CONTRACT REPORT NO. 3-145

BEHAVIOR OF STABILIZED SOILS UNDER REPEATED LOADING

Report I

BACKGROUND, EQUIPMENT, PRELIMINARY INVESTIGATIONS, REPEATED COMPRESSION AND FLEXURE TESTS ON CEMENT-TREATED SILTY CLAY

by

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ABSTRACT

Current methods of pavement design which make provision for the use of stabilized soils as components of the pavement structure generally base the selection of both quality and thickness of those materials on static tests such as the CBR procedure. In military operations these tests are desirable because of their simplicity. However it appears desirable to establish the validity of such procedures through the performance of tests which more closely simulate the loading conditions encountered in the field, i.e. dynamic or repeated load type tests. Thus the objectives of these studies are to evaluate the behavior of stabilized soils under dynamic loading conditions and develop improved criteria for quality design and suitable thickness selection within a more rational framework.

More specifically the investigation is concerned with an examination of the soil stabilization requirements established by the Corps of Engineers for military roads and airfields in the theater of operations within the above noted framework. The specific goals for the period covered by this report are:

1. To establish appropriate soil types, stabilizers, and treatment conditions to be employed in the test program.
2. To evaluate reference properties for the soils, stabilizers, and treatment conditions established.
3. To adapt existing test equipment to the special requirements of stabilized soils.
4. To conduct investigations for establishment of the limits of behavior and for development of measuring techniques required for use with treated soils.
5. To initiate systematic studies of stabilized soil in repeated compression and flexure.

Two soils were selected for study, namely Vicksburg Silty Clay (CL) and Vicksburg Buckshot Clay (CH) since there is considerable performance data on these materials and because both, through suitable treatment,

fall within the range of stabilization requirements set forth by the Corps of Engineers.

From the preliminary testing program cement treatment levels of 3 percent for the Vicksburg silty clay and 6 percent for the Vicksburg buckshot clay were determined as adequate to meet the stabilization requirements (CBR = 20 after treatment).

During this past year the majority of dynamic testing was limited to tests on the treated silty clay and included both repeated load axial compression tests on cylindrical specimens and repeated flexure tests on beam specimens. Studies included (1) influence of stress intensity on behavior in repeated compression, (2) influence of curing time on behavior in repeated compression, and (3) fatigue behavior in repeated flexure. Generally the number of load repetitions in the dynamic tests was limited to about 24,000 stress applications. This number is considerably more severe, however, than those established in the current Corps criteria.

Results of the stress intensity study indicated that the modulus of resilient deformation (analogous to an elastic modulus) of the treated silty clay was sensitive to stress intensity, decreasing in magnitude with increase in axial stress. At axial stresses greater than 25 psi, however, the resilient modulus again increased with further increase in stress. In addition, repeated compressive stresses up to 70 percent of the ultimate strength at the start of the test had no significant affect on strength.

The studies of the influence of curing time indicated that strength progressively increases and strain at failure progressively decreases with increase in curing period. Specimens of all ages were able to withstand 24,000 applications at compressive stresses equal to 80 percent of the strength at the start of loading. Of interest in this study is the fact that limited stress applications at early curing times may be beneficial in terms of ultimate performance.

While the results of the flexure tests are limited, the data obtained thus far indicate that the cement-treated silty clay exhibits fatigue in that the higher the flexural stress the fewer the number of repetitions to failure. Of interest also is the fact that the tensile strain at failure in the beam specimens was of the order of one percent of the compressive strain at failure in the cylindrical specimens.

In general the results obtained thus far indicate that cement-treated soil designed to meet the Corps of Engineers' criteria for CBR and compressive strength can safely withstand repeated compressive and flexural stresses of the magnitude and number prescribed for different classes of military operations, at least in the case of laboratory prepared specimens.

The studies have indicated, however, that more detailed investigation of the influence of water content, mixing procedures and method of compaction are required since the data obtained thus far show that these variables have a significant effect on the strength and resilience characteristics of the cement-treated silty clay.

Extension of these studies to the cement-treated buckshot clay is also indicated so that the variable of soil type can be considered. In addition,studies of the use of lime as an admixture could also appear warranted for both types of soil because of potential benefits in terms of field construction.

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FOREWORD

This report presents the results of studies conducted at the University of California, Berkeley, under Contract No. DA-22-079-eng-414 for the Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi, during the period 17 August 1964 - 16 August 1965. This work was sponsored by the U. S. Army Materiel Command, DA Project No. 1-V-0-21701-A-046-05.

This study was carried out under the supervision of Professors James K. Mitchell and Carl L. Monismith of the Department of Civil Engineering. Dr. Chih-Kang Shen and Mr. Mian-Chang Wang conducted the laboratory testing program. Technical assistance in the development of apparatus and measuring systems was provided by Mr. Clarence K. Chan.

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I. INTRODUCTION

Although stabilized soils have been used for many years in pavement structures for both military and non-military applications, nearly all evaluations of the mechanical properties of these materials have been made under static loading conditions, and behavior under dynamic loading has received little attention. Furthermore the quality design (i.e., treatment level, compaction conditions, etc) of stabilized soils and the determination of the effects of stabilization on properties are usually based on tests such as unconfined compression, California Bearing Ratio, or stabilometer for strength, and wet-dry and freeze-thaw for durability. These types of tests are useful for studies of such factors as permanent deformation, ultimate strength, and the effects of adverse environmental conditions.

While the importance of these factors with respect to pavement design and performance certainly cannot be overlooked, it would appear that dynamic behavior of stabilized soils is of at least equal importance, since roads and airfields are subjected to a continuing series of rapidly applied short duration loads under the action of traffic. It is reasonable to expect, therefore, that these repetitive stresses may lead to property changes or fatigue failures in stabilized soils just as in the case of other paving materials. Current Corps of Engineers' design criteria for stabilized roads and airfields take recognition of this fact through specification of numbers of coverages for the design life of a pavement. At the same time little direct data are available to show the effects of repeated stresses on such treated soils.

Unquestionably, simple static load tests such as the CBR are considerably easier to perform than repeated loading tests. Thus it is to be hoped, particularly for military operations, that the simpler tests provide an adequate measure of probable pavement performance under dynamic as well as static loads. The validity of such an approach can only be determined after studies of the behavior of stabilized soils under dynamic loading. Furthermore, new approaches to pavement design based on the application of layered system elastic theory require knowledge of elastic properties which are probably best determined using dynamic loading methods.

The Corps of Engineers (1963) has established soil stabilization requirements for military roads and airfields in the theater of operations. These requirements are based on certain minimum initial soil strength conditions prior to treatment, maximum treatment levels, and minimum strengths at the end of a specified curing period. The CBR test is used as the basic indication of quality, and the particular values required depend on the operational category of the road or airfield. Limiting values of wheel load and numbers of coverages are specified.

This report presents the results of studies conducted to evaluate soils stabilized in accordance with these criteria under repeated loading and subjected to stresses of intensity and duration representative of those to which the prototype stabilized materials will be subjected. The long range objectives of the research are to develop improved criteria for quality design of stabilized soils and to establish suitable thickness design procedures for stabilized soils pertinent to the military road and airfield stabilization problem and requirements. The specific goals for the period covered by this report, 17 August, 1964 - 16 August, 1965 were:

1. To establish appropriate soil types, stabilizers, and treatment conditions to be employed in the test program.
2. To evaluate reference properties for the soils, stabilizers and treatment conditions established.
3. To adapt existing test equipment to the special requirements of stabilized soils.
4. To conduct investigations for establishment of the limits of behavior and for development of measuring techniques required for use with treated soils.
5. To initiate systematic studies of stabilized soil in repeated compression and flexure.

In all studies carried out during the period covered by this report, portland cement was used as the stabilizer. Where appropriate, the results of studies carried out on soil-cement of a quality considerably superior to that of cement treated soil sufficient to meet Corps of Engineers' Criteria for Theater of Operations use are included in order to illustrate significant features. These studies on regular soil-cement are described in detail in "Behavior of Cement Stabilized Soil Under

Repeated Loading" by Chih-Kang Shen, a dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, University of California, Berkeley, September, 1965.

II. BACKGROUND INFORMATION

Field Observations

Field performance studies of pavements containing stabilized soil sections evaluate behavior under repeated loading conditions, since the effects of traffic are observed. Special test section evaluations and studies of existing roads and airfields have demonstrated clearly that stabilization of bases, subbases, and subgrades gives improved performance over the untreated materials alone (Highway Research Board, 1962; Hveem et al, 1963; Mitchell and Freitag, 1959; FAA, 1964). Nickols (1962) notes that treated subgrades used under conventional roads have proved of value in reducing pavement deflections under traffic.

Investigations of a lime-stabilized soil at the Waterways Experiment Station (1962, 1963) indicate that stabilized layers would permit a 20 to 30 percent thickness reduction from usual flexible-pavement design requirements. In all cases, the CBR of the stabilized layer was greater than 40. Because pavements containing stabilized soils must contain at least two distinct layers, however, it has been difficult to isolate the true dynamic behavior of each specific component.

Dynamic testing of unsurfaced test sections of a quality comparable to that required for Forward Area Stabilized Soil Roads has been carried out by the Road Research Laboratory in Great Britian and by the Corps of Engineers. Analysis of the results (Mitchell and Freitag, 1959) suggested that in the case of very weak subgrades (CBR less than 3) thickness requirements using soil-cement may be slightly less than for flexible pavements according to the CBR design curves. These few field studies have provided only limited data on stabilized soil behavior under traffic; more full scale field tests are needed. Because of the high costs and relatively long time periods involved in such tests, however, increasing use has been made of laboratory repeated load testing in an effort to simulate field conditions.

Repeated Loading Studies

The assessment of the destructive effects of a varying sequence of loads to which a pavement is subjected and the changes of environment during the life of the pavement is still a formidable problem that must be solved if rational methods of pavement design are to be developed. The results of recent studies indicate that many failures can be attributed to fatigue resulting from excessive elastic deflections of the pavement under moving loads. Use is now being made of elastic layer theory to analyze stress-deformation behavior (see, for example, Conference Proceedings, Structural Design of Asphalt Pavements, University of Michigan, 1962).

Appropriate material constants must be selected if elastic theory is to be correctly applied. Approaches for evaluating these constants for different components of the pavement include vibratory testing, plate load testing, conventional slow rate of loading tests, and repeated loading tests. Of these methods, repeated load tests are probably the most representative of actual traffic effects. Furthermore, even for cases wherein it is desired to examine material behavior without regard to theoretical considerations (as may turn out to be the case for relatively low-quality materials such as those adequate to satisfy Theaters of Operations criteria) the repeated loading test still provides a valuable indication of probable behavior. Variables can be studied independently without resorting to expensive test sections. Already, as a result of such studies, the importance of several factors in influencing the behavior of both untreated and treated soils has been established.

Untreated Soils

Detailed studies of the effects of repeated loading on the strength and deformation characteristics of compacted clay have been made at the University of California (Seed, Chan, and Monismith, 1955; Seed and McNeill, 1956; Seed, McNeill, and deGuenin, 1958; Seed and Chan, 1958; Seed and Chan, 1961; Seed, Chan, and Lee, 1962). Some of the most significant conclusions from these investigations are:

1. The deformation of compacted silty clay specimens may be greater when subjected to repeated stress applications than when subjected to a sustained stress of the same magnitude. The strength after repeated loading, as measured in normal compression tests, may, however, exceed that of previously unloaded specimens.

2. A large number of repeated stress applications can cause increased stiffness of the soil. This stiffness may be destroyed, however, as a result of further large deformations.
3. The amount of deformation under repeated load application is dependent on frequency of loading in the case of thixotropic soils.
4. Stress history influences the magnitude of deformation under repeated loading. Repeated application of stresses of low intensity may improve the resistance of the soil against high intensity stresses in the future.
5. Tests on the AASHO Road Test clay showed that resilient deformation* varied with the number of load applications. The greatest resilient deformation occurred somewhere between 1 and 5000 load applications, depending on the initial conditions of the soil.
6. The resilient deformation of compacted clay varies with the magnitude of the applied deviator stress intensity. Fig. 1 shows that at low stress intensities the resilient modulus of AASHO Road Test subgrade soil decreases rapidly with increasing deviator stress. When deviator stress is greater than 15 psi, however, the resilient modulus increases slightly with increasing deviator stress. This increase may be attributable to densification of the sample under high repeated loading stress intensity.
7. Samples compacted wet of optimum water content using a method producing a dispersed structure exhibited larger resilient deformations and lower moduli than samples compacted using a method producing a flocculent structure.

In the case of cohesionless soils the effect of confining pressure must be considered, since its influence on resilient modulus may be very significant. Trollope, Lee and Morris (1962) observed that the modulus of resilient deformation increased with an increase in confining pressure and was independent of the applied stress level for a sand subjected to slow repeated cyclic loads.

Mitry (1962) found from triaxial repeated loading tests on dry granular material that the modulus of resilient deformation, M_R, varies with effective confining pressure according to

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*In keeping with the terminology introduced by Hveem (1955), recoverable deformations are referred to herein as resilient deformations and the term resilient modulus designates the applied stress divided by the recoverable strain.

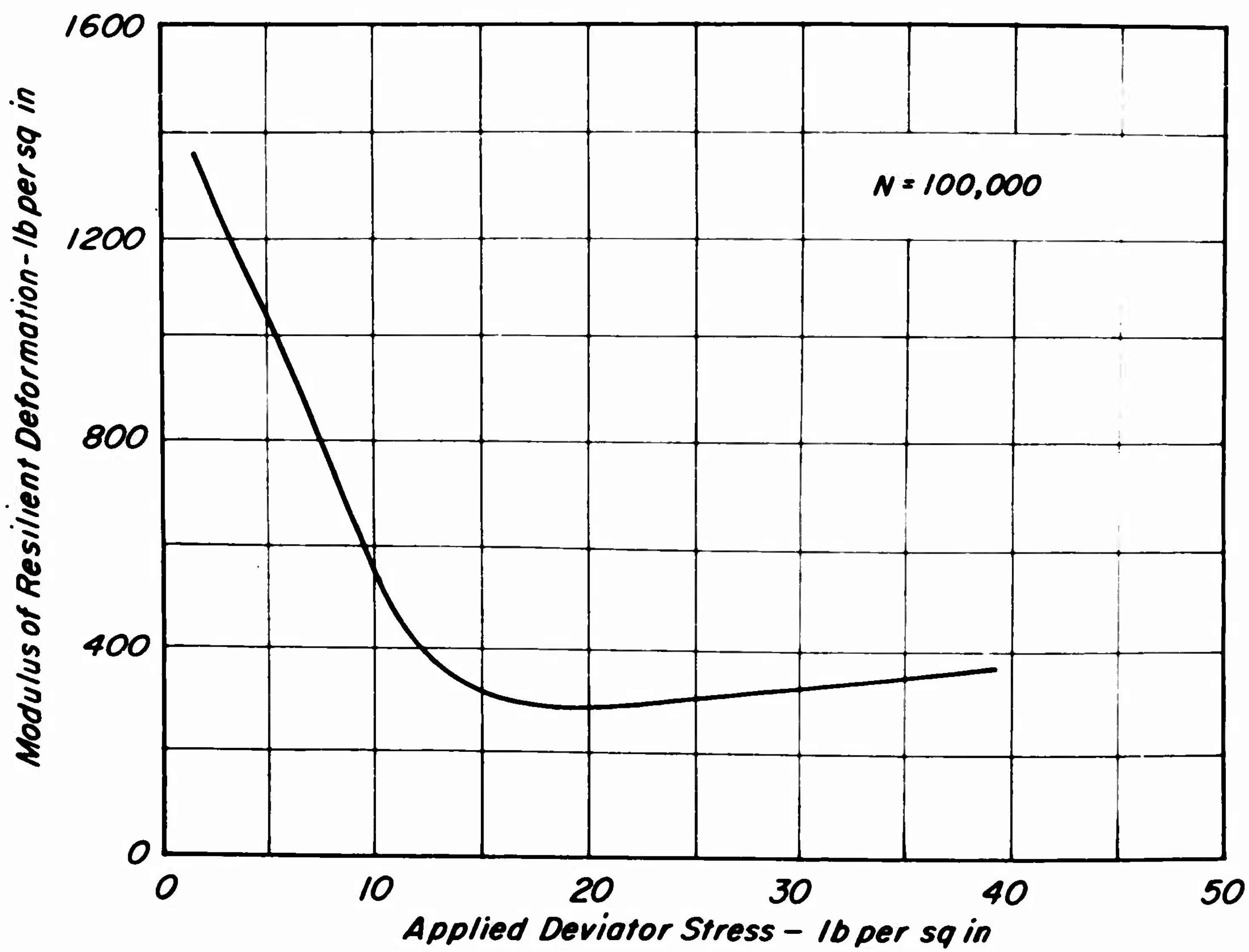

Fig.1-EFFECT OF STRESS INTENSITY ON RESILIENCE CHARACTERISTICS-AASHO ROAD TEST SUBGRADE SOIL.

(After Seed, Chan & Lee 1962)

$$M_R = K \sigma_3^{\,n} \tag{1}$$

where K and n are constants, and σ_3 is the effective confining pressure in psi. He found K = 12,500 and n = 0.35 for a uniform, rounded sand and K = 7000 and n = 0.55 for a well-graded, crushed gravel meeting the State of California specifications for a Class II aggregate base.

Stabilized Soils

Two small-scale laboratory studies on the effect of repeated loading on stabilized soils have been carried out at the University of California (Gandais, 1962; Robichon, 1963). In the first study, a lean clay soil was treated with 3.5 percent lime or 10 percent cement. Specimens were compacted at optimum moisture content using kneading compaction and subjected to repeated load compression tests after various curing times. A repeated load stress of about 15 percent of the static compressive strength was applied at a frequency of 20 per minute for a duration of 0.25 seconds until 100,000 repetitions had been obtained.

The results of this study showed:

1. Strength was increased by as much as 20 percent as a result of repeated loading. The effect was more marked for cement-treated specimens than for those treated with lime, and the effect decreased with increased curing time.
2. Curing times in the range of 1 to 28 days had little effect on the total or resilient deformation at the end of 100,000 load repetitions.
3. In general the resilient deformation decreased slightly with number of repetitions, whereas the total deformation increased slightly.

In the second study, samples of AASHO Road Test subgrade soil were treated with 10 percent cement over a range of water contents and subjected to repeated load stresses of 30 psi. Results showed:

1. The strength of specimens not soaked prior to testing was increased by 30 to 50 percent as a result of repeated loading. The strengths of soaked samples were little affected by repeated loading.
2. Both resilient and total deformation remained essentially constant during repeated loading and no fatigue failures were observed.

As noted in the introduction, a much more detailed study of the behavior of soil-cement in repeated compression and flexure has been completed (Shen, 1965). The results of this work will not be summarized here, but pertinent findings will be presented later in this report in appropriate sections.

Dunn (1960) tested sand-clay mixtures stabilized with portland cement under dynamic conditions. Cylindrical specimens were subjected to a 40 psi repeated compressive stress at a frequency of 106 cycles per minute. This loading had little effect on the physical properties, a result attributed to the fact that the repeated load stress was only 2 to 10 percent of the strength of the material. Dunn also determined the dynamic modulus using sonic velocity measurements on beams. He found the modulus determined in this manner to be twice as great as that determined as a secant modulus for compression specimens. This probably resulted from the fact that the dynamic test measures only elastic, time-independent properties, whereas the static test includes the influence of visco-elastic effects. Dunn observed also that the dynamic modulus increased as a result of soaking prior to testing. It was suggested that this may result from the fact that water is incompressible, and the higher the degree of saturation the greater the sonic velocity.

Whittle and Larew (1964) tested micaceous soils stabilized with 5 percent Type III portland cement. Repeated load stress-strain curves were obtained by subjecting a series of identical samples to varying levels of repeated deviator stress and determining the equilibrium strain for each stress level. These values of strain were then used to plot the repeated load stress-strain curve. The results showed the ultimate strength as determined from the repeated load procedure to be considerably less than the ultimate strength of identical samples measured using conventional loading apparatus. The strain at failure remained nearly the same under both types of loading. They concluded that samples of this treated soil would fail if subjected to repeated load stresses of 60 percent of the static strength.

Ahlberg and McVinnie (1962) studied the fatigue behavior of lime-fly ash-aggregate mixtures using beam specimens. They concluded that the number of cycles required to cause failure, N, depended on the ratio of the maximum applied tensile stress, $\sigma_{T_{max}}$, to the modulus of rupture, M_{re}, according to

$$\frac{\sigma_{T_{max}}}{M_{re}} = 1.0 - 0.0798 \log N \qquad (2)$$

These previous investigations on the behavior of untreated and treated soils have provided information that may be summarized briefly as follows. The deformation of untreated cohesive soils under repeated loading may be greater than for the soil subjected to static loading. Its stiffness and strength may be increased as a result of repeated loading. Stress history may influence the subsequent behavior of specimens under the action of repeated loads, with a number of low-intensity stress applications producing improved resistance to deformation under higher intensities of stress. Resilient moduli of cohesive soils are dependent on stress intensity, water content, and method of compaction. The resilient modulus of untreated cohesionless soils is dependent on confining pressure.

In the case of stabilized soils, the strength may be increased or decreased as a result of repeated compressive stresses. At low stress intensities, repeated loading may have beneficial effects on strength and stiffness. Resilient moduli determined in repeated loading tests may be significantly greater than those determined using normal strength tests.

III. SELECTION OF TEST CONDITIONS

Using current concepts of military operations in forward areas, the Corps of Engineers (1963) has defined various classifications of roads and airfields with respect to specific operational functions and use characteristics. Requirements for stabilization in terms of strength and thickness parameters adequate to satisfy these operational needs were developed using a thickness-of-layer approach as opposed to a flexural-strength approach. Maximum limits of curing time and quantity of stabilizing material to achieve the stabilization objectives are also indicated. Consideration has been given by the Corps to the need to improve the strength of wet weak soils and to waterproof and dustproof soils possessing adequate natural strength. Only stabilization directed at meeting the need for strength improvement is considered in this report.

The operational characteristics needed for design of stabilized-soil roads in Forward Areas are given in Table 1 and for military airfields in the Theater of Operations in Table 2. These tables provide values for loading parameters, traffic intensity, and design life.

The short design life, the need to keep treatment levels to a minimum, the relatively weak condition of the soils to be stabilized (thus indicating weak subgrades), and the relatively large tolerable rut depths of 2 to 4 in. and elastic deformations of up to 1 in., governed the Corps of Engineers' selection of the thickness-of-layer design in preference to a flexural-strength method. Thus the stabilized layer must possess a shear strength adequate to resist, within itself, the stress of the applied load; and it must be sufficiently flexible that the deformation permitted by the weaker underlying soil does not cause the surface layer to fail. No benefit in load distribution due to any flexural rigidity of the structural layers is assumed.

On this basis, minimum strength requirements for stabilized soil and required thickness for stabilized layers have been estimated for the different classes of roads and airfields and are listed in Table 3. Also indicated in Table 3 are controlling initial soil conditions, curing terms, and treatment levels. Stabilization of soils with initial CBR values less than those indicated is considered impractical. Upper treatment levels were selected from a logistical standpoint on the basis that the

TABLE 1

OPERATIONAL CHARACTERISTICS FOR STABILIZED-SOIL ROADS IN FORWARD AREAS

Road Class	Function	Controlling Initial Soil Condition	Representative Using Vehicles*	Loading Parameters: Maximum Single-Axle Load,** lbs	Loading Parameters: Tire Pressure, psi	Intensity of Traffic: No. of Passes (All Vehicles)	Intensity of Traffic: Period of Use
1-R	Provide immediate access by combat elements to specific sites such as assembly, bivouac, artillery, bridge construction, missile launching sites, etc.	Water content at field maximum (variable rating cone index from 20 to 50 depending on soil type; equivalent to CBR of about 1)	Cargo trucks up to 5 tons	13,000 with single wheel, or 15,000 with dual wheel	70	200	2 weeks
2-R	Provide suitable all-weather supply road for division operations (i.e. serve as a division main supply route)	CBR = 4 (soil moderately wet with limited supporting ability)	Same as above	Same as above	Same as above	6150/	2 months

* Considers wheeled vehicles only.

** Maximum axle loads based on maximum 7-1/2-ton pay load for 5-ton trucks.

/ The total number of vehicle passes is assumed to consist of about 5000 with 2-1/2-ton trucks and about 1150 with 5-ton trucks. This is based on an estimated 450 tons per day supply requirement for an infantry division in an attack situation and assumes 75 percent of load hauled by 2-1/2-ton trucks (average 4-ton pay load) and 25 percent by 5-ton trucks (average 6-ton pay load). For design purposes, the traffic can be expressed in terms of equivalent passes of some representative basic load and wheel configuration, based on a method developed by WES for highway design involving mixed traffic (U. S. Army Engineer Waterways Experiment Station, CE, Revised Method of Thickness Design for Flexible Highway Pavements at Military Installations. Technical Report No. 3-582, Vicksburg, Miss., August 1961.). Using this procedure, the intensity of traffic is calculated to be equivalent to about 1300 passes of an 18,000-lb, single-axle, dual-wheel configuration on an 11-ft-wide roadway with wheel wander distributed normally in a path about 40 in. wide. A similar computation results in 44 equivalent passes of the basic load for the class 1-R road.

(From Waterways Experiment Station Misc. Paper No. 3-605, 1963)

TABLE 2

OPERATIONAL CHARACTERISTICS FOR MILITARY AIRFIELDS IN THE THEATER OF OPERATIONS

Airfield Class	Function	Controlling Initial Soil Condition	Representative Types of Using Aircraft	Critical Loading Parameters: Gear Load and Configuration	Critical Loading Parameters: Tire Pressure, psi	Intensity of Traffic: No. of Coverages	Intensity of Traffic: Period of use
1-A (Forward area)	Short-life, emergency-operation field for Army liaison and light transport aircraft	Minimum CBR of 4	AC-1* AO-1* U1-A L-series	10,000 lb (single-wheel)	35	40	2 to 3 weeks
2-A (Support area)	Minimum-operation base for medium cargo and fighter-type aircraft	Minimum CBR of 4	C-130* C-131 C-119 C-123 F-100 series	40,000 lb (single-tandem; 60-in. c-c, 400-sq-in. contact area)	50	200	4 to 6 months
3-A (Rear area)	Minimum-operation base for heavy cargo aircraft	Minimum CBR of 4	C-124*	94,000 lb (twin; 44-in. c-c, 630-sq.-in. contact area)	75	200	4 to 6 months

* Critical aircraft.

(From Waterways Experiment Station Misc. Paper No. 3-605, 1963)

TABLE 3

SUMMARY OF SOIL STABILIZATION OBJECTIVES

Military Road or Airfield Class	Controlling Initial Soil Condition CBR	Estimated Minimum Strength Requirments for Stabilized Soil: CBR	Estimated Minimum Strength Requirments for Stabilized Soil: Approximate Equivalent Unconfined Compressive Strength psi	Estimated Required Thickness of Stabilized-Soil Layer in.	Desirable Maximum Limits to Achieve Required Stabilization: Curing Time hr	Desirable Maximum Limits to Achieve Required Stabilization: Treatment Level, % Soil Weight
Primary Function of Stabilization: Strength Development						
Roads						
1-R (Access)	1	5	25 to 30	10	2	8
2-R (Division MSR)	4	20	80 to 100	12	24	6
Airfields						
1-A (Forward area)	4	(No requirement for strength development)				
2-A (Support area)						
With M8 mat	4	(No requirement for strength development)				
Without M8 mat	4	10	45 to 55	9	24	6
3-A (Rear area)						
With M8 mat	4	15	60 to 80	12	24	6
Without M8 mat	4	20	80 to 100	22	24	6

(From Waterways Experiment Station, Misc. Paper No. 3-605, 1963) stabilizer should provide the same operational effectiveness, on a weight per unit area basis, as a steel landing mat.

Tables 1, 2, and 3 have been used to guide the selection of initial soil conditions, stabilization treatment levels, curing conditions, and loading conditions for use in the present study. For most test series, initial conditions which give a CBR of 4 and which after treatment and curing for 24 hours yield a CBR of 20 have been selected.

Since stabilized layers in forward areas are to be used in the unsurfaced condition, the tire pressures indicated in Tables 1 and 2 represent critical values of repeated compressive stress to which the stabilized soil will be subjected. Use was made of the two-layer elastic theory solutions presented by Fox (1948) in order to estimate the tensile stresses to be induced at the base of the stabilized layer. Values so determined provided a guide for selection of the loading conditions to be used in the flexural tests.

Several of the loading conditions given in Tables 1 and 2 were analyzed, and it was found that maximum radial tensile stresses at the base of the stabilized layer would be induced by the C-124 aircraft. Wheel loading for this case was approximated by assuming a circular area having a radius of 14 in. and subjected to a uniform pressure of 75 psi. Values of moduli were related to CBR by using the empirical correlation that $E = 1560$ CBR (in psi), reported by Peattie (1962). On this basis the modulus of a 4-CBR subgrade was assumed as 6250 psi, and values of tensile stress were determined for different assumed values of thickness and CBR of stabilized layer. For the thicknesses of layers and other conditions summarized in Table 3, the results shown in Fig. 2 indicate values of tensile stress at the base of the stabilized layer of about 4 to 25 psi. It is of interest to note that the tensile stress, while significantly affected by layer thickness, is virtually independent of the strength of the stabilized layer for the loading conditions shown.

It is also of interest to know the compressive stress induced at the top of the subgrade under the stabilized layer. Values of this stress were determined for various thicknesses and strengths of the stabilized layer assuming the same loading conditions as for the flexural stress analysis. The results of this analysis, shown in Fig. 3, can be used to

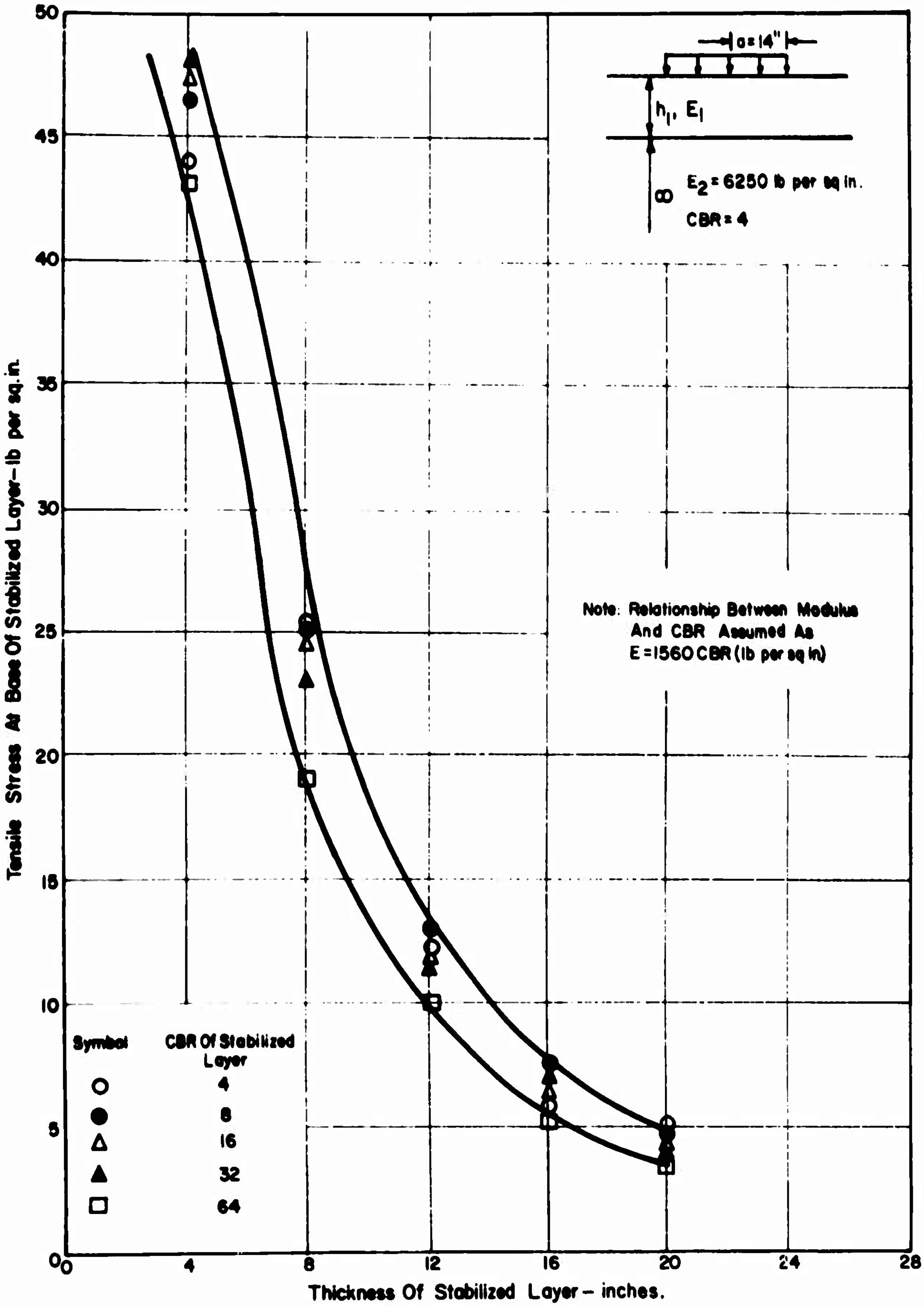

Figure 2 - TENSILE STRESS IN STABILIZED LAYER AS A FUNCTION OF LAYER THICKNESS.

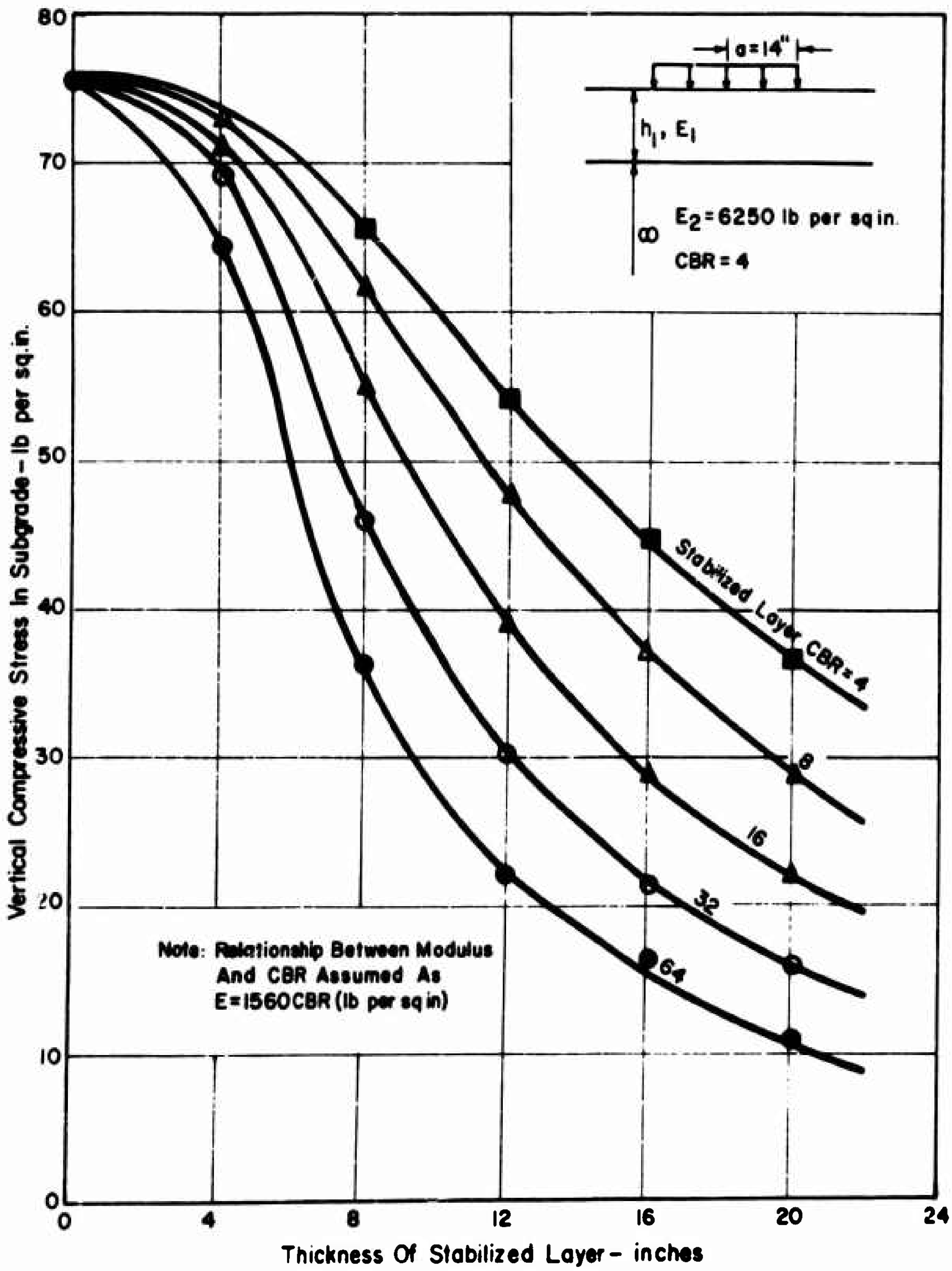

Figure 3 - COMPRESSIVE STRESS IN SUBGRADE AS A FUNCTION OF STABILIZED LAYER THICKNESS.

determine whether a layer of given thickness is able to provide adequate subgrade protection. In this way it may be possible to examine CBR and elastic theory criteria simultaneously. For example, from Table 3, it may be seen that a 22-in. stabilized layer is indicated over a subgrade with a CBR of 4 for a rear area airfield, designed for the C-124 aircraft. For a stabilized layer having a CBR of 20, Fig. 3 indicates that the vertical compressive stress under a 22-in. thick stabilized layer would be about 18 psi. According to the tabulation of equivalent compressive strengths in Table 3, it would appear that a CBR of 4 would be adequate to withstand a compressive stress of 18 psi.

IV. SOILS AND REFERENCE PROPERTIES

Two soils were selected for use in these investigations: Vicksburg silty clay, a non-expansive material of low plasticity (CL), and Vicksburg buckshot clay, an expansive material of high plasticity (CH). These soils were chosen as materials which would be representative of typical soils requiring stabilization and which might be encountered in military operations. Bulk quantities of each soil were provided by the U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi. There are two significant additional advantages in using these soils: (1) they have been used in several previous stabilization studies (M.I.T., Waterways Experiment Station, and University of California) and thus considerable information on their behavior is available, and (2) they are readily obtainable. They have been used for field test programs at the Waterways Experiment Station. Classification data for these soils are presented in Table 4, and the grain size distribution curves are shown in Fig. 4.

In order to establish appropriate initial conditions prior to stabilization, the CBR characteristics of the untreated soils were determined over a wide range of densities and water contents for specimens both in the as-compacted state and after soaking. In this way it was possible to determine what compaction conditions would give a CBR of 4 or more and thus provide a material which would be suitable for stabilization according to the criteria listed in Tables 1 and 2.

The Corps of Engineers "15 point method" ("family of curves approach") was used. CBR samples were prepared using impact compaction* over a range of water contents and using three different compactive efforts (20, 35, and 55 blows per layer). In all cases a surcharge load of 5 lb was used during the test; this surcharge was believed to be representative of the conditions for forward area pavements. The test results illustrated in Fig. 5 for Vicksburg silty clay tested in the as-compacted condition show clearly that CBR values of the order of 4 are attained only at water contents appreciably wet of optimum. In this region, density and CBR are low and are essentially independent of the impact compaction effort. For compaction water contents less than about 15 percent, the CBR values are high and quite sensitive to changes in dry density.

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*6 in. dia. by 4.5 in. high specimens, 10 lb. hammer with 18-in. drop, 5 layers.

TABLE 4

SOIL CLASSIFICATION DATA

	Vicksburg Silty Clay	Vicksburg Buckshot Clay
Liquid Limit, percent	35.1	58.8
Plastic Limit, percent	21.7	26.8
Plasticity Index, percent	13.4	32.0
Specific Gravity	2.65	2.70
AASHO Classification	A-6	A-7
Unified Classification	CL	CH

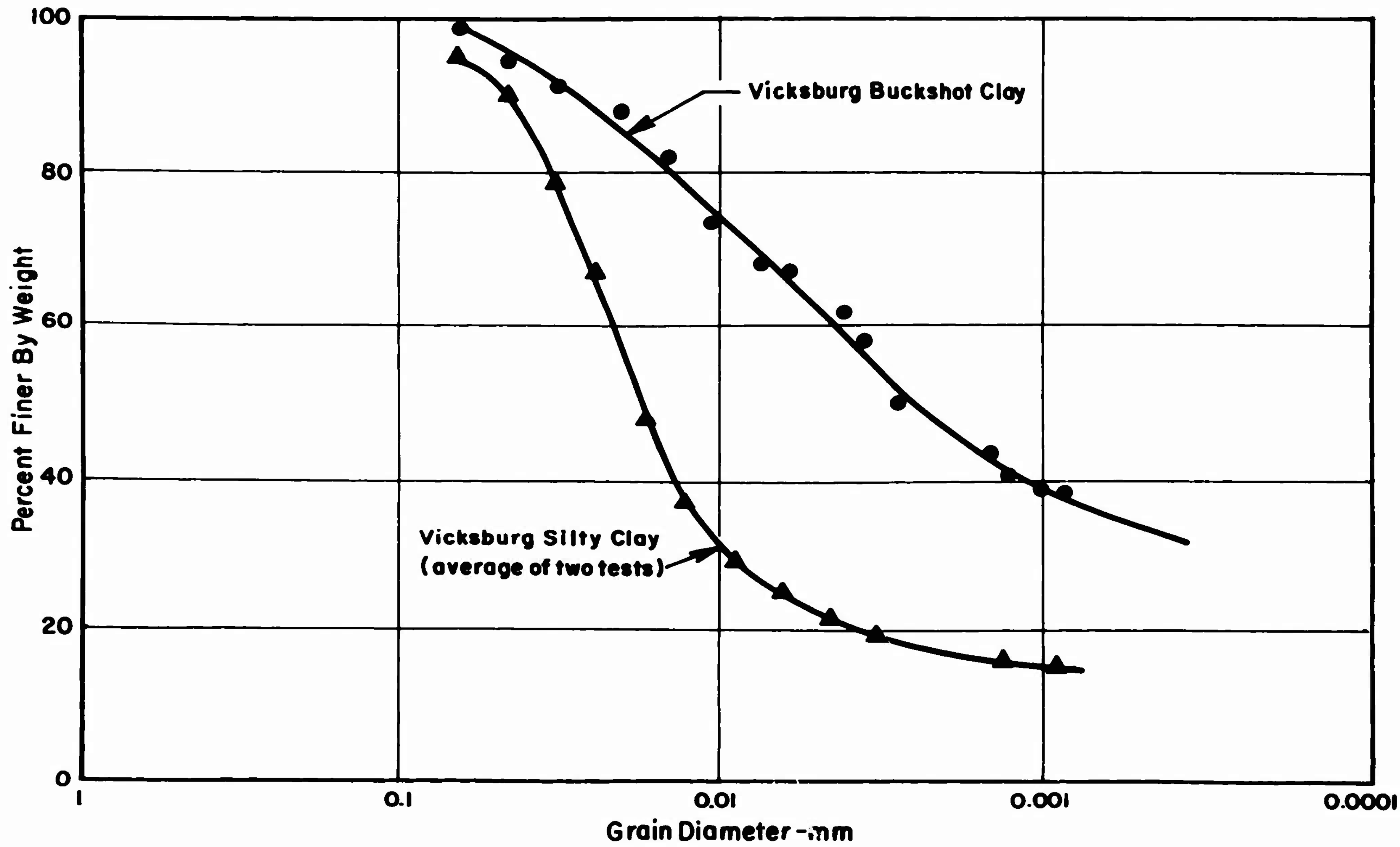
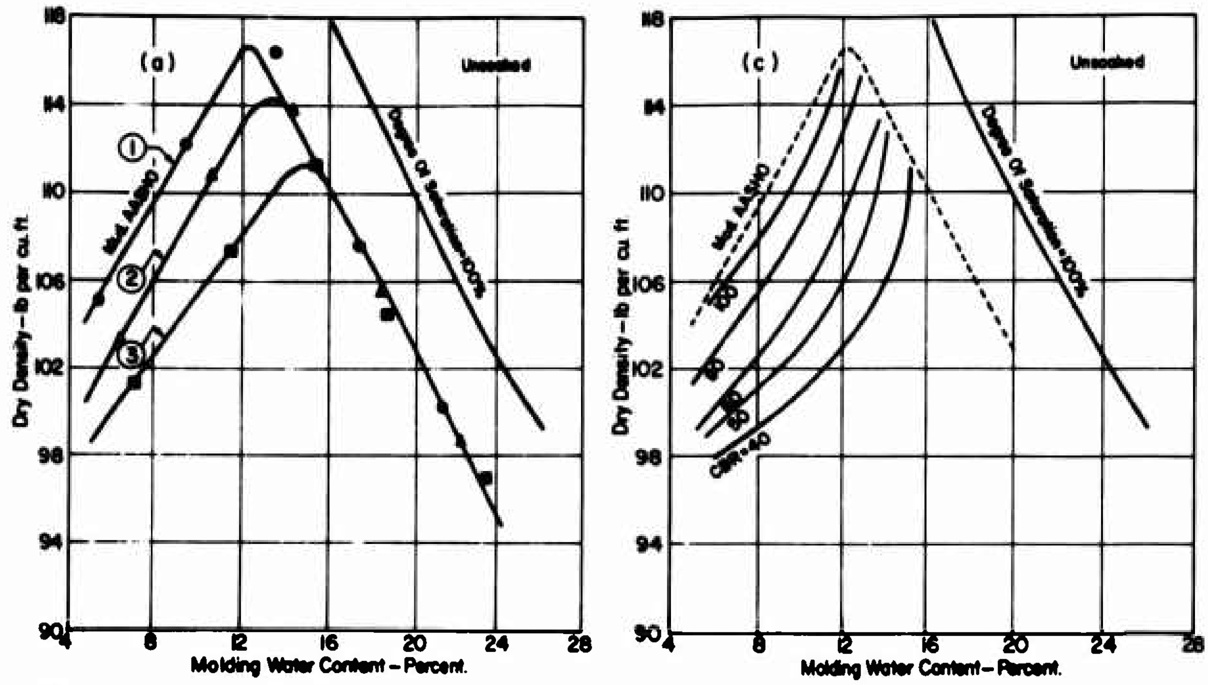


Figure 4 - GRAIN SIZE DISTRIBUTION CURVES FOR SOILS USED IN STUDY.



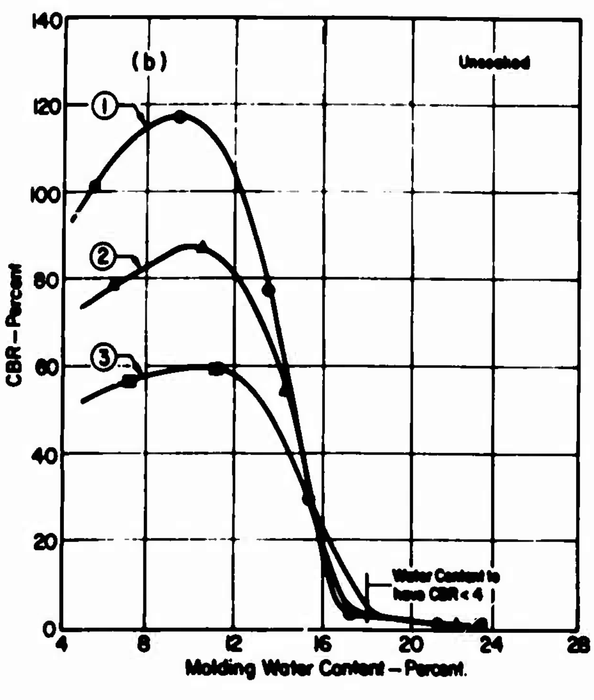


Figure. 5 - COMPACTION AND CBR CHARACTERISTICS OF VICKSBURG SILTY CLAY AS COMPACTED.

Several additional specimens were prepared wet of optimum in order to better define the critical value of water content that would give an initial CBR of 4, the critical value for stabilization purposes according to Table 2. Fig. 6 shows the variation of density and CBR with water content. Again it is clear that the compactive effort had little effect on the results. From a consideration of these results as well as those in Fig. 5, a water content of 19 percent was selected for preparation of Vicksburg silty clay samples having an initial CBR of about 4. Subsequent work was then directed toward the determination of a treatment level required to raise the CBR to 20 after a curing period of 24 hours.

Similar tests were carried out using the Vicksburg buckshot clay. Fig. 7 shows that as-compacted CBR values of 4 or less are reached only at water contents considerably greater than optimum for the various compactive efforts. The results of additional tests conducted in the high water content range are shown in Fig. 8 and indicate that the critical CBR of 4 is reached at a water content of about 30 percent.

The "15 point method" was also used to study the CBR and swelling characteristics of specimens after soaking. Swelling was permitted during the 4-day soaking period under a surcharge load of only 5 lb since, as noted earlier, unsurfaced conditions (low surcharge on the soil) are of greatest interest. Fig. 9 presents the results for Vicksburg silty clay. The density data in Fig. 9(a) and the CBR data in Fig. 9(b) have been cross plotted to give the contours of equal CBR shown in Fig. 9(c). It is clear from these contours that it would be very difficult to obtain a CBR of 20 or greater to meet design criteria for forward roads and airfields on the basis of compaction alone.

A similar set of tests with the buckshot clay gave the results shown in Fig. 10. The high swelling exhibited by this soil resulted in the very low CBR values after soaking. Contours of equal swelling are shown in Figs. 11 and 12 for the silty clay and buckshot clay, respectively. Total swelling was measured in terms of the change in specimen height at the end of the 4-day soaking period.

The data in Figs. 5 through 12 provide a reference or starting point from which known initial sample conditions in the absence of or prior to stabilization may be selected. Although the majority of the repeated-load

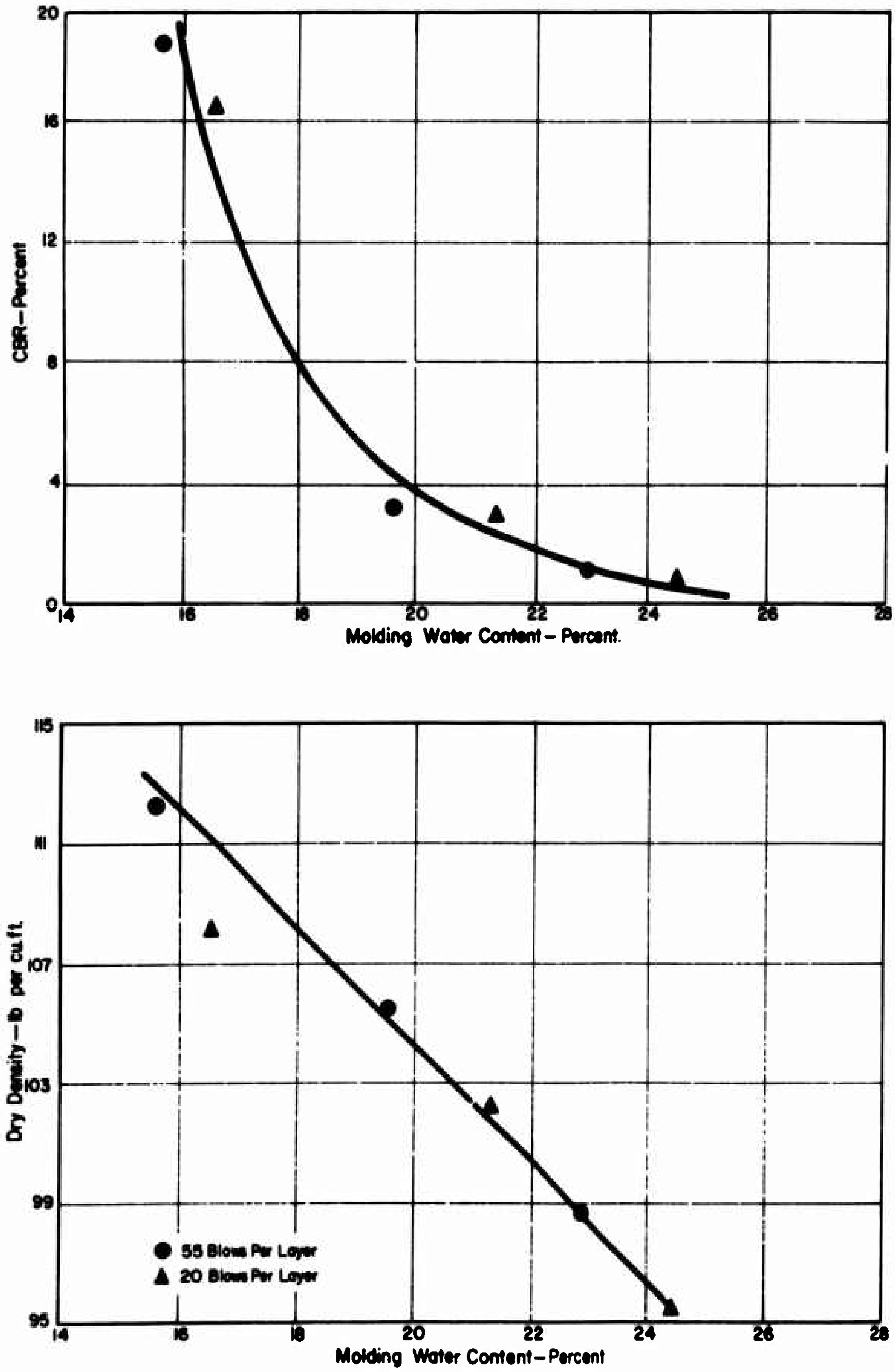


Figure 6 - VARIATION OF DENSITY AND CBR WITH MOLDING WATER CONTENT FOR VICKSBURG SILTY CLAY SAMPLES COMPACTED WET OF OPTIMUM.

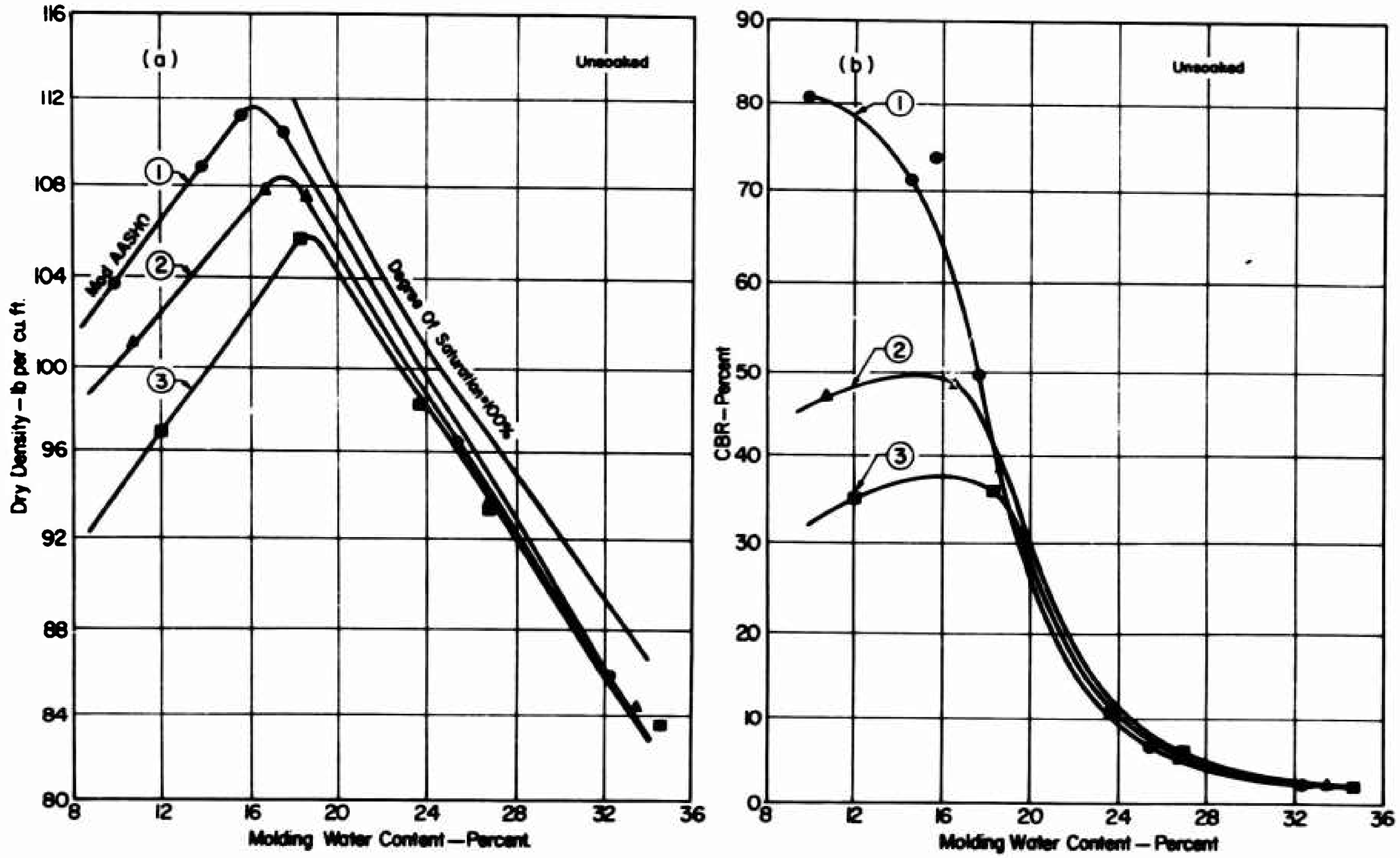


Figure. 7-COMPACTION AND CBR CHARACTERISTICS OF BUCKSHOT CLAY AS COMPACTED.

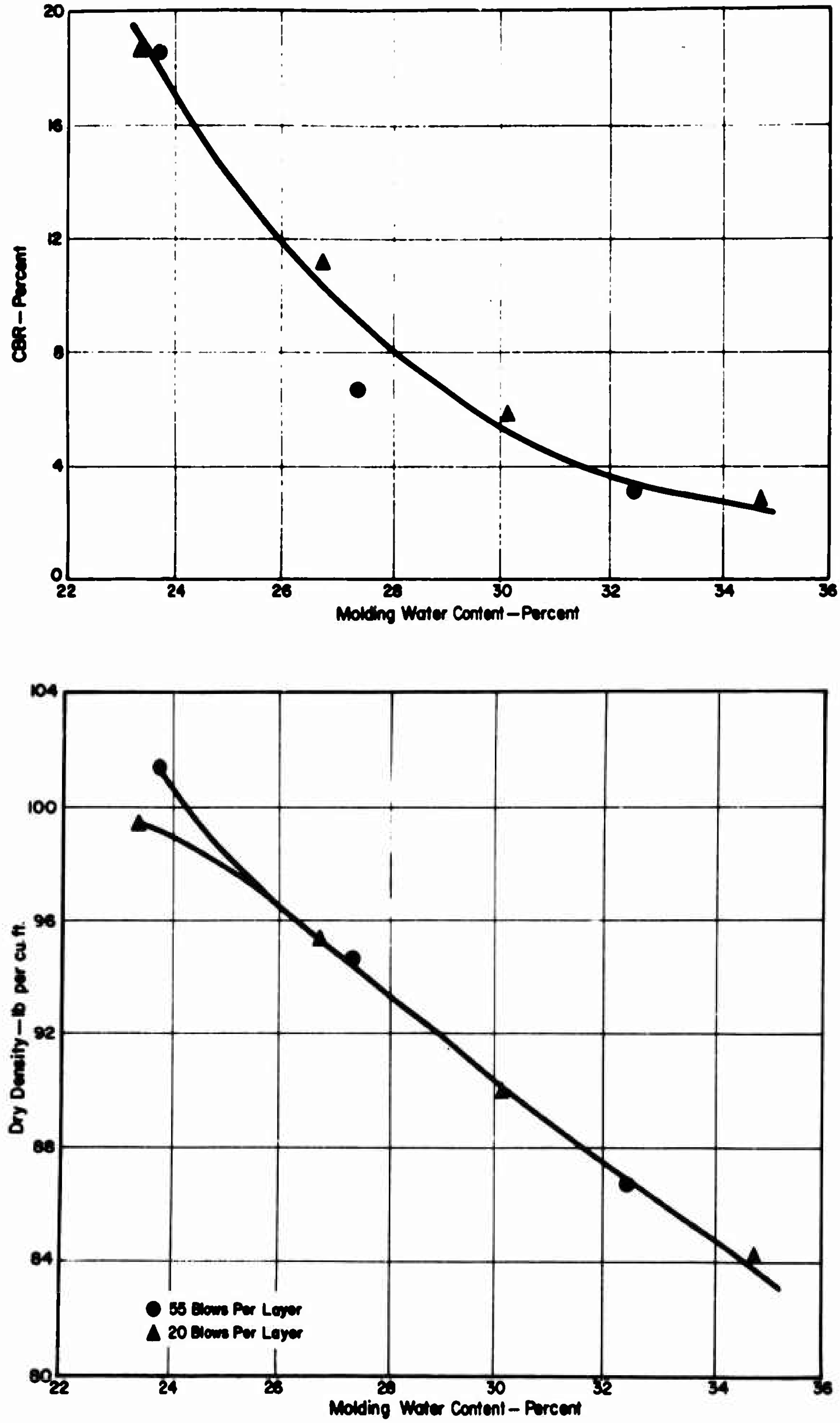
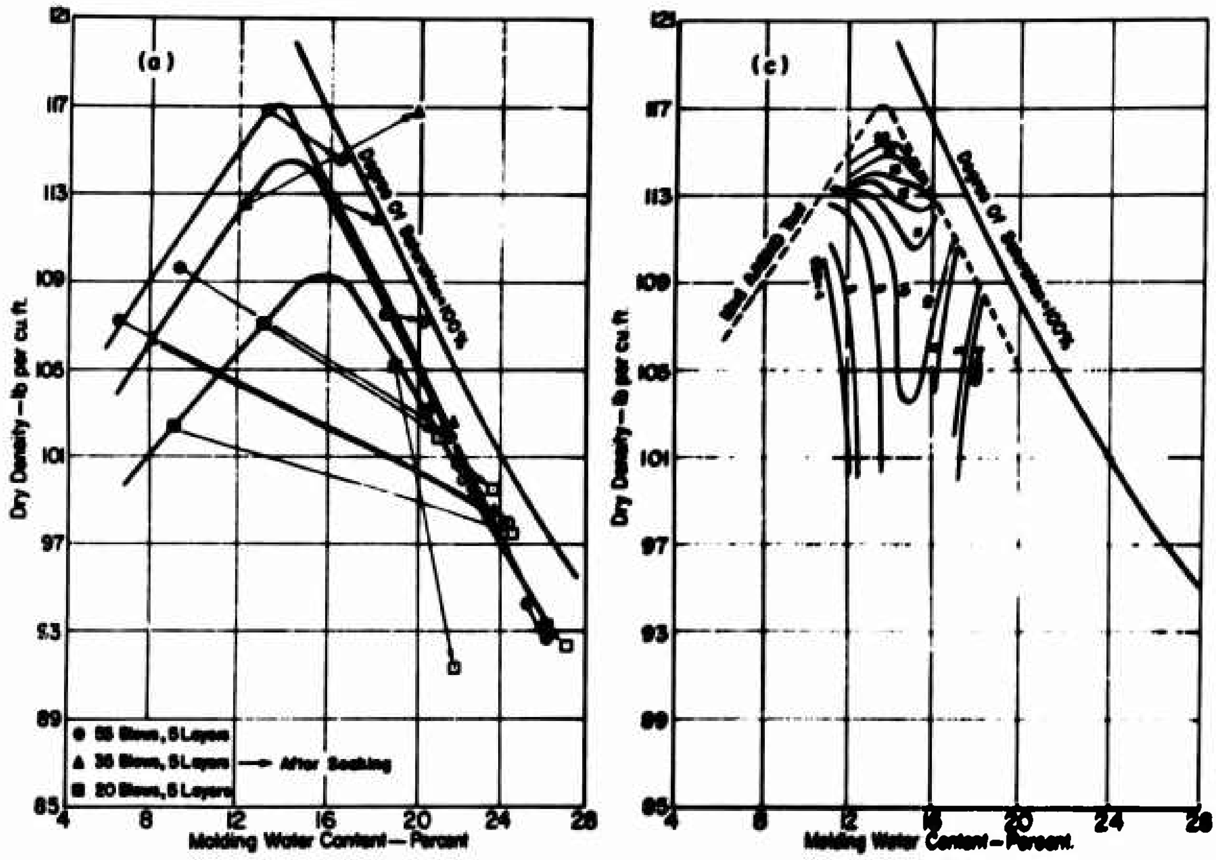


Figure 8 – VARIATION OF DENSITY AND CBR WITH MOLDING WATER CONTENT FOR BUCKSHOT CLAY SAMPLES COMPACTED WET OF OPTIMUM.



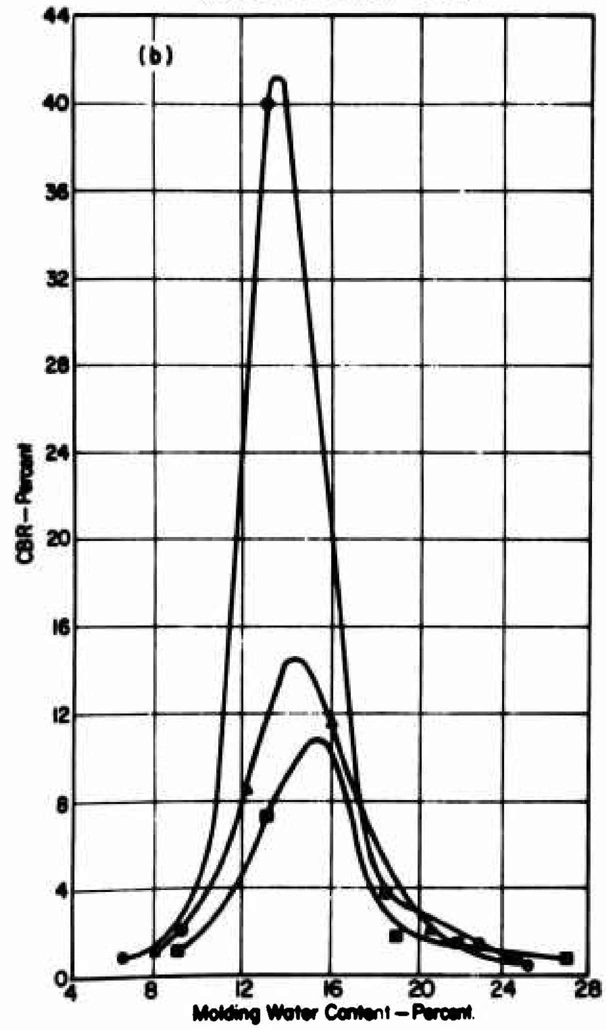


Figure 9—COMPACTION AND CBR CHARACTERISTICS OF VICKSBURG SILTY CLAY - AFTER SOAKING.

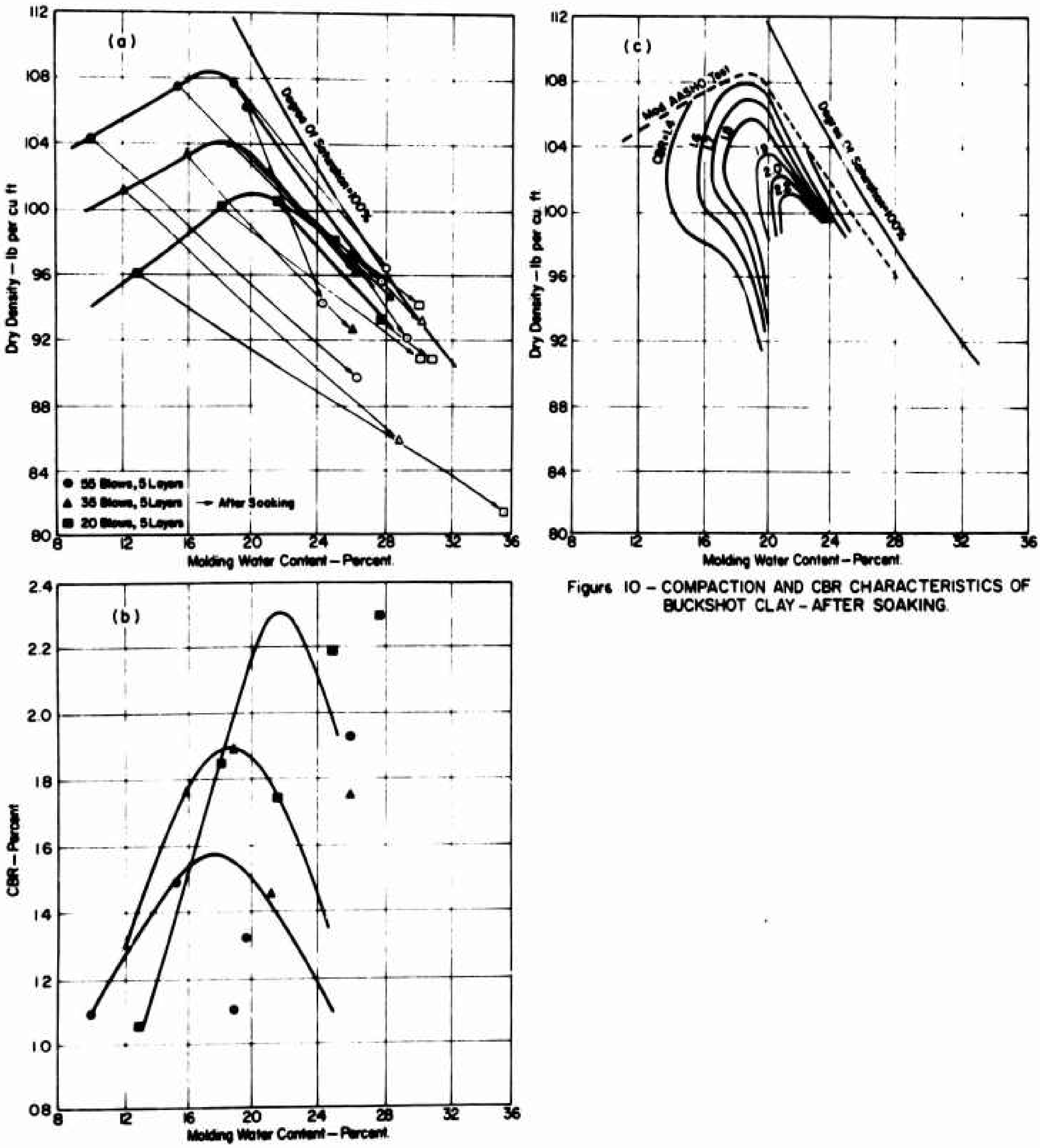


Figure 10 – COMPACTION AND CBR CHARACTERISTICS OF BUCKSHOT CLAY – AFTER SOAKING.

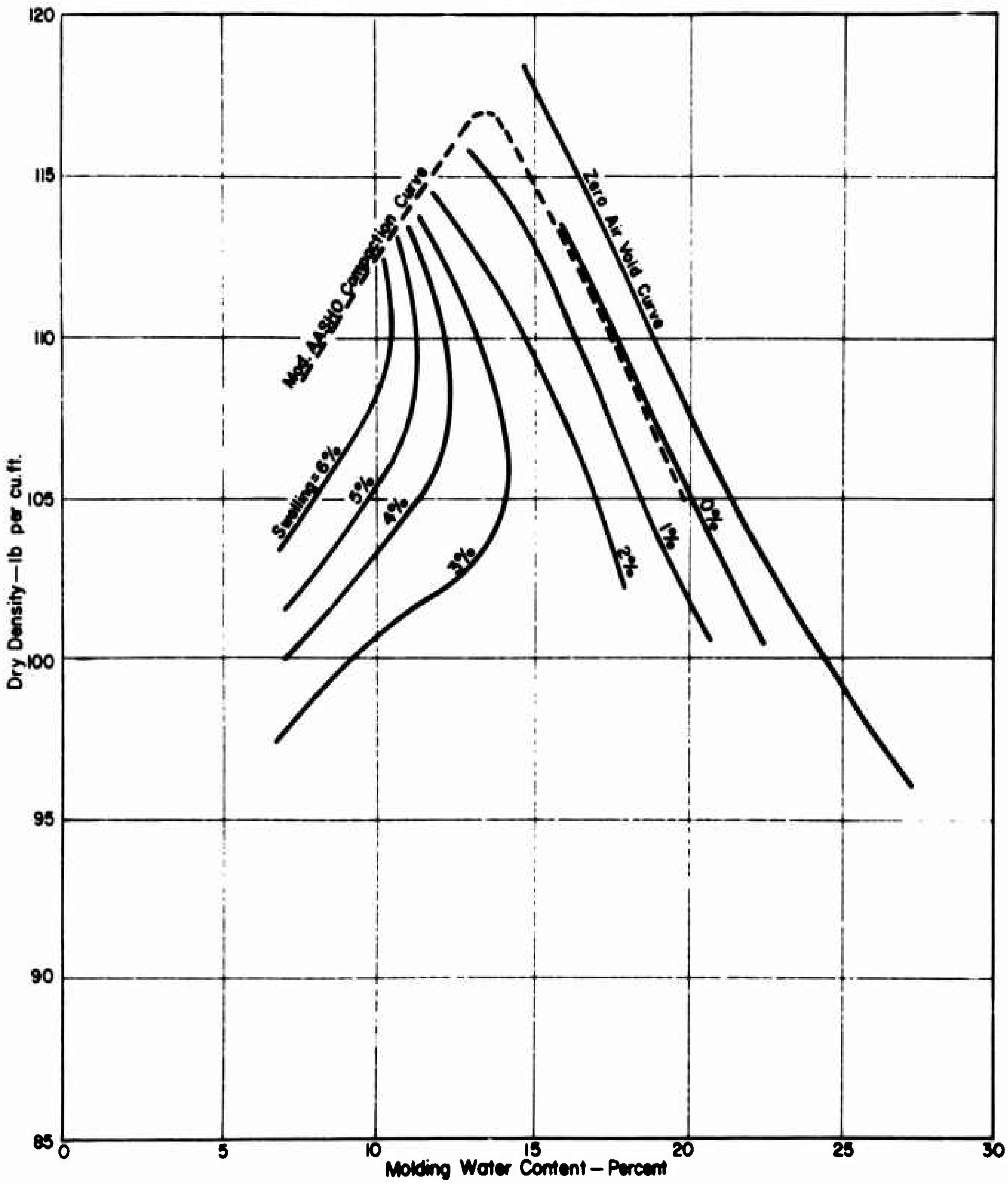


Figure 11 - SWELLING CHARACTERISTICS OF COMPACTED VICKSBURG SILTY CLAY.

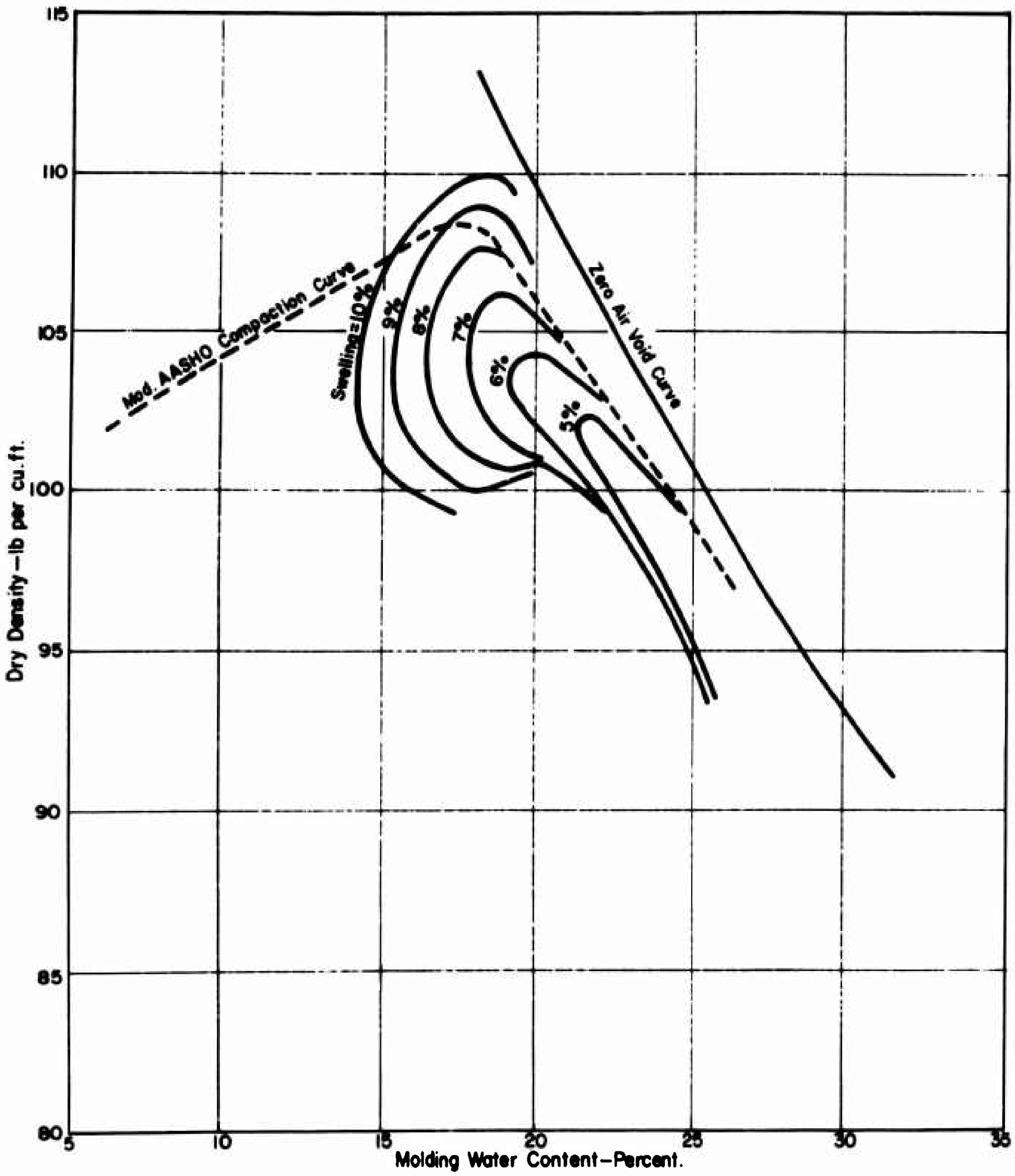


Figure 12 - SWELLING CHARACTERISTICS OF COMPACTED BUCKSHOT CLAY.

test programs described in this report employed samples stabilized from an initial CBR condition of 4, it is anticipated that future studies will incorporate the initial soil strength as a variable. The reference data summarized in these figures will thus aid in these studies.

V. REPEATED-LOADING APPARATUS

The testing program made use of both repeated-load compression tests on cylindrical specimens and repeated-load flexure tests on prismatic beam specimens. The repeated-loading apparatus used in this study is the same as has been in use at the University of California Soil Mechanics and Bituminous Materials Laboratory for a number of years. This equipment has been described by Seed and Fead (1959). With this equipment it is possible to vary load magnitude, frequency, and duration. For the tests conducted thus far, the frequency of load application was maintained at 20 per minute, the duration of load application was 0.1 second, and the load rise time was about 0.01 second. Typical load and deflection traces for cylindrical compression samples are shown in Fig. 13(a) and for beam samples in Fig. 13(b).

Cylindrical compression specimens for repeated loading (1.4 in. in diameter by 3.5 in. in height) were prepared using a modified Harvard Miniature Kneading Compactor. Each sample was wrapped for curing and testing within two rubber membranes separated by a film of silicone grease. The triaxial compression cell for repeated-loading tests was the same as that described by Seed, Mitchell, and Chan (1960). No cell pressure was used for these tests.

Beam samples were prepared using the Triaxial Institute Kneading Compactor (1951) with a rectangular tamping foot. A steel mold 12 in. long, 3 in. wide and 2 1/2 in. in height was used for forming specimens. Samples were compacted in equal layers. After the kneading compaction, the top surface was levelled using static pressure on the sample, after which the specimen was extruded from the mold. It was then wrapped in Saran sheet for curing and testing. Curing of both compression and flexural specimens was carried out at approximately 68°F in a moist room.

A sketch of the apparatus used for flexural tests is shown in Fig. 14. In this figure it will be noted that one of the two roller supports is fixed on the 14-in. by 6 in. by 3/4-in. steel base plate; the other is free to move, thus preventing development of stresses resulting from support restraints. The seating bars are 1 in. wide and 3 in. long and rest on 3/4-in. steel rollers 3 in. long. Load is transferred to the midpoint

Cylindrical Samples
Dual LVDT

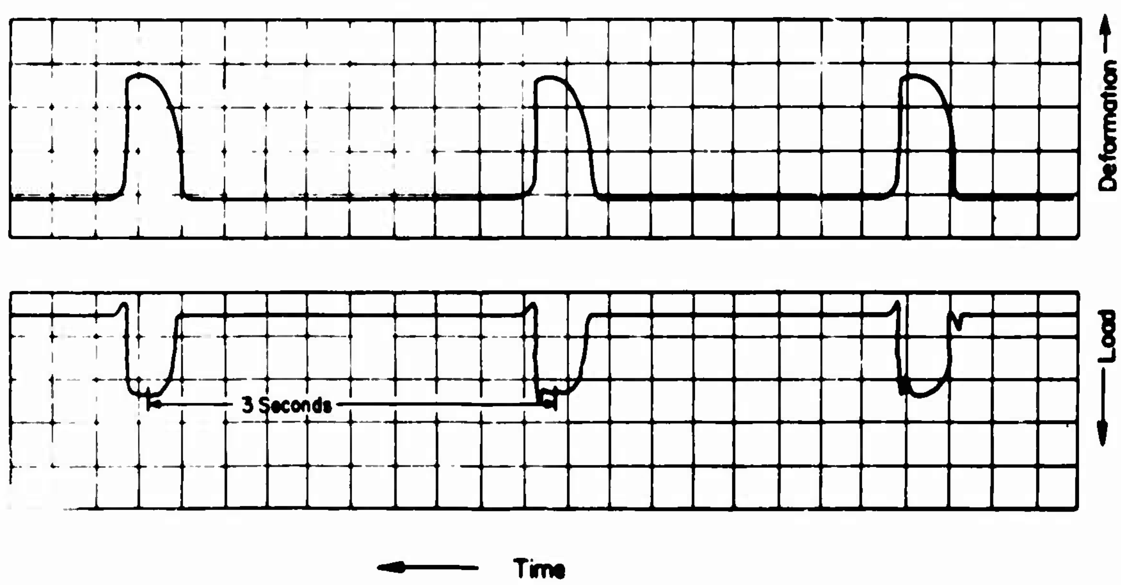


Figure 13(a) - TYPICAL LOAD AND DEFORMATION VERSUS TIME TRACES - COMPRESSION TESTS.

Beam Samples
Single LVDT

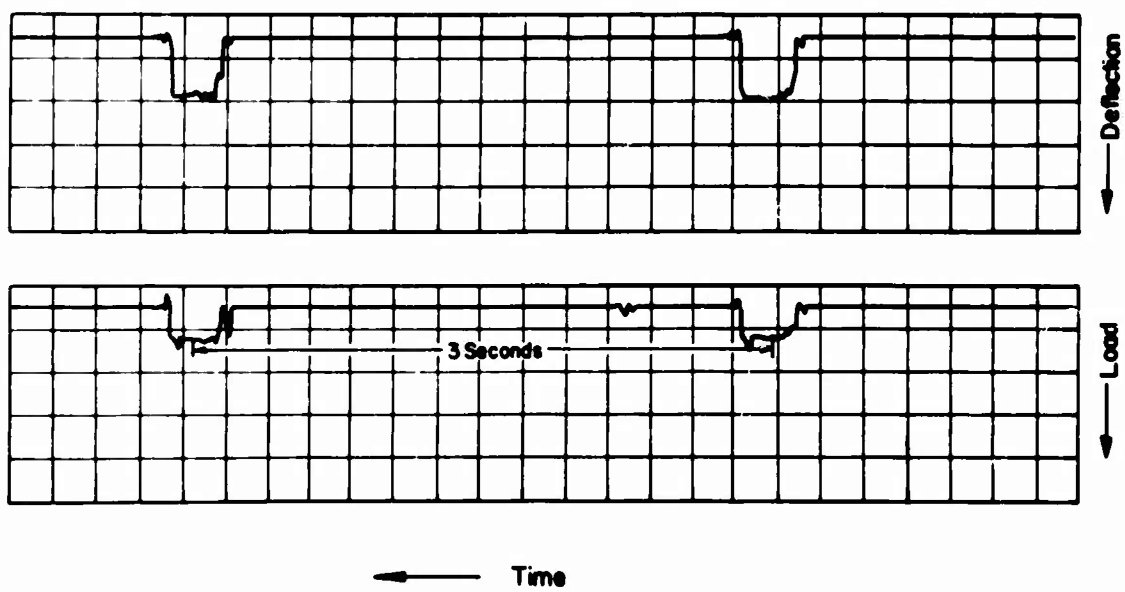


Figure. 13(b) - TYPICAL LOAD AND DEFLECTION VERSUS TIME TRACES - BEAM SAMPLES.

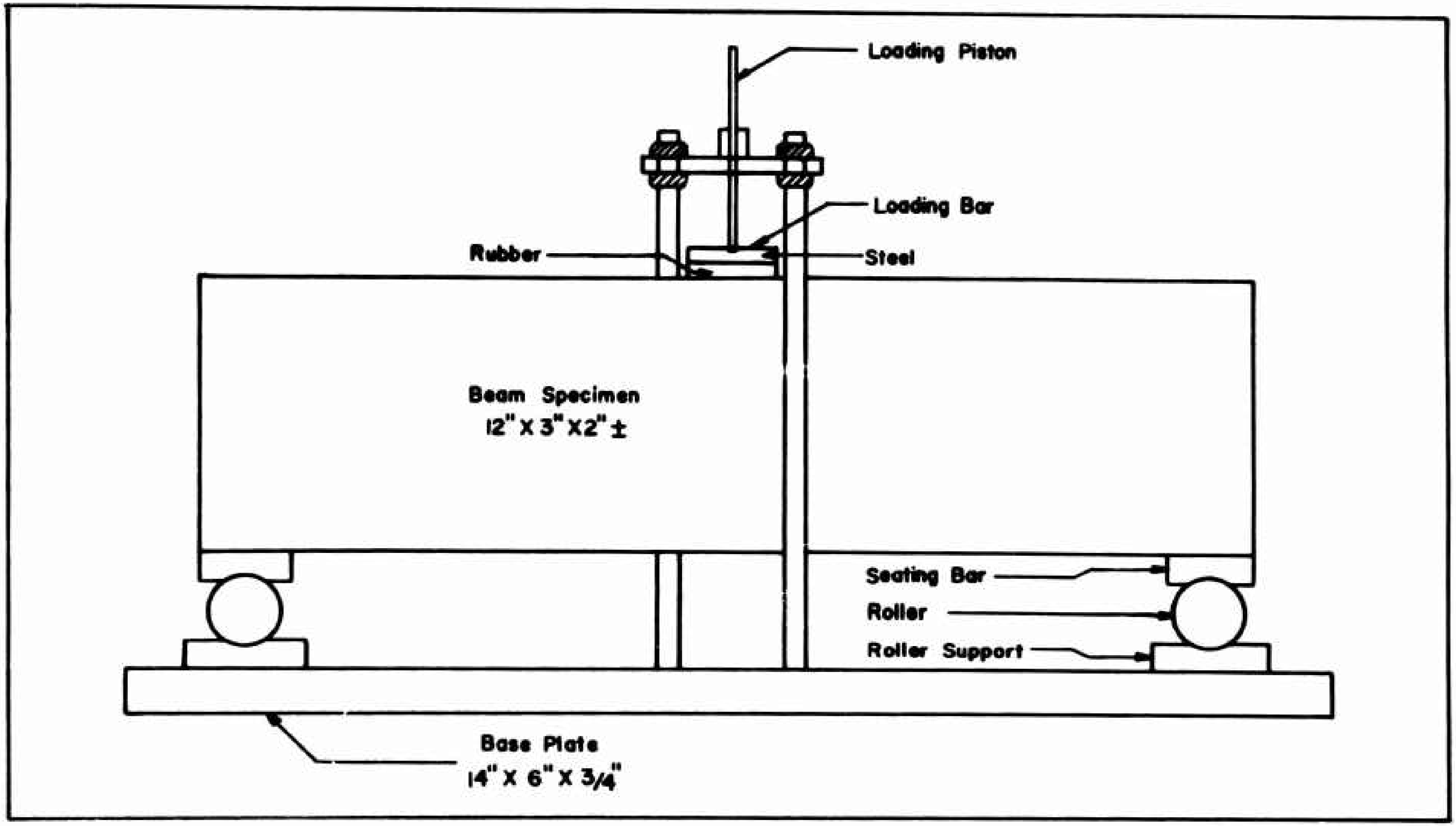


FIG. 14- FLEXURAL TEST APPARATUS.

of the beam through a two-layered loading bar. The layer in contact with the sample is composed of hard rubber; whereas, the upper layer is steel. Simple beam theory can be used for stress-deflection analysis of the specimens.

Deformation of specimens was measured, whenever possible, with dial gages. In some cases, however, the samples were so stiff as a result of stabilization that the deflections were smaller than could be accurately determined. In addition, the application of large loads to such specimens caused deflections of the apparatus of the same order of magnitude as the measurements themselves, an undesirable situation.

Consequently for some of the cylindrical compression tests and in all of the flexural tests, deflections were measured using linear variable differential transformers (LVDTs). Fig. 15 illustrates schematically the arrangement for cylindrical compression tests; as shown in the figure two LVDTs were connected in parallel to increase sensitivity and to give representative average values of deformation. The LVDTs were mounted directly to the sample with aluminum clamps as shown. One clamp held the transformer coil assembly and the other the core rod. For the beam tests, a single LVDT was used as shown in Fig. 16. A small hole was drilled on the neutral axis at mid-span of each of the beam, and a small nut was cemented into the hole with a fast-setting cement. The LVDT core could then be attached to the beam with a screw. For both types of test, the output of the LVDTs was recorded on Sanborn Strip Chart Recorders. A typical deflection trace is shown in Fig. 13.

In both the compression and beam tests, hydrostone was used to obtain a smooth surface for load transfer between the sample and its supports. This served to improve stability and prevent rocking of the specimen.

A photograph of the compression test apparatus is presented in Fig. 17; the beam testing arrangement is shown in Fig. 18; and the complete testing arrangement with the loading frame and recording equipment is shown in Fig. 19.

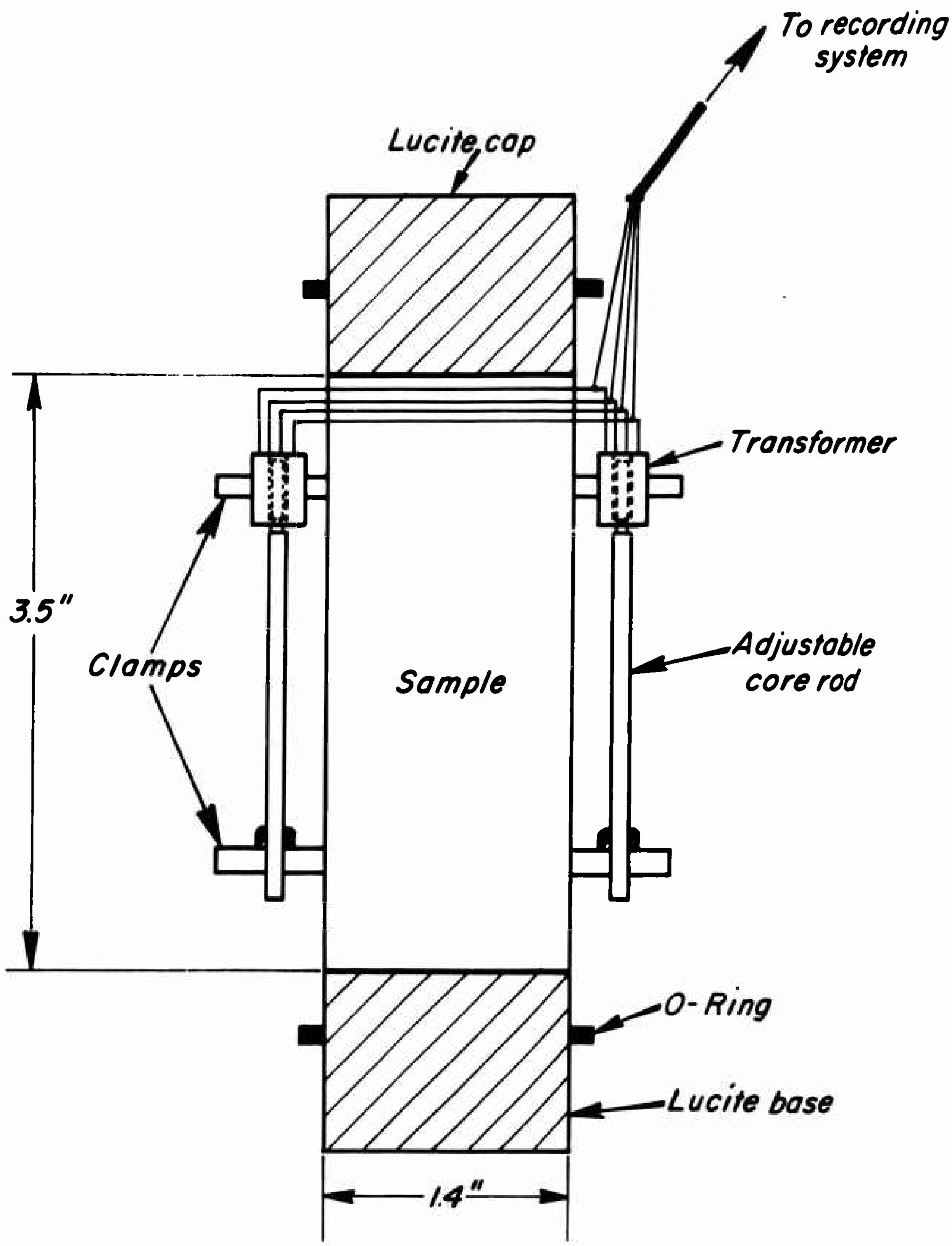


Fig. 15- LINEAR VARIABLE DIFFERENTIAL TRANSFORMER ASSEMBLY FOR DEFLECTION MEASUREMENTS ON CYLINDRICAL SAMPLE.

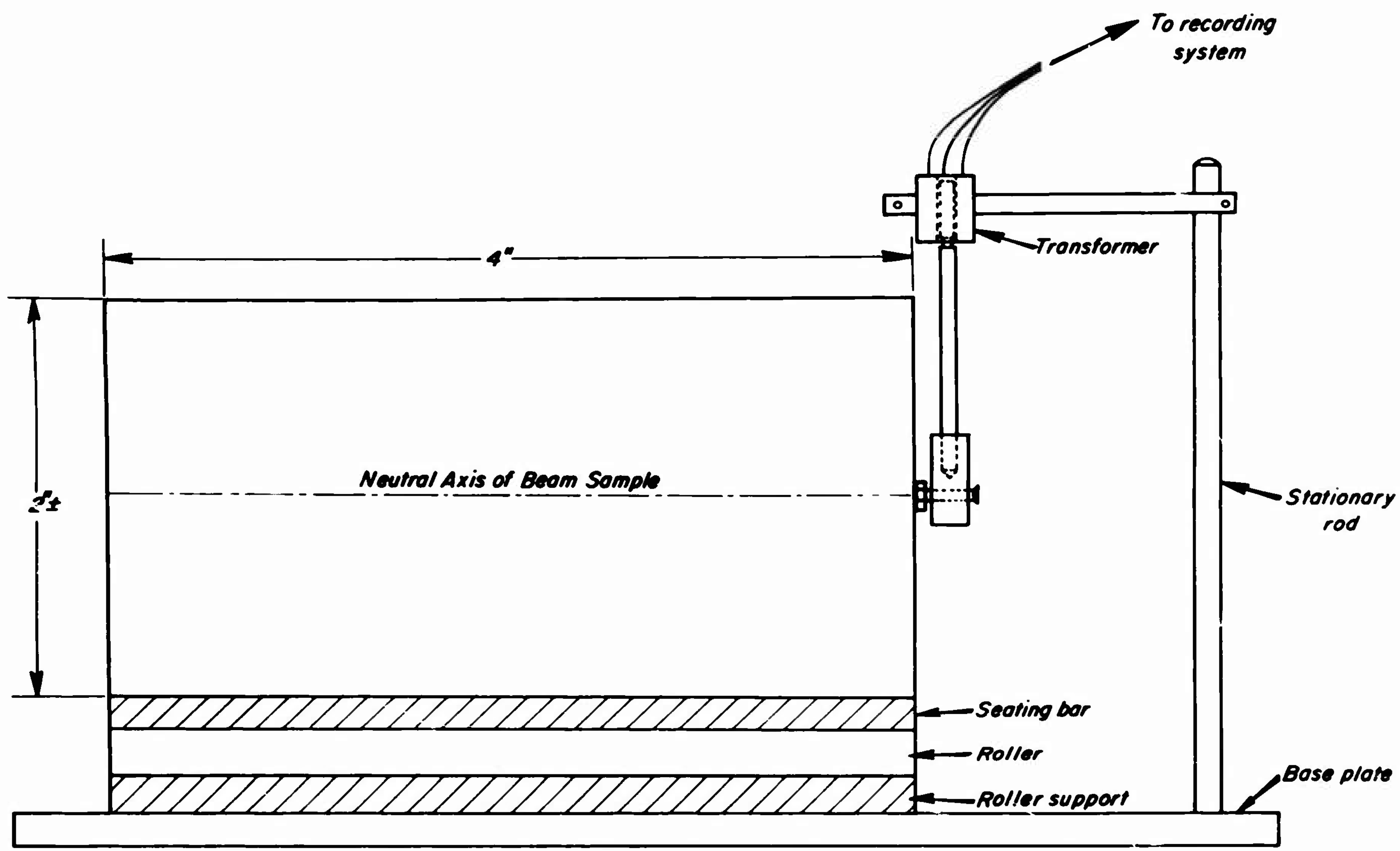


Fig.16 - LINEAR VARIABLE DIFFERENTIAL TRANSFORMER ASSEMBLY FOR DEFLECTION MEASUREMENTS ON BEAM SAMPLES.

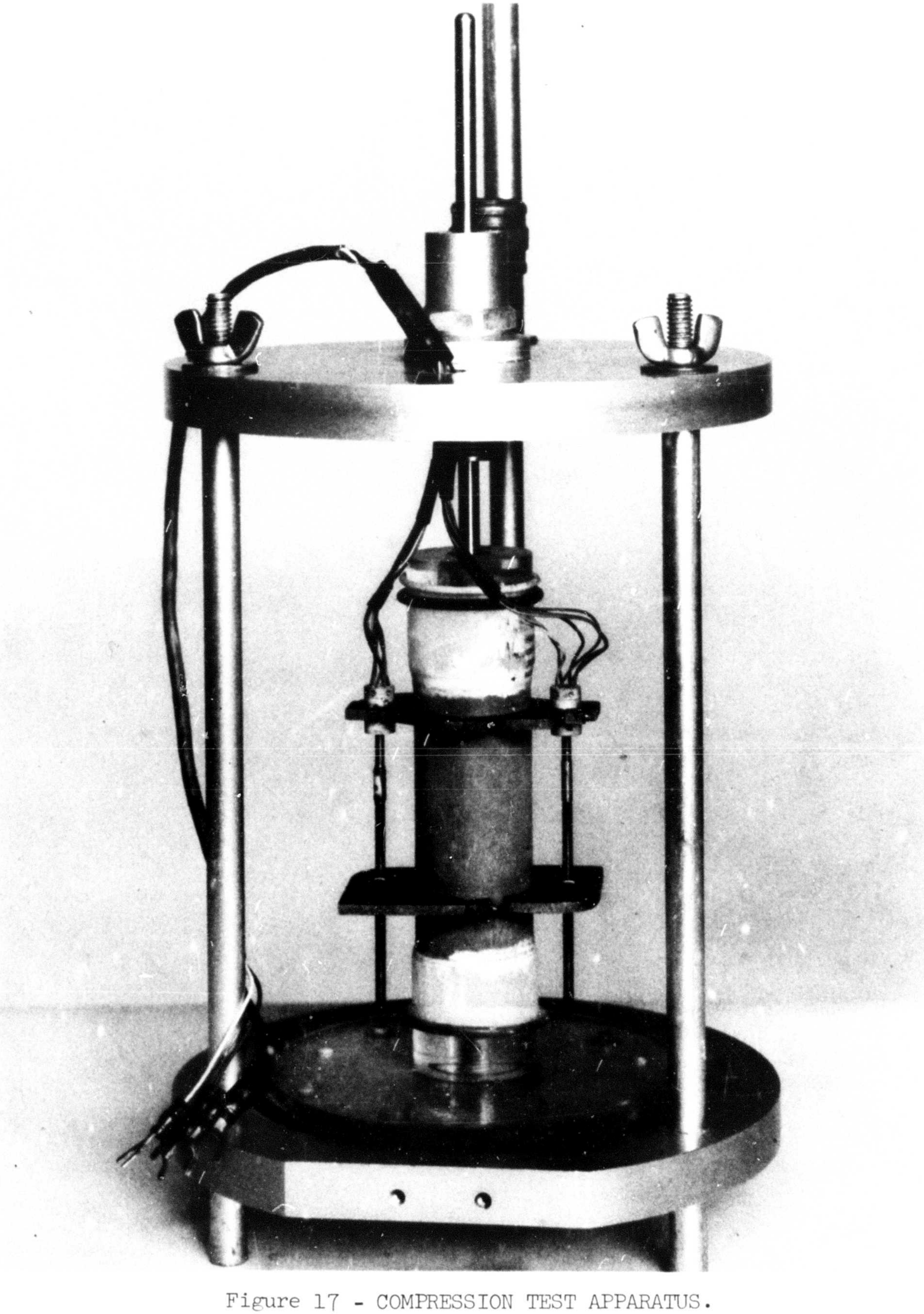


Figure 17 - COMPRESSION TEST APPARATUS.

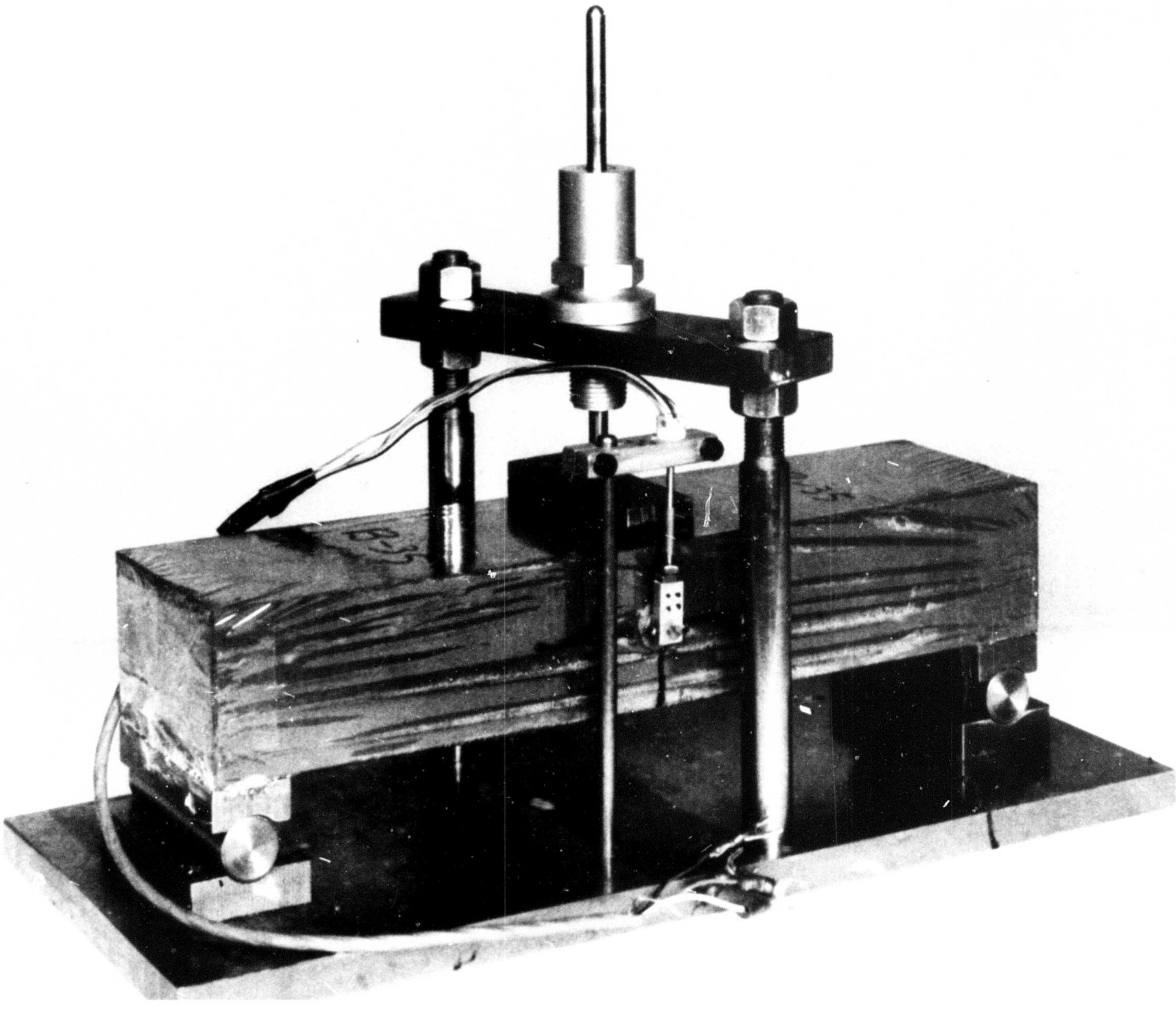


Figure 18 - FLEXURAL TEST APPARATUS.

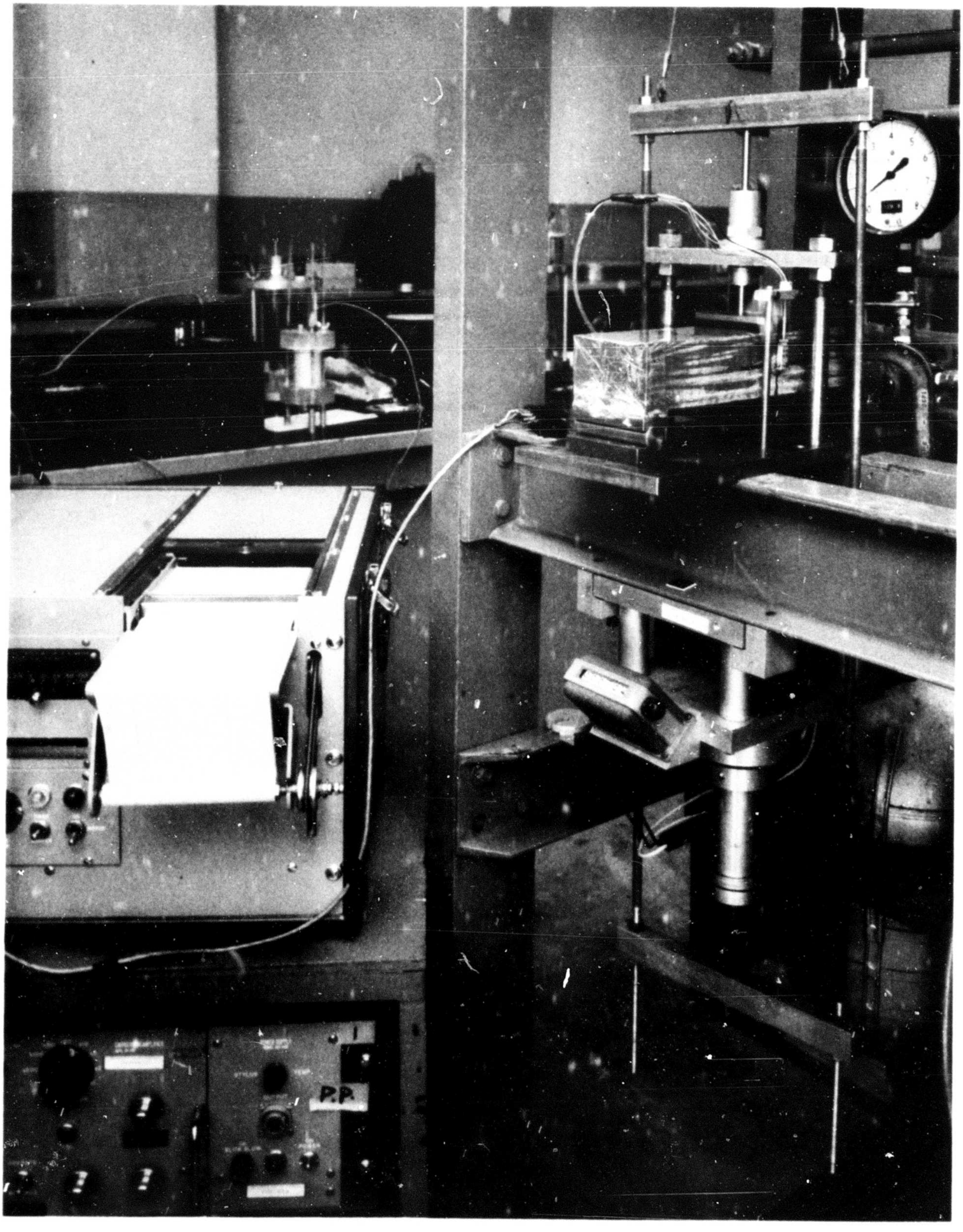


Figure 19 - FLEXURAL TEST APPARATUS

AND RECORDING EQUIPMENT.

VI. PRELIMINARY INVESTIGATIONS

After ranges of water contents had been established that would result in a CBR of 4 for the untreated soil, it was necessary to determine stabilization treatment levels that would result in a CBR of 20 for the treated soil after 24 hours of curing. This value of CBR was selected since it represents the minimum requirement for military roads and airfields subjected to the highest loadings. At the same time a CBR of 20 is the highest minimum acceptable value (see Table 3) for the different classes of roads and airfields. It was desired to carry out the initial repeated loading studies on samples possessing reasonable strength, since previous experience with stabilized soils was obtained using high strength specimens. It would seem appropriate, as noted before, in future studies to examine lower strength stabilized specimens.

It was also necessary in these preliminary tests to establish suitable mixing and compaction procedures for the treated specimens. Two different mixing sequences were investigated. In the "wet mix" sequence the dry soil was mixed with the necessary amount of water to give the desired water content. The mixture was placed in a plastic bag and allowed to equilibrate over night. Cement* was then added and thoroughly mixed, and compaction followed. In the "dry mix" sequence the dry soil was first mixed with the cement, then water was added, and compaction followed. Hand mixing was used with each procedure, and the mixing time for cement, soil, and water together was maintained at 5 to 7 minutes.

A further variable that was investigated in these preliminary tests was the influence of method of compaction. Specimens as prepared for the CBR test (cylinders 6 in. in diameter and 4.5 in. high) are not convenient for either repeated load compression tests or repeated load flexural tests. For example, specimens 1.4 in. in diameter and 3.5 in. high (modified Harvard miniature compactor size) are best suited for the repeated load compression tests used in this study and specimens 2.0 in. high, 3 in. wide and 12 in. long for the repeated flexure tests because of fabrication and equipment

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*All studies during this report period were conducted using Portland cement as the stabilizer. Properties of this portland cement are given in Appendix A.

requirements. CBR tests cannot be carried out on either of these types of specimen. Furthermore, kneading compaction is more convenient for preparing specimens of the desired size than is impact compaction. Thus, tests were conducted to determine the effects of method of compaction on unconfined compressive strength and the relationships between CBR and this strength. In these tests water contents of 18 to 19 percent were used for the silty clay and 30 to 31 percent for the buckshot clay, since at these water contents both untreated soils have a CBR of about 4. It was found that 3 percent cement was required to raise the CBR of the silty clay to 20 after a 24-hour period of cure, whereas 6 percent cement was needed for equivalent stabilization of the buckshot clay.

Table 5 presents values of CBR for the silty clay treated with 3 and 6 percent cement at two curing times and as affected by the two methods of compaction. These results are also illustrated in Fig. 20. It can be seen that both the mixing and compaction procedures influence the results; however, the general pattern of behavior is not well defined. For example, at a cement content of 3 percent, "wet" mixing apparently produces samples having a greater CBR then those prepared using "dry" mixing; in addition, kneading compaction produces stronger specimens than impact compaction. On the other hand, at a cement content of 6 percent, "dry" mixing is superior to "wet" mixing and impact compaction produces slightly higher CBR values than kneading compaction.

This latter result is more consistent with earlier findings of Groves (1964) who observed that static compaction produced stronger specimens than kneading compaction for samples of silty clay treated with 13 percent cement and compacted wet of optimum. Since the effect of method of compaction on strength, at least for untreated soils, is related to induced shear strain and dispersion of the soil structure (Seed and Chan 1959) and since impact compaction induces less shear strain than kneading compaction, it would be expected that specimens prepared by kneading compaction at 3 percent cement content (Fig. 20) would be weaker than those prepared by impact compaction. An offsetting factor, however, is the possibility that because of the greater shear strain induced during kneading compaction, the degree of mixing of cement and soil is improved sufficiently to raise the strength.

TABLE 5

INFLUENCE OF MIXING PROCEDURE ON CBR OF CEMENT-STABILIZED

VICKSBURG SILTY CLAY

(Impact Compaction)

Cement Content %	Mixing Procedure	Molding Water Content, %	Dry Density pcf	Curing Time Hours	CBR %
0	---	19.0			4.1
3	Wet	19.0	107.4	2	11.9
3	Dry	18.5	106.2	2	11.3
3	Dry	18.4	106.3	2	8.3
3	Wet	19.0	107.4	24	22.0
3	Dry	18.5	106.2	24	19.3
3	Dry	18.4	106.3	24	21.7
6	Wet	19.2	107.8	2	18.3
6	Dry	19.0	107.2	2	21.7
6	Wet	19.2	107.8	24	46.2
6	Dry	19.0	107.2	24	90.0

(Kneading Compaction)

Cement Content %	Mixing Procedure	Molding Water Content, %	Dry Density pcf	Curing Time Hours	CBR %
3	Wet	18.6	108.2	2	13.5
3	Dry	18.2	107.7	2	9.0
3	Wet	18.6	108.2	24	39.7
3	Dry	18.2	107.7	24	29.0
6	Wet	18.9	108.1	2	11.6
6	Wet	17.8	108.4	2	18.4
6	Dry	17.9	107.7	2	16.0
6	Wet	18.5	108.1	24	49.0
6	Wet	17.8	108.4	24	51.0
6	Dry	18.5	107.7	24	80.0

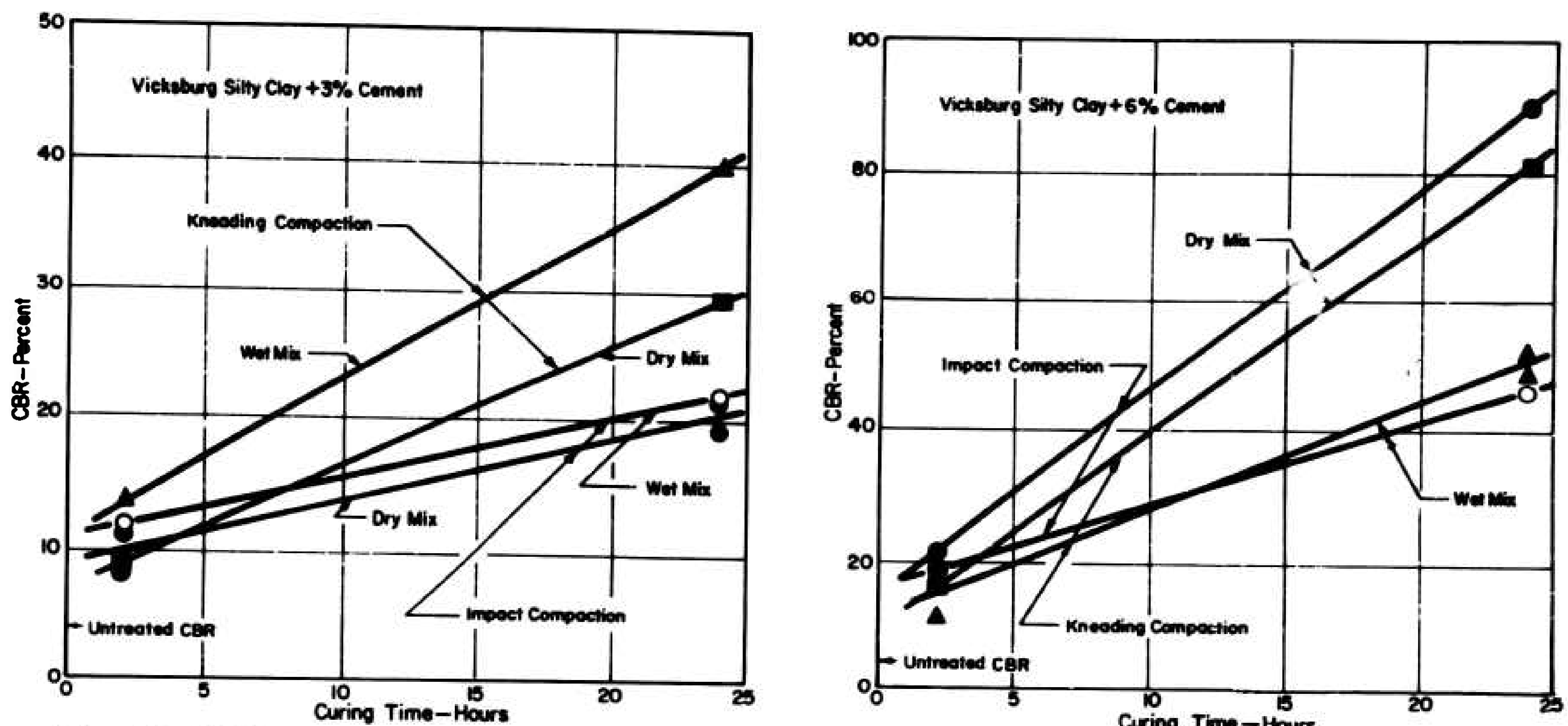

Figure 20 - EFFECTS OF MIXING, COMPACTION AND CURING TIME ON THE CBR OF CEMENT TREATED VICKSBURG SILTY CLAY.

Table 6 presents values of unconfined compressive strength for specimens of silty clay treated with 3 and 6 percent cement using different mixing and compaction procedures. Test specimens prepared by impact compaction were trimmed from standard CBR specimens immediately after compaction, whereas the specimens prepared by kneading were compacted directly to the appropriate size for testing. The results are plotted in Fig. 21. Again it may be seen that kneading compaction resulted in stronger specimens than impact compaction at 3 percent treatment; similar results were also obtained for specimens containing 6 percent cement. Some loss of strength in the impact compaction specimens may, however, have resulted from the trimming process. Fig. 21 indicates an advantage of "dry" mixing as opposed to "wet" mixing in terms of unconfined compression strength.

The effect of mixing procedure on the CBR and unconfined compression strength of buckshot clay treated with 6 percent cement are presented in Tables 7 and 8 and Fig. 22. The data clearly indicate that "dry" mixing results in specimen of higher strength than "wet" mixing. This is probably attributable to the fact that the buckshot clay is a highly plastic, heavy clay which makes thorough mixing of admixtures very difficult when the clay is wet.

It would appear from these results that both mixing sequence and method of compaction have a significant influence on the strength of stabilized specimens. The interrelationships of these factors appear complex and their detailed investigation is beyond the scope of the present study. A thorough investigation of the phenomena involved would appear in order, however.

All of the CBR and compression strength data as presented in Tables 5 through 8 have been used to plot Fig. 23, which shows the variation of unconfined compression strength with CBR. A definite correlation appears to exist although it is not linear over the entire range. For values of CBR up to about 30, however, it appears that a unit increase in CBR is equivalent to about a 3-psi increase in unconfined compression strength. This factor is slightly less than the range of 4 to 6 which may be deduced from the values listed by the Corps of Engineers in Table 3.

TABLE 6

INFLUENCE OF MIXING PROCEDURE ON UNCONFINED COMPRESSIVE STRENGTH OF CEMENT-STABILIZED VICKSBURG SILTY CLAY

(Impact Compaction)

Cement Content %	Mixing Procedure	Molding Water Content, %	Dry Density psf	Curing Time Hours	Unc. Comp. Str. psi
3	Wet	19.0	106.6	2	41.2
3	Wet	19.0	106.8	2	41.8
3	Dry	18.8	104.8	2	38.8
3	Dry	18.1	105.4	2	45.7
3	Wet	17.6	106.4	24	68.0
3	Wet	17.9	104.6	24	51.8
3	Dry	17.8	105.4	24	76.7
3	Dry	18.0	105.7	24	72.8
		(Kneading Compaction)			
3	Wet	18.2	107.0	2	54.6
3	Wet	18.2	106.9	2	51.3
3	Dry	18.1	106.6	2	47.9
3	Dry	18.1	107.0	2	49.7
3	Wet	18.1	107.1	24	90.4
3	Wet	18.1	107.3	24	101.7
3	Dry	18.0	106.6	24	109.3
3	Dry	18.0	107.1	24	101.8
		(Impact Compaction)			
6	Wet	18.9	108.3	2	68.4
6	Wet	18.6	107.6	2	52.5
6	Wet	18.6	108.1	2	56.5
6	Dry	18.5	107.5	2	73.1
6	Dry	18.5	107.0	2	56.4
6	Wet	18.9	107.3	24	94.0
6	Wet	18.9	107.6	24	111.5
6	Wet	18.6	107.6	24	100.0
6	Wet	18.6	108.0	24	89.7
6	Dry	18.5	107.1	24	134.3
6	Dry	18.5	107.0	24	137.8

TABLE 6 (Continued)

(Kneading Compaction)

Cement Content %	Mixing Procedure	Molding Water Content, %	Dry Density psf	Curing Time Hours	Unc. Comp. Str. psi
6	Wet	18.5	107.5	2	67.5
6	Wet	18.5	107.6	2	69.3
6	Wet	18.5	106.3	2	67.5
6	Wet	18.5	106.3	2	65.0
6	Dry	18.0	107.1	2	63.3
6	Dry	18.0	107.5	2	71.8
6	Dry	18.4	105.5	2	56.5
6	Dry	18.4	105.3	2	64.5
6	Wet	18.3	107.7	24	145.6
6	Wet	18.3	107.3	24	128.7
6	Wet	18.6	105.8	24	132.3
6	Wet	18.6	106.2	24	135.2
6	Dry	18.3	107.7	24	185.3
6	Dry	18.3	107.3	24	194.2
6	Dry	17.6	106.7	24	180.0
6	Dry	17.6	107.3	24	204.0

TABLE 7

INFLUENCE OF MIXING PROCEDURE ON CBR OF VICKSBURG BUCKSHOT

CLAY STABILIZED WITH 6% CEMENT

(Impact Compaction)

Mixing Procedure	Molding Water Content, %	Dry Density pcf	Curing Time Hours	CBR %
Untreated	31.0	89.8	--	4.2
Wet	30.5	90.0	2	9.1
Dry	30.6	89.8	2	13.7
Wet	30.5	90.0	24	14.7
Dry	30.6	89.8	24	26.7

TABLE 8

INFLUENCE OF MIXING PROCEDURE ON THE UNCONFINED COMPRESSIVE STRENGTH OF VICKSBURG BUCKSHOT CLAY STABILIZED WITH 6% CEMENT

(Impact Compaction)

Mixing Procedure	Molding Water Content,%	Dry Density pcf	Curing Time Hours	Unc. Comp. Str. psi
Wet	31.0	90.1	2	14.0
Wet	31.0	89.6	2	12.7
Dry	30.3	89.3	2	38.0
Dry	30.3	90.0	2	43.5
Wet	31.0	89.8	24	33.0
Wet	31.0	90.6	24	33.3
Dry	30.3	89.9	24	68.0
Dry	30.3	89.9	24	78.4

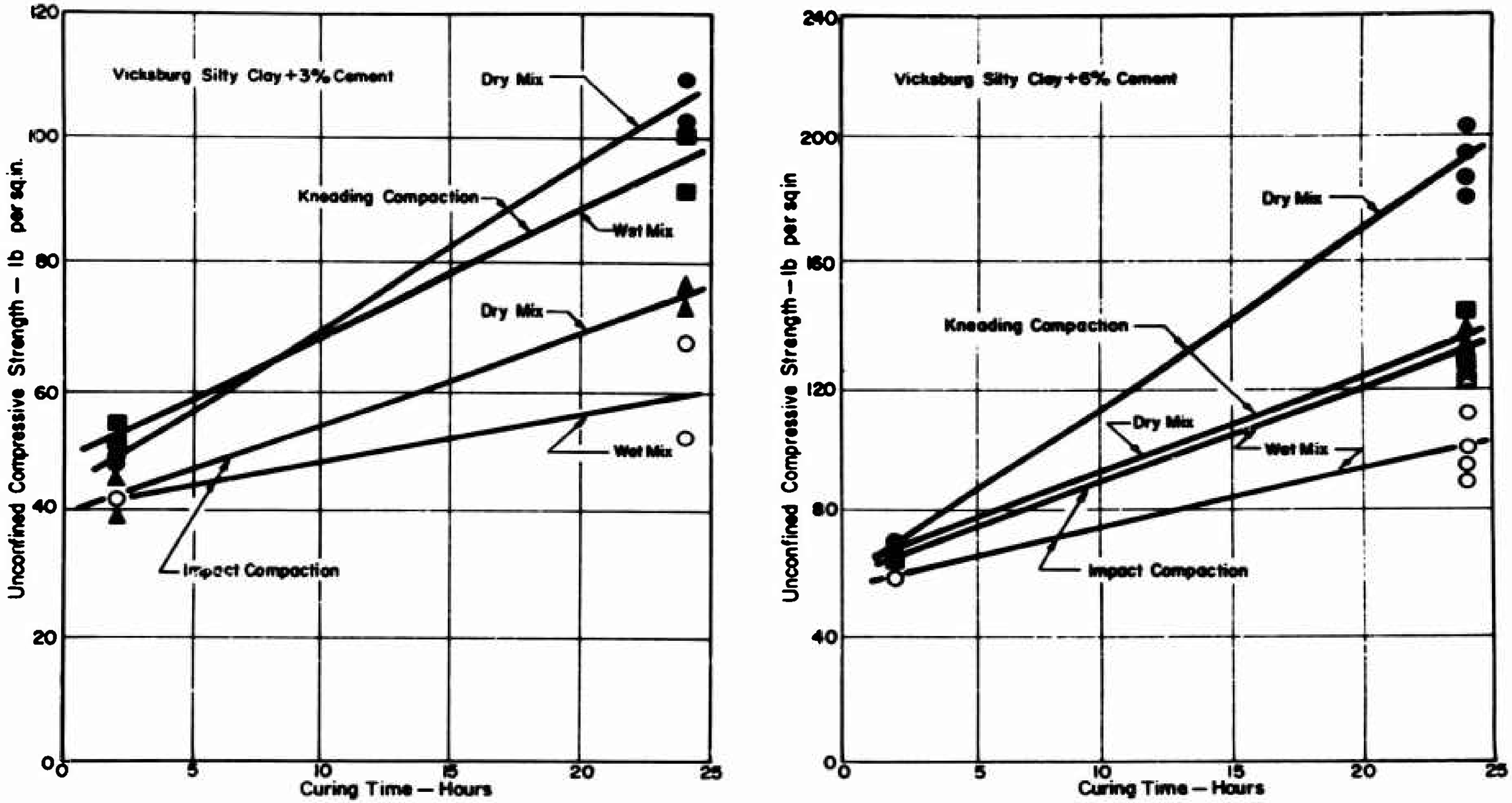

Figure 21 - EFFECTS OF MIXING, COMPACTION AND CURING TIME ON THE UNCONFINED COMPRESSIVE STRENGTH OF CEMENT TREATED VICKSBURG SILTY CLAY.

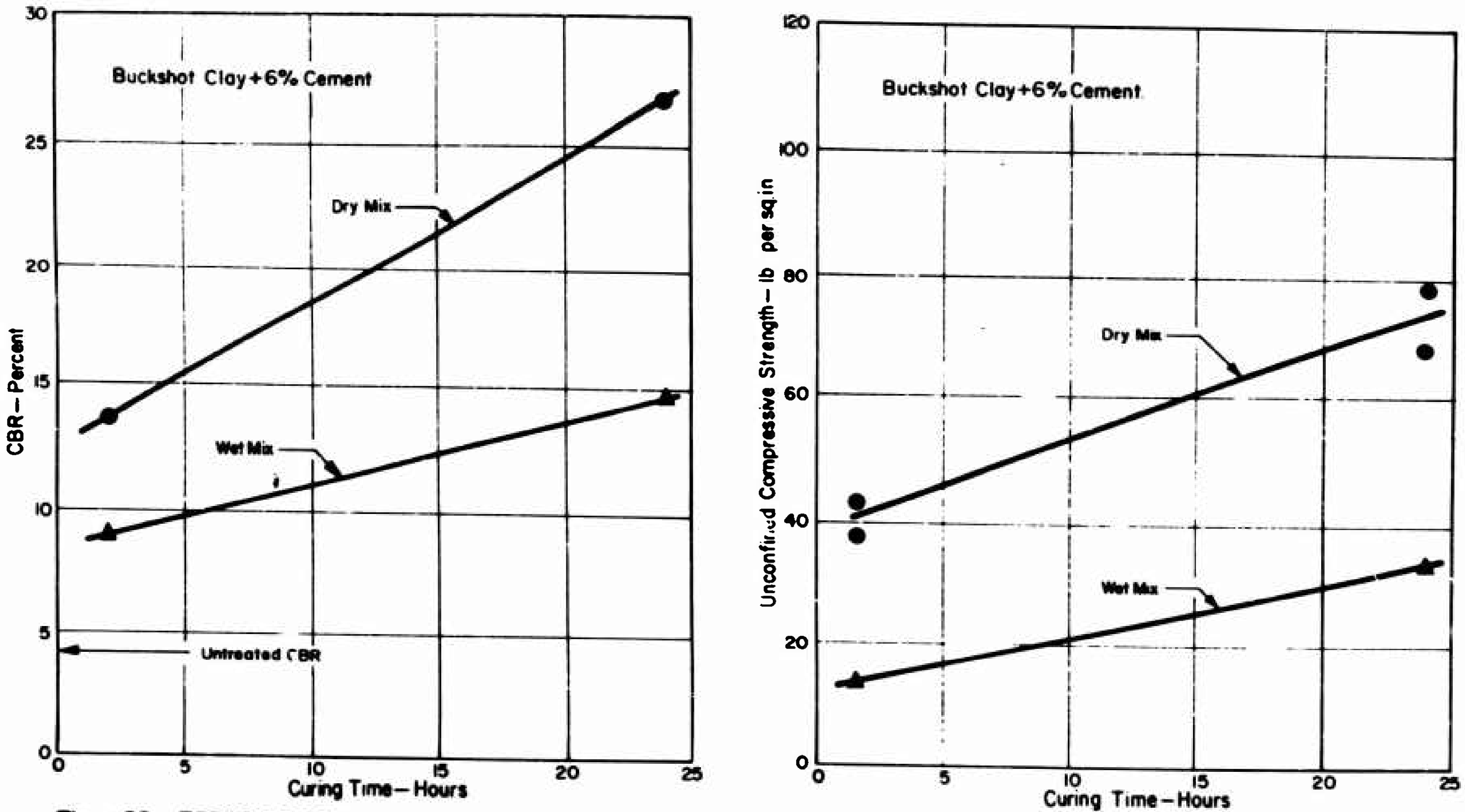

Figure 22 - EFFECT OF MIXING PROCEDURE ON CBR AND UNCONFINED COMPRESSIVE STRENGTH OF CEMENT TREATED BUCKSHOT CLAY.

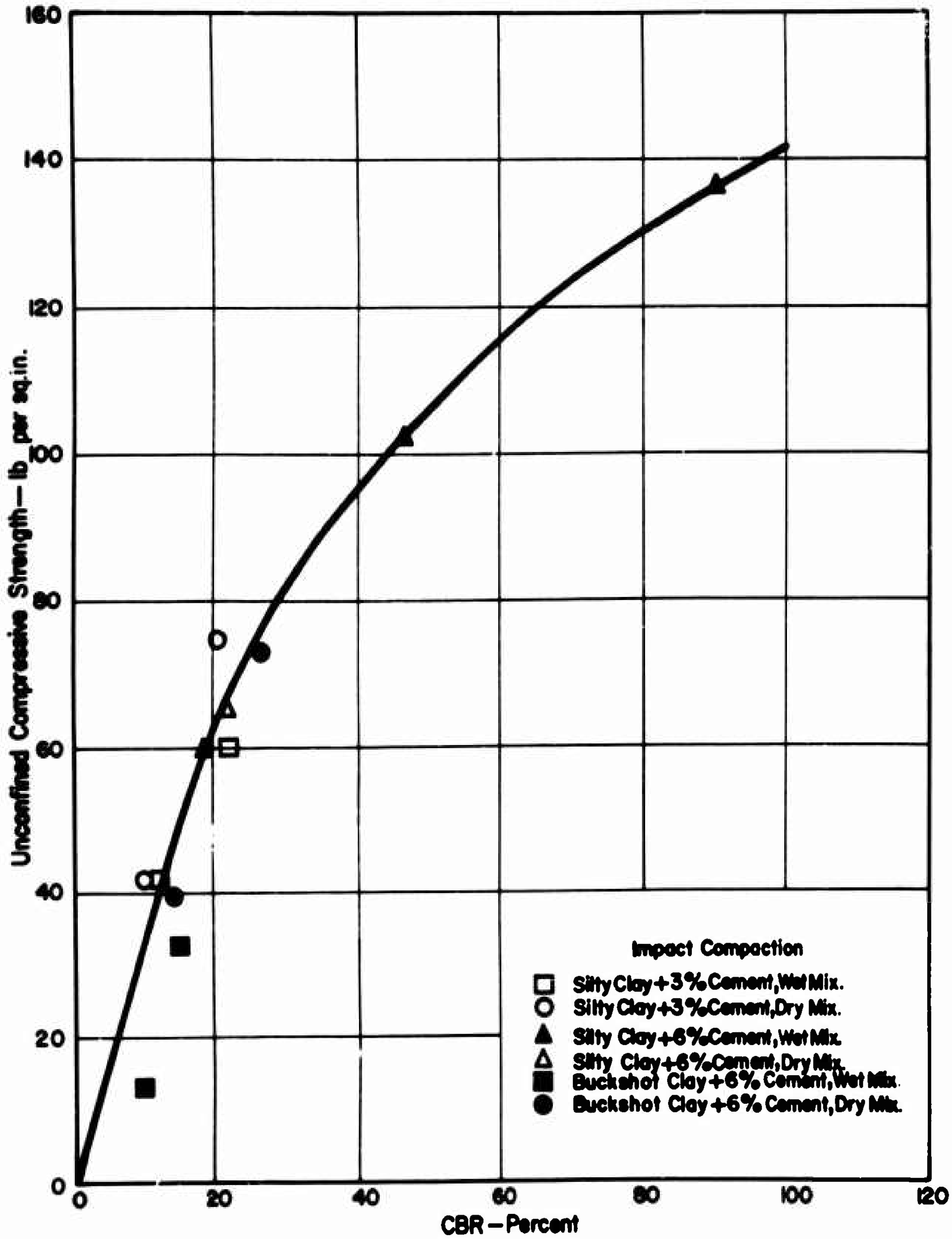

Figure23 - RELATIONSHIP BETWEEN UNCONFINED COMPRESSIVE STRENGTH AND CBR.

After consideration of the test results reported above and the requirements for the repeated load test program, it was decided that samples should be prepared using dry mixing and kneading compaction. The advantages of this mixing procedure as compared to wet mixing are that it is simpler and it permits more uniform and reproducible samples to be prepared. The major disadvantage of dry mixing is that it does not simulate field stabilization to the same extent as does wet mixing.

Kneading compaction was selected as the most practical for laboratory use since it minimizes material waste and layering effects in compacted specimens; in addition, available data (Seed, Chan and Lee, 1962) suggest that kneading compaction better simulates field conditions than impact compaction.

VII. BEHAVIOR OF CEMENT-TREATED SILTY CLAY IN REPEATED COMPRESSION

Test series have been carried out to evaluate the effects of repeated compressive stresses on Vicksburg silty clay treated with 3 percent cement. Water contents were selected to produce an untreated material with a CBR of about 4 and a treated material with a CBR of about 20 after a curing period of 24 hours. Test variables included repeated stress intensity, curing period, and molding water content. In all cases repeated loading was carried out for one day, which resulted in about 24,000 load applications to each specimen, unless failure developed sooner. This resulted in a considerably greater number of load applications than required by the military road and airfield criteria, Tables 1 and 2. Furthermore, the loading period was much shorter than that for which the military pavements must be designed. Thus the laboratory loading conditions were considered to be more severe than those to which the material would be subjected in the field. On the other hand, the longer period of exposure in the field could make weathering effects important.

A stress-strain curve in unconfined compression for a specimen of silty clay (water content-18.8 percent; cement content-3 percent; and curing period-24 hours) not subjected to repeated loading is shown in Fig. 24. This specimen exhibited brittle failure at a strain of about 45 percent. The modulus of deformation in compression for such specimens (secant modulus based on the peak stress) averages 2200 psi.

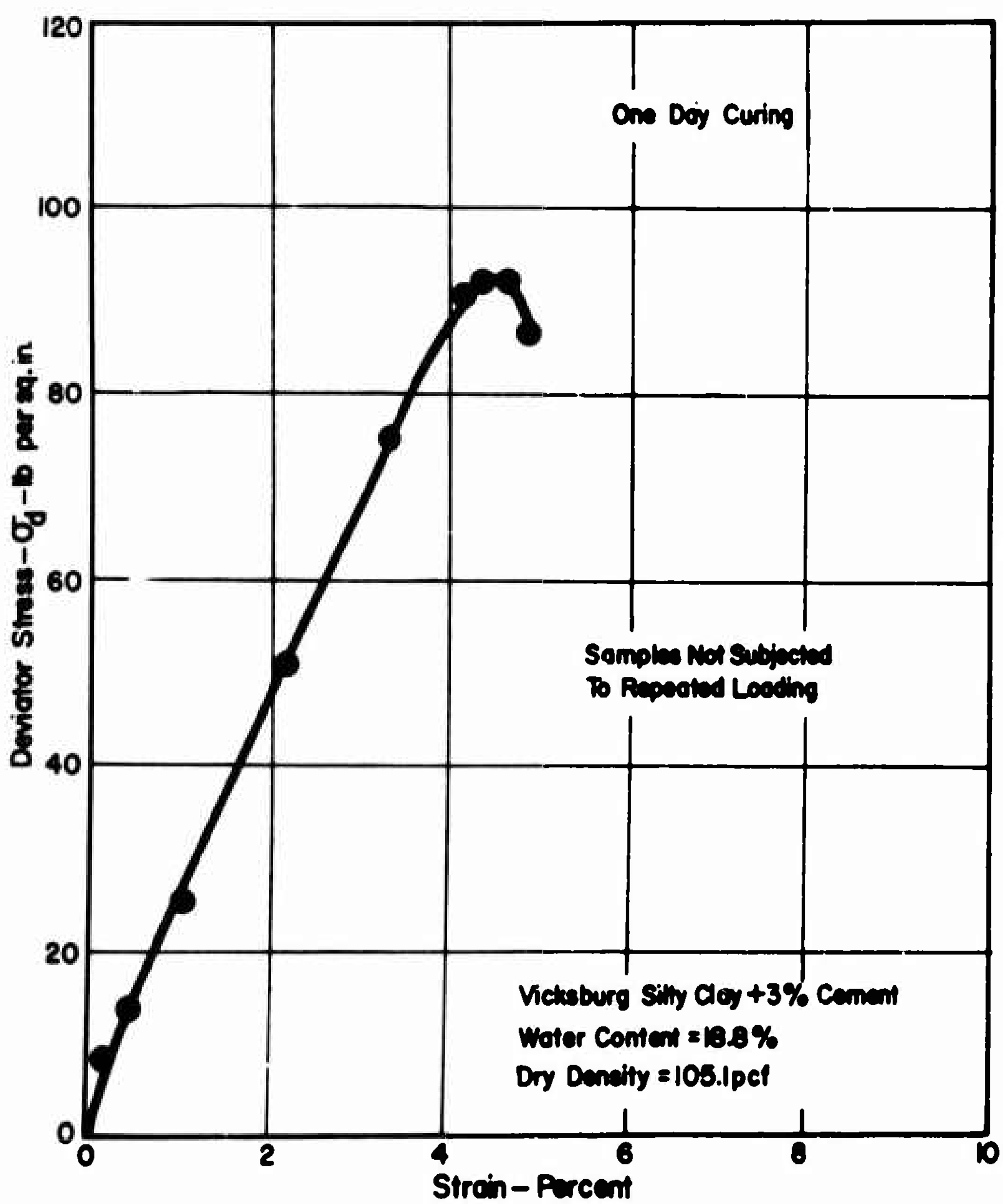

Figure 24 - BEHAVIOR OF CEMENT TREATED SILTY CLAY IN UNCONFINED COMPRESSION.

VIII. INFLUENCE OF STRESS INTENSITY ON BEHAVIOR IN REPEATED COMPRESSION

Specimens of silty clay treated with 3 percent cement and cured for 24 hours were subjected to different repeated compressive stress intensities in the range of 5 to 70 psi, representing stress levels in the range 5 to 75 percent of the initial strength. Table 9 lists water contents, densities, repeated load stress intensities, and strengths for these specimens. Comparison of these strengths with those specified in Table 3 for satisfactory stabilization indicates that adequate stabilization had been achieved. Total axial deformation as a function of number of load applications is shown in Fig. 25. The general shape of the curve is the same at each stress intensity. Total strain increases with increasing numbers of load applications and reaches a constant value after about 1000 repetitions.

The strains plotted in Fig. 25 include both permanent and recoverable deformation. Resilient or recoverable deformation as a function of number of load applications is shown for each specimen in Fig. 26. It may be seen that in almost all cases the resilient deformation is a maximum at the start of the test and decreases with increased numbers of stress applications. This pronounced decrease in resilient deformation would appear to be responsible for the leveling off of the total deformation curves at large numbers of load applications (Fig. 25).

The decrease in resilience that occurs during the test can be attributed primarily to two causes: (1) slight densification and increase in stiffness resulting from the deformations which occur at low numbers of stress applications and (2) cement hydration which occurs during the course of testing leading to greater sample resistance since the specimens are in the early stages of curing.

The data in Fig. 26 have been used to evaluate the moduli of resilient deformation at 100, 1000, and 10,000 load applications for different stress intensities. These results are plotted in Fig. 27. The general shape of these curves is similar to those obtained by Seed, Chan, and Lee (1962) for untreated specimens of the AASHO Road Test subgrade soil (a silty clay designated as an A-6 material according to the HRB classification system). At low stress intensities the modulus decreases rapidly with increase in stress, probably because the stress-strain curve for the material is curvilinear. At stress intensities greater than about 25 psi, the

TABLE 9

EFFECT OF REPEATED STRESS INTENSITY ON STRENGTH AND RESILIENCE OF CEMENT-TREATED SILTY CLAY

Sample No.	Dry Density pcf	Water Content %	R.L. Stress Level psi	Compressive Strength (psi) After R.L. N = 24000	Compressive Strength (psi) Control	Compressive Strength (psi) Percentage of Unloaded Strength	Strain at Failure ϵ_f %	Modulus of Resilient Deformation M_R (psi) AT N = 100	Modulus of Resilient Deformation M_R (psi) AT N = 1,000	Modulus of Resilient Deformation M_R (psi) AT N = 10,000
D-7	105.1	18.8	--		92	--	4.5			
8	104.7	18.8	--		97	--	4.2			
9	104.7	18.9	5	96		103	4.2	16.0×10^3	14.6×10^3	22.7×10^3
10	105.0	18.9	10	83		89	3.7	13.5	13.0	17.2
11	104.8	18.8	40	98		105	4.5	8.0	9.4	13.2
12	104.9	18.8	50	89		96	3.5	10.2	11.2	17.6
13	104.0	19.0	20	88		95	5.7	5.4	6.4	10.0
14	104.0	19.0	30	93		100	5.0	6.2	7.0	11.1
15	104.1	19.0	60	93		100	6.4	10.7	13.2	18.7
*16	104.1	19.0	70	108		116	6.0	11.3	13.0	17.2
17	105.2	18.7	15	86		92	3.5	8.55	8.9	12.5
18	105.2	18.7	25	100		107	4.8			
19	105.3	18.6	25	92		99	3.5			
20	105.2	18.6	--		89	--	4.3			

Vicksburg silty clay + 3% cement, 24 hours curing

*Crack observed on sample.

R.L. = Repeated loading

N = Number of load repetitions

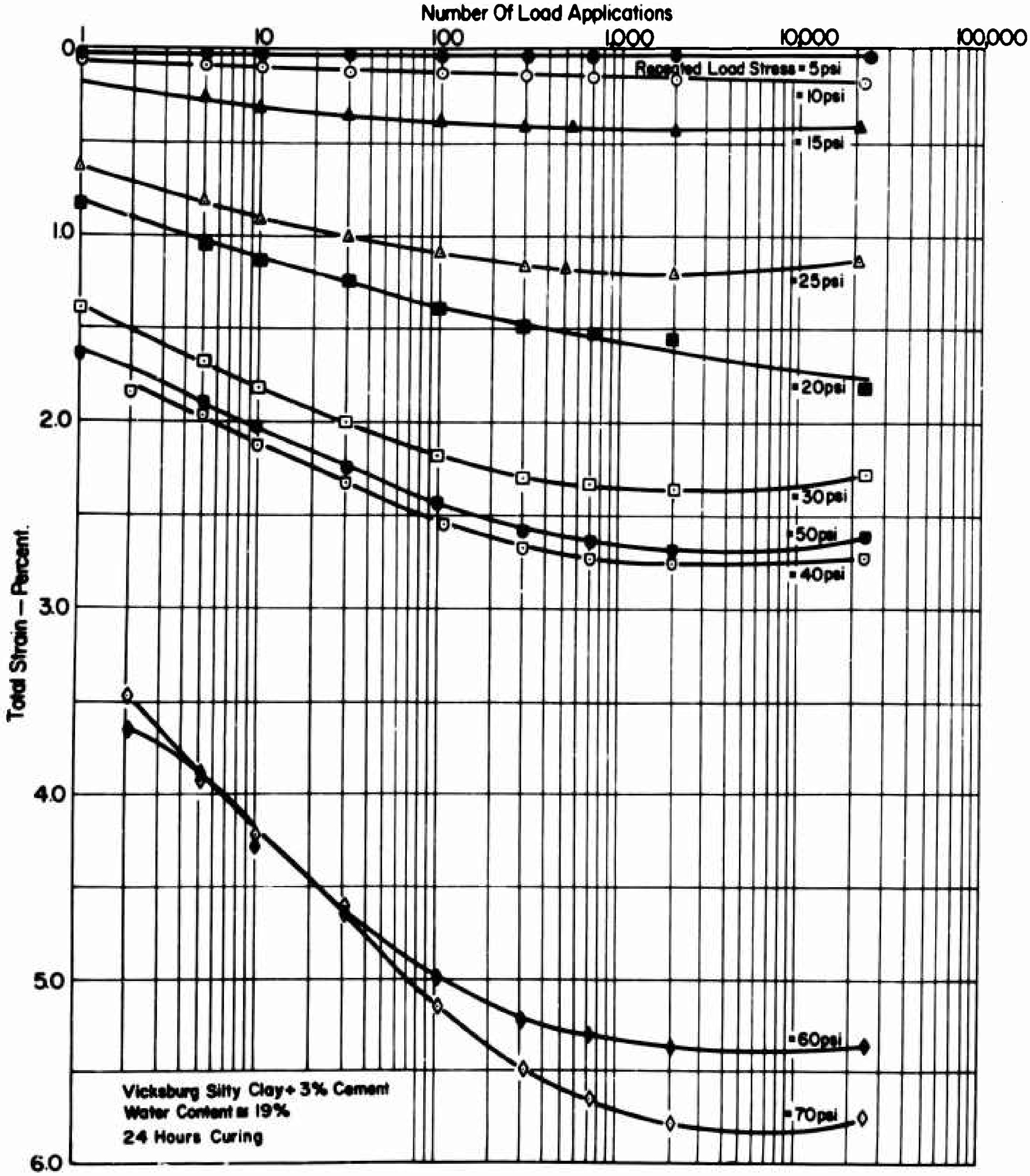

Figure 25 - TOTAL STRAIN VERSUS NUMBER OF LOAD APPLICATIONS FOR VICKSBURG SILTY CLAY — CEMENT.

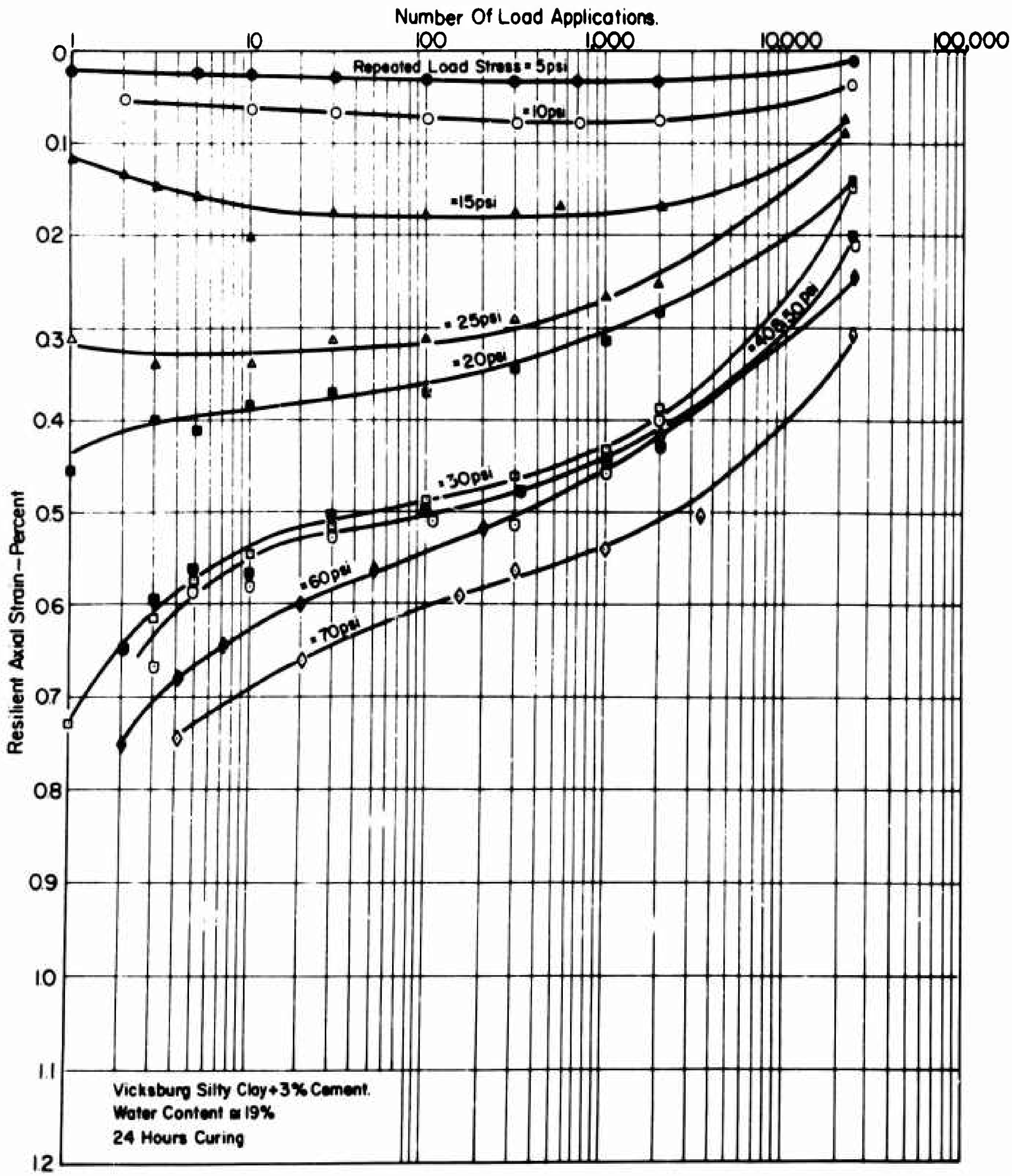

Figure 26-RESILIENT STRAIN VERSUS NUMBER OF LOAD APPLICATIONS FOR VICKSBURG SILTY CLAY—CEMENT.

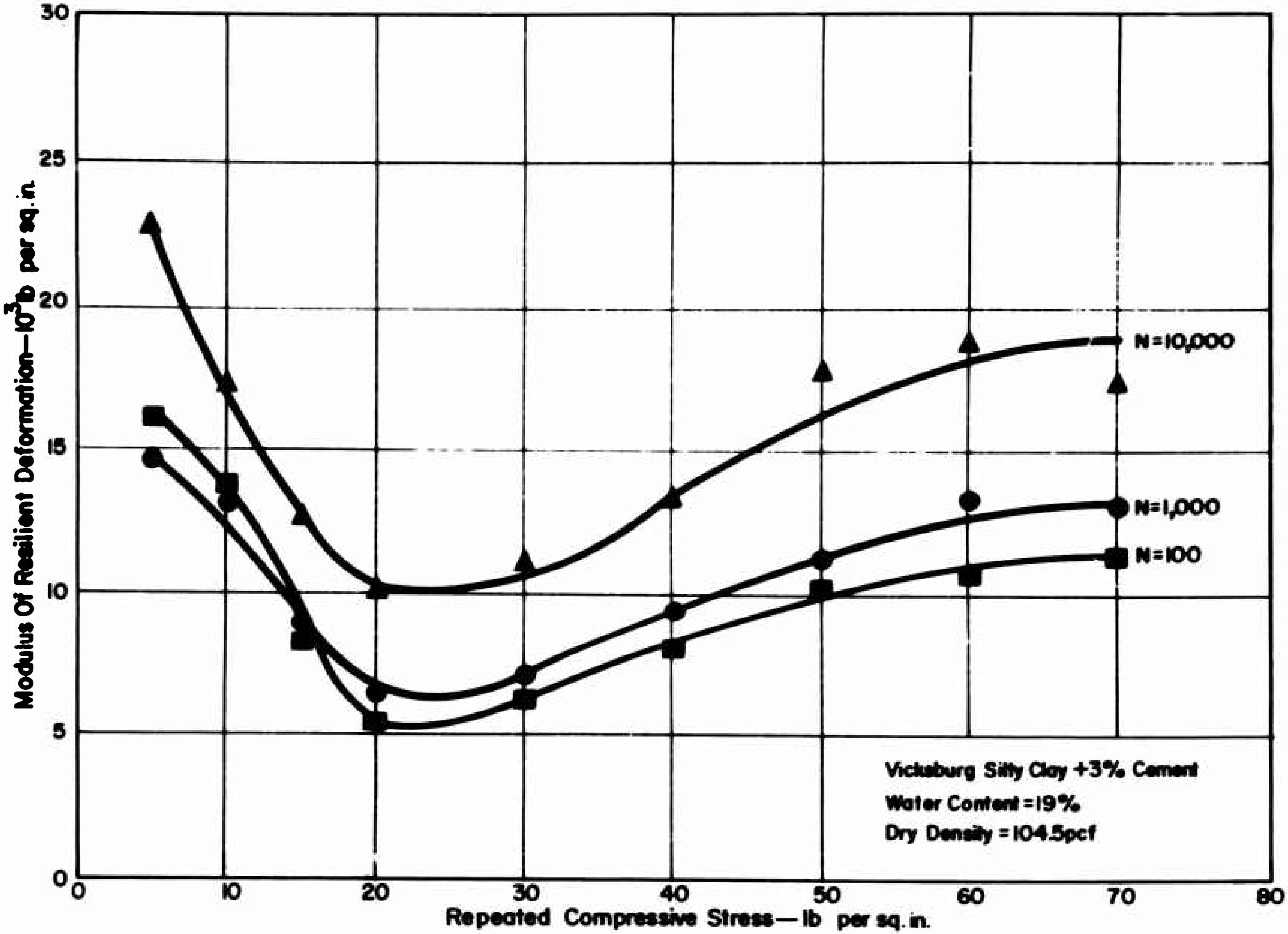

Figure 27 - RESILIENT MODULUS AS A FUNCTION OF COMPRESSIVE STRESS INTENSITY FOR CEMENT TREATED SILTY CLAY.

resilient modulus shows an increase with increase in compressive stress intensity. It is probable that this increase in modulus results from densification of the specimens at the higher stress intensities at low numbers of load applications. In Fig. 26 it is apparent that the rate of decrease of resilient strain with increase in number of load applications is much greater at high stress intensities than at low stress intensities. The greater part of this decrease can be attributed to densification since the effect of increased curing time would be expected to be more or less independent of stress intensity.

Values for the modulus of resilient deformation at all stress intensities and numbers of load application, Fig. 27, are significantly larger than the value of 2200 psi determined from normal strength tests reported earlier. The short periods of load application in the repeated-load tests tend to minimize time-dependent deformations which develop in normal strength tests, thus accounting for the behavior.

It may be seen from Table 9 that for stresses up to 70 psi, repeated loading had no significant effect on the ultimate strength as compared to that for specimens not subjected to repeated loading. Thus measurable fatigue effects did not appear in this test series.

A stress strain curve as determined by normal compression tests is shown in Fig. 28 for specimens previously subjected to 24,000 repetitions at a stress level of 40 psi. The positive strain intercepts at zero deviator stress represents permanent deformation at the end of repeated loading. Comparison of Fig. 28 with Fig. 24, which shows the stress-strain characteristics of a specimen not subjected to repeated loading, again indicates the increase in stiffness of the stabilized soil as a result of the repeated loading. It may also be noted that brittle failure developed at about the same total strain and stress intensity for the samples subjected to repeated loading as for the samples not so loaded. Thus, although the stabilized soil had its structure greatly stiffened as a result of the repeated stress, ultimate strength properties were little influenced.

The results obtained in this investigation may be compared with those reported by Shen (1965) for soil-cement* (cement treated-13 percent by

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*As defined by PCA/ASTM durability requirements.

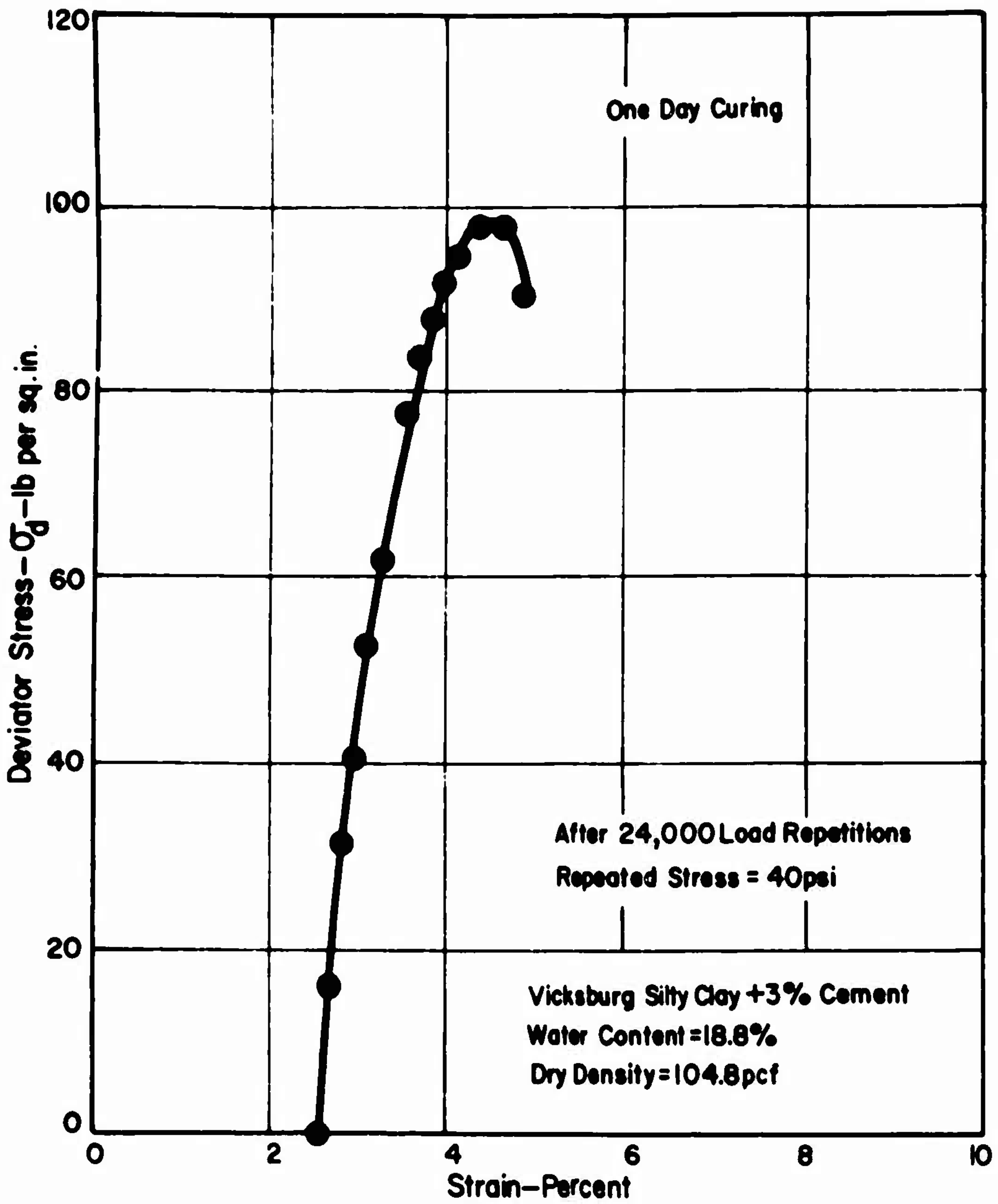

Figure 28 - BEHAVIOR OF CEMENT TREATED SILTY CLAY IN UNCONFINED COMPRESSION AFTER REPEATED LOADING.

dry weight of soil) prepared from Vicksburg silty clay. The effect of stress intensity on modulus was determined for three different soil-cement water contents, designated A, B, and C in Fig. 29. Values of resilient modulus at 1000-load applications as a function of repeated stress intensity are shown in Figs. 30 and 31 for these three conditions. It may be seen that water content, as well as stress intensity, is a significant variable. Further illustration of the effect of water content is presented in a subsequent section. It is sufficient to note at this time that as water content increases, so does the deformability of the soil-cement. Evidence of this is also presented in Fig. 32, which shows the strain at failure as a function of molding water content for compression tests performed by Shen.

The curves in Figs. 30 and 31 show that resilient modulus decreases with an increase in stress intensity for stresses up to about 50 percent of the strength, above which the modulus is approximately constant. No increase in modulus was noted for larger stresses as had been reported by Seed, Chan and Lee (1962) for the untreated AASHO Road Test silty clay and as shown in Fig. 27 for Vicksburg silty clay treated with 3 percent cement. This probably was due to the fact that the soil-cement specimens were so stiff that even large repeated stresses could cause little structural change and densification. Even at the highest water contents and stress intensities, the soil-cement had a modulus of resilient deformation of more then 30,000 psi. In most cases the modulus values for the soil-cement were several hundred thousand psi as compared to the range of 5000 to 25,000 psi for the samples studied in this investigation. This further illustrates the fact that normal soil-cement and cement-treated soil sufficient to satisfy Corps of Engineer's criteria are in reality quite different structural materials.

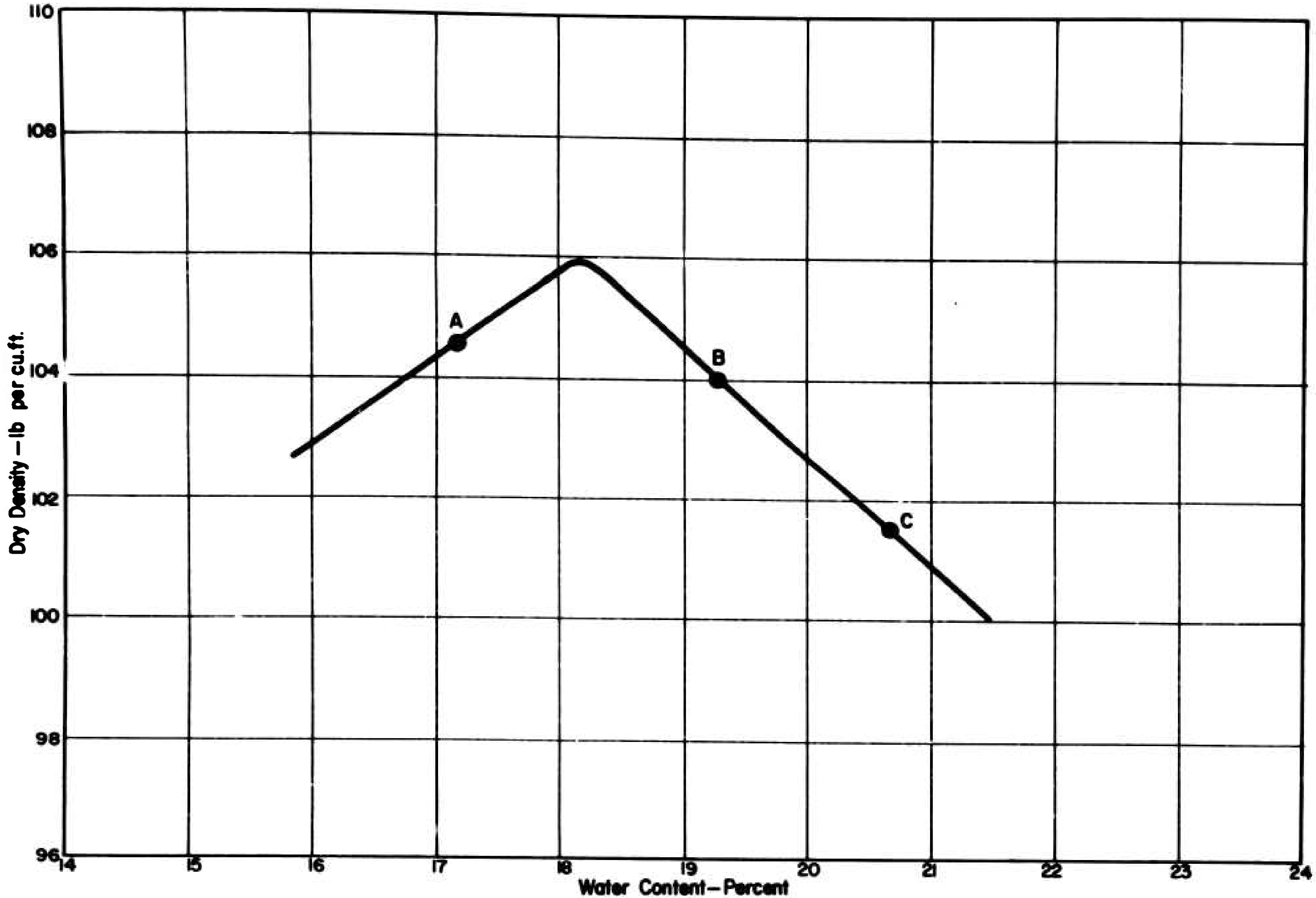

Figure 29-COMPACTION CURVE — VICKSBURG SILTY CLAY-CEMENT.

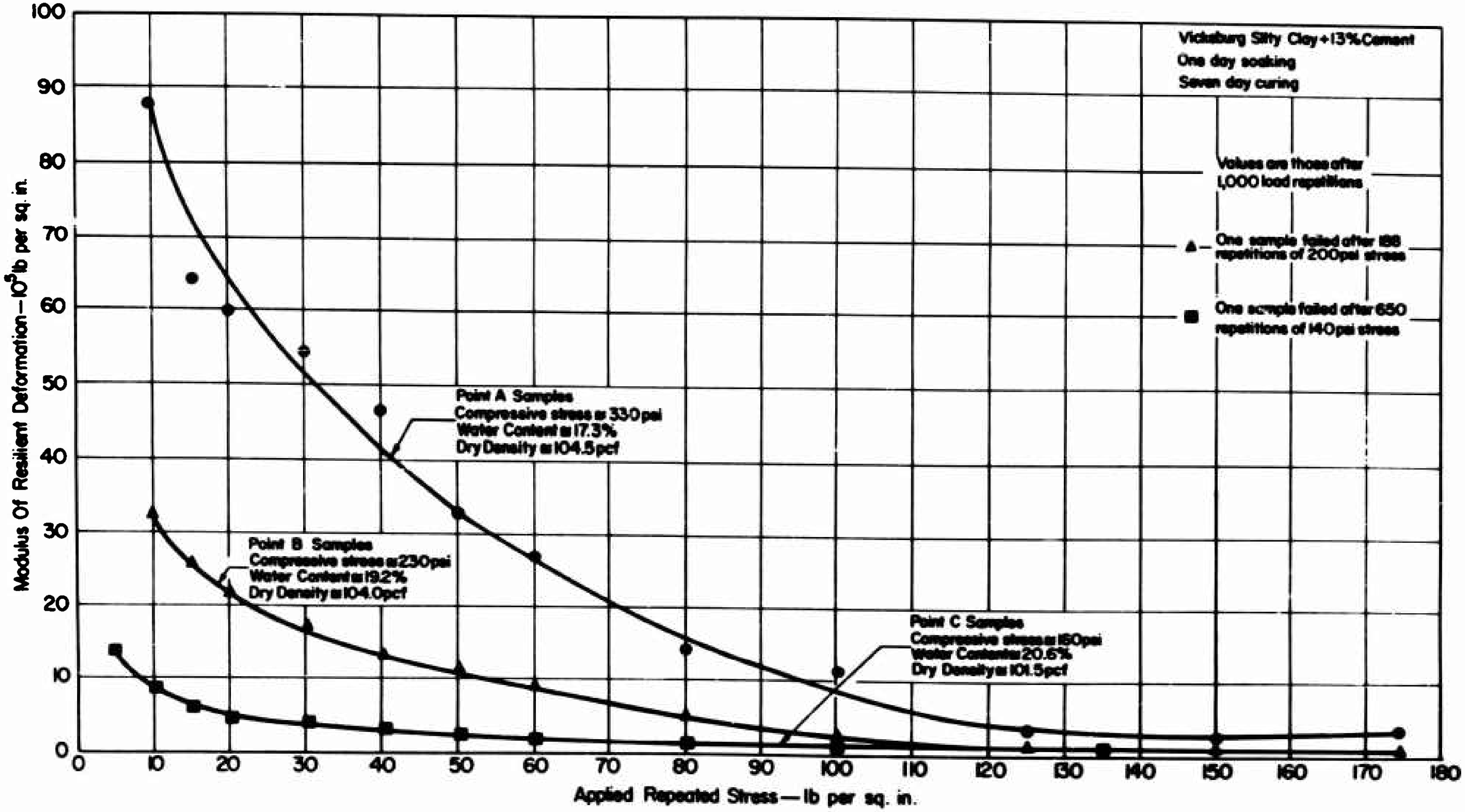

Figure 30 - EFFECT OF STRESS INTENSITY ON RESILIENT MODULUS IN COMPRESSION FOR VICKSBURG SILTY CLAY — CEMENT.

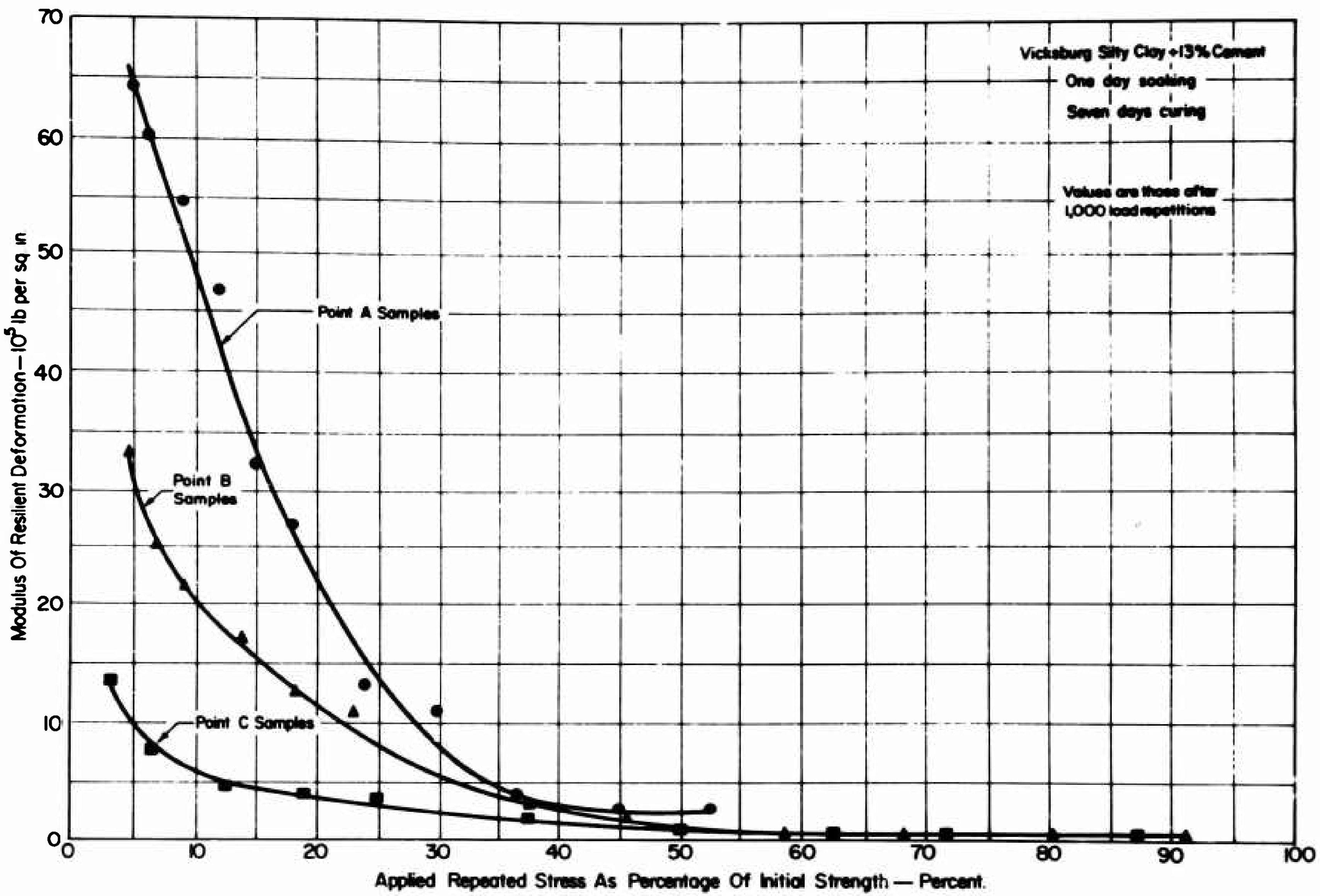

Figure 31 - EFFECT OF STRESS LEVEL ON RESILIENT MODULUS IN COMPRESSION FOR VICKSBURG SILTY CLAY—CEMENT.

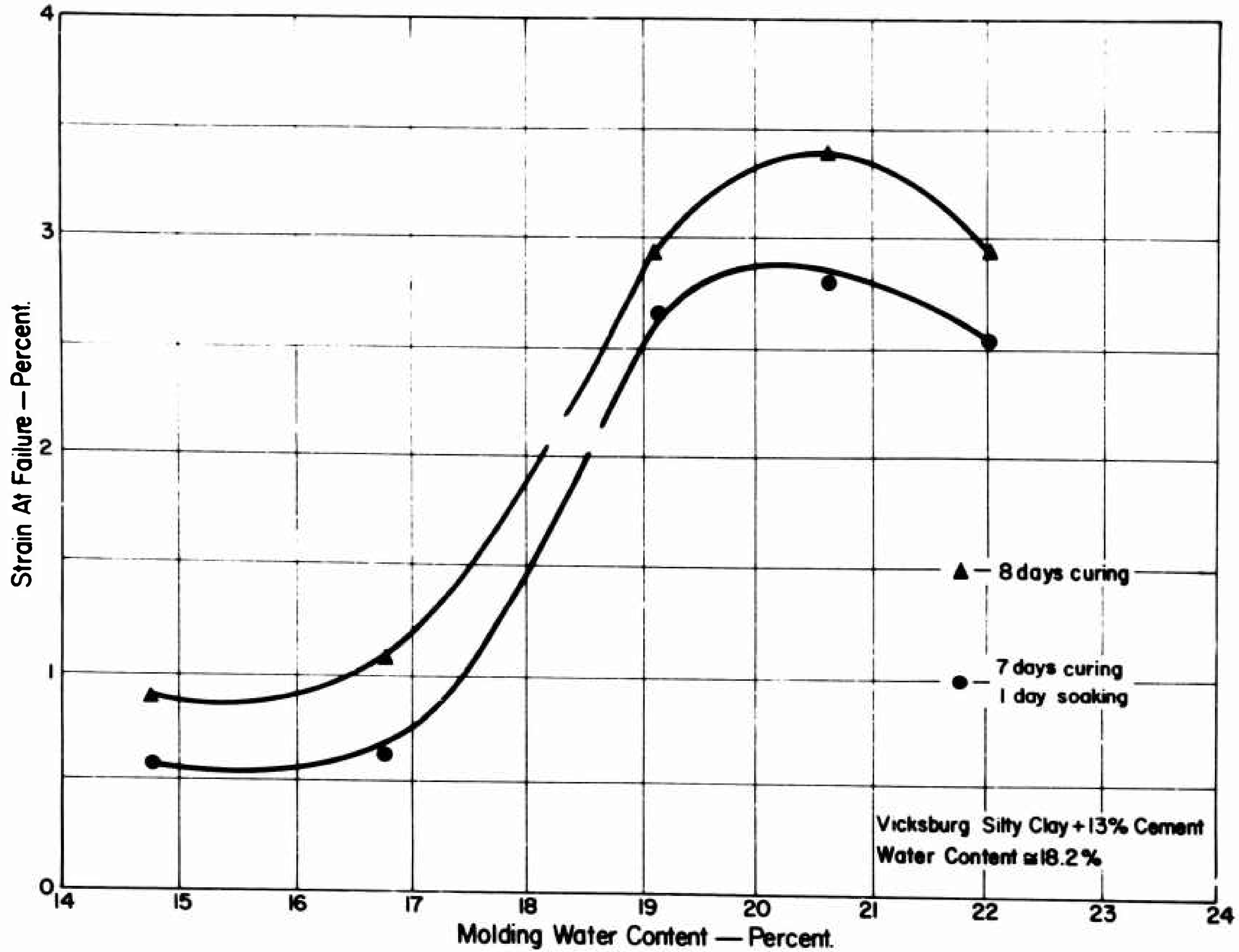

Figure 32 - RELATIONSHIP BETWEEN WATER CONTENT AND STRAIN AT FAILURE IN COMPRESSION TESTS FOR VICKSBURG SILTY CLAY – CEMENT.

IX. INFLUENCE OF CURING TIME ON BEHAVIOR IN REPEATED COMPRESSION

Tests were performed to determine the effect of curing time on the behavior of silty clay treated with 3 percent cement and subjected to repeated compressive stresses. The variation of strength in normal compression tests as a function of curing times in the ranges of 2 hours to 8 days was determined. The results of these tests are listed in Appendix B. Fig. 33 shows a progressive increase in strength as curing time increases. Fig. 34 shows that strain at failure decreases progressively as curing time increases, reflecting the fact that increased curing not only leads to an increase in ultimate strength but also to an increase in the stiffness of the sample.

At the end of each curing period, specimens were subjected to repeated load compressive stresses at levels of 80 and 95 percent of the strength at that particular time. Thus the longer the curing period prior to the start of repeated loading, the higher is the actual stress intensity applied to the sample. Tests were continued until failure or 24,000 load repetitions, whichever occurred first.

Only one specimen failed prior to 24,000 load repetitions of an 80 percent stress level. On the other hand, for specimens loaded to 95 percent of the initial strength, fatigue failures developed for curing periods greater than 18 hours (except for one sample). At very early ages, specimens loaded to 95 percent of their initial strength successfully carried the full 24,000 repetitions. This behavior probably indicates that at these early ages the stabilized soil is gaining strength, due to cement hydration, at a rate faster than the rate of destruction under the action of the repeated stresses. On the other hand, for tests started after longer curing periods, the destructive effects of the repeated stress exceed the strength increase due to curing during the test period.

In addition the fact that the stabilized soil is not as brittle at the shorter curing periods as after longer times would appear to indicate that in this condition it is better able to deform without rupture under the action of the repeated stress. In this connection Yamanouchi (1963) found, as a result of laboratory and field tests, that opening a pavement with a base course consisting of soil cement to traffic immediately after

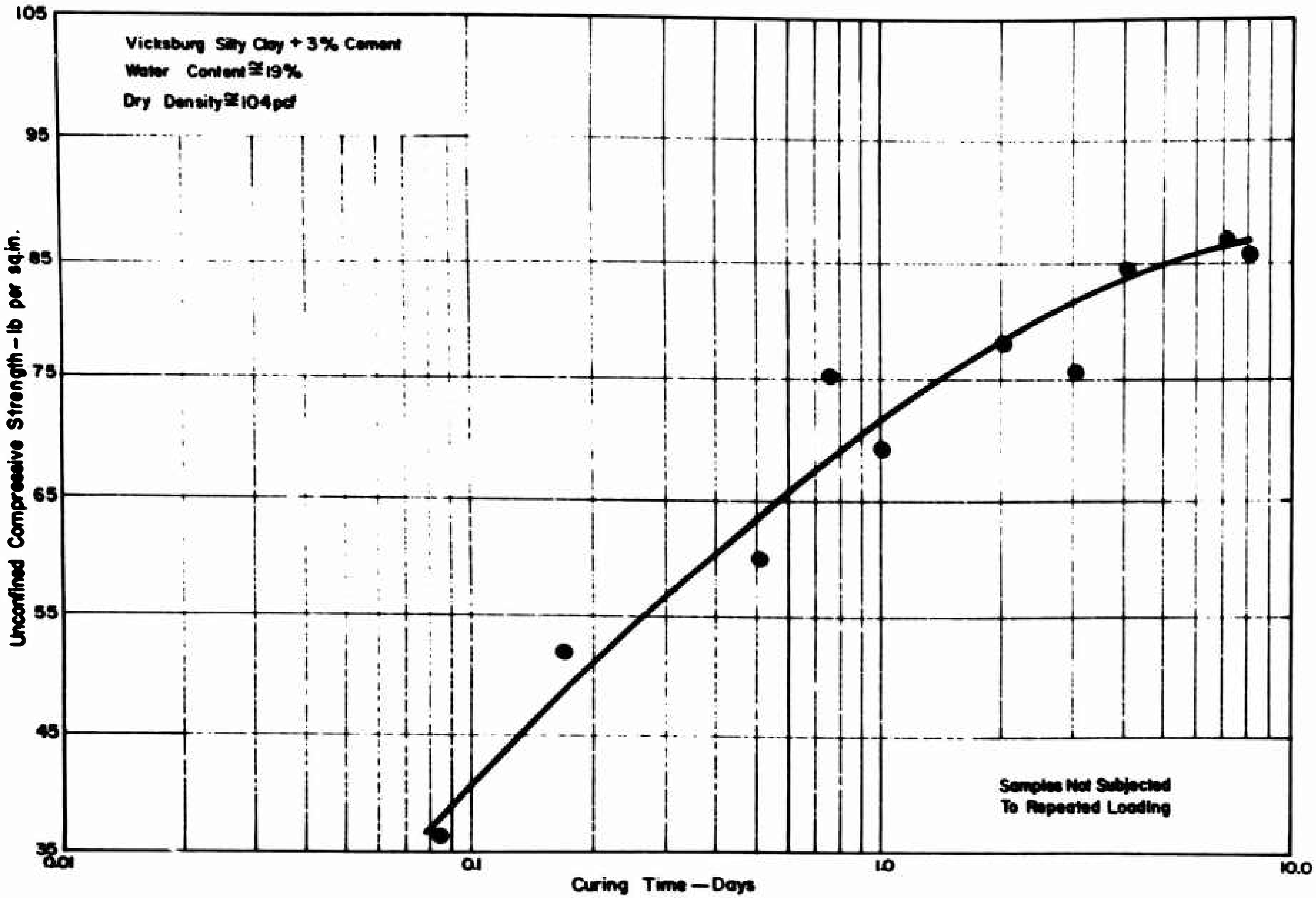

Figure 33-VARIATION OF UNCONFINED COMPRESSIVE STRENGTH WITH CURING TIME.

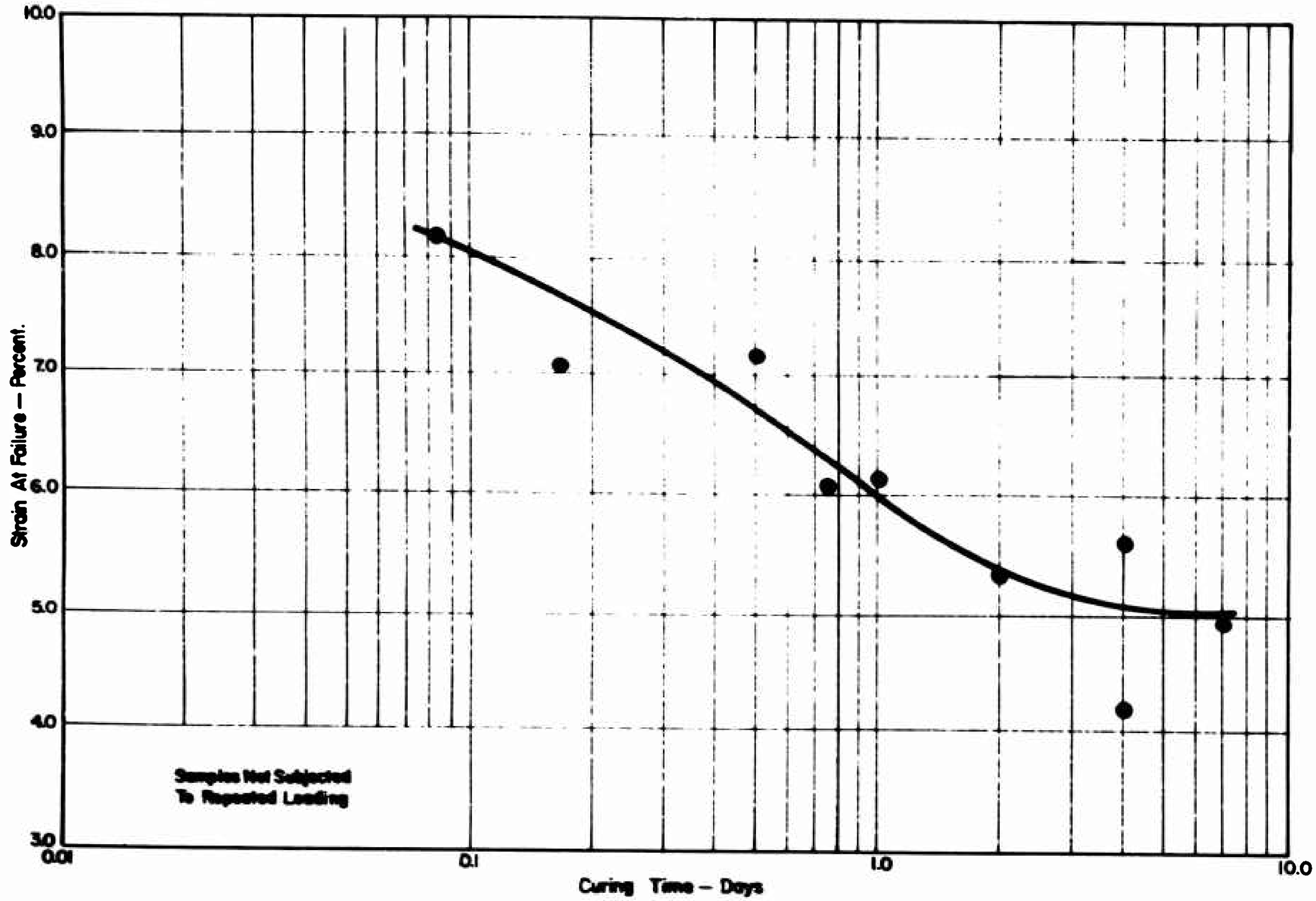

Figure 34 - VARIATION OF STRAIN AT FAILURE WITH CURING TIME.

construction instead of first permitting a curing period had no detrimental effect on the soil-cement. In fact he observed that the cracking which developed was less severe in the case of the pavement opened immediately. It is interesting to note also that Yamanouchi found that the seven-day strength of specimens was increased if a one-day period of repeated loading was started immediately. On the other hand loading begun on the third to the fifth days caused a reduction in the seven day strength. In his tests, however, the applied repeated stress intensity was very low relative to the strength of the stabilized soil.

The variation of resilient modulus in compression with curing time after 100, 1000, and 10,000 load applications is shown in Figs. 35, 36, and 37, respectively. It may be seen that in general the modulus for a 95 percent stress level is slightly greater than that at an 80 percent stress level. This trend, as well as the general range of values, is about the same as the results shown in Fig. 27 for lower stress intensities. It is important to keep in mind when considering these results that the greater the curing period, the greater the actual stress required for each stress level.

Values of modulus after 100 and 1000 repetitions are essentially the same, and the general trend is for an increase in modulus for a given stress with an increase in curing time. On the other hand, after 10,000 load repetitions, the modulus is higher than at 1000 repetitions; but a definite decrease with increasing curing time may be noted in Fig. 37, at least at the 80 percent stress level. The fact that modulus increases with curing time for a given stress level at low numbers of stress repetitions probably reflects the fact that the stiffness of specimens increases at longer curing times; this is evidenced for example by the strain at failure, Fig. 34. The fact that after a large number of repetitions the modulus decreases with increasing curing time may be an indication of a greater tendency for fatigue in the older specimens, perhaps due to the more brittle and less resilient structure that develops after longer curing periods.

The effect of the repeated loading on the ultimate strength of specimens subjected to repeated stresses 80 and 95 percent of the ultimate unloaded strength is shown in Fig. 38. It should be noted that the comparison is made between strength after repeated loading and strength in

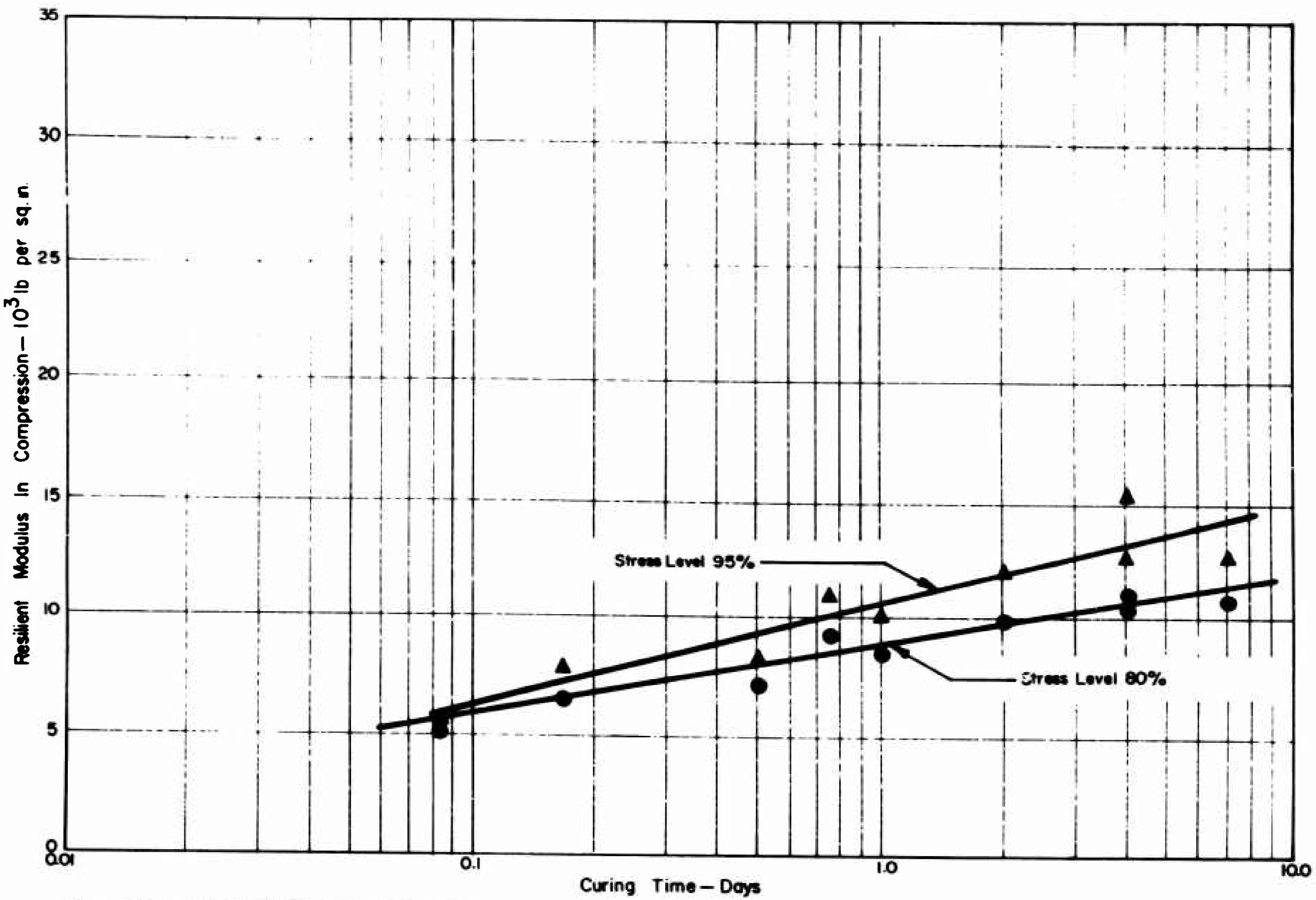

Figure 35 - VARIATION OF RESILIENT MODULUS WITH CURING TIME — AFTER 100 LOAD APPLICATIONS.

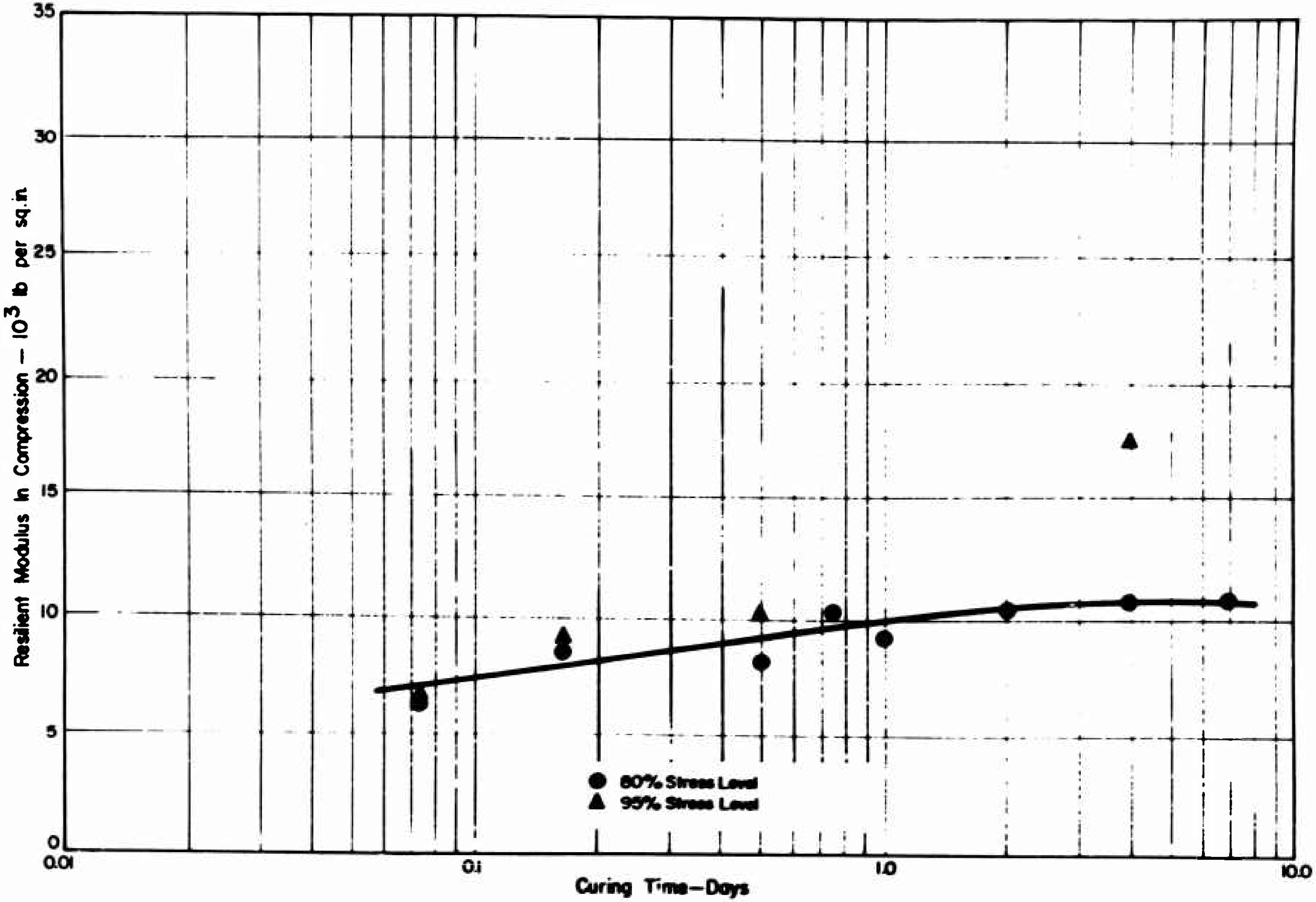

Figure 36 - VARIATION OF RESILIENT MODULUS WITH CURING TIME — AFTER 1,000 LOAD APPLICATIONS.

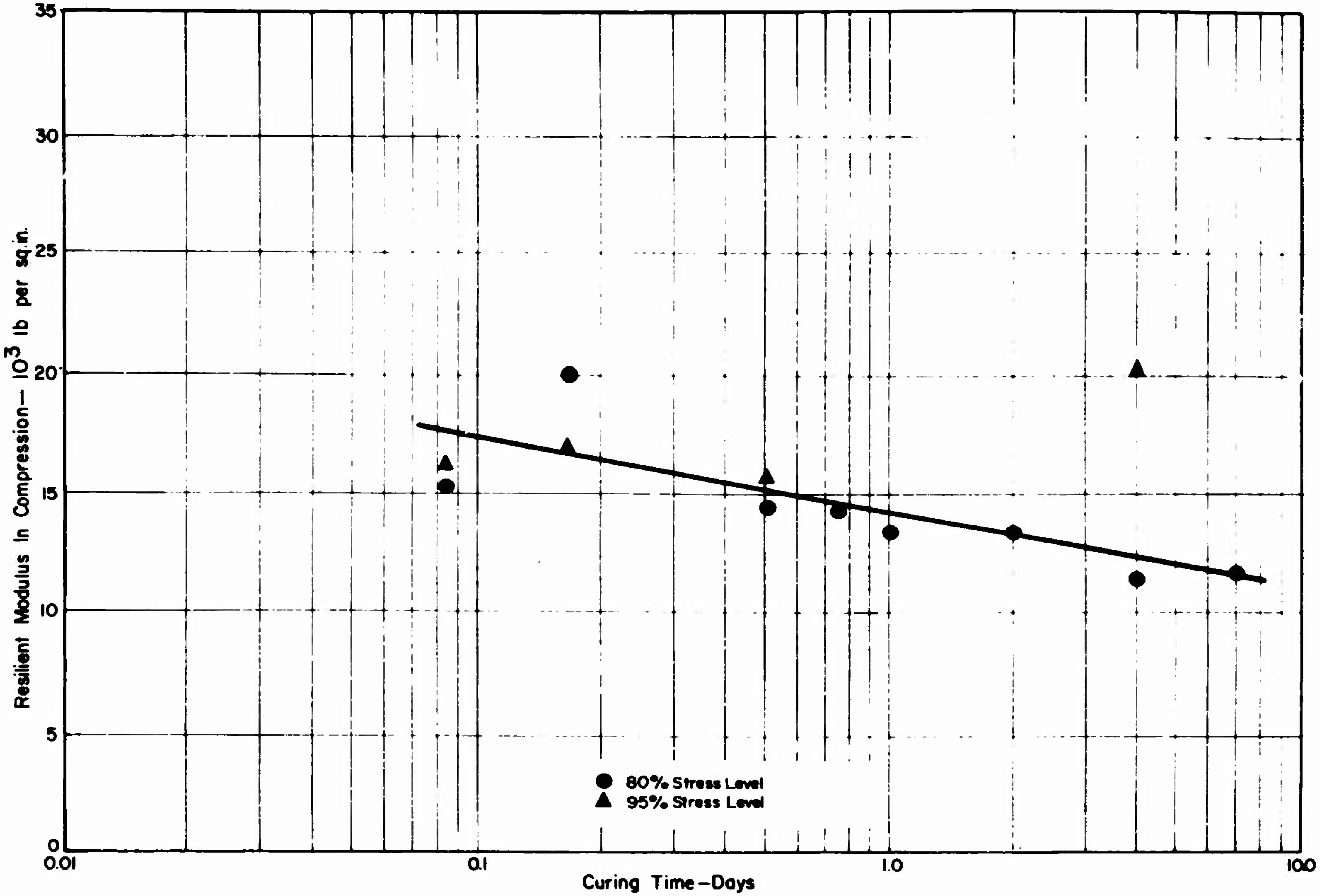

Figure 37 - VARIATION OF RESILIENT MODULUS WITH CURING TIME — AFTER 10,000 LOAD APPLICATIONS.

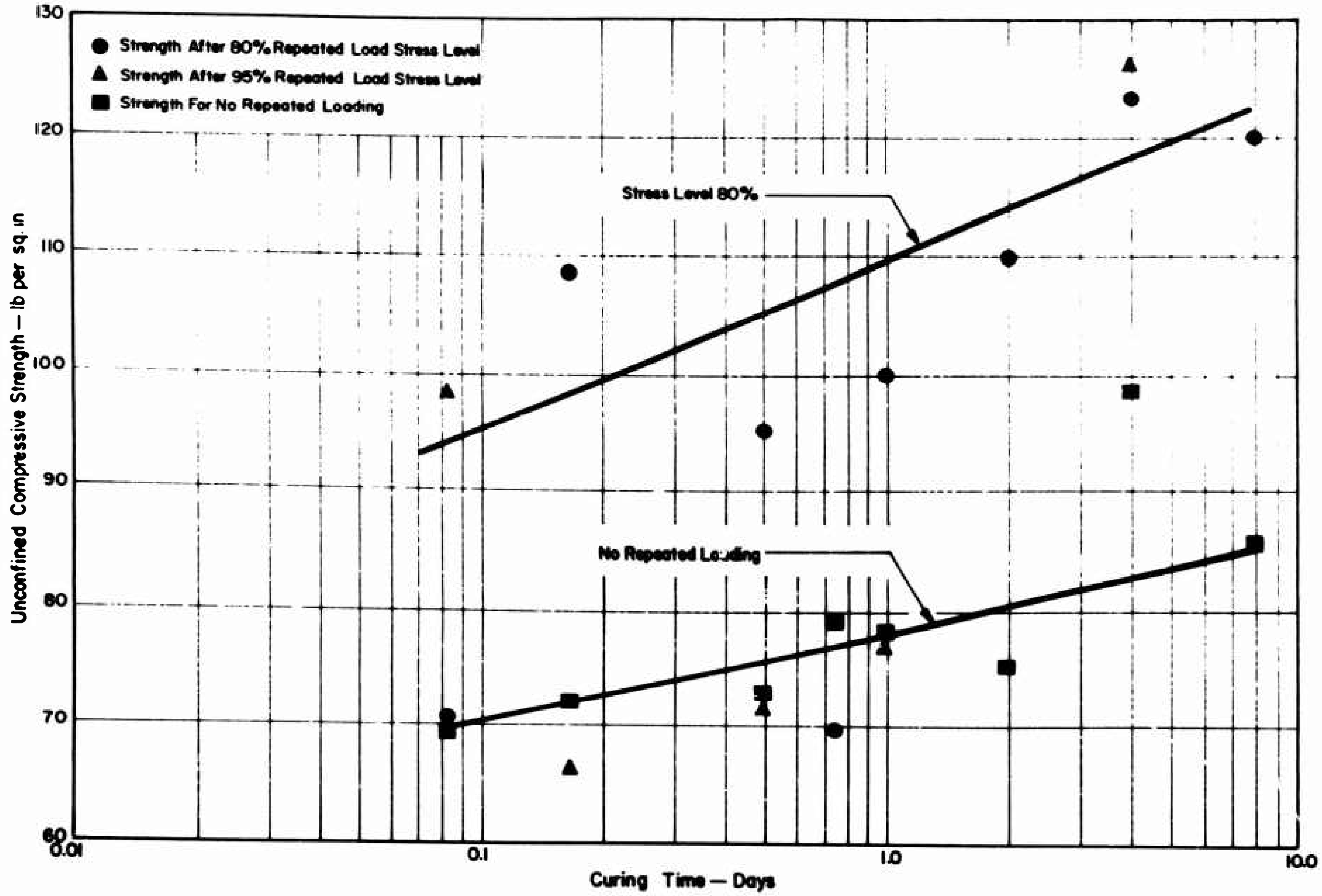

Figure 38 - EFFECT OF REPEATED LOADING AND CURING TIME ON STRENGTH.

the absence of repeated loading, thus additional curing time provided by the repeated loading period has been accounted for. Fig. 38 shows that strength was significantly increased as a result of repeated loading, particularly for samples subjected to an 80 percent repeated stress level. The behavior of samples subjected to the 95 percent stress level is less clear, since many of these specimens showed fatigue failure. Of the samples that successfully withstood 24,000 load repetitions, some exhibited no change in strength, whereas others showed a strength increase. The data for strain at failure are quite scattered (Fig. 39), and no definite conclusions appear warranted except that in general the longer the curing period, the less the failure strain.

Shen (1965) has studied the effects of curing time on the repeated load behavior in compression of soil-cement prepared from Vicksburg silty clay. Curing periods prior to repeated loading of from 1 to 70 days were used. The variation of strength with curing time is shown in Fig. 40. A repeated-load stress of 60 percent of the strength at the start of each test was used. All specimens were soaked for one day prior to testing.

Fig. 41 shows the variation of total strain with number of load applications for different curing periods. It will be noted that the greater the curing time, the less is the permanent deformation after any specific number of load applications, even though the actual stress intensity was increased with curing time in order to maintain the 60 percent stress level. That specimens become progressively stiffer with increased curing time, as noted earlier, accounts for this result. Strain at failure was 3 to 4 percent for samples cured for one day, whereas it decreased to 1 to 2 percent after 70 days of curing.

The variation of resilient deformation with number of load applications for different curing times is shown in Fig. 42. This figure illustrates that the greater the curing time, the less resilient is the soil-cement. In addition the curves show that resilient strain increases to a maximum somewhere between 50 and 10,000 load applications and then decreases. This shape of curve results from a combination of the destructive effect of repeated stress application and strengthening due both to hydration of cement during the test itself and to slight densification that may develop. These effects are most pronounced for samples at short

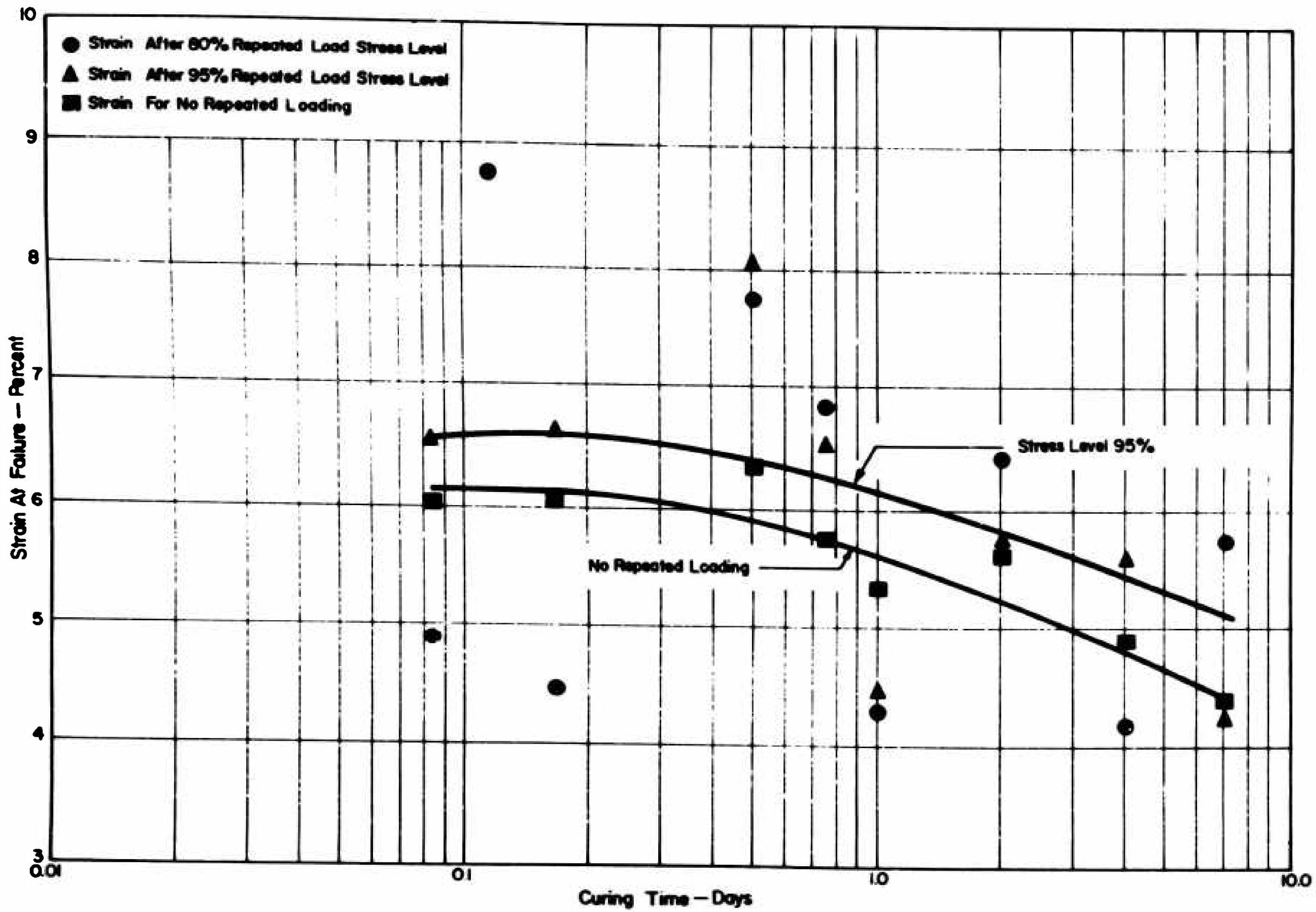

Figure 39-EFFECT OF REPEATED LOADING AND CURING TIME ON STRAIN AT FAILURE.

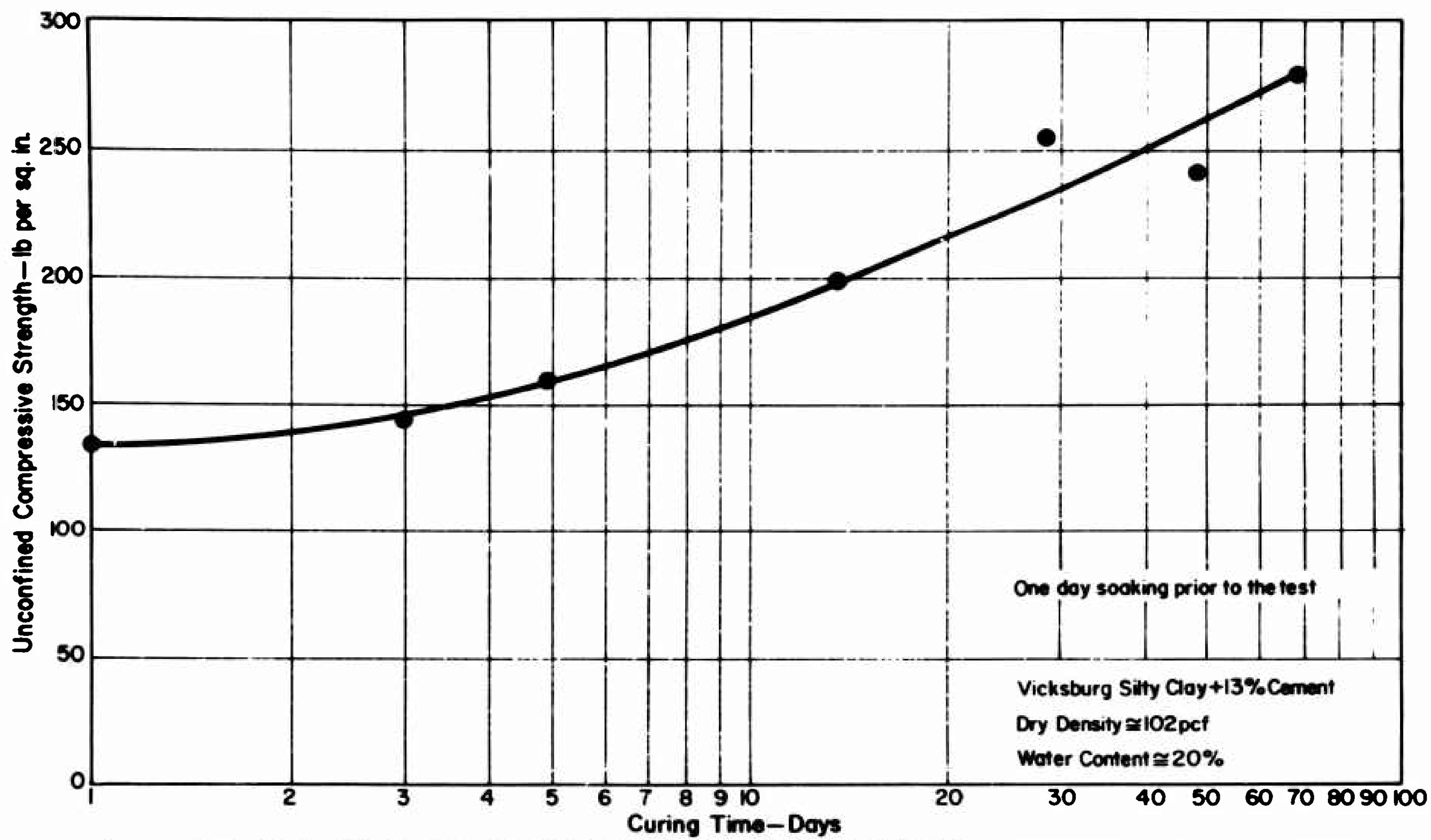

Figure 40 - RELATIONSHIP BETWEEN CURING TIME AND UNCONFINED COMPRESSIVE STRENGTH FOR VICKSBURG SILTY CLAY — CEMENT.

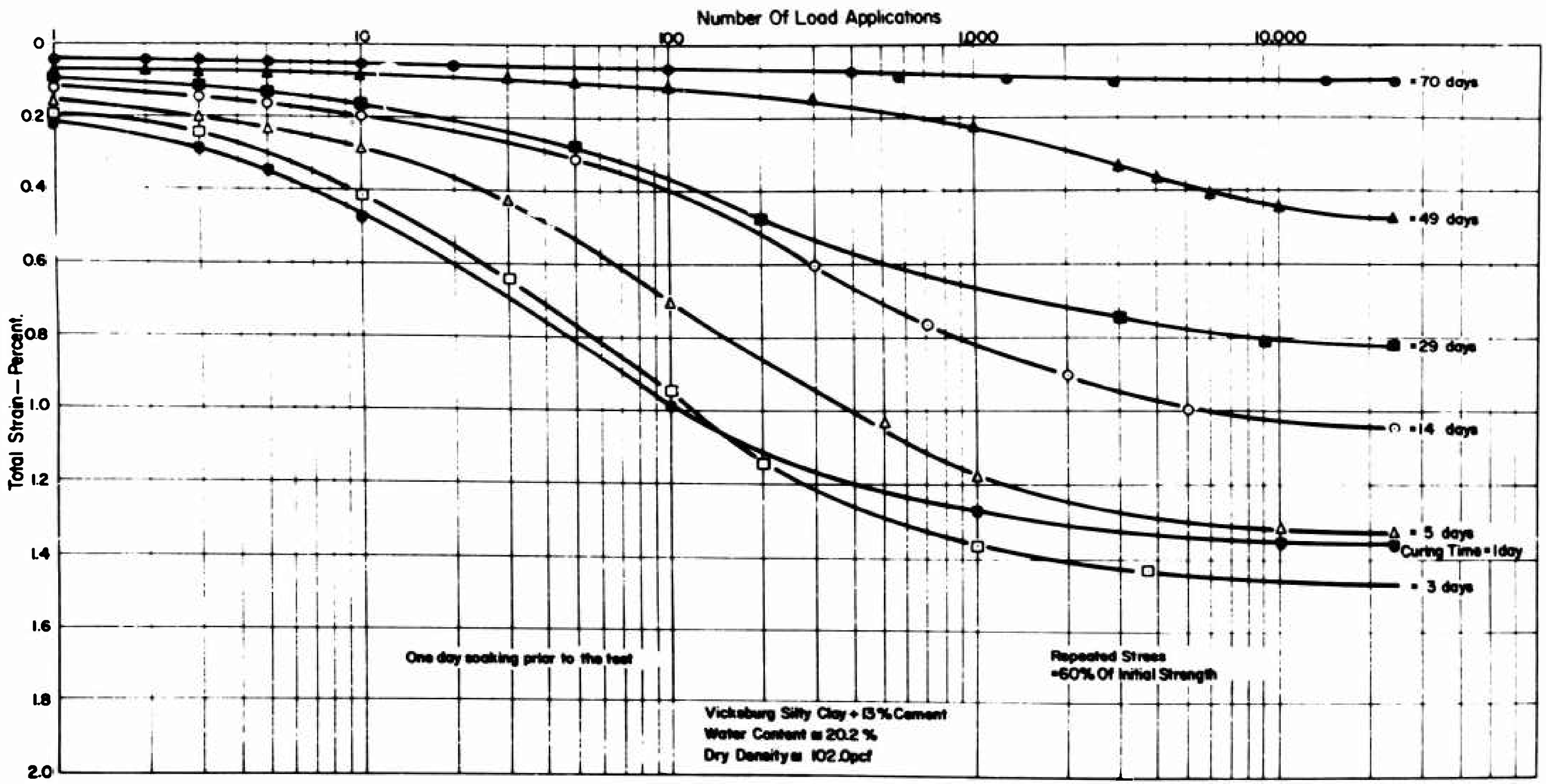

Figure 41 - EFFECT OF CURING TIME ON THE TOTAL DEFORMATION OF VICKSBURG SILTY CLAY CEMENT IN COMPRESSION.

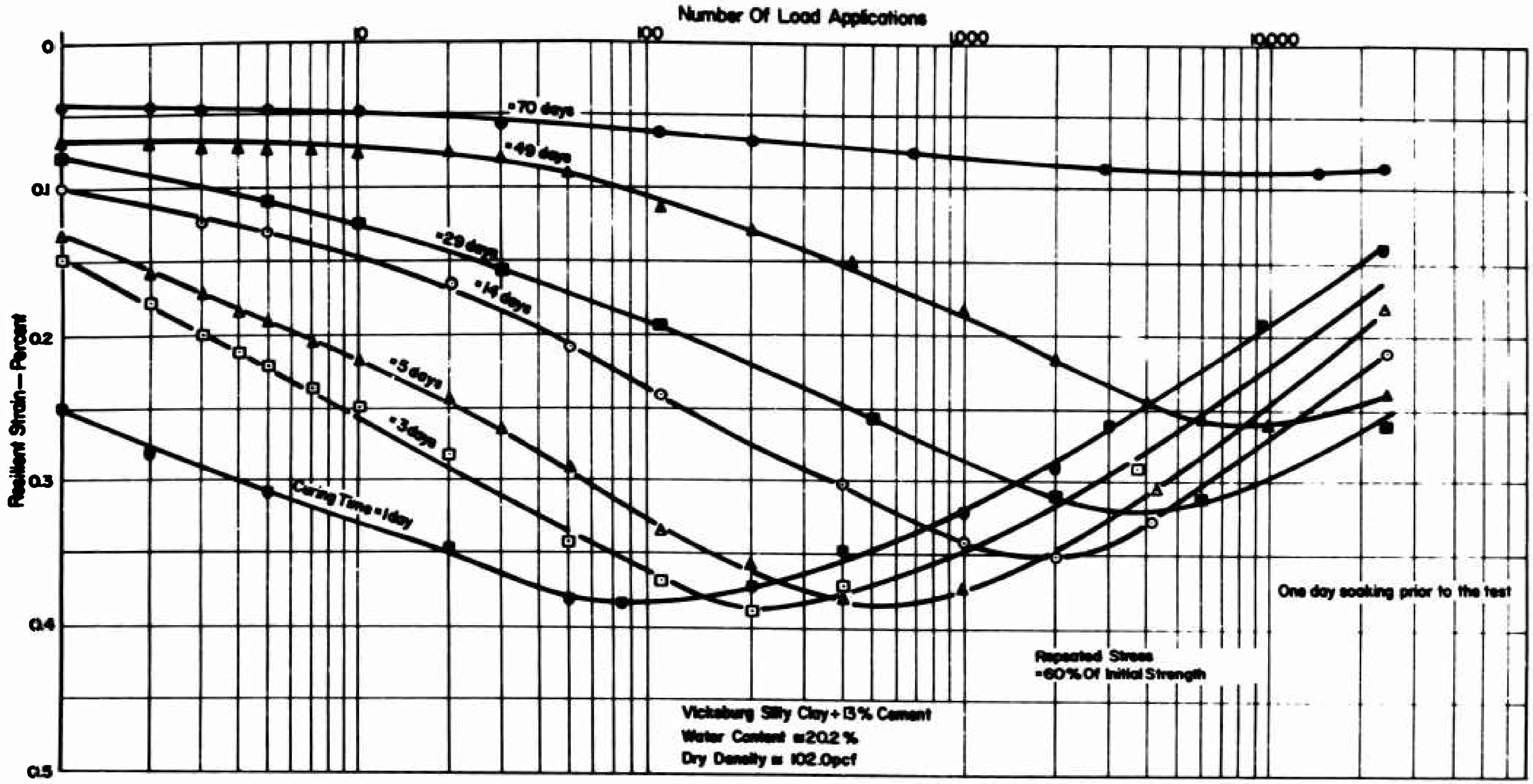

Figure 42 - EFFECT OF CURING TIME ON THE RESILIENT DEFORMATION OF VICKSBURG SILTY CLAY CEMENT IN COMPRESSION.

curing times, since it is at early ages that cement hydration is most rapid and the sample is still resilient enough to withstand slight structural alterations.

Fig. 43 shows the variation of the minimum modulus of resilient deformation with curing time. It would appear from this figure that the longer a so l-cement is cured before loading, the less will be the resilient deformations. The results reported by Yamanouchi (1963) suggest, however, that at least for low stress levels, this effect may not be particularly significant, since the material, at early ages, has a greater capability to withstand the higher deformations without rupture.

Finally, Fig. 44 shows the effect of curing period on strain at failure and Fig. 45, the effect of repeated loading at 60 percent stress level on the unconfined compression strength for different periods of curing. As might be expected, repeated loading had the greatest effect on the strength of specimens cured for the shortest periods, in this instance a beneficial one.

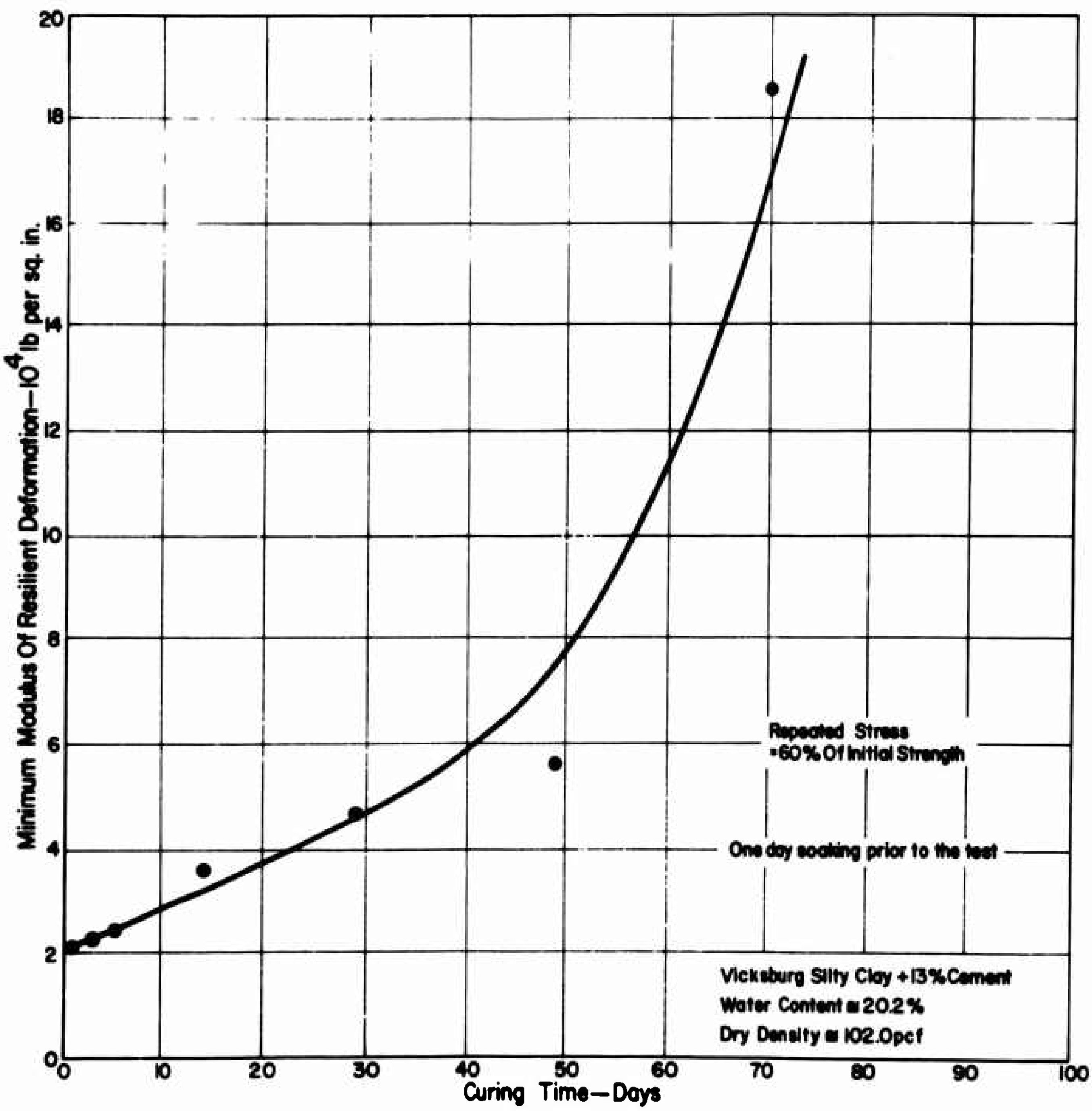

Figure 43 - MINIMUM MODULUS OF RESILIENT DEFORMATION IN COMPRESSION AS A FUNCTION OF CURING TIME FOR VICKSBURG SILTY CLAY-CEMENT.

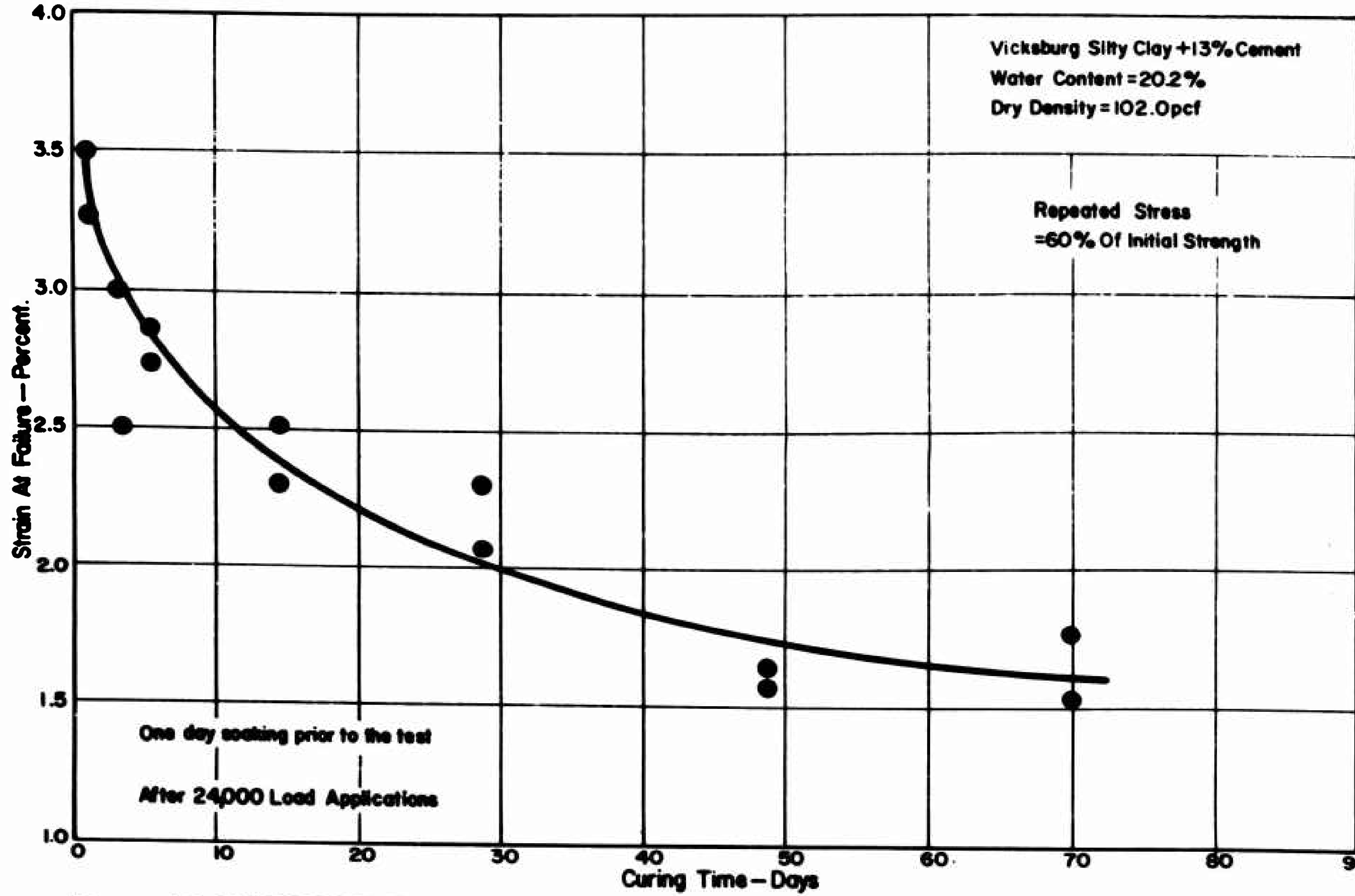

Figure 44-COMPRESSIVE STRAIN AT FAILURE AS A FUNCTION OF CURING TIME FOR VICKSBURG SILTY CLAY — CEMENT.

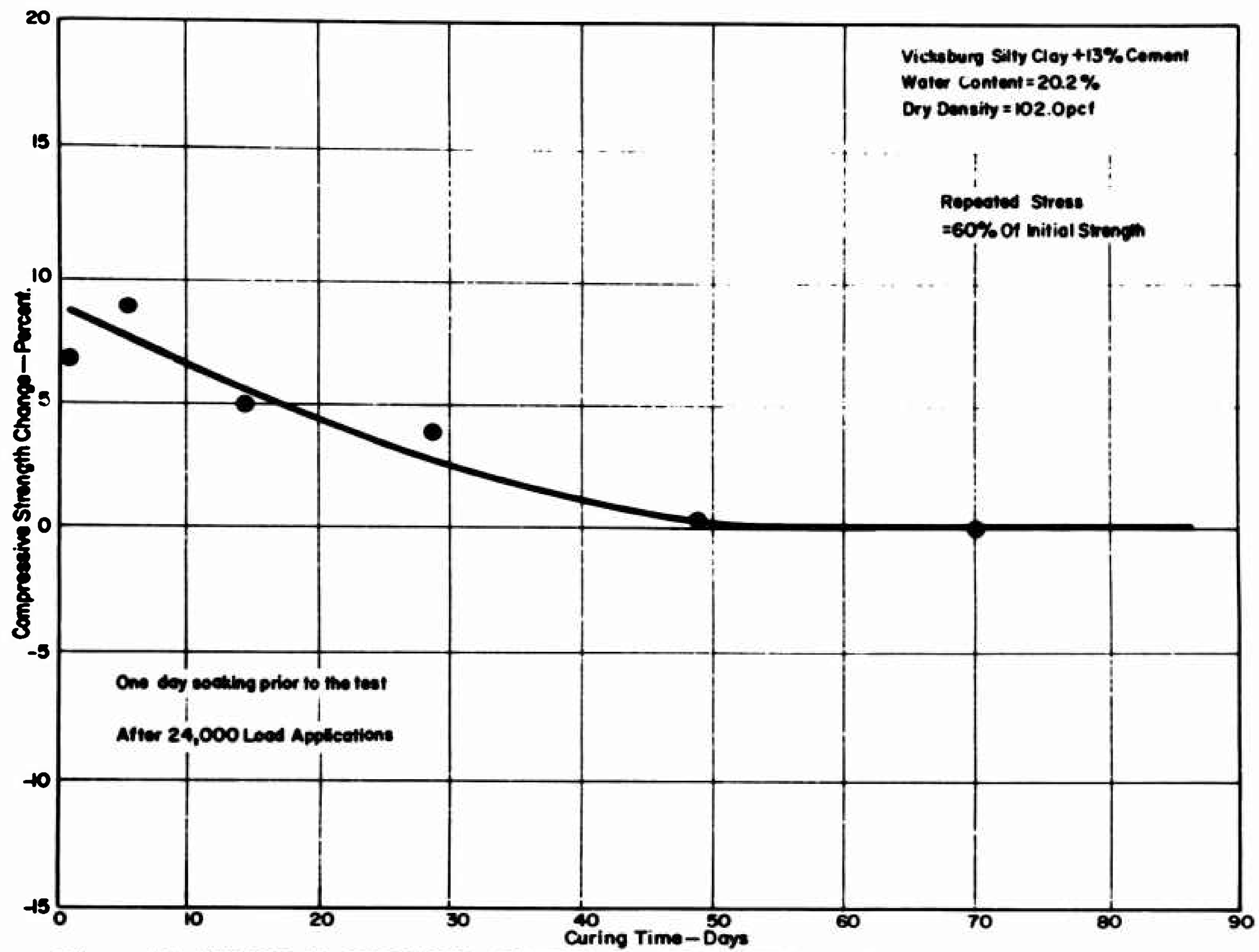

Figure 45-CHANGE IN STRENGTH CAUSED BY REPEATED LOADING AS A FUNCTION OF CURING TIME FOR VICKSBURG SILTY CLAY — CEMENT.

X INFLUENCE OF WATER CONTENT ON BEHAVIOR IN REPEATED COMPRESSION

Since it was found that samples stabilized to meet the minimum Corps of Engineers' criteria for military roads and airfields could withstand repeated compressive stresses of a number and intensity greater than those called for, some investigation of the resistance of weaker specimens was carried out in order to find the limits in material composition beyond which the treated soil could no longer withstand the prescribed loads. Samples were compacted at water contents of 20 to 22 percent (initial CBR <4) using 3 percent cement and cured for 24 hours. They were then subjected to repeated compressive stresses of 35, 50, or 75 psi until a total of 24,000 repetitions had been recorded unless failure occurred sooner.

The results of these tests are tabulated in Appendix C. Table 10 summarizes the relationships between water content, density, initial strength, and the repeated load stress and number of repetitions required to cause failure. It is interesting to note that the sample compacted at 19.9 percent water content was able to withstand 48 repetitions of a stress of 75 psi, which is significantly greater than the 63.3 psi that caused failure in a normal strength test.

It is also significant that, for samples which did not fail during repeated loading, the final strength was significantly greater than for specimens not subjected to repeated loading. This is more easily seen in Fig. 46, which shows strength as a function of water content. The two-day strength curve in the figure represents the strength of specimens of the same age as the repeated-load specimens at the end of repeated loading, but not subjected to a repeated load history.

The variation of resilient modulus with water content for the 35-psi repeated stress is shown in Fig. 47. As would be expected, the higher the moisture content the more resilient the specimen. Many more tests are needed, however, before definite conclusions can be drawn relative to the specific combinations of stress, water content, and density that will cause failure at any particular number of load repetitions. Further investigations in this area are warranted in order to better delineate the behavior relative to the Corps of Engineers' criteria. This is particularly important since the water

TABLE 10

RESISTANCE TO REPEATED LOADING AS A FUNCTION OF

MOLDING WATER CONTENT FOR VICKSBURG SILTY CLAY

Water Content %	Dry Density pcf	Repeated Stress Intensity, psi	Repetitions at Failure	Initial Strength* psi
19.9	103.1	75	48	63.3
20.9	101.8	50	342	56.4
21.9	100.2	35	No failure at 24,000	48.7

*Unconfined compressive strength after 24 hours curing.

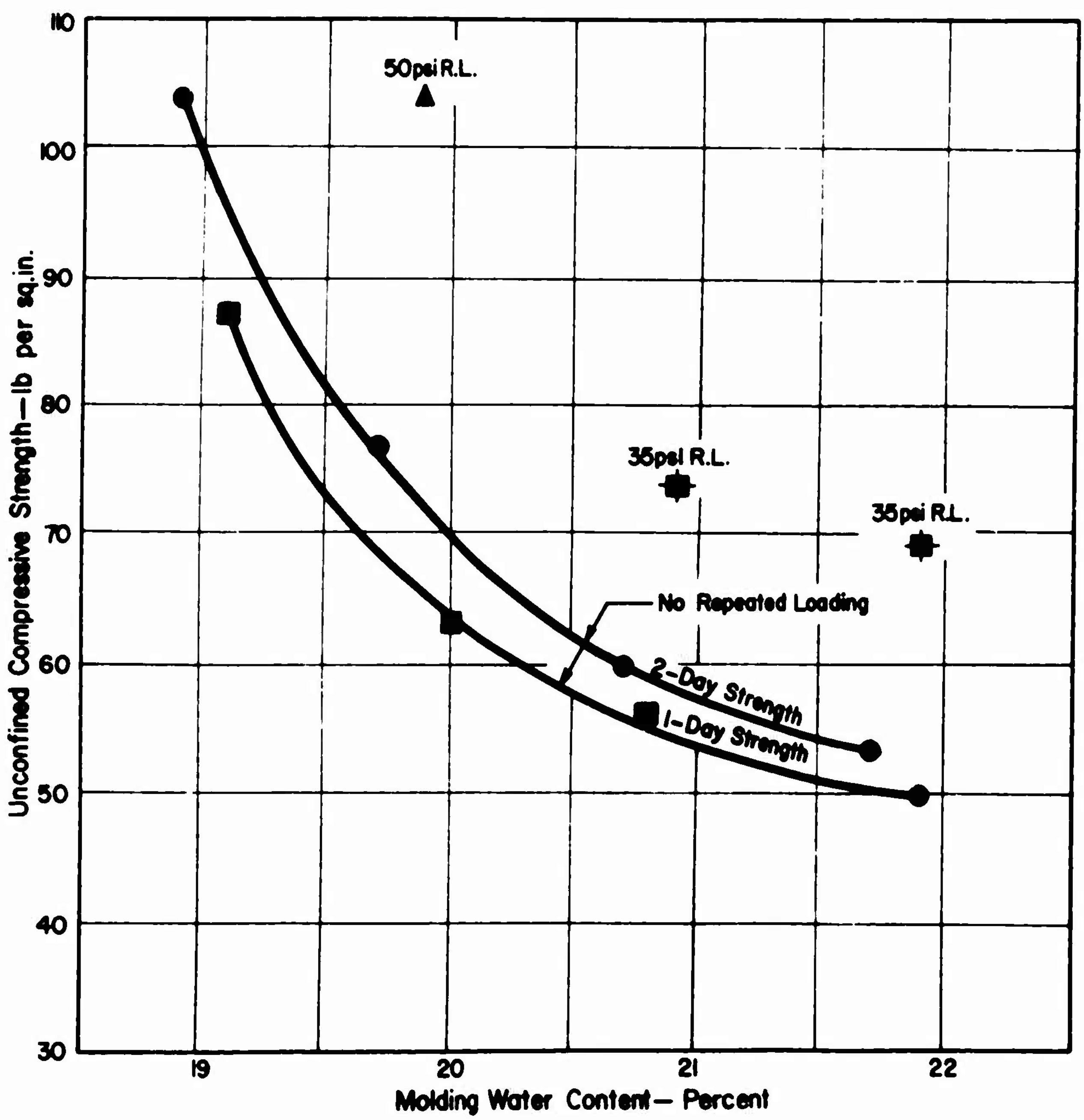

Figure 46 - EFFECT OF MOLDING WATER CONTENT ON COMPRESSIVE STRENGTH.

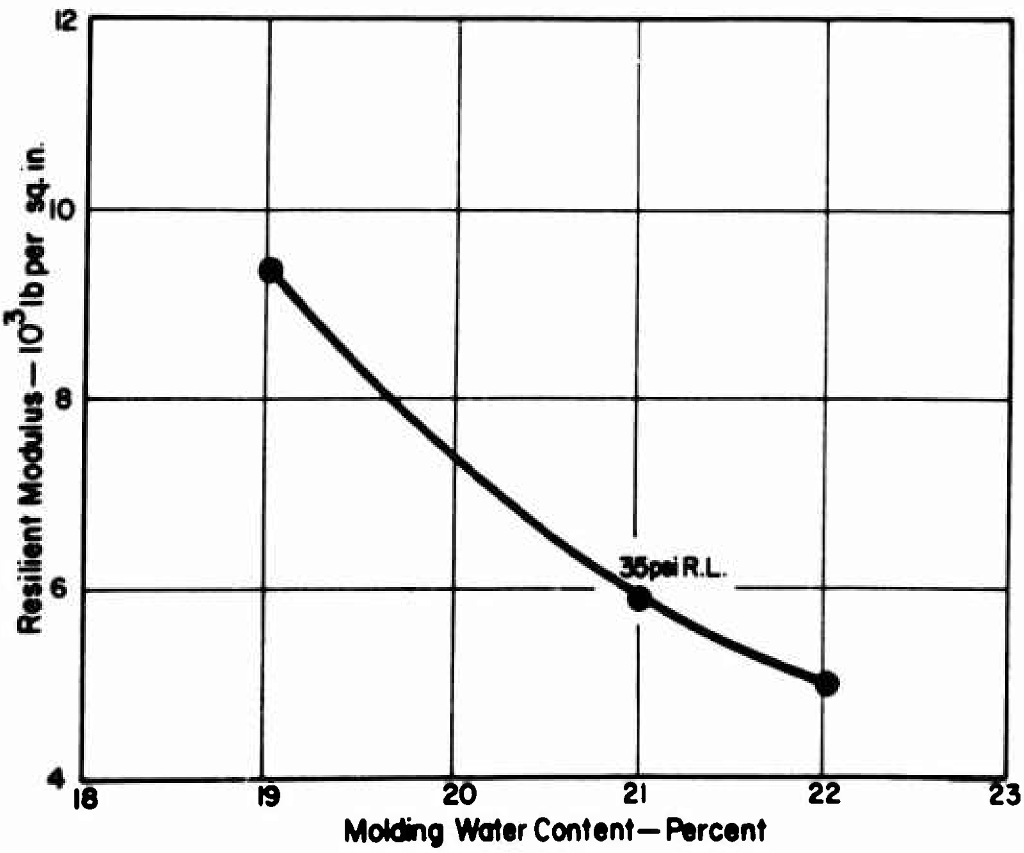

Figure 47 - VARIATION OF RESILIENT MODULUS WITH COMPACTION WATER CONTENT.

contents of interest for military stabilization may be appreciably wet of optimum where only slight changes in moisture content can result in very significant changes in strength and resilience.

Shen (1965) made a thorough investigation of the effect of compaction density and water content on the resilience characteristics of soil-cement made with the silty clay. Fig. 48 shows compaction curves obtained by kneading compaction using three different efforts. Moduli of resilient deformation for these specimens after 1000 load applications are shown in Fig. 49 for three different conditions of sample and test. These are (1) Samples soaked for 24 hours after curing and tested under a repeated stress of 40 psi, (2) Unsoaked samples tested under a repeated stress of 20 psi, and (3) Soaked specimens subjected to a repeated stress of 20 psi.

These results clearly illustrate the great sensitivity of resilience properties to molding water content and density. It may be noted also that at water contents wet of optimum the density and water content may be equal, but resilience characteristics, strength, and other properties may differ for samples prepared using different compaction efforts. As found by Seed and Chan (1959) for untreated silty clay, the greater shear strains induced by kneading compaction at high compaction efforts can cause a more dispersed and resilient structure for the silty clay-cement. Thus attainment of a particular density and moisture content alone will not assure specific strength and resilience properties. Consideration must be given also to the method of compaction and compactive effort.

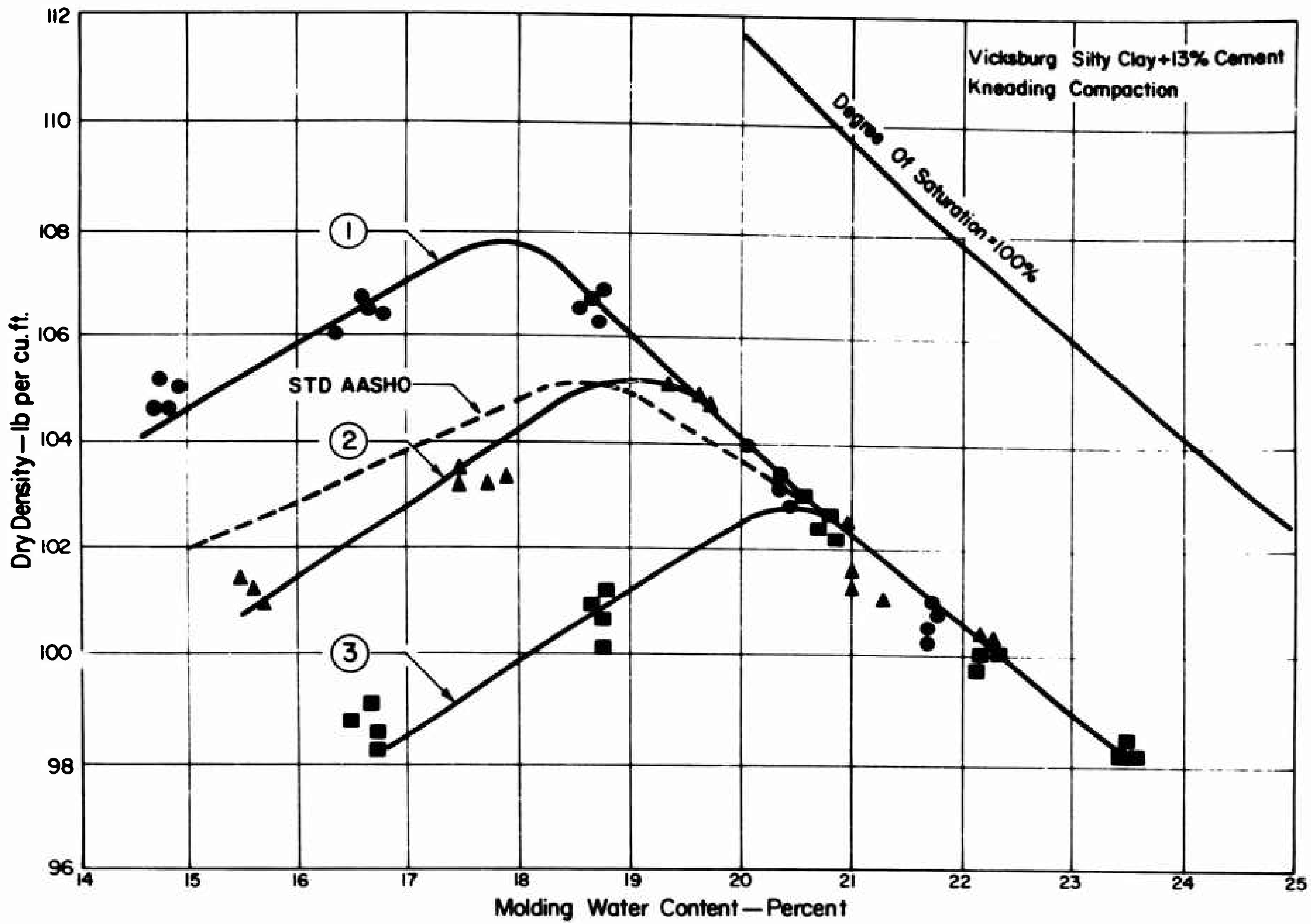

Figure 48-COMPACTION CURVES—VICKSBURG SILTY CLAY—CEMENT.

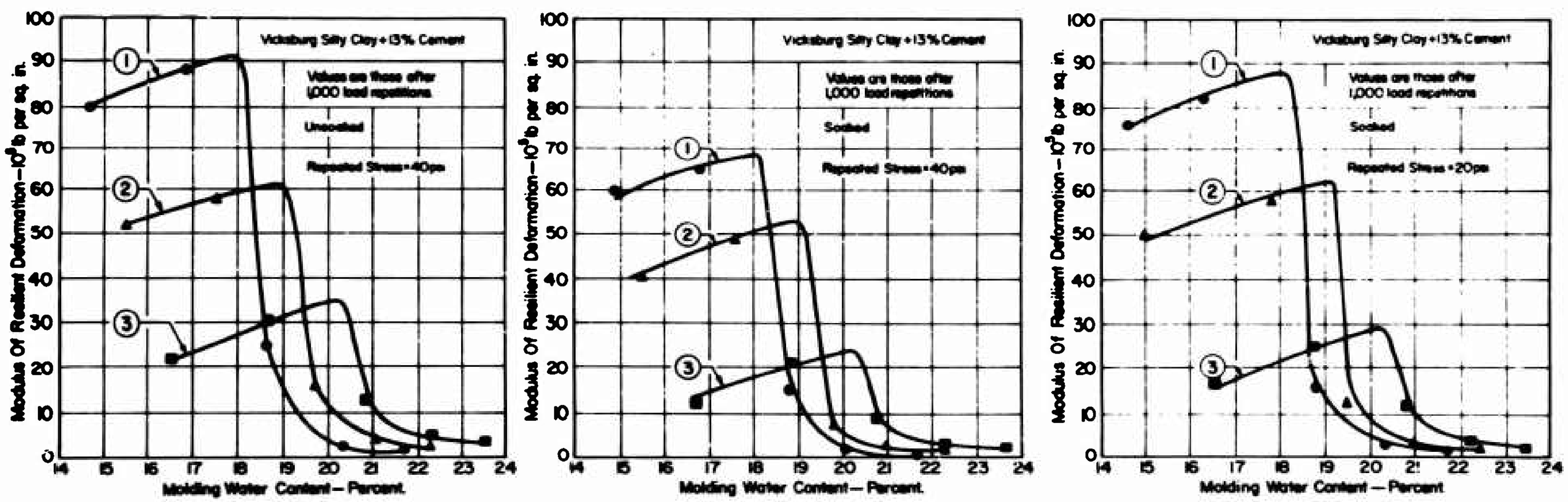

Figure 49 - RELATIONSHIP BETWEEN WATER CONTENT AND MODULUS OF RESILIENT DEFORMATION IN COMPRESSION FOR VICKSBURG SILTY CLAY-CEMENT

XI BEHAVIOR OF CEMENT-TREATED SILTY CLAY IN REPEATED FLEXURE

Only a limited number of repeated-load flexural tests have been carried out thus far. The importance of this type of loading cannot be overlooked, however, because of the distinct possibility of cracking caused by bending stresses. To date all of the flexural tests have been performed on samples of silty clay stabilized with 3 percent cement. The values for parameters such as modulus of rupture, tensile stress, and modulus of resilience have been calculated assuming the validity of simple beam theory.

Fig. 50 shows tensile stress vs. strain curves determined by normal slow rate of loading flexural tests on samples compacted at 19.6 percent water content and cured for 24 and 48 hours. In these specimens failure occurred at a tensile strain of 0.04 to 0.05 percent. Furthermore, the stress-deformation behavior was non-linear and failure occurred abruptly. For the specimens whose behavior is illustrated in Fig. 50, the modulus of rupture was of the order of 16 psi. From Fig. 2 it may be noted that tensile stresses of this magnitude or greater might be anticipated should stabilized layers of 10 inches thickness or less be subjected to loadings from C-124 aircraft.

Influence of Curing Time and Stress Intensity on Behavior In Repeated Flexure

In order to obtain some indication of critical combinations of stress intensity and strength at which flexural fatigue failure would develop, a limited number of tests have been run on specimens cured for 16, 20, and 24 hours and subjected to repeated flexural stress intensities of 60 percent or more of the initial strength. The results of these tests are given in Table 11.

Total and resilient flexural strains as well as the resilient modulus in flexure were determined using measured midspan deflections and simple beam theory. Thus the reported values have the same limitations as those associated with the assumption of true elastic behavior.

While insufficient data are yet available to permit complete definition of the fatigue characteristics of silty clay treated with 3 percent cement, the results of these test series do indicate some trends. Fig. 51 shows the number of load applications required to cause failure as a function of flexural stress intensity for specimens cured for 20 and 24 hours.

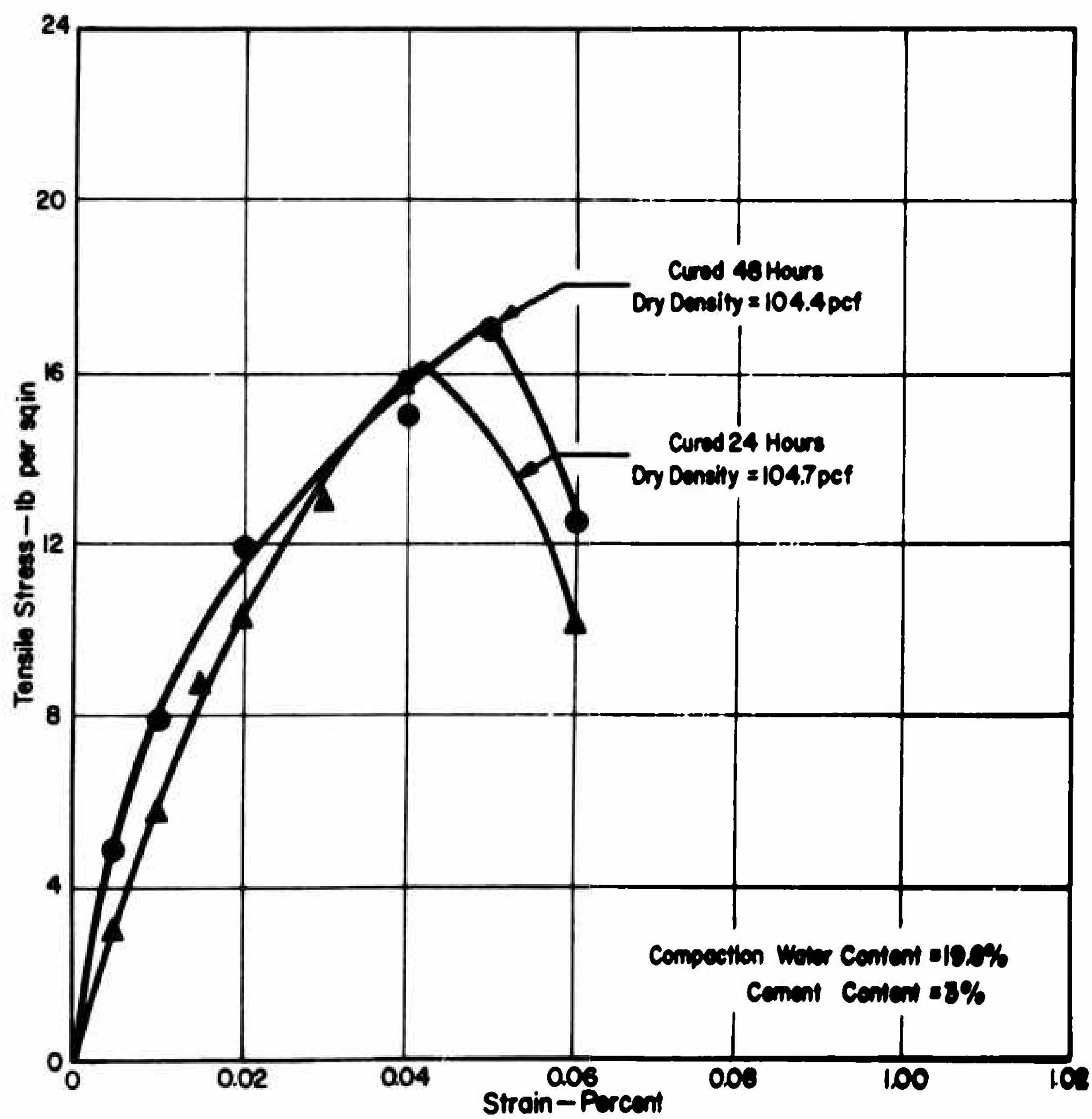

Figure 50 – STRESS VERSUS STRAIN BEHAVIOR OF CEMENT TREATED SILTY CLAY IN FLEXURE.

TABLE 11

INFLUENCE OF CURING TIME AND STRESS INTENSITY ON BEHAVIOR OF

CEMENT-TREATED SILTY CLAY IN REPEATED FLEXURE

		Repeated Load Stress		Modulus of Rupture - psi				Strain at
Curing Time-hrs.	Sample No.	psi	% of Strength	Before R.L.	Control*	After R.L.	Repetitions at Failure	Failure 10^{-2}%
16	B-32	0	0	13.2			-	10.4
	-45	0	0	13.7			-	9.9
	-31	0	0		17.4		-	8.7
	-34	0	0		15.1			
	-36	7.9	60			22.8	NF	10.8
	-33	9.2	70			-	6040	4.4
	-37	10.6	80			23.4	NF	9.1
	-43	10.6	80			20.8	NF	9.9
20	B-22	0	0	15.7			-	11.2
	-26	0	0	15.4			-	12.6
	-29	0	0		17.8		-	11.0
	-30	9.2	60			21.9	NF	10.4
	-28	10.8	70			-	2600	4.2
	-27	12.3	80			-	460	4.5
24	B-4	0	0	19.6			-	4.6
	-44	0	0	15.6			-	-
	-6	0	0		17.3		-	3.2
	-3	11.8	67			21.9	NF	2.1
	-42	11.8	67			-	2000	6.0
	-7	13.7	78			-	1040	7.7
	-5	15.7	89			-	40	4.1
	-2	17.6	100			0	2	-
	-1	22	125			-	12	-

Cement Treatment Level = 3%
Dry Density = 105.0 ± 0.5 psf
Water Content = 19.0 ± 0.3%

NF = no failure after 24,000 repetitions
*No repeated loading, but same age as specimen after 24,000 repetitions.
R.L. = Repeated loading

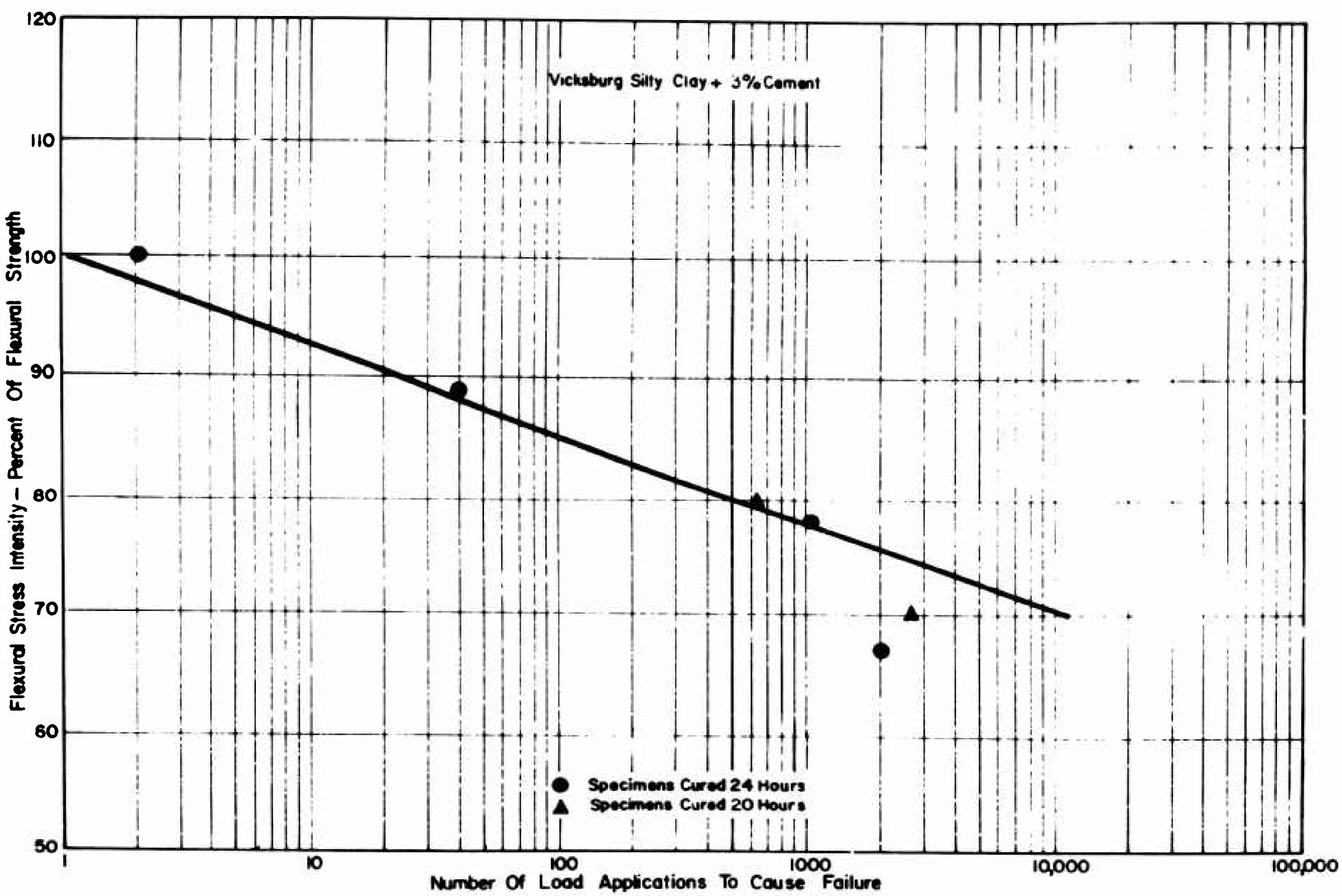

Figure 51 - NUMBER OF LOAD APPLICATIONS TO CAUSE FAILURE AS A FUNCTION OF FLEXURAL STRESS INTENSITY.

The data in this figure indicate, as would be expected, that the greater the stress intensity the fewer the number of repetitions required to cause failure.

For those specimens that did not fail after 24,000 load repetitions the modulus of rupture was greater than for specimens of the same age which were not subjected to repeated flexure as noted in Table 11. In an earlier section it was also indicated that the compressive strength was increased as a result of repeated compressive stresses. The increase in compressive strength can be explained in terms of densification, closing of small fissures, etc., under the action of the compressive stress. Reasons for the increase in flexural strength as a result of repeated flexural stresses are less obvious, since it might be anticipated that each application of tension to the bottom half of the beam specimen would be progressively more destructive.

Values of modulus of resilience as a function of curing time, stress intensity, and number of load repetitions do not show consistent variations, and no definite trends can be established at this time. The values are of the same order of magnitude for each curing period; i.e., 30,000 to 60,000 psi. These values are larger than those obtained for samples of the same composition and tested in compression, i.e., 5000 to 20,000 psi. It is not altogether clear why the flexural modulus is higher than the compression modulus; however, it may result from the fact that the material is more deformable in compression and the specimens can withstand large deformations without rupture, whereas in flexure they cannot. Thus resilient moduli in flexure can be determined only for stress intensities and numbers of load repetitions where deflections are small. Extremely significant in this regard is the fact that the tensile strain at which failure occurs in flexure is only of the order of one percent of the compressive strain at failure. This is apparent from a comparison between failure strain values in Table 11 and those in Table 9.

The effect of the repeated flexural stress on the static stress-strain characteristics is shown in Fig. 52. Because the strength is greater after repeated loading, unless fatigue failure developed, the static modulus is also greater. The results in Table 11, however, show that the strain at failure may only be slightly affected.

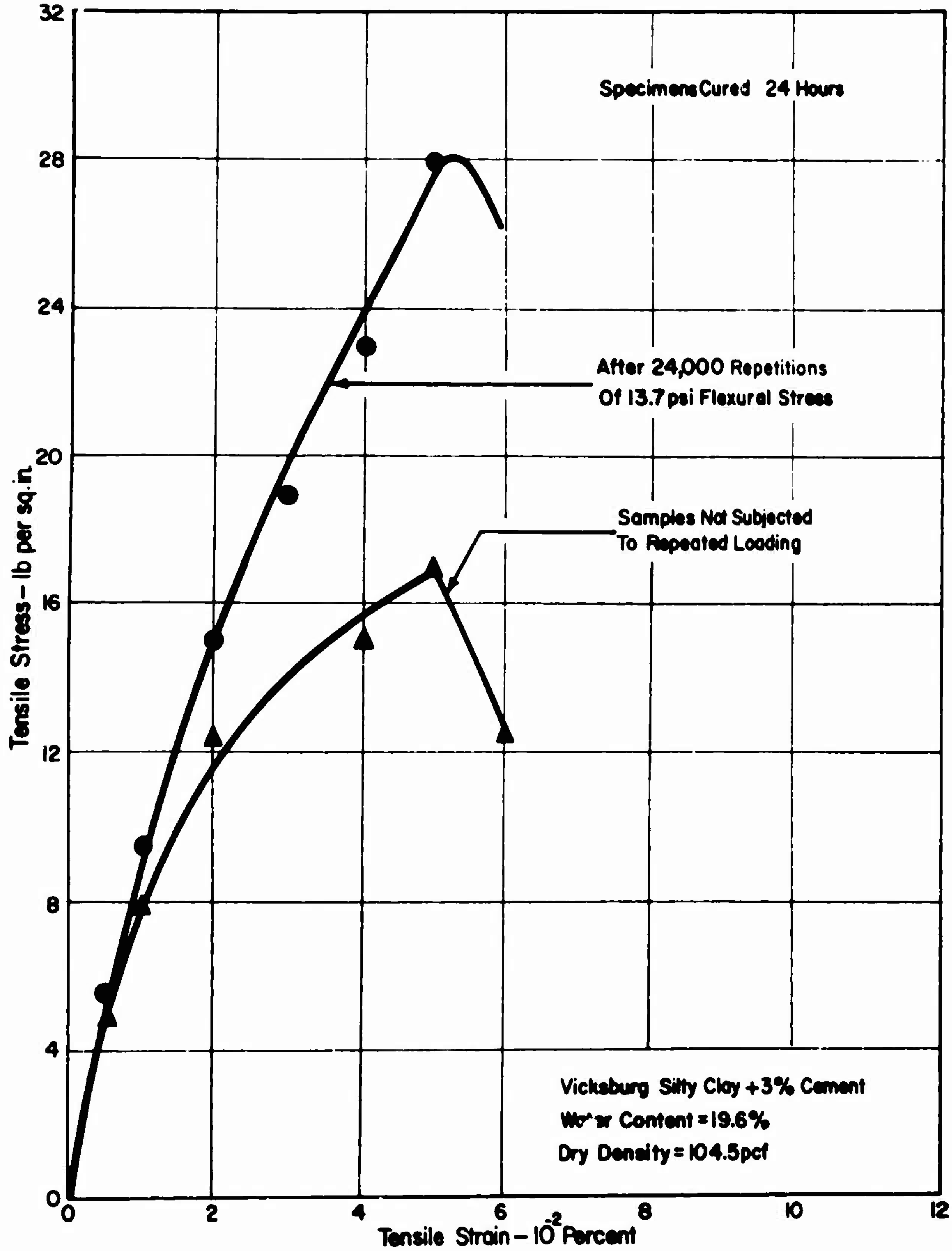

Figure 52 - EFFECT OF REPEATED LOADING ON THE STRESS—STRAIN BEHAVIOR IN FLEXURE FOR CEMENT TREATED SILTY CLAY.

Influence of Molding Water Content and Stress Intensity on Behavior in Repeated Flexure

Four test series have been initiated to establish the influence of initial compaction conditions on the behavior in repeated flexure. The results of these tests are summarized in Table 12. Four different water contents were used, ranging from 18 to 22 percent. Repeated flexural stresses of from 60 to 100 percent of the initial flexural strength were applied.

Insufficient fatigue failures, beyond those already discussed in connection with Fig. 51, developed. Thus it is not at this time possible to make general conclusions concerning the relationships between fatigue, initial water content, and stress intensity. Modulus of rupture data, summarized in Fig. 53 show the expected decrease in strength with increase in water content. The data also show that the effect of repeated flexural stress application was to increase strength for those specimens which did not fail in fatigue during the test. The difference between the initial strength and control strength curves in Fig. 53 represents the strength increase due to cement hydration during the period of the repeated flexure test.

Summary of Flexural Test Results

The results of the few beam tests conducted thus far are inadequate to permit formation of many specific, generally applicable conclusions; however the following observations are significant.

1. Flexural strength of specimens that did not fail during the test was increased as a result of repeated flexural stress applications.
2. For the water contents investigated, the resilient modulus in compression is less than the resilient modulus in flexure.
3. The tensile strain at failure for beam specimens is only of the order of one percent of the compressive strain at failure for cylindrical specimens.
4. A unique relationship between flexural stress intensity and number of repetitions to failure may exist for specimens of the same initial composition.

Further study of stabilized soil in flexure is needed to more fully define the behavior.

TABLE 12

INFLUENCE OF WATER CONTENT AND STRESS INTENSITY ON BEHAVIOR OF CEMENT TREATED SILTY CLAY IN REPEATED FLEXURE

Composition	Sample No.	Repeated Load Stress psi	Repeated Load Stress % of Strength	Modulus of Rupture psi Before R.L.	Modulus of Rupture psi Control*	Modulus of Rupture psi After R.L.	Repetitions at Failure	Strain at Failure (10^{-2}%)
Water Content = 18.0%**	B-16	0	0	18.6			--	4.6
Dry Density = 105.5 pcf	-17	0	0		26.2		--	9.1
	-19	0	0		22.0			7.9
	-20	14.4	77			29.7	NF	8.1
	-21	16.2	87			30.4	NF	8.4
Water Content = 19.0%**								
Dry Density = 105 pcf	B- 4	0	0	19.6			--	4.6
	- 6	0	0		17.3		--	3.2
	- 3	11.8	60			21.9	NF	2.1
	- 7	13.7	70				1040	7.7
	- 5	15.7	80				40	4.1
	- 2	17.6	90				2	-
	- 1	22	112				12	-
Water Content = 17.7%**	B-10	0	0	16.1			--	3.9
Dry Density = 104.5 pcf	- 8	0	0		17.1		--	5.0
	-38	9.7	60			21.5	NF	10.0
	- 9	11.8	73			22.5	NF	8.7
	-11	13.7	85			27.9	NF	5.0
Water Content = 21.3%**	B-15	0	0	12.4			--	4.0
Dry Density = 102.3 pcf	-12	0	0		16.4		--	5.0
	-39	7.4	60			17.0	NF	8.8
	-14	9.8	79			20.3	NF	7.0
	-13	11.7	95				1700	6.2

** Nominal Water Content

Cement Treatment Level = 3%
Curing Time = 24 hours

NF = No failure after 24,000 load repetitions

*No repeated loading but same age as specimen after 24,000 repetitions.

R.L. = Repeated loading

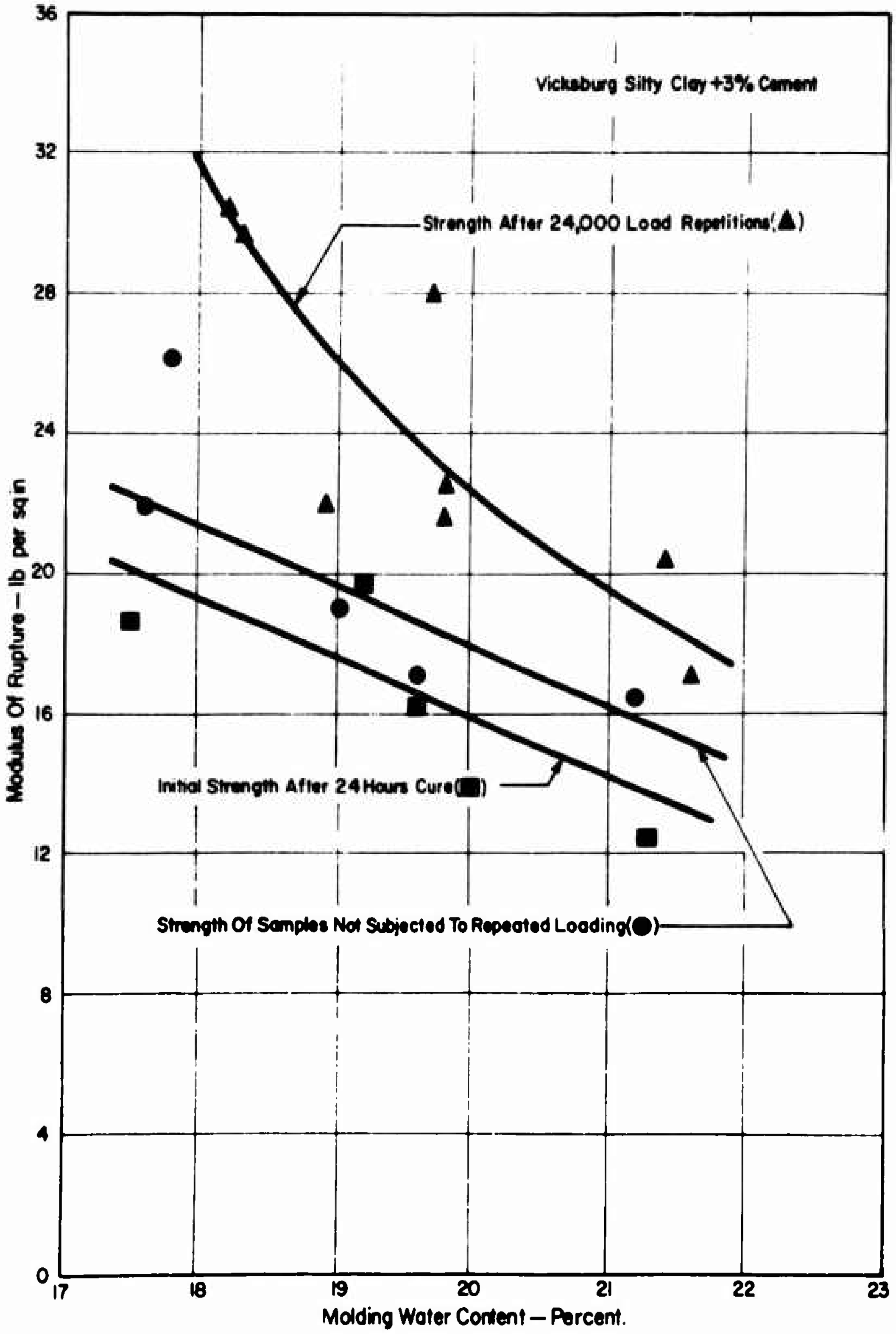

Figure 53 - EFFECT OF REPEATED FLEXURAL STRESS ON THE STRENGTH OF CEMENT TREATED SILTY CLAY.

Behavior of Soil-Cement Under Repeated Flexural Loading Conditions

Shen (1965) has conducted repeated loading tests on beam specimens of soil-cement made with Vicksburg silty clay (13% cement treatment). A typical load vs. deflection curve for a specimen tested under static loading conditions is shown in Fig. 54. It is interesting to note that a linear relationship to failure exists between load and deflection for this material. This contrasts with the behavior in compression where a definite nonlinear relationship was observed. Also significant are the rather low flexural strains at failure, of the order of 0.05 to 0.10 percent, as opposed to 0.5 to 3.5 percent for compression specimens.

Typical resilient strain vs. number of load applications curves for beam specimens are shown in Fig. 55. In general, the resilient properties were only slightly affected by repeated loading. Measurements of resilient strain as a function of applied repeated flexural stress intensity resulted in the relationship shown in Fig. 56. Since the resilient strain is insensitive to number of load applications and since a linear relationship exists between resilient strain and stress intensity, it follows that the resilient modulus remains constant with number of load repetitions and with stress intensity, as indicated in Fig. 57.

Variation in molding water content has a pronounced effect on the properties of beam specimens. Fig. 58 shows that as the water content increases there is a large reduction in the modulus of rupture and resilient modulus. Thus specimens at higher water content are, as would be expected, more deformable than low water content specimens. On the other hand, Fig. 58 shows that the strain at failure tends to decrease at higher water contents. Thus not only are specimens weaker at high water contents, but also they are unable to withstand as much total deformation without failure as the drier material.

It should be borne in mind when considering Shen's results that they pertain to a relatively strong structural material with a modulus of rupture of the order of 100 to 200 psi, and a modulus of resilient deformation in flexure of the order of 400,000 psi. In the case of specimens stabilized in

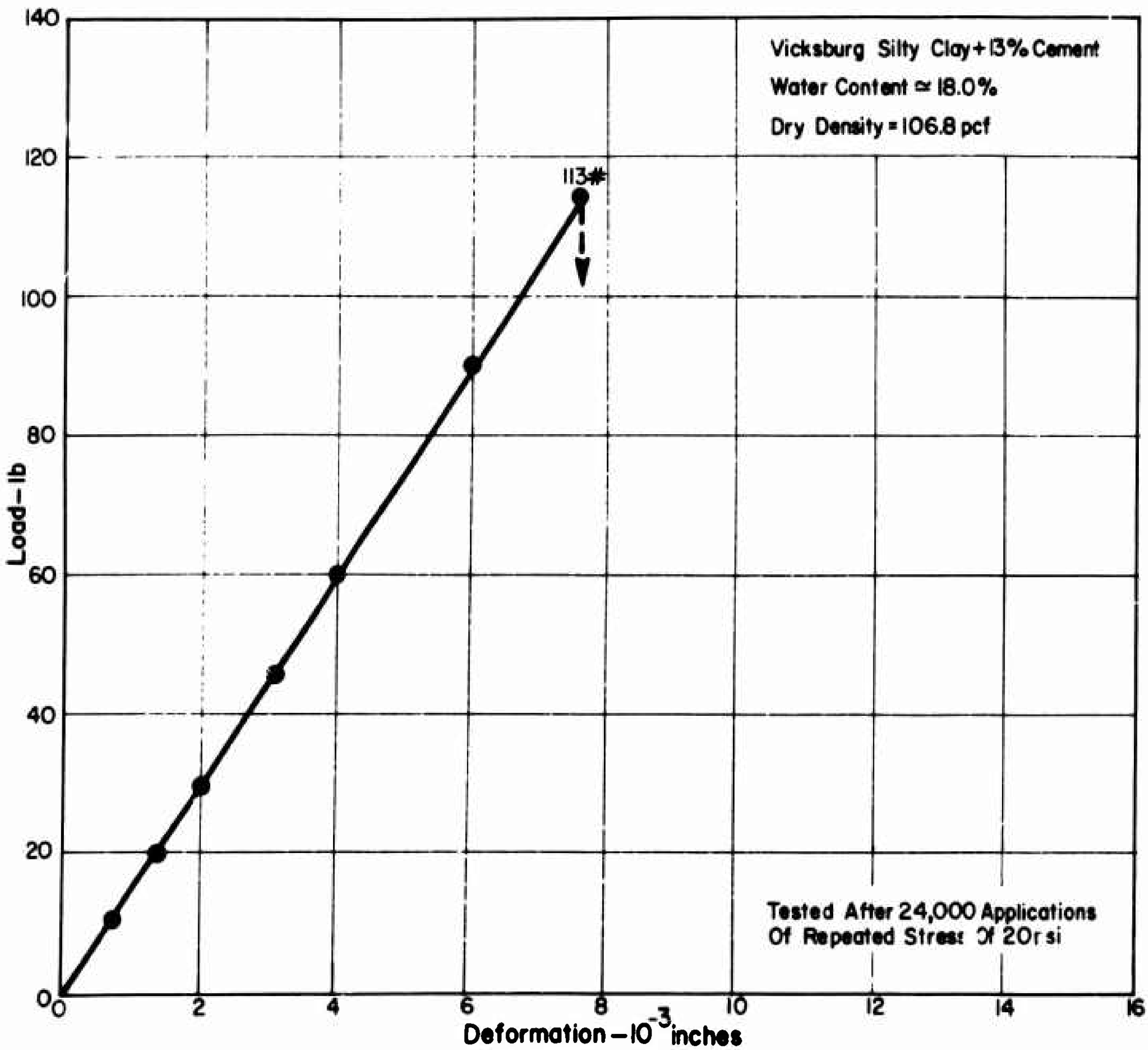

Figure 54 - LOAD-DEFORMATION CURVE FOR VICKSBURG SILTY CLAY-CEMENT IN FLEXURE.

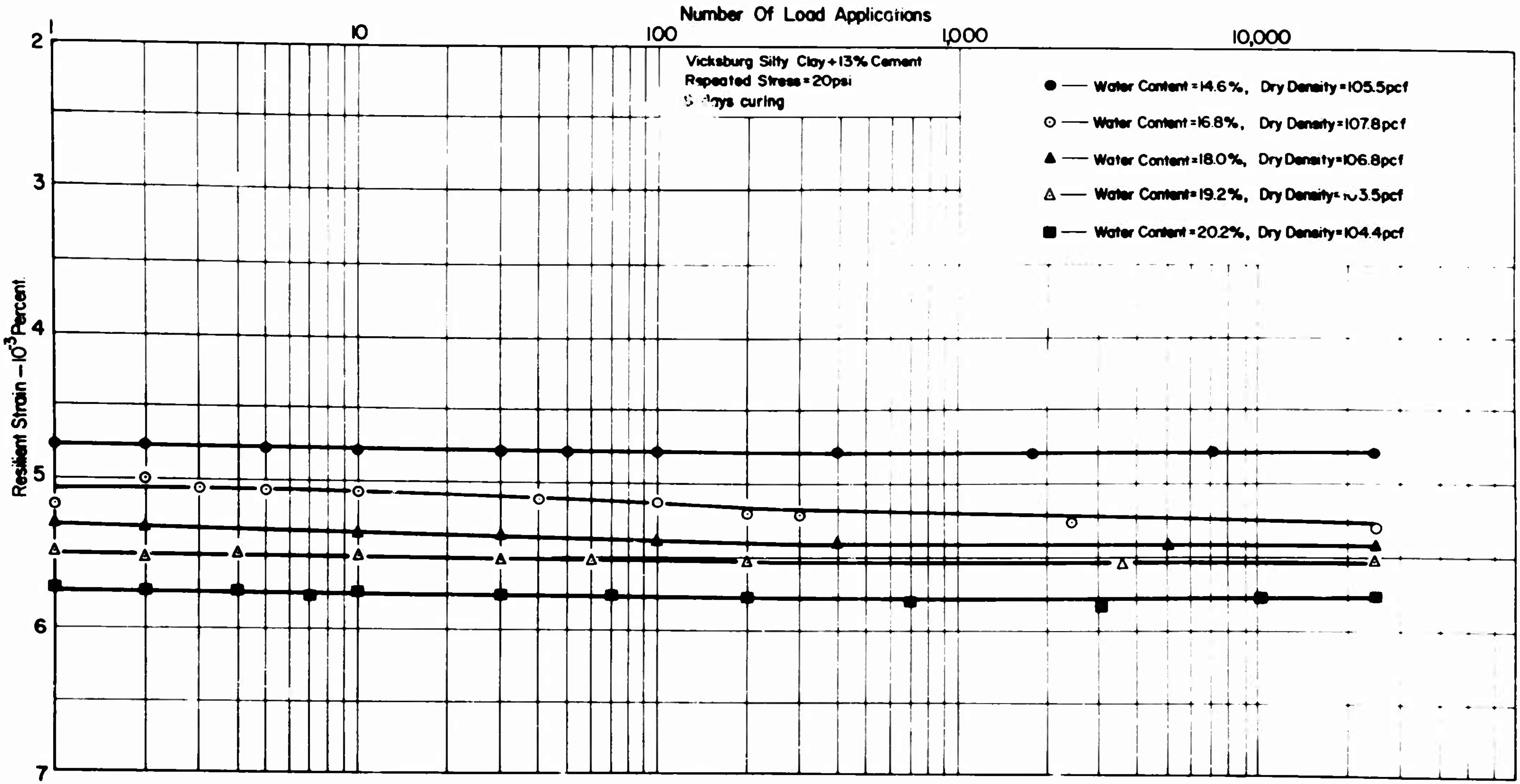

Figure 55 - EFFECT OF WATER CONTENT AND DRY DENSITY ON RESILIENT DEFORMATION OF VICKSBURG SILTY CLAY — CEMENT IN REPEATED FLEXURAL TESTS.

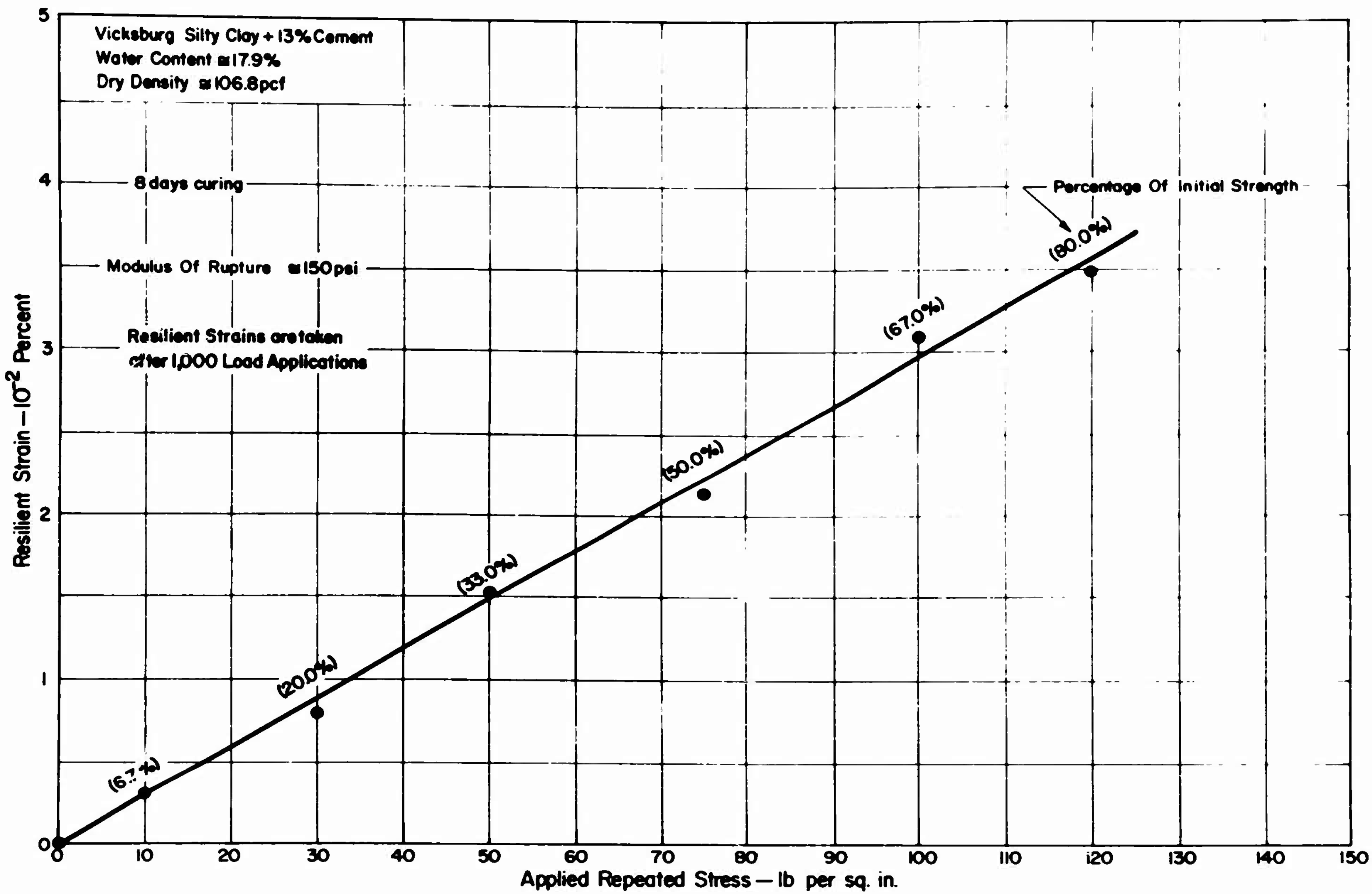

Figure 56 - EFFECT OF STRESS INTENSITY ON RESILIENT DEFORMATION OF VICKSBURG SILTY CLAY — CEMENT.

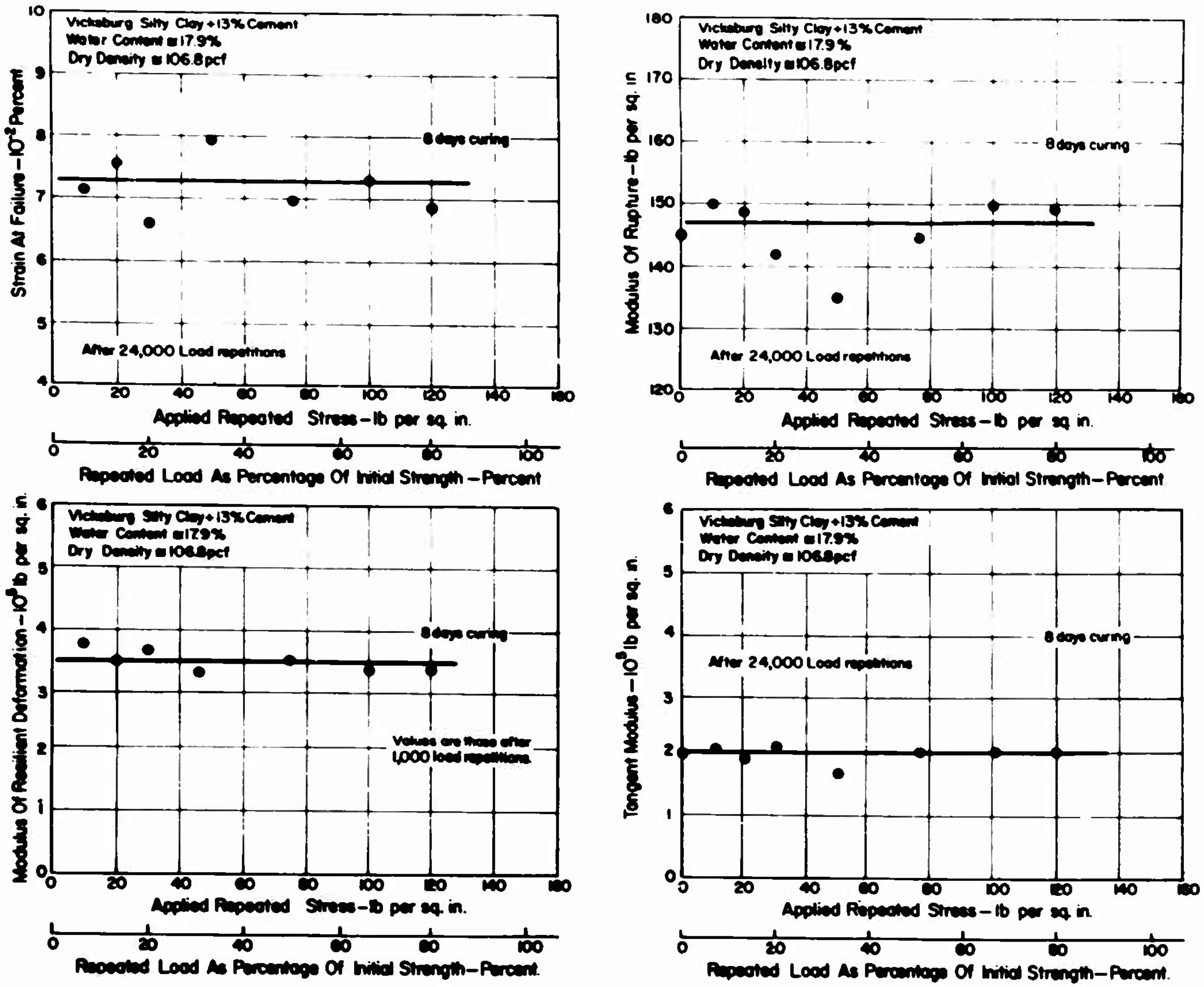

Figure 57 - EFFECT OF REPEATED FLEXURAL STRESS INTENSITY ON PROPERTIES OF VICKSBURG SILTY CLAY – CEMENT.

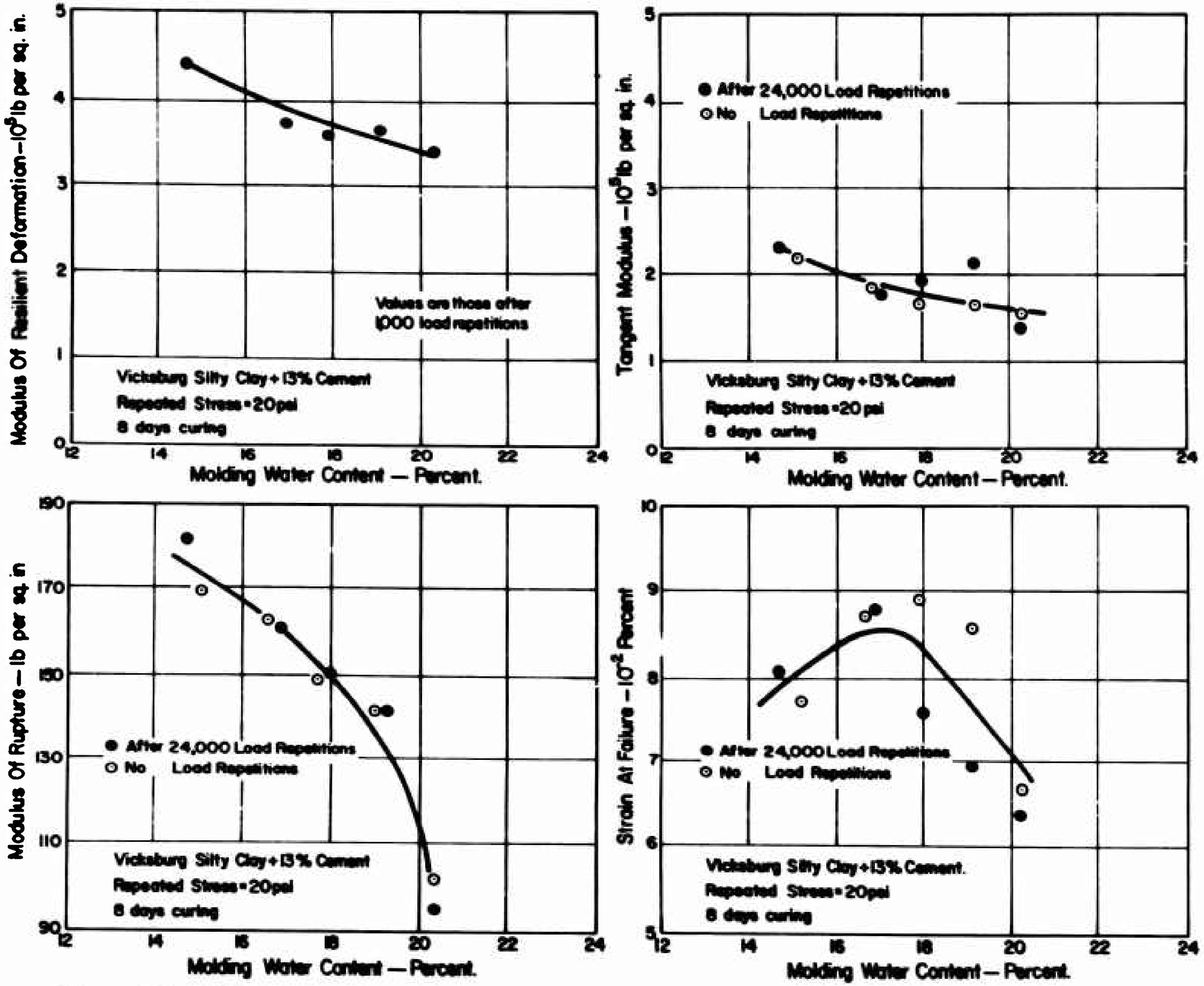

Figure 58 - EFFECT OF REPEATED FLEXURAL STRESS ON THE PROPERTIES OF VICKSBURG SILTY CLAY - CEMENT.

accordance with the Corps of Engineers' criteria, however, values of modulus of rupture were less than 30 psi and the modulus of resilient deformation in flexure was in the range of 30,000 - 60,000 psi.

Comparative Behavior of Silty Clay-Cement in Compression and Flexure

The results of Shen's (1965) study clearly show that the properties of soil-cement in compression and flexure are different. Similar results have been observed for material stabilized in accordance with the Corps of Engineers' criteria. Fig. 59 summarizes the comparative behavior for silty clay-cement (Shen, 1965) under static loading conditions. It may be seen that the stabilized soil strength and strain at failure are more sensitive to water content variation under compressive loading conditions than tensile loading conditions. In addition, both the strength and strain at failure are greater in compression than in tension.

The modulus of resilient deformation in compression is extremely sensitive to water content, whereas the resilient modulus in flexure is essentially independent of water content (Fig. 60). At the lower moisture contents (dry of optimum) the modulus in compression is much greater than that in tension, whereas they are approximately equal at the higher water contents (wet of optimum).

That moduli of resilient deformation in compression and flexure may be significantly different and that the modulus in compression varies widely with water content would imply that selection of appropriate values for analysis and design will be difficult and uncertain.

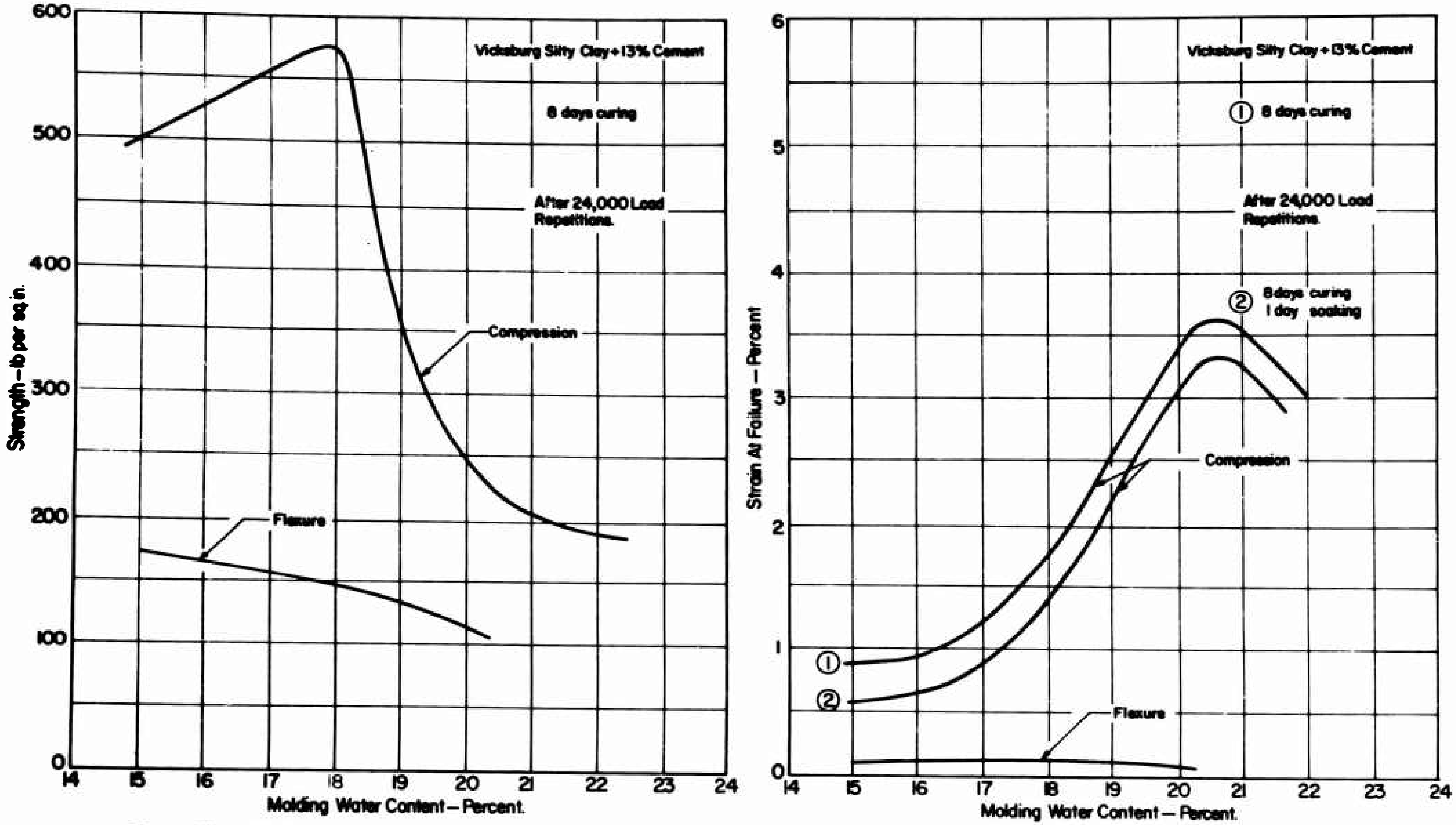

Figure 59 - COMPARISON OF THE PROPERTIES OF VICKSBURG SILTY CLAY—CEMENT SAMPLES IN COMPRESSION AND FLEXURE

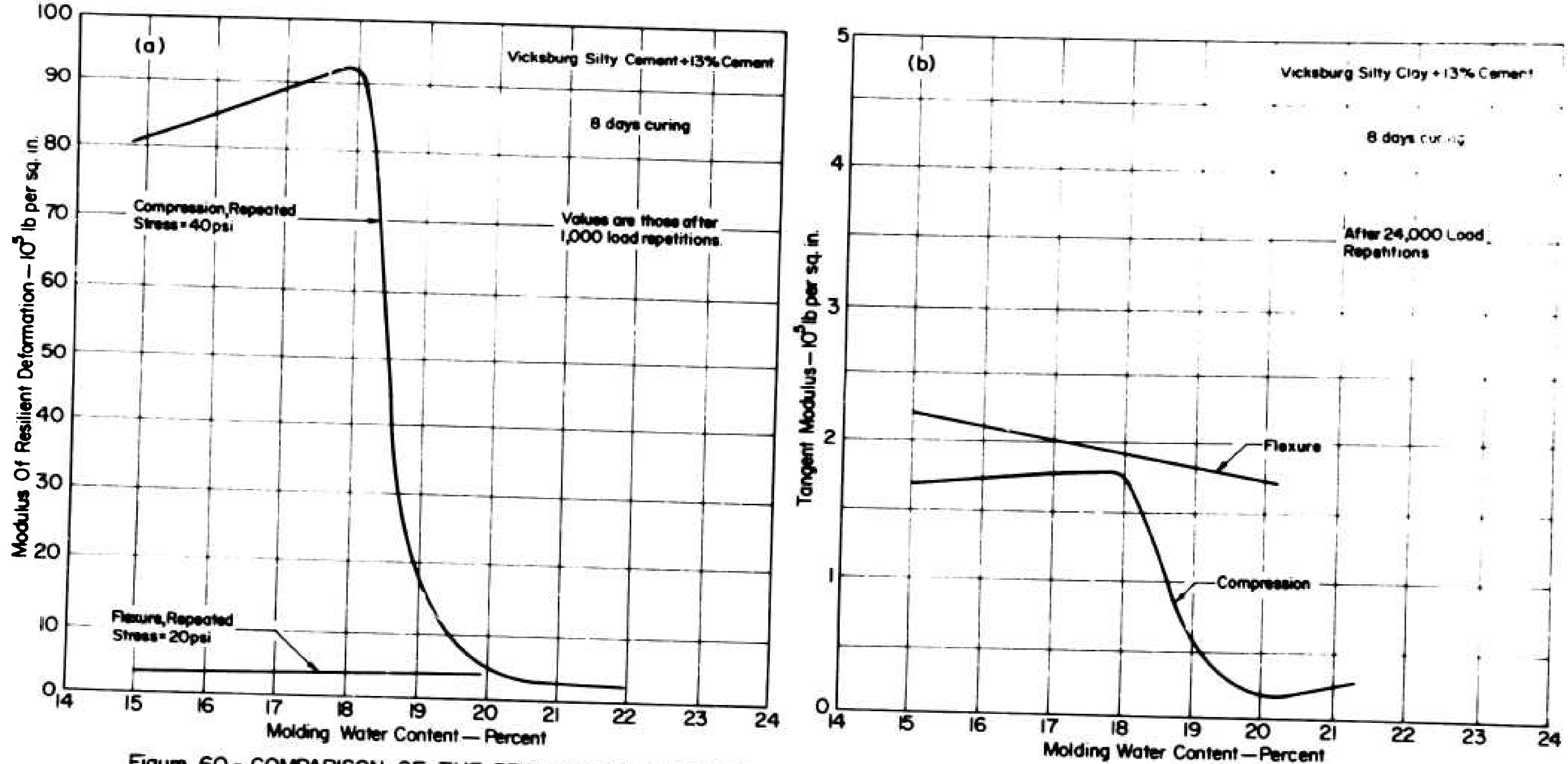

Figure 60 - COMPARISON OF THE PROPERTIES OF VICKSBURG SILTY CLAY — CEMENT SAMPLES IN COMPRESSION AND FLEXURE

XII. SUMMARY AND CONCLUSIONS

This report has presented the results of studies initiated to investigate the behavior of soils stabilized to meet Corps of Engineers' Theater of Operations Criteria under the action of repeated compressive and flexural stresses. Existing information on the behavior of stabilized soils under repeated loading has been reviewed and found to be meager. The importance of the problem is great, however.

Testing conditions for this study were established using Corps of Engineers' Criteria for Military Roads and Airfields in the Theater of Operations. These criteria specify initial soil conditions in terms of CBR and values of CBR and compressive strength after stabilization. Also indicated are stress intensities, numbers of repetitions, and total duration of the loading period. Soils used were Vicksburg silty clay (CL) and Vicksburg buckshot clay (CH). A cement treatment level of 3 percent was found adequate to raise the CBR of the silty clay from 4 to 20; whereas 6 percent cement was required to effect the same stabilization of the buckshot clay.

Test results showed that the properties of treated soils were significantly influenced by both the mixing and compaction procedures used. A dry mixing procedure was adopted wherein air-dry soil and cement are mixed prior to the addition of molding water. This procedure is simpler and gives more consistent results than addition of dry cement to moist soil. Compaction of specimens was performed by kneading compaction. More thorough investigations of the effects of compaction method and mixing procedure on properties of the stabilized soil are indicated. As a part of these preliminary studies of mixing and compaction it was determined that an approximate linear relationship between CBR and unconfined compressive strength existed up to a CBR of about 30. One unit of CBR was found to be equivalent to about 3 psi of compressive strength. This compares with a factor of 4 to 6 suggested by the Corps of Engineers.

Repeated load compression tests were conducted using cylindrical specimens; flexural repeated load tests were performed on prismatic specimens loaded as simple beams with a concentrated load at the center. Unless otherwise indicated, the tests were conducted using silty clay treated with

3 percent cement. Deflections were measured using linear variable differential transformers except in cases where deflections were sufficiently large so that they could be accurately indicated by a dial gage. Repeated load stress intensities were selected to conform with actual intensities to be expected in the field. The duration of repeated loading was generally a maximum of one day. During this period 24,000 load repetitions were applied, representing a considerably more severe loading condition than 200 coverages of a C-124 aircraft applied over a period of 4 to 6 months or 6150 passes of a 13,000-lb wheel load applied in 2 months, as called for by Corps of Engineers' criteria.

The results of a study of the influence of stress intensity on behavior in repeated compression showed that resilient deflections decreased with increasing numbers of load repetitions. The modulus of resilient deformation was found to decrease with increase in compressive stress intensity at low stresses. At stresses greater than about 25 psi the modulus increased with increase in stress intensity, probably because of densification of the specimen under the higher stresses. Moduli of resilient deformation determined from the repeated loading tests were found to be considerably greater than moduli determined on the basis of static stress-strain tests. Repeated compressive stresses up to 70 percent of the ultimate strength at the start of the test had no significant effect on strength, indicating the absence of significant fatigue effects. Samples were considerably stiffer after being subjected to repeated loading; whereas, total strain at failure was not influenced by repeated loading.

The results of a study of the influence of curing time on behavior in repeated compression showed that strength progressively increases and strain at failure progressively decreases with increase in curing period. Specimens of all ages were able to satisfactorily withstand 24,000 applications of compressive stress equal to 80 percent of the strength at the start of loading. For specimens loaded to 95 percent of the initial strength, however, fatigue failure developed for curing periods greater than 18 hours. It appears that limited stress applications at early curing times may, in fact, be beneficial in terms of ultimate performance. At early ages the material is plastic and able to densify or readjust under load.

The variation of resilient modulus in compression with curing time for a given stress intensity depends both on the number of repetitions and age of specimen. Strength was significantly increased as a result of the repeated stress applications at a stress level of 80 percent.

Strengths, resilient deformations, and resilient moduli were found to be very sensitive to molding water content for water contents wet of optimum. Increases in water content in this range result in weaker, more resilient specimens. Insufficient data are available as yet to permit definite conclusions relative to specific combinations of stress, water content, and density that will cause failure. Further study of these effects is needed, since it is the wet of optimum range that is of greatest concern for stabilization for military operations and it is in this range that water content variations have the most pronounced effects on properties.

These results of repeated load compression tests on silty clay treated with 3 percent cement were compared with those obtained by Shen (1965) on the same silty clay used for soil-cement (13 percent cement content). Shen also found that modulus of resilient deformation decreased significantly with increase in stress intensity up to about 50 percent of the compressive strength. It remained constant for higher stress levels, however. Water content and density were found to be significant variables, particularly in the range wet of optimum. Resilient moduli for the soil-cement were several hundred thousand psi as compared with 5000 to 25,000 psi for samples studied in this investigation.

A limited number of flexural tests have been conducted so far on specimens of silty clay treated with 3 percent cement. Analysis showed that actual tensile stress in the field may approach the flexural strength of the material. The data suggest a correlation showing that the greater the stress intensity, the fewer the number of repetitions to cause failure. For samples that were able to withstand 24,000 load repetitions without fatigue failure, the ultimate strength was higher than for identical specimens of the same age not subjected to repeated loading, a somewhat surprising result.

Values of resilient modulus in flexure were in the range of 30,000 to 60,000 psi as compared with 5,000 to 20,000 psi for samples tested in compression. Tensile strain at failure in beam specimens was only about one percent of the compressive strain at failure in cylindrical specimens.

As for specimens tested in compression, an increase in water content for specimens compacted wet of optimum resulted in decrease in strength and modulus.

Shen's (1965) results for flexural tests on soil-cement made with the silty clay showed the resilient properties to be only slightly affected by the repeated loading. He also observed a linear relationship between resilient strain and stress intensity. Variation in molding water content had a pronounced effect on the behavior. The soil-cement studied by Shen had moduli of rupture and resilient deformation of the order of 10 times greater than for the cement-treated silty clay studied, in this investigation.

The results appear thus far to indicate that cement-treated soil designed to meet the Corps of Engineers' criteria for CBR and compressive strength can safely withstand repeated compressive and flexural stresses of the magnitude and number prescribed for different classes of military operation, at least in the case of laboratory-prepared specimens. It is necessary, however, that the detrimental effects of cracking be investigated. A more detailed study of the effects of water content variation, mixing procedures, and method of compaction must also be carried out. The behavior of cement-treated buckshot clay is to be studied as well as stabilization using lime instead of portland cement.

APPENDIX A

PROPERTIES OF PORTLAND CEMENT

Chemical Analysis

Silicon Dioxide	22.14% by weight
Ferric Oxide	3.40
Alumimum Oxide	4.80
Calcium Oxide	64.61
Ignition Loss	1.22
Sulphite	2.10
Tricalcium Silicate	51.85
Dicalcium Silicate	24.40
Tricalcium Aluminate	6.89
Tetracalcium Aluminofinite	10.34

Physical Properties

Blane Fineness			3200 cm^2/gm.
False Set			
Initial	36.5 mm		
Final	34.5 mm	(None)	
Compressive Strength (2" mortar cubes)			
		1 day	1275 psi
		3 days	2310 psi
		7 days	3610 psi

APPENDIX B

EFFECT OF CURING TIME ON BEHAVIOR OF CEMENT-TREATED SILTY CLAY IN REPEATED COMPRESSION--VICKSBURG SILTY CLAY + 3 PER CENT CEMENT

Sample No.	Water Content	Dry Density	Curing Period	Repeated Stress Intensity psi	Repeated Stress Intensity % of Strength	No. of Load Applications	Unconfined Compression Strength psi Before R.L.	Unconfined Compression Strength psi After R.L.	Unconfined Compression Strength psi Control	Resilient Modulus At 100 Appl.	Resilient Modulus At 1000 Appl.	Resilient Modulus At 10,000 Appl.	Strain at Failure %	Water Content at Failure
C-23	19.4	103.3	2 hrs				35.0						8.13	19.1
24	19.4	103.4	2 hrs				37.8						8.20	19.1
25	19.3	103.6	2 hrs	28.8	80	24,000		70.3		5.17×10^3	6.49×10^3	15.4×10^3	4.88	19.1
26	19.3	103.6	2 hrs	34.2	95	24,000		98.1		5.43×10^3	6.71×10^3	16.3×10^3	6.53	19.2
27	19.2	103.7	2 hrs						71.3				6.44	18.8
28	19.2	103.7	2 hrs						68.0				5.64	18.9
5	19.2	103.9	4 hrs				48.1						7.21	18.8
6	19.2	104.1	4 hrs				55.0						6.93	18.8
7	19.2	103.6	4 hrs						69.5				6.66	18.7
8	19.2	103.9	4 hrs						74.4				5.45	18.6
11	19.4	103.2	4 hrs	49.0	95	24,000		66.0		7.7×10^3	9.2×10^3	17.0×10^3	6.60	19.1
12	19.4	103.8	4 hrs	40.3	80	24,000		108.7		6.4×10^3	8.6×10^3	20.0×10^3	4.46	19.1
47	19.3	103.1	12 hrs				63.3						7.15	19.1
48	19.3	103.2	12 hrs				55.6						7.20	19.3
49	19.5	103.0	12 hrs	48.0	80	24,000		95.0		7.0×10^3	8.2×10^3	14.5×10^3	7.74	19.0
50	19.5	103.2	12 hrs	57.0	95	24,000		72.1		8.1×10^3	10.1×10^3	15.7×10^3	8.02	19.1
51	19.4	103.0	12 hrs						71.8				6.66	18.7
52	19.4	103.2	12 hrs						73.2				5.99	19.1
35	19.4	103.4	18 hrs				76.0						6.66	19.0
36	19.4	103.6	18 hrs				74.2						5.46	19.0
37	19.3	103.8	18 hrs	71.1	95	289		-		10.9×10^3	-	-	≈ 6.5	19.0
38	19.3	103.6	18 hrs	60	80	24,000		69.5		9.1×10^3	10.2×10^3	14.3×10^3	6.81	18.8
39	19.2	103.6	18 hrs						80.0				5.77	18.8
40	19.2	103.7	18 hrs						78.1				5.75	18.7

R.L. = Repeated loading

APPENDIX B (Contd)

Sample No.	Water Content	Dry Density	Curing Period	Repeated Stress Intensity psi	Repeated Stress Intensity % of Strength	No. of Load Applications	Unconfined Compression Strength psi Before R.L.	Unconfined Compression Strength psi After R.L.	Unconfined Compression Strength psi Control	Resilient Modulus At 100 Appl.	Resilient Modulus At 1000 Appl.	Resilient Modulus At 10,000 Appl.	Strain at Failure, %	Water Content at Failure
C-13	19.5	103.1	24 hrs				70.5						6.45	19.1
14	19.5	103.4	24 hrs				67.4						5.76	19.1
15	19.5	103.0	24 hrs	55	80			100.0		$8.4x10^3$	$9.2x10^3$	$13.4x10^3$	4.27	19.2
16	19.5	103.3	24 hrs	65.2	95	24,000		77.6		$9.9x10^3$	$11.4x10^3$	$14.1x10^3$	4.43	19.1
41	19.3	103.3	24 hrs						73.6				5.52	18.9
42	19.3	103.5	24 hrs						82.2				5.16	18.9
41	19.3	103.3	2 dys				73.6						5.52	18.9
42	19.3	103.5	2 dys				82.2						5.16	18.9
43	19.3	103.3	2 dys	62.5	80	24,000		109.9		$9.8x10^3$	$10.3x10^3$	$13.4x10^3$	6.40	18.9
44	19.3	103.5	2 dys	74	95	<1,000		-		$11.9x10^3$	-	-	≈5.72	18.9
45	19.0	104.0	2 dys						72.5				5.45	18.9
46	19.0	103.8	2 dys						78				5.90	18.9
29	19.2	104.0	4 dys				106.5						4.42	18.5
30	19.2	104.2	4 dys				97.2						4.12	18.6
31	19.1	104.3	4 dys	96.5	95	24,000		126.3		$15.3x10^3$	$17.3x10^3$	$20.1x10^3$	5.56	18.5
32	19.1	104.2	4 dys	81.5	80	24,000		123.3		$11.0x10^3$	$10.7x10^3$	$11.4x10^3$	4.16	18.5
33	19.3	103.8	4 dys						105.5				5.18	18.6
34	19.3	103.9	4 dys						91.7				4.57	18.7
17	19.1	103.9	7 dys				88.4						5.36	18.7
18	19.1	104.1	7 dys				85						4.48	18.7
19	19.1	103.8	7 dys	69.5	80	24,000		120		$10.7x10^3$	$10.7x10^3$	$11.6x10^3$	5.72	18.7
20	19.1	104.1	7 dys	82.5	95	500		-		$12.6x10^3$	-	-	≈4.2	18.9
21	19.0	104.0	7 dys						81.6				4.57	18.7
22	19.0	104.5	7 dys						89.4				4.10	18.6
58	19.4	103.2	4 dys						80.5					
55	19.7	102.7	4 dys						76.3					
56	19.7	102.8	4 dys				72.2							
54	19.5	103.3	4 dys				84.4							
57	19.4	103.3	4 dys	80.2	95	715				$12.6x10^3$	-	-		
53	19.5	103.3	4 dys	67.5	80	<2,000				$10.3x10^3$	-	-		

R.L. = Repeated loading

APPENDIX C

EFFECT OF WATER CONTENT ON BEHAVIOR OF CEMENT-TREATED SILTY CLAY SUBJECTED TO REPEATED COMPRESSION STRESSES

Sample No.	Water Content	Dry Density	Repeated Stress Intensity psi	Repeated Stress Intensity % of Strength	No. of Load Applications	Unconfined Compression Strength psi Before R.L.	Unconfined Compression Strength psi After R.L.	Unconfined Compression Strength psi Control	Resilient Modulus At 100 Appl. psi.	Resilient Modulus At 1000 Appl. psi	Resilient Modulus At 10,000 Appl. psi
L1	19.9	103.6	75	118.4	48(F)		--		-	-	-
L2	19.9	103.5	50	78.9	26,500		104.2		7,900	8,900	13,000
L9	20.0	103.1				62.4					
L10	20.0	103.1				64.2					
W13	19.7	103.3						72.6			
W14	19.7	103.2						80.9			
L3	20.9	101.6	50	88.5	342(F)		--		8,500	-	-
L4	20.9	101.4	35	62.1	25,500		73.7		5,900	6,900	9,700
L11	20.8	101.8				57.1					
L12	20.8	101.7				55.7					
W15	20.7	101.2						61.6			
W16	20.7	101.2						58.3			
L5	21.9	100.9	35	72.0	24,900		69.1		5,000	5,800	1,300
L13	21.9	100.2				47.8					
L14	21.9	100.2				49.5					
W17	21.7	99.7						54.4			
W18	21.7	99.6						52.1			

Vicksburg Silty Clay + 3% Cement
24 hour curing period
R.L. = Repeated loading

Appendix D

Effect of Methyl Bromide Treatment on Soil Properties

During the course of the research it was necessary to obtain an additional supply of Vicksburg silty clay for preparation of specimens. U. S. Department of Agriculture regulations made it necessary that the soil be fumigated using methyl bromide before it could be shipped from Mississippi to California.

Tests carried out at the Waterways Experiment Station (Memorandum for Record, WESSS 3, 16 June 1965) led to the conclusion that "fumigation of soil with methyl bromide gas influences the responsiveness of Vicksburg clayey silt to stabilization with cement or lime." The strength of stabilized fumigated soil was slightly less than that of the stabilized soil not subjected to methyl bromide treatment. In these tests the concentration of fumigant used to treat the soil was about 20 times greater than minimum requirements.

The soil actually shipped to the University of California was treated with a lower concentration of methyl bromide than was used for the tests at the Waterways Experiment Station. In this case the concentration was about four times greater than minimum requirements. Tests on this material treated with 3 percent portland cement were carried out, giving the results shown in Table D-1. It may be seen from these results that the behavior of the soil was not significantly affected by the fumigation. Therefore the new batch of soil was considered suitable for continuation of test programs previously initiated.

TABLE D-1

PROPERTIES OF UNTREATED AND METHYL BROMIDE TREATED SILTY CLAY

	Methyl Bromide Treated	Untreated
Liquid Limit, %	35.3	35.1
Plastic Limit, %	22.0	21.7
Specific Gravity	2.65	2.65
After Treatment with 3% cement and compaction to 103.2 pcf at 19.5% water content:		
Strength at 24 hrs, psi	70.3	69.0
Strength at 48 hrs, psi	71.9	77.9
Strength after repeated loading, psi	95	89
Resilient Moduli, psi:		
80% stress level, at 100 repetitions	9.2×10^3	8.4×10^3
at 1000 repetitions	9.9×10^3	9.2×10^3
95% stress level, at 100 repetitions	10.9×10^3	9.9×10^3
at 1000 repetitions	12.3×10^3	11.4×10^3

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13. ABSTRACT Current methods of pavement design using stabilized soils as components of the pavement structure generally base selection of both quality and thickness of those materials on static tests such as the CBR procedure. To validate such procedures, the objectives of these studies are to evaluate the behavior of stabilized soils under dynamic loading conditions and develop improved criteria for quality design and thickness selection within a more rational framework. More specifically the study is concerned with examination of soil stabilization requirements established by the Corps of Engineers for military roads and airfields in the theater of operations within this framework. Two soils, Vicksburg Silty Clay and Vicksburg Buckshot Clay, were selected for study because of the considerable performance data on these soils and because, through suitable treatment, they fall within the range of stabilization requirements of the Corps. To date, most of the dynamic testing has been performed on the treated silty clay. In general the results obtained thus far indicate that cement-treated soil designed to meet Corps' criteria for CBR and compressive strength can withstand repeated compressive and flexural stresses of the magnitude and number prescribed for different classes of military operations. However, more detailed investigation of the influence of water content, mixing procedures, and method of compaction are required since the data obtained show that these variables significantly affect the strength and resilience characteristics of the cement-treated silty clay.

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