STABILITY AND SWELL PRESSURE CHARACTERISTICS OF COMPACTED CLAYS

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ABSTRACT

This paper discusses some of the factors affecting the density vs. stability relationships of compacted clays and some of the limitations of the concept that the stability of a compacted soil increases with an increase in density.

A series of tests performed on silty clay, in which stability was measured by triaxial compression tests, are described. It is shown that the relationship between density and stability of a 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. For the silty clay, when the stability is defined as the load required to cause 10 percent strain or less, an increase in density at a given water content caused an increase or decrease in stability depending upon the water content and the range of densities involved; at constant degrees of saturation, however, an increase in density always caused an increase in stability.

The effect of compaction method on the density vs. stability relationship is illustrated. Test data are presented for two soils, a silty clay and a sandy clay, comparing the stabilities, at various water contents and densities, of partially saturated samples compacted by impact methods, static pressure and kneading action. It is shown that, at equal water contents and densities, samples compacted by static pressures exhibit higher stabilities than samples compacted by impact or kneading methods; also, that the stabilities of samples at equal densities and water contents, compacted by impact and kneading methods, are very similar, with kneading compaction producing somewhat higher stabilities at lower degrees of saturation, and impact compaction producing slightly higher stabilities at higher degrees of saturation. For static compaction, both soils showed an increase of stability with increase in density at all water contents, while for samples compacted by impact and kneading methods, an increase in density at a given water content did not necessarily lead to an increase in stability.

The effect of saturation on the stability of compacted clays is shown and the influence of water content at compaction on the stability of saturated samples having the same density and water content is illustrated.

Finally, a comparison is made of the stability and swell pressures developed at various densities of samples of the sandy clay compacted by kneading action and static pressure and subsequently saturated by exudation of moisture from the samples under static loads. It is shown that very much higher swell pressures and stabilities are exhibited by the statically compacted samples than by the samples prepared by kneading action.

INTRODUCTION

The compaction of soils to improve their engineering properties is common practice in earthwork construction. In order to ensure that the soil is adequately compacted, it is customary to make density measurements on the compacted soil and to require that the dry density equal or exceed a certain minimum value; this minimum value is usually a high percentage (90 or 95 percent) of the highest maximum density which could reasonably be expected from field compaction equipment. As long as the density exceeds the desired minimum value, compaction is considered to be satisfactory; and it is usually considered that the higher the density to which the soil is compacted, the greater will be the improvement in its engineering properties.

In adopting the dry density as a criterion of soil compaction it is implicitly assumed that density is a measure of the desirable characteristics of a soil such as strength or stability, compressibility or permeability. Recent investigations (U.S. Waterways Experiment Station, 1949-1950, 1951; Foster, 1953; Seed and Monismith, 1953) have shown, however, that this is not necessarily so. The purpose of this paper is to discuss some of the limitations of the concept that an increase in density leads to an increase in stability and to describe some of the factors which affect the density vs. stability relationship of a compacted clay. The effect of compaction on the swell pressure exerted by a compacted clay is also briefly discussed.

LABORATORY COMPACTION TESTS

A variety of laboratory compaction procedures are in use at the present time. The most widely used method is that of dropping a weight onto the surface of the soil — a process referred to as impact compaction. In some cases the 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. In other methods the soil is compacted by repeatedly applying a predetermined pressure to small areas of the soil, maintaining the pressure for a small element of time, and then gradually reducing the pressure — a process termed kneading compaction.

Samples prepared at the same density and water content by the various compaction methods have different stress-strain characteristics. However, investigations indicate that samples prepared by kneading action bear the closest resemblance to samples compacted by equipment in the field (Seed *et al.,* 1954). This method of compaction has therefore been used for preparing samples for the majority of tests described in the following pages.

DETERMINATIONS OF 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, although it is more or less generally agreed that a strain of about 10 percent is certainly in this category. Because of the difficulty of obtaining a direct measure of the stability of a soil, a variety of laboratory test methods for measuring indices of stability have been developed, and these indices have been correlated with the performance of soils underlying pavements.

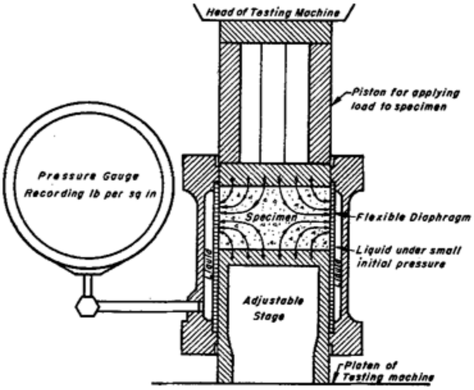
In California, the index of stability used for design is the Resistance

Value as measured by a Hveem Stabilometer test (Hveem and Carmany, 1948). This is a closed-system, triaxial-compression test, as shown in Figure 1, using a specimen 4 in. in diameter and about 2½ in. 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.

Another test which may be used to measure the relative stabilities of soils is the triaxial compression test performance under constant lateral pressure. Either the ultimate strength of a test specimen or the load required to cause a particular strain may be used as an index of stability. This type of test has the advantage that comparisons of the relative stabilities of samples may be made for different magnitudes of allowable strain; however it is not so readily performed as the stabilometer test.



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

Fig. 1— Hveem Stabilometer.

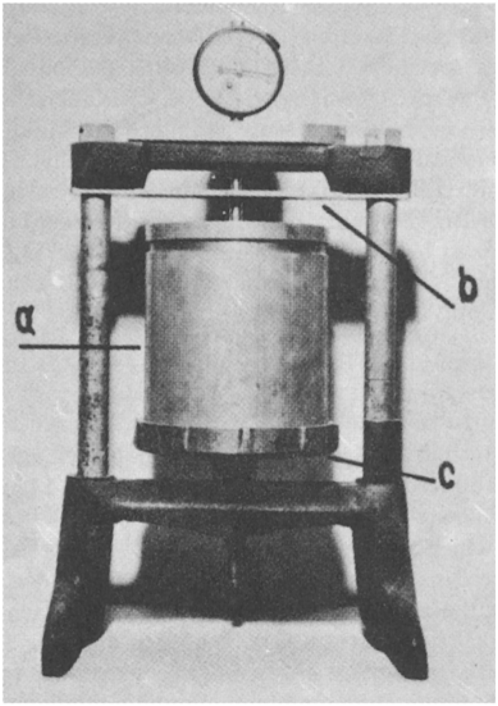


Fig. 2— Expansion pressure device: (a) mold, (b) proving bar, (c) adjustable base.

EFFECT OF ALLOWABLE STRAIN ON THE DENSITY VS. STABILITY RELATIONSHIP OF CLAY SOIL COMPACTED BY KNEADING ACTION

The form of the density vs. stability relationship for a clay soil compacted by kneading action and the effect of the definition of stability on this relationship may be shown by the results of tests performed on a silty clay soil from Vicksburg, Mississippi (Seed and Monismith, 1953). Series of tests were made to establish the relationship between density and water content and between stability and water content for the soil at each of six different compactive efforts. After compaction, samples were subjected to triaxial compression tests of the unconsolidated — undrained type and indices of stability at 1 percent and 10 percent strain were obtained by determination of the moduli of deformation at 1 percent strain and the stresses required to cause 10 percent strain. Modulus of deformation at 1 percent strain is defined as the ratio of stress to strain at the point on the stress vs. strain curve where the strain is 1 percent; it is numerically equal to one hundred times the stress required to cause 1 percent strain.

The results of these tests are shown in Figures 3 and 4. Figure 3 shows the density vs. water content curves, and the modulus of deformation at 1 percent strain vs. water content curves, 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 aproached 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.

The significance of these results is best seen from the modulus of deformation-density-water content relationship shown in Figure 5. These curves, showing modulus of deformation vs. dry density at a series of constant water contents, were interpolated from the results in Figure 3. 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.

The effect of dry density and water content on the stress required to cause 10 percent strain is shown in Figures 4 and 6. As for the modulus of deformation data, the relationship between density and stability at constant water contents shown in Figure 6 have been interpolated from the test data in Figure 4. It is readily seen that within the range of densities investigated, there is considerable difference between the effect of increasing density on the stress required to cause 10 percent strain and on the modulus of deformation at 1 percent strain. At water contents below 13 percent the stress required to cause 10 percent strain increases consistently with density but for water contents above 14 percent, the stress required to cause 10 percent strain may increase or decrease with increase in density depending on the range of densities considered: however the effect of density changes is not as great as for modulus of deformation.

It will be seen from these results that the effect of density and water content on the strength of a partially saturated soil depends on the criterion used to define stability. Test results for the silty clay show that if the ultimate strength or the stress required to cause 20 percent strain is used as the index of stability, then within the range of working conditions, stability

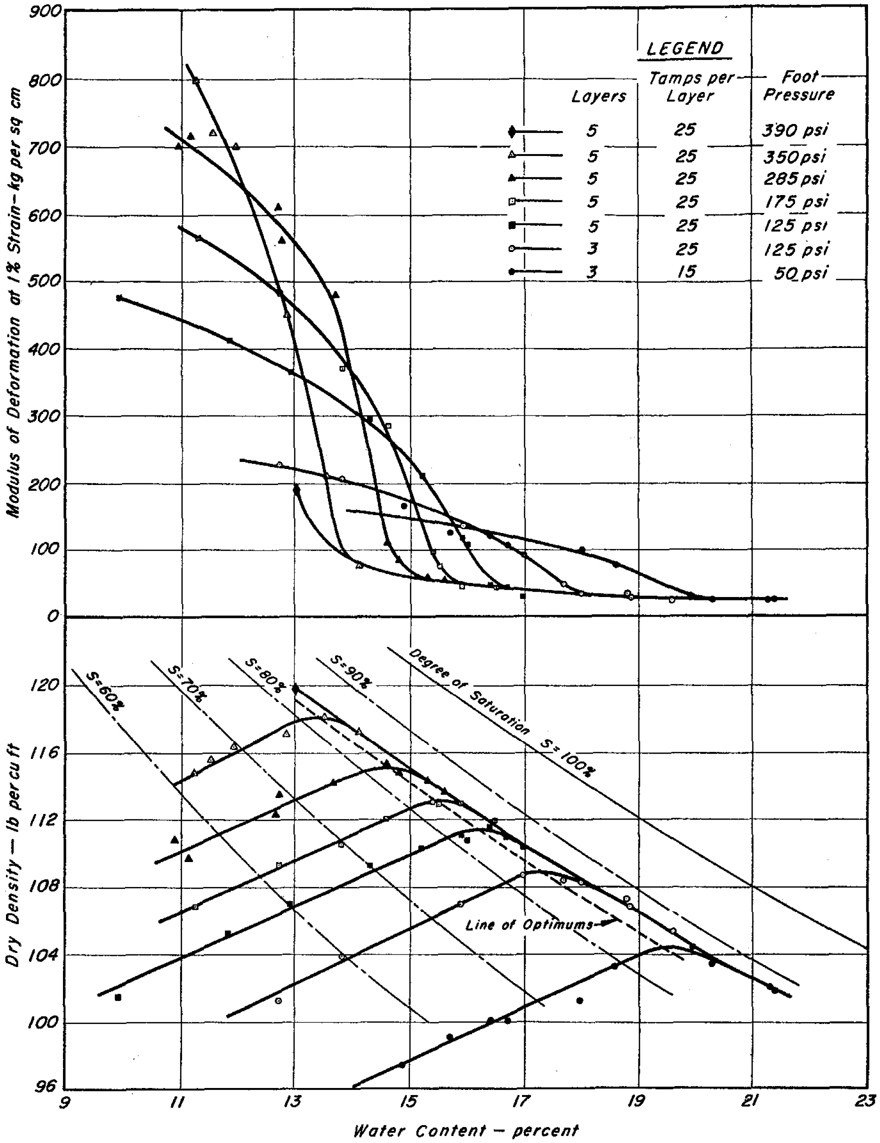


Fig. 3— Relationship between water content, dry density, and modulus of deformation at 1% strain.

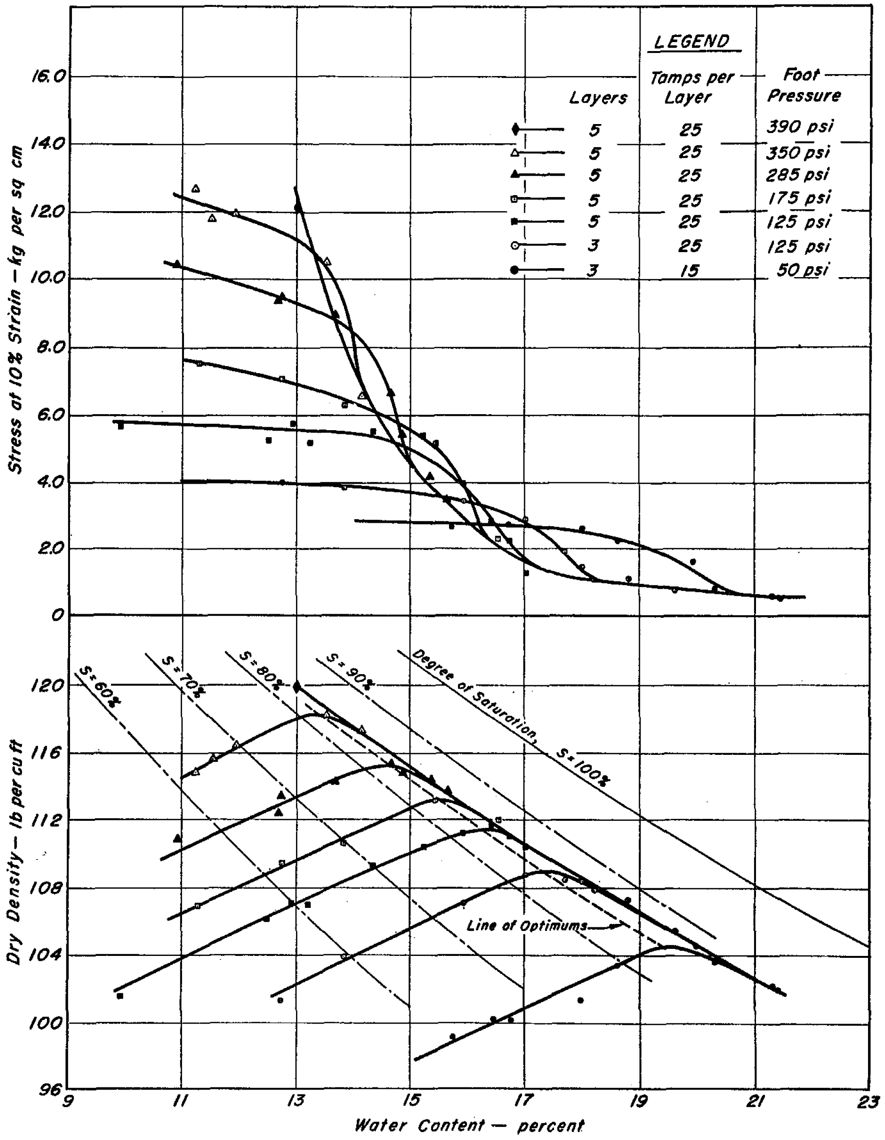


Fig. 4— Relationship between water content, dry density, and stress at 10% strain.

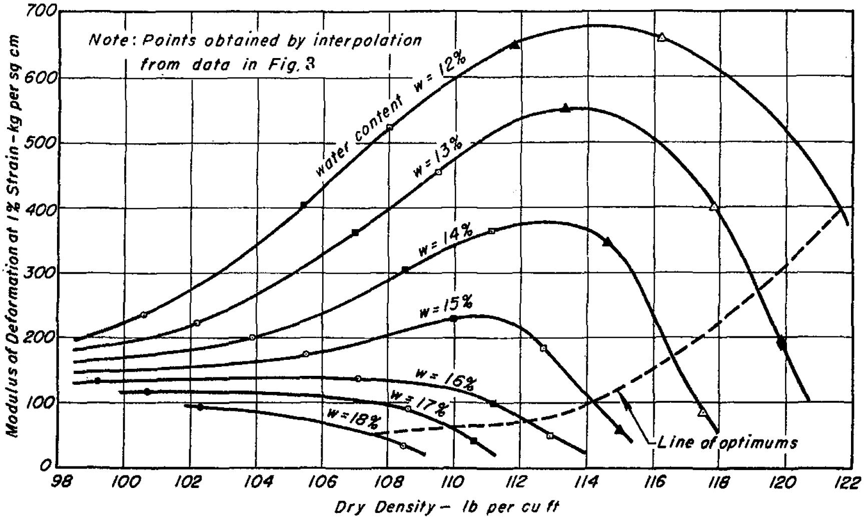


Fig. 5— Relationship between dry density and modulus of deformation at 1% strain for constant water contents.

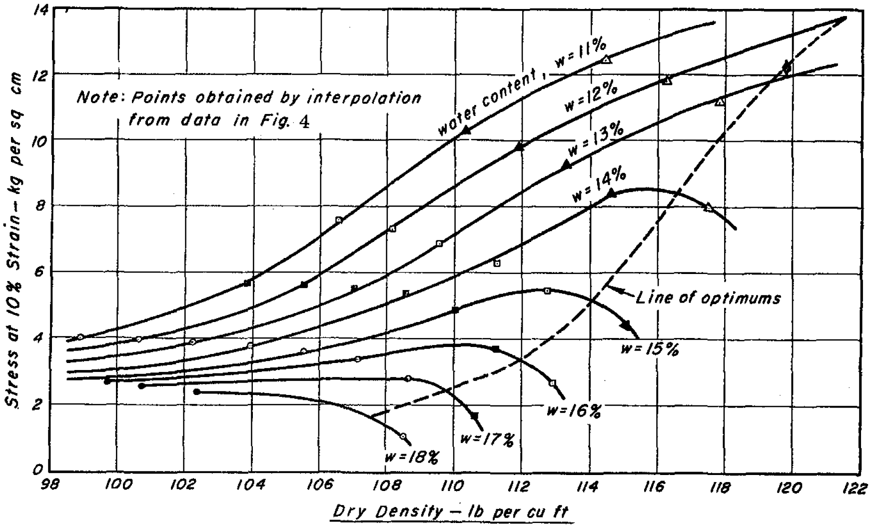


Fig. 6— Relationship between dry density and stress at 10% strain for constant water contents.

always increases with density. However, the strain at which stability is determined in most design procedures is considerably less than 10 percent, and on the basis of this test data it would therefore be expected that for partially saturated soils compacted by kneading action, an increase in density would not necessarily lead to an increase in stability.

In order to obtain some idea of the condition to which this soil might be compacted in the field, standard Proctor and modified AASHO compaction 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 lb./cu. ft.
Modified AASHO	14%	117 lb./cu. ft.

On the basis of the standard Proctor compaction 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 compaction 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 lb. 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 indicate, therefore, that for compaction at the optimum water content determined by the modified AASHO compaction test, the density may be increased to a relative density of almost 100 percent (based on the modified AASHO test) with beneficial effects on stability; this has also been shown by extensive field experience.

These results illustrate, however, the deleterious effects of over-compacting 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 test (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 over-emphasized.

Examination of the data in Figures 3 and 4 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 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 vs. density for various constant values of the degree of saturation are shown in Figure 7a; these curves have been obtained by interpolation from the data in Figure 3. 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 7b and 7c. It is interesting to compare the curves in Figure 7a with those showing the relationship between density and modulus of deformation at constant values of water content in Figure 5. 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 7 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.

EFFECT OF COMPACTION METHOD ON THE DENSITY VS. STABILITY RELATIONSHIP OF PARTIALLY SATURATED CLAYS

In recent years, investigations have been conducted to determine the effect of different methods of compaction on the density vs. stability relationship of clay soils and to provide comparative data from which tentative conclusions regarding the qualitative nature of these effects may be drawn (U.S. Waterways Experiment Station, 1949-1950; Seed *et al.,* 1954).

The density vs. stability relationships for samples of a silty clay soil prepared by kneading, impact and static compaction are shown in Figure 8. In these tests the stabilities were determined by a Hveem Stabilometer and the samples were tested as compacted. It will be seen that the method of compaction has a significant effect on the test results.

For purposes of comparison, the density vs. stability relationships shown in Figure 8 are reproduced in Figure 10. Figure 10a compares the stabilities at various water contents and densities, for specimens of the silty clay compacted by kneading and impact methods. It will be seen that in general

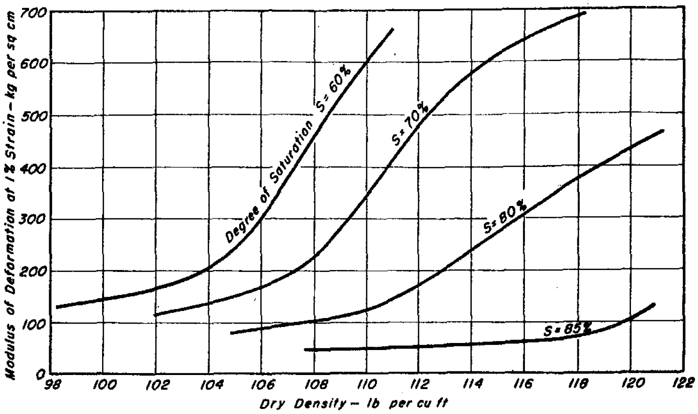


Fig. 7a— Relationship between dry density and modulus of deformation at 1% strain for constant degrees of saturation.

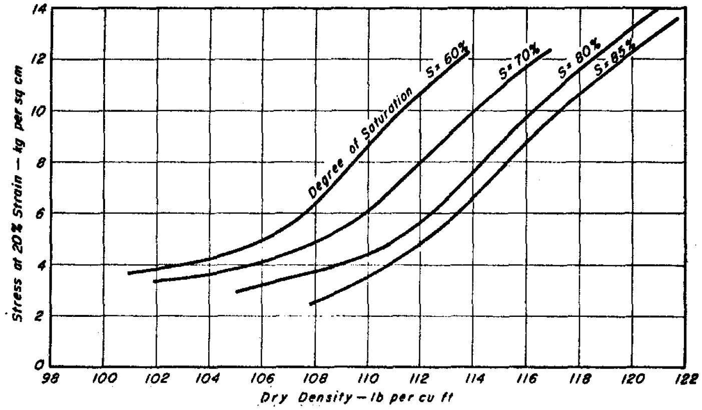


Fig. 7b— Relationship between dry density and stress at 20% strain for constant degrees of saturation.

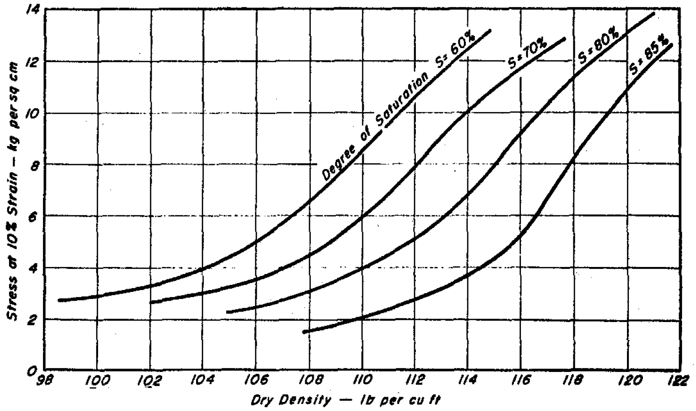
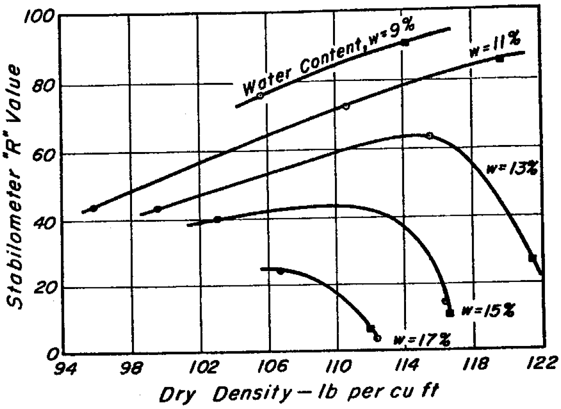
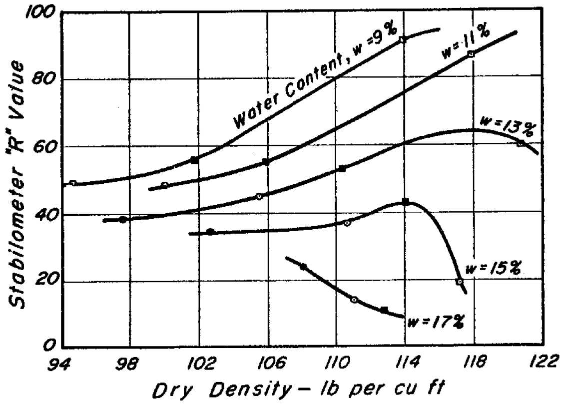


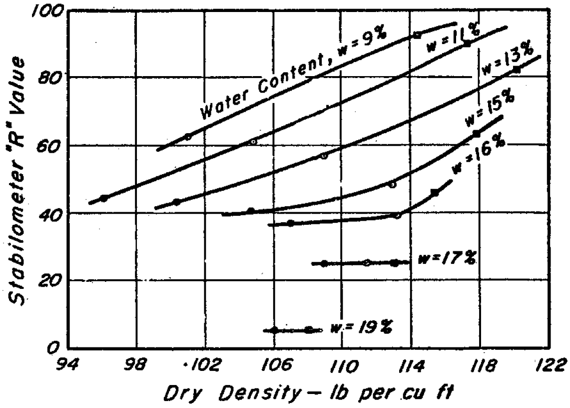
Fig. 7c— Relationship between dry density and stress at 10% strain for constant degrees of saturation.



Kneading Compaction



Impact Compaction



Static Compaction

Fig. 8— Effect of compaction method on stability vs. density relationships at constant water contents.

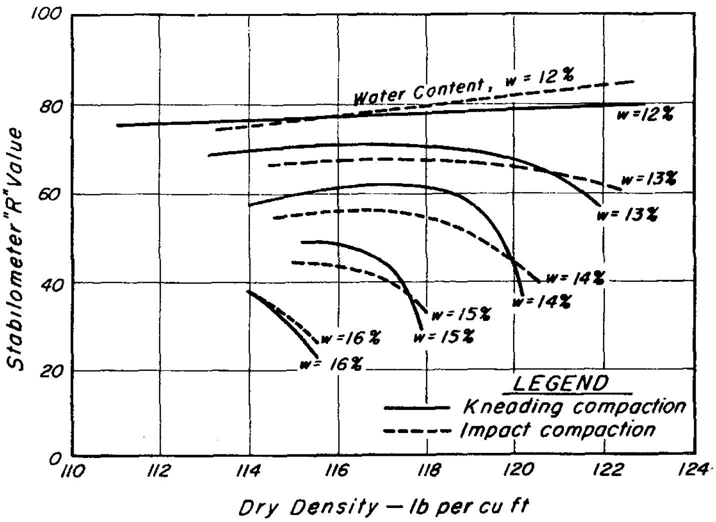


Fig. 9a— Effect of kneading and impact compaction on density vs. stability relationship at constant water contents for sandy clay.

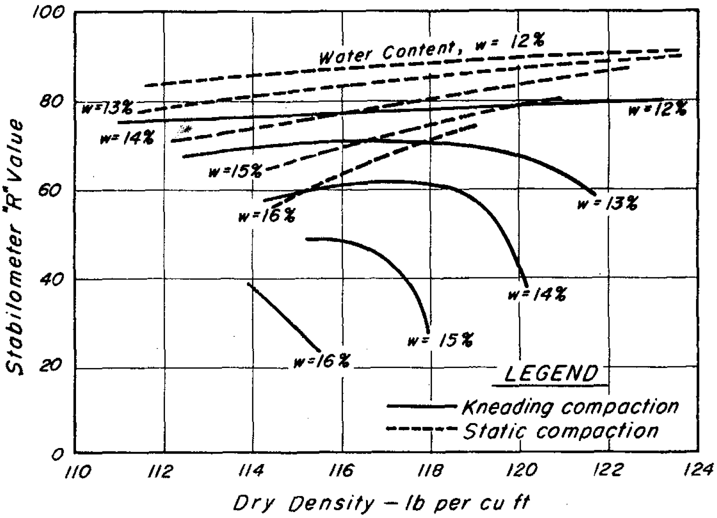


Fig. 9b— Effect of kneading and static compaction on density vs. stability relationship at constant water contents for sandy clay.

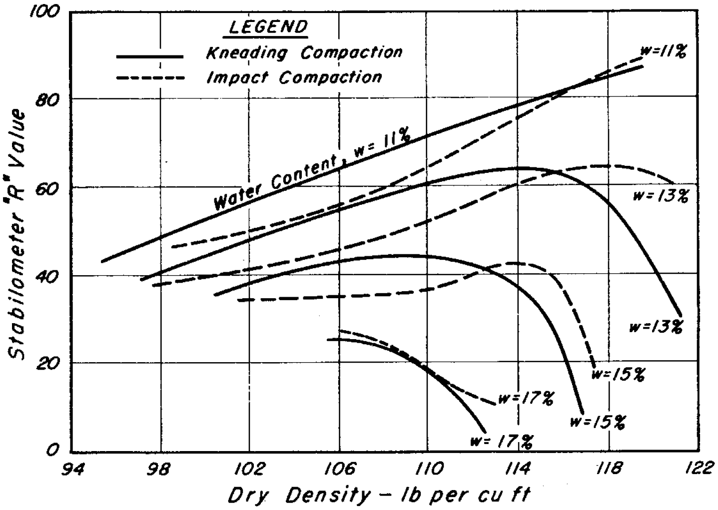


Fig. 10a— Effect of kneading and impact compaction on density vs. stability relationship at constant water contents for silty clay.

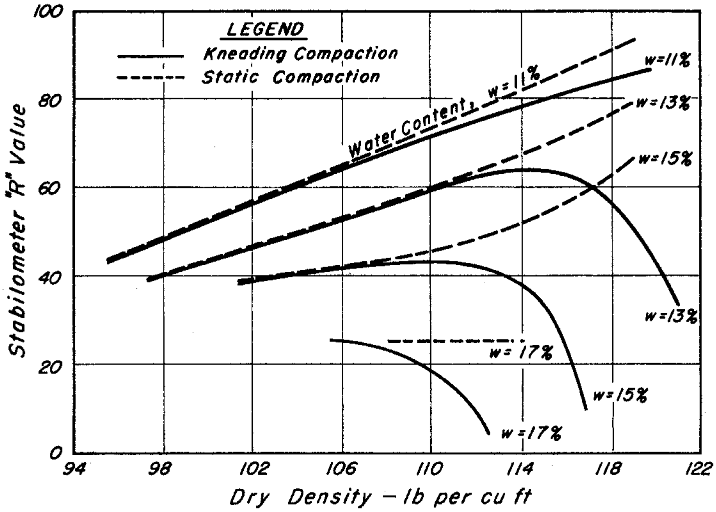


Fig. 10b— Effect of kneading and static compaction on density vs. stability relationship at constant water contents for silty clay.

the density vs. stability curves for these two methods of compaction are very similar in form but that kneading compaction produces slightly higher stabilities at the lower densities and impact compaction results in somewhat higher stabilities at the higher densities. The higher densities on the curves in this type of plot are associated with the higher degrees of saturation; thus at higher degrees of saturation impact compaction produces the higher stabilities while at lower degrees of saturation, kneading compaction produces higher stabilities. Comparison of the densities at which impact compaction begins to give higher stabilties with the position of the line of optimums for the compaction curves shows that it is at water contents just below and above the optimum water content for the particular compactive effort being used that impact compaction causes higher stability than kneading compaction; at water contents well below optimum, kneading compaction results in the higher stabilities. However, at no stage is there any very great difference between the results obtained by these two methods.

It is interesting to note that both kneading and impact compaction result in samples which, at lower degrees of saturation, show an increase in stability with increase in density at a given water content but at the higher degrees of saturation show a reduction in stability with increase in density at constant water content. This reduction in stability with increase in density is more pronounced for specimens prepared by kneading compaction than for those prepared by impact compaction.

The stabilities, at various water contents and densities, of samples of silty clay prepared by kneading and static compaction are compared in Figure 10b. The most important difference in the results for these compaction methods is that samples prepared by static compaction always show an increase in stability with an increase in density at any water content while for samples prepared by kneading compaction the stability is reduced if, at water contents greater than about 12 percent, the density is increased at the higher degrees of saturation. This difference results in a considerable discrepancy between the stabilities of samples prepared by static and kneading methods. For example, at a water content of 15 percent and a density of 116 lb. per cu. ft., the Resistance Value of a sample prepared by kneading compaction is only 22, while that for a sample prepared by static compaction is 56, an increase of approximately 150 percent. In terms of pavement thickness for a typical flexible pavement designed by the State of California design procedure for a highway with heavy traffic, a Resistance Value of 22 would indicate a required thickness of pavement and base of about 18 inches, while a Resistance Value of 56 would indicate a required thickness of only about 9 inches. If kneading compaction most satisfactorily reproduces the effects of field compaction, the dangers of designing a pavement for a partially saturated subgrade condition on the basis of tests on samples prepared by static compaction are immediately evident.

At lower degrees of saturation, the stabilities of samples of the silty clay prepared by static and kneading compaction appear to be almost identical. Thus, at equal water contents and densities, the stabilities of samples prepared by static compaction were always equal to or greater than those of samples prepared by kneading compaction. Comparison of the curves in Figures 10a and 10b show this to be true also for static and impact compaction.

The density vs. stability relationships for samples of a sandy clay prepared by kneading, impact and static compaction procedures are compared in Figures 9a and 9b. It will be seen that in general the qualitative effects of the different compaction methods are similar to those discussed for the silty clay.

EFFECT OF SATURATION ON THE STABILITY OF A COMPACTED CLAY

In the large majority of cases, pavement designs are based on the assumption that the compacted subgrade will become saturated at some time in the life of the pavement which it supports. It is of interest therefore to consider the effect of saturation on the stability of a compacted clay.

The effect of saturation on the stabilities of samples of sandy clay prepared at various water contents using a constant kneading compactive effort is shown in Figure 11. Some of the samples were tested as compacted while others were tested after saturation at constant dry density. For samples prepared at water contents below the optimum, there is a large change in stability after saturation but for samples prepared at water contents above the optimum, and therefore with initially high degrees of saturation, there is only a slight change in stability after saturation.

The large effects of saturation on the stabilities of samples having initially low degrees of saturation causes the form of the density vs. stability after saturation relationship to be quite different from those discussed previously. For samples prepared using a constant compactive effort, the stability after saturation vs. initial water content relationship is similar in form to the dry density vs. initial water content relationship. However the stability does not depend simply on the density to which the soil is compacted, but also on the water content at which it is compacted; examination of test data shows that this factor may have an appreciable effect on the stability of a soil after saturation.

EFFECT OF WATER CONTENT AT COMPACTION ON THE STABILITY OF SATURATED CLAY

The effect of water content at compaction on the stabilities of saturated samples of a sandy clay is shown by the test results in Figure 12. Samples were prepared by kneading compaction, using a constant compactive effort, at water contents above and below the optimum. All samples were then saturated without any appreciable change in density and their stabilities were determined by Hveem Stabilometer tests. The conditions of the samples after compaction and after saturation are shown in Figure 12; it will be seen that all samples were essentially fully saturated at the time of test-

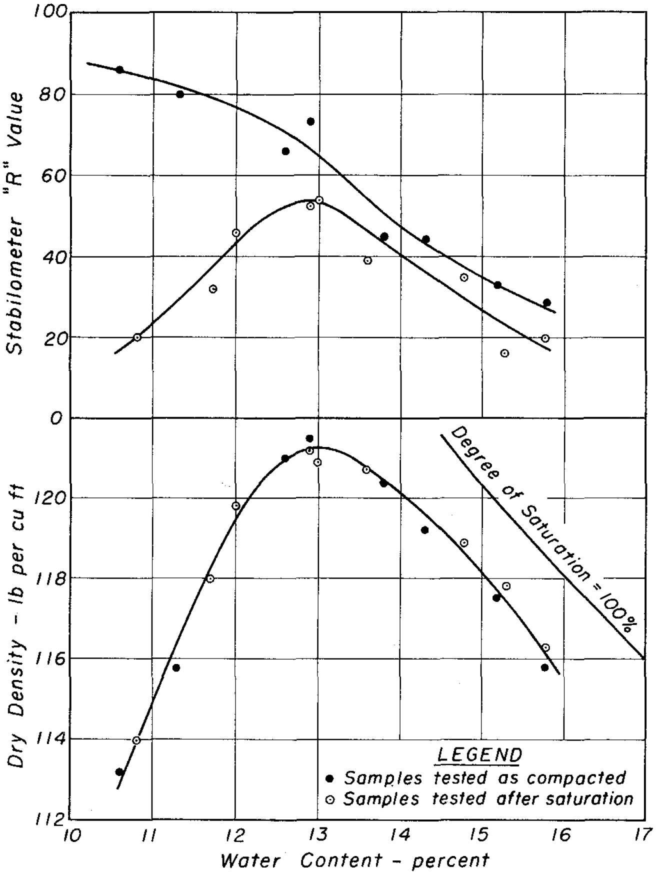


Fig. 11— Effect of saturation on the stability of compacted samples of sandy clay.

ing. Also shown in Figure 12 are plots of the stability after saturation vs. final water content and vs. final density.

It is apparent that for this soil, the stabilities of samples compacted at water contents below optimum are considerably higher than those of samples compacted at water contents above optimum. The significance of this result may be seen as follows. The maximum density for this soil in a modified AASHO compaction test is about 123 lb. per cu. ft. At a relative density of 95 percent the soil would therefore have a dry density of 117 lb. per cu. ft. Using the data in Figure 12, if the soil were compacted to this density at a water content of 15.5 percent, and then saturated without change in density, the Resistance value would be about 27. If the soil were compacted at a water content of 11.5 percent, using the same compactive effort, the same density would be achieved but after saturation without change in density the soil would have a Resistance value of about 41, an increase of about 50 percent over the previous value.

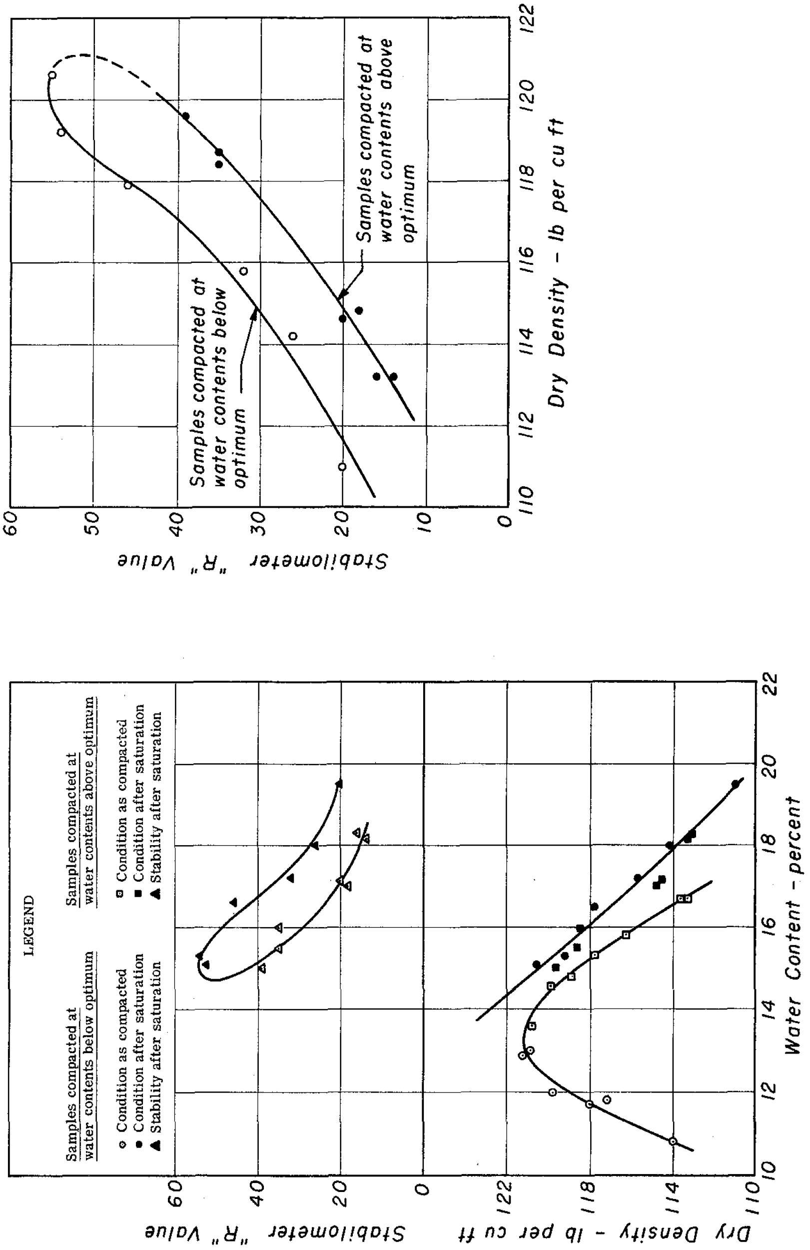


Fig. 12— Relationship between dry density, water content at compaction and stability of saturated samples of sandy clay.

The magnitude of this effect will not be the same for all soils but it may well be of significance for economical pavement design.

EFFECT OF COMPACTION METHOD ON THE STABILITY AND SWELL PRESSURES OF SAMPLES SATURATED BY EXUDATION

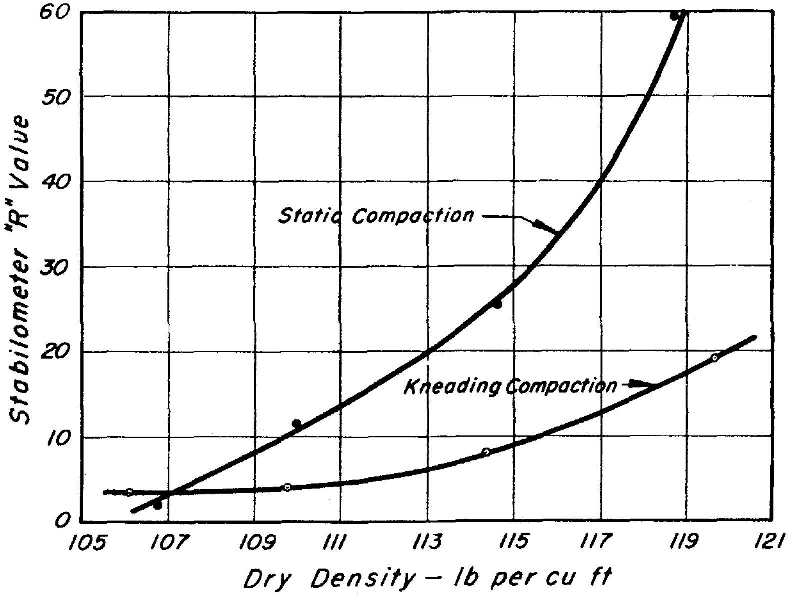
In the pavement design procedure used by the State of California Division of Highways, samples are prepared by kneading compaction, at water contents usually on the wet side of optimum, and are then saturated by applying static pressure until moisture is exuded. These samples are then used to determine the stability of the soil and also the swell pressure exerted by the soil when it is confined in a mold and immersed in water.

Swell pressures are measured in the standard device shown in Figure 2. After moisture has been exuded, the sample is allowed to stand for half an hour with the ends of the mold covered. A perforated metal disc with a vertical stem is then placed on top of the sample and the mold is fitted in the swell pressure device. In this position the lower end of the sample rests on the adjustable base of the device and the base is adjusted until the stem of the perforated plate on top of the sample is just tight against the proving bar. Water is then poured on top of the sample and the subsequent deflection of the proving bar over a period of several days is measured by a dial gauge. The proving bars are relatively stiff, a pressure of 1 psi exerted by the sample causing a deflection of only 0.003 inch; thus only a very slight expansion of the soil is permitted during the swell pressure measurements. After the swell pressure has been measured, the stability of the sample is determined by a Hveem Stabilometer test.

The significant effects of compaction method on the swell pressures and stabilities determined in this way for clay samples saturated by exudation after preparation by kneading and static compaction are shown by the test results in Figures 13 and 14.

The results of tests on a sandy clay are shown in Figure 14. It will be seen that for equal densities, samples prepared by static compaction have considerably higher Resistance values and swell pressures than samples prepared by kneading compaction. At a dry density of 110 lbs. per cu. ft., which for this soil is the maximum density determined by the standard AASHO compaction test, the Resistance value of a sample prepared by static compaction is about 30 percent greater than that of a sample prepared by kneading compaction and the swell pressure is about 400 percent greater. At a density of 123 lbs. per cu. ft., which is the maximum density as determined by the modified AASHO compaction test for this soil, the Resistance value of a sample prepared by static compaction is also about 30 percent greater than that of a sample prepared by kneading compaction, and the swell pressure is about 100 percent greater.

The results of tests on a silty clay are shown in Figure 13; the qualitative effects of the compaction methods are similar to those described above.



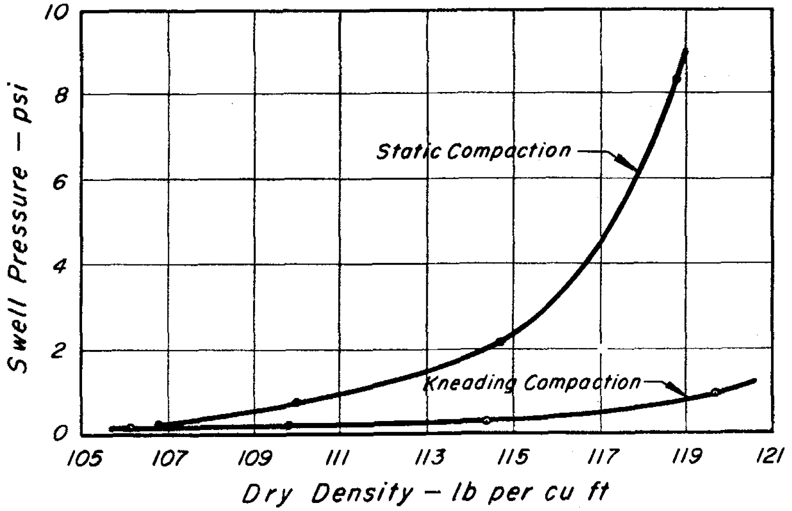


Fig. 13— Density vs. stability and density vs. swell-pressure relationships for samples of silty clay prepared by static and kneading compaction and saturated by exudation.

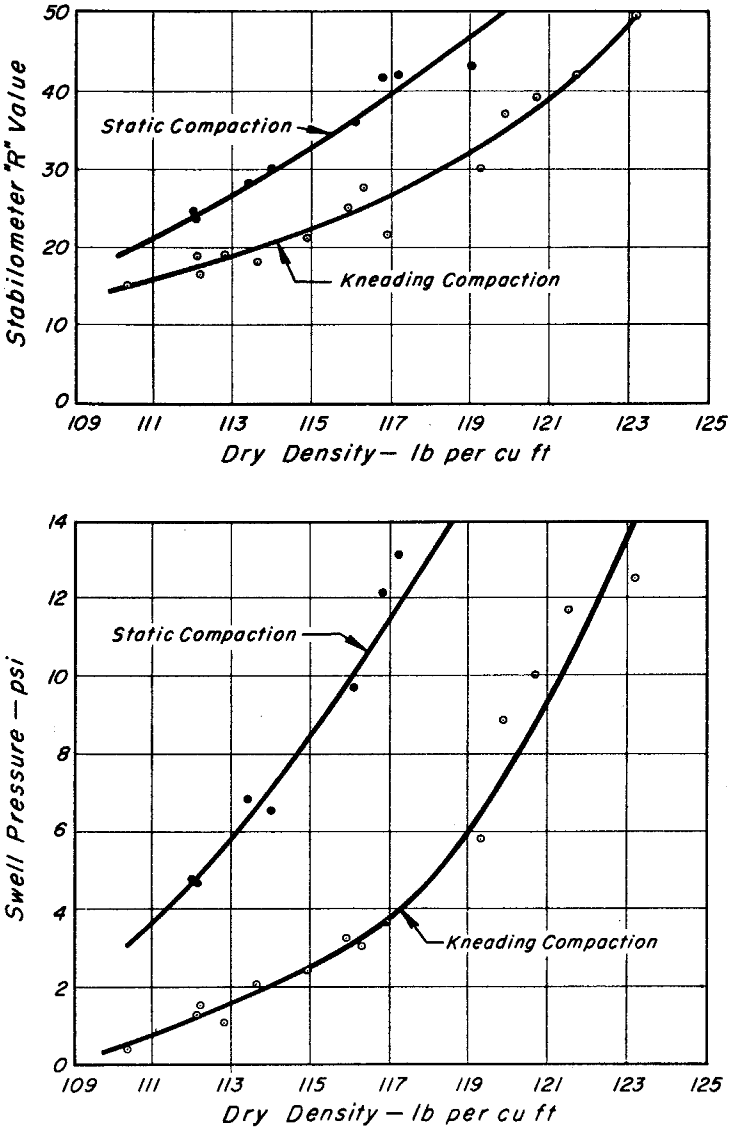


Fig. 14— Density vs. stability and density vs. swell-pressure relationships for samples of sandy clay prepared by static and kneading compaction and saturated by exudation.

For the silty clay, the maximum dry density in the standard AASHO compaction test was 107 lbs. per cu. ft. and the maximum dry density in the modified AASHO compaction test was 117 lbs. per cu. ft. At a dry density of 107 lbs. per cu. ft., the Resistance values and swell pressures for samples prepared by kneading and static compaction are about the same; but at a dry density of 117 lbs. per cu. ft. the Resistance value of a sample prepared by static compaction is about 200 percent greater than that of a sample prepared by kneading compaction while the swell pressure is about 800 percent greater.

If, as available evidence would indicate, kneading compaction more closely duplicates the effects of field compaction equipment than does static compaction, the erroneous values for desirable pavement thickness which might be obtained if designs were based on the results of tests on samples prepared by static compaction are immediately apparent.

CONCLUSION

The primary purpose of this paper has been to describe some of the factors affecting the stability and swell pressure characteristics of compacted clays. In methods of pavement design based on the results of tests performed on samples prepared in the laboratory, it is desirable that the test samples should have the same properties as those of the soil compacted in the field. A knowledge of the density vs. stability relationships for partially saturated soils is required if the most economical pavements are to be designed for areas in which it is relatively certain that the supporting soil will not become saturated (U.S. Engineer Dept., 1951). An understanding of the influence of density and water content at compaction is required for the most efficient placement of soils in the field. It is only through a better understanding of the factors affecting the properties of compacted soils that these results can be achieved and soils may be used to better advantage in earthwork structures.

REFERENCES

Foster, C. R. (July 1953) *Reduction in soil strength with increase in density:* Proceedings Separate No. 228, American Society of Civil Engineers, New York.

Hveem, F. N., and Carmany, R. M. (1948) *The factors underlying the rational design of pavements:* Proceedings, Highway Research Board, vol. 28, pp. 101-136.

Seed, H. B., Lundgren, R., and Chan, C. K. (1954) *The effect of compaction method on the stability and swell pressure characteristics of soils:* Highway Research Board, Bulletin 93, 1954.

Seed, H. B., and Monismith, C. L. (1953) *Some relationships between density and stability of subgrade soils:* Highway Research Board, Bulletin 93, 1954.

U.S. Engineer Dept. (July 1951) *Airfield pavement design: Flexible pavements:* Engineering Manual for Military Construction, Part XII, Chapter 2, Appendix B.

U.S. Waterways Experiment Station (April 1949-June 1950) *Soil compaction investigation:* Technical Memorandum 3-271: 1-5, Vicksburg, Mississippi.

U.S. Waterways Experiment Station (May 1951) *Airplane landing mat investigation, engineering tests on steel, pierced type, M8 and aluminum, pierced type M9:* Technical Memorandum 3-324, Vicksburg, Mississippi.