# Soil Deformations in Normal Compression And Repeated Loading Tests

H. B. SEED, Associate Professor of Civil Engineering, and
ROBERT L. McNEILL, Graduate Research Engineer II
Institute of Transportation and Traffic Engineering
University of California, Berkeley

This paper presents data comparing the deformation characteristics in repeated load tests of specimens of two soils having similar stress-strain relationships in normal compression tests. The tests were performed on a silty clay from Vicksburg, Mississippi, and a clayey silt from the subgrade of the Idaho test road. Specimens were prepared to a degree of saturation of about 90 percent by the method used by the California Division of Highways. Comparable samples were then tested in normal triaxial compression tests and in triaxial compression tests in which the axial load was repeatedly removed and re-applied 1,000 times. By interpolation the behavior in repeated load tests of samples of the two soils having similar stress-strain characteristics in the normal compression tests was determined and shown to be quite different, both insofar as irrecoverable deformation and resilient deformation are concerned.

● IN a previous paper presented before the Highway Research Board it has been shown that the method of load application to a soil has an important effect on the magnitude of soil deformation (1). For example, a specimen subject to repeated loading has been found to deform many times more than an identical specimen subjected to a sustained load of equal magnitude. This difference in soil behavior under different types of loading raises the question whether tests performed under conditions of slowly increasing stress can satisfactorily indicate the performance of a soil under the repetitive type of loading to which it is subjected under a pavement.

A pavement may be considered to have failed when the deformation of the soil below the wearing surface is of such a magnitude as to cause an uneven riding surface or to cause cracking of the surfacing material. The object of pavement design procedures is to determine the thickness of pavement and base which must be placed over a subgrade in order that the deformation of the subgrade will not be excessive. Thus, for a satisfactory method of pavement design, it is necessary to devise some means of evaluating the resistance to deformation of the subgrade when it is subjected to a series of repeated loads of different magnitudes, durations and frequencies.

Recent research (2) has shown that it is not sufficient to evaluate only the resistance to permanent or plastic deformation of the subgrade, but also the elastic or resilient properties of the subgrade soil. A series of investigations conducted by the California Division of Highways have shown that there is a close correlation between observations of cracking and fatigue-type failures in bituminous pavements and the measured deflections of these pavements due to passing wheel loads. It appears, therefore, that large elastic deformations in a soil are a primary cause of pavement failure.

While in many cases soils having low resistance to plastic deformation may also exhibit high resilient deformations, it seems likely that some soils may exhibit extremely small plastic deformations and yet have high elastic deformations. Such soils would probably cause fatigue failure in the surfacing much more readily than would a soil exhibiting a larger plastic deformation but a much smaller elastic movement. It is apparently necessary, therefore, to evaluate separately the resistance of a soil to plastic flow and the elastic or resilient properties of soil in order to design a satisfactory pavement.

Most methods of pavement design now in use are based on an index of soil strength or resistance to deformation determined by some type of test in which the total load is slowly applied over a period of several minutes. These indices of strength have been correlated empirically with the performance of soil underlying actual pavements and thus provide a fairly reliable index for design. It does not, however, necessarily follow that a strength index determined under conditions of slow stress increase will satisfactorily indicate either the plastic deformation of the soil or the resilient deformation of the soil under conditions of repeated loading. If soils having the same strength index behave in similar fashions under repeated loading, then any difference between the effects of repeated loads and gradually increased loads will be taken into account in the empirical correlation with pavement performance. If, however, soils having the same strength index are affected to different extents by repeated loading, then the correlation of strength index with pavement performance can be only approximate.

The investigation described in this paper was conducted to throw some light on the extent to which soil strength tests carried out in the normal manner using a gradually increasing stress can be used as an index of the plastic deformation and resilient deformation of the soil under conditions of repeated loading. Series of tests were performed on saturated specimens of two different types of soil, prepared at various water contents, to determine their stress versus strain characteristics in triaxial compression tests under normal loading conditions and also when subjected to a series of 1,000 applications of a constant load. By interpolation from these results, the behavior under repeated loading conditions of specimens of the two soils having similar stress versus strain characteristics in the normal type of tests were compared.

## SOILS USED IN THE INVESTIGATION

The soils used in the investigation were:

1. A silty clay from Vicksburg, Mississippi. This soil had a liquid limit of 37 and a plastic limit of 23.
2. A silty soil from the subgrade of the WASHO Test Road in Malad, Idaho. This soil had a liquid limit of 36 and a plastic limit of 26.

## TESTING PROCEDURES

### Preparation of Specimens

All of the tests were performed on compacted samples of soil prepared in a manner similar to that used in the California Division of Highways pavement design procedure. The soil was mixed to the desired water content, allowed to condition for a period of 24 hours and then compacted in a 1.4-in. diameter mold using the Harvard Miniature Kneading Compactor (3). Samples having a height of 4.5 in. were compacted in 10 layers using 20 tamps per layer and a tamping pressure of such a magnitude as to result in a sample having a degree of saturation between 85 and 90 percent. The samples were then subjected to a static pressure until moisture was exuded, at which stage the pressure was released. This procedure resulted in samples having a degree of saturation of about 90 percent.

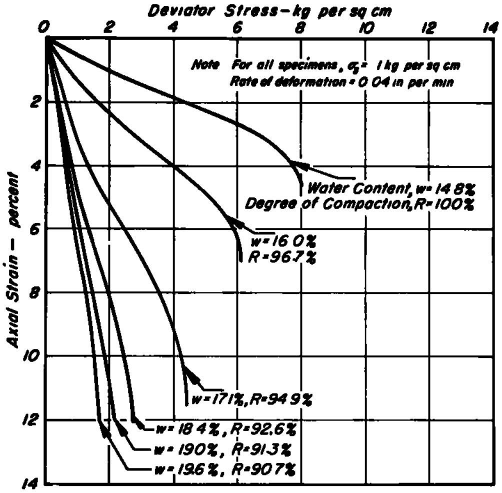


Figure 1. Stress versus strain characteristics of specimens of Vicksburg silty clay in normal triaxial compression tests.

For each soil two samples were prepared at each water content; one of these samples was subjected to a normal triaxial compression test and the other to a repeated loading test. After compaction each specimen was placed between a lucite cap and base and surrounded by two thin rubber membranes which were sealed against the cap and base by neoprene O-rings. The specimens were then assembled in the triaxial compression cells for testing.

## Normal Triaxial Compression Tests

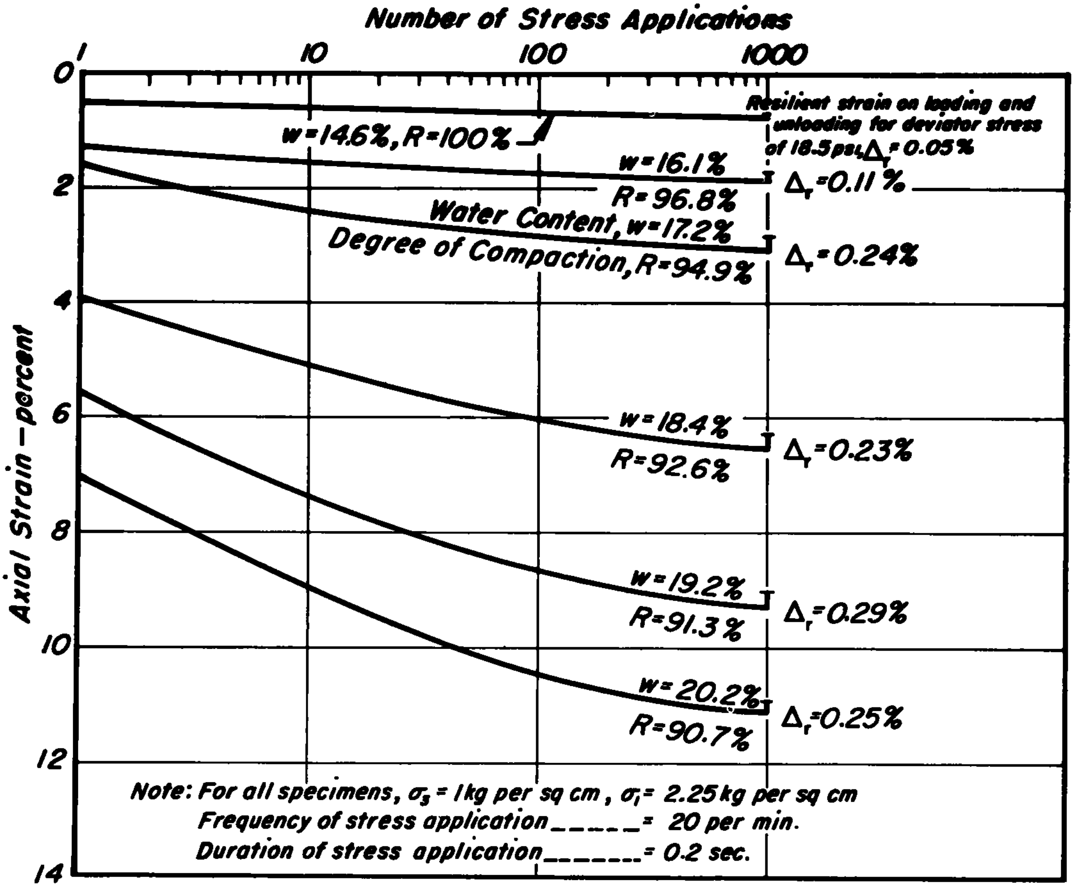
For the normal triaxial compression tests, the specimens were surrounded by water in the triaxial compression cell, a confining pressure of 1 kg per sq cm was applied by means of air pressure in the upper part of the cell, and the specimen was loaded axially by placing the cell in a standard type of compression testing machine. The rate of load increase was controlled to maintain a constant rate of deformation of the specimen of 0. 04 in. per minute. The deformation of the specimen during loading was measured by a dial indicator attached to the piston applying load to the specimen.

## Repeated Loading Tests

In the repeated loading tests a specimen was assembled in the triaxial compression cell as for the normal type of test, a confining pressure of 1 kg per sq cm was applied, and the specimen was then subjected to 1,000 applications of a 12. 5 kg load corresponding to a deviator stress of about 1. 25 kg per sq cm. Each load application was for 0. 2 second duration with an interval of 3 seconds between applications.

## RESULTS OF NORMAL COMPRESSION AND REPEATED LOAD TESTS ON VICKSBURG SILTY CLAY

The results of a series of normal triaxial compression tests performed on specimens of Vicksburg silty clay at various water contents are shown in Figure 1, and the deformations of essentially identical specimens in the repeated loading tests are shown in



Note: For all specimens, $\sigma_3$ = 1kg per sq cm, $\sigma_1$ = 2.25kg per sq cm
Frequency of stress application_____ = 20 per min.
Duration of stress application______ = 0.2 sec.

Figure 2. Deformation characteristics of specimens of Vicksburg silty clay in repeated loading tests.

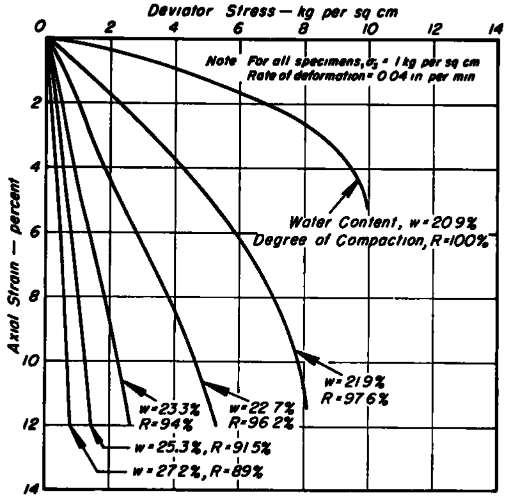


Figure 3. Stress versus strain characteristics of specimens of Idaho clayey silt in normal triaxial compression tests.

Figure 2. The specimens had water contents ranging from 14. 6 percent to 20. 2 percent and a constant degree of saturation of about 90 percent. Since the degree of saturation is the same for all specimens, the water contents are directly related to the dry densities which varied from 116. 1 pcf at a water content of 14. 8 percent to 105. 1 pcf at a water content of 20. 2 percent. The degrees of compaction of the specimens, based on the modified AASHO compaction test, are shown in the figures. As would be expected, the specimens having the higher water contents and lower densities exhibited the larger deformations under equal stresses in the normal triaxial compression tests and at equal numbers of stress applications in the repeated load tests.

It is interesting to note the large change in deformation occurring in the repeated load tests for a small change in degree of compaction. For example, a specimen

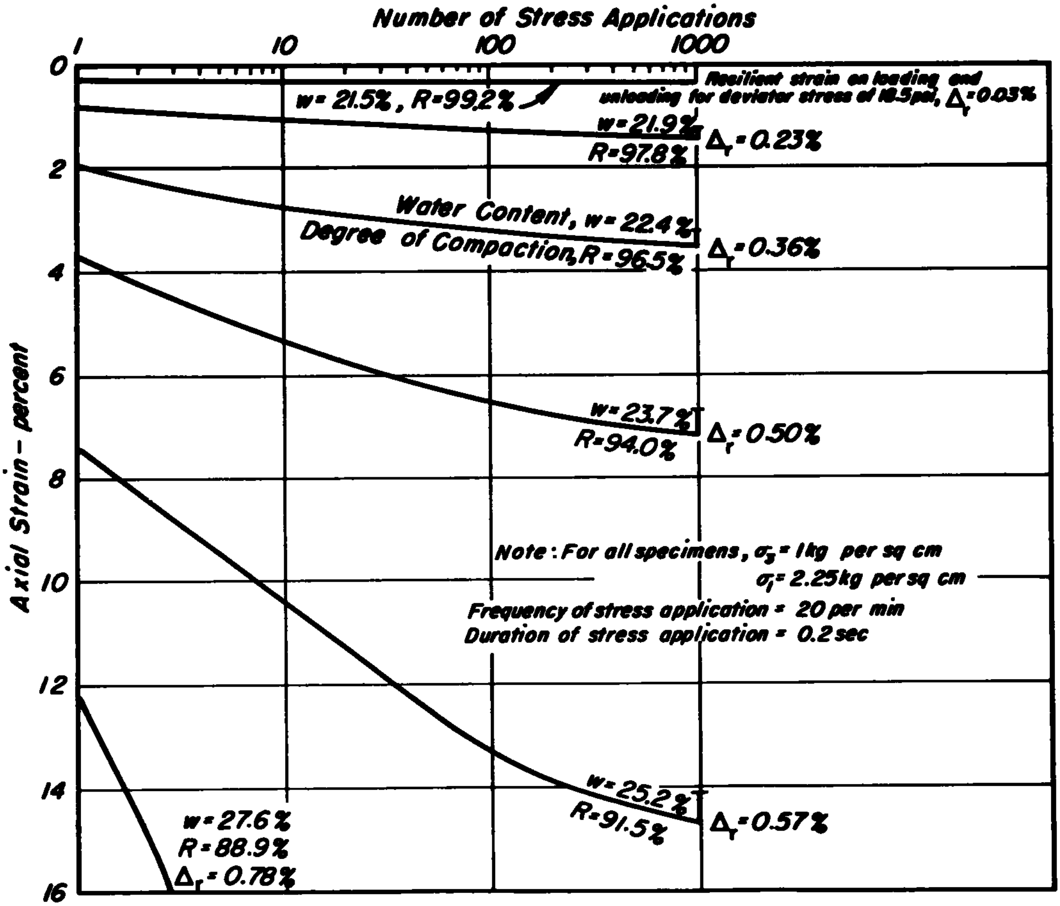


Figure 4. Deformation characteristics of specimens of Idaho clayey silt in repeated loading tests.

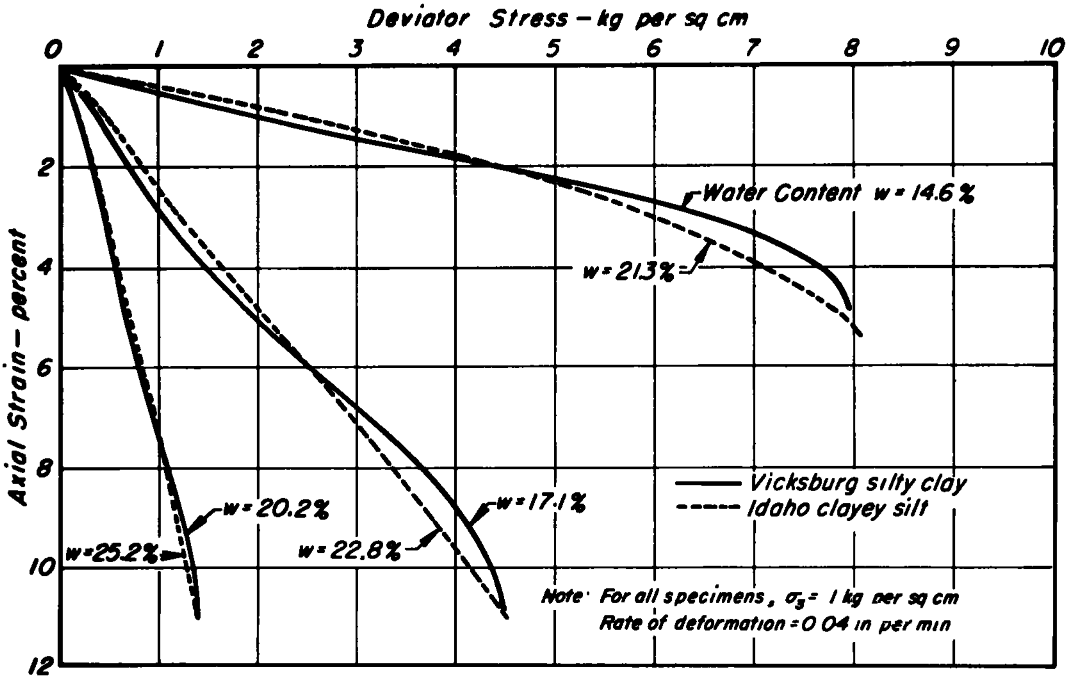


Figure 5. Comparable stress versus strain relationships for specimens of silty clay and clayey silt in normal triaxial compression tests.

having a degree of compaction of 95 percent deformed only 3 percent after 1,000 stress applications, but a specimen having a degree of compaction of about 91 percent deformed more than three times this amount.

In addition to showing the total deformation of the specimens due to a series of applications of the same load, Figure 2 also shows the resilient deformation occurring on application and removal of the load. It is interesting to note that this resilient strain changes only slightly from 0. 24 percent to 0. 29 percent for a change in degree of compaction from 95 percent to 91 percent. Thus although the density of the specimen has a large effect on the total deformation, within this range of densities it has only a small effect on the resilient deformation.

## RESULTS OF NORMAL COMPRESSION AND REPEATED LOAD TESTS ON IDAHO SILTY CLAY

The results of the tests performed on specimens of Idaho silty clay at various water contents are shown in Figures 3 and 4. For this soil the specimens had water contents ranging from 20. 9 to 27. 6 percent and a constant degree of saturation of 92 percent; this range of water contents corresponds to degree of compaction values ranging from 99 to 89 percent, based on the modified AASHO compaction test.

These data also show clearly the influence of a small change in the degree of compaction on the deformation characteristics. For this soil a specimen having a degree of compaction of 96. 5 percent deformed only 3. 5 percent after 1,000 stress applications, but a specimen at a degree of compaction of 91. 5 percent deformed about 15 percent. However, the change in resilient deformation was not so marked, the same change in degree of compaction causing an increase in resilient strain from 0. 36 to 0. 57 percent. Thus, for this soil also, density changes would appear to have a much greater effect on total deformation than on the resilient properties of the soil.

## COMPARISON OF DEFORMATION CHARACTERISTICS OF VICKSBURG SILTY CLAY AND IDAHO CLAYEY SILT

The data presented in Figures 1 to 4 permit a comparison of the deformation characteristics of the silty clay and the clayey silt. For example, it is possible by interpolation in the data in Figures 3 and 4 to compare the behavior in the repeated load tests of specimens of the two soils having similar stress versus strain characteristics in the normal compression tests.

Consider the stress versus strain curve for a specimen of the Vicksburg silty clay at a water content of 14. 8 percent shown in Figure 5. By interpolation in the stress versus strain curves for the Idaho clayey silt in Figure 3, it may be shown that a specimen of clayey silt at a water content of 21. 3 percent has a similar stress versus strain relationship in the normal type of triaxial compression test. For comparison purposes these two curves are shown in Figure 5. Having determined that specimens of the two soils at these water contents behave in a similar manner in the normal type of test, it is now possible to compare their behavior in the repeated load tests. This comparison is shown in Figure 6. The curve for the silty clay was obtained by test and is reproduced from Figure 2 while that for the clayey silt was interpolated from the data in Figure 3. It will be seen that the specimens behave differently in the repeated load tests, although in both cases the deformation is extremely small.

A similar comparison can be made for specimens exhibiting greater deformations in the normal triaxial compression tests. For example, in these tests a specimen of silty clay at a water content of 17. 1 percent has a stress versus strain relationship similar to that of a specimen of clayey silt at a water content of 22. 8 percent (Figure 5). The deformations of corresponding specimens in the repeated load tests are shown in Figure 6. In this case, the specimens deform almost equal amounts under the first load appli-

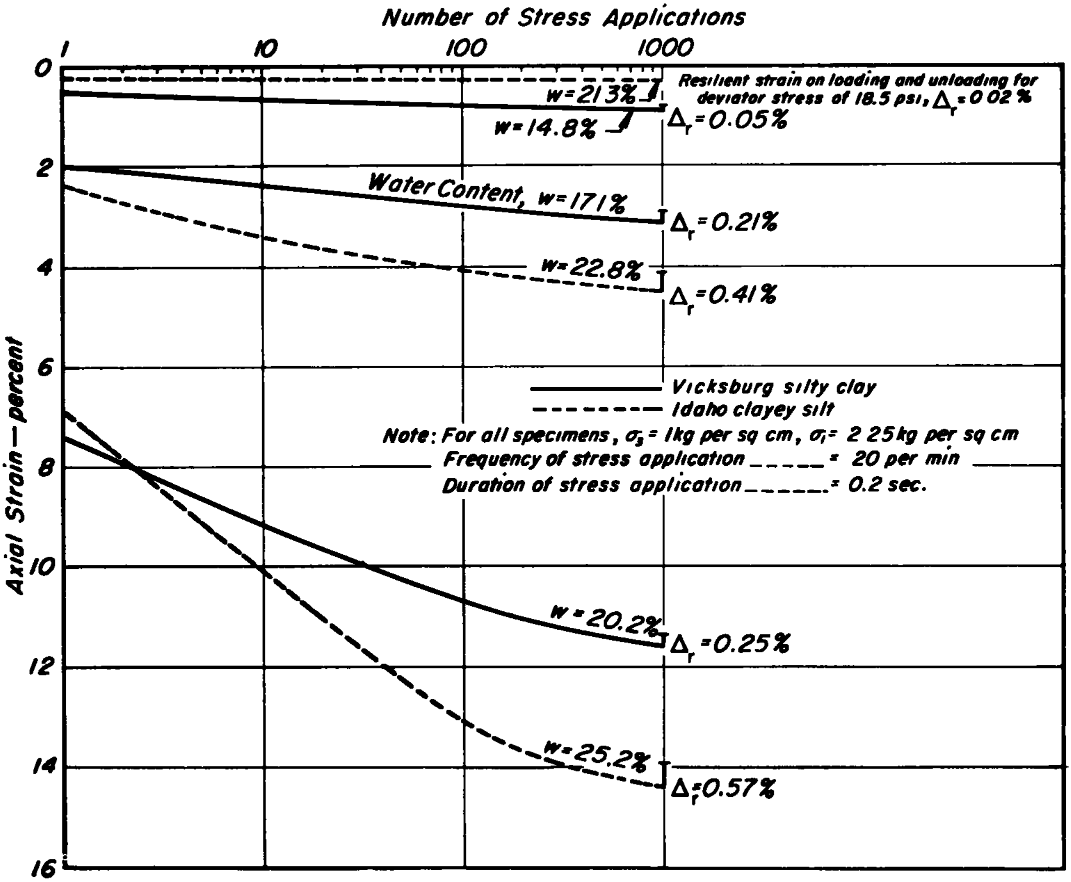


Figure 6. Deformation characteristics in repeated loading tests of specimens having similar stress versus strain relationships in normal triaxial compression tests.

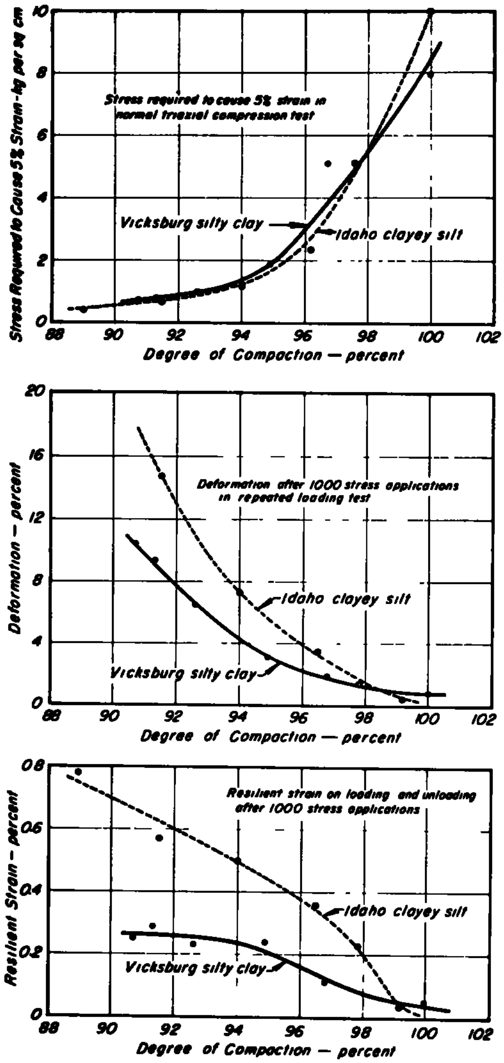


Figure 7. Deformation characteristics of silty clay and clayey silt at equal degrees of compaction.

cation but after 1,000 applications the clayey silt has deformed about 50 percent more than the silty clay. Furthermore, the resilient deformation of the two specimens is considerably different, the Idaho soil exhibiting a resilient strain of 0.41 percent as compared with only 0.21 percent for the silty clay.

At still higher water contents the difference in behavior of the two soils in repeated load tests is even more marked. For example, a specimen of silty clay at a water content of 20.2 percent and a specimen of clayey silt at a water content of 25.2 percent also have similar stress versus strain characteristics in normal triaxial compression tests. However, it will be seen from Figure 6 that there is a great difference in the behavior of these two specimens in the repeated load tests. Under the first few applications the clayey silt deforms less than the silty clay, but subsequently the deformation of the clayey silt is appreciably greater than that of the silty clay. The resilient deformations also differ greatly, a specimen of clayey silt having a resilient strain of about 0.57 percent as compared with only 0.25 percent for the silty clay.

One of the difficulties in making a comparison of the deformation characteristics of the two soils used in this investigation is that of determining the degree of similarity which should be achieved between the stress versus strain curves of the corresponding specimens. The general shape of the stress versus strain curves in normal triaxial compression tests for specimens of the two soils is somewhat different, with the result that curves which are closely alike at low strains may be considerably different at high strains and vice versa. Thus, for example, the stress versus strain curve for a specimen of silty clay having a water content of 14.8 percent is similar at low strains to that of a specimen of clayey silt having a water content of 21.5 percent and at higher strains to the curve for a specimen of clayey silt at a water content of 21.2 percent. In comparing the effects of repeated loading on specimens, it is therefore necessary to define the range of strain in the normal compression tests at which comparable specimens of the two soils should have similar stress versus strain curves.

In most pavement design procedures the index of soil stability is determined as the stress required to cause a certain amount of strain. However, the strain at which the strength index is determined varies considerably. In some procedures, specimens requiring the same stress to cause 5 percent strain are considered to have equal strength indices, while in other procedures specimens might be considered to have equal strength indices if they require the same stress to cause 3 or 8 percent strain. The stress versus strain curves used for comparison in Figure 5 have been selected to coincide at about half the maximum strength. Corresponding specimens in repeated load tests have been shown to have different deformation characteristics. This difference in deforma-

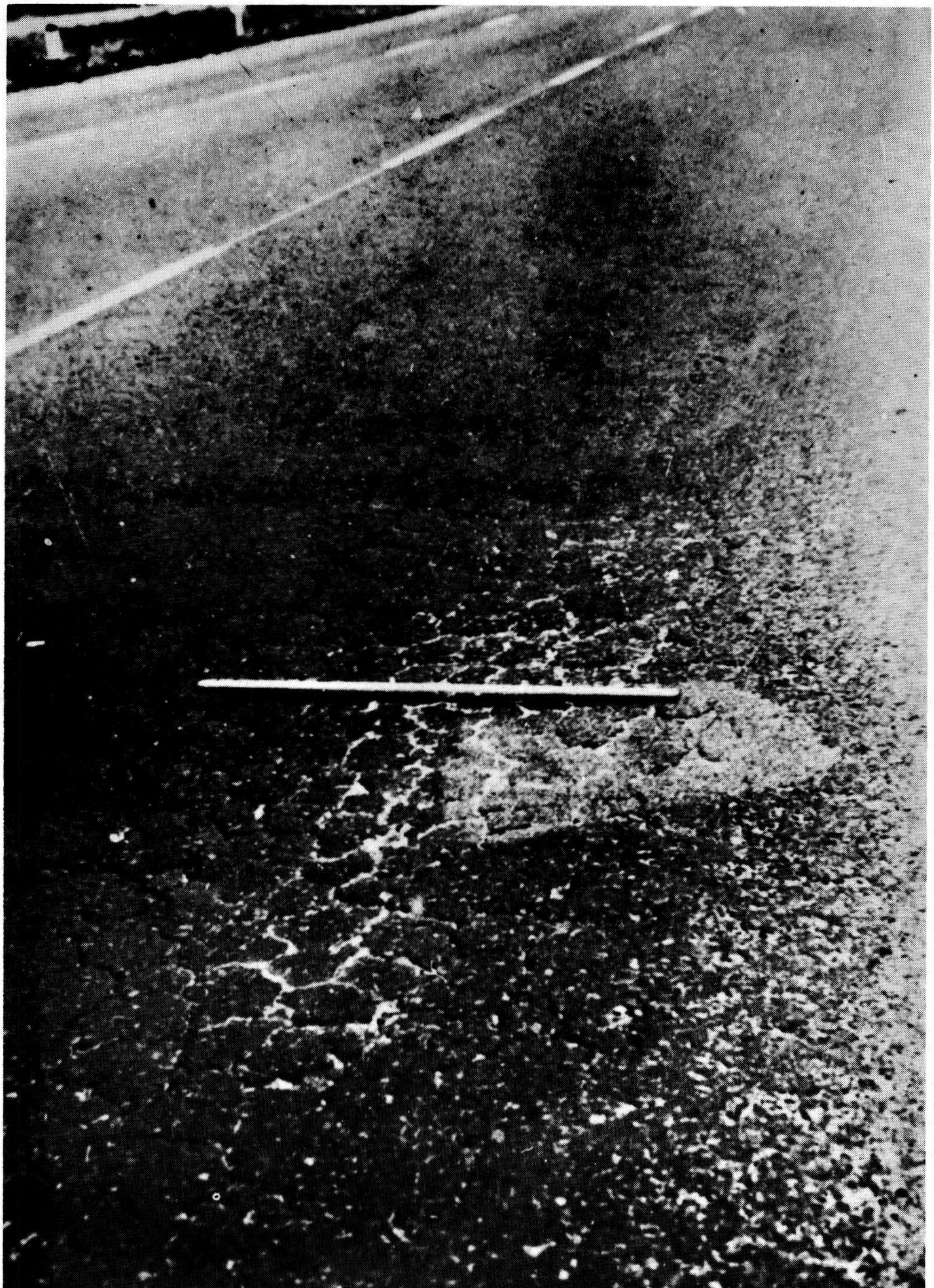


Figure 8. Pavement surface fatigue failure caused by resilient deformations of the subgrade.

tion characteristics in repeated load tests may be shown to exist regardless of the axial strain selected as a basis for establishing the similarity of stress versus strain relationships obtained in normal compression tests.

## COMPARISON OF DEFORMATION CHARACTERISTICS OF SILTY CLAY AND CLAYEY SILT AT EQUAL DEGREES OF COMPACTION

It is revealing to compare the influence of degree of compaction on the deformation characteristics of these soils. Figure 7 shows the total deformation after 1,000 stress applications, the resilient strain in the repeated load tests and the stress required to cause 5 percent strain in the normal type of triaxial compression tests for specimens at various degrees of compaction.

It will be seen that for both soils the higher the degree of compaction the smaller is the resilient deformation during repeated loading. However, for the Vicksburg silty clay the resilient strain changes only slightly for degrees of compaction ranging from 90 to 95 percent, while for a similar range of degrees of compaction the Idaho clayey silt shows an appreciable change in resilient deformation. Furthermore, for the range of degrees of compaction of practical interest the Idaho soil exhibits much higher resilient deformations than the silty clay.

At equal degrees of compaction the two soils require approximately equal stresses to cause 5 percent strain in the normal compression tests. In the repeated load tests, however, a specimen of the Idaho soil deforms about 50 percent more than a specimen of silty clay having an equal degree of compaction. This fact again indicates that deformation characteristics determined under normal loading conditions will not necessarily indicate the behavior of soil under repeated loading conditions.

## CONCLUSION

The data presented in this paper are not intended to show that established methods of testing soils for the design of pavements are necessarily unreliable. Long experience has indicated that these established methods provide reasonably satisfactory data for design purposes, and this fact cannot be disregarded on the basis of a single investigation of limited scope. The differences in behavior of the soils used in this investigation may, however, serve to explain some of the pavement failures which occur from time to time even though established design methods have been used. The investigation shows clearly that deformation characteristics determined under normal loading conditions are not necessarily indicative of soil deformation under repeated loading conditions, but further investigations are required before the applicability of this result to other types of soil can be ascertained.

It has recently been shown that the resilient or elastic deformation of subgrade soils may be an important factor causing failure or cracking of a flexible pavement. Figure 8 shows a pavement with extensive cracking even though there is little evidence of any plastic deformation of the subgrade (4). The cracking may well be attributed, therefore, to high resilient deformations leading to fatigue failure in the surfacing material. A secondary purpose of this investigation, then, was to demonstrate that the resilient characteristics of a soil are not necessarily related to test data obtained from normal compression tests. For the two soils used in this investigation a strength index determined at high strains does not provide an index of resilient deformation; infact, the initial tangent moduli of the stress versus strain curves do not appear to serve this purpose. Thus if resilient deformations are to be included as a factor in pavement design, a new testing procedure would appear to be required to determine their relative magnitudes. Repeated loading of specimens in triaxial compression tests provides a convenient means of measuring this type of movement, and at the same time determining the relative resistance to permanent deformation of different soils.

Finally the investigation throws some light on the characteristics of the subgrade soil from the Idaho test road. This soil exhibits an appreciably higher resilient deformation than the silty clay with which it is compared, even though the Atterberg limits of the two soils do not differ appreciably; hence, in view of the correlation between pavement failures and resilient deformation of the pavement under load, some degree of caution would perhaps be warranted in extending the conclusions drawn from this test road to pavements constructed on less resilient types of soil.

## REFERENCES

1. Seed, H. B., Chan, C. K., and Monismith, C. L., "Effects of Repeated Loading on the Strength and Deformation of Compacted Clay," Proceedings, Highway Research Board, 34th, 1955, pp. 541-558.
2. Hveem, F. N., "Pavement Deflections and Fatigue Failures," Design and Testing of Flexible Pavement, Bulletin No. 114, Wash. D. C., Highway Research Board, 1956.
3. Wilson, Stanley D., "Small Soil Compaction Apparatus Duplicates Field Results Closely," Engineering News-Record, Vol. 145, No. 18, November 2, 1950, pp. 34-36.
4. Vallerga, B. A., "On Asphalt Pavement Performance," Proceedings, Assoc. of Asphalt Paving Technologists, 24th, 1955.

HRB:OR-21