LABORATORY KNEADING OF SOIL TO SIMULATE FIELD COMPACTION

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SYNOPSIS

The basic principles of soil compaction are discussed and the fundamental requirements for a satisfactory laboratory-compaction test are set forth. It is contended that the laboratory-compaction test should produce curves that duplicate the field-compaction curves. Field-compaction curves obtained in the investigations of the Waterways Experiment Station are used as criteria by which the efficacy of laboratory-compaction procedures is judged. Field curves obtained by the use of sheepsfoot rollers and rubber-tired rollers are compared with laboratory curves obtained by static loading, impact loading (Proctor compaction), and "kneading static compaction." The kneading static compactor developed at Northwestern University for simulating more closely the action of field compacting equipment is described in detail. Data are presented to show that the position of the optimum curve with respect to the zero air-voids curve is a function of the time increment that the foot pressure is maintained. It is shown that the kneading static compactor can be used to duplicate field compaction.

● In the construction of earth dams, highways, airports, backfilling for foundations, and any other earth-fill construction work, soil compaction is utilized to minimize settlements and to insure stability in the constructed earth fill. For every type of soil and for every method of compacting the soil, there is an optimum water content at which the greatest amount of soil can be packed into a given volume. 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 that particular compaction procedure.

In preliminary studies, laboratory soil-compaction tests are performed on representative samples of the soil to be used in the structure, usually in conjunction with some form of shear, penetration, or consolidation tests. The data thus obtained are used by the engineer for the design and preparation of the construction specifications. To obtain reliable data for the above purposes, the laboratory soil compaction test should meet at least three important requirements: (1) it should produce optimum water contents and densities close enough to field results to be used for field compaction control; (2) it should produce complete compaction curves that are reasonably the same as those produced by the field compaction equipment; and (3) it should produce soil specimens having stress-strain characteristics acceptably close to those of the field compacted soils.

Laboratory soil-compaction procedures, as commonly used today, ordinarily meet the first requirement fairly well when the intensity of laboratory compaction is coordinated with the type and size of roller to be used in the field compaction. The second and third requirements have received little attention, even though the field compaction and, in many cases, the laboratory compaction of the samples, on which physical tests are performed for design data, are accomplished at water contents and to densities different from the optimums. The purpose of this paper is to present test equipment, procedures, and resulting data to meet the second requirement.

PRINCIPLES OF SOIL COMPACTION

The principles of soil compaction were first described by R. R. Proctor and published in *Engineering News-Record* in a series of four articles in 1933.[1] The laboratory compaction test developed by Proctor consisted essentially

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[1] R. R. Proctor, "Fundamental Principles of Soil Compaction," Engineering News-Record, Aug. 31, Sept. 7, 21 28, 1933.

in tamping the soil, at various water contents, into a cylindrical mold about 4 in. in diameter and 5 in. deep. In Proctor's own words, "the soil is compacted in three layers . . . each layer is subjected to 25 firm 12-in. strokes, using a rammer of 5½-lb. weight with a striking area 2 in. in diameter." In the original Proctor compaction test, the ramming is done by manual blows and not by a free-falling weight as most laboratories use today. The water content and unit dry weight of each compacted specimen are determined and these data establish the compaction curve.

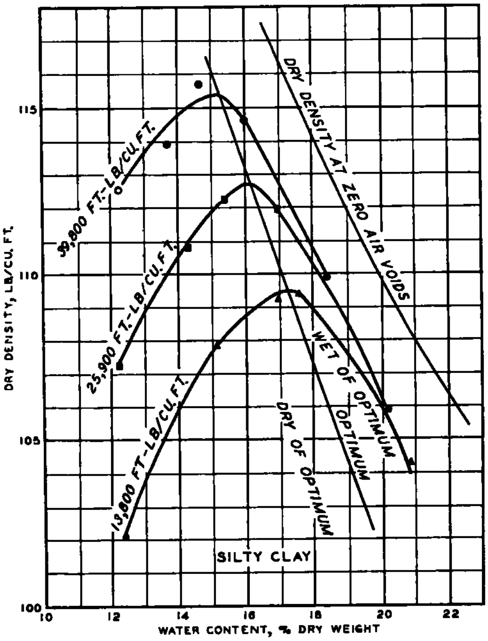

Figure 1. Dry density versus water content: Impact compaction.

Typical curves for impact compaction, commonly referred to as Proctor compaction, are shown in Figure 1. For a given compactive effort, the compacted dry density, or dry weight per unit volume, increases with increase in water content up to a certain point called the optimum; for further increase in water content beyond this point, the dry density decreases. A change in compactive effort produces a different curve and different optimum water content and density points. The amount of compactive effort in impact compaction is frequently measured by the foot-pounds of input energy per cubic foot of compacted soil. It can be varied by changing the weight of the rammer, the height of fall of the rammer, the thickness and number of soil layers, or by changing the number of blows per layer. In Figure 1 the compactive effort was varied by changing both the number of blows and the number of soil layers. As the compactive effort was increased, the compaction curves moved upward and to the left, producing higher densities and lower optimum water contents.

The optimum curve, which is the curve drawn through the optimum points for a series of varying compactive efforts, is more or less parallel to the zero air-voids curve. The zero air-voids curve is a convenient reference curve, representing the condition of water content and dry density at which a unit volume is completely filled by soil solids and water; in other words, 100 percent saturation. It is, therefore, a limiting curve of dry density and water content that can never be exceeded under any circumstances. Neither laboratory nor field compaction procedures, carried out in relatively short time periods and using reasonable amounts of pounding or rolling, can produce compaction points which fall on the limiting curve. In general, the optimum curve for impact compaction represents 80 to 85 percent saturation and the points closest to the limiting curve usually do not greatly exceed 90 percent saturation. As indicated in Figure 1, the region to the left of the optimum curve is commonly referred to as the "dry side of optimum" and the region to the right of the optimum as the "wet side of optimum." The Proctor or impact soil compaction test with particular amounts of compactive effort has been standardized by the American Society for Testing Materials and the American Association of State Highway Officials, and these specific standards of impact compaction are the most commonly used laboratory soil compaction tests.

In some instances static loading has been substituted for impact loading. In the static-loading compaction test, the load is usually increased at some specified rate until a given load is attained and this load is maintained for a specified period of time. The compaction curves for the static compaction test do not consistently have the same general shape as the impact curves, and the locations of the optimum lines for the two methods are quite different. The facts that these two different methods of compaction (impact and static) do not produce identical compaction curves, and that the stress-strain characteristics are quite different for soils compacted by these two methods were first presented in a report published by the Waterways Experiment Station, Vicksburg, Mississippi, in 1944.[2]

In 1945 and 1946, the Waterways Experiment Station conducted an extensive study of field and laboratory compaction of three soils. The field compaction portion of this investigation was carried out with careful and accurate field control of uniformity of soils and of compaction water contents. As a result of the careful planning and supervision, reliable and consistent field compaction curves were obtained for the sheepsfoot and rubber-tired rollers in use at that time. The field test results have been summarized by W. J. Turnbull and G. McFadden,[3] and a series of five reports has been published on the results of this investigation.[4]

Report No. 2 of the series, "Compaction Studies on Silty Clay," July 1949, shows clearly that neither the compaction curves obtained by field rolling nor the stress-strain curves obtained from tests on field-compacted specimens were duplicated by the impact and static laboratory compaction methods used in the investigation and previously described. This was positive evidence that the laboratory-compaction procedures were not meeting the requirements previously outlined.

The reliable field-compaction curves obtained in the Waterways Experiment Station's investigation provide criteria by which the efficacy of laboratory compaction procedures can be judged. Obviously, the first step in improvement should be to try to find methods for laboratory compaction which will duplicate in their entirety the field-compaction curves. In particular, an improved laboratory-compaction method should produce curves which have the same relative positions with respect to the zero air-voids curve as the field curves.

The characteristics of roller compaction in the field, by either sheepsfoot or rubber-tired rollers, are as follows:

The sheepsfoot of the roller or the surface of the tire comes onto the soil with little or no impact. It pushes on the soil with a definite pressure for an appreciable period of time, since the rollers operate at speeds between 2 and 6 mph.; then the pressure is removed and comes onto the soil again at an adjacent location in the next pass of the roller. In addition, the rotation of the roller drum or the tire causes a small rotating "kneading" or shoving action and, in some rollers, a rocking of the contact surface as it adjusts itself to the soil surface. In all cases the intensity of pressure exerted by the roller contact surfaces on the soil must be sufficient to cause relatively large shear deformations in the soil, since rapid compaction can be achieved only by shear deformations in which the relative positions of soil grains are changed with respect to each other. In other words, the stresses on the contact surfaces must exceed the bearing capacity of the uncompacted soil and, after several passes, should be less than the ultimate bearing capacity of the partially compacted soil but large enough to cause effective shear deformations.

On the basis of this analysis of the characteristics of field compaction, P. C. Rutledge and J. O. Osterberg at Northwestern University in 1946, set up the following desirable characteristics for a laboratory soil compaction device: (1) the compacting foot should not apply impact to the soil; (2) the compacting foot should apply a controlled pressure to the soil for a controlled period of time, and variation of both the contact pressure and the contact time over reasonable ranges corresponding to those anticipated in the field should be possible; (3) the compacting foot should cover a moderately small portion of the surface area of the soil sample being compacted so that shear deformations involving lateral flow of the soil could take place; (4) the operation of the device should be as nearly automatic as possible.

The compaction device to meet these characteristics was designed by J. O. Osterberg and constructed by the Northwestern University Soil Mechanics Laboratory in 1946–47.

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[2] "The California Bearing Ratio Test as Applied to the Design of Flexible Pavements for Airports," Waterways Experiment Station, T.M. No. 213-1, October 1944.

[3] W. J. Turnbull and Gayle McFadden, "Field Compaction Tests," Proceedings, Second International Conference on Soil Mechanics and Foundation Engineering, Rotterdam, Vol. 5, pp. 235–239 (June 1948).

[4] "Soil Compaction Investigation," series of five reports, Waterways Experiment Station, T.M 3-271, April, July, Oct. 1949, Feb , June 1950.

DESCRIPTION OF COMPACTION APPARATUS

The compaction device finally designed and constructed is a compressed-air-operated apparatus which can be used to perform impact-compaction tests automatically as well as to compact by the principles outlined in the preceding section. The latter type of compaction has become known as "kneading static compaction" and will be so referred to in subsequent discussion. Figure 2 shows the machine arranged for kneading static compaction and Figure 3 shows the arrangement for impact compaction. The operating parts of the machine are primarily assembled from standard, commercially available, air-control valves and mechanisms as noted in the figures. The machine can be changed from one type of compaction equipment to the other in about 20 min. In either case, a standard CBR compaction mold 6 in. in diameter by 7 in. deep is used. The depth of the compacted sample may be shortened by the use of spacer blocks in the lower portion of the mold. Usually the soil is compacted into a sample 4½ in. deep.

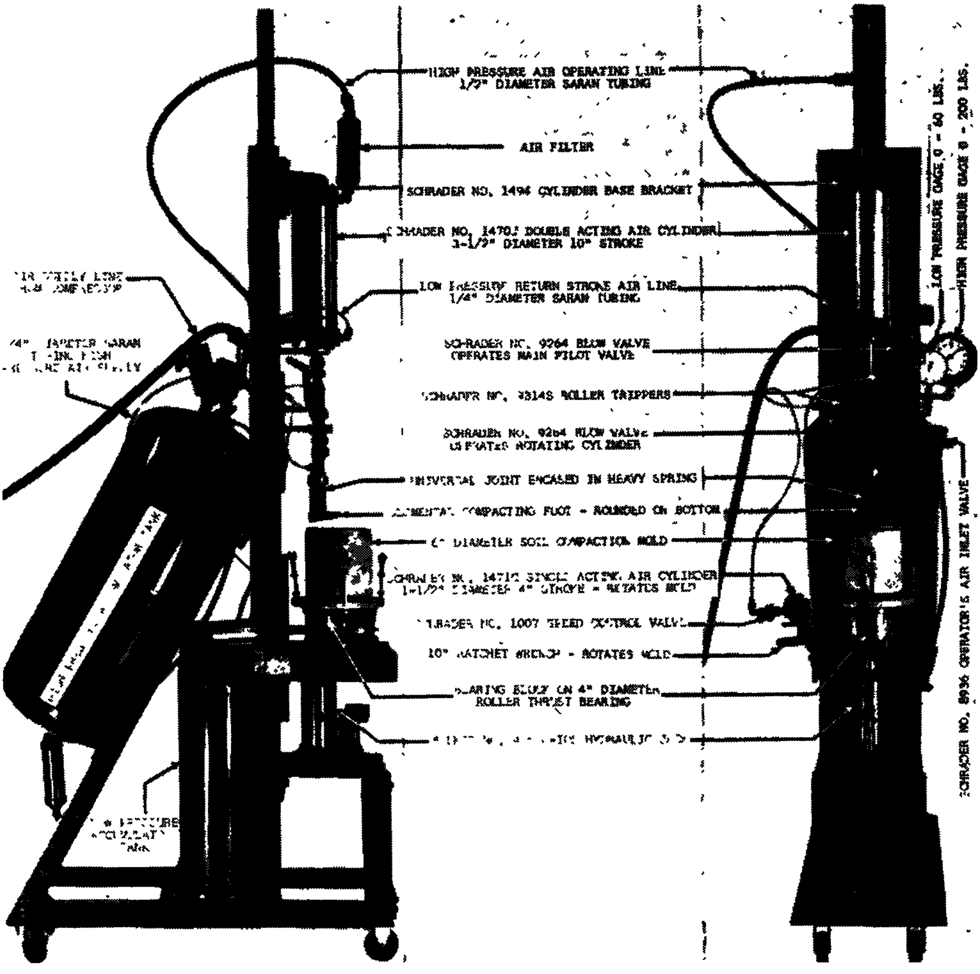

Figure 2. Kneading compaction by Northwestern air-operated soil compactor.

In the kneading static compaction, Figure 2, both the foot pressure and the time the foot is held down are adjustable through a standard pressure-regulating valve and a standard "pilot" valve which controls the cycling operation of the device. The foot goes up and down automatically at a predetermined rate and the compaction mold is rotated after each stroke by a ratchet wrench actuated by a small air cylinder. The foot has a slightly rounded bearing surface and is connected to the piston shaft by a universal joint, which has a stiff spring around it. This design allows some flexibility of the foot so that it can tilt or rotate on a nonuniform bearing surface, while the rounded bearing surface causes slight rocking of the foot and some spreading action in the soil. Thus a certain amount of kneading action is obtained.

For the impact compaction, Figure 3, a 20-lb. weight is lifted and dropped automatically through a constant height of 9 in. The constant height of fall is obtained by means of the ratchet arrangement. As the depth of soil in the mold increases, the weight catches higher and higher on the ratchet, thus maintaining the height of fall constant. The 20-lb. weight dropped 9 in. gives the same energy per blow and approximately the

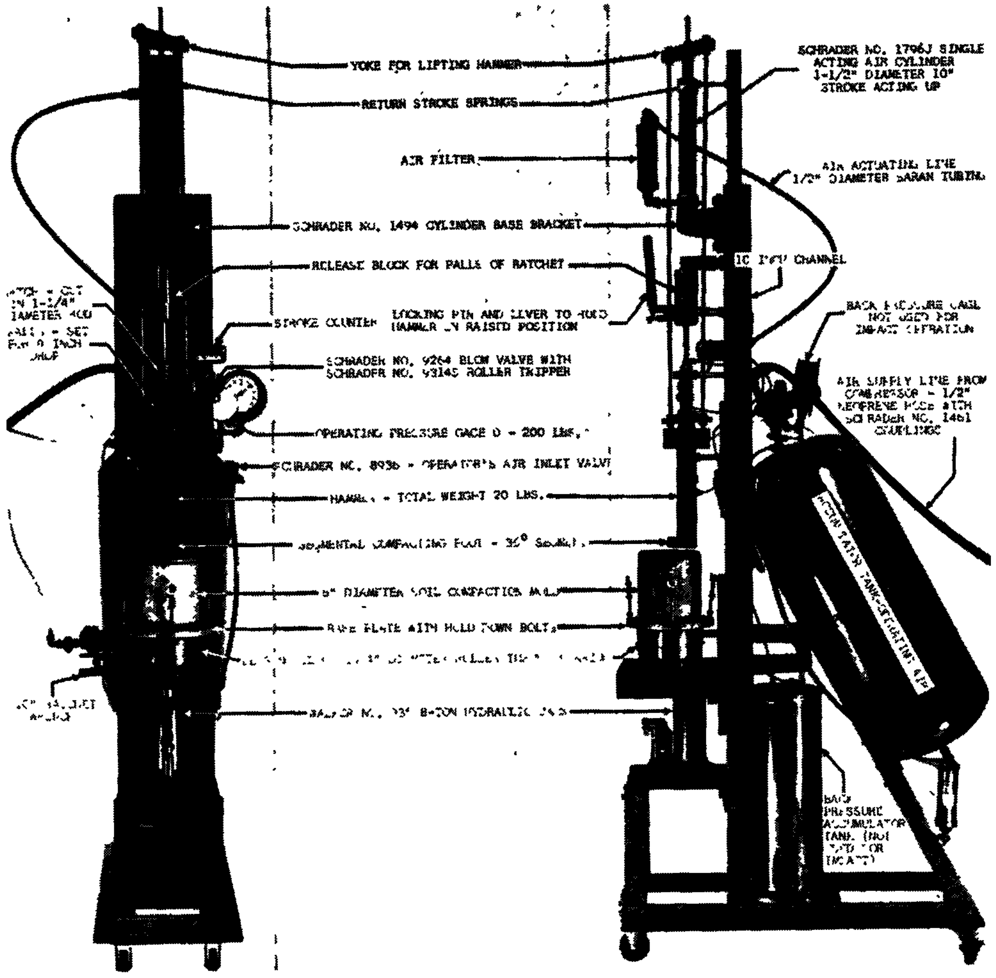

Figure 3. Impact compaction by Northwestern air-operated soil compactor.

same intensity of pressure as the 10-lb. hammer dropped 18 in. of the standard modified Proctor or modified AASHO tests. Using a 9-in. drop makes the compaction machine more compact and simplifies the design.

TEST PROCEDURES

Tests to establish the type of laboratory compaction results obtainable with the new kneading static equipment were performed on a soil furnished by the Waterways Experiment Station from one of their field test sections. The soil used was the low-plasticity silty clay previously referred to and for which a maximum difference between the location of field and standard laboratory, compaction curves had been observed. Both impact and kneading static laboratory-compaction tests were performed on this soil and all laboratory-compaction tests were performed with the Northwestern air-operated soil compactor. The field-compaction test data used herein as criteria by which the laboratory results are judged are taken directly from the Waterways Experiment Station Report No. 2. Some laboratory static-compaction test data also are taken from this report for comparisons

Impact-compaction tests, using the 20-lb. weight dropped 9 in., were made for the following compactive efforts: 25 blows on each of 3 layers (13,800 ft.-lb. per cu. ft. of compacted soil); 28 blows on each of 5 layers (25,900 ft.-lb. per cu. ft. of compacted soil); and 43 blows on each of 5 layers (39,800 ft.-lb. per cu. ft. of compacted soil).

For comparison, the standard Proctor or standard AASHO requires 12,350 ft.-lb. per cu. ft. of compacted soil, and modified AASHO requires 56,000 ft.-lb. per cu. ft. of compacted soil. The reason for using 39,800 ft.-lb. per cu. ft. as the upper limit in these tests rather than the modified AASHO was because 300 psi. was the maximum pressure available for the kneading compaction. The impact compaction had to be reduced to 39,800 ft.-lb. per cu. ft. to obtain a maximum density comparable to the 300-psi. kneading compaction.

In the kneading-compaction tests, the number of layers and the number of strokes per layer were maintained constant, and the compactive effort was varied by varying the foot pressure and the length of time the pressure was maintained on the foot. All kneading compaction samples were compacted in five layers with 40 strokes on each layer. Three foot pressures were used: 100 psi., 200 psi., and 300 psi.; and three time increments for the foot were investigated, namely, 0.03 min., 0.04 min., and 0.05 min. In both types of test 10 blows, or strokes, of the compacting foot is equal to one complete coverage of the surface of the soil sample. Thus, four complete coverages of the compaction surfaces were obtained for each layer in the kneading compaction tests.

RESULTS OF TESTS

A significant result of the Waterways Experiment Station tests on the silty clay was that the optimum line for the field compaction was considerably closer to the zero air-voids curve than the optimum line for the laboratory impact compaction or the laboratory static compaction. Preliminary tests with the Northwestern air-operated kneading-compaction machine showed that the position of the optimum water content could be shifted toward or away from the zero air-voids curve by increasing or decreasing the time that the foot pressure acts on the soil. As the time increment for foot pressure application was increased, the density and the optimum water content increased slightly, i.e., moved closer to the zero air-voids curve. This is illustrated in Figure 4.

Comparative curves for typical impact compaction and typical kneading compaction are shown in Figure 5. Although the curves for the two methods have the same general shape, the optimum water contents for the kneading compaction are consistently about 1 percent higher at the same optimum densities than the optimum water contents for the impact compaction.

In Figure 6 the locations of the optimum lines for the various methods of compaction for both field and laboratory and for various time increments on the kneading-compaction foot are compared. For clarity the compaction curves are omitted, and only the optimum points are shown. The optimum line for the 0.04-min. kneading compaction is identical with the line connecting the field optimums for the 20,000-lb. wheel load and the sheepsfoot roller, with the exception that the optimum for six coverages with the 20,000-lb. wheel load has a water content about 0.7 percent higher than that indicated by the optimum line connecting the other three field optimums. It is not clear why this point should be closer to the zero air-voids curve. The static compaction optimum line (in which the load is applied in one application with a plunger that just fits into the mold) is much further away from zero air-voids than that for any of the other methods.

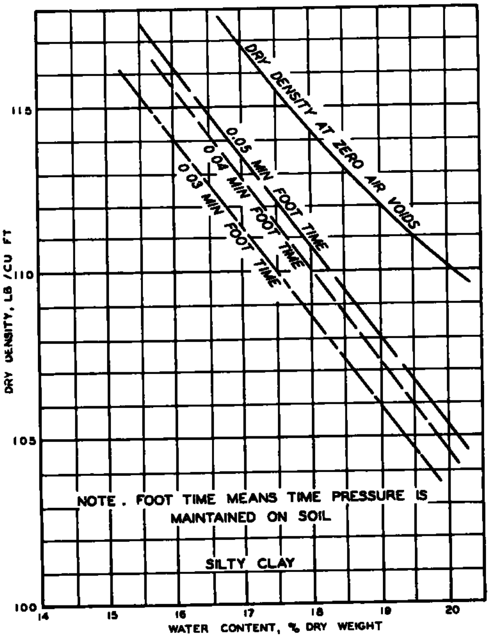

Figure 4. Effect of foot time on position of kneading optimum.

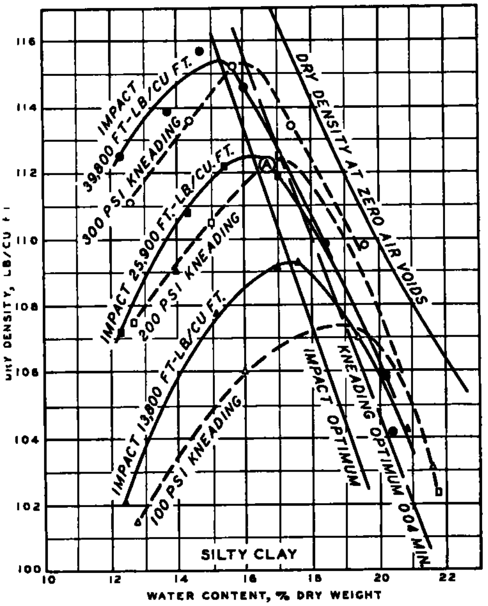

Figure 5. Dry density versus water content: Comparison of impact with kneading compaction.

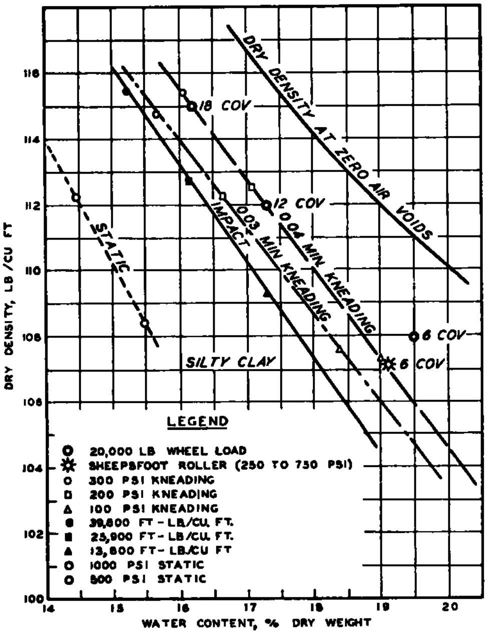

Figure 6. Dry density versus water content: Optimum for field and laboratory compaction.

This difference in the location of the optimum with respect to the zero air-voids curve for the different methods of compaction may be considerably more serious than it would seem at first glance. A difference of 1 percent in water content between the field optimum and the laboratory optimum would be of no serious consequences, at least from a practical point of view, if the compaction test were used only to establish the values of water content and density to use for construction specifications and for field compaction control. However, this is only the first requirement for a completely reliable laboratory-compaction method. The method should also produce test specimens for shear, penetration, and consolidation tests that have stress-strain characteristics acceptably representative of the prototype. Before the stress-strain characteristics for specimens compacted by different methods can be considered to be the same, a reasonable minimum requirement is that the laboratory and field compaction curves should coincide. In Figure 5, a specimen at point A with a dry density of 112.2 lb. per cu. ft. is on the wet side of optimum for the impact compaction, while at the same water content and density, it is on the dry side of optimum for kneading compaction.

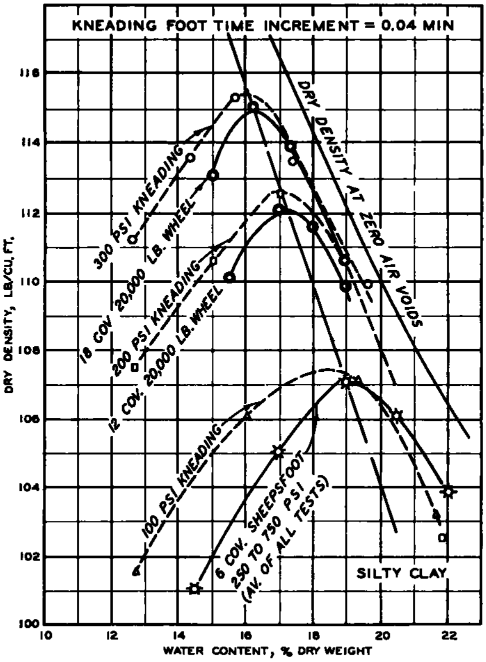

Figure 7. Dry density versus water content: Comparison of field compaction with laboratory kneading compaction.

The Waterways Experiment Station has published rather conclusive evidence of the difference in stress-strain characteristics for dry side of optimum versus the wet-side test specimens as well as for different methods of compaction.

A comparison is made in Figure 7 of the compaction curves obtained by field rolling with those resulting from kneading compaction on the same soil. Field compaction curves are shown for 12 and 18 coverages of a 20,000-lb. wheel load on a rubber tire with a 65-psi. contact pressure and for six coverages of a sheepsfoot roller. The sheepsfoot roller curve is the average for field test with theoretical foot pressures of 250 psi., 500 psi., and 750 psi. on the roller. The three kneading-compaction test curves approximate fairly closely the shape and position of the field-compaction curves, particularly those for the rubber-tired wheel load. It is believed, therefore, that this type of laboratory-compaction test has considerable promise for fulfilling the three requirements outlined at the beginning of this paper. It is also interesting to note that a small-scale adaptation of this same idea of compaction has recently been proposed by S. D. Wilson of Harvard University and has been reported by him to yield results closely approximating the field compaction curves.[5]

It is probable that only specimens compacted under conditions closely approximating field conditions will have physical properties reasonably similar to field physical properties. The data presented in this paper are for one soil only, a low-plasticity silty clay, and the results are not directly applicable to other soils. The tests at the Waterways Experiment Station included a clayey sand. The differences between field and standard laboratory-compaction curves were much less pronounced for the clayey sand than for the silty clay. This might be taken as an indication that the differences become less pronounced with decreasing plasticity and more pronounced with increasing plasticity. However, there is insufficient evidence to warrant this conclusion and it is only suggested as a possibility.

CONCLUSIONS

1. The location of the optimum line with respect to the zero air-voids curve varies with the method used for compacting the soil.
2. With the kneading-compaction method, the position of the optimum line can be shifted by changing the time increment for the compacting foot. Increasing the time increment for the foot causes the optimum line to move closer to the zero air-voids curve.
3. For the soil studied, the kneading-type compaction can produce compaction curves closely approximating those obtained by field rolling compaction.
4. The compressed-air-operated kneading-type soil compactor designed and developed at Northwestern University can be used successfully to obtain compaction of 6-in.-diameter specimens closely approximating field compaction.

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[5] S. D. Wilson, "Small Soil Compaction Apparatus Duplicates Field Results Closely," Engineering News-Record, Vol 145 No. 18, pp. 34-36 (Nov 2, 1950).