Behavior of Soil-Cement in Repeated Compression and Flexure

CHIH-KANG SHEN, Assistant Professor of Civil Engineering, Loyola University of Los Angeles*; and
JAMES K. MITCHELL, Associate Professor of Civil Engineering and Associate Research Engineer, Institute of Transportation and Traffic Engineering, University of California, Berkeley

•RECENT field evaluations (7, 10) have shown consistently that flexible pavements containing cement-treated layers give better performance under traffic loads than untreated gravel bases of the same thickness. Nussbaum and Larsen (14) established from the results of plate load tests that untreated granular bases may deflect from 1.5 to 3.3 times as much under a given load as an equal thickness of soil-cement. In rigid pavements cement-treated bases reduce the hazardous effect of pumping at the joints. In addition, Childs (3) has shown that for constant edge deflection an 8-in. concrete slab bonded to a 5-in. cement-treated base was able to support 200 percent of the load carried by the 8-in. slab on a 5-in. gravel subbase.

The quality design (i.e., treatment level, compaction conditions, etc.) of stabilized soils is usually based on tests such as unconfined compression, California bearing ratio, and the Hveem stabilometer for strength; and wet-dry and freeze-thaw for durability. Strength evaluations of this type all make use of static loading conditions. There is very little knowledge of the behavior of stabilized soils under dynamic loading conditions. It is well known, however, that the properties of most materials can be significantly altered, and, in fact, failure due to fatigue may result under the action of repeated subfailure stresses with intensities less than the static strength of the material.

Although investigations of the resilience characteristics of compacted subgrade soils under triaxial repeated loading tests have been reported by Seed et al. (16, 17, 18, 19, 22, and 23) and Ahmed and Larew (1), among others, and the resilient characteristics of unbound granular base courses have been investigated by Mitry (13), Biarez (2), Trollope, Lee and Morris (24), and others, knowledge of the resilience characteristics of cement-stabilized soils is limited. (In accordance with the terminology introduced by Hveem (11), recoverable deformations are referred to in this paper as resilient deformations, and the corresponding moduli as resilient moduli.)

Recent advances in the application of Burmister's three layer elastic theory to problems of pavement analysis and design (4, 5, 12, and 15) make knowledge of the elastic properties of cement-stabilized soils all the more important. Values of properties as determined by dynamic tests may be quite different from those determined by conventional static tests. Layered-theory approaches deal primarily, however, with stresses and strains generated in the pavement structure under the action of moving loads. Thus there is need for additional information concerning soil-cement behavior under the action of repeated dynamic stresses.

This paper presents the results of an investigation of the behavior of soil-cement subjected to repeated loads of subfailure magnitude in both compression and flexure and of the resultant effects on strength and deformation properties.

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*Formerly Assistant Specialist, Institute of Transportation and Traffic Engineering, University of California, Berkeley.

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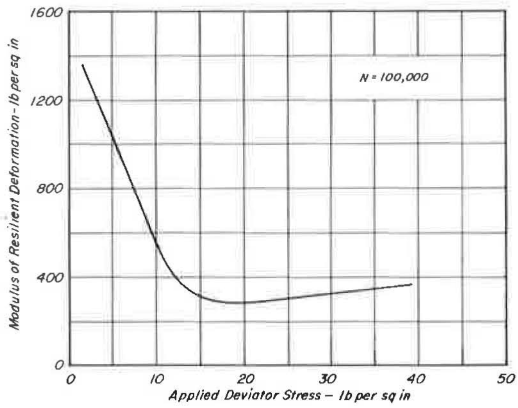

Figure 1. Effect of stress intensity on resilience characteristics, AASHO Road Test subgrade soil (23).

PREVIOUS WORK

Previous studies of untreated soils and base-course materials under the action of repeated compressive stresses have shown that such factors as stress history, frequency and intensity of repeated stress, and number of load repetitions may influence the properties significantly. In a detailed investigation of the resilience characteristics of compacted subgrade soils Seed, Chan, and Lee (23) established the importance of the following factors.

1. Number of load applications. The resilient deformation varied with the number of load applications, and the greatest value occurred between one and 5,000 applications, depending on the initial conditions of the soil.
2. Applied repeated loading stress intensity. The resilient deformation of compacted clay varies with the magnitude of the applied deviator stress intensity. At low stress intensities the resilient modulus of AASHO Road Test subgrade soil decreased rapidly with increasing values of the deviator stress (Fig. 1). At deviator stresses greater than 15 psi, the resilient modulus increased slightly with increasing deviator stress. This increase of modulus with increased stress was attributed to the densification of the sample under high repeated loading stress intensities.
3. Method of compaction. Samples compacted wet of optimum water content using a method producing a dispersed structure (e.g., kneading) showed larger resilient deformations and lower moduli than samples compacted using a method producing a flocculent structure (e.g., static).

In the case of cohesionless soils, confining pressure may influence resilient modulus significantly. Trollope et al. (24) 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 (13) found, from triaxial repeated loading tests on dry granular material, that the modulus of resilient deformation varied with the effective confining pressure according to the equation, $E = K \cdot \sigma_3^n$, where K and n are constants, depending on the material investigated, and σ_3 is the effective confining pressure, in psi. He found K = 12,500 and n = 0.35 for Monterey sand and K = 7,000 and n = 0.55 for gravel.

The properties of cement-stabilized soils under static loading conditions and a limited amount of information concerning the elastic properties and dynamic moduli are given in Reference 9. Dunn (6) reported the results of a study in which specially prepared sand-clay mixtures stabilized with portland cement were tested under dynamic conditions. Cylindrical specimens were subjected to a 40-psi compressive stress at a frequency of 106 cpm. This repeated loading had little effect on the physical properties, and it was concluded that this was due to the fact that the repeated load stress was small in relation to the strength of the material (2 to 10% of the compressive strength).

Dunn also determined the dynamic modulus from sonic velocity measurements on beams, and obtained values about two times greater than those determined as a secant modulus in compression tests. This was probably because the dynamic test deals primarily with elastic effects, and soil-cement exhibits time-dependent deformation properties which influence static test results.

Whittle and Larew (27) studied the effects of repeated loads on elastic micaceous soils stabilized with 5 percent type III portland cement. Results showed that the ultimate strength as determined from a repeated load stress-strain curve was considerably less than the ultimate strength obtained from identical samples using conventional loading. The strain at failure, however, remained nearly the same under both types of loading. They concluded that specimens would fail under repeated loading when the magnitude of the repeated load stress is greater than 60 percent of the ultimate compressive strength.

EXPERIMENTAL PROGRAM

Notation

N = number of repeated loading applications,

w/c = molding water content,

γ_d = dry density,

$\sigma_{max\ c}$ = unconfined compressive strength,

$\Delta\sigma_{max\ c}$ = change of unconfined compressive strength in percentage,

S_{max} = modulus of rupture in flexure test,

σ_c = applied repeated compressive stress,

σ_T = applied repeated tensile stress,

ϵ_{RC} = resilient strain in compression test,

ϵ_{RF} = resilient strain in flexure test,

ϵ_{TC} = total strain in compression test,

ϵ_{TF} = total strain in flexure test,

ϵ_{fc} = strain at failure in compression test,

ϵ_{fF} = strain at failure in flexure test,

M_{RC} = modulus of resilient deformation in compression test,

M_{RF} = modulus of resilient deformation in flexure test,

E_{SC} = tangent modulus in compression test, and

E_{SF} = tangent modulus in flexure test.

Materials

The two soils chosen for this study are similar to materials used in the field for soil-cement stabilization. They were silty clay from Vicksburg, Miss., and a river sand with added fines from Eliot, Calif. The Vicksburg silty clay (VSC) represented a typical subgrade material, and the Eliot sand mixture (ESM) represented a typical stabilized base course material. A gradation curve of the ESM indicated its adequacy to meet base course specifications (AASHO E grading, designation M147-57). It was composed of, by weight, 80 percent Eliot sand, 10 percent kaolinite (grain size finer than 2μ), 5 percent No. 84 Ottawa sand and 5 percent silica flour (passing No. 325 sieve but coarser than 2μ).

Figure 2 shows the grain-size distribution curve of ESM and the range of AASHO E grading material, as well as the particle-size distribution curve for VSC. The physical properties of the untreated soils are given in Table 1.

According to the AASHO soil classification system, VSC is an A-6 soil, and the ESM is an A-2-4 soil.

Cement Treatment Level

The amount of cement used in each of the two soils was determined using freeze-thaw (ASTM D560-44) and wet-dry (ASTM D559-44) tests on specimens compacted to maximum density at optimum moisture content using standard AASHO compaction.

TABLE 1

PHYSICAL PROPERTIES OF VICKSBURG SILTY CLAY AND ELIOT SAND MIXTURE

Soil	L. L. (%)	P. L. (%)	P. I. (%)	Sp. Gr.	Mineral Comp. of -2μ Fraction
VSC	37-39	23-24	14	2.72	Mont., illite, quartz
ESM	20.6	15.4	5.2	2.70	Kaolinite

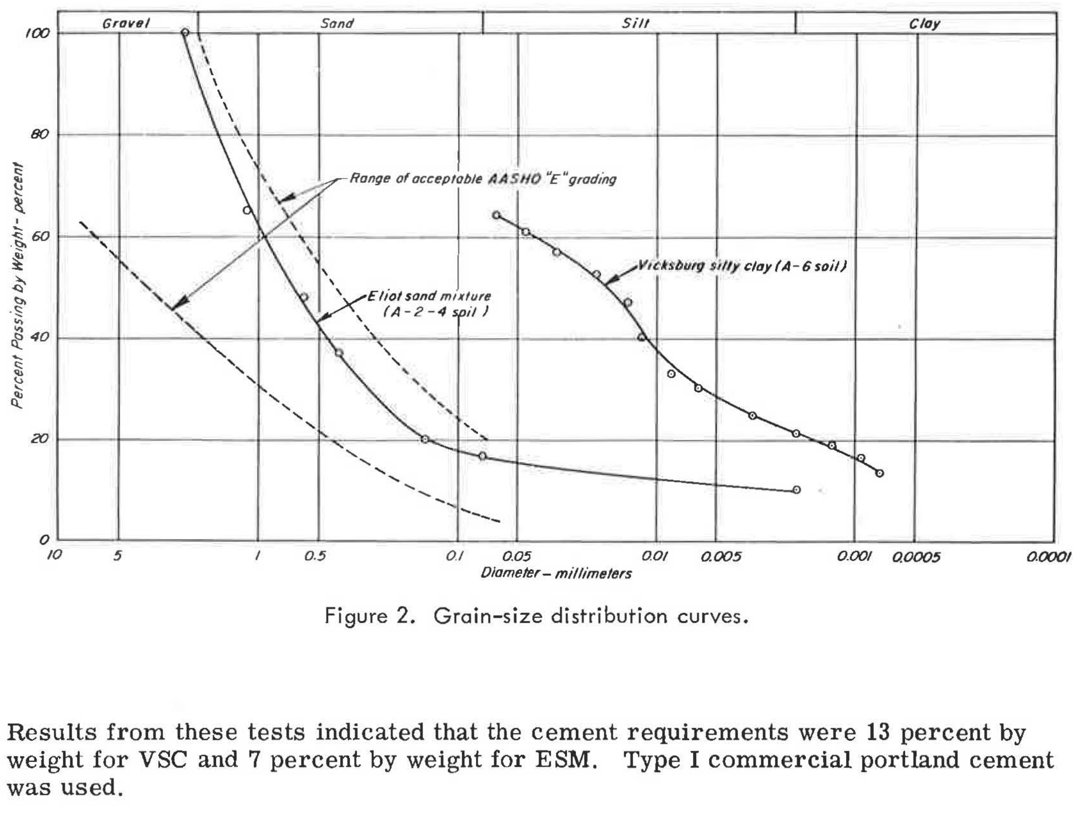

Figure 2. Grain-size distribution curves.

Results from these tests indicated that the cement requirements were 13 percent by weight for VSC and 7 percent by weight for ESM. Type I commercial portland cement was used.

Types of Tests and Selection of Stress Intensities

Both triaxial compression tests on cylindrical specimens and flexural tests on beam specimens were conducted. Appropriate ranges of repeated loading stress intensities were selected on the basis of computations using three-layer elastic theory for highway and airfield loading conditions, assuming the VSC to be a stabilized subgrade material and the ESM to be a stabilized base course. In tests where applied stress intensity was not considered as a variable, stress intensities of 50 and 100 psi were used for ESM in compression and 50 psi in flexure; 20 and 40 psi were applied to VSC in compression, and 20 psi in flexure.

Mixing

Soil and the appropriate amount of cement were first mixed in an air-dry condition, then the necessary amount of water was added to the air-dry mixture and thoroughly mixed for about 3 min. Inasmuch as delaying compaction after mixing reduces the dry density and strength of a compacted specimen (26), the time lapse between mixing and compaction was kept constant for all samples. The amount of water-cement-soil mixture mixed each time was enough for two cylindrical specimens or for one beam specimen; and the time lapse from after mixing to the completion of compaction was approximately 10 min.

Sample Compaction

Cylindrical Samples. —Compaction was performed using a modified Harvard Miniature kneading compactor. Samples were compacted in 1.4-in. diameter molds to an approximately 3.5-in. trimmed height. The sample was placed between a lucite cap and base, enclosed in two rubber membranes (with a thin film of silicone grease in between), sealed top and bottom by O-rings, and stored under water for curing.

Beam Samples. —Beam samples were compacted using the Triaxial Institute kneading compactor (25) with a rectangular tamping foot $2\frac{2}{3}$ by 2 in. in plan. A steel mold 12 in. long 3 in. wide and $2\frac{1}{2}$ in. deep was used. The finished sample was extruded from the mold and wrapped with Saran sheet for curing.

Curing

All samples, except those used for the study of the effects of curing time were cured for 7 days. Some samples were soaked unconfined for a period of 24 hr after 7 days of curing.

Repeated Loading Apparatus

The repeated loading equipment was the same as that used for a number of years in the soil mechanics laboratory at the University of California (20).

In both compression and flexure tests the load applications were 20/min, the average duration of a load application was 0.1 sec, and the load rise time was about 0.01 sec. Figure 3 is a typical load vs time trace.

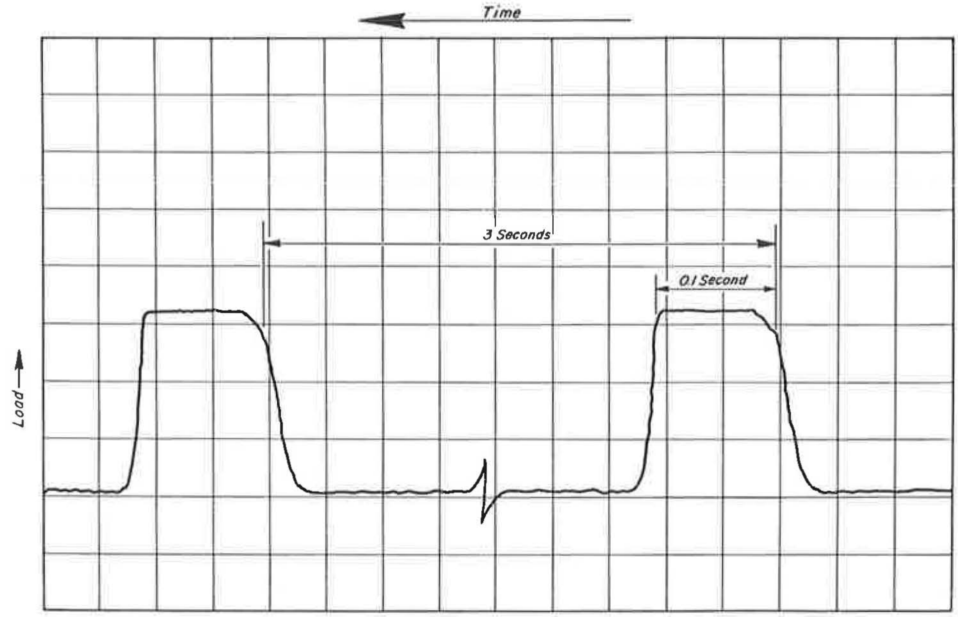

Figure 3. Repeated loading time vs load trace.

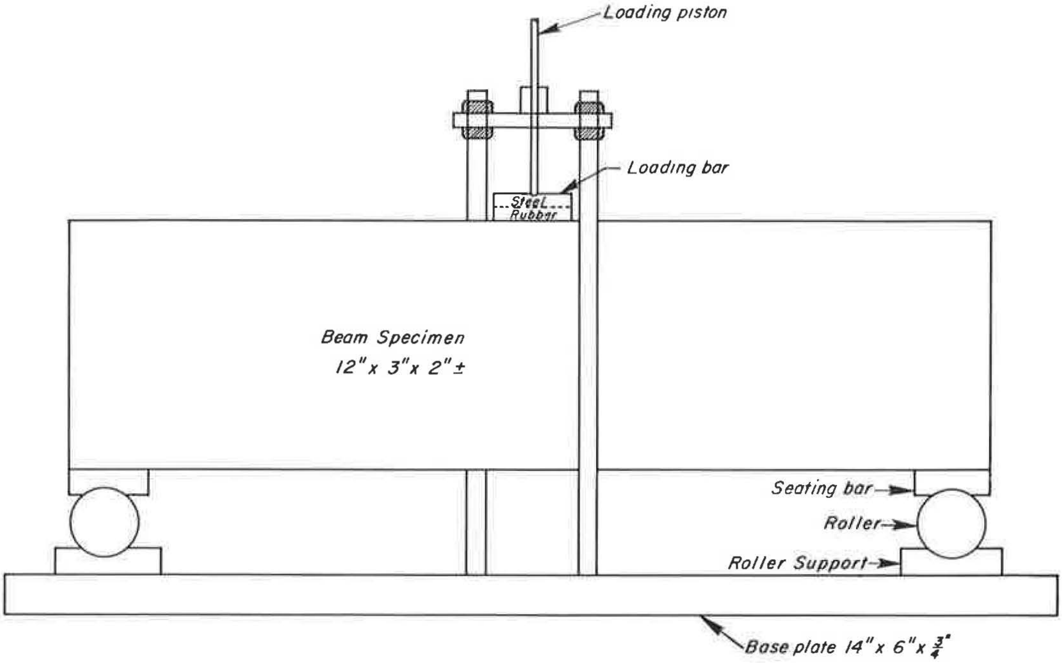

Figure 4. Flexural test apparatus.

Repeated loading compression tests were carried out inside triaxial compression cells. No confining pressure was used. All samples were tested undrained, and no pore pressure measurements were attempted.

A simple apparatus was used for flexural tests (Fig. 4). One of the two roller supports was fixed on the 14- by 6- by ¾-in. steel base plate; the other was free to move, thus giving simple support conditions. Load was applied using a loading piston and was transmitted to the beam by a two-layered loading bar, which was seated on the top of the midspan of the beam. This loading bar was made of a plate of steel sealed to a layer of hard rubber. Approximate simple-beam elastic theory could be used for stress-deflection analysis of the results obtained.

Measuring and Recording Systems

Since the soil-cement specimens, especially the ESM, were very stiff in relation to untreated soils, accurate measurement of deformation was difficult. The amount of deformation under repeated loading was of the order of only 1×10^{-5} in./in. or less in some cases, and could not be accurately measured using a dial gage. Moreover, the magnitudes of the applied repeated loads were comparatively high, ranging from 40 to about 250 lb. Thus the elastic deformation of the apparatus was appreciable. Therefore, a measuring technique independent of apparatus deflections was needed for this research.

A technique for measuring the relative deformation of compression specimens which made use of Schaevitz type 100M-L linear variable differential transformers (LVDT's) was found successful. Dual LVDT's were connected in parallel to increase the sensitivity of the measuring system and to give representative average values of deformation. They were mounted directly on the specimens by means of two small aluminum alloy clamps (Fig. 5). One clamp held the transformer coil assembly; the other the adjustable core rod.

Bonded-wire strain gages were used to measure the deflection of ESM beam specimens under repeated loading. A four-arm Wheatstone bridge was formed by connecting

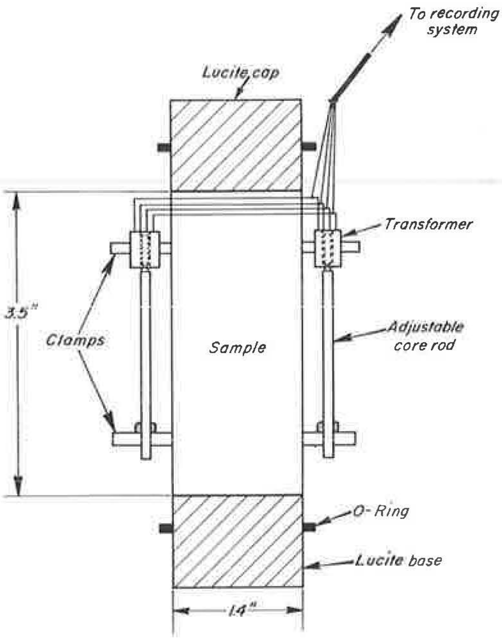

Figure 5. Linear variable differential transformer assembly for deflection measurements on cylindrical sample.

two active and two compensation strain gages. Strain gages could not be securely bonded to the smooth, moist surfaces of VSC beam specimens; therefore, LVDT's were used. Measurements were taken both at the middle and the ends of the span. The adjustable core rod was connected to the beam at mid-height (neutral axis), and the transformer coil assembly was fixed on a stationary rod screwed into the base plate (Fig. 6).

Both the transformers and the strain gages were wired to model 150-1100AS Sanborn carrier preamplifiers, which were in turn wired to a model 152-100BP, two-channel, direct-writing Sanborn recorder. Calibration curves were established before testing. Occasional checks were made to insure that accuracy was consistently maintained.

Conventional Strength Tests

After being subjected to a specific number of repeated loading applications (generally 24, 000), all samples, except for those which failed during the course of repeated loading tests, were tested using

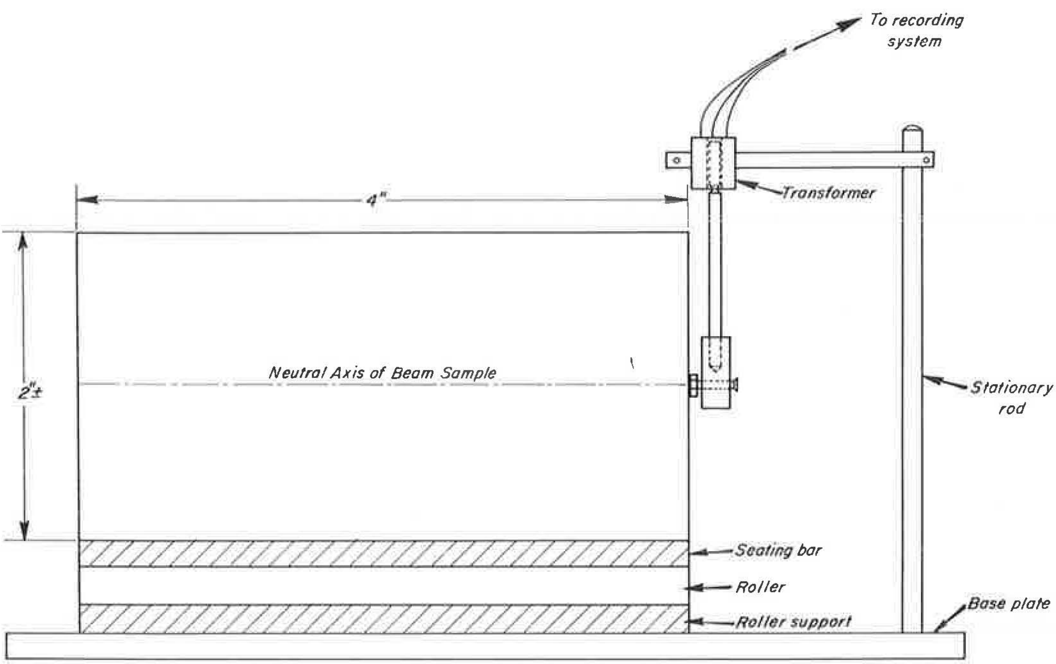

Figure 6. Linear variable differential transformer assembly for deflection measurements on beam samples.

conventional compression or flexural strength tests. A dummy sample of the same age as the corresponding repeated loading sample was also tested to determine the effect of repeated load application on the mechanical properties.

RESULTS

Repeated Load Compression Tests

Effect of Density and Moisture Content. —The effects of moisture content and density on behavior under repeated compressive loading were determined using specimens compacted along three curves (Figs. 7 and 8). Six identical samples were prepared at each point on the curves. All samples were cured for 7 days following compaction. Four specimens were then soaked for 24 hr. Repeated loading tests were carried out on two

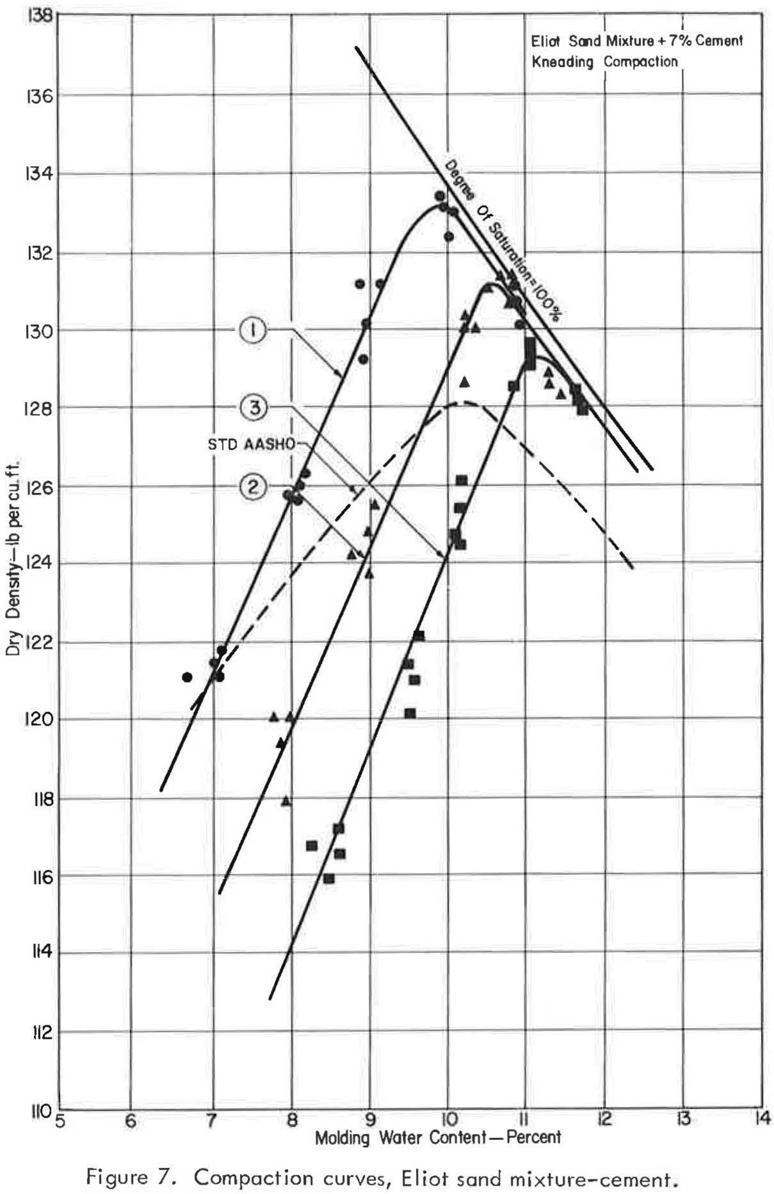

Figure 7. Compaction curves, Eliot sand mixture-cement.

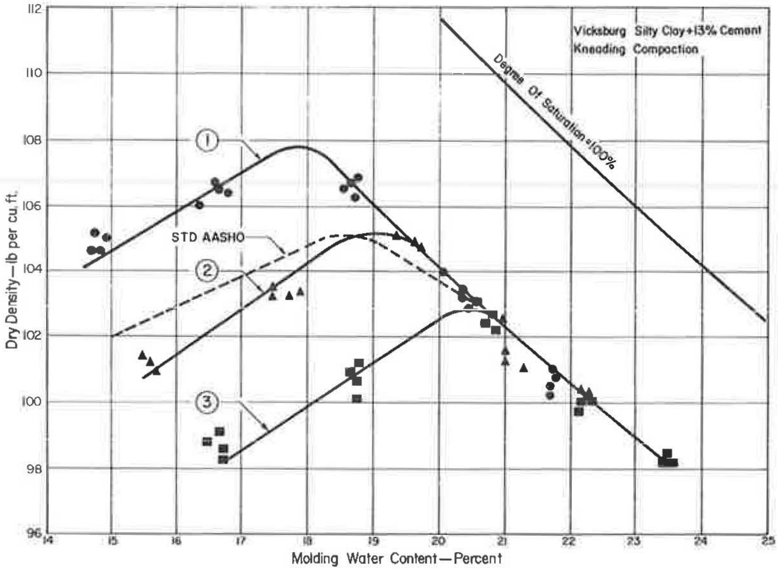

Figure 8. Compaction curves, Vicksburg silty clay-cement.

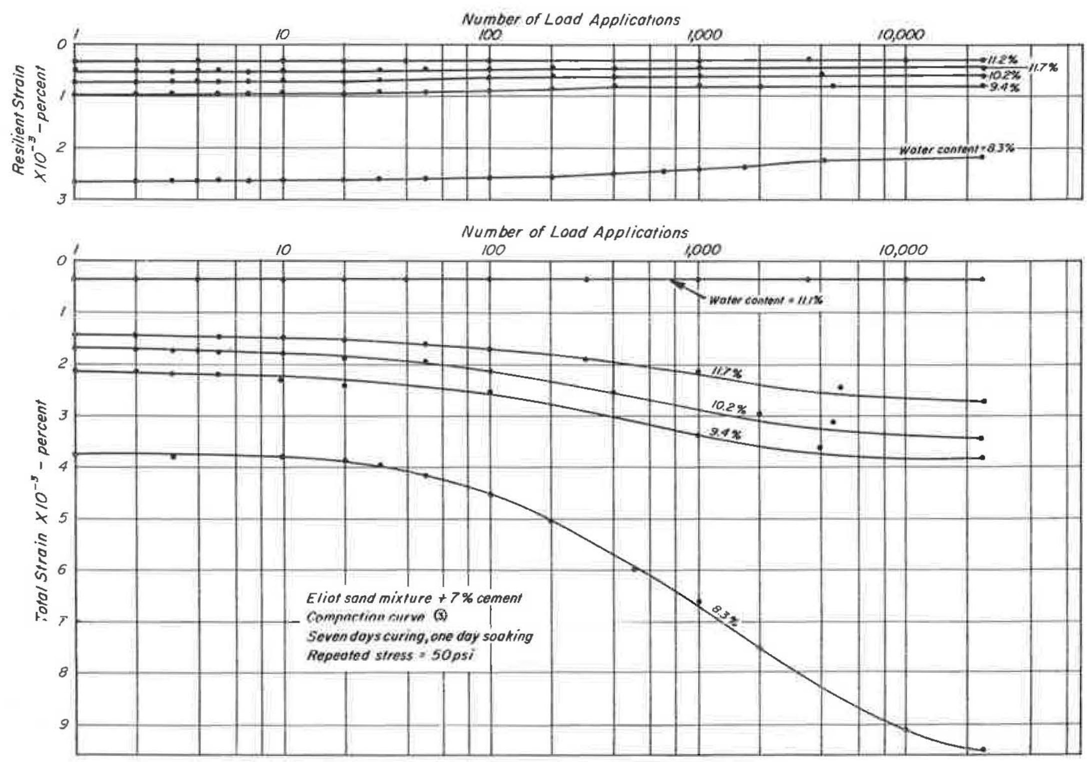

Figure 9. Deformation of Eliot sand mixture-cement samples in repeated compression tests.

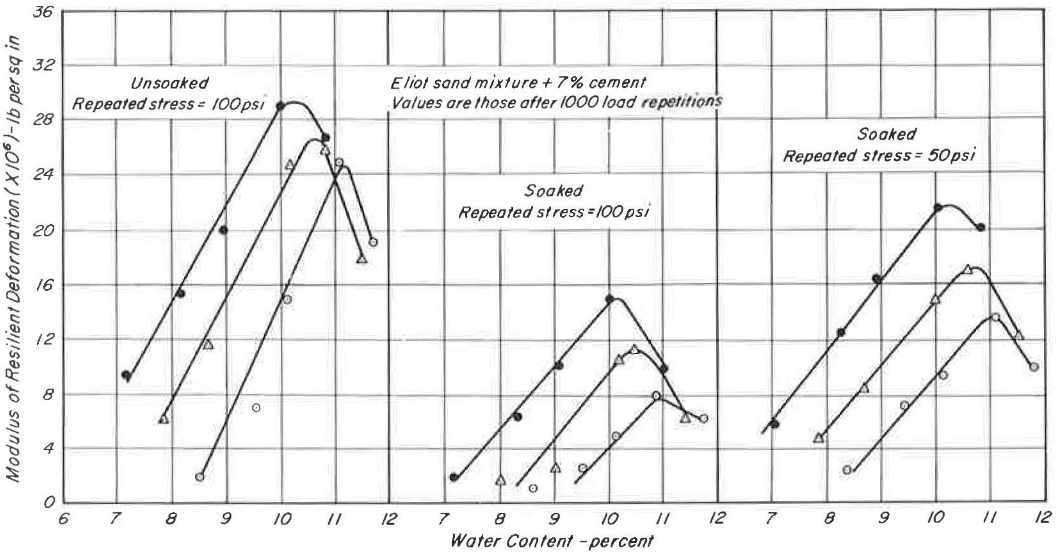

Figure 10. Relationship between water content and modulus of resilient deformation in compression for Eliot sand mixture-cement.

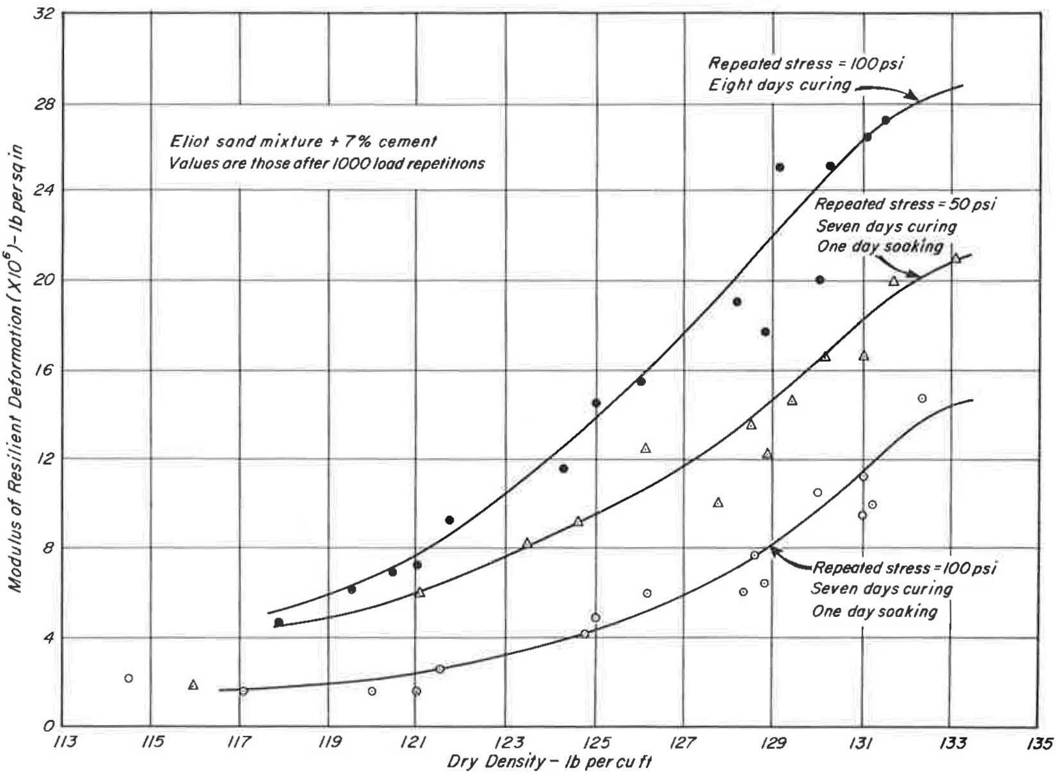

Figure 11. Relationship between dry density and modulus of resilient deformation in compression for Eliot sand mixture-cement.

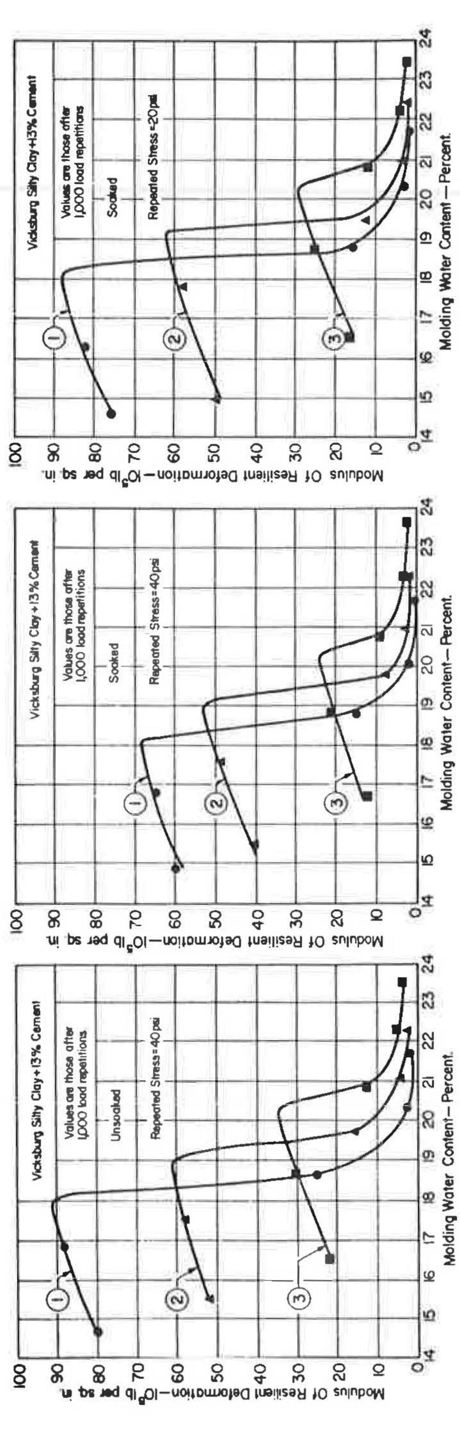

Figure 12. Relationship between water content and modulus of resilient deformation in compression for Vicksburg silty clay-cement.

soaked samples and one unsoaked sample on the eighth day after compaction. Tests were stopped after approximately 24,000 repeated load applications, and the specimens were subjected to unconfined compression tests. The strengths of dummy samples which had not been subjected to repeated loading were also determined.

Figure 9 shows typical plots of the variation of resilient (ϵ_{RC}) and total (ϵ_{TC}) compressive strains with the number of load applications (N) for ESM-cement. At the comparatively low (but realistic in relation to traffic-induced stresses) applied repreated load stress intensities (less than 30 percent of the initial strength for VSC-cement and 40 percent for ESM-cement) both the resilient and total strains are small. There is little variation in resilient strain with increase in number of load applications.

The variation of modulus of resilient deformation (M_{RC}) in compression, after 1,000 load repetitions, with molding water content, is shown in Figure 10 for the ESM. Both the stress intensity and soaking affect the values of M_{RC}. The maximum values of M_{RC} for soaked specimens were only about half of the corresponding values for unsoaked specimens under the same stress intensity. Figure 10 suggests that for the ESM-cement the modulus is related primarily to dry density for given conditions of curing and applied stress. Figure 11 bears out this relationship, indicating that M_{RC} is uniquely related to density without influence of molding water content.

The variation of M_{RC} with molding water content for the VSC-cement specimens is shown in Figure 12. Sharp reductions in moduli values occur at or near optimum water content, and no unique correlation with density appears to exist. The results show further that both soaking and applied stress intensity influence the results.

Figure 13 shows the relationship between water content and unconfined compressive strength for VSC-cement. Essentially, the same pattern as shown in Figure 12 is indicated. Thus for specimens prepared wet of optimum using

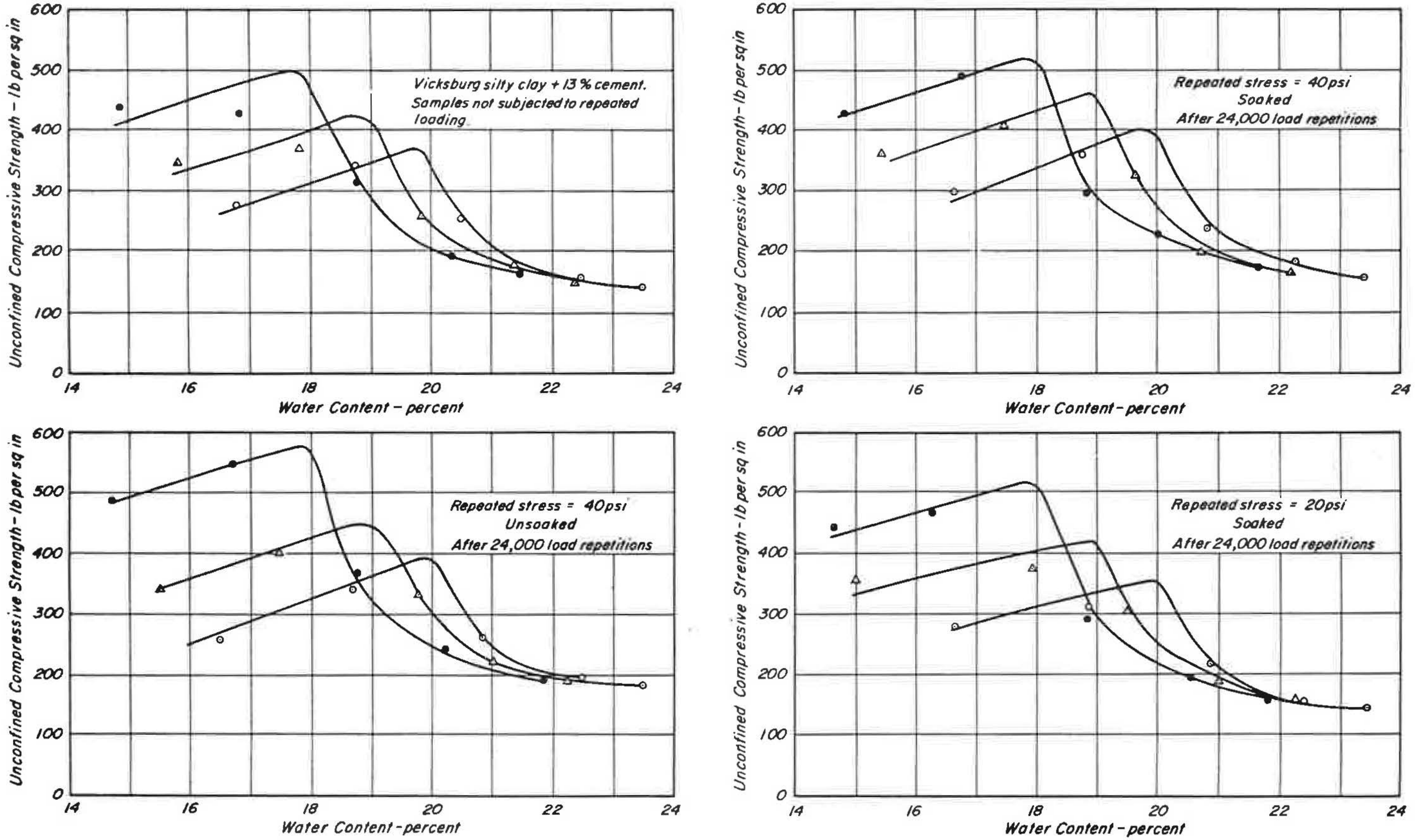

Figure 13. Relationship between water content and unconfined compressive strength for Vicksburg silty clay-cement.

kneading compaction, a higher compactive effort may result in lower modulus and strength. This type of behavior was observed by Seed and Chan (21) for untreated VSC, and could be explained in terms of the more dispersed structure induced at high kneading compactive efforts. It appears that even in the presence of cement, which should tend to flocculate the clay particles before hydration, the silty clay remains structure-sensitive, and density alone cannot be taken as a criterion of behavior.

Further evidence of this structure-sensitivity was obtained by Groves (8), who investigated the effect of method of compaction on the strength of the silty clay-cement. His results showed that samples compacted wet of optimum by static compaction were stronger than those compacted to the same density by kneading compaction. Static compaction does not induce significant shear strain, thus the soil structure retains a flocculent character, whereas kneading compaction disperses and weakens the structure. These effects of compaction method are similar to those reported by Seed and Chan for the untreated silty clay.

Finally, it appears from Figure 13 that 24,000 repetitions of compressive stress had little fatigue effect on the VSC-cement specimens, because the strengths are little different and in some cases greater than those of specimens of the same age not subjected to repeated loading. Similar behavior was observed for the ESM-cement. As previously noted, however, the repeated stress intensities were only of the order of 10 to 40 percent of the ultimate strength.

Contours of equal values of M_{RC} taken at 1,000 load applications are shown in Figures 14 and 15 for VSC-cement and ESM-cement, respectively. In the case of VSC-cement, the modulus of resilient deformation varies with compactive effort, molding water content, and dry density; whereas parallel horizontal contours of M_{RC} for ESM-cement indicate that molding water content and compactive effort have little influence on the values of modulus of resilient deformation, and the higher the compaction density the higher the modulus.

Effect of Stress Intensity. —The studies of moisture content and density effects suggested that M_{RC} varies with the applied repeated loading stress intensity. Tests were conducted to investigate this variation in more detail and to study the effect of the magnitude of the applied repeated loading stress on other properties of soil-cement.

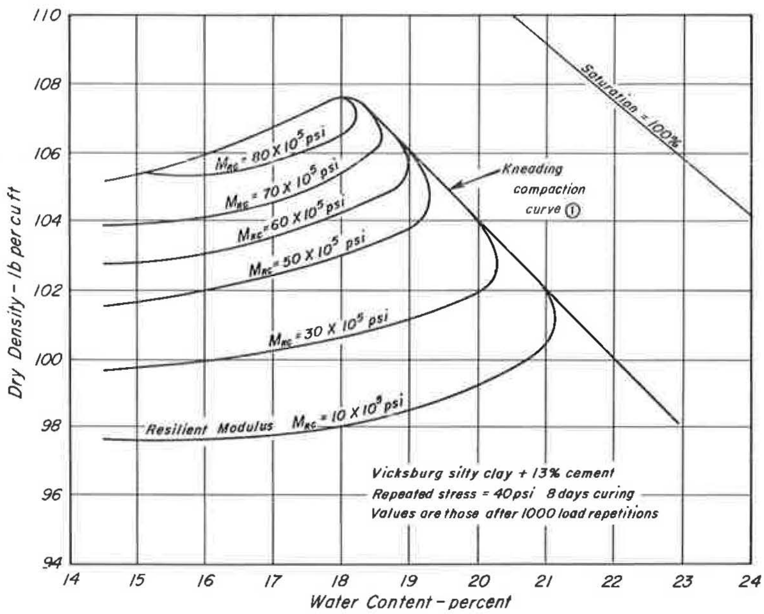

Figure 14. Relationship between dry density, water content and modulus of resilient deformation in compression for Vicksburg silty clay-cement.

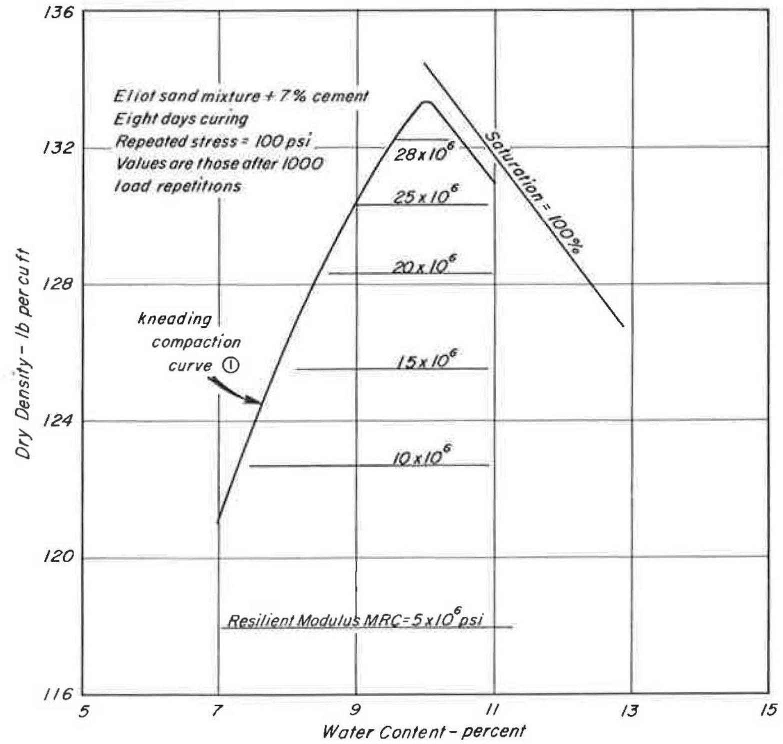

Figure 15. Relationship between dry density, water content and modulus of resilient deformation in compression for Eliot sand mixture-cement.

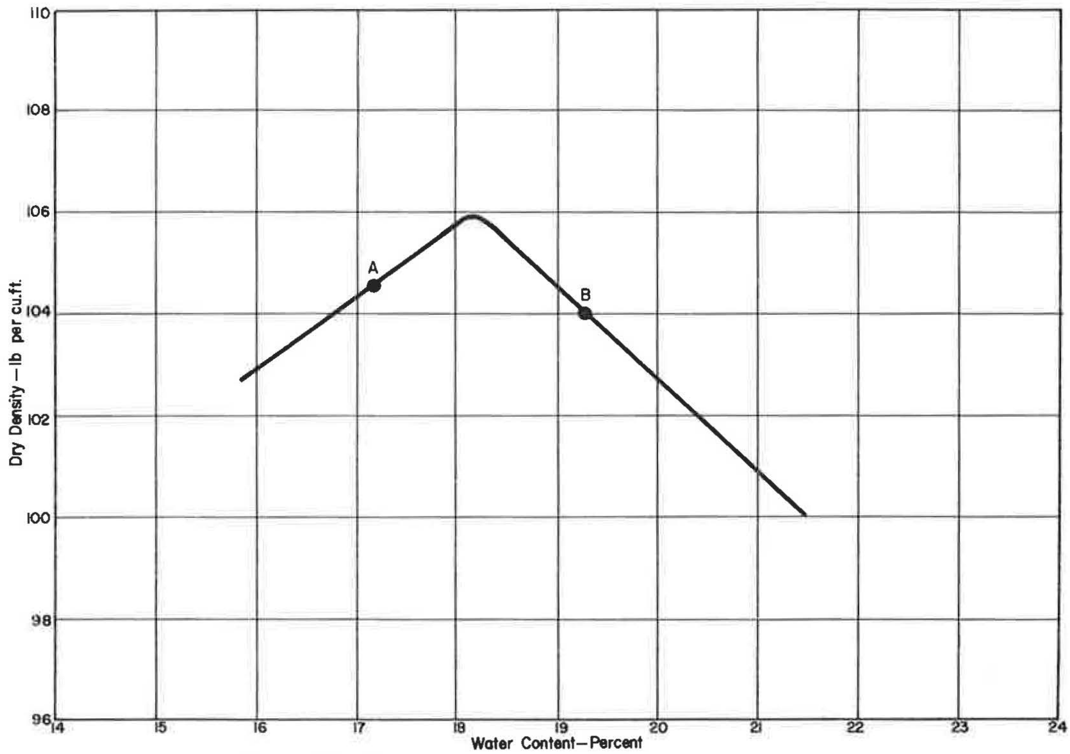

Figure 16. Compaction curve, Vicksburg silty clay-cement.

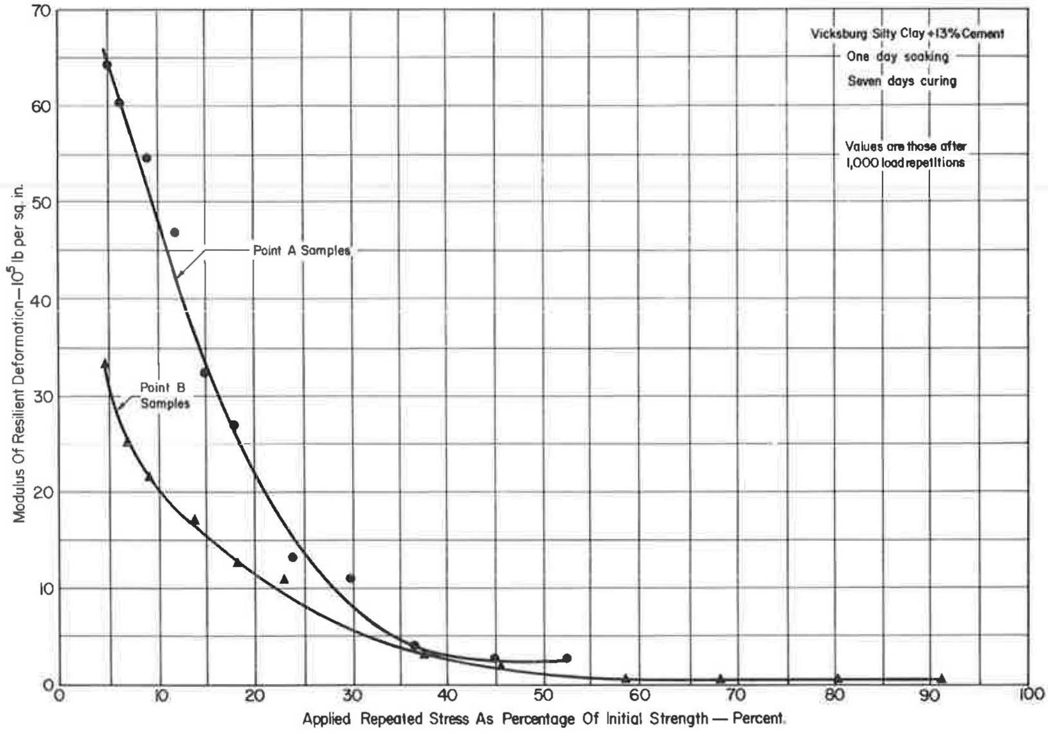

Figure 17. Effect of stress level on resilient modulus in compression for Vicksburg silty clay-cement.

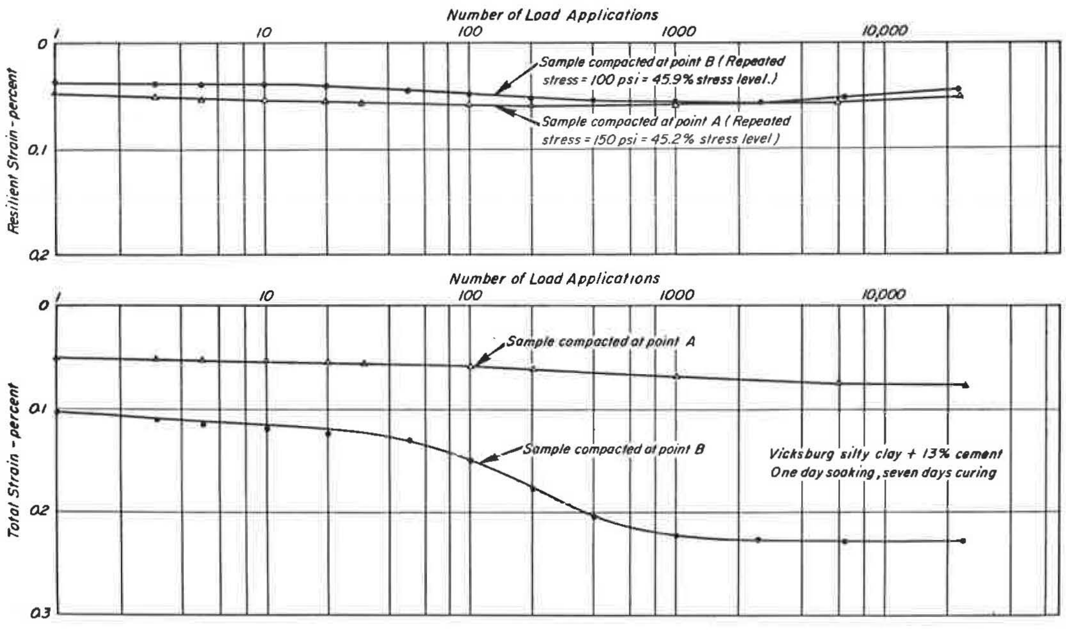

Figure 18. Resilient and total strains vs number of load applications curves in repeated compression for Vicksburg silty clay-cement.

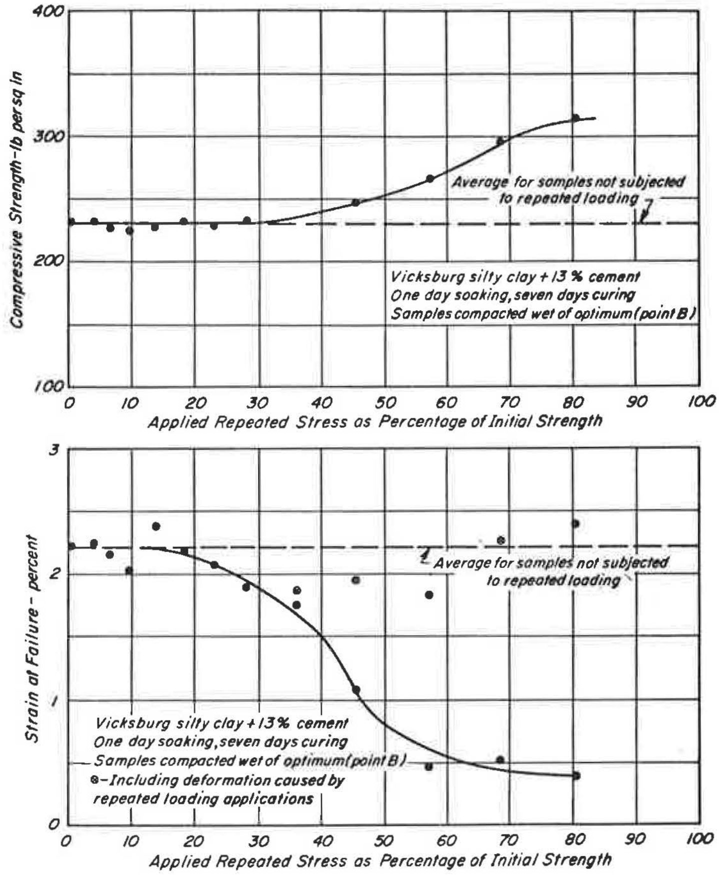

Figure 19. Effect of repeated stress intensity on properties of Vicksburg silty clay-cement in compression.

VSC-cement samples were compacted at two water contents (Fig. 16). Point A samples were compacted dry of optimum water content, whereas samples at point B were at the same dry density wet of optimum. Only soaked samples were used for this study.

The variation of the modulus of resilient deformation with applied stress intensity is shown in Figure 17. For each curve the resilient modulus, determined at N = 1,000, varies greatly at low stress intensities; the smaller the applied stress intensity, the higher the modulus. For stress intensities greater than about 40 percent of the initial strength, however, M_{RC} remains almost constant.

No fatigue failures were observed in point A samples, which were subjected to applied repeated loading stress intensities up to about 53 percent of the initial strength. One sample at point B, however, when subjected to 200-psi repeated loading stress intensity (corresponding to 92% of the initial strength) failed after 188 load applications.

A comparison was made of a dry-side sample VSD 37, at a water content of 17.5 percent, and a wet-side sample VSWC 6, at a water content of 19.1 percent, both subjected to repeated loading stress intensities of about 45 percent of their individual initial strengths (150 psi for VSD 37 and 100 psi for VSWC 6). In this case the resilient strains of the two samples were essentially the same (Fig. 18). The modulus of resilient deformation of the dry-side sample, however, was about 1.5 times greater than that of the wet-side sample because the applied repeated loading stress intensities were in that ratio; and conversely, the total strain of the former was less than one-half that of the latter.

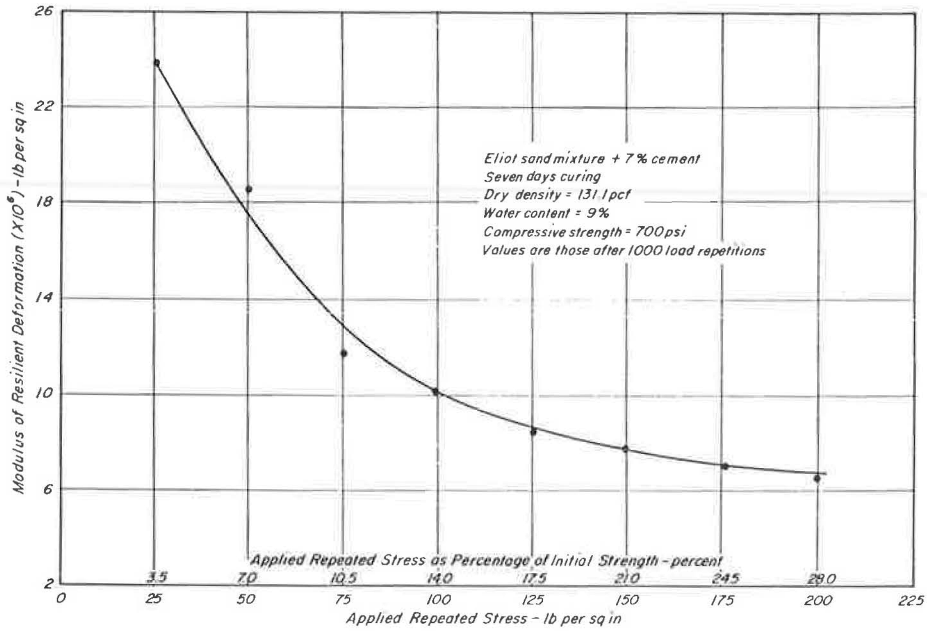

Figure 20. Effect of stress intensity on resilience characteristics in repeated compression tests for Eliot sand mixture-cement.

For point A samples, with repeated loading compressive stresses up to about 53 percent of the initial strength, no significant change of mechanical properties was noticed at the end of 24,000 repetitions. Point B samples, however, when subjected to repeated loading stresses of 50 percent or more of their initial strengths became stronger and stiffer, as indicated by the unconfined compressive strength and strain at failure values shown in Figure 19. If the amount of axial strain which occurred during repeated loading applications was included in the calculations, all samples when compacted under the same condition would tend to fail at about the same strain whether or not previously subjected to repeated loading. The strengthening effect at high repeated stress intensities may have resulted from densification during the test.

Figure 20 shows the variation of modulus of resilient deformation after 1,000 repetitions with respect to the magnitude of applied repeated loading stress for ESM-cement. Within the range of the repeated loading stresses applied, M_{RC} decreased as the magnitude of the applied repeated loading stress increased. No fatigue failures were observed. Measurements using higher repeated loading stress intensities would have been desirable; such measurements could not be made, however, because of the limited capacity of the repeated loading apparatus.

Effect of Number of Load Repetitions. —Identical samples of VSC-cement were compacted wet of optimum at a water content of 19.2 percent and a dry density of 105.5 pcf. All samples were cured for 7 days and soaked for 24 hr before testing. The average initial strength of these samples was about 260 psi. Specimens were subjected to a repeated loading stress of 170 psi, which corresponded to about 65 percent of the initial strength, for 1,000, 5,000, 10,000, 50,000, and 100,000 applications. After being subjected to the designated number of applications, the samples were tested to failure in unconfined compression tests.

Figure 21 shows the variation of resilient and total deformations with the number of load applications for each sample. The maximum resilient deformation occurred between about 1 and 500 load applications. The value of resilient strain at N = 100,000 was only about one-fifth to one-fourth of the maximum value. Figure 22 shows the

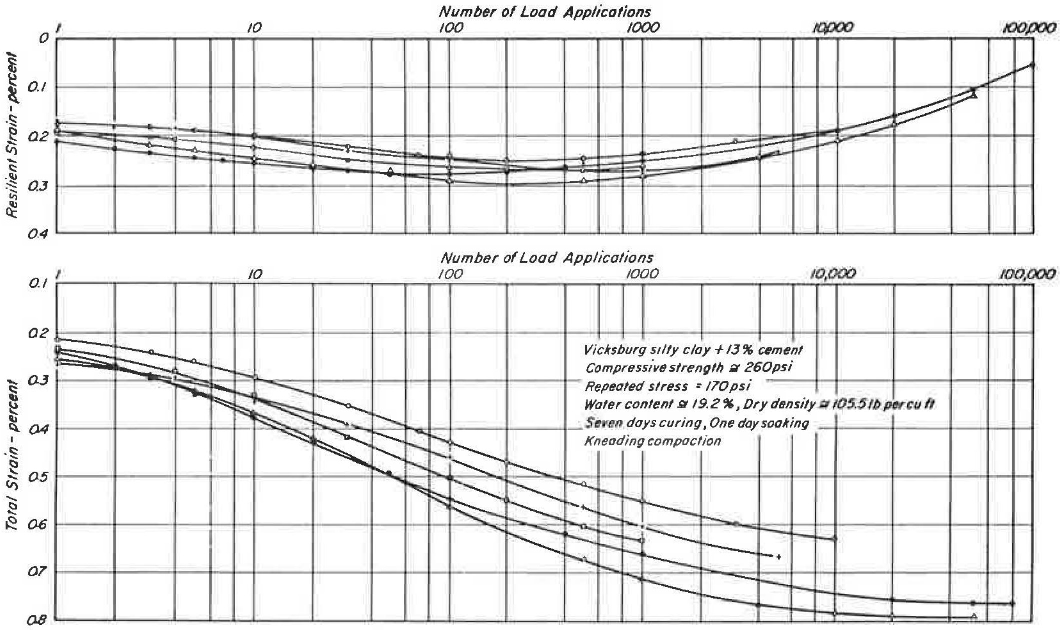

Figure 21. Relationship between deformation and number of load applications for Vicksburg silty clay-cement samples in repeated compression tests.

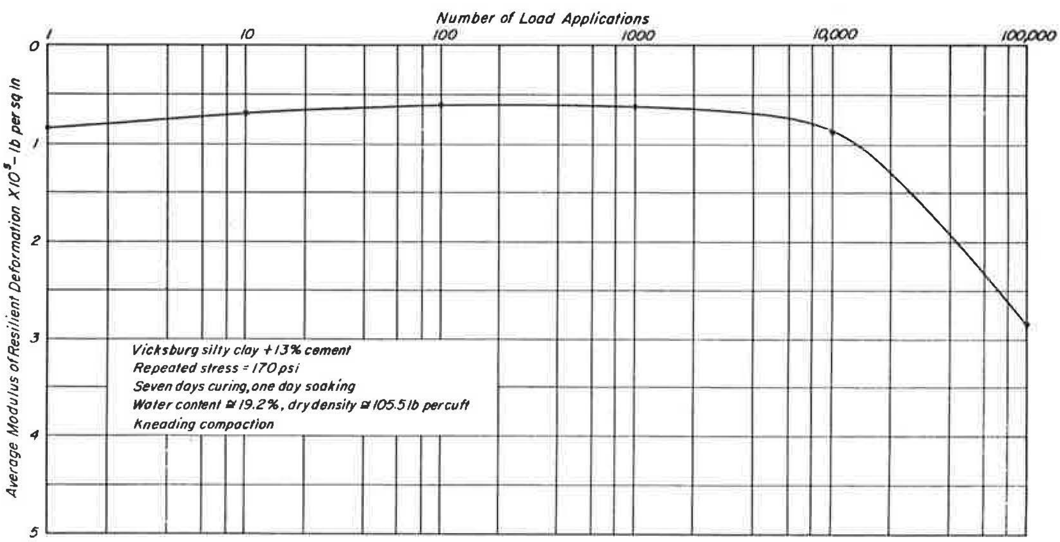

Figure 22. Average modulus of resilient deformation vs number of load applications for Vicksburg silty clay-cement samples in compression.

variation of the average resilient modulus for all samples with the number of load applications. The results also indicated that within the range of the number of repetitions studied, the greater the number of load applications, the greater the increase in unconfined compressive strength in relation to dummy samples of the same age.

The ESM-cement samples were studied in the same way as the VSC-cement samples. The initial strength of samples was about 700 psi with a dry density of 131.5 pcf and a water content of 9.1 percent. A repeated loading stress intensity of 100 psi was used. There was no significant change in values of resilient strain with respect to the numbers of the load applications at this relatively low stress intensity. An increase of 5 to 10 percent, however, was attained in unconfined compressive strength as a result of repeated loading.

Influence of Time of Curing. —Some of the early test results for silty clay-cement showed that the properties of samples subjected to high repeated loading stress intensities varied greatly with the number of load applications. A series of tests was carried out to determine whether this behavior was true for samples of all ages or only for samples cured for short periods. Samples were compacted at a water content of 20.2 percent and a dry density of 102 pcf, and cured for 1, 3, 5, 14, 29, 49, and 70 days. Samples were soaked for a period of 24 hr before testing. Repeated loading stresses of 60 percent of the respective initial strengths at each age were used, and the samples were subjected to 24,000 load applications. Initial strength values of samples of different ages are shown in Figure 23.

Figure 24 shows the variation of resilient and total strains with the number of load applications for samples of different ages. The resilient strains increased to a maximum in all samples at different numbers of load applications, and as the number of load applications increased, the resilient strain decreased. The occurrence of the maximum resilient strain value depended on the age of the sample at the start of the test. The younger the sample, the smaller was the number of load applications required to reach this point (Fig. 25). This behavior reflects the composite effects of the structural breakdown caused by the repeated stress applications and the greater strengths associated with longer curing periods. Figure 26 shows the minimum value of resilient modulus with respect to time of curing, indicating that the minimum modulus of resilient deformation of the sample cured for 70 days was about nine times as high as that of the sample cured for 1 day. Thus it can be concluded that the duration of curing period can have a significant influence on the modulus of resilient deformation in compression.

The change in strength as a result of repeated loading is shown in Figure 27. The strengths of the samples cured for 7 weeks or more were not affected by repeated loading applications at a stress level of 60 percent. In would appear, however, that

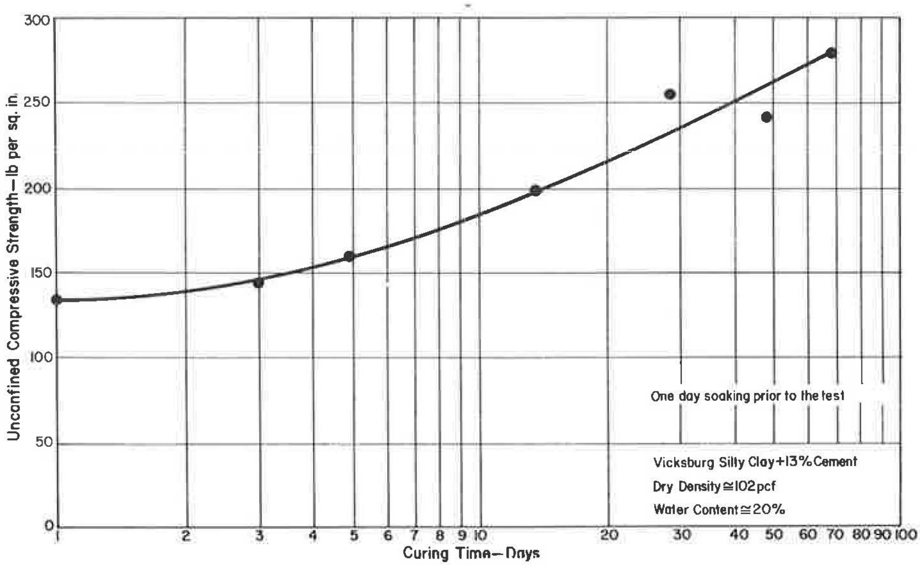

Figure 23. Relationship between curing time and unconfined compressive strength for Vicksburg silty clay-cement.

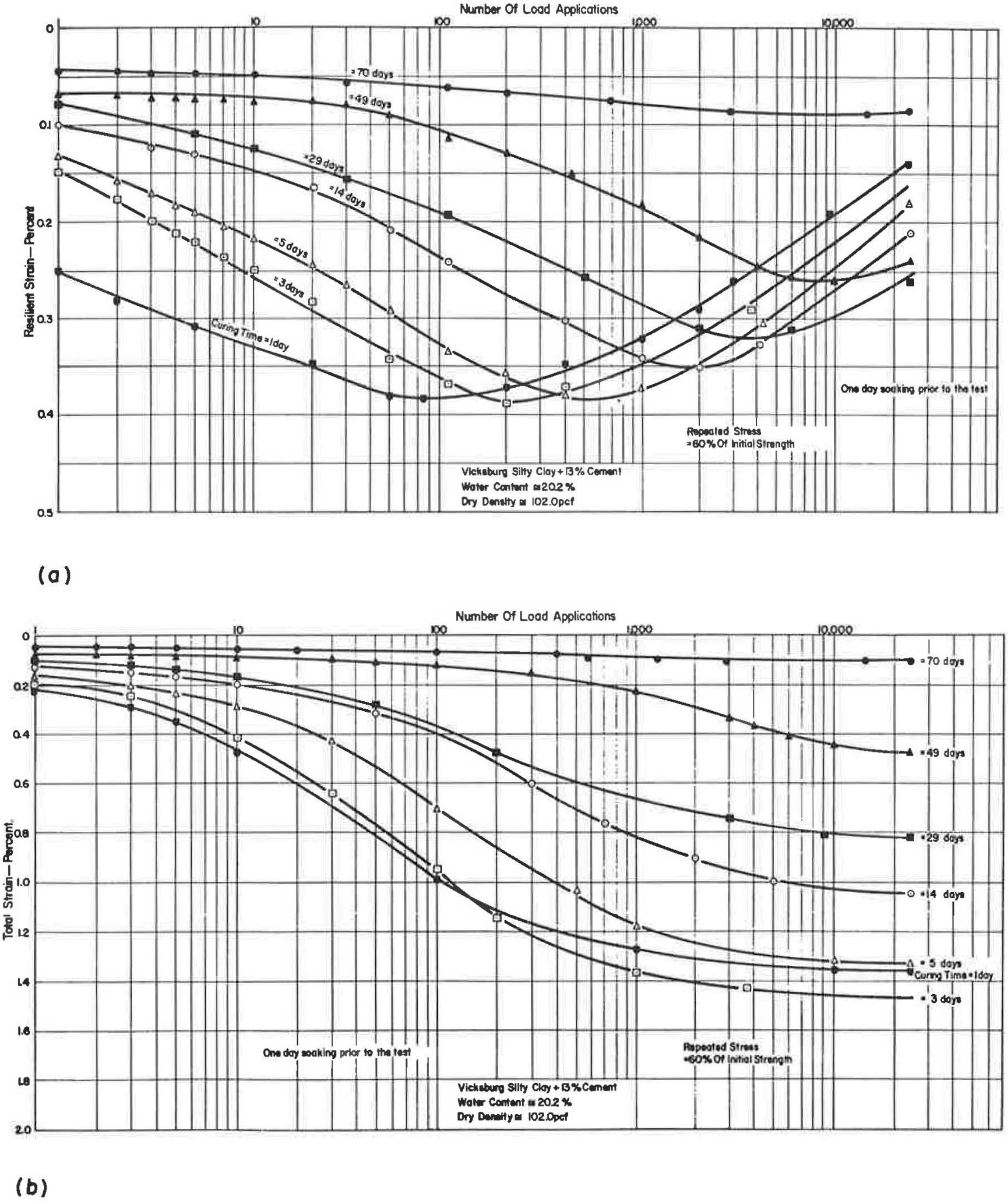

Figure 24. Effect of curing time on (a) resilient deformation of Vicksburg silty clay-cement in compression and (b) total deformation of Vicksburg silty clay-cement in compression.

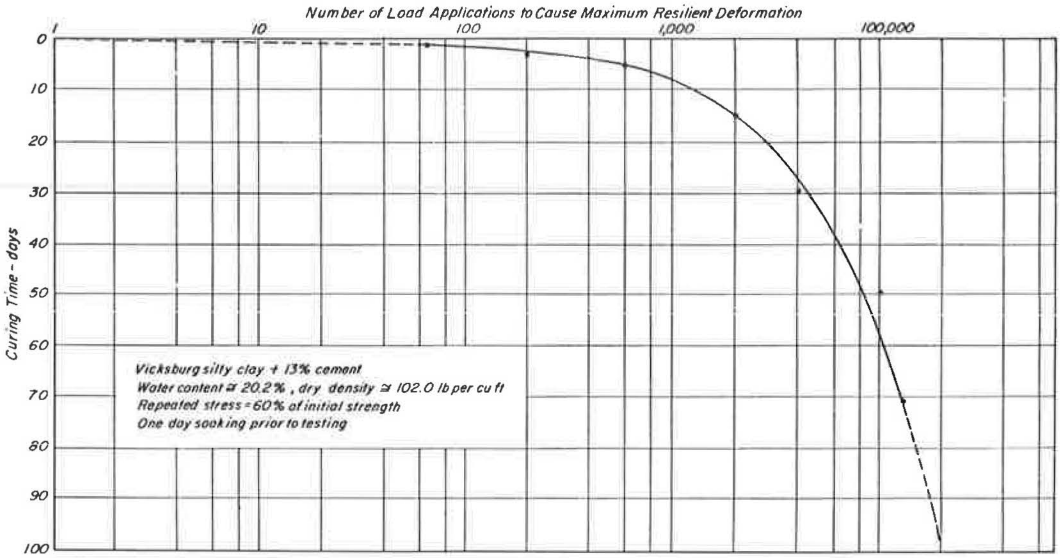

Figure 25. Effect of curing period on number of load applications to cause maximum resilient deformation in compression for Vicksburg silty clay-cement.

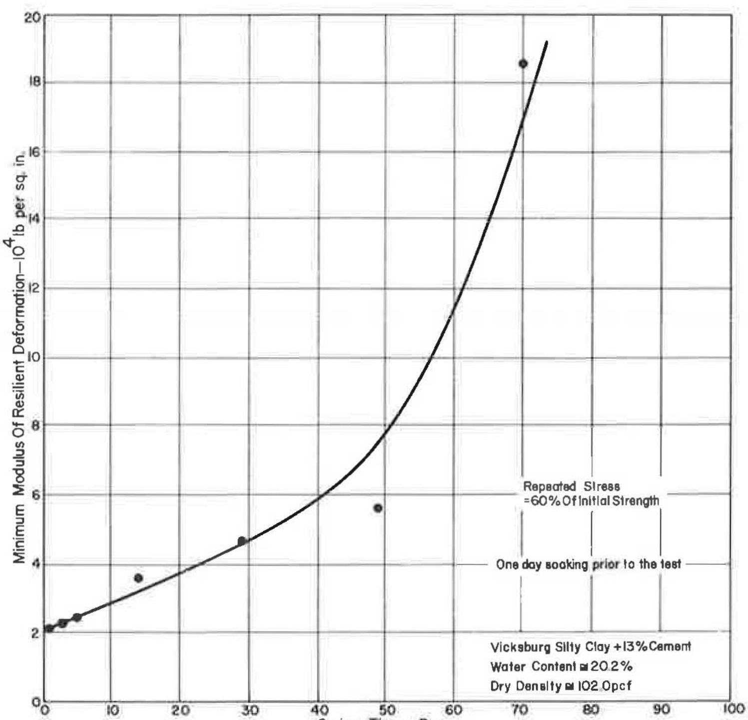

Figure 26. Minimum modulus of resilient deformation in compression as a function of curing time for Vicksburg silty clay-cement.

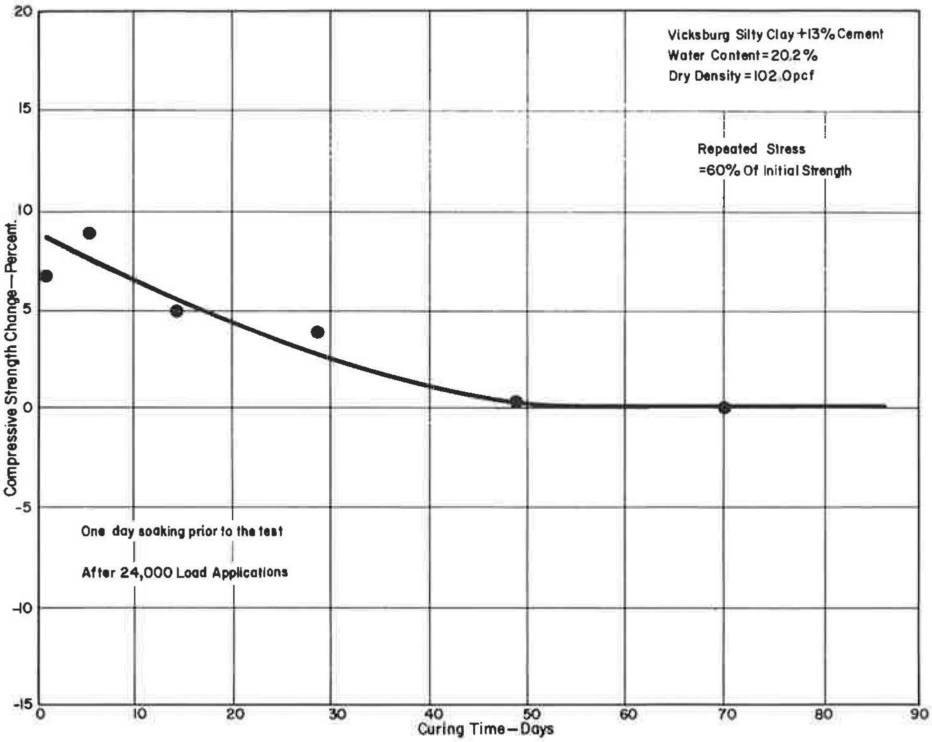

Figure 27. Change in strength caused by repeated loading as a function of curing time for Vicksburg silty clay-cement.

repeated loading in compression tends to strengthen samples cured less than 7 weeks. This is probably because at earlier ages the specimens are still sufficiently deformable that the repeated stresses can cause further densification and decreases of particle spacing at contact points.

Repeated Load Flexure Tests

Effect of Density and Moisture Content. —For each soil-cement, ten samples were compacted at five different water contents along the compaction curves shown in Figure 28. Samples were cured for 8 days after compaction and were not soaked before testing. Repeated loads were applied so as to give a tensile stress of 20 psi in VSC-cement samples and 50 psi in ESM-cement samples. All tests were carried to 24,000 applications. Very little variation of resilient modulus in flexure (ϵ_{RF}) was observed throughout the test period. The effect of repeated loading on the flexural properties of beam samples was minor (Figs. 29 and 30). A typical maximum deflection vs load curve for a sample of silty clay-cement from a conventional flexural test is shown in Figure 31. A straightline relationship up to the failure point is observed, thus making possible the application of elastic beam theory.

Effect of Repeated Stress Intensity. —VSC-cement samples were compacted at a water content of 18 percent and a dry density of 106.8 pcf. Repeated tensile stresses of 10, 30, 50, 75, 100, 120, and 135 psi were applied. One sample failed in fatigue after 600 load applications of a repeated loading stress intensity of about 90 percent of the initial modulus of rupture. Otherwise, the flexural properties of the beam samples were not affected by the high stress intensity repeated loading applications. Figure 32 shows the variation of resilient flexural strain, ϵ_{RF} at N = 1,000, with different applied repeated tensile stress intensities. This straightline relationship indicates that the

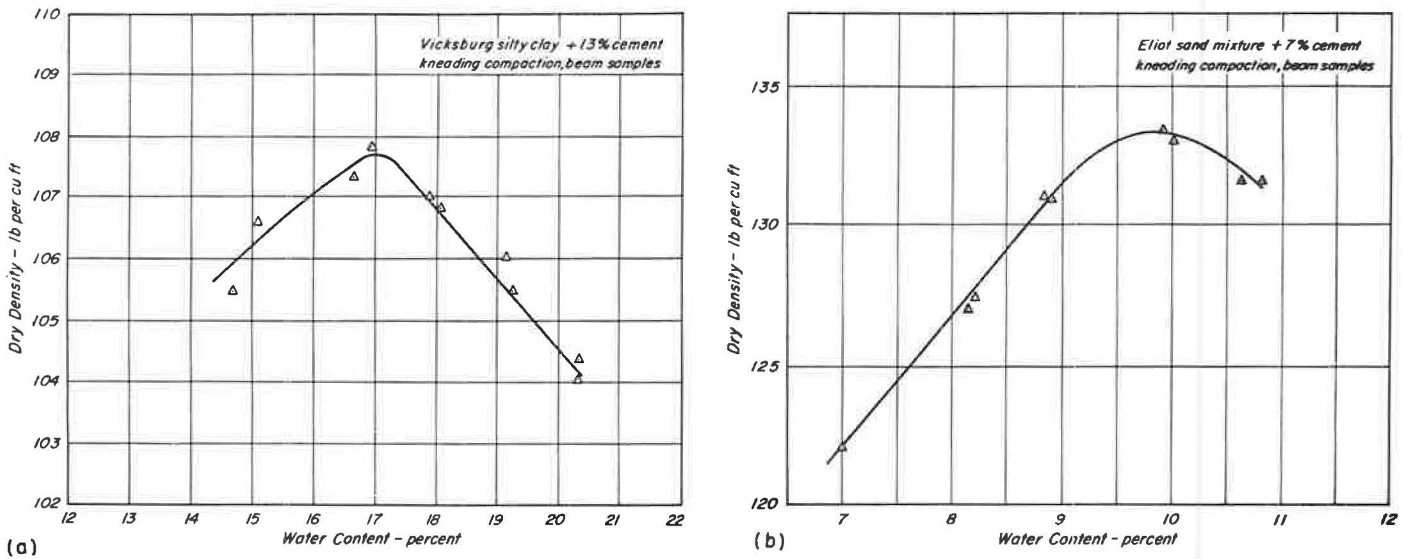

Figure 28. Compaction curves for (a) Vicksburg silty clay-cement beam samples; (b) Eliot sand mixture-cement beam samples.

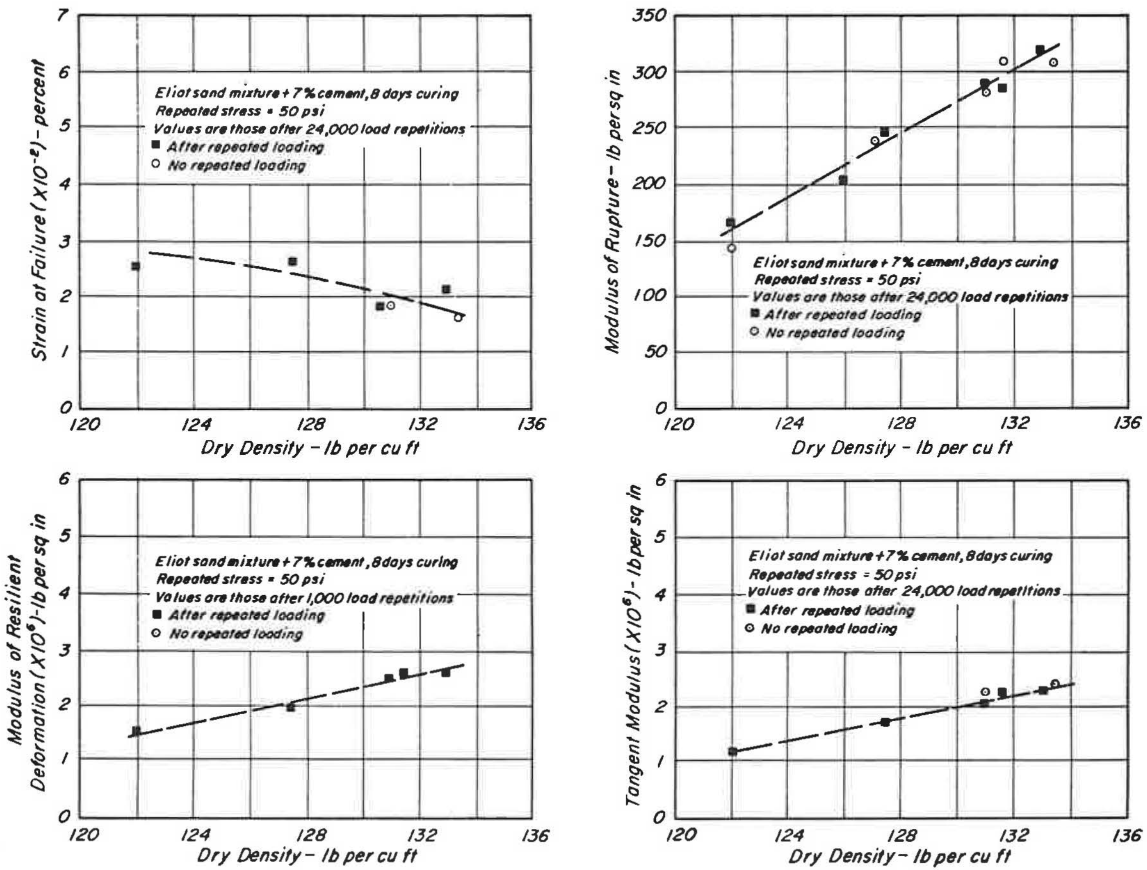

Figure 29. Effect of repeated flexural stress on the properties of Eliot sand mixture-cement.

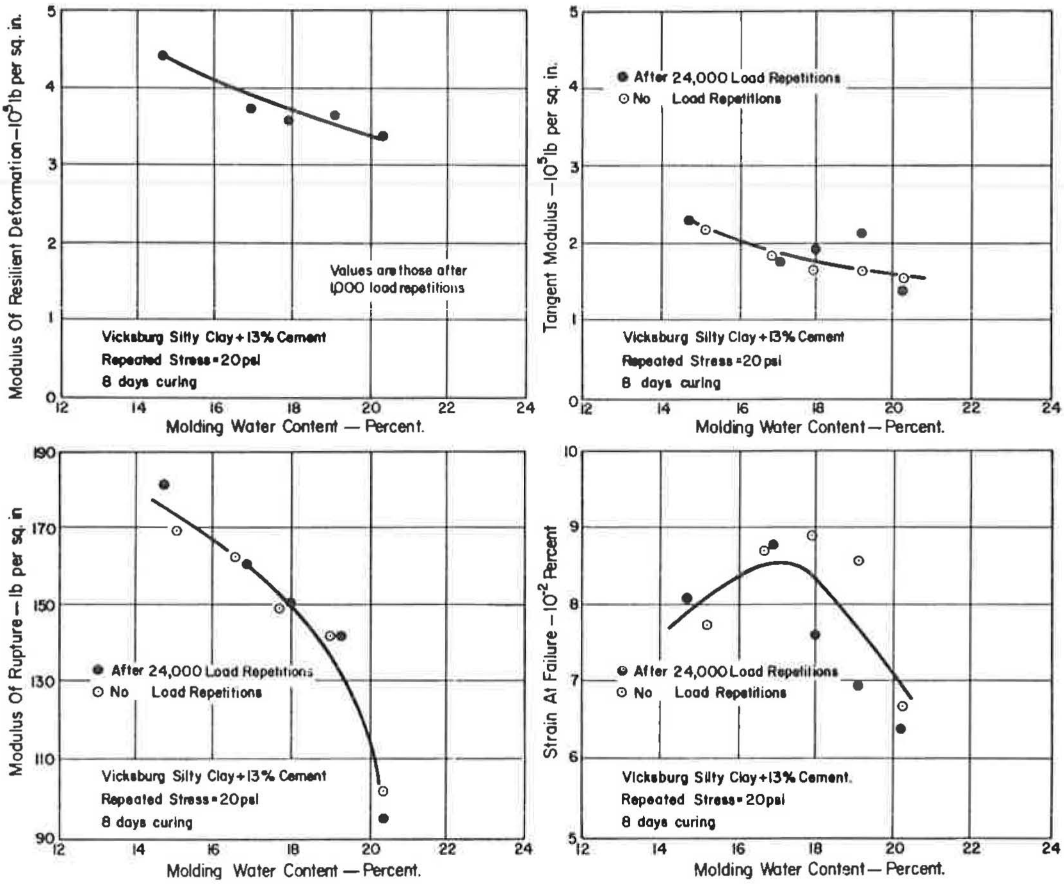

Figure 30. Effect of repeated flexural stress on the properties of Vicksburg silty clay-cement.

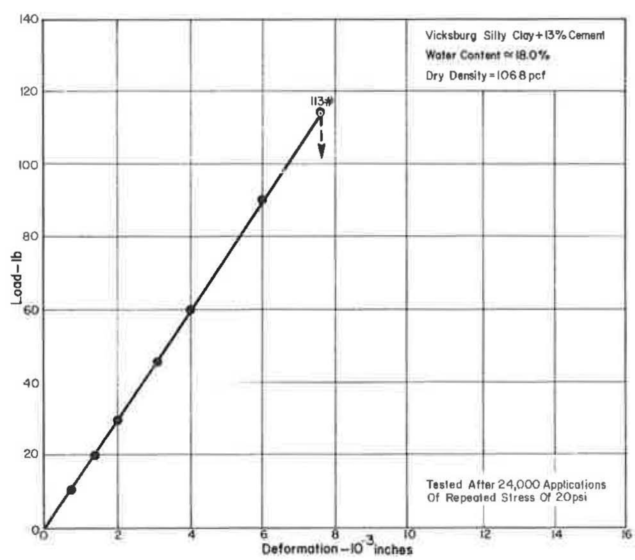

Figure 31. Load-deformation curve for Vicksburg silty clay-cement in flexure.

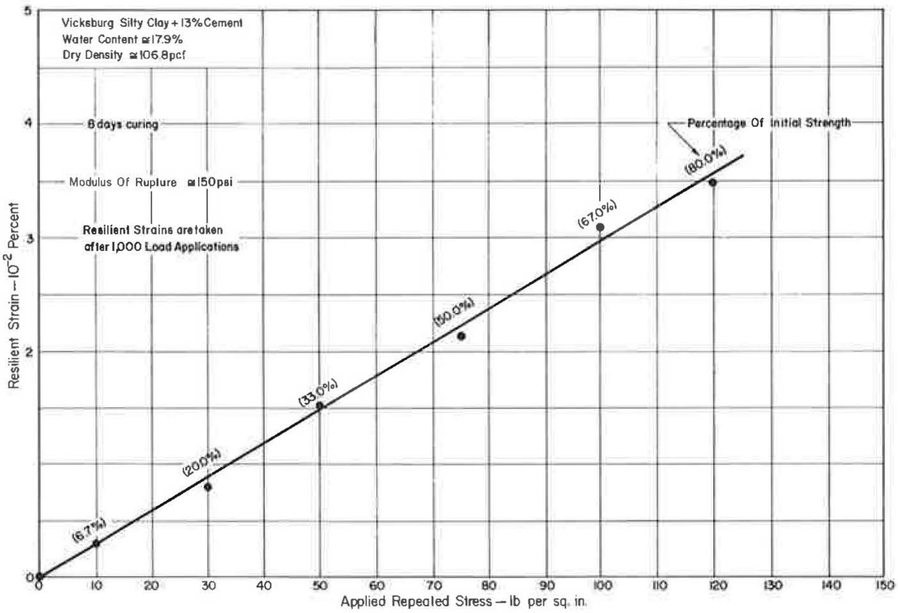

Figure 32. Effect of stress intensity on resilient deformation of Vicksburg silty clay-cement.

modulus of resilient deformation in flexure is independent of the magnitude of applied repeated stress.

ESM-cement samples were compacted at a water content of 9.1 percent and a dry density of 132.0 pcf. Repeated flexural tensile stresses of 15, 30, 70, 100, 125, 150, 200, and 225 psi were applied. Different magnitudes of repeated loading stresses had no significant influence on properties. One sample failed during the course of repeated loading under a stress of 225 psi, which corresponded to about 75 percent of the initial modulus of rupture of the sample.

Variations in number of load applications up to 100,000 had little effect on the properties of VSC-cement and ESM-cement subjected to repeated stress intensities of 20 and 50 psi, respectively.

COMPARISON OF BEHAVIOR IN COMPRESSION AND IN FLEXURE

In the analysis of pavement structures, it is important to ascertain whether properties such as resilient modulus and strength are the same in tension and compression. A comparison of these properties under the two types of loading may be made using the test results obtained in this investigation.

Vicksburg Silty Clay-Cement

1. The modulus of resilient deformation in compression varies greatly with compaction conditions, applied stress intensity, curing period, and number of load applications at high intensities, thus indicating that the stress-strain relationship of cylindrical samples under loading is not linear. Similar results were found by Seed et al. (23) for compacted clay samples. In flexure tests, however, the modulus of resilient deformation varies little with compaction conditions and is almost invariant with both the applied stress intensity and the number of load applications up to 100,000.

Figure 33a shows values of modulus of resilient deformation with respect to molding water content both in compression and in flexure. The modulus of a dry-side sample in compression could be as much as 30 times that in flexure. This difference decreases as the molding water content increases. Essentially the same values of modulus are recorded for both types of tests at a molding water content of 20 percent or more.

2. Figure 33b compares the tangent modulus as determined by static compression and flexure tests. In this case, greater values were observed in flexure tests.

3. In flexure tests, the values of the modulus of resilient deformation are about two times greater than the tangent modulus values. On the other hand, values of the tangent modulus in compression tests are only about 2 to 10 percent of the modulus of resilient deformation. These differences are believed to be caused by the fact that the stress-strain curve obtained from a static test, which is the basis for the static modulus calculation, includes the effects of both elastic and plastic strains. The time of loading in the repeated loading tests is so short that little opportunity is provided for plastic deformation to develop. The greater variation between resilient and static values in compression tests than in flexural tests probably reflects the fact that the specimens were much more brittle in flexure.

4. Fatigue failure occurred in both types of tests at a repeated loading stress intensity of about 90 percent of the initial strengths.

5. The values of the modulus of rupture in flexure tests ranged from one-fourth to one-half of the strength in unconfined compression tests (Fig. 34a). This result agrees with the values in HRB Bulletin 292 (9).

6. The strains at failure in flexure tests range from 3 to 14 percent of the values for compression tests. The largest difference appears wet of optimum water content (Fig. 34b). A very low strain at failure in flexure may be one of the important factors governing the failure of soil-cement layers in pavement structure.

Eliot Sand Mixture-Cement

1. Moduli of resilient deformation in both compression and flexure increase significantly with dry density. Figure 35a shows that the modulus of resilient deformation in compression is about 4 to 10 times greater than in flexure.

2. Figure 35b shows a comparison of the tangent modulus from both types of static tests. Values in flexure are about 10 times greater than those in compression.

3. In flexure the values of the modulus of resilient deformation are about equal to the values of the tangent modulus. In compression, however, values of the modulus of resilient deformation are 10 to 100 times greater than the values of the tangent modulus.

4. The values of modulus of rupture in flexure range from one-third to one-half of the strength in unconfined compression (Fig. 36a).

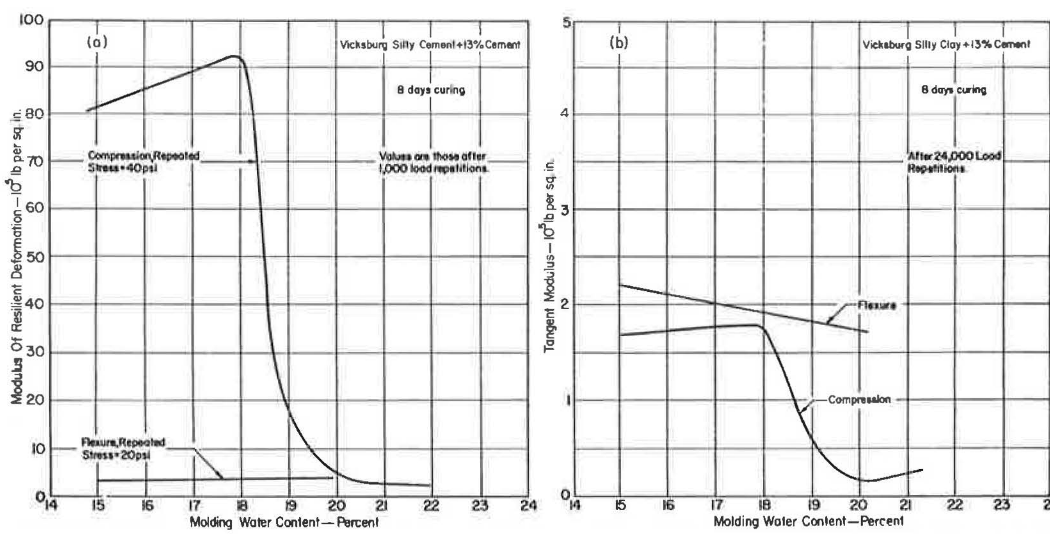

Figure 33. Comparison of the properties of Vicksburg silty clay-cement samples in compression and flexure.

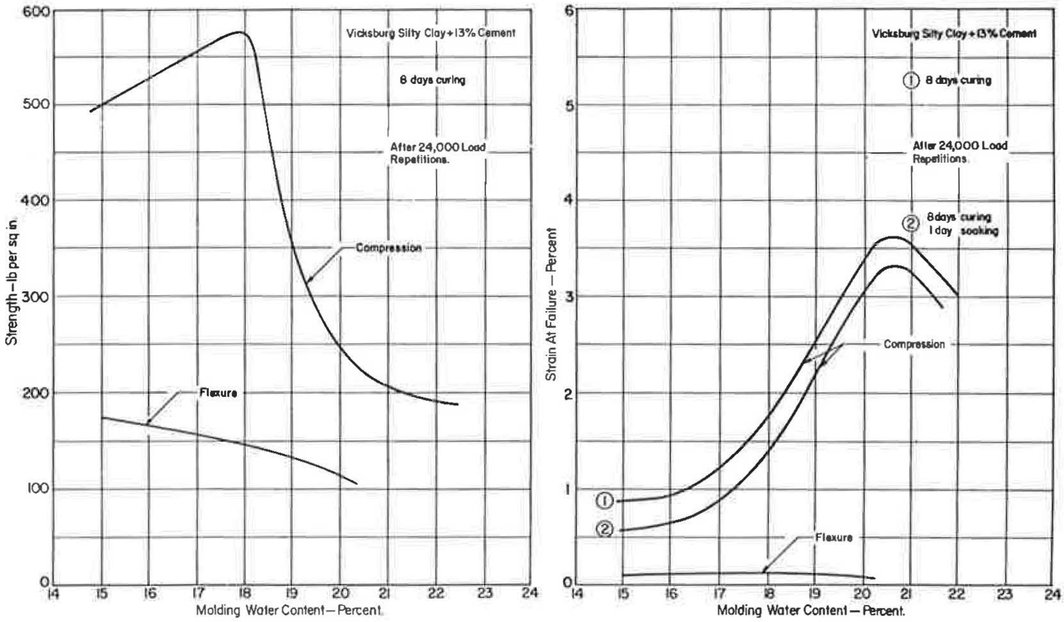

Figure 34. Comparison of the properties of Vicksburg silty clay-cement samples in compression and flexure.

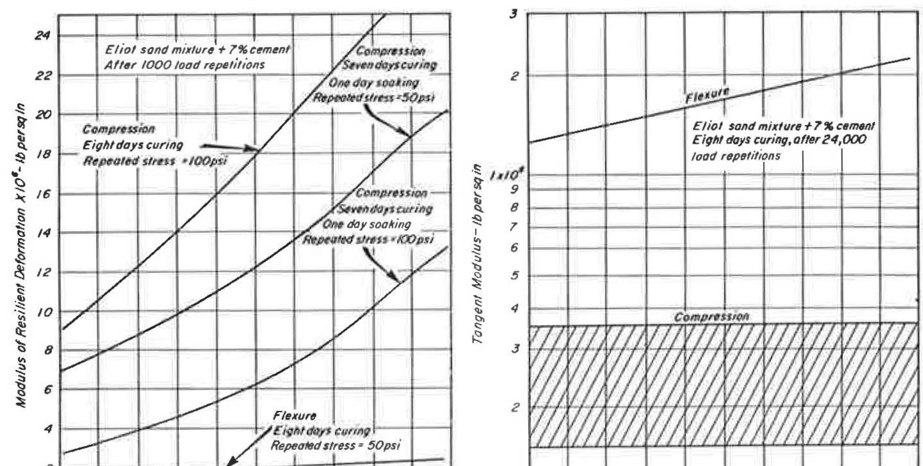

Figure 35. Comparison of the properties of Eliot sand mixture-cement samples in compression and flexure.

5. The strain at failure in flexure is only 5 percent that of the values in compression (Fig. 36b).

Table 2 summarizes the ranges of the foregoing values. Table 3 summarizes a few of the most significant differences in the behavior of soil-cement samples subjected to

TABLE 2

EXPERIMENTAL VALUES OF THE ELASTIC AND STRENGTH PROPERTIES OF SOIL-CEMENT

Material	Type of Loading	Water Content (%)	Dry Density (pcf)	Strength[a] (psi)	Resilient Modulus (psi)	Static Modulus (psi)	Strain at Failure (%)	Remarks
VSC-cement	Compression	14.5 ↓ 22	–	570 ↓ 200	90×10^5 ↓ 2×10^5	1.8×10^5 ↓ 0.2×10^5	0.8 ↓ 3.5	M_{RC} varies with compaction conditions, curing period, N, and applied stress. Fatigue failure occurred at R. L. stress level of 90 percent. Kneading compaction causes dispersed soil structure on wet side of optimum.
	Flexure	15 ↓ 22	–	175 ↓ 100	4.4×10^5 ↓ 3.4×10^5	2.3×10^5 ↓ 1.7×10^5	0.09 ↓ 0.07	M_{RF} varies little with compaction conditions. No variation with N and applied stress. Fatigue failure occurred at R. L. stress level of 90 percent.
ESM-cement	Compression	7 ↓ 12	122 ↓ 132	400 ↓ 750	8×10^6 ↓ 24×10^6	1.5×10^5 ↓ 3.0×10^5	0.38 ↓ 0.46	M_{RC} varies with γ_d, N, applied stress, and treatment condition.
	Flexure	7 ↓ 11	122 ↓ 132	160 ↓ 320	1.5×10^6 ↓ 2.7×10^6	1.2×10^6 ↓ 2.4×10^6	0.03 ↓ 0.02	M_{RF} varies with γ_d, no variation with N and applied stress. Fatigue failure occurred at R. L. stress level of 75 percent.

[a]Compressive strength or modulus or rupture.

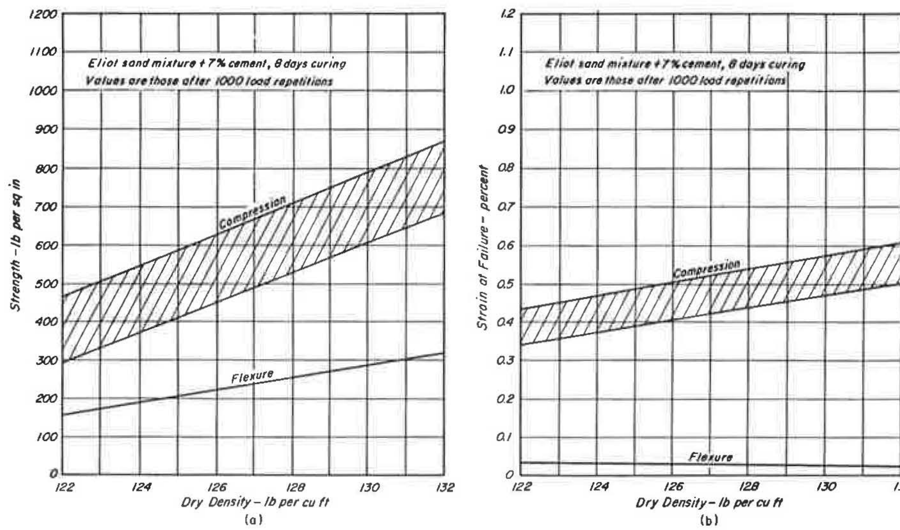

Figure 36. Comparison of the properties of Eliot sand mixture-cement samples in compression and in flexure.

TABLE 3

DIFFERENCES IN THE BEHAVIOR OF SOIL-CEMENT SUBJECTED TO REPEATED STRESSES IN COMPRESSION AND FLEXURE

Behavior	Compression	Flexure
Modulus of resilient deformation	High (varies with applied stress intensity)	Low (independent of applied stress intensity)
Fatigue failure occurred at about	90 percent R. L. stress level (VSC-cement)	90 percent R. L. stress level (VSC-cement) 75 percent R. L. stress level (ESM-cement)
Strain at failure	High	Low
Effect of repeated loading on properties	Large	Small

repeated compressive and flexural stresses as derived from this study. These results clearly indicate that consideration must be given to the type of loading when selecting values of soil-cement properties for use in analysis.

CONCLUSIONS

This study has been concerned with the investigation of the dynamic properties, the resilience characteristics, and the fatigue behavior of two types of soil-cement (a silty clay and a sand) under the action of both repeated compressive and flexural stresses. Major conclusions from this study may be summarized as follows.

1. Under constant repeated stress, the modulus of resilient deformation in both compression and flexure at a given number of load applications is directly related to dry density for ESM-cement samples. The higher the dry density, the greater is the modulus. In the case of VSC-cement, the modulus of resilient deformation in flexure of beam samples decreases as molding water content increases. For cylindrical

samples the resilient modulus in compression is greatly influenced by dry density, molding water content, and compactive effort. This is due to the structure-sensitive character of specimens compacted wet of optimum moisture content. In both materials, the ranges of modulus variation are greater in compression than in flexure.

2. The modulus of resilient deformation of soil-cement in repeated compression is greatly affected by the magnitude of the stress intensity. The resilient modulus decreases rapidly with increasing applied stress intensity at low stress levels. There is, however, only very little change in resilient modulus with change in stress at applied stress intensities greater than 30 to 40 percent of the initial strength of the sample.

The unconfined compressive strengths of the ESM-cement samples are increased by about 10 percent of their initial values after being subjected to 24,000 low stress intensity repeated loadings (stress intensity of 15 percent of the strength). In VSC-cement, however, increase of strength was only noticed in the samples subjected to higher stress intensities (up to 80 percent of the strength). An increase in strength of 8 to 35 percent was recorded at these stress levels.

The relationships between resilient modulus and applied stress intensity and the relationship between strength variation and applied stress intensity in repeated flexure tests do not parallel those in compression tests. In flexure tests both the resilient modulus and the strength are virtually unaffected by the magnitude of the applied repeated stress intensity.

3. Results from the repeated flexure tests have indicated that the resilient deformation remains almost unchanged with respect to number of load applications, even at applied stress intensities very close to the limiting value which causes fatigue failure. Results from the repeated compression tests have shown that only at applied stress levels of less than about 30 to 40 percent of the initial strength is the magnitude of resilient deformation not affected by the number of load applications. At higher applied stress intensities, resilient deformations vary with the number of load applications, with the maximum values occurring between about 1 and 500 load applications. The resilient deformation at $N = 100,000$ may be only about one-fifth to one-fourth of the maximum value.

4. The longer the curing period before the start of repeated compression, the greater the minimum resilient modulus for a repeated loading stress equal to a given percentage of the initial strength.

5. Soaked samples yield smaller values of resilient modulus than unsoaked samples when subjected to the same magnitude of repeated loading stress.

6. The values of modulus of resilient deformation are several times greater in compression than in flexure, except in VSC-cement samples compacted wet of optimum where essentially the same values of modulus are recorded in both types of tests.

7. The values of modulus of rupture range from one-fourth to one-half of the values of unconfined compressive strength.

8. The strain at failure in flexure is only about 5 to 15 percent of that in compression.

9. The tangent modulus as determined by static tests is greater in flexure than in compression. In ESM-cement, the difference is as much as 10 times.

10. The minimum stress intensity required to cause fatigue failure in VSC-cement samples is about 90 percent of the strength of the sample both in compression and in flexure, whereas in ESM-cement samples the minimum stress intensity is around 75 percent of the strength in flexure. No fatigue failures developed in cylindrical ESM-cement samples, because of the limited capacity of the repeated loading piston and the high strength of the ESM-cement.

The results of this study provide information that can be used in the analysis of pavement structures containing soil-cement layers. It is believed that the repeated loading test may provide a realistic means of assessing soil-cement properties in the laboratory for predicting field behavior under repetitive traffic loads. Inasmuch as the results indicate that values for moduli may be considerably different when evaluated under static loading rather than repeated loading conditions, it is particularly important that consideration be given to the type of test for selection of property values.

Furthermore, consideration must be given to the fact that properties in compression and flexure differ.

Finally, it should be emphasized that all results are for samples prepared and tested in the laboratory. Field tests are needed to verify many of the findings, and careful consideration must be given to the effects of shrinkage and temperature cracking that might develop in the field, but which did not affect the laboratory specimens.

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