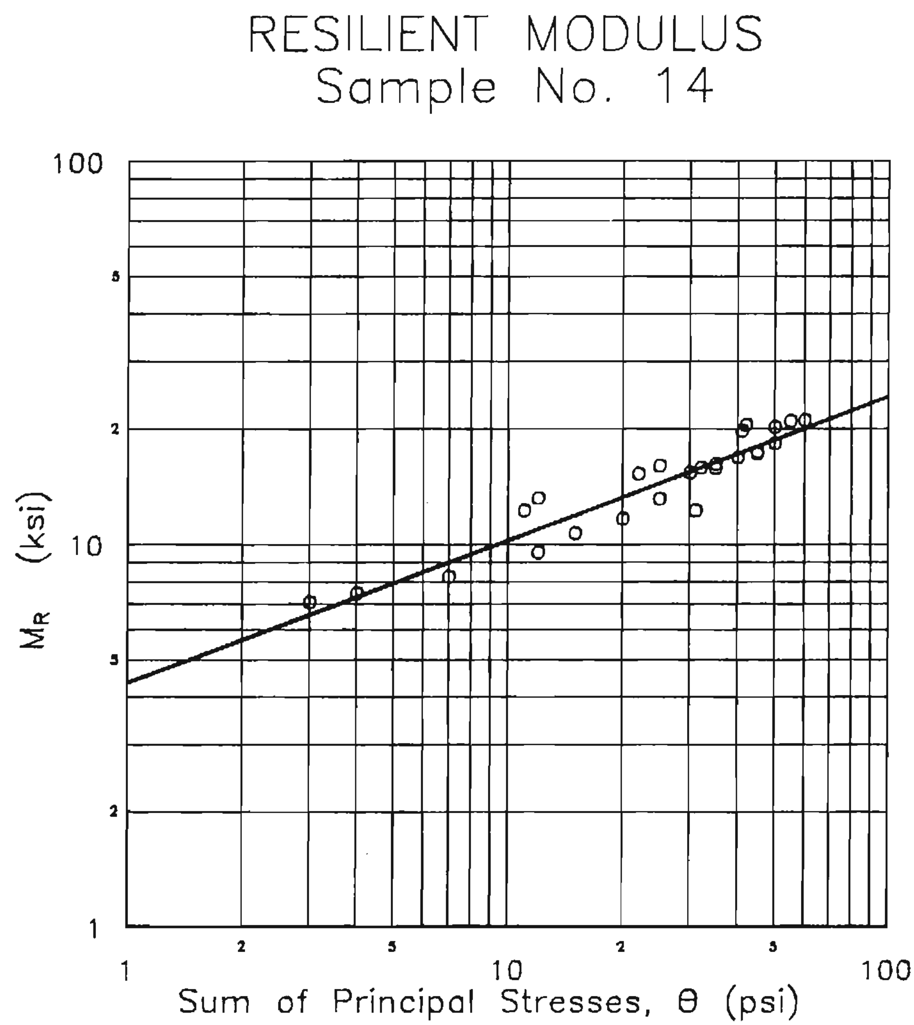


$$M_R = 6.935 \times \theta^{0.304}$$

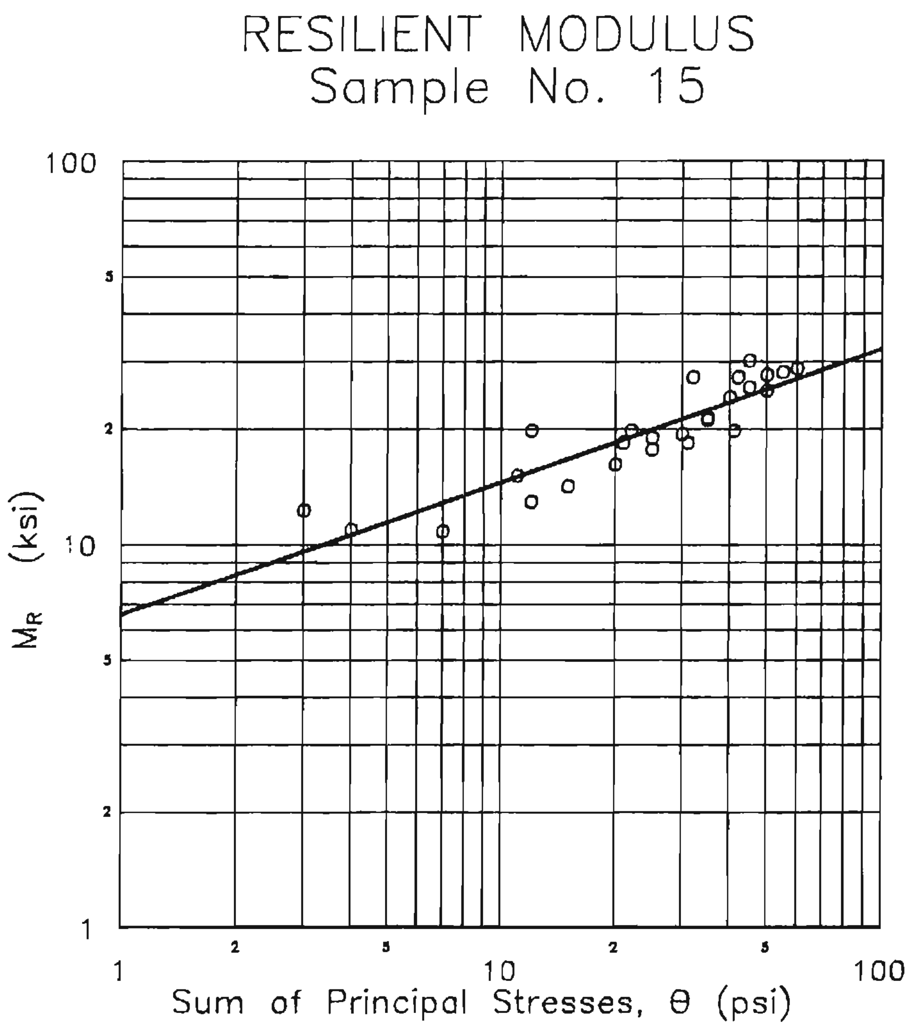
RESILIENT MODULUS
Sample No. 13



$$M_R = 6.866 \times \theta^{0.333}$$

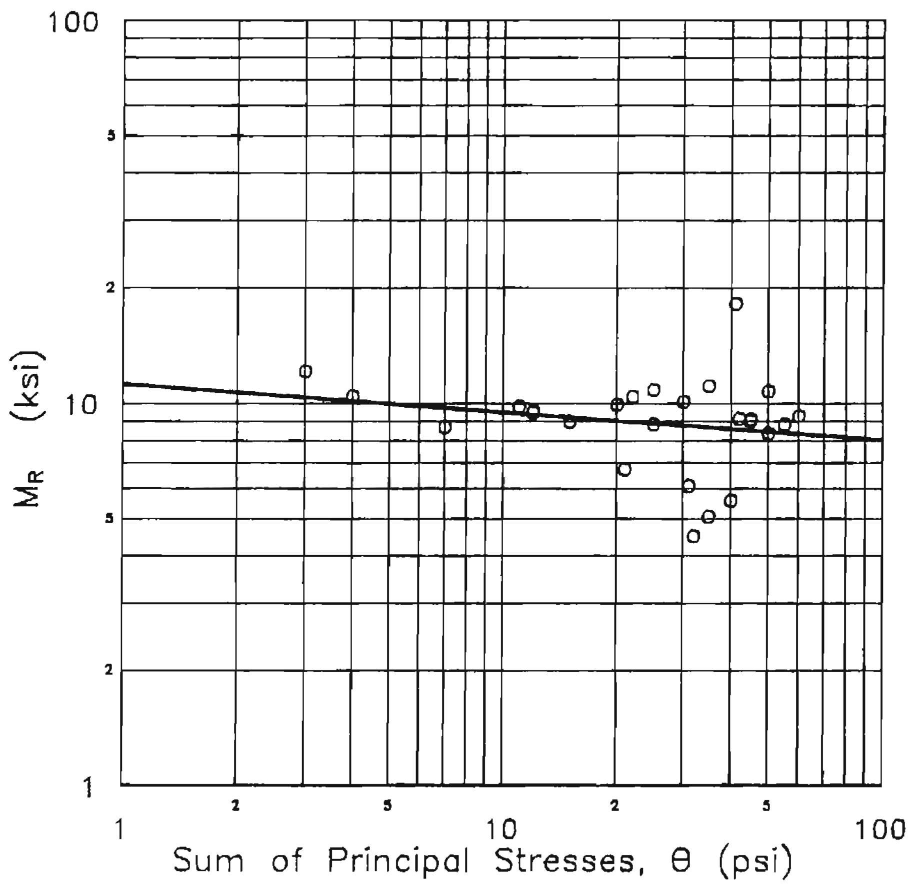


$$M_R = 4.339 \times \Theta^{0.374}$$

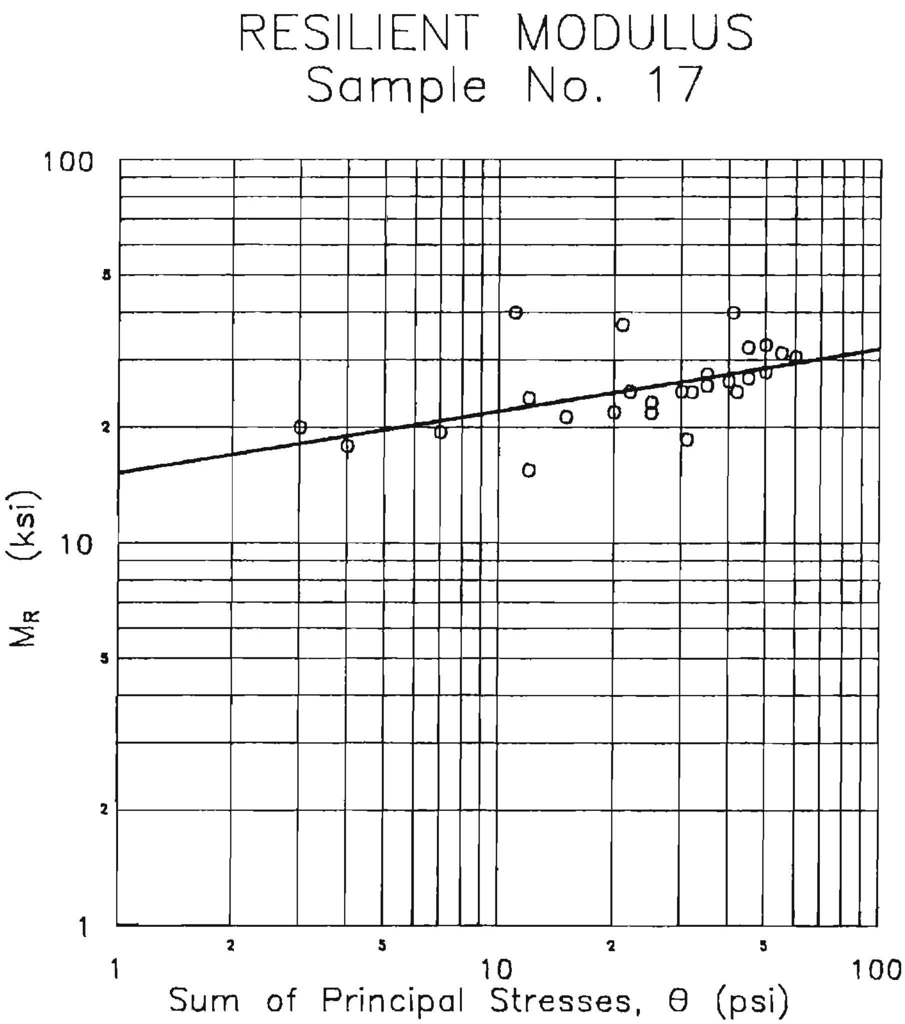


$$M_R = 6.544 \times \theta^{0.346}$$

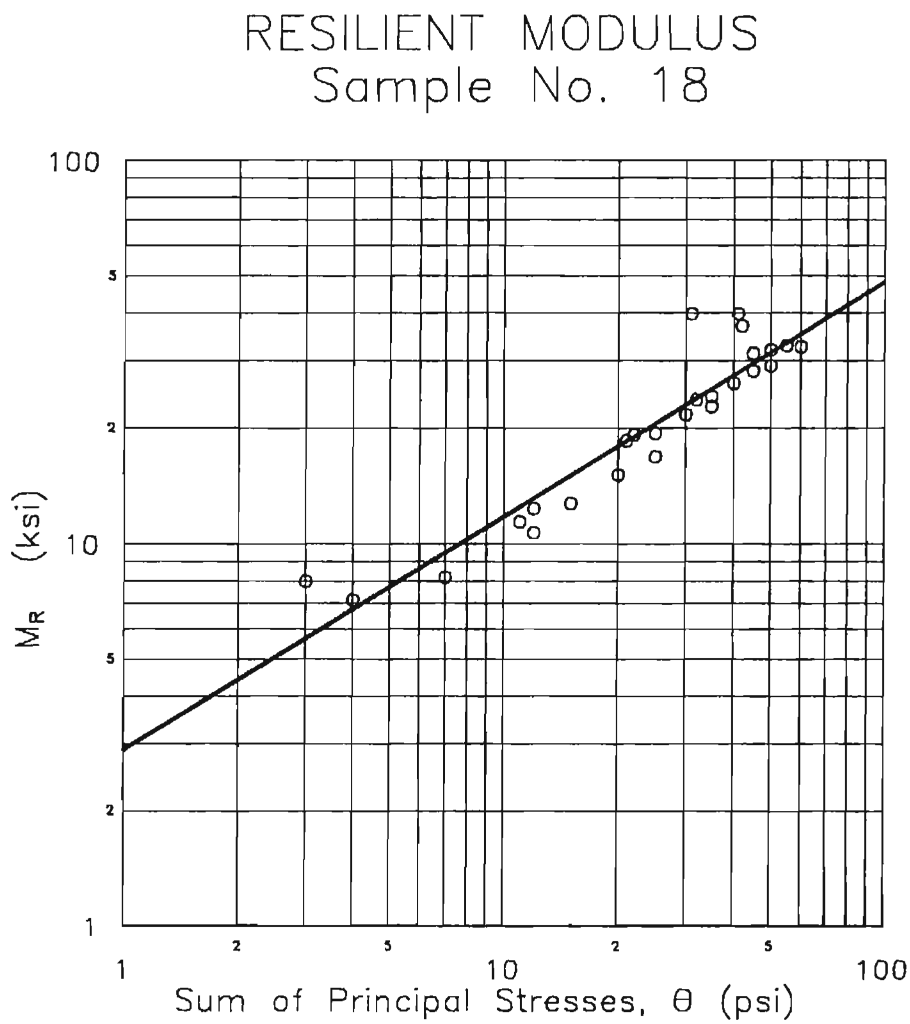
RESILIENT MODULUS
Sample No. 16



$$M_R = 11.192 \times \theta^{-0.073}$$

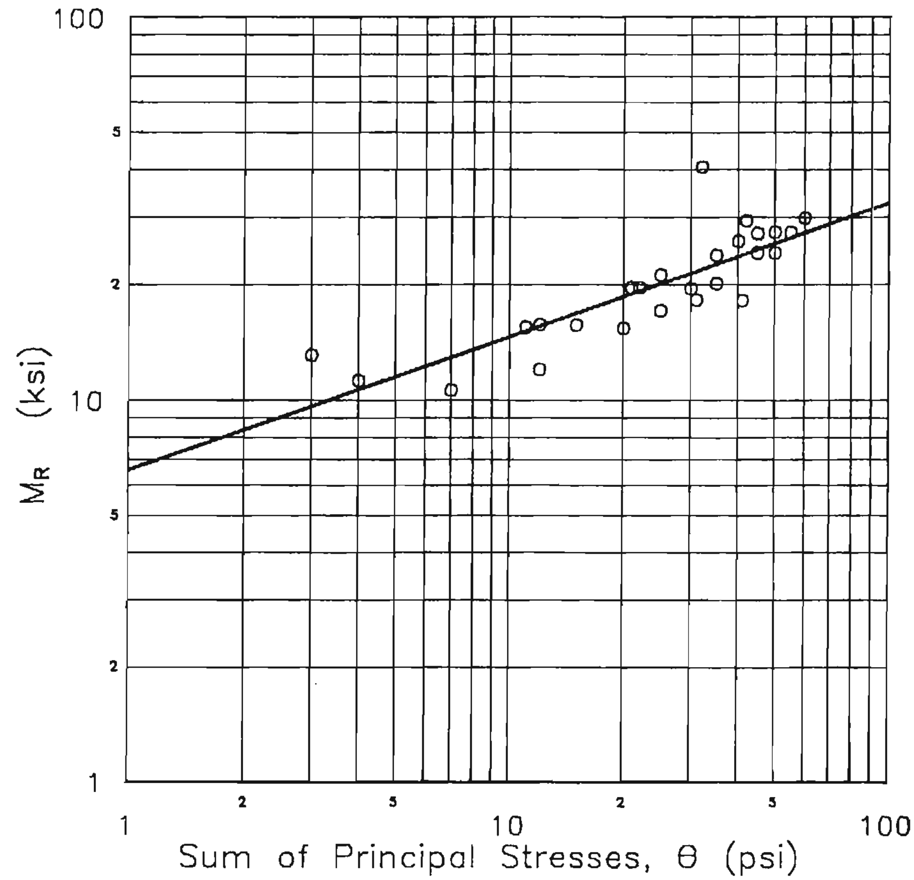


$$M_R = 15.211 \times \Theta^{0.162}$$

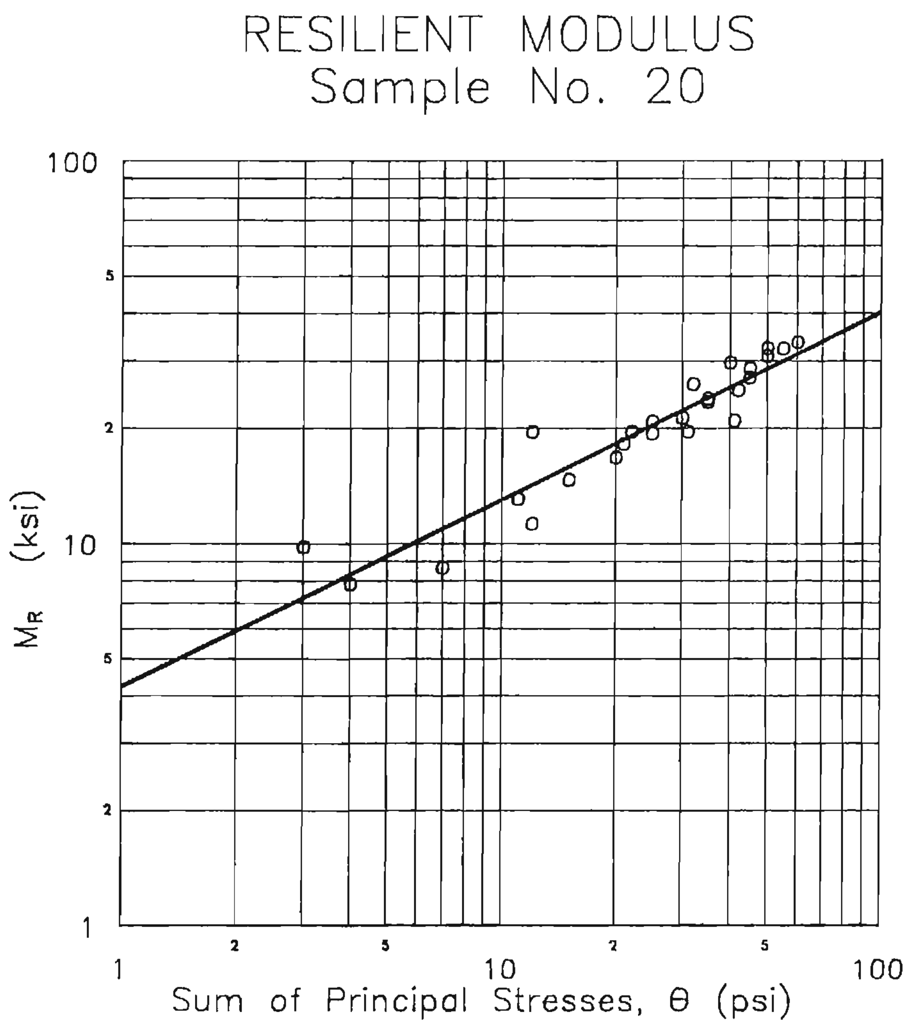


$$M_R = 2.880 \times \theta^{0.610}$$

RESILIENT MODULUS
Sample No. 19



$$M_R = 6.565 \times \theta^{0.348}$$



$$M_R = 4.196 \times \theta^{0.490}$$