Relationship Between Density and Stability of Subgrade Soils

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This paper discusses some of the limitations of the concepts that the stability of a compacted soil increases with an increase in density and that every effort should be made to attain the highest practical density in field compaction. Comprehensive test data on the relationship between density, stability, water content, and degree of saturation for two soils compacted by kneading action are presented, together with a description of the Triaxial Institute kneading compactor. In the tests, stability is measured by triaxial-compression tests and by the Hveem Stabilometer. The significance of the criterion of stability adopted with respect to the relationship between density and stability is discussed. The relationship between the attainable stabilities and those determined by specifications based on the standard Proctor and modified AASHO compaction tests is demonstrated.

Data are also presented on the density-versus-stability relationships of soils compacted by impact and static procedures, and the effect of compaction method on the density-versus-stability relationship is shown. The conflicting conclusions which may be reached on the basis of tests on samples prepared by static and impact methods or by static and kneading methods are indicated.

● SINCE the principles of soil compaction were first described by R. R. Proctor (1) some 20 years ago, the use and interpretation of soil-compaction tests have changed relatively little. Though new compaction procedures have been developed, tests are still conducted to determine the optimum water content at which a given compactive effort will produce the maximum density of the soil. This water content and density are then used as criteria for field compaction of earth fills and pavements.

In adopting these criteria, it is implicitly assumed that density is a measure of the desirable characteristics of the compacted soil, such as strength or stability, compressibility, and sometimes permeability. A recent article (2) states: "This optimum condition, producing a maximum density for the given compaction method, is generally the strongest and most permanently stable condition for the soil resulting from the particular compaction procedure." Properly interpreted, this statement is no doubt true, but its validity will depend on the conditions to which the compacted soil is exposed. There is considerable evidence (3, 4, 5, 6, 7) that maximum strength and maximum density of a soil, even for the same compaction method, are not necessarily attained at the same time; this evidence has been obtained in both laboratory and field tests. Nevertheless, many engineers seem to believe that the higher the density to which a soil is compacted, the greater will be its strength and stability and that every effort should always be made to obtain the highest possible density. It would seem pertinent, therefore, to discuss some of the limitations of this concept as indicated by the results of recent laboratory tests. Such a discussion is particularly desirable now that pavements are being designed for conditions other than complete saturation (8); an understanding of the relationship between density and stability would seem to be essential for the intelligent design of such pavements.

LABORATORY COMPACTION TESTS

The object of any laboratory compaction test is to reproduce in the laboratory the compaction effects produced by equipment in the field. A variety of procedures are in use at the present time. In most

tests, the soil is compacted by dropping a falling weight on to the surface of the soil, a process referred to as "impact compaction." In some cases, soil is compacted by subjecting it to a static load, which is built up slowly to some predetermined value and then released, a process referred to as "static compaction." The fact that these two methods of compaction result in density-water-content curves having different forms and that they produce soil specimens having quite different stress-strain characteristics has long been recognized (3).

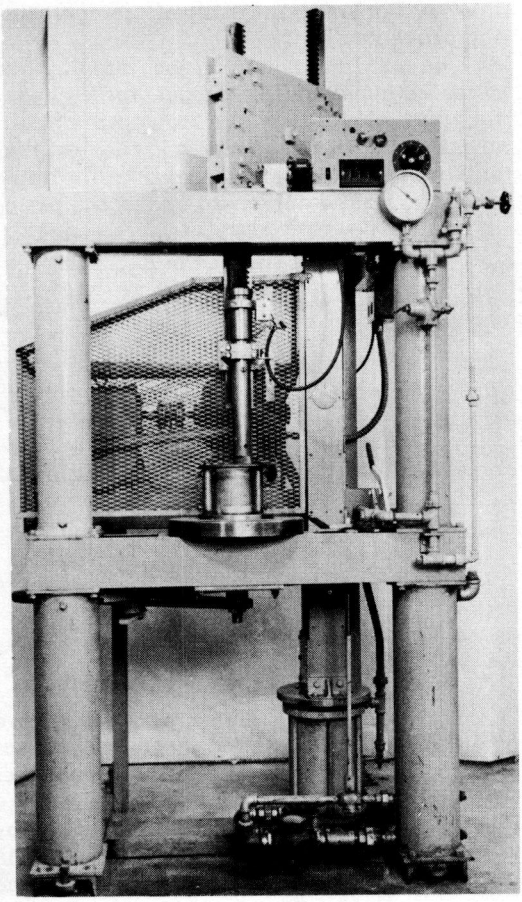


Figure 1. Triaxial Institute Kneading Compactor.

Extensive studies of soils compacted in the field by sheepsfoot and rubber-tired rollers have also shown that the stress-strain characteristics of those soils are different from those prepared in the laboratory by either static or impact compaction. Since laboratory-prepared

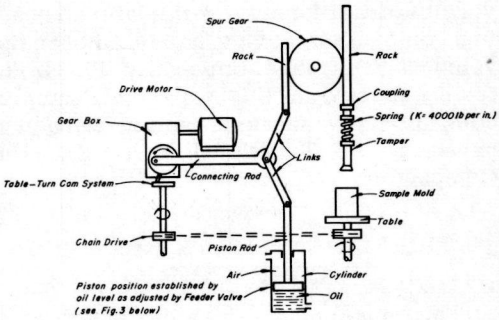


Figure 2. Compactor mechanical tamping system.

specimens are used for design purposes, in recent years considerable effort has been devoted to the development of laboratory procedures which will satisfactorily duplicate the effects of field compaction.

These efforts have resulted in a compaction method which more closely simulates the effect of sheepsfoot or rubber-tired rollers. The action of this equipment is to build up the pressure on a small area of soil to a definite value, maintain this pressure for a small element of time, and then gradually reduce the pressure; this method of load application has been termed a "kneading action." It has been shown that the compaction of soil specimens by this method offers good possibilities for the satisfactory preparation of laboratory samples having properties sufficiently close to those of the soil compacted in the field.

A laboratory kneading compactor has been developed at Northwestern University (2) and, on behalf of the Triaxial Institute, a model originally designed and used by the California Division of Highways has been modified and developed at the Uni-

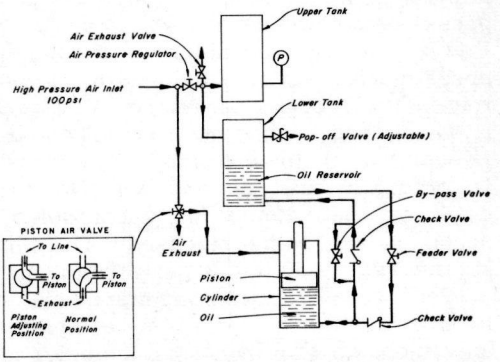


Figure 3. Compactor hydropneumatic control system.

versity of California. A miniature kneading compaction device has also been developed at Harvard University (9). In the tests reported in this paper, all samples compacted by kneading action were prepared by the Triaxial Institute Kneading Compactor.

TRIAXIAL INSTITUTE KNEADING COMPACTOR

This equipment, a view of which is shown in Figure 1, may be used for compacting soil or asphalt samples. It is a mechanical device for applying a series of tamps of fleeting pressures by means of a tamping foot to a sample contained in a cylindrical mold. The shape of the tamping foot is approximately that of a segment of a circle having the same diameter as the forming mold; its area is approximately a fourth that of the cross-sectional area of the mold.

A schematic drawing of the mechanical tamping system, which employs a toggle-press principle, is shown in Figure 2. Power for the operation of the toggle-press mechanism is provided by an electric motor through a speed reduction gear, flywheel, and connecting rod. The action is such that in any one tamp the pressure is gradually built up and then allowed to dwell on the sample for a fraction of a second before being released. The compaction rate is 30 tamps per minute.

The overall dimensions were selected to provide ample space for compacting specimens up to 6 inches in diameter and 12 inches in height.

In order to control the pressure exerted on the test specimen by the tamper, a combination hydraulic-pneumatic control system is used. A schematic drawing of this system is shown in Figure 3. Air from a high-pressure line passes through a pressure regulator, which can be set at any predetermined value, into the upper portion of the oil reservoir. This reservoir is situated in the pipe column which also serves as a member of the compactor frame. A feeder valve controls the flow of oil into the cylinder containing the piston, which is attached to the lower link of the press. This feeder valve is used to adjust the height of the tamper in the mold prior to the start of the compacting procedure.

The maximum load on the tamping foot remains constant throughout the compaction procedure since, as soon as the piston exerts more pressure on the oil than exists in the compressed air in the tank, oil is squeezed out from under the piston through a one-way check valve back into the oil reservoir and a pop-off valve, which is set at the predetermined pressure, allows excess air to escape. To ensure that the full pressure will always be applied to the sample, a bypass valve is kept open a certain amount during the entire process. The pressure of the compressed air and the setting of the bypass valve govern the pressure exerted by the tamper on the sample.

Before the compactor is used, it must first be calibrated by measuring the load exerted by the tamper foot for different air pressures and settings of the bypass valve. This is done by inserting a dynamometer above the tamper foot and obtain-

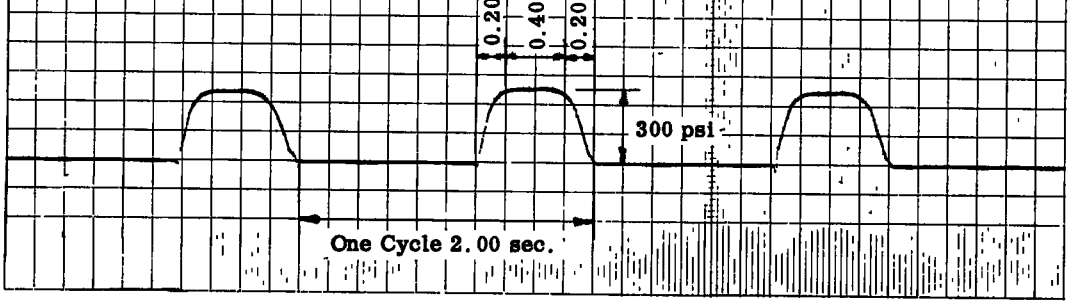
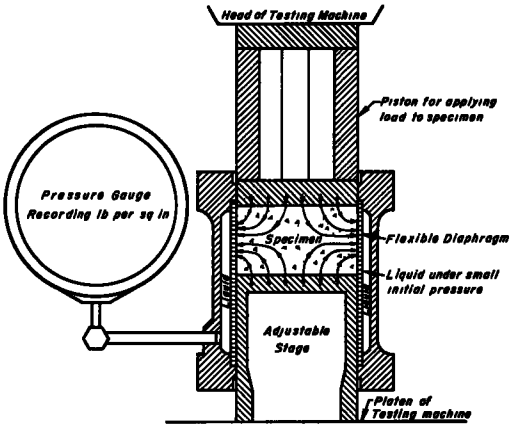


Figure 4. Typical oscillogram showing load vs. time relationship for the Triaxial Institute Kneading Compactor.

ing oscillograms of the relationships of load versus time. A typical oscillogram obtained in this way during compaction of a silty clay is shown in Figure 4. It will be seen that the pressure-versus-time curves consist of three distinct parts: first, the application, second the dwell, and third, the release.



Note: Specimen given lateral support by flexible side wall which transmits horizontal pressure to liquid Magnitude of pressure may be read on gauge

Figure 5. Hveem Stabilometer.

STABILITY

The stability of a soil may be broadly defined as the load or pressure which it can support without excessive deformation. Exactly what constitutes excessive deformation is a matter of opinion. Because of the difficulty of measuring stability in the field a variety of laboratory methods for measuring stability have been developed and correlated with the performance of soils underlying pavements. Thus these test methods provide fairly reliable means for measuring the relative stabilities of soils.

Probably the most widely used index of the stability of a subgrade soil is the California Bearing Ratio which is based on the resistance to penetration of the soil by a plunger having a base area of 2 sq. in.

In California, the index of stability used for design is the resistance value as measured by a Hveem Stabilometer test (10). This is a closed-system, triaxial-compression test, as shown in Figure 5, using a specimen 4 inches in diameter and about 2½ inches high. The vertical load on the specimen is applied at a constant rate of strain (0.05 inches per minute) while the pressure is allowed to build up in the liquid cell which encircles and confines the specimen laterally. The lateral pressure, P_H, transmitted through the specimen when the vertical pressure, P_V, is 160 psi. is recorded. An indication of the surface roughness of the specimen is then obtained by determining the displacement, D, of the specimen, and the resistance value or stabilometer R value is computed from the formula

$$R = 100 - \frac{100}{\frac{2.5}{D}\left(\frac{P_V}{P_H} - 1\right) + 1}$$

The R values determined in this way have been correlated with the service behavior of soils under pavements and have been found to be a satisfactory measure of relative stabilities.

A third test which may be used to measure the relative stability of a soil is the triaxial compression test, performed under constant lateral pressure. Either the ultimate strength of a test specimen or the modulus of deformation at a particular strain may be used as an index of stability.

In the tests reported in this paper, all three of the above methods were used. The methods are used, however, only to compare relative stabilities of samples, and no attempt is made to compare the values obtained by the various methods.

RELATIONSHIP BETWEEN DENSITY AND STABILITY OF SOILS COMPACTED BY KNEADING ACTION

Since kneading compaction best simulates the effects of compaction equipment, it was considered desirable to determine the relationship between density and stability for samples compacted by this method. A comprehensive investigation was made using a silty-clay soil (liquid limit = 37, plastic limit = 23) from Vicksburg, Mississippi. A series of tests were made to establish the relationships between density and water content and between strength or modulus of deformation and water content for the soil compacted at each of six different compactive efforts.

For tests at any one compactive effort,

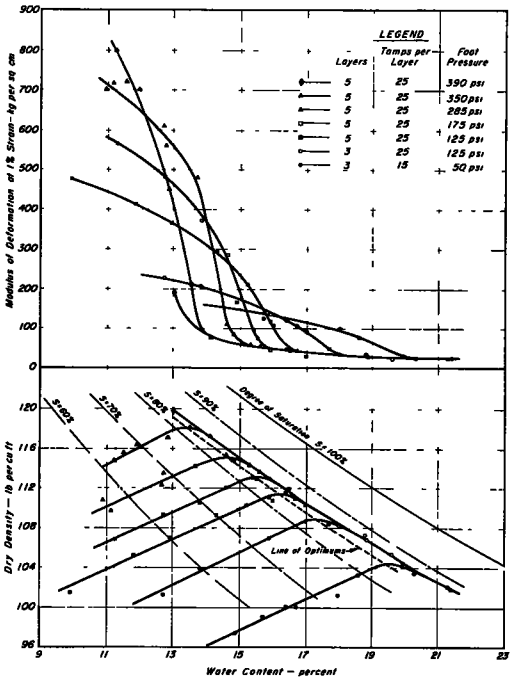


Figure 6. Relationship between water content, dry density, and modulus of deformation at 1% strain.

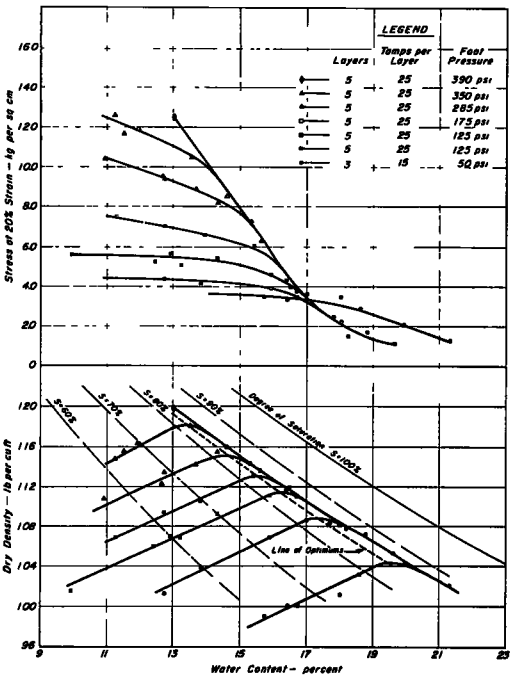


Figure 7. Relationship between water content, dry density, and stress at 20 percent strain.

the soil was first oven dried and samples were then mixed at about six different water contents. Each sample was placed in a sealed container and allowed to condition for one day prior to compaction. The samples were then compacted in 6-inch-diameter molds to form specimens 4½ inches high. The compacted samples were used to determine the relationship of dry density versus water content in the usual manner. After the weight and vol-

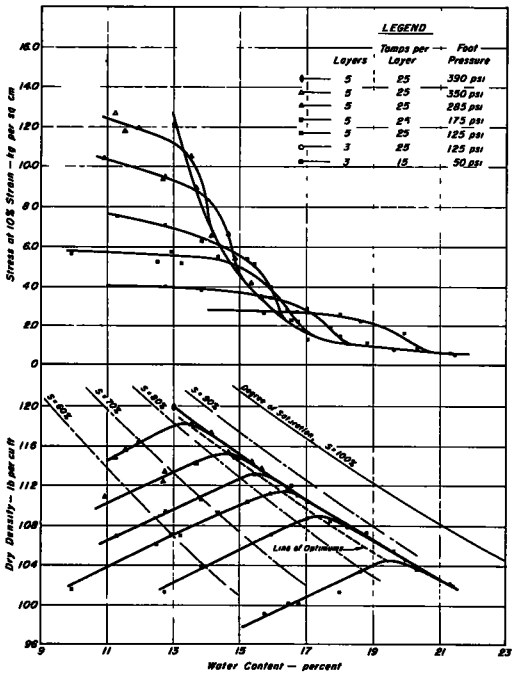


Figure 8. Relationship between water content, dry density, and stress at 10 percent strain.

ume of a compacted sample had been measured and a sample had been taken for water-content determination, a specimen was cut from the sample having a diameter of 1.4 inches and a height of about 4 inches.

This specimen was subjected to a triaxial-compression test of the unconsolidated, undrained type, using a confining pressure of 1 kg. per sq. cm. Load was applied at the rate of 8 kg. per min. until failure, and the stress-versus-strain relationship for the specimen was determined. In this way the water content, density, strength, and deformation characteristics of each compacted sample were obtained.

The results of these tests are shown in Figures 6, 7, and 8. Figure 6 shows the density-versus-water-content curves and the modulus of deformation at 1 percent strain versus water content for each compactive effort. It will be seen that for each compactive effort the modulus of deformation is low on the wet side of optimum but that it begins to increase as the optimum water content is approached and, for the range of water contents used in these tests, continues to increase with decreasing water content on the dry side of optimum even though the density of the samples is decreasing.

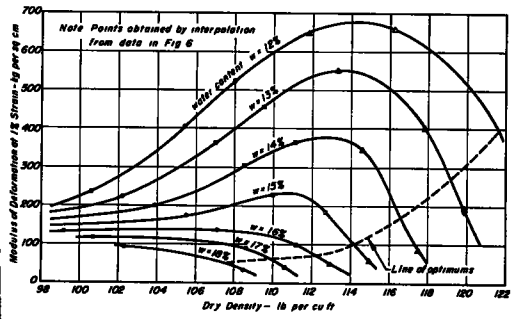


Figure 9. Relationship between dry density and modulus of deformation at 1% strain for constant water contents.

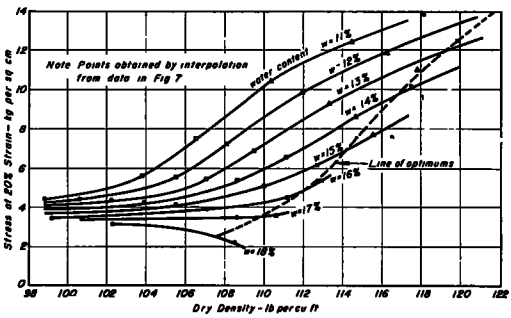


Figure 10. Relationship between dry density and stress at 20% strain for constant water contents.

The significance of these results is best seen from the relationship of modulus of deformation, density and water content as shown in Figure 9. These curves, showing modulus of deformation versus dry density at a series of constant water contents, were interpolated from the results in Figure 6. It will be seen that the effect of increased density on the modulus of deformation of the soil depends on both the water content and the range of densities considered. At a water content of 13 percent, an increase in dry density from 100 to 110 lb. per cu. ft. caused an increase in modulus of deformation from 190 to 470 kg. per sq. cm.; at a water content of 17 percent, however, the same increase in density caused a reduction in modulus of deformation from 120 to 50 kg. per sq. cm. Thus, a given increase in density may increase or decrease the modulus of deformation, depending on the water content of the soil.

Again, at a water content of 13 percent, an increase in dry density from 100 to 114 lb. per cu. ft. caused an increase in modulus of deformation from 190 to 560 kg. per sq. cm., but a further increase from 114 to 120 lb. per cu. ft. caused a reduction in modulus of deformation from 560 to 175 kg. per sq. cm. The effect of increased density may thus be to increase or reduce the modulus of deformation depending on the range of densities concerned.

Conditions under which an increase in density may cause a reduction in strength or deformation index are associated with the characteristic overlapping of the curves, in Figure 6, showing the relationship of this index to the water content of the soil.

The effect of dry density and water content on the strength of the compacted soil is shown in Figures 7 and 8. On the dry side of the optimum water content for any given compactive effort, specimens failed by shearing along a well-defined plane. At about the optimum water content and at higher water contents, specimens bulged considerably but continued to support increasing loads. For such specimens, failure is considered to occur when the deformation becomes excessive; it is often defined as the stress required to cause say 10 or 20 percent strain of the test specimen.

Figures 7 and 10 show the variation of strength with dry density and water content when failure is defined as the stress required to cause 20 percent strain. As for the modulus of deformation data, the curves in Figure 10 have been obtained by interpolation from the data in Figure 7. It is readily seen that within the range of densities investigated there is a marked difference between the effect of increasing

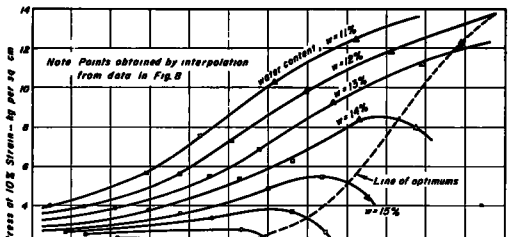


Figure 11. Relationship between dry density and stress at 10% strain for constant water contents.

density on strength and on modulus of deformation. Except for the high water content of 18 percent, an increase in dry density in all cases caused an increase in strength; this type of density-stability

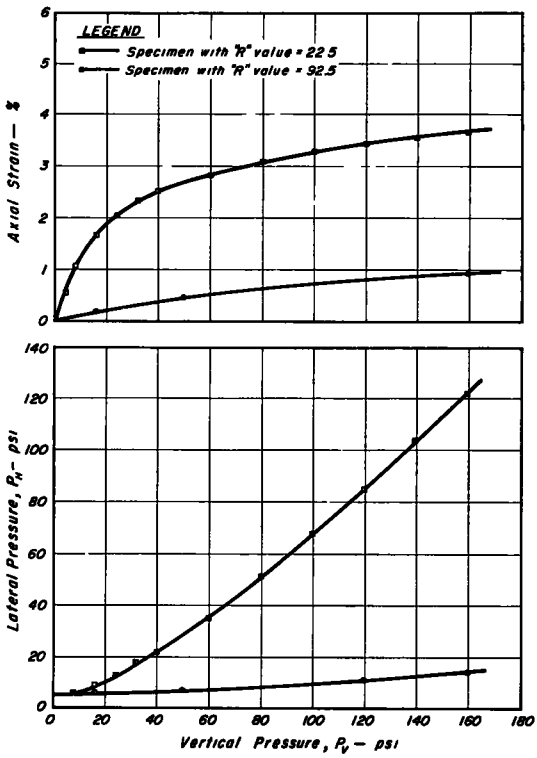


Figure 12. Typical results of stabilometer tests on specimens of silty clay with high and low stabilities.

relationship is associated with cases where there is no overlapping of the curves of stability versus water content for constant compactive efforts. The magnitude of the effect of increasing density, however, decreased with increasing water content. At a water content of 14 percent, an increase in density from 100 to 110 lb. per cu. ft. caused an increase in strength of about 50 percent, while at a water content of 17 percent, the same increase in density had practically no effect on the strength.

The test results when failure is defined as the stress required to cause 10 percent strain are shown in Figures 8 and 11. For these results, as for the modulus of deformation at 1 percent strain data, there is some overlapping of the curves of strength versus water content for constant compactive efforts, indicating that an increase in dry density may cause a reduction in strength. In this case there is more variation in form of the curves of strength versus density at constant water contents than for the curves in Figure 10. For the range of densities and water contents investigated, the strength increases consistently with density for water contents below 13 percent, but for water contents above 14 percent, the strength may increase or decrease with increasing density depending on the range of densities considered.

It will be seen from these results that the effect of density and water content on the stability of the soil depends on the criterion used to define stability. If the ultimate strength or the stress at 20 percent strain is used as a criterion of stability, then it may in general be true that stability increases with density. If the modulus of deformation at 1 percent strain or the strength as defined by the stress required to cause 10 percent strain is used as a criterion of stability, then for partially saturated soils, stability may

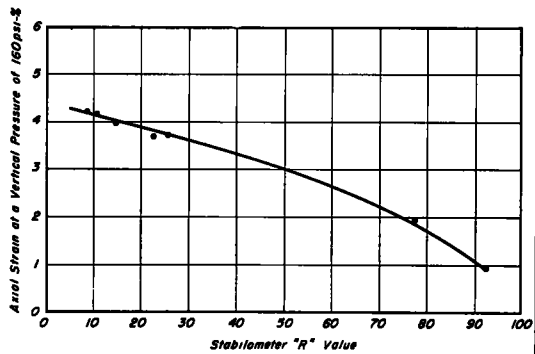


Figure 13. Relationship between stabilometer R value and axial strain at which R value was determined.

increase or decrease with increasing density. In tests which are customarily used as criteria of stability, the strain of the specimen at which the measurement is taken is not always clearly defined. For example, in the California Bearing Ratio test, the strain of the soil subjected to load at the time the measurement is made is probably of the order of 5 percent. In the Hveem Stabilometer test, the strain of the specimen at the time the stability is determined varies with the water content and stability of the specimen.

Typical results of stabilometer tests on specimens of the silty clay having high and low stabilities are shown in Figure 12. It will be seen that for the specimen having a resistance value of 92.5 the strain at which this value was determined was 0.9 percent, while for the specimen having a resistance value of 22.5 the strain was 3.7 percent. For the Vicksburg silty clay, the variation of the strain at which the resistance value was determined for specimens with resistance values ranging from 7 to 92.5 is shown in Figure 13; the strains range from 0.9 to 4.2 percent. Thus in both the CBR and the Hveem Stabilometer tests, the stability of the soil is determined at strains appreciably less than 10 percent; on the basis of the compression-test data, it would be expected that an increase in density would not necessarily lead to an increase in stability, therefore, for soils compacted by kneading action.

In order to obtain some idea of the condition to which this soil might be compacted in the field, standard Proctor and modified AASHO tests were conducted to determine the optimum water contents and maximum dry densities given by these compaction procedures. The tests gave the following results:

Compaction Test	Optimum Water Content	Maximum Dry Density
Standard Proctor	18 %	105 pcf.
Modified AASHO	14 %	117 pcf.

On the basis of the standard Proctor test, this soil might be compacted at a water content of 18 percent to a relative compaction of 100 percent, that is to a dry density of 105 lb. per cu. ft. At this water content, both the modulus of deformation at 1 percent strain and the strength of the compacted specimens, show a slight reduction with increase in density; at a relative compaction of 100 percent based on the standard Proctor test, the modulus of deformation and the strength are higher than can be attained at higher values of relative compaction.

If compaction is controlled by the modified AASHO test, the soil might be compacted at a water content of 14 percent to a relative compaction of 90, 95 or 100 percent depending on the specifications, that is, to a density between 105 and 117 per cu. ft. It will be seen from Figure 9 that at a water content of 14 percent the maximum value of the modulus of deformation is attained at a density of 113 lb. per cu. ft., that is, a relative compaction of 97 percent. However, a further increase in relative compaction to 100 percent causes the modulus of deformation to be reduced to only 33 percent of its maximum value. In the case of strength (for 10 percent strain), the strength increases with density up to a relative compaction of 99 percent with only a slight reduction occurring if the relative compaction is further increased to 100 percent.

These results illustrate the deleterious effects of overcompacting a soil as well as those of using too high a water content. At the optimum water content of the standard Proctor compaction test (18 percent), the maximum modulus of deformation at 1 percent strain was only 95 kg. per sq. cm., while at the optimum water content of the modified AASHO compaction tests (14 percent), the maximum modulus of deformation was 385 kg. per sq. cm. Again, at a water content 1 percent above the modified AASHO optimum, the maximum stability for a relative compaction of 95 percent was only about 65 percent of that attained at the same relative compaction at the optimum water content. The importance of careful water content control in obtaining the maximum stability of partially saturated soils cannot be overemphasized.

Examination of the data in Figures 6, 7, and 8 shows that for each compaction curve there is a marked change in stability at about the optimum water content. At water contents above the optimum the stability is low, while at water contents below the optimum the stability is relatively high. These results would seem to indicate that the lower values of stability are associated with higher degrees of saturation, rather

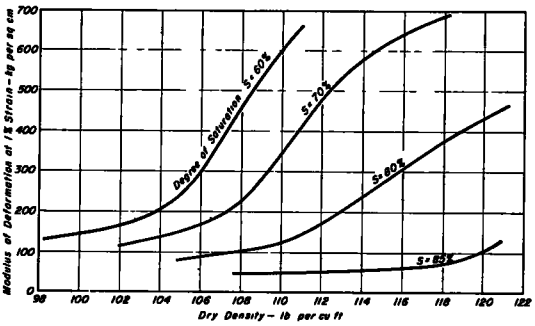


Figure 14a. Relationship between dry density and modulus of deformation at 1% strain for constant degrees of saturation.

than particular water contents, and that the degree of saturation may be a more-important factor in determining stability than the water content. Curves of modulus of deformation at 1 percent strain versus density for various constant values of the degree of saturation are shown in Figure 14a; these curves have been obtained by interpolation from the data in Figure 6. For a given degree of saturation, in all cases the modulus of deformation increases with density. The same is true of strength as may be seen from Figures 14b and 14c. It is interesting to compare the curves in Figure 14a with those showing the relationship between density and modulus of deformation at constant values of water content in Figure 9. While the stability of the soil at a given water content may increase or decrease with an increase in density, it may be concluded from Figure 14 that, within the range of densities and water contents investigated, for a given degree of saturation, the stability will increase with an increase in density and, for a given density, the lower the degree of saturation the higher will be the stability.

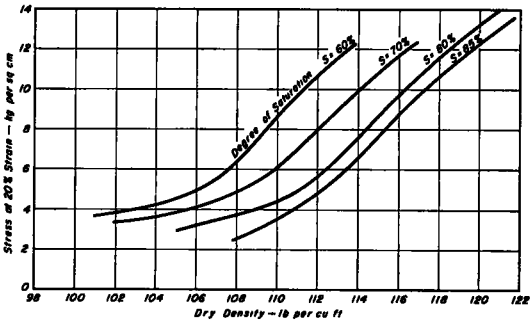


Figure 14b. Relationship between dry density and stress at 20% strain for constant degrees of saturation.

USE OF LINE OF OPTIMUMS FOR PREDICTING STABILITY CHANGES

It has been suggested (7) that the density and water-content conditions at which further increase in density causes a reduction in stability might be predicted from the position of the line of optimums determined by compaction tests. The line of optimums is the smooth curve passing through the peaks of a series of compaction curves and is usually approximately parallel to the zero air-voids curve. Consideration of the fact that the density versus stability relationship is dependent on the definition of stability will show that

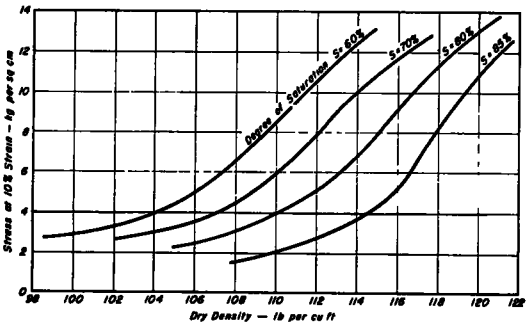
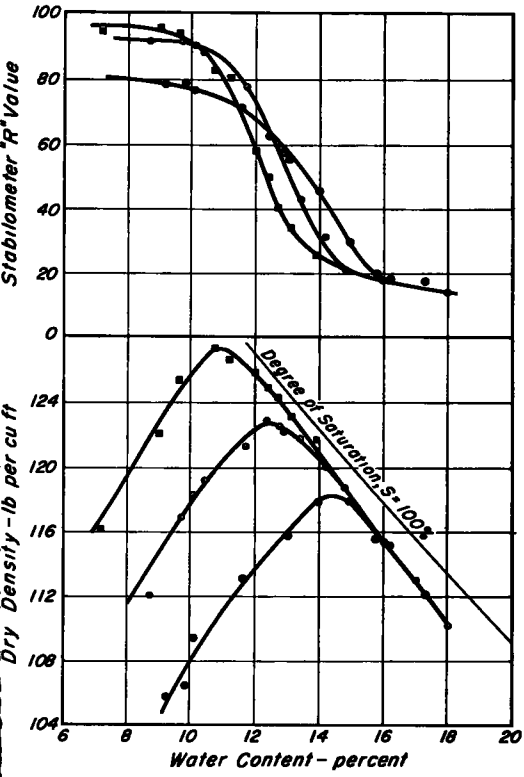
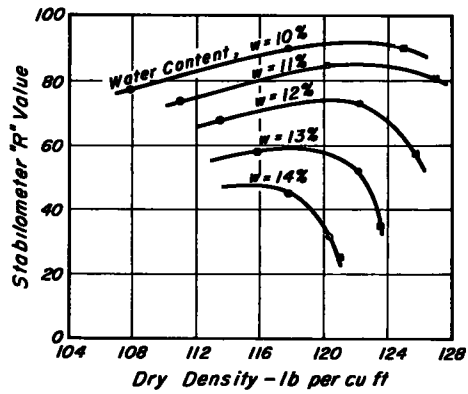


Figure 14c. Relationship between dry density and stress at 10% strain for constant degrees of saturation.

any relationship between the line of optimums and the configuration of the curves of density versus stability will also depend on the definition of stability, that is, on the magnitude of the strain used in the determination of stability. It is somewhat fortuitous, therefore, if the position of the line of optimums, when plotted on the curves of the density versus stability, happens to coincide with the peak points of these curves.

This may be seen from the results in Figures 6 to 11. The line of optimums determined by the compaction curves (Figures 6, 7, and 8) has been plotted on the curves of density versus modulus of deformation in Figure 9 and on the curves of density versus strength in Figures 10 and 11. It will be seen that the peak points of the curves of density versus modulus of deformation occur at densities lower than those determined by the line of optimums; that if strength is determined on the basis of 10 percent strain, the line of optimums





LEGEND

	Layers	Tamps per Layers	Foot Pressure
■——	5	25	550
○——	5	25	350
●——	5	25	150

Figure 15. Water content, density, and stability relationships for sandy clay for kneading compaction.

corresponds fairly closely with the peak points of the density-versus-strength curves; and that if strength is determined on the basis of 20 percent strain, the peak points of the curves of density versus strength occur, if at all, at densities considerably higher than those determined by the line of optimums.

Thus it would appear that if stability is defined as the stress required to cause 5 to 10 percent strain in the triaxial-compression tests, the line of optimums will be a good indicator of the density and water content conditions at which further increase in density will cause a reduction in stability; for other amounts of strain, the method would be unsatisfactory. It is interesting to note that the magnitude of the strain for which the line of optimums gives a satisfactory indication of the peak points on the density versus stability curves is of the same order of magnitude as that used in the CBR test. It was for stability determinations made by this test that the use of the line of optimums for indicating peak points of stability was suggested and found to be relatively satisfactory. A similar approximate correlation should not necessarily be expected, however, if other methods of stability determination are used.

EFFECT OF COMPACTION METHOD ON THE STABILITY VERSUS DENSITY RELATIONSHIP

In order to determine whether the general form of the relationship of stability versus density established for the Vicksburg silty clay is applicable to other types of soil and to determine whether the form of the relationship is affected by the method of compaction, two series of tests were made on a sandy clay from Antioch, California.

All samples of soil were mixed and conditioned in the same manner as that used for the silty clay soil previously described.

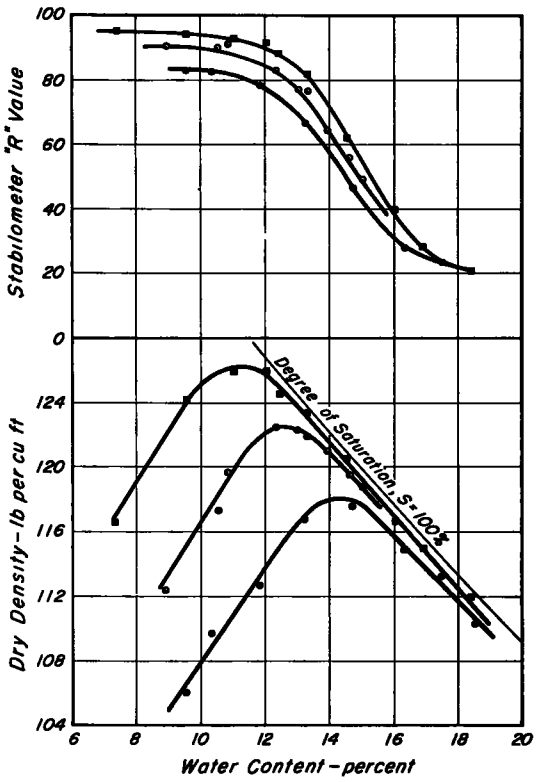
In the first series of tests, samples 4 inches in diameter and 4½ inches in height were prepared using the kneading compactor. Each sample was compacted in five layers using 25 tamps per layer.

Samples were prepared using tamping pressures of 150, 350, and 550 psi. After the density of the compacted soil had been determined, the upper 2¼ inches of the sample was trimmed off and used for water content determination while the lower 2¼ inches was subjected to a Hveem Stabilometer test and a measure of its relative stability obtained by determination of the resistance value. The results of these tests are shown in Figure 15. It will be seen that there is the characteristic overlapping of the curves of stability versus water content for the various compactive efforts and that the general form of the curves of stability versus density at constant water contents is similar to that obtained for the silty clay soil.

In the second series of tests, samples 4 inches in diameter and about 2¼ inches high were prepared by subjecting the soil to static pressures of 250, 500, and 1,000 psi. These pressures were chosen to give a range of densities approximately the same as that obtained in the kneading-compaction tests. The samples were compacted in metal molds with plungers top and bottom and the pressure was increased to the desired value at a loading rate of 600 lb. per min. After compaction the resistance value of each specimen was determined by a Hveem Stabilometer test. The results are shown in Figure 16.

In this case there is no overlapping of the curves for stability versus water content for constant compactive efforts, and the curves of stability versus density for constant water contents show a consistent increase in stability with increasing density. Thus for the same soil, the general form of the relationship of density versus stability for specimens prepared by static compaction is quite different from that for specimens prepared by kneading compaction. Conclusions with regard to the density-stability relationship drawn from tests on statically compacted soils may therefore be entirely erroneous when applied to soils compacted by kneading action.

In the majority of pavement-design procedures, the samples on which stability



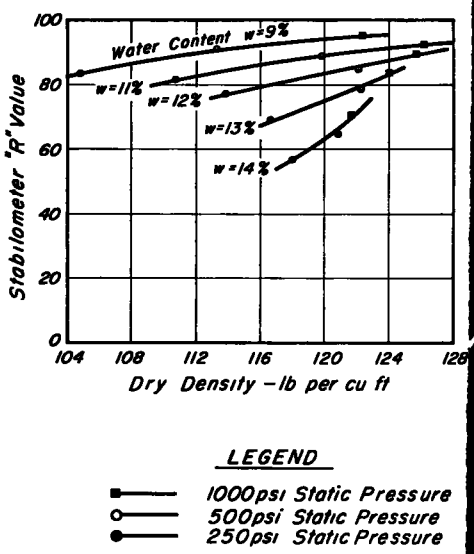


Figure 16. Water content, density, and stability relationships for sandy clay for static compaction.

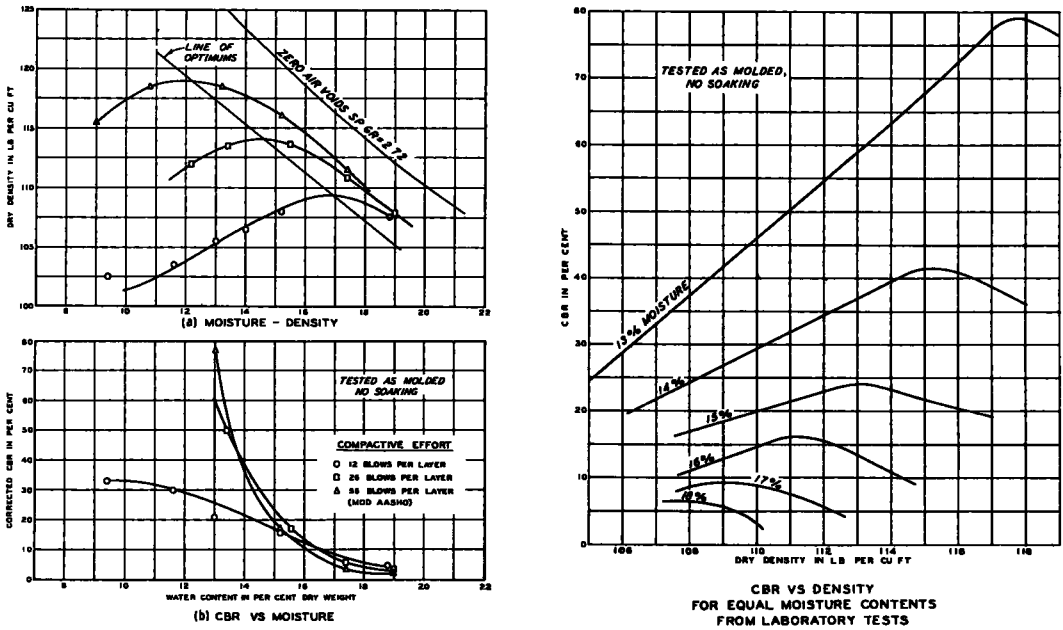


Figure 17. Water content, density, and stability relationships for sandy clay for impact compaction (courtesy C.R. Foster).

tests are made are prepared by impact compaction. The question is thus raised as to how closely this method of compaction will reproduce the properties of soils compacted in the field. At the present time only limited information is available on this aspect of soil compaction, due to the difficulty of obtaining data for field-compacted soils. However, considerable data

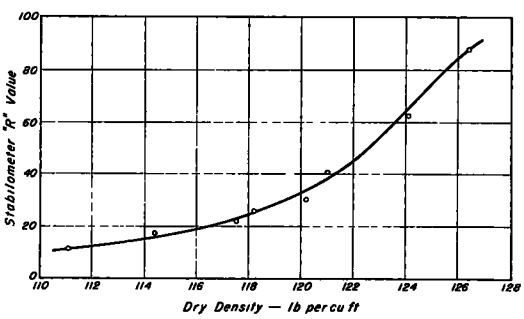


Figure 18. Relationship between density and stability for saturated samples of clayey sand for kneading compaction.

has been obtained by the Corps of Engineers on the density-versus-stability relationship of soil samples prepared by impact compaction. Typical results obtained by the Corps of Engineers in tests of this type, in which the California Bearing Ratio is used as an index of soil stability, are shown in Figure 17. The general form of the curves is similar to that obtained for the specimens prepared by kneading compaction. Although samples prepared by impact compaction show some divergence from the properties of field-compacted soils (3), they have the same general characteristics as samples prepared by kneading compaction and show the same loss of stability, in spite of increased density, at the higher degrees of saturation.

DISCUSSION OF RESULTS

The primary purpose of this investigation was to determine the limitations of the widespread belief that soil stability increases with increasing density. The results have shown that for soils compacted by impact methods or kneading action, the validity of this concept depends on the criterion of stability adopted; when larger strains are permissible in defining a stable soil mass, the concept may be quite true. But for low strains and strains of the order used in the CBR and Hveem Stabilometer tests, an increase in density at a given water content may cause a decrease in stability depending on the range of densities and the water content of the soil involved. For samples of a soil compacted

by static forces, however, an increase in density was always associated with an increase in stability as measured by a Hveem Stabilometer.

While it is believed that kneading compaction most-closely duplicates the action of rollers in the field and that compacted subgrades may become less stable if compacted beyond a certain limit, this result does not necessarily mean that every effort should not be made to obtain the highest possible density. The tests reported in this investigation show that for a given degree of saturation, stability always increases with increasing density. This result is apparently equally true for all degrees of saturation, including the condition of complete saturation. Typical results of the relationship between density and stability for saturated soil samples are shown in Figure 18. Thus, if a subgrade is likely to become saturated at any time in the life of the pavement which it supports, the higher the density to which it can be compacted without subsequent swelling, the higher will be the subgrade stability for which the pavement can be designed. Since the large majority of pavements are designed for the saturated condition, compaction to the highest practical density is justified.

It is only for partially saturated soils that increased density may have a deleterious effect on stability. It is necessary, therefore, to take this effect into consideration when the most-economical pavements are to be designed for areas in which it is reasonably certain that the supporting soil will not become saturated. The importance of the relationship between density and stability under those conditions has been recognized for some years by the Corps of Engineers and has been incorporated into their pavement-design method (8).

The density-versus-stability relationship is also important in the design of base courses protected by asphaltic membranes, such as those used in the construction of the fill sections of the Houston Freeway and in other areas (11). By this means, changes in water content of a soil may be prevented and soils which would have low stability when saturated may be safely used for base-course construction. By selecting the water content at compaction and the desirable density in accordance with the relationship of density versus stability, such soils may develop extremely high stabilities if properly protected. However, the desirable water content and density for this purpose would have no particular relationship to the optimum water content and maximum density determined by a standard compaction test.

Finally, it would seem desirable to mention briefly the difficulty of determining accurately the stability of specimens having water contents varying along their lengths. The significance of this effect was clearly demonstrated in the triaxial compression tests on the silty clay, when on one occasion, the porous base plate of the specimen was accidentally wetted and after placement of the test specimen, the lower 1/10 inch or so of the 4-inch-tall specimen absorbed this moisture. Instead of the anticipated modulus for 1 percent strain of about 800 kg. per sq. cm., the test data showed the specimen to have a modulus of about 520 kg. per sq. cm. This low value could not be accounted for until the water in the bottom of the specimen was discovered during the dismantling of the apparatus. Assuming a modulus of 40 kg. per sq. cm. for the bottom 1/10 inch of the specimen, it may readily be shown that although the remaining 3.9 inches of the specimen had a modulus of about 800 kg. per sq. cm., the overall modulus of deformation would appear to be about 520 kg. per sq. cm. Such results emphasize the need for careful testing techniques and procedures and the obvious difficulty of interpreting the stability of nonuniform test specimens.

CONCLUSIONS

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

1. The relationship between density and stability of soil depends on the criterion used to define stability: the greater the permissible strain before a sample is considered unstable, the greater is the possibility that an increase in density will cause an increase in stability.

2. For samples of two soils, a silty clay and a sandy clay, compacted by kneading action, an increase in density at a given water content caused an increase or a decrease in stability (for strains less than 10 percent) depending on the water content and the range of densities in-

volved; however at a constant degree of saturation, an increase in density always caused an increase in stability.

3. The relationship between the line of optimums determined by compaction tests and the density and water content conditions at which further increase in density will cause a reduction in stability will depend on the method used to evaluate stability.

4. Samples prepared by impact compaction have the same general characteristics as samples compacted by kneading action.

5. Samples of a sandy clay compacted by static pressure always showed an increase in stability, as measured by a Hveem Stabilometer, for an increase in density at constant water content, even though samples compacted by kneading action showed no consistent relationship.

6. For saturated subgrade conditions, the higher the density of the subgrade the greater will be its stability. However for partially saturated subgrades, the desirable density for maximum stability will depend on the water content of the subgrade and too high a density may have a deleterious effect on stability.

7. In designing and constructing pavements resting on partially saturated subgrades, the selection of the desirable density of the subgrade should be based on the anticipated maximum water content of the subgrade and the density versus stability relationship for the soil.

ACKNOWLEDGMENT

The assistance of F. N. Finn and C. K. Chan in performing some of the tests described in this paper and of G. Dierking, who prepared the figures, is gratefully acknowledged.

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Discussion

ROBERT HORONJEFF, Lecturer and Research Engineer, Institute of Transportation and Traffic Engineering, University of California — Seed and Monismith have presented an excellent paper on the relationships between density, water content, and stability. Of particular interest to the writer are the relationships between various degrees of saturation on the modulus of deformation of a soil as shown in Figures 14a, 14b, and 14c. As the axial strain is increased the modulus of deformation is affected less by the degree of saturation. For example, for a density of 110 lb. per cu. ft. an increase in degree of saturation from 60 to 85 percent results in a reduction in the modulus of deformation in the amount of 550 kg. per sq. cm. when the strain is one percent, whereas when the strain is 20 percent the reduction in modulus is only 26 kg. per sq. cm.

It is unfortunate that the authors were not able to include the relationships shown in their paper for a strain of 5 percent. It is the writer's opinion that 5 percent strain represents an upper limit of strain for defining stability as the authors have defined it. It would be interesting to compare the relationships for 1 percent strain with the corresponding relationships with 5 percent strain.

The authors have shown conclusively that generally it is most advantageous from a strength standpoint to compact earth fills on the dry side of optimum regardless of the compactive effort.

Most pavement-design procedures require that the thickness of the pavement structure be predicated on a saturated subgrade. Seed and Monismith have stated that their relationships apply to partially saturated soils; also that the Corps of Engineers has given considerable attention to the relationship of density, water content and stability. The writer has taken some data developed by the Corps of Engineers to show the importance of the moulding water content. Figure A shows the relationships of density and water content to strength for a silty clay. The chart on the right-hand side of the figure shows the relationship between

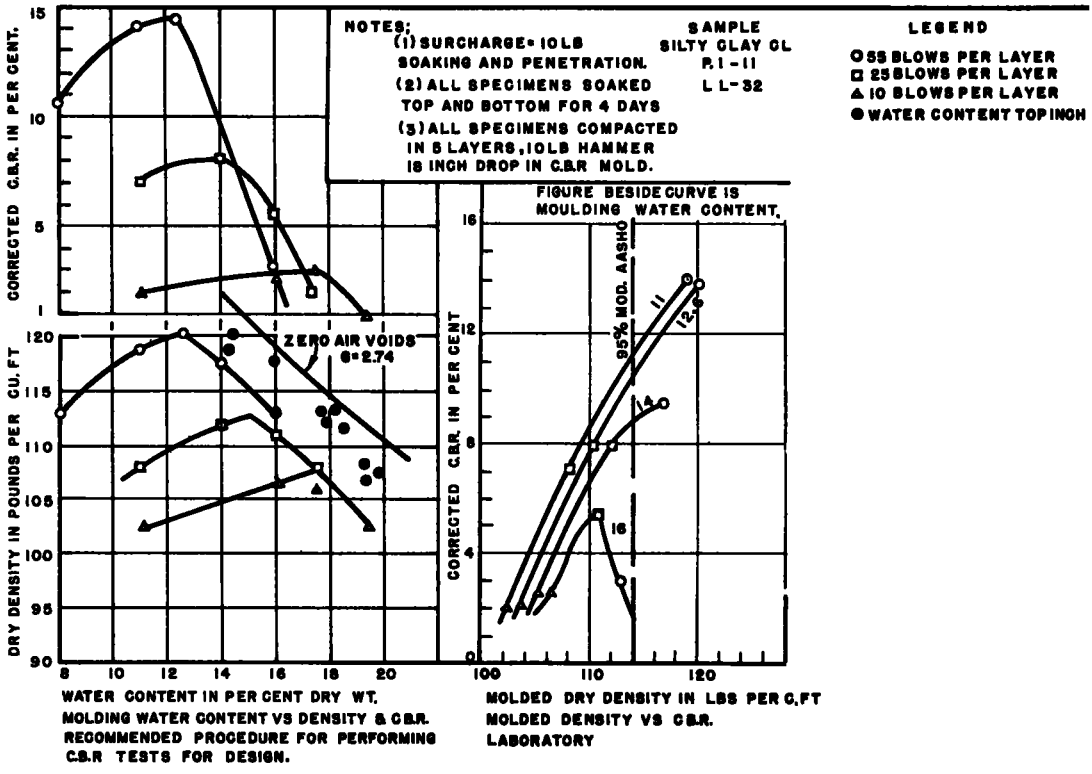

Figure A.

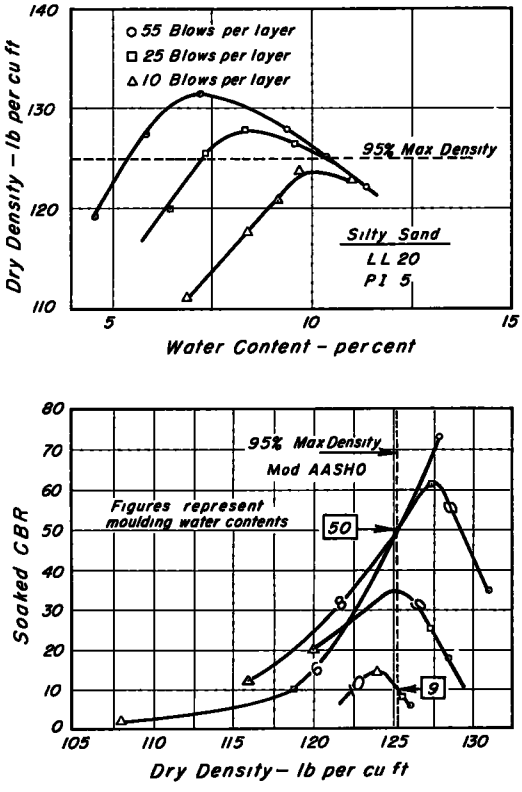

Figure B.

soaked CBR and density for various moulding water contents. The chart is similar to the relationships presented by the authors in Figures 9, 10, and 11, except that the strength is expressed in terms of soaked CBR. The chart supports the authors findings that the greater strengths occur on the dry side of the optimum water content.

The writer recognizes that soaking a soil sample for 4 days does not necessarily mean it is saturated, not even in the top inch or so. Nevertheless there are many soils which are close to full saturation within the depths influenced by the CBR test piston after a 4-day soaking period. Thus one can see that the moudling water content has a profound effect on the strength of a soil in a saturated or nearly saturated condition. From a practical standpoint the importance of controlling the water content in the field is evident. Again referring to Figure A for a specified density of 114 lb. per cu. ft., a range in water contents between 11 and 13 percent does not affect the CBR values very much. However, if the water content were allowed to increase to 16 percent the CBR would be reduced materially. Considering a single wheel load of 50,000 lb. and a tire pressure of 100 psi., an increase in water content from 11 to 16 percent means a reduction in CBR from 11 to 2. This reduction would require an increase in pavement thickness of over 20 inches.

Figure B shows a similar relationship for a sandy clay. It will be noted that for a specified density of 125.5 lb. per cu. ft. an increase in water content from 8 to 10 percent reduces the CBR from 50 to 9.

The effect of moulding water content on the stability of a soil cannot be overemphasized. The moulding water content affects not only the stability immediately upon completion of construction of a pavement but also the stability when the subgrade soil reaches a nearly saturated condition.

W. H. CAMPEN, Manager, Omaha Testing Laboratories — This paper is not only interesting but it also deals with a fundamental aspect of soil stabilization. In fact, the principal purpose of the authors is to show that excess densification of soils is not only possible but that it may result in loss of strength.

Before expressing my views on the main subject of the paper, it should be mentioned that the data in the paper substantiates two well-established properties of soil: (1) density of compacted soils increases with the compactive effort and (2) strength of compacted soils increases as the moisture content decreases with all compactive efforts.

The data in the paper also show that at a given moisture content the strength increases with density up to a point where the compactive effort produces excessive kneading or manipulation. This compactive effort is somewhat greater than the one required to produce optimum moisture equal to the given moisture content. At this point an increase in density takes place but the strength decreases, if strength is measured at strains similar to those obtained in the CBR test.

The increase in density must be due to the expulsion of air or gases. The reduction in stability is no doubt due to an increase in the lubricating action of the clay portion of the soil. The fact that compaction by static force does not re-

veal this behavior substantiates this assumption.

While it should be recognized that in the laboratory it is possible to reduce strength by increasing density, it must be pointed out the deleterious effect does not have much practical significance. For instance, the data in Figure 17, obtained by the modified AASHO method of compaction and the CBR method of measuring strength, shows that the soil used has a maximum density of 119 lb. and an optimum moisture of 12 percent. This soil might be compacted in the field to a relative density of 95.5 percent or 114 lb. per cu. ft. At this density the soil has an optimum moisture of 14.75 percent and a CBR of 27 percent. At a density of 116 lb. at the same moisture content the soil has a CBR of 25 percent. If the soil were compacted to 99.5 percent or 117.5 lb. per cu. ft., the corresponding optimum moisture would be 13 percent. At this water content and density the soil has a CBR of 79 percent. At a density of 119 lb. and the same water content it has a CBR value of 77 percent. Thus it will be noted that the loss of strength due to over densification is comparatively small.

Even though it can be shown in the laboratory that a loss of strength can accompany an increase density, it is doubtful if the same thing can happen in the field. It may be that compaction by sheepsfoot rollers can produce this result, but it is unlikely that traffic can do so. The rollers might do it if compaction were done at constant moisture content by a series of rollers capable of applying pressure in ascending order. On the other hand, traffic could hardly do it for the reason that it cannot expel air or apply a kneading action. These two reactions can hardly take place, since the subgrade soils are usually covered with a considerable thickness of superimposed layers.

In connection with this discussion, it would seem appropriate to mention loss of stability in bituminous mixtures, because it is often confused with similar occurrence in soils. Traffic can and often does reduce the stability of bituminous mixtures to a large degree. That is because the traffic acts directly on the mixtures, which are usually used as wearing surfaces, and thus densifies them, if improperly designed, to a point where the asphaltic cement becomes a lubricant. On the other hand, it has already been pointed out that soils are not likely to be densified or activated by traffic, and even if they are, the loss of strength is comparatively small.

In concluding the comments, I wish to emphasize the fact that water is the principal foe of stability, and since the amount of water can be limited by density, as much density as possible, within practical limits, should be developed in the compaction of soils.

H. B. SEED and C. L. MONISMITH, Closure — The authors express their appreciation to Horonjeff and Campen for their interesting discussions. In closing, it would seem desirable to comment on Campen's observations that the deleterious effect of too high a density does not have much practical significance and that it is doubtful if the same thing could happen in the field. Campen reaches these conclusions by using data from the curves for samples prepared by impact compaction. The stabilities of samples prepared by this method are not so greatly affected by changes in density as are those of samples prepared by kneading compaction. (Seed, H. B., Lundgren, R., Chan, C. K., "The Effect of Compaction Method on the Stability and Swell Pressure Characteristics of Soils," Proceedings of the Highway Research Board, 1954).

The optimum water contents for samples compacted to a given density by field equipment are somewhat greater than those determined by impact methods, and an analysis based on compaction and stability data for samples prepared by kneading compaction would show that density changes of the order considered by Campen can have a substantial effect on stability values. That this effect can be of practical significance and that the same effect can occur in the field is illustrated by a recent paper (Foster, C. R., "Reduction in Soil Strength with Increase in Density," Proceedings Separate No. 228, New York: American Society of Civil Engineers, July 1953).

Results obtained by the Corps of Engineers and presented in this paper show that a large change in stability occurred in the field as a result of an increase in density under the action of heavy traffic.