DEPARTMENT OF SOILS

Effects of Repeated Loading on the Strength and Deformation of Compacted Clay

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This paper presents results of tests made to determine some effects of repeated loading on the strength and deformation of compacted specimens of a silty clay in triaxial compression tests. Apparatus for applying repeated loads of varying periods and frequencies to test specimens is described. Test data to compare the effects of repeated loads and sustained loads on the strength and deformation of test specimens and the effect of frequency of loading and magnitude of applied stress on the deformation of partially saturated specimens subjected to 50,000 to 100,000 applications of stress is presented. In addition, data on the compression and rebound occurring during repeated load applications are analyzed. Conclusions are drawn with regard to the effects of frequency of loading and magnitude of loading on the deformation occurring during repeated stress application.

● A RATIONAL approach to the design of pavements requires an understanding of the effects of repeated loads on the strength and deformation of soils. The soil underlying a pavement is subjected to a continuous series of rapidly applied and rapidly released stresses of varying magnitudes and frequencies, and a satisfactory design requires that the soil deformation under these stresses shall not exceed a tolerable limit. The duration of stress application to the soil depends on the speed of the moving vehicles; the interval between stress applications depends on the frequency of traffic; and the magnitude of stress application depends on the vehicle weight, number of wheels, and tire pressure. A satisfactory design method therefore involves a determination of the magnitude of soil deformation due to various vehicle speeds, traffic frequencies, and stress magnitudes, and hence a determination of the effects of the various factors which might influence the deformation of soils subjected to repeated stress applications.

Most methods of pavement design now in use are based on an index of soil strength 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 the performance 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.

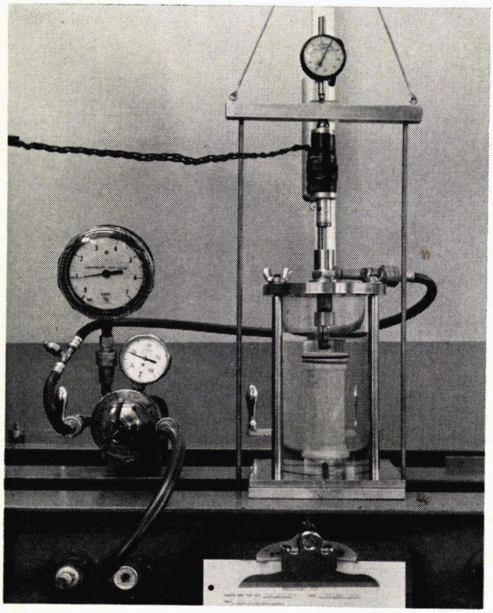


Figure 1. Triaxial compression cell.

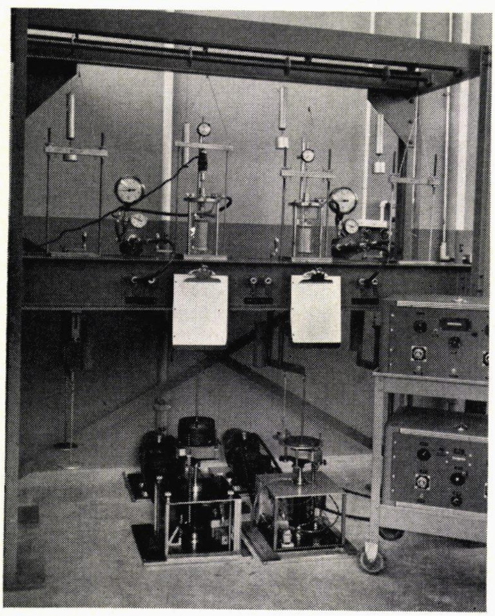


Figure 2. Loading frame and repeated-loading equipment.

The purpose of the investigation described here is to determine the effects of repeated loading on the strength and deformation of soils. Time has not permitted an investigation of all phases of the subject, but the results obtained to date may be of sufficient interest to warrant presentation. The paper presents, therefore, test data to show a comparison of the effects of sustained and repeated loads on the strength and deformation of test specimens, some effects of magnitude of applied stress on the compression and rebound occurring during repeated stress applications, and the effect of frequency of loading and magnitude of applied stress on the deformation of partially saturated specimens of silty clay in triaxial compression tests.

INSTRUMENTATION

Triaxial Compression and Loading Equipment

All the tests in the investigation were performed on specimens having a diameter of 1.4 inches and a height of about 4 inches. As the tests continued over long periods of time it was necessary to protect the specimens against loss of moisture. After a specimen had been trimmed to the required size, it was placed between a lucite cap and base and surrounded by two thin rubber membranes with a layer of grease between the membranes. The membranes were sealed against the lucite cap and base by means of neoprene "O" rings and the entire specimen was placed under water in the triaxial compression cell, as shown in Fig. 1. When the specimen was to be subjected to a confining pressure during the test, air pressure of the desired magnitude was applied to the top of the cell. The specimen was then loaded axially by placing the entire cell under the loading yoke of a loading frame as shown in Fig. 2. Deformation of the specimen was measured by a dial indicator placed over the loading yoke directly in line with the piston applying load to the specimen.

Repeated Loading Unit

The type of loading desired for this study was a repeated load rapidly applied and rapidly removed with negligible impact effects and with suitable controls to regulate the duration of load application and the interval between applications. It was originally intended that the minimum period of load application should be 0.1 second; this corresponds approximately to the time of loading of a base course for traffic moving at 60 miles per hour. In order to simplify the apparatus, however, the minimum period of duration was subsequently changed to 1 second. The maximum duration of the load application and the interval between loads are of course unlimited, as the traffic may be stationary or very sparse. The practical limit was set at 1 hour. Some of the other general requirements imposed on the apparatus were dependability for continuous long-time operation (up to about one month) and portability.

The apparatus finally developed was a simple, lever-type loading frame, with a movable carriage for applying and removing weights from the hanger of the frame. The loading frame and carriage are shown in Fig. 2. An electronically controlled hydraulic system was used to raise and lower the carriage after the appropriate time intervals. This system, which is shown schematically in Fig. 3, consists essentially of a pump supplying oil through a four-way solenoid valve to apply pressure to either the top or bottom of the piston on which the carriage is mounted. A second solenoid valve shuts off the return line to hold the carriage in any one position. A step-by-step description of the complete cycle is as follows:

Starting on the down stroke, which lowers the weights on to the hanger of the loading unit, a pre-set timer closes a relay in the electronic circuit which in turn opens the four-way solenoid valve to the top of the piston. At the same time the relay operating the shut-off valve or normally open solenoid valve opens to allow the oil in the cylinder below the piston to return to the reservoir through an adjustable restriction valve. The adjustment of the restriction valve allows some control over the rate of loading and can be adjusted to give a slow enough flow to eliminate impact loading effects. When the weights are transferred from the carriage to the hanger, the microswitch mounted on the carriage is actuated and causes the electronic circuit to close the relay for the normally open solenoid valve, thus stopping further movement of the carriage. This actuation also sets into operation a timing unit which, after the pre-set time has elapsed, starts the up-stroke, during which the carriage removes the weights from the hanger. The timing unit closes the relay controlling the four-way solenoid valve and at the same time opens the relay operating the normally open solenoid valve. Thus flow is allowed into the cylinder below the piston, and the oil on top of the piston returns to the reservoir. The restriction valve has a free flow feature on the up-stroke, since there is no danger of impact in unloading. As the weights are picked up by the carriage, the microswitch is compressed, and the electronic circuit closes the relay operating the normally open solenoid valve, stopping any further movement of the carriage. At the same time a timing unit is set into operation starting another complete cycle.

Whenever the shut-off or normally open solenoid valve is closed, a bypass valve opens at 100 psi fluid pressure, and oil is pumped directly back to the reservoir; thus the pump operates continuously.

The feature of stopping the carriage as soon as the load is applied or removed from the hanger allows the piston, which has a total travel of 3 inches, to adjust to the level of the hanger. The total operating travel of the piston during any cycle is dependent on the stiffness of the specimen and the lever ratio used in the loading frame. In this investiga-

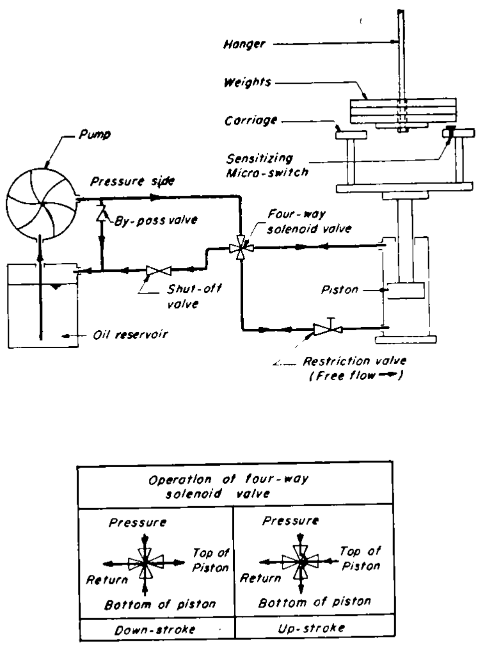


Figure 3. Schematic diagram of a repeated-loading apparatus.

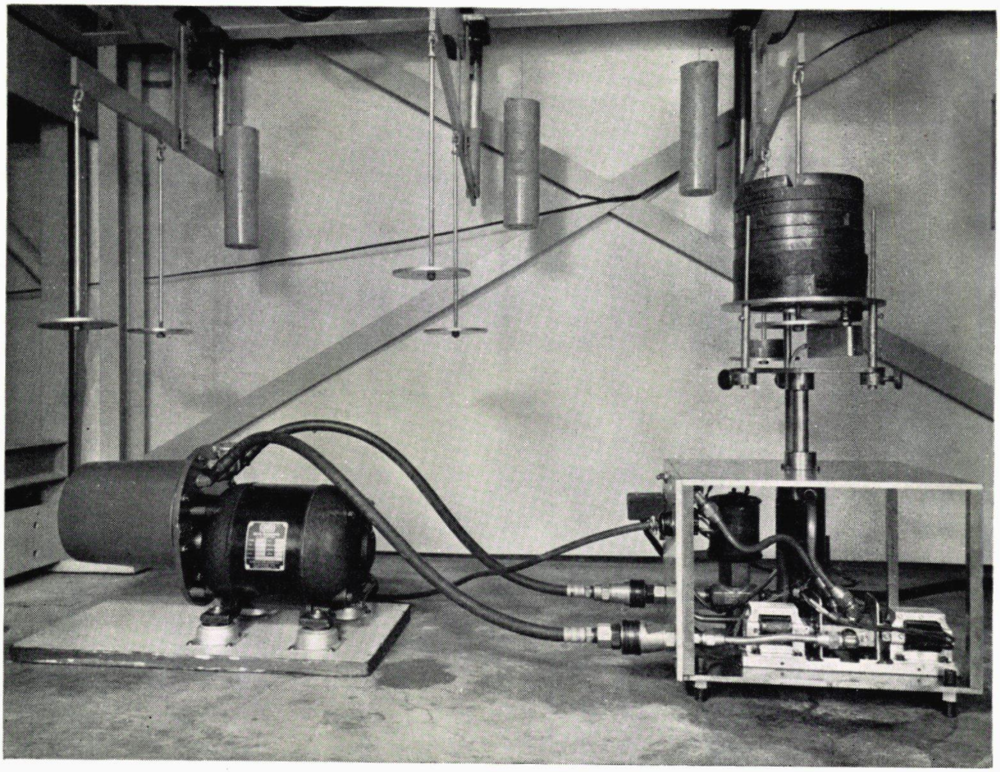


Figure 4. Repeated-loading apparatus, hydraulic system and carriage.

tion the operating distances were approximately 1 inch. This automatic adjustment is important, especially if the deformation of the specimen is large.

Fig. 4 shows the hydraulic unit in operation. On the left is the motor for the pump and the reservoir. The bypass valve and the pump itself are located within the reservoir. On the right, the hanger passes freely through the slots of the weights.

Electronic Controls

Basically, the electronic unit receives the signal from the microswitch mounted on the carriage and starts the timers and relays used to control the two solenoid valves.

The main features of the electronic unit are:

1. *The Momentary Sensing Unit.* Essentially this unit consists of the sensing microswitch mounted on the carriage and a circuit to convert the switching action into an electrical pulse. The use of different timing units to control the up and down periods of the carriage required a pulse to initiate the timing units. Although the microswitch would still be required, the circuit of the momentary sensing unit could be eliminated if equal up and down timings were used, since the same switch could be used for reinitiation of the timing unit.

2. *Timing Units.* Three General Electric timing units were employed in the electronic circuit. The ranges of the units were 0 to 12 seconds, 0 to 120 seconds, and 0 to 1 hour. Two selection switches allow the use of any combination of time intervals within these three ranges for the periods following the up and down strokes of the piston.

3. *Variable-Resistance Delay.* The purpose of this delay is to ensure that the piston has sufficient travel for the load to be completely removed or applied. The variable resistance permits adjustment of the delay between the activation of the timing unit and the activation of the relay operating the normally open solenoid valve.

4. *Discriminator Alternate Relay.* This relay sends the power to operate the four-way solenoid valve in the correct alternating sequence.

5. *Automatic Reset.* Since the electronic system consisted mostly of relays, minor failures in their operation could easily occur due to dust particles settling between the contacts. In order to prevent such minor failures from stopping the entire operation of the apparatus permanently, an automatic reset system has been incorporated. Whenever there is a stoppage in the apparatus, a relay closes and a thermal delay switch resets the unit. The thermal delay is necessary in order to allow the system to adjust to the starting position before resetting. A telecron motor with a worm gear is used in conjunction with a microswitch to limit the automatic resetting to only four cycles, so that in case of serious trouble or when a sample fails, the unit will stop operating. This automatic reset is especially convenient in cases where the apparatus operates overnight.

6. *Minor Accessories.* These include: safety limit switches on the top and bottom of the range of the piston to stop the apparatus when the specimen fails and a counter to record the number of cycles.

The repeated loading apparatus developed has a practical limitation of about 0.2 second on the minimum time required for reversal of the direction of movement of the carriage. This is due to the time necessary for the mechanical movements of the piston and the activation of the many electronic switches. If this minimum time interval is used, there is some impact effect during loading, since an unrestricted flow of oil is required to cause such rapid movement of the piston. For negligible impact effect, the minimum time of load application is approximately ½ second; this corresponds to traffic traveling at about 12 miles per hour. If a faster rate of loading were desired to simulate more rapidly moving traffic, some other type of loading system would be required.

Recording of Rate of Stress Application

For checking the timing of repeated loads and ensuring that there was no impact effect during loading, a dynamometer was installed between the loading yoke and the piston applying load to the specimen. Bonded SR-4 electrical resistance strain gages were mounted on the dynamometer and the response of these gages during repeated stress applications was recorded on a Sanborn Strain Amplifier. A typical load vs. time recording is shown in Fig. 5. It will be noted that there is a short period of stress increase, a longer period in which the stress is sustained and then a short period of stress removal followed by a suitable interval before the same stress cycle is repeated. However, there is no evidence of any significant impact effects during the application of stress.

SOIL USED IN INVESTIGATION

All the tests reported in this paper were made on a silty clay from Vicksburg, Mississippi. The soil had a liquid limit of 37 and a plastic limit of 23. The density vs. water content relationship for the soil, as determined by the modified AASHO compaction test, is shown in Fig. 6.

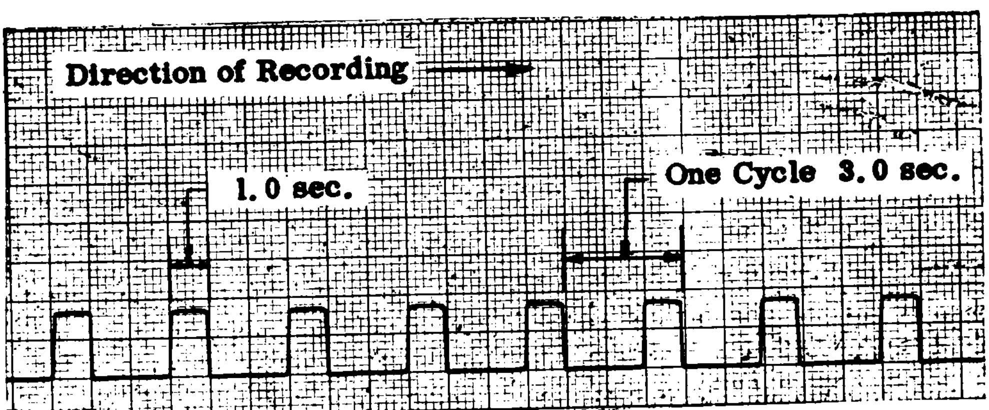


Figure 5. Typical oscillogram showing load-versus-time relationship for repeated load applications.

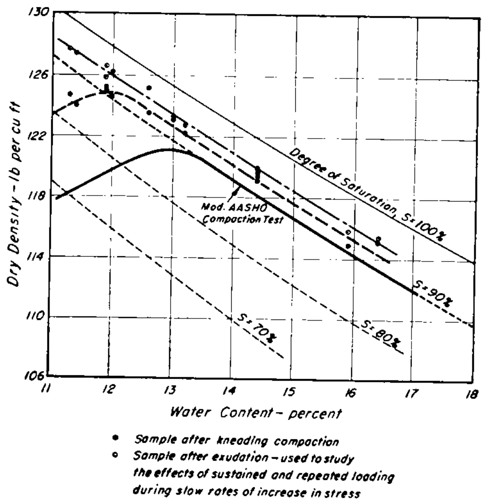


Figure 6. Density versus water-content relationship for silty clay.

COMPARISON OF EFFECTS OF REPEATED AND SUSTAINED LOADS ON SOIL DEFORMATION

At the outset of the investigation it was considered desirable to determine if there was any significant difference between the effects of sustained loads and repeated loads on the deformation of soils. For this purpose identical specimens were trimmed from the same block of compacted soil, and observations were made of their deformations when subjected to sustained and repeated stresses of equal magnitudes.

The soil was compacted in a 6-inch diameter mold using the Triaxial Institute Kneading Compactor. The compacted sample was then subjected to static pressure until moisture was exuded, the pressure was released and identical test specimens were trimmed from the sample. This method of preparation enabled samples to be prepared with degrees of saturation ranging from 92% to 97%.

The specimens thus prepared were protected from loss of water and mounted in the triaxial compression cell as previously described; however, in these preliminary tests they were loaded without lateral confinement. Axial stress was applied in equal increments to the specimens, as in a normal unconfined compression test, until the applied stress was equal to some predetermined proportion of the unconfined compression strength. This stress was then sustained on one specimen while on the other specimen it was repeatedly removed for a period of 5 seconds and reapplied for a period of 1 second.

Typical results obtained in such a test are shown in Fig. 7a. The sample was compacted at a water content of 13.2 percent to a dry density of 122.3 lb per cu ft; the degree of saturation was 93%. The deformations of similar specimens loaded to 60% of the normal unconfined compression strength and then subjected to sustained and repeated loads are shown in the figure. In this test, three specimens were used, two of which were subjected to sustained stress and one to repeated stress applications.

It will be seen that the three specimens had similar stress vs. strain characteristics during the initial loading period. However, the increases in strain occurring in a period of 9 days for the two specimens under a sustained load of 10 kg per sq cm were each about 1.25% while the specimen under a repeated load of the same magnitude, deformed an additional 7.5%; repeated loading thus caused considerably more deformation than a sustained load of equal magnitude.

Similar test data for specimens having a water content of 14.1%, a dry density of 119.5 lb per cu ft and a degree of saturation of 92% are shown in Fig. 7b. Using a normal rate of loading, three specimens were loaded to 60% of their unconfined compressive strength. During this period the specimens deformed approximately equal amounts. The specimen on which this load was sustained deformed an additional 1.25% in 2 days. Two specimens on which this load was repeatedly removed and re-applied, both deformed additional amounts of 6½% in the same period.

The marked increase in deformation of the specimens subjected to repeated stress applications appears even more remarkable when it is considered that the load was actually only applied to these specimens for one sixth of the time it was applied to the specimens under sustained load.

THE EFFECTS OF REPEATED LOADING DURING SLOW RATES OF INCREASE IN STRESS

To further compare the effects of repeated and sustained loads on soil deformation, a series of tests were made under conditions of increasing stress. Identical specimens were subjected to three types of tests:

1. *Normal unconfined-compression tests,* in

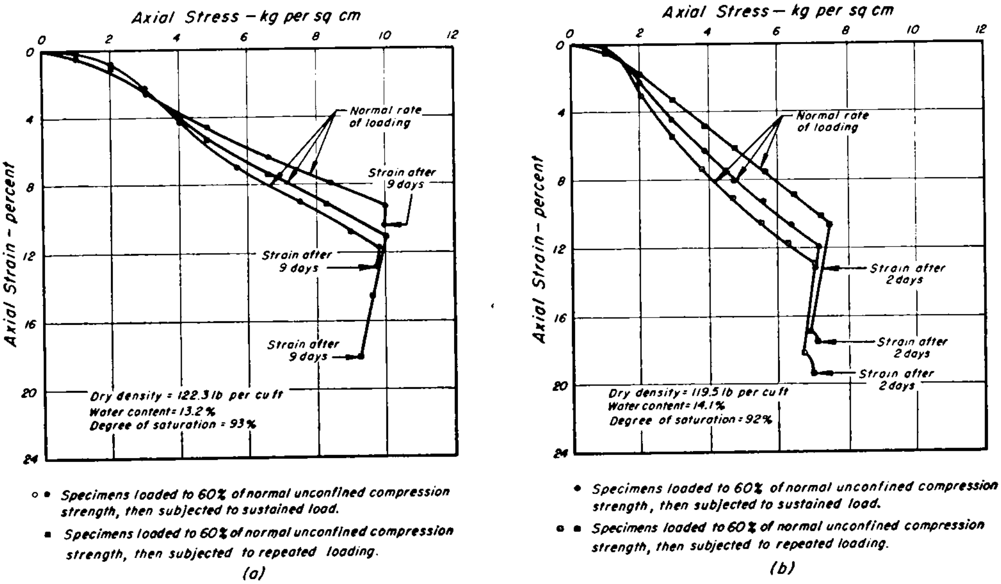


Figure 7. Stress-versus-strain relationships for specimens subjected to sustained and repeated loading.

which the specimens were loaded to failure by applying load increments at a constant rate over a period of approximately 10 minutes.

2. *Slow rate of loading, sustained load tests,* in which the specimens were loaded by applying a stress increment equal to one tenth of the normal unconfined compressive strength every hour until failure occurred; the applied load was sustained throughout the periods between load increments.

3. *Slow rate of loading, repeated load tests,* in which the specimens were loaded by applying a stress increment equal to one tenth of the normal unconfined compressive strength every hour until failure occurred, but with the entire load being repeatedly removed and applied throughout the test; each application lasted for 1 second and the period between applications was 5 seconds.

The tests were performed on samples prepared at various water contents by kneading compaction to a degree of saturation of about 90% and then subjected to static pressure until moisture was exuded. The final degree of saturation was about 95%. The densities and water contents of the samples, after compaction by kneading and after exudation of moisture are shown in Fig. 6. The range of densities of the samples tested was from 95 to 105% of the maximum density obtained in the modified AASHO compaction test.

Specimens were trimmed from the compacted samples and subjected to the three types of test described above. The results of these tests are summarized in Figs. 8, 9, 10, and 11. The results shown are the averages of two tests of each type performed on specimens trimmed from the same compacted sample.

The compressive strength of a soil is usually defined by one of two criteria. In soils where the specimen fails by developing a shear plane, the strength is often considered to be the maximum stress which the specimen is able to support. However, the deformation of the specimen before the shear plane develops may be excessive, and in such cases the strength may be defined as the stress required to cause a specified amount of strain. The maximum permissible strain will vary with the purpose for which the soil is to be used; for pavement design it is usually considered to be of the order of 5% or 10%.

The stresses required to cause 5% strain in each of the three types of test are shown in Fig. 8. Throughout the range of densities of the samples investigated, that is, densities varying from 95% to 105% of the maximum density obtained in a modified AASHO com-

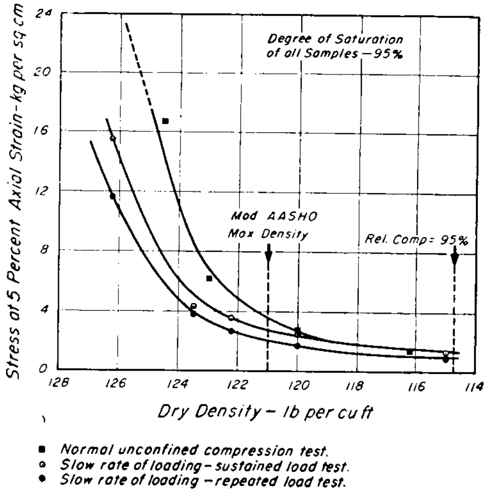


Figure 8. Relationship between stress required to cause 5% axial strain and dry density.

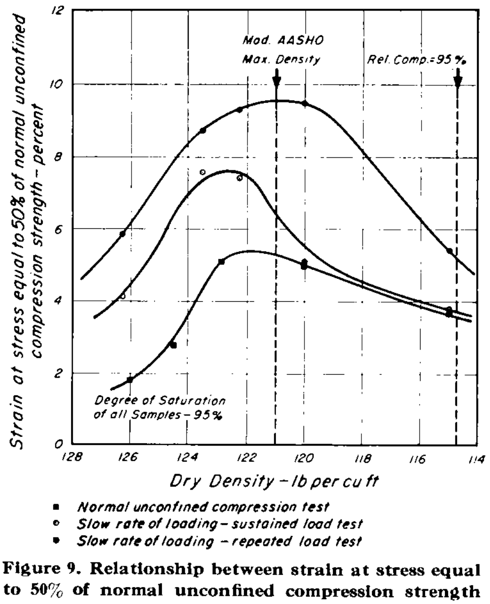


Figure 9. Relationship between strain at stress equal to 50% of normal unconfined compression strength and dry density.

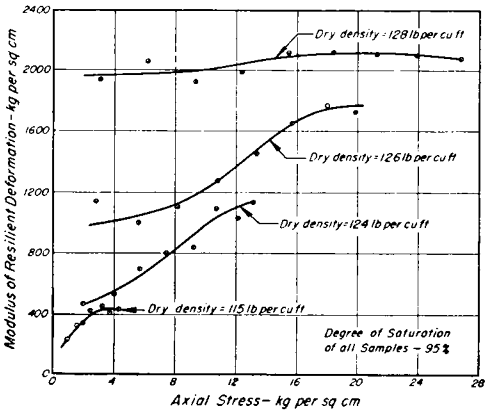


Figure 10 Relationship between modulus of resilient deformation and repeated stress.

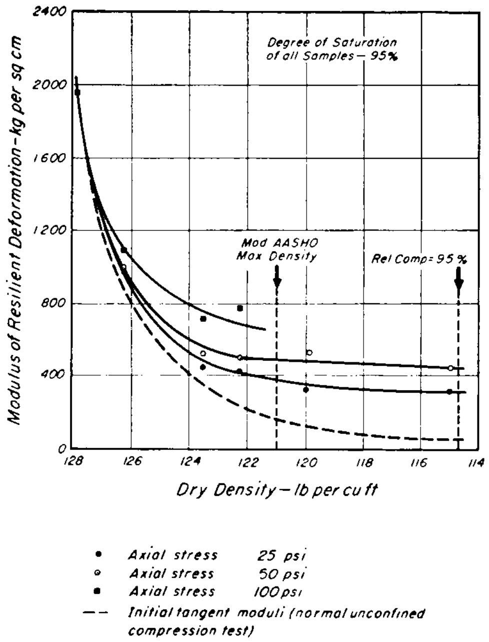


Figure 11. Relationship between modulus of resilient deformation and dry density.

paction test, the stress required to cause 5% strain of a specimen subjected to 'slow rate of loading—repeated load' tests was lower than that required to cause 5% strain of a similar specimen subjected to either of the other types of tests. Within the range of densities of practical interest, that is, samples having a relative compaction between 95% and 100%, the stress required to cause 5% strain of a given specimen in either a normal unconfined compression or a "slow rate of loading—sustained load" test was approximately the same; however, only about 60% to 70% of this stress was required to cause the same deformation in a "slow rate of loading—repeated load" test. Similar results were obtained for the stress required to cause 10% strain. These data are further evidence of the larger deformations which occur under repeated loading conditions as compared with sustained load conditions.

In engineering practice, a factor of safety of about 2 is sometimes applied to the normal unconfined compression strength of a clay soil to determine the maximum allowable stress for use in design. At this design stress, the strain of a specimen in a normal unconfined compression test is usually relatively small; however, under different loading conditions the deformation occurring under this stress may be appreciably larger. A comparison of the deformation of specimens caused, in the three types of test, by a stress equal to one half of the normal unconfined compression strength of the specimens is shown in Fig. 9. For specimens having a relative compaction between 95 and 100%, the strain is approximately the same in either the normal unconfined compression or the "slow rate of loading—sustained load" test; however the specimen would deform approximately 60% more in a "slow rate of loading—repeated load" test than in a normal unconfined compression test.

In the repeated load tests, the amount of compression and rebound occurring after each application and removal of the load was recorded. In general, after the loads had been repeatedly applied for about three minutes the compression and rebound for each application appeared to be constant. The ratio of the applied stress to the deformation occurring under each load application at this stage in the test has been termed the modulus of resilient deformation. The manner in which the modulus of resilient deformation varied as the load was increased in the "slow rate of loading—repeated load" tests is shown in Fig. 10. It is seen that the modulus of resilient deformation increased as the stress was increased, except near failure; in other words, in spite of their high degree of saturation (95%), the specimens became stiffer with increasing magnitude of repeated stress. At a water content of 16% and a dry density of 115 lb per cu ft, corresponding to approximately 95% of the maximum density determined by the Modified AASHO compaction procedure, the modulus of resilient deformation was almost doubled when the stress was increased from 1 to 3 kg per sq cm. Thus an increase in applied stress does not cause a proportional increase in the resilient deformation occurring under repeated stress conditions.

The moduli of resilient deformation for vertical stresses of 25, 50 and 100 psi and for specimens of various densities are shown in Fig. 11. For purposes of comparison the initial tangent moduli determined from the stress vs. strain curves obtained in normal unconfined compression tests are also shown. It is interesting to note that for densities in the range of 95% to 100% of the maximum density obtained in the modified AASHO compaction test, there was very little variation in the modulus of resilient deformation for a constant applied stress of 25 or 50 psi. However for samples having a relative compaction greater than 100%, the modulus of resilient deformation increased rapidly with density.

The moduli of resilient deformation determined in the repeated load tests are considerably greater than the initial tangent moduli for identical samples determined by normal unconfined compression tests. The difference between the moduli determined by these tests is greater for the lower densities and the higher values of repeated stress. This means that under repeated stress applications, the elastic compression and rebound of the soil is considerably less than that indicated by a test conducted with a normal rate of loading. For example, at a relative compaction of 95%, the modulus of resilient deformation for a stress of 25 psi in the repeated load test was 500% greater than the initial tangent modulus obtained by a normal unconfined compression test. In terms of deformation, the compression and rebound under a repeated stress of 25 psi was only 15% of that indicated by the initial tangent modulus determined by a normal unconfined compression test.

EFFECT OF FREQUENCY OF STRESS APPLICATION ON SOIL DEFORMATION

A series of tests were conducted on partially saturated samples to determine how the deformation of the soil was influenced by the frequency of stress application. Samples of various water contents were compacted by the Kneading Compactor in 6-inch diameter molds to densities approximately equal to 90% of the maximum density obtained in the Modified AASHO compaction test. Identical specimens trimmed from these samples were subjected to a confining pressure of 14.2 psi and then to a series of axial stress applications of equal intensities and durations but with different fre-

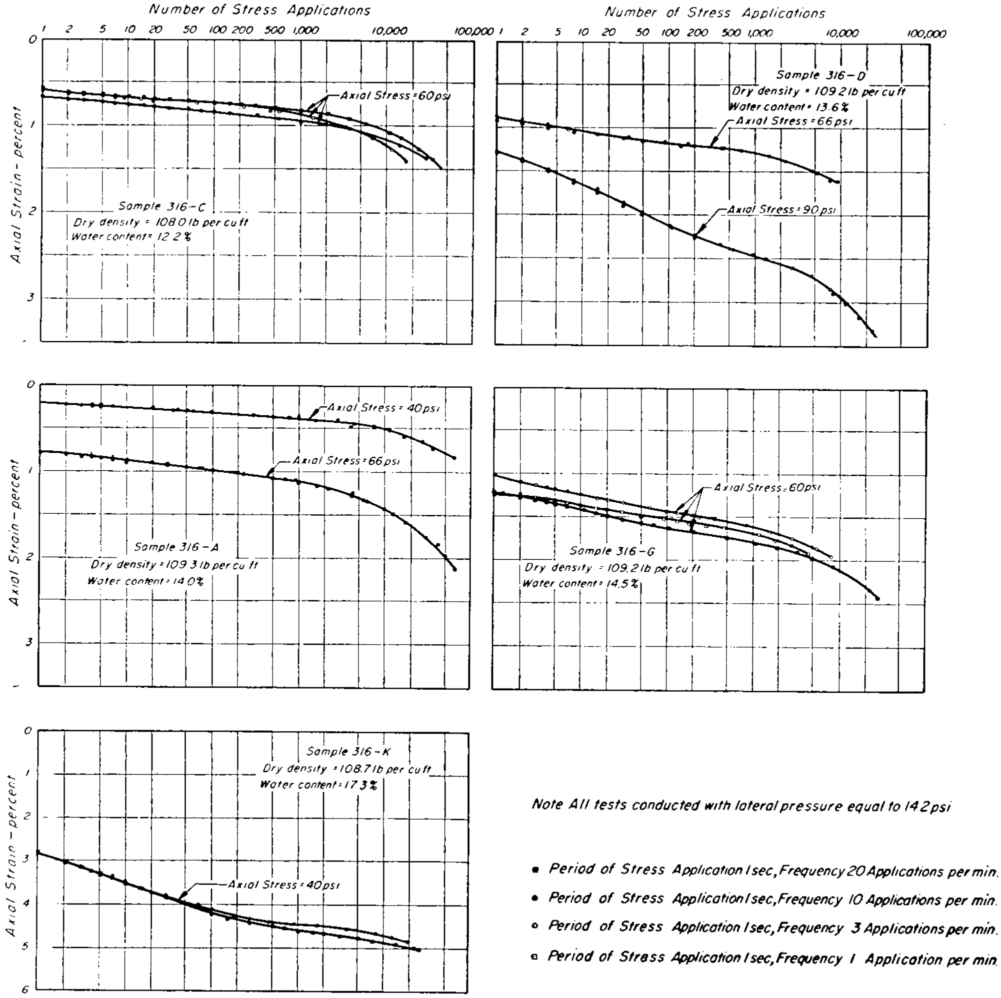


Figure 12. Effect of frequency of stress application on soil deformation.

quencies of application. The frequencies investigated ranged from 1 to 20 applications per minute. The number of stress applications varied from 10,000 to 100,000, and in all cases the duration of the applied stress was 1 second.

Typical results obtained in a number of such tests are shown in Fig. 12. In general it was found that, for frequencies in the range investigated, the deformation of a specimen depended only on the number of stress applications and was independent of the frequency of the applications.

For example, two specimens were trimmed from a compacted sample having a water content of 17.3% and a dry density of 108.7 lb per cu ft. The lateral pressure of 14.2 psi was applied and each specimen was subjected to a series of repetitions of a 40 psi axial stress. The stress was applied for periods of 1 second, but on one specimen it was applied 20 times per minute while on the other specimen it was applied 3 times per minute. After the same number of stress applications there was very little difference between the deformations of the two specimens. One application caused an axial strain of about 2.8% which was increased to 4.2% after 100 applications and 4.8% after 10,000 applications. It is interesting to note the large deformation caused by one stress application, compared with the deformation caused by subsequent repetitions of this stress.

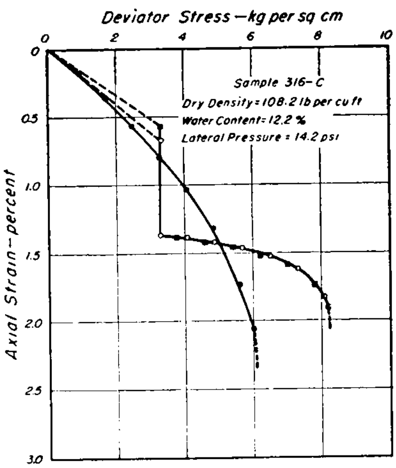
Fig. 12 shows similar test data for specimens of different water contents. Although similar specimens subjected to repeated loads of equal magnitude but different frequencies occasionally showed small differences in deformation after a given number of repetitions, these differences were in all cases quite small and there was no consistent difference in the effects of high and low frequencies of application.

Numerous tests were carried out in the frequency range of 20 applications per minute to 3 applications per minute from which it would seem reasonable to conclude that up to at least 100,000 applications of stress, the specimen deformation depended only on the number of stress applications and was not affected by the frequency of application. A limited number of tests indicated that this conclusion is also valid to frequencies as low as 1 application per minute.

INCREASE IN STRENGTH DUE TO REPEATED STRESS APPLICATION

In the tests to determine the effect of frequency of loading, the specimens were loaded to failure after the desired number of repetitions of load had been applied. In all cases the strength of the specimens after being subjected to repeated loading was found to be greater than that of previously unloaded specimens. Furthermore, the greater the number of load repetitions and the greater the axial compression during repeated loading, the greater was the increase in strength of the specimen.

Typical examples of this increase in strength due to repeated stress applications are shown in Figs. 13a and 13b. Fig. 13a shows the results of tests on three specimens. The first of these was loaded to failure in approximately 10 minutes in a normal type of triaxial compression test using a lateral pressure of 1 kg per sq cm and found to have a strength of 6 kg per sq cm. The other two specimens were subjected to the same lateral pressure and then to repeated applications of a 60 psi



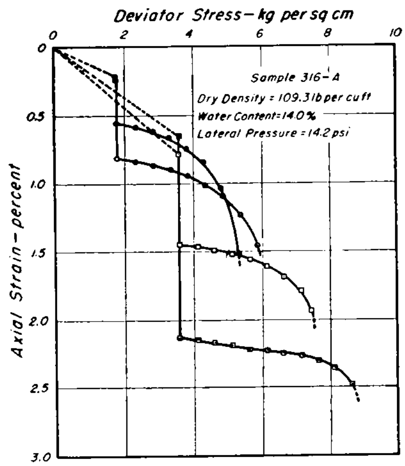
• Loaded to failure in approx. 10 min. in a normal quick triaxial compression test

∘ Loaded to failure in approx. 5 min. after 30,000 cycles with deviator stress 3.3 kg/cm².

▪ Loaded to failure in approx. 5 min. after 34,000 cycles with deviator stress 3.3 kg/cm²

--- Stress vs strain for first application of repeated load.

(a)



• Loaded to failure in approx. 5 min. after 12,000 cycles with deviator stress 1.8 kg/cm²

∘ Loaded to failure in approx. 5 min. after 60,000 cycles with deviator stress 1.8 kg/cm²

▪ Loaded to failure in approx. 5 min. after 10,000 cycles with deviator stress 3.6 kg/cm²

▫ Loaded to failure in approx. 5 min. after 65,000 cycles with deviator stress 3.6 kg/cm²

--- Stress vs strain for first application of repeated load.

(b)

Figure 13. Effect of repeated loading on the strength of partially saturated silty clay.

axial stress until they had the same axial strain of 1.35%; on one specimen, 30,000 repetitions of stress were applied and on the other specimen 34,000 repetitions were required to cause the same axial strain. These two specimens were then loaded to failure using a normal loading procedure and found to have the same strength of 8.2 kg per sq cm, representing an increase in strength of about 35% over that of the first specimen.

Fig. 13b shows the results of tests on four specimens trimmed from the same compacted sample. Two of the specimens were subjected to 12,000 and 60,000 repetitions of a 40 psi axial stress, causing axial strains of 0.55% and 0.8% respectively. The other two specimens were subjected to 10,000 and 65,000 repetitions of a 66 psi axial stress causing axial strains of 1.45% and 2.12% respectively. The four specimens were then loaded to failure. The specimen with the least deformation during repeated loading had a strength of 5.4 kg per sq cm and the specimen with the highest deformation during repeated loading had a strength of 8.75 kg per sq cm. The specimens with 0.8% and 1.45% strains during repeated loading had strengths of 5.9 and 7.5 kg per sq cm respectively.

The increase in strength of the specimens due to repeated load application may be attributed partly to an increase in density of the specimens during the tests; a part of the measured strength increase may also be due to an increase in strength with time. The tests were conducted on partially saturated specimens and it would be expected that a part of the axial compression would be due to compaction. However, it is interesting to note the considerable increase in strength of the soil after a large number of repeated stress applications. In the tests shown in Fig. 13a repeated loading caused the specimens to increase in strength by about 35%. In the tests shown in Fig. 13b an increased magnitude of repeated loading caused an increase in strength of about 60%.

It is also interesting that such large strength increases can occur in compacted soils. The samples were compacted by 125 tamps, using a tamping pressure of 225 psi, to a relative density of 90% based on the Modified AASHO test. Presumably, as evidenced by the data in Fig. 13a, a series of applications of even a 60 psi pressure can cause further increase in density and an increase in strength. These data would seem to demonstrate the beneficial effects that highway traffic may have on the strength of partially saturated subgrades.

EFFECT OF APPLIED STRESS ON SOIL DEFORMATION DURING REPEATED LOADING

A number of tests were conducted to investigate the effect of the magnitude of the axial stress on the deformation of partially saturated test specimens subjected to repeated loading in triaxial compression tests. Samples were compacted by kneading compaction in 6 inch diameter molds. From each compacted sample, five or six specimens were trimmed and subjected to triaxial compression tests using the same lateral pressure of 14.2 psi. However the axial stress was varied for different specimens, within the range of 28 to 114 psi depending on the stiffness of the specimens. In any series of tests on specimens trimmed from the same sample, the same frequency of stress application was used and the period of stress application was 1 second.

The results of four series of such tests on specimens of various water contents but approximately equal densities are shown in Figs. 14 and 15. In each test series, the general pattern of the curves of strain vs. number of stress applications is the same.

The curve, on a semi-logarithmic plot, expressing the relationship between strain and number of applications of stress, also has a somewhat characteristic shape; it is relatively flat for a number of applications and then curves downwards relatively sharply. However, the number of applications at which this sharp curvature in the curve develops varies with both the magnitude of the applied stress and the water content of the specimen. From the tests conducted to date, it appears that for two specimens exhibiting a similar magnitude of strain in the initial part of the strain vs. number of stress-application curves, the sharp downward curvature in the curve occurs at a lower number of repetitions for the drier specimens than for the wetter specimens.

It is interesting to note that a specimen may support a considerable number of stress applications without any apparent sign of excessive deformation and then fail relatively suddenly

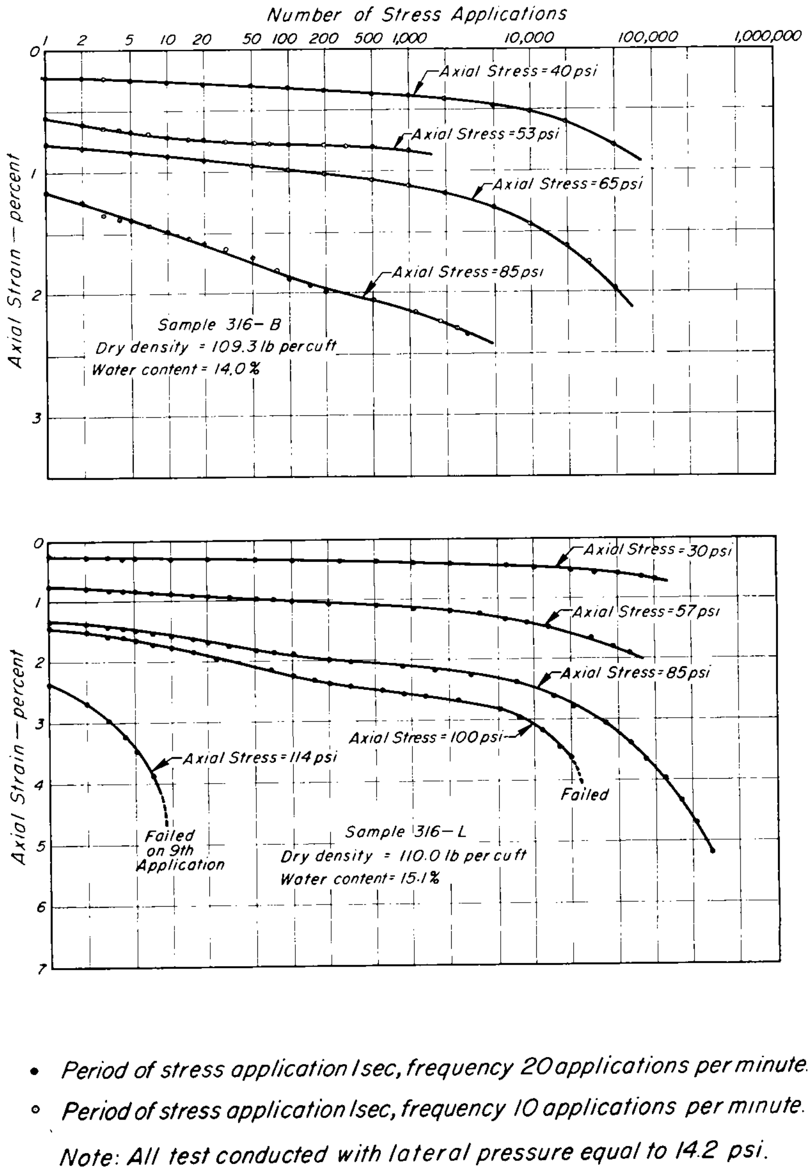


Figure 14. Effect of applied stress on soil deformation during repeated loading.

after a small number of additional applications. For example, a specimen with a water content of 15.1% and a density of 110 lb per cu ft deformed only 3.5% after 20,000 repetitions of a 100 psi stress but failed completely after 23,000 repetitions.

Within the range of water contents investigated and for samples with approximately equal densities, the lower the water content the lower was the deformation under 1 application of a given stress. This may be seen from Fig. 16 which shows the deformation of the various specimens after 1 application of stress. A similar pattern of curves is obtained if the deformation after any constant number of applications of stress is plotted against stress, as shown in Fig. 17 for 100,000 stress applications. Thus it would appear that a general

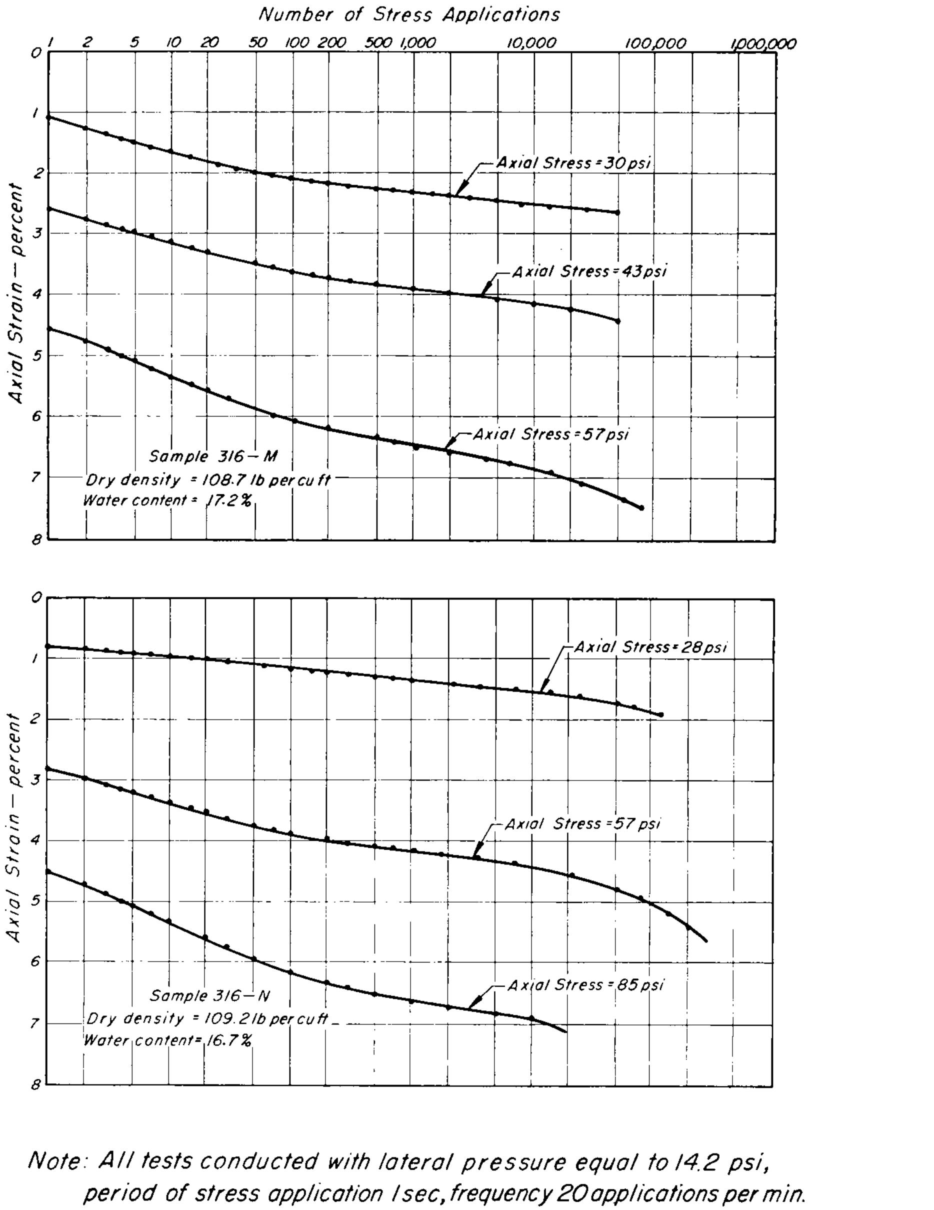


Figure 15. Effect of applied stress on soil deformation during repeated loading.

relationship might exist, for all the samples, between the deformation after 1 application of a given stress and the deformation after any number of applications of the same stress. Unfortunately no such general relationship could be established due to the different positions at which the sharp downward curvature develops in the strain vs. number of stress applications curves for samples of different water contents.

From a series of curves showing the deformation of identical specimens under different numbers and magnitudes of repeated stress applications, it is possible to establish a rela-

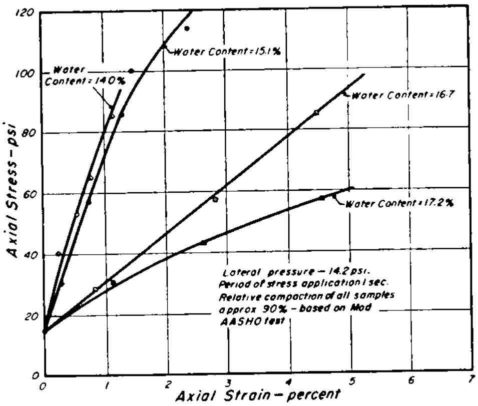


Figure 16. Deformation after one stress application for specimens of various water contents.

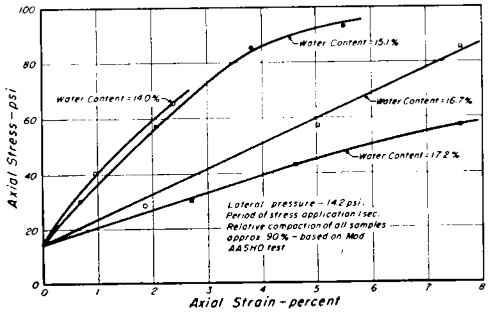


Figure 17. Deformation after 100,000 stress applications for specimens of various water contents.

tionship between numbers and magnitudes of applied stresses causing the same deformation of the specimen. Thus, a given number of applications of any given stress can be shown to be equivalent, in terms of specimen deformation, to a different number of applications of any other stress. For example, the equivalent effects of different numbers and magnitudes of repeated stress applications for sample 316L, having a water content of 15.1% and a density of 110 lb per cu ft are shown in Fig. 18; the curves in this figure were determined from the test data in Fig. 14 by plotting magnitudes and numbers of applications of stress causing equal amounts of strain. Fig. 19 shows the same information in a somewhat different and possibly more convenient form; the curves in this figure were determined from the curves in Fig. 18.

From a series of curves such as that shown in Fig. 19 the deformation of a specimen of the same condition and subjected to the same lateral pressure after any number of applications of any axial stress can readily be determined. Furthermore, by interpolating between the curves, equivalent numbers of applications of different stresses can be obtained. For example, 1,000 applications of a 90 psi axial stress cause the same strain, 2.3%, as 1 million applications of a 43 psi axial stress or about 12 million applications of a 30 psi axial stress. An equivalent number of repetitions of a standard axial stress could be determined for any number of repetitions of any axial stress, if desired.

The concept of equivalent wheel loads has been used for some years in the method of pavement design used by the State of California Division of Highways. The anticipated numbers and magnitudes of wheel loads to be imposed on a proposed highway are converted, by means of the chart shown in Fig. 20, to an equivalent number of repetitions of a 5,000-lb wheel load; this equivalent number of repetitions is included as a factor in the determination of the required pavement thickness. The curves for determining equivalent wheel loads in Fig. 20 were indicated by test-track studies.

It will be seen that there is some similarity between the curves in Fig. 19 and the design curves shown in Fig. 20. It would not be reasonable to expect any close degree of agreement between the design curves and those determined by this investigation since a determination of equivalent numbers and magnitudes of stress applications for use in design must take into account factors not included in the experimental data presented in this paper. For example, the tests were conducted using a constant lateral pressure of 14.2 psi; this condition is not likely to be realized in practice where the higher vertical pressures on subgrades will be accompanied by higher lateral pressures. Nevertheless, the fact that there is some similarity between the results of these preliminary tests and data indicated by experience with actual pavements does lend support to the belief that investigations of the effects of repeated loading on soils may lead to a more rational method of pavement design. It also provides support for the concept of equivalent wheel loads as a means

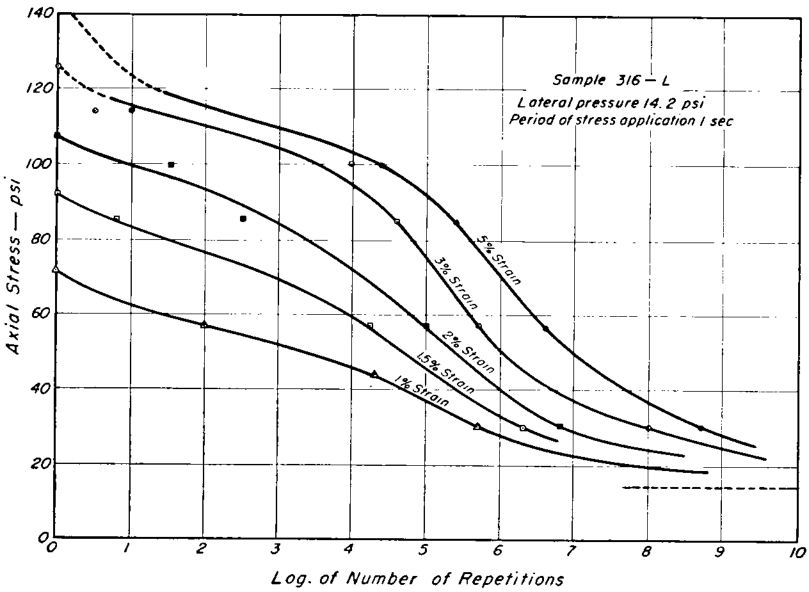


Figure 18. Combinations of axial stress and number of repetitions causing equal axial strains.

of determining the influence of intensity and frequency of traffic on the desirable thickness of pavement, and indicates that laboratory tests may ultimately provide more data on which to base the determination of the effects of different traffic intensities.

From the results presented in Figs. 14 and 15 it appears that equivalent numbers and magnitudes of stress applications established for one soil condition will not necessarily apply to other soil conditions. Furthermore, equivalent numbers and magnitudes of stress

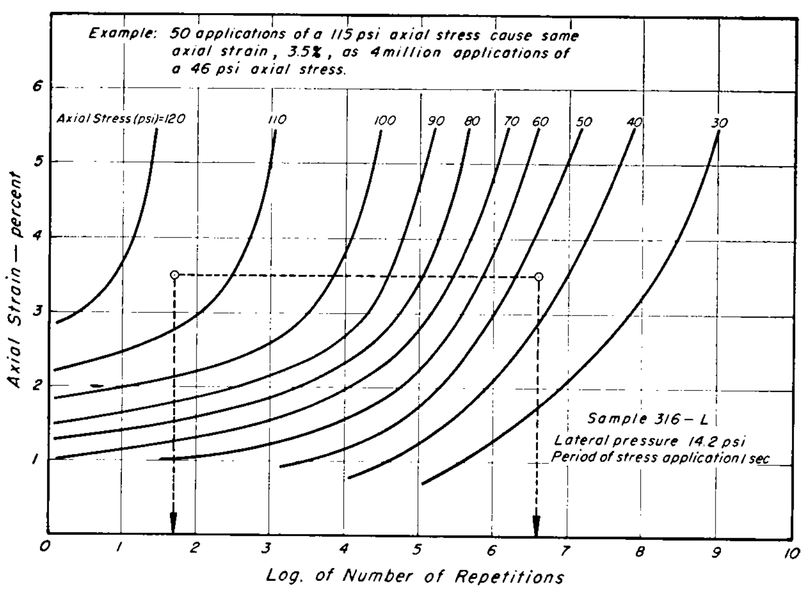


Figure 19. Chart for determining equivalent number of stress applications.

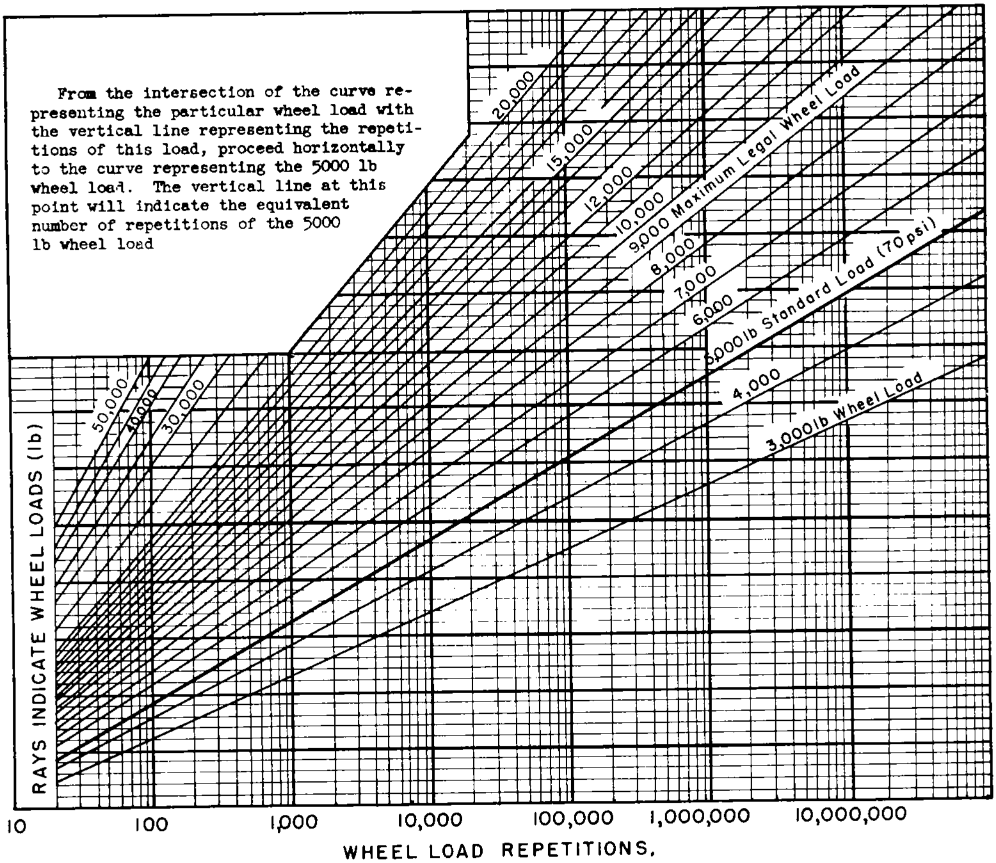


Figure 20. Chart for converting miscellaneous dual-tire wheel loads to the equivalent number of 5,000-lb. dual-tire wheel loads, June 1, 1950. Courtesy F. N. Hveem.

applications may be quite different for different soils. It is hoped that further investigations will throw some light on these subjects.

CONCLUSIONS

The main conclusions presented in the preceding pages may be summarized as follows:

1. The deformation of specimens of silty clay subjected to repeated stress applications at the rate of 10 per minute, was considerably greater than that of similar specimens subjected to a sustained stress of the same magnitude.

2. The stress required to cause 5% strain of specimens of silty clay in "slow rate of loading—repeated load" tests was lower than that required to cause 5% strain of similar specimens in "slow rate of loading—sustained load" tests or normal unconfined compression tests. For samples having a relative compaction, based on the modified AASHO compaction test, of 95% to 100%, the stress required to cause 5% strain of a given specimen in a "slow rate of loading—repeated load" test was only 60% to 70% of that required to cause 5% strain of the specimen in either a normal unconfined compression or a "slow rate of loading—sustained load" test.

3. For specimens having a relative compaction of 95% to 100%, the strain under a stress equal to one half the normal unconfined compressive strength, was about 60% greater in a "slow rate of loading—repeated load" test than in either a "slow rate of loading—sustained load" test or a normal unconfined compression test.

4. In "slow rate of loading—repeated load"

tests on samples of silty clay having degrees of saturation of about 95%, the modulus of resilient deformation increased as the stress increased, except near failure; that is, the specimens became stiffer with increasing magnitude of repeated stress.

5. The moduli of resilient deformation of unconfined samples of silty clay having a degree of saturation of about 95% were considerably greater than the initial tangent moduli for identical specimens determined by unconfined compression tests.

6. The results of numerous tests to determine the deformation of partially saturated specimens of silty clay subjected to repeated applications of a constant stress in triaxial compression tests indicate that up to at least 100,000 applications of stress, the specimen deformation depends only on the number of stress applications and is independent of the frequency of stress application within the frequency range of 3 to 20 applications per minute. A limited number of tests indicate that this conclusion is also valid to frequencies as low as 1 application per minute.

7. The strength of partially saturated specimens of silty clay having a relative compaction of 90%, after being subjected to repeated loading, was considerably greater than that of previously unloaded specimens; and the greater the axial compression during repeated loading the greater was the increase in strength. A series of applications of only a 60 psi axial stress caused an increase in strength of about 35%.

8. A partially saturated specimen of silty clay subjected to repeated applications of a constant stress in a triaxial compression test may withstand a considerable number of stress applications without any apparent sign of excessive deformation and then fail relatively suddenly after a small number of additional applications.

9. From a series of curves showing the deformation of identical specimens under different numbers and magnitudes of repeated stress applications, it is possible to establish a relationship between numbers and magnitudes of applied stresses causing the same deformation of the specimen.

10. The fact that there is some similarity between laboratory test results to determine equivalent numbers and magnitudes of repeated loads and data indicated by experience with actual pavements suggests that further laboratory investigations of the effects of repeated loads may lead to improved methods of pavement design.

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