COMPACTION OF EARTH EMBANKMENTS

By L. W. Hamilton, *Associate Engineer, U. S. Bureau of Reclamation*
Edmund F. Preece, *Senior Engineer, National Park Service*
T. E. Stanton, *Materials and Research Engineer, California Division of Highways*
A. W. Johnson, *Soils Engineer, State Highway Commission of Kansas*
K. B. Woods, *Formerly Assistant Engineer, Bureau of Tests, Ohio Department of Highways*
and Dr. Leo Casagrande, *General Inspector for German Highways*

Arranged By Harold Allen

Materials Engineer, U. S. Bureau of Public Roads

TOPICAL INDEX

THEORY

Hamilton: Several explanations have been advanced for soil compaction phenomena. Most of these concentrate on the mechanics of the water in the soil-water mixture. The most plausible theories will be discussed, for an understanding of the mechanics involved is essential in studying soil mechanics or analyzing construction problems.

Proctor's theory may be outlined briefly as follows: The ordinary soil mass is composed of gravels, sands, silts, and clays, and compaction is the act of forcing the fine grains into the voids between the larger grains. It is contended that the water coats the surface of the soil grains and serves as a lubricant, reducing the frictional resistance between these soil grains and permitting the compacting force to become more efficient in arranging the soil fines into the voids between the larger grains. If the moisture content is not sufficient to produce adequate lubrication, the density of the compacted mass will be relatively low, because the compacting force is not enough to overcome the frictional resistance between the soil grains. As the moisture content (lubricant) is increased, a point will be reached where the compacting force will overcome this resistance and will cause the fines to be forced into the voids between the larger grains, and the maximum density will be obtained. As the moisture is increased beyond this point, the compacting force compresses the small volume of entrapped air in the soil mass. This compression gives rise to hydrostatic pressure, which tends to separate the soil grains by partial flotation, thereby causing a reduction in density.

The lubrication theory seems reasonably valid for many soils and types of compaction. For example, observations have shown that soils having approximately the same gradation usually agree closely on optimum moisture content. Also, fine-grained soils, require much more moisture for adequate lubrication than coarse grain soils. Likewise, varying surface conditions of the soil grains require varying moistures. Further substantiation of the theory is given by the fact that, as the compacting force is increased, the maximum density increases and the optimum moisture decreases. This follows normal expectancy since the increased force would lessen lubrication requirements.

Another consideration associated with the lubrication theory is that materials compacted at the optimum moisture content undergo most of their consolidation during the construction of the embankment or the original loading. At this condition, there is adequate lubrication present to allow the consolidation to occur without requiring saturation. On the other hand, material placed dry may show little or no consolidation until the embankment become saturated.

Although the lubrication theory is logical, it may not be technically correct. Probably its outstanding feature lies in the simple and logical manner in which it may be explained, permitting comprehension by men not experienced in the field of soil mechanics.

The theory of moisture films advanced by C. A. Hogentogler, Jr.,[1] is also one of major importance. This theory may be described briefly as follows: The soil grains, especially those of the fine-grained, cohesive nature, are encased in water jackets. The water in the jackets is attracted by the minerals of the soil grains and has different characteristics in the innermost and outermost layers of the films. The contention is that the innermost layers are extremely cohesive and that this cohesiveness is decreased as the distance from the soil surface is increased and gradually grades out to the properties of free water. The character of these films is affected by the physical shape and size of the soil grains, the chemical composition of the soil, the kind of adsorbed ions on their surface, and the chemistry of the added water.

This theory indicates that, if the moisture content was low and the moisture films very thin, there would be high resistance between the soil grains as the thin films are extremely cohesive. As the moisture is increased, these films would become thicker and less cohesive, enabling them to serve as lubricants. At the maximum density, these films reach a thickness which gives a cohesive strength at the points of contact that just fails to balance the compacting force. This allows the compacting force to arrange the fines efficiently into the voids of the larger grains and results in maximum density. As the optimum moisture is exceeded the increase in film thickness causes a corresponding increase in the separation of the soil grains and, consequently, a decrease in density. Also, as the films thicken, their strength is decreased, resulting in decreased stability of the compacted mass, which is reflected by the rapidly decreasing penetration resistance.

The entire theory, when applied to different materials and types of compaction, seems very logical for all cases. Furthermore, it may be used in explaining other phenomena, including shrinkage of fine-grained soils by drying, and expansion by wetting; the apparent variation of cohesion and frictional resistance with variation of moisture content; and increased strength of materials compacted to high densities.

Comparing the lubrication and film theories, it seems that the latter is a more comprehensive and scientific expression of the former.

A third theory contends that the moisture throughout the soil mass creates surface tensions which aid the compacting force in forcing the soil grains into closer contact. It is the conventional explanation of the shrinkage of fine-grained soils and also the explanation of their cohesiveness. I do not agree with such analysis entirely but believe the correct approach should include both the surface-tension and moisture-film theories.

The Effects of and Reasons for Compaction

The basic reason for compacting earth fills is to produce a soil mass that will satisfy the three criteria, settlement or consolidation, permeability, and shear value or stability. To date, not enough

[1] Hogentogler, C. A., Jr., "Essentials of Soil Compaction," *Proceedings*, Highway Research Board, Vol. 16, p. 309, 1936.

data are available to establish definitely the value of compaction in respect to these three properties. However, all available information indicates that compaction is essential.

The logical theory for the compaction of earth material, as already stated, is that soil compacted to its maximum density contains minimum moisture when saturated, and, therefore, the stability should be maximum. It is also maintained that compaction lowers the permeability of the soil mass because the pore space is reduced in total amount as well as in size of individual pore openings. The increased density should also reduce the settlement of the soil mass to a minimum.

The foregoing statements are logical in theory but remain to be definitely established as true. It may be said, however that, in general, observations on construction work and laboratory studies substantiate the concepts.

Effects of Moisture

In the compaction of soils, the moisture condition is so closely related to the results that it is of primary importance.

For a study of the effect of moisture on the compaction of soil, let us examine a typical density-moisture curve. (See Fig. 1.) This soil, compacted at 6 per cent moisture is, to all appearances, extremely stable. The compacted mass is very hard and until the development of recent information the compaction would have been considered satisfactory. However, in this condition, the mass has about 26 per cent voids by volume and can take on water up to about 13.2 per cent by weight, when it becomes saturated. At 13.2 per cent moisture, the material would be relatively unstable, as indicated by a penetration resistance of practically zero.

During the saturation process, there are two possibilities; one, above-described softening, which is very undesirable; the other, that the soil would consolidate to a higher density and might, due to increased density, remain fairly stable. The larger part of this consolidation would occur simultaneously with saturation, because, as compacted the material is very hard and stable and does not become unstable until wetted. This type of consolidation is undesirable because both the strain and softening occur simultaneously.

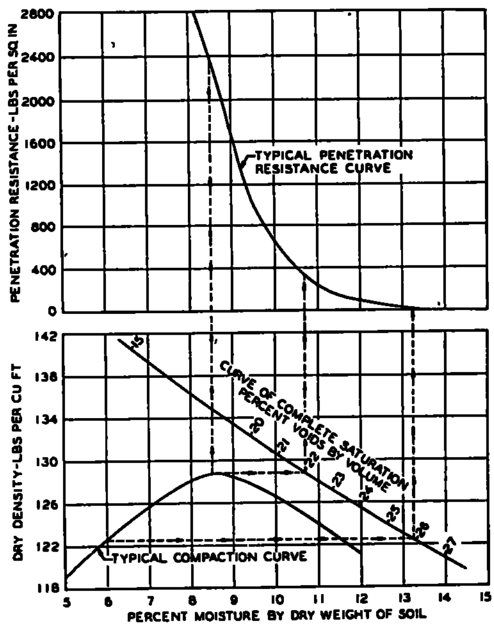

Figure 1. Effects of Moisture upon Compacted Density

Next, consider the soil compacted at the optimum moisture (8.5 per cent). This soil is not nearly so firm as the one compacted dry as indicated by the penetration resistance of about 2,350 lb. per sq. in. Yet this mass has only about 22 per cent voids by volume and can take on water up to about 10.7 per cent. At this saturated moisture, the indicated penetration resistance is about 330 lb. per sq. in. or some 33 times firmer than the same soil compacted dry.

This reasoning shows how variations in

placement moisture affect the predicted saturated stability. This analysis is largely synthetic in nature and may not be strictly true, as the materials in a structure would consolidate some as construction progresses. Consequently, even before the structure is saturated, the consolidation of the soils, especially those at the optimum moisture or above, probably would increase in density to such an extent that the final (saturated) moisture is limited to even less than that

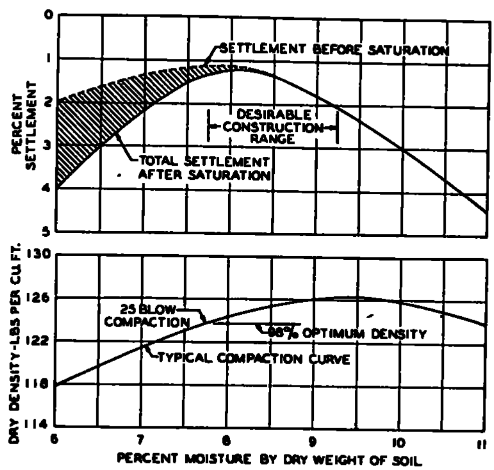

Figure 2. Effects of Compacting Moisture upon Settlements. Settlement measurements made on specimens 3-in. thickness—8-in. diameter. Settlement measurements observed before percolating water added and then after complete saturation. Consolidating load 15,000 lbs. per sq. ft.

indicated. Materials placed dry and hard have been observed to settle very little under average load conditions and take their settlement as they are saturated. On the other hand, the settlement of material at optimum moisture is not appreciably affected by the saturating water.

The relationship of consolidation to placement moisture, as observed on laboratory specimens, is shown in Figure 2. The shaded areas indicate the amount of consolidation following saturation of the specimen. The materials placed dry show much more final settlement than the materials placed at the optimum density and moisture. The settlement curve has about the same shape as the compaction curve and shows the minimum settlement to occur at nearly the optimum conditions.

Another important consideration of the effect of variation in placement moisture is the permeability of the soil mass. Observations have shown extremely wide variation in the permeability of the soil mass, depending upon placement moisture conditions. In general, these observations have shown that soils compacted dry have percolation rates that are many times (as much as several hundred times for some soils) the percolation rates of the same soils compacted wet. Undoubtedly, this is true for a short time, but whether or not it remains true in structure is a question that is yet to be answered. The important consideration is the rapid saturation of the structure.

Effects of Variations in the Compacting Force

The foregoing discussion describes the variations that are produced by changing moisture conditions, assuming the compacting force to be constant. Observations have shown that these trends are still relatively true as the compacting force is changed.

The change in density resulting from variation of the compacting force is illustrated in Figure 3.

Many observations have been made in which the compaction has been applied in different manners, such as; varying the number and length of drop and the weight of the Proctor rammer; by applying pressures with a sheepsfoot attached to a hydraulic press and applied at different pressures and different number of applications; by using a large piston with many feet on it; and by observations of construction on which roller weights and roller trips were varied.

All these gave the same general trends shown in Figure 3, and indicated in general that the density obtained is a function of the work applied. Laboratory observations indicate that, within limits, the method of applying the work is not important; however, field observations have, within limits, favored increased roller weight as being more effective.

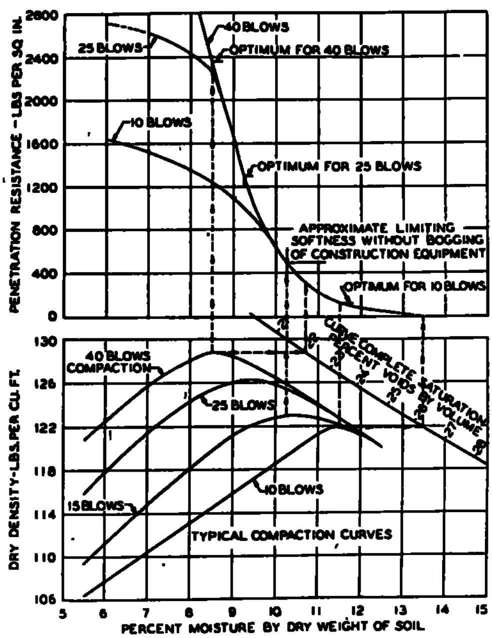

Figure 3. Typical Compaction Curves that Show Effects of Variations in the Compaction Applied.

The increase in density for increased roller trips up to about 10 or 12 passes has been favorable, but beyond this, comparatively small.

The curves shown on Figure 3 indicate that for each compacting force there is a different optimum moisture. As the compacting force is increased, the density of the dry soil is increased and the optimum moisture becomes less. The increased compaction not only gives more favorable density but gives a much more stable mass, which is indicated by the changes in penetration resistance. The penetration resistances are 130, 500, 1,300 and 2,360 lb. per sq. in. for 10-, 15-, 25-, and 40-blow compactions, respectively.

The increase in penetration resistance is important because, if the embankment is soft, much difficulty will be had with bogging of equipment thereby increasing construction costs. Soon after Proctor's theories were set forth, numerous objections were raised that fills placed at the optimum moisture for the rollers used were entirely too soft and presented many construction difficulties. In recent years, roller weights have been greatly increased and control effected until most of these objections have been overcome. The heavier rollers have allowed the soils to be placed at much lower moistures and have resulted in fills that are firm, permitting efficient handling of construction equipment.

Despite the most efficient construction-control operations, variations will occur, especially in moisture content. Heavy rollers capable of producing a high degree of compaction, simulating the 40-blow compaction shown in Figure 3, generally cause favorable densities regardless of reasonable variation of moisture. However, if light rollers are used the moisture must be rigidly controlled to give satisfactory density. This fact is the predominating reason for the adoption of heavy rolling equipment as the increased compaction permits less rigid moisture control.

Another advantage to be gained through increased compaction is brought out by laboratory observations of settlement, shown graphically in Figure 4. There is a wide variation between the settlement of material compacted equivalent to 15 blows and 25 blows. There is also a significant reduction in the settlement as the compaction is increased from 25 to 35 blows.

Percolation tests on materials compacted to high densities show a noticeable decrease in permeability although the difference seems to be less than that noted with changes in placement moisture. Penetration-resistance tests made on saturated specimens compacted to high densities show a great increase of this resistance compared to samples placed at the lower densities. In the author's opinion, this indicates an increase of the saturated stability.

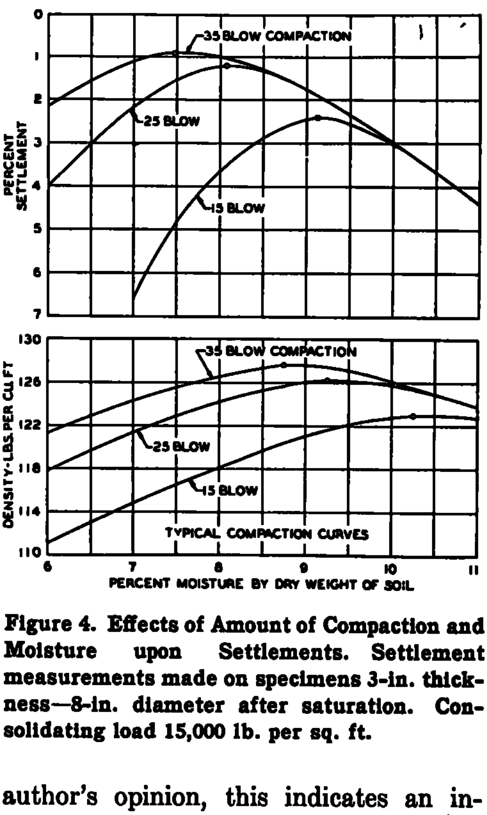

Figure 4. Effects of Amount of Compaction and Moisture upon Settlements. Settlement measurements made on specimens 3-in. thickness—8-in. diameter after saturation. Consolidating load 15,000 lb. per sq. ft.

Another and very important reason for the compaction of soil is for economy in design of structures. The present stage of development has not justified any significant changes in design, but further experience in theories, effects, and methods of control to obtain desired conditions will undoubtedly result in economy.

PRELIMINARY SOIL STUDIES AND SURVEYS

Woods: It is apparent from a study of typical embankment failures that their elimination may be obtained by: (1) proper design, (2) wasting of unsuitable material, and (3) proper embankment compaction. The last item can be controlled by an embankment specification while the first two are directly dependent upon the soil profile.

Soil Profile

The term soil profile as used in Ohio[2] involves the mapping of the data obtained by complete investigations of all soil and geological stratifications encountered in foundation, cut, or subgrade which may influence the design, construction, and maintenance of a highway. The procedure includes mapping and testing soil layers which will be encountered as subgrade so that weakness may be corrected. Foundations must be tested to minimize failures from overloading. Embankment materials must be mapped and tested to eliminate unsuitable materials and to aid in the use of poor materials. Landslides must be investigated and adequate information provided for the proper design of drainage.

Conditions are so variable that both mapping and embankment construction are difficult. To illustrate; variations in topography are pronounced, the southern and eastern portions of the State being very hilly, and the remainder rolling to level. Approximately two-thirds of the State is covered with a deep mantle of glacial drift which complicates soil mapping due to the complex patterns of soil types encountered. In the hilly regions the geological formations are also com-

[2] For a detailed description of the general use of the Soil Profile in Ohio, see "Soil Mechanics Applied to Highway Engineering in Ohio," by K. B. Woods and R. R. Litehiser, O. S. U. Engineering Experiment Station, *Bulletin* No. 99.

plex, ranging from the Ordovician System through the Silurian, Devonian, Mississippian and Pennsylvanian, to and including a portion of the Permian. Add to this the fact that there is considerable variation in climate from north to south. In addition floods are particularly hazardous to some highway projects over the entire length of the Ohio River and certain other streams emptying into the Ohio.

The information for the soil profile is obtained by borings, test pits, and examinations of exposed surfaces in highway cuts. The survey party includes a competent soils engineer, a note keeper, and unskilled assistants and is supplied with a set of plans containing cross sections and the ground line and proposed grade elevations and profile.

The first procedure normally involves auger borings and all soil in foundation and cuts are mapped. When rock is encountered geological logs are made of rock cuts and other pertinent geological information. If foundations are found to be questionable, test pits are dug and undisturbed samples obtained.

The samples are taken to the laboratory, tested, and classified. The entire project then goes to the drafting room where the mapping of the profile and cross sections is completed. The finished profile is submitted to the Design Bureau where slope determinations for the cuts and fills are made, subgrade treatment provided for when necessary, the spacing and location of drains determined, and provisions made for the wasting of unsuitable material.

Soil Classification by Density

Rock. The hills of eastern Ohio contain enormous quantities of sandstone, much of which makes excellent embankments. All-rock embankments are not common, for most cuts in the hills also contain shale and overburden. Unfortunately the use of rock where it is most needed and where it is available has, until recently, been neglected. This is particularly true in embankment areas subject to flooding and for side-hill fills which tend to pocket water. The stability of such areas can be increased appreciably by constructing part or if possible all of the embankment or rock to permit the full flow of water.

Granular Material. Gravel-sand-silt clay mixtures which may be considered as granular soils make good embankments. Such soil types require but little field supervision to obtain good compaction, settlement is slight, they make good subgrades for both flexible or rigid pavements, and will not slip or slough but may erode readily. These soils are identified by their grading, low liquid and plastic limits and by dry weight density peaks of from 120 to 135 lb. per cu. ft. These types also meet the Bureau of Public Roads A-1, A-2 and A-3 classifications.

Silt. Soils with maximum dry weight peaks of 110.0 to 120.0 lb. per cu. ft. are usually silts and can be considered fair for use in embankment. Such soils usually fit the A-4 classification. These soils have average water holding capacity and may contain sufficient cohesive clay to act as a binder in holding the soil together without expanding under capillary water action. They are normally stable but are subject to erosion unless adequately protected. When improperly compacted in embankment, instability often results due to the filling of the air void spaces with capillary or seepage water. Failure includes sloughing, erosion, and heaving during freezing weather.

Clay. Clay soil is always susceptible to sliding and instability, when wet. The slipping plane clays are characterized by high liquid limits and high plasticity index numbers. The sloughing clays usually have high liquid limits and low plasticity index numbers. Clay soils seldom exceed 110 lb. per cu. ft. dry weight by laboratory test and have high optimum moistures. Expansive clays and organic silts having dry weight peaks of less than 100 lb. per cu. ft. should be considered questionable for use in embankments, and unsatisfactory for 25- or 30-ft. fills unless designed accordingly and rigid construction control exercised. When clays are poorly consolidated there is immediate danger of sloughing and sliding if the material is exposed to saturation by ground water percolation, rains and floods. Flattening the slopes of poorly consolidated clays subject to saturation seldom improves the condition and may even be detrimental because the amount of moving load is increased. The stability of clay can be greatly increased by increasing density. Laboratory tests show conclusively that such material can be compacted at the optimum moisture content with air voids of from 7 to 8 per cent.

Soils with maximum dry weights of less than 100 lb. per cu. ft. usually require exceptionally high optimum moisture contents to obtain the ideal density and at the same time they have a high percentage of air voids. Since the plastic limit of low-weight soils is only slightly above the optimum moisture, it can easily be exceeded without the soils changing in volume. For this reason, it is a questionable procedure to attempt to stabilize 100 lb. per cu. ft. soil without adding a granular material or otherwise using special design.

Density soil summaries showing the averages results of tests of over 2700 samples received in 1936, 1937, and 1938 are shown in Table 1.

TABLE 1

DENSITY SOIL SUMMARY OF TESTS ON 834 OHIO SAMPLES IN 1938. TOTALS BY DRY WEIGHT PEAKS

Range in Proctor Dry Weight Maximum Densities, lb. per cu. ft.	Number of Samples Tested	Mechanical Analysis					Atterburg Tests			Proctor Test						Approx. B.P.R. Class (for Comparison)	Laboratory Classification
		Retained on No. 4 Sieve, %	Passing No. 4 Retained on No. 10, %	Course Sand Passing No. 10, Ret. on No. 60, %	Fine Sand Passing No. 60, Ret. on No. 200, %	Passing No. 200 Sieve, %	Lower Liquid Limit	Lower Plastic Limit	Plasticity Index	Wet Weight	Water, %	Bearing	Dry Weight	Water, %	Bearing		
70- 74.9	1	1.0	11.0	76.6	7.2	4.2	N.P.	N.P.	N.P.	105.8	44.6	...	73.6	43.6	.	....	Unsatisfactory or very poor
85- 89.9	3	15.1	6.0	11.2	4.9	62.8	51.7	28.2	25.7	113.8	30.6	320	87.6	29.2	473	...	
90- 94.9	17	1.1	0.5	5.6	5.7	87.1	49.8	25.2	24.6	117.9	29.0	356	92.3	26.5	617	A-5, A-8	
95- 99.9	51	1.1	2.3	10.4	4.8	81.4	46.9	22.5	25.7	121.3	24.6	376	98.1	22.3	633	A-5, A-8	
100-104.9	157	1.8	1.9	10.0	6.6	79.8	40.5	21.3	19.4	124.5	22.0	424	102.7	20.5	622	A-6, A-7	Poor
105-109.9	245	3.2	2.3	10.9	8.3	75.3	35.7	19.1	16.8	127.4	19.4	461	107.4	18.0	682	A-6, A-7	
110-114.9	201	5.3	3.7	16.6	11.7	62.7	31.6	18.2	13.6	130.5	16.9	507	112.3	15.8	746	A-4	Fair
115-119.9	83	10.3	5.5	24.0	14.2	46.0	26.0	16.8	10.8	133.3	14.3	577	117.1	13.5	800	A-4	
120-124.9	50	14.1	8.2	29.4	13.7	34.6	22.5	15.7	8.1	137.0	12.5	627	122.1	12.2	823	A-1, A-2, A-3	Good
125-129.9	24	17.1	11.4	33.6	11.6	26.3	19.4	15.0	5.4	140.7	10.8	706	127.4	10.4	865	A-1, A-2, A-3	
130-134.9	2	12.1	9.2	25.9	14.9	37.9	16.1	13.9	3.5	142.4	9.9	....	130.4	9.3	....	A-1, A-2, A-3	Excellent
Total ...	834	.....	... .	.....	. . .	....	......	....	. . . .	...	....	....	. ...	....	.. .	. . .	....

Shale. Shale varies greatly in physical characteristics. Most of that found in Ohio is a clay shale which is relatively stable as it occurs in nature but disintegrates quickly when exposed to the weather. A high percentage of the constituents of weathered shale will pass a No. 200 mesh sieve.

Embankments made of shale often cause trouble. In the usual process of constructing shale embankments, the shale as finally compacted will be broken down to particles of less than 6 in. in size. Due to the firmness of the particles, the embankments when observed soon after construction appear to be quite stable. Unfortunately many of the voids are left unfilled and disintegration soon starts due to the combined action of air, erosion, wetting, and drying, freezing and thawing.

Shale should be placed in embankments in such a fashion that it will be pulverized as much as possible without being allowed to lose all of its natural moisture content. Enough soil fines should be used to completely fill the voids and sufficient water added to insure proper compaction at the optimum moisture content.

Rock with Clay or Clay Shale. In the Ordovician outcrop area of southwestern Ohio an unusual condition exists; most hill cuts contain from 10 to 40 per cent of limestone mixed with clay shale. When cuts are made in the outer slopes, the shale is usually found to be disintegrated to a very plastic clay, and it is very difficult to compact in embankments because the slab-like rock pieces cause an excess of air voids in the finished job. If and when these voids become filled with water, sloughing or sliding often results, particularly on side-hill fills. In such places the rock must be broken sufficiently to obtain a dense impervious embankment or instability will result eventually.

Johnson: The preliminary soils survey of which laboratory soils identification and compaction tests are a part, forms the basis for determining the need of compaction; and the type of moisture and density control most nearly suited to the road design; the soil type and the manner in which the various soils are to be used in the embankment. The purpose of the survey, as it is related to the problem of compaction, is to locate, identify and determine the compaction characteristics of all materials which will form a part of the finished road structure. Since earthwork quantities are directly related to soil compaction, the survey includes detailed field studies of the existing soil moisture and soil density. The results of these studies are later used in the determination of earth shrinkage and excavation quantities and the water requirements for compaction.

In Kansas representative samples of each soil from a project are submitted to the soils laboratory for test. Atterberg plasticity tests, specific gravity and mechanical analysis tests are conducted on all soils. Inasmuch as shrinkage tests and moisture equivalent tests have already been conducted on thousands of samples representing all ordinary soils they are now conducted on samples only when special studies are made.

Compaction tests are then made on all soils which have not been shown to be similar by the results of the routine tests. Shear tests, moisture absorption and swell tests, slaking tests and other special tests to obtain a more direct measure of individual soil properties are made when it is deemed necessary.

Compaction requirements as related to Soil Type and Design

A given soil has a number of related properties, directly dependent upon the state of compaction and moisture content at which soil exists in the road. Thus when the soil moisture and density are controlled during construction, the soil properties which heretofore were considered only in a general way, now also can be controlled and used in road design. For a given soil, for example, clay, the engineer is interested largely in density when it is to be compacted in foundations under fills or in the body of the fill itself, since settlement is the primary problem. If other more desirable soils are not available for use in the top of the fill as subgrade material, the moisture content at which the clay is compacted is as important as is the density. If the road is to carry a light type of sand gravel surfacing, only sufficient moisture to obtain compaction and bonding is necessary. If the road is to carry a base course and bituminous surfacing, it should be compacted at a moisture content which will give maximum compaction and result in a minimum of softening due to absorption of moisture, the action of frost and other agents. Subgrades for concrete pavements requires compaction at moisture contents which will result in maximum resistance to volume change due to the absorption of water.

Preliminary soils survey data include the results of soil moisture and soil density tests. Excessively wet soils encountered in channel changes are either used in side road entrances, farm entrances, plugs for old channels, etc., where compaction is unnecessary, or are wasted entirely. Density tests form the basis for a rational method of selecting the shrinkage factor to use in determining excavation quantities. Studies of compaction data on a large number of Kansas projects have shown that 92 to 95 per cent of the density found by the standard compaction test are obtained in construction. By assuming that the soil will, on the average, be compacted to 95 per cent of the density found by the Kansas standard compaction test[3] and using the cut densities obtained for the various soils throughout the project, the shrinkage percentage is computed.

[3] See page 162.

METHODS OF TEST AND CONTROL

Stanton: In California, laboratory tests are made to determine the optimum moisture and maximum consolidation obtainable under a load of 2000 lb. per sq. in. The tests are made on samples of the material which will be used in constructing the embankment. Representative samples of soil are taken with an orchard post hole auger, soil tube, or other suitable equipment. A representative portion of the sample is compacted to a standard degree by either the testing machine method or the field method.

In the testing machine method enough dry loose soil is measured to fill a 6 by 8 in. cylinder mold and then removed and moistened to a consistency which will give maximum compaction. The amount of water necessary is determined quite closely by adding just sufficient water so that soil will ball readily in the hand but still can be broken without crumbling or pulverizing appreciably at the breaking point. If in doubt as to the exact amount of water to be used, additional compaction tests are made varying the water one or two per cent each side of the first test, thereby arriving at the correct moisture content. The amount of water necessary to obtain maximum compaction with most types of soil has been found to be between about 7 and 16 per cent. The moistened soil is then replaced in the cylinder mold and a compressive load of 2000 lb. per sq. in. applied. The volume of soil compacted in this manner and the dry weight are recorded, from which the dry weight per cubic foot compacted is computed.

For field soil compaction tests the equipment consists of a sensitive 5-lb. scale or balance and a soil compacting outfit, consisting of a 2½-in. diameter cylinder fitted with a cap, tamping shaft, piston, and wrench (Fig. 5).

In compacting soil by the field method, dry soil is measured into the cylinder to a height of between 10 and 13 in. Five pounds of dry soil are usually required, except in light materials such as diatomaceous earth or shale. This measured amount of dry soil is moistened, as described under (a) to a consistency which will give maximum compaction and compacted in the cylinder in five equal layers. Each layer is consolidated by dropping the tamper 20 times from a height of 18 in. After compacting the fifth layer the piston is placed on top of the soil in the cylinder and seated by five 18-in. free drops of the tamper. With the tamping shaft resting on the piston the indicated height of soil to the nearest one tenth inch is read at a point level with the top of the tube. The dry weight per cubic foot of compacted soil is then determined.

When material coarser than 1 in. is present in the embankment the sample is separated on the 1-in. sieve and the dry weight per cubic foot compacted determined by the field method for the minus one inch material. Correction for the coarser rock is then made on the basis of quantity and specific gravity.

These preliminary tests are made to assist in determining a proper shrinkage factor for material from excavation to embankment and further to afford data relative to optimum moisture required for suitable consolidation.

Similar tests are made from time to time during construction on samples from each three or four foot layer as the embankment is completed, the test procedure case being to excavate material from a test hole, dry and weigh the removed material, determine the volume of the test hole either by the loose sand or the rubber tube water displacement method (Figs. 6 and 7) and from these data determine the relative consolidation as compared with the preliminary test made on the loose material before placing in the embankment. It is customary practice to provide in the specifications that the compaction in

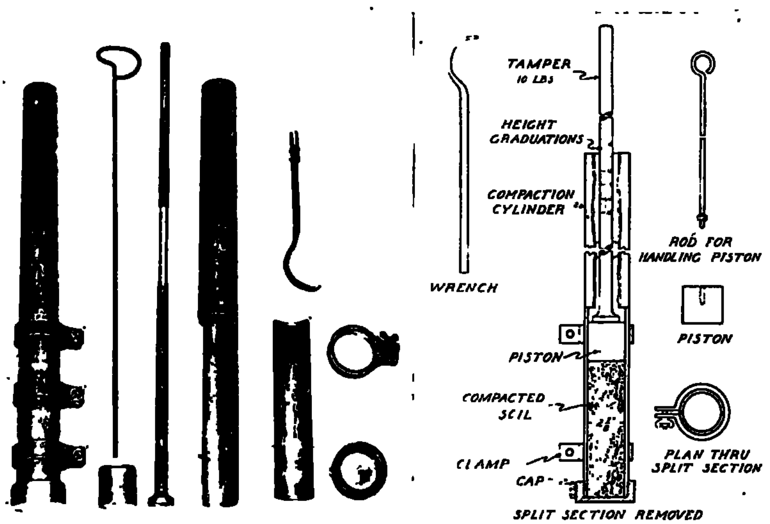

Figure 5. Compaction Outfit for determination of Optimum Moisture Developed by O. J. Porter, California Division of Highways, 1929

embankment shall be not less than 90 per cent of that determined by subjecting the specimen to a compression of 2000 lb. per sq. in. in the laboratory testing machine, thereby making due allowance for difficulty in securing equivalent compaction under standard fill compaction methods.

Different types of soil such as sand and clay which may have somewhat low unit weights when compacted, may when mixed together have a compacted dry weight very much greater than either had before mixing. Therefore,

Figure 6. Sampling of Soil from the Roadway for a Relative Compaction Test. Left to right are Orchard post hole auger, sample, scale and rubber bag. The volume occupied by the sample is being measured by the water displacement method. A thin rubber bag (Figure 7) is first placed in the test hole to prevent the water from soaking into the adjacent soil.

where different types of soil occur in layers of an embankment each sample tested must consist of only one kind of soil. If, however, various strata are present in excavation and borrow pits the test samples must consist as nearly as possible of a mixture of the various kinds of soil in about the proportion in which it is anticipated they will be mixed in each layer or portion of the embankment.

The customary procedure is to determine the optimum moisture content for typical materials at the commencement of a grading project and subsequently run only enough tests on samples from the embankments, to obtain the maximum dry weight for use in computing the relative compaction.

Woods: The desirability of compaction control is almost universally acknowledged among highway engineers. Among the desirable features of such control are: elimination or decrease of settlement and increase in the general

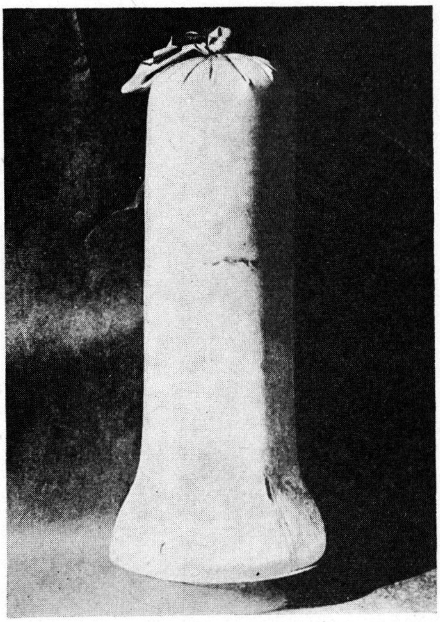

Figure 7. Volume Measurement by Water Displacement. A 4-, 6- or 8-in. gum rubber bag, 3-in. long, wall thickness approximately 0.01-in.

stability of the embankment since the air voids are quite small and there is little room for the holding of seepage or capillary water. It is obvious that such control is absolutely essential for silt-clay or shale embankments which may be inundated. Maximum compaction of the embankment can be obtained with a minimum of rolling by controlling the moisture content. The following is a description of the density test, originally developed in California[4] and now used for embankment construction control in Ohio.

A slightly damp 6-lb. sample is taken from a portion of the material passing the No. 4 sieve. The sample is thoroughly mixed and compacted in the cylinder in three approximately equal layers, each layer receiving 25 blows from the tamper which is dropped from a height of one foot above the soil. The soil is then struck off to the level of the cylinder and the weight determined. A reading is then taken with the penetration resistance device. A small sample of the compacted soil is oven dried to determine the moisture content. The soil is removed from the cylinder and broken up until it will pass a No. 4 sieve, water is added, and the above procedure repeated. This series of determinations is continued until the soil becomes very wet.

The moistures are computed by means of the following formula:

$$W = \frac{W_w}{W_0} \times 100$$

The dry weight is computed by means of the formula:

$$D_w = \frac{WW}{W_c + 100} \times 100$$

wherein:

W_c = Moisture content in per cent
W_w = Weight of water
W_0 = Weight of oven-dried soil
D_w = Dry weight in pounds per cu. ft.
WW = Wet weight in pounds per cu. ft.

The wet weight, dry weight, and penetration resistance results of the density test are then plotted against their respective moisture contents and a smooth curve drawn through the resulting points. The peak of the dry-weight curve represents the maximum density for the given material under the given compaction, and the percentage of water at this point represents the optimum moisture content. These curves are then used in control of the embankment construction.

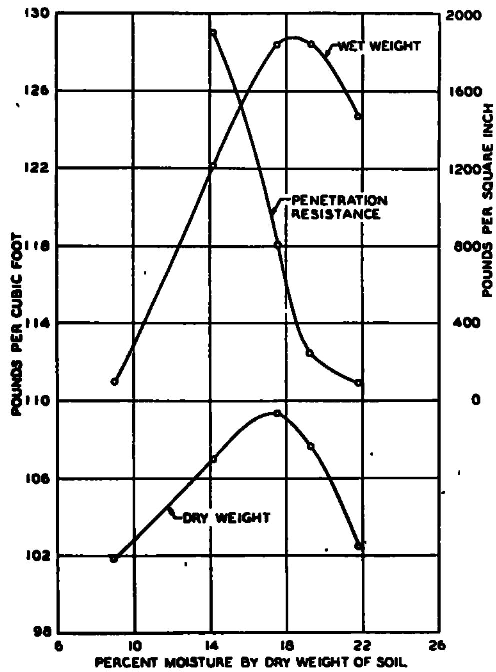

Figure 8. Sample Embankment Control Curve Used for Controlling Moisture Content and Percentage of Compaction in Earth Embankment construction.

Control during construction consists of determining the moisture content of the embankment material and attempting to maintain the optimum moisture content by allowing the material to dry or by adding water. The embankment being placed at the optimum moisture is checked for compaction so as to control the amount of rolling.

The wet soil is compacted in the density cylinder and weighed, and the wet

[4] See Engineering News-Record, Vol. 111, July–December, 1933, for article by R. R. Proctor.

weight per cubic foot computed. The penetration resistance of the wet soil in the cylinder is then determined. By comparing the wet weight per cubic foot and the penetration resistance with the values on the laboratory wet-weight density and penetration resistance curves for the soil being tested, a corresponding moisture content can be selected. To illustrate, assume the wet weight per cubic foot in the cylinder to be 126.4 and the penetration resistance as 1320 lb. per sq. in. Using the curve in Figure 8, the moisture content is 17.2 per cent. Should the penetration resistance reading and the wet weight per cubic foot not check by more than about two per cent difference in moisture content, the curve being used does not represent the soil being tested. This is a very important point which is often overlooked and which led to the development of typical curves (Fig. 9) or the use of curves from other projects, in Ohio.

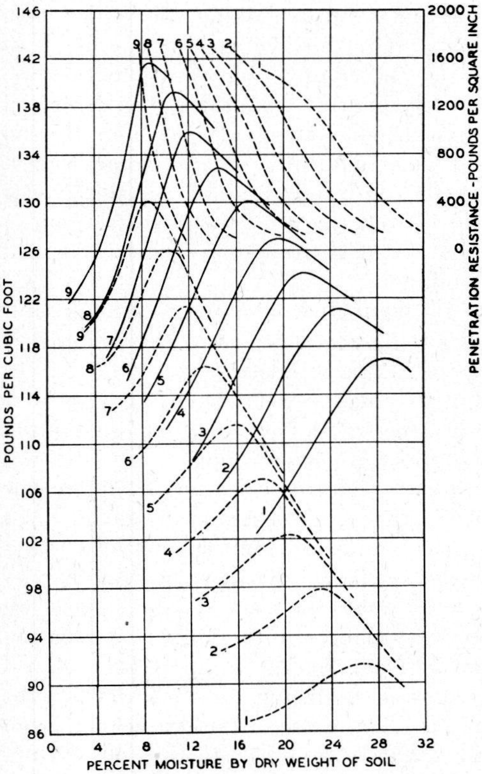

Figure 9. Typical Embankment Control Curves Averaged for Each Five Pound Dry Weight Peak Range for 1383 Ohio Soil Samples Received in 1937.

For checking compaction approximately 15 lb. of material is taken from the rolled embankment with a post-hole auger weighed and moisture content determined. The hole is filled with dry sand of known loose weight per cubic foot (See Fig. 10) and the volume of the hole computed. The wet weight per cubic foot of the compacted soil is computed by dividing the wet weight of the soil removed from the fill by the volume of the hole. The dry weight per cubic

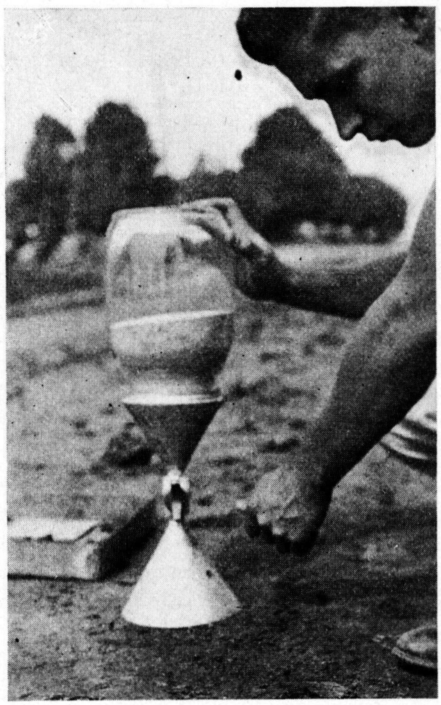

Figure 10. Volume Determination on a Fill Layer on an Ohio Project. (Sand calibration device modeled from a development of the Illinois State Highway Department.)

foot and the percentage of compaction can be computed as follows:

$$D_w = \frac{WW}{W_c + 100} \times 100$$

and compaction per cent

$$= \frac{D_w}{\text{Wt. per cu. ft. at peak of dry wt. density curve}} \times 100$$

wherein:

W_c = Moisture content in per cent
W_w = Weight of water
W_o = Weight of oven-dried soil
D_w = Dry weight in pounds per cu. ft.
WW = Wet weight in pounds per cu. ft.

Chief among the difficulties encountered in the use of the test is the fact that the soil types on any given highway project may vary widely. It can be readily seen that it may be difficult to have density curves available for the constantly changing material.

In an endeavor to offset the disadvantage of always having a curve made for each variation of soil type, an extensive series of tests has revealed that a curve made from a similar soil, regardless of the source of supply, can be used to check the compaction as long as the weight per cubic foot and penetration resistance determinations in the cylinder check approximately the same moisture content. It is not uncommon in Ohio to find compaction being checked on a project by curves made from soil from different counties. It is an important development and is facilitating embankment control to a marked degree in the State.

Another important point to be considered in checking the compaction of an embankment is the presence of small quantities of material retained on the No. 4. sieve. Since the embankment control curve was obtained by utilizing only the material passing the No. 4 sieve, any appreciable amount of larger material in the embankment will increase the apparent density due to the higher specific gravity of the stone as compared with the bulk specific gravity of the compacted dry soil. This discrepancy can be corrected by substituting soil for the stone in making the compaction tests. On the average embankment in Ohio, the compaction results are seldom greatly in error if considered as described under field control or corrected by deducting one-third of the total weight of the material retained on the No. 4 sieve from the total weight of the material removed from the compacted embankment.

In testing embankment control samples it has been observed that all curves have a characteristic shape, the curves for the higher weight materials assuming steeper slopes with the maximum weights at lower optimum moisture contents. In addition, most materials with the same maximum weight per cubic foot have identical curves. As a result typical density control curves can be made for each type of soil. (See curves made from samples tested in 1937, Fig. 9). All samples were placed in groups according to their dry weight peaks. Divisions were made on each five-pound interval starting at 90 lb. per cu. ft. All samples in each 5-lb. interval were then averaged and one curve drawn from these averages to represent all the curves for this interval. Since the curves are all approximately similar, interpolations can be made if the 5-lb. interval is too great. Such curves provide an excellent means of making a quick soil classification and can be used to control the placing of embankment. In places where the type of soil changes so rapidly that it is practically impossible to obtain representative samples, such curves are often an improvement over those especially prepared.

In selecting the type curve to use for the soil in question first determine the wet weight per cubic foot and the penetration resistance in the cylinder. With these data select from the typical density curves the one upon which the wet weight per cubic foot and the penetrations resistance most nearly coincide with those determined.

For example, using Figure 9, let 122.0 lb. equal the wet weight per cubic foot of the soil in the density cylinder, and 800 lb. equal the penetration resistance in pounds per square inch.

Since these results placed on the typical curve both give a moisture content of approximately 19.0 per cent from curve 3, this curve approximates the true curve for the soil in question. After selecting the curve for the material, the soil may also be classified. Since curve 3 has a dry weight peak of 102.5 pounds, any material which it represents will likely be an A-6 or A-7 subgrade soil with a liquid limit of approximately 40.0 and a plasticity index something under 20.0.

Preece: The practical construction man cannot be expected to take an active interest in soil mechanics unless through its application to construction some of the uncertainties are removed. A control procedure that adds to the normal difficulties and produces only benefits that are intangible cannot be expected to gain more support than the very minimum required by specifications.

In connection with the cooperative development of state parks, the National Park Service exercises technical supervision of jobs in almost every State. It was early apparent that the control method to be specified must be simple enough to be performed by men with no experience in soil mechanics, and productive of easily discerned benefits. To accomplish this, it was essential that the control technique must satisfy the following requirements;

(a) The apparatus should be simple, rugged, and require a minimum of calibration and adjustment. Particularly should delicate, mechanically complex, and expensive apparatus be avoided;

(b) The technique should not imply a greater accuracy of measurement or a greater refinement of result than is justified by the approximations upon which it is based; and

(c) The procedure should be such that it could be performed satisfactorily by a careful workman, certainly by the average construction foreman.

Various devices were studied and one after another eliminated either because they didn't work so well in the fill containing the stone fraction that had been sieved out in the laboratory, or because the job was finished before anyone became well enough experienced to obtain consistent results but particularly because too much time was required for the test and either the job was held up or proceeded on the assumption that the test would prove the material to be satisfactory. This didn't always follow but the work was completed by the time that was determined.

Insofar as compaction is concerned, the construction supervisor wants to know two things: first, that the material is in that condition at which it can be compacted to the required degree with the least effort; and, second, when compaction is completed so that any unnecessary work may be avoided. In other words, he wants to know that the material is at the proper water content, and then, that it is compacted to maximum unit weight for that water content.

Proctor's work on the relation of compacted density to water content is too well known to require any discussion here. It might be pointed out in passing, however, that the maximum unit weight obtained by the Proctor procedure at optimum water content is maximum for that compacting method only and not maximum for the particular soil at optimum water content for any and all compacting methods. It is well known that the compacted unit weight obtainable at a given water content can be varied considerably by changing the number of blows, or the thickness of the layers, or the rigidity of the support upon which the compaction is performed. Proctor's procedure was

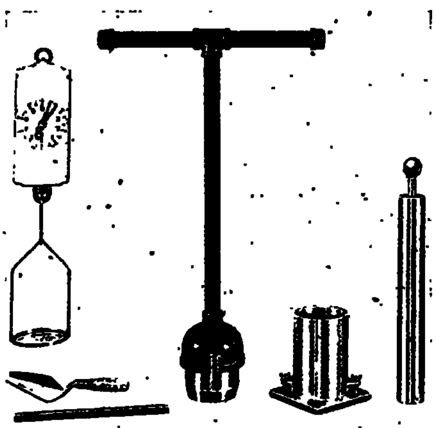

Figure 11. Soil Compaction Control Kit, National Park Service Design

designed to result in a degree of compaction comparable with that obtained in the field by means of sheeps-foot rollers. Maximum compaction by this method may, therefore, be considered to be a compacted or relative maximum unit weight for the particular water content at which the compaction is performed. In this discussion the term compacted unit weight will be used.

Attention is called to the effect of the support on which the compaction is performed. In the engineering laboratory of the National Park Service we have found considerable variation in the compacted unit weight depending on whether the compaction cylinder rests on the concrete floor, over the leg of a table, or in the center of the table. The writer has viewed with some suspicion the claims of consistent relation between the laboratory and field compactions when he has seen the laboratory compaction performed without giving any consideration to the rigidity of the support. All compactions in the National Park Service laboratory are performed on a special base consisting of a box approximately 15 in. square and 18 in. deep filled with clean sand. The sand is covered at the top with a heavy canvas upon which the cylinder rests. If a similar support were used by all laboratories, results would be much more comparable. The agreement of our laboratory compactions with those on the job appears to be very satisfactory. This will be discussed farther on.

The engineering laboratory furnishes the field with two water content-compacted unit weight curves, one in terms of the dry unit weight and the other in terms of the wet unit weight. Since the field man must deal with the wetted soil it is the latter that is the most useful to him. He also has a compaction control kit consisting of the Proctor cylinder and hammer, a core cutter, scale, straightedge, and a trowel. (Fig. 11.) In gravelly soils it is sometimes difficult to obtain a satisfactory core. In such cases a volume of the soil is excavated by means of the trowel, weighed, the volume determined by measuring the volume of the hole and the unit weight computed. For this purpose a thin, rigid plate about 18 inches square having a nipple in its center to which a rubber sack is attached is used. Before excavating the sample the bearing area for the plate is smoothed off. The sample is then dug out, the plate seated, and the rubber sack filled with water, the volume of water required giving the volume of the sample in place This plate is easily made and is not shown in Figure 11

On the job sufficient soil is screened through the No 9 sieve for that corresponding to approximately 5 lb in the compacted unit weight dry The compaction is performed exactly as in the laboratory and the compacted wet weight determined The proper curve is then entered with this value and the water content determined If this is too low water must be added to the fill when it is spread If it is too high, the spread fill must be worked over by harrowing or blading so that it will dry Compacting is not started until the material is within the limits for water content dictated by the laboratory The limits vary with different materials For some soils the compacted unit weight varies considerably for a small change in water content either above or below optimum On the other hand, in the vicinity of optimum water content some soils have a very slight change in compacted unit weight for a change of several per cent in water content For the first type the permissible variation from optimum is much less than for the second type Usually the permissible variation in water content is that corresponding to 2 lb in the compacted unit weight dry Although there are two values for water content for each compacted unit weight below that corresponding to optimum water content, a single compaction will usually be sufficient If the compacted unit weight determined is within the permissible limits, it makes no difference which leg of the curve applies If the compacted unit weight falls outside the permissible limits, it will usually be apparent whether the water content is above or below optimum If not, 4 oz of water added to the material and a second compaction will fix the proper point on the curve for the first determination

The core cutter is identical in area and depth with the compaction cylinder This is not an essential condition but it is a convenient one After five or six trips of the compacting equipment a core is taken and the compacted unit weight determined As soon as this is within the proper limits rolling is stopped

The reason why proper water content prior to compacting is important will be apparent if the water content-compacted unit weight is considered It has already been pointed out that compacted unit weight can be increased for a given water content by increasing the number of blows Hence, within reasonable limits of variation, a given soil may be compacted to the same unit weight as that obtained at optimum water if given sufficient additional blows Or, in terms of the job, the same compacted unit weight as obtained for optimum water can be obtained at any water content within reasonable limits if a sufficient number of trips of the roller are made in addition to those necessary at optimum Obviously the additional trips add to the construction cost So, of course, does drying The competent construction supervisor will readily determine for the particular job when it is more economical to roll a few more trips instead of drying and when it isn't

The present control kit has been in use but a short time and experience records are scarce Three dams have been completed under this control, however, and fragmentary records are available for others The three completed structures are located in Pennsylvania, North Carolina and Alabama The soils are quite different in character as well as their condition of wetness in the borrow These jobs report that compaction was completed on the average with eight to ten trips of the sheepsfoot roller and that the compacted unit weight in place varied from 2½ lb per cu. ft. below to 2 lb. per cu. ft. above that determined by laboratory test. The variations above and below the laboratory value were approximately 60 and 40 per cent respectively of the total number of variations which places the average compacted unit weight on the job slightly above the laboratory determination.

The close relation between the laboratory determination and the actual con-

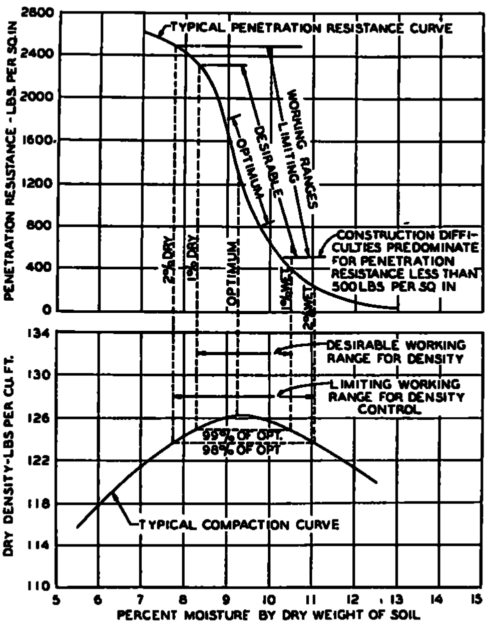

Figure 12. Example of the Use of the Compaction-penetration Resistance Curve for Compaction Control Operations.

struction are, of course, of considerable interest. We find our greatest satisfaction, however, in the fact that the men on the jobs who have used the control are enthusiastic. In every case they have found the method simple in operation and of a very decided benefit to them both in the character of the completed work and the reduction of construction costs.

Hamilton: Moisture control is maintained by the use of the penetration-resistance needle (Proctor's plasticity needle). From the combined laboratory compaction and penetration-resistance test, made on representative samples of the soils to be used in the compacted fill, the penetration resistance at optimum moisture is obtained. The laboratory determined penetration resistance is used as a point of aim for the first compaction operations. The inspector usually selects a range of moisture which indicates about one per cent variation from the maximum density as indicated by the compaction test, (for example, see Fig. 12). From this range of moistures (one wetter than optimum and one drier than optimum), the corresponding needle readings form a working boundary for the first compaction operations.

As the field compaction operations proceed, the results are carefully measured and checked by density and moisture measurements on the fill.

The material extracted from the fill by these measurements is then used for a standard laboratory compaction test. The field density and moisture test data and the laboratory test data are then plotted on the same graph and comparisons noted. A few such comparisons will indicate the optimum moisture for the compacting equipment in use.

In case the fill density is higher than the standard compaction, the optimum moisture for the roller will be drier than the optimum for the standard compaction, or, if the fill density is lower than this standard, the optimum for the roller will be wetter than the standard optimum.

The inspector can estimate the probable moisture very closely by drawing a curve about parallel to the standard density curve, as shown by Figure 3. This curve should be drawn approximately through the measured density points. A second curve should be drawn through the optimum, for the standard compaction, which about parallels the zero air-voids curve (curve of complete saturation). The intersection of these constructed curves will indicate the approximate optimum moisture for the roller and roller passes in use.

The new moisture content is then applied to the original moisture-penetration-resistance curve and a new control standard tentatively established. The inspector, by carefully checking operations and the resulting compaction, can soon arrive at the best working moisture for the rolling conditions in use. The proper moisture is then expressed in a range of penetration resistances, such as desired needle range, 1,200 to 1,500 lb. per sq. in.; and allowable working range, 500 to 1,800 lb. per sq. in.

The advantage of the penetration-resistance needle over any other moisture meter yet tried is that the penetration resistance at the optimum density, as a rule, varies only slightly and is not affected by changes in the soil. This, however, cannot be set forth as a positive rule, and the density results must be checked by thorough observations during construction.

Another indication of proper moisture for the roller is that there should be a very small wave in front of the roller as it moves along. If the roller seems to crawl out until the feet are penetrating to less than about three-quarters of their length, the soil is usually too dry for the most efficient compaction.

The final check of the control measures is a compacted fill of adequate stability, all conditions considered. This, of course, is a broad and general statement. At present, the tangible yardstick of measurement is the compacted density of the fill.

The fill density is determined by sand-hole density measurements, which, if carefully executed, are fairly accurate. There are, however, several possibilities of error which should be guarded against in these determinations.

The most common error is that density holes squeeze, especially if the soil is wet or soft. This causes the fill density to appear much higher than it actually is. Such results have led some inspectors to form an erroneous conclusion that the fill compacted rather wet and soft results in better densities. In fact, many density measurements seem to indicate that, if the penetration resistance of the soil mass is less than 500 lb. per sq. in., the inspector should use the results of density measurements cautiously.

Difficulty in making density determinations also has been encountered on soils containing an appreciable amount of cobbles. The inspector, in making such determinations, should observe well the compactness of the fines between the larger stones. Such observations have led to changes in compaction requirements. The excess of larger stones reduces the efficiency of the compacting equipment to such an extent that it has been deemed necessary to use mechanical separation and limit the maximum size and percentage of cobbles of certain borrow materials. The by-product (larger cobbles) of the separation can be used in the pervious outer shells of the fill.

In addition to knowing how to make density tests on the fill, the inspector should recognize the probable points of weakness and check these frequently. Several points on the embankment where one can expect to find low densities are:

1. The junction between power-tamped sections and the rolled embankment.
2. Where rollers turn.
3. Where improper moisture is found to exist in the soil.
4. Where too thick layers have been placed.

5. Areas not rolled the specified number of times.
6. Where dirt-clogged rollers were used.
7. Where soils contain a considerable amount of cobbles.
8. Areas rolled by rollers that have lost ballast.
9. Where soils were compacted when they contained frost.
10. Where the soils change character.
11. Power-tamped soils, due to the personal elements involved.

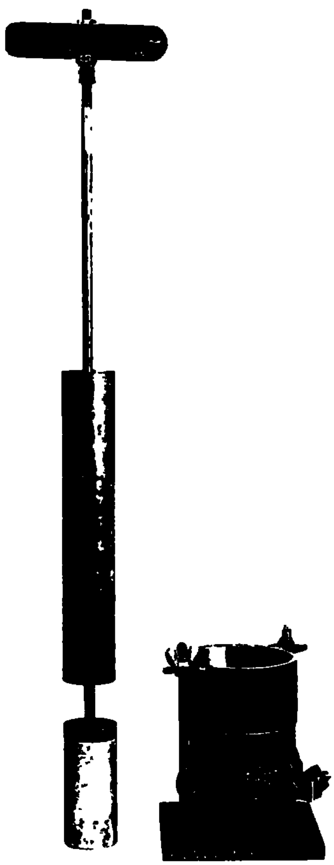

Figure 13. The Compaction Hammer and Cylinder Used in Making the Kansas Standard Compaction Test. The hammer delivers a blow equivalent to the drop of a 5½ pound hammer through a distance of 18 inches.

If the density results are not satisfactory, the inspector can usually determine the cause. In most cases, the causes are insufficient control by the contractor. If this is the case, operations should be stopped until the conditions are righted. The correction can usually be made by rerolling unless the soil is too wet, in which case, the compacted mass may be broken up to facilitate drying, then recompacted after sufficient drying.

The Bureau of Reclamation requires each job to keep and submit a 10-day progress report, describing all developments and including all measured data. These reports are studied in detail and compared with other jobs, and, where warranted, control measures are questioned and suggestions given for correction.

Johnson: The Kansas standard compaction test consists in compacting soil in layers in a mold 4 in. in diameter with a volume of $\frac{1}{30}$ cu. ft. Twenty-five blows, of a specially constructed hammer delivering a blow equivalent to the drop of a 5½ lb. hammer through a space of 18 in. are applied to each layer. All ordinary soils are compacted in three layers. Clays having plasticity indices in excess of 25 are compacted in four layers.

The type of compaction hammer and mold used in making the "Standard Compaction Test" is shown in Figure 13.

Field Inspection Tests for the Control of Compaction

Three standard methods have been set up for use in determining the soil density of compacted fills. These are: (1) the sand density method, (2) the undisturbed core overflow volumeter method, (3) the drive tube method. The sand density method consists of depositing sand of a known density in a hole bored with an auger to determine the volume of the mass of soil removed.

A portion of the previously weighed soil is dried, the moisture content determined and the weight of the dry soil computed. The weight per unit volume is then computed. The overflow volumeter method consists of removing a core of undisturbed material, obtaining its weight and determining its volume by means of a syphon type overflow volumeter. The soil moisture is obtained by drying a small representative sample prior to volume determinations. The soil density is then computed from the volume weight determinations. The drive tube method consists of driving a steel tube with a special cutting edge into the compacted lift, removing the head, cutting the soil flush with both ends of the cylinder, weighing the wet soil, obtaining the soil moisture content on a small sample and computing the density.

The two first mentioned methods have been used almost exclusively since drive tubes have not been made standard equipment on earthwork jobs. *The overflow volumeter method, although it was the first method used has been largely replaced by the sand density method.*

Bound work sheets, in the form of a pocket size field book are provided for the use of the field testing engineers conducting density tests.

The Proctor Resistance to Penetration needle has been used on a few projects involving large quantities of soil of a uniform type and moisture content. The Proctor needle has not been used with success on ordinary earthwork projects, involving light cut and fills with frequent changes in soil type, soil structure and soil moisture content. This is also true for gravelly soils.

As previously mentioned, shales, shale clays and very non-uniform gravelly soils are compacted under specifications which do not contain standard compaction requirements. Nevertheless, density tests are conducted for use in determining relative compaction and the shrinkage or swell of the various materials from cut to fill. This enables the engineer to determine relatively, how nearly they approach their original density, and thus provides data which may be of value for use in setting up requirements for future projects where the materials are similar. Inspection of rolling materials of this nature is dependent entirely upon the judgment of the engineer and his interpretation of

TABLE 2

STATE HIGHWAY COMMISSION OF KANSAS. WEEKLY REPORT ON ROLLING AND TAMPING OF EARTHWORK

Station	Elevation	Specific Gravity	Standard Compaction Ds	Cut Density Dc	Fill Density Df	$\frac{Df}{Dc}$ Balance Factor	Volume Occupied by			Actual Water Content Compacted	Soil Sample
							Solid, %	Water, %	Air, %		
borrow pit											
Lt. 139 + 00	0–1′	2.60	107.5	104						22.0	16
126 + 00	872	2.60	107.5		98.7	0.95	61	35	4	22.0	16
130 + 00	872	2.60	107.5		104.0	1.00	64	33	3	19.8	16
134 + 00	873	2.60	107.5		102.0	0.98	63	34	3	20.5	16
137 + 00	873.5	2.60	107.5		99.6	0 97	62	38	0	24.0	16
borrow pit											
Lt. 91–97	1–2′	2.60	107.5	101						19.8	16
95 + 00	857	2.60	107.5		104.0	1.03	64	31	.5	18.9	16
93 + 00	852	2.60	107.5		97.2	0.96	60	30	10	19.0	16
96 + 00	858	2.60	107.5		99.4	0.98	61	31	8	19.8	16
91 + 00	859	2.60	107.5		97.5	0.97	60	34	6	22.0	16

the results obtained as shown by density tests.

Results of density tests conducted during construction are reported weekly to the central office. Table 2 is a typical report sheet showing computations used in analyzing test data.

The densities are checked against the soil type as shown by laboratory test results and the location of the soils as shown by the preliminary soils profile. The results are studied for uniformity of compaction, and the relation of the results to the type of equipment used.

Plotting the soil, moisture contents and soil densities in a similar manner to that used in showing the standard compaction curve has been of value in analyzing test results. This method has made it possible to obtain a mental picture of the soil moisture density relations for any given equipment, procedure and soil type on a project and at the same time to compare these relations with those obtained by the standard compaction test.

CONSTRUCTION METHODS

Hamilton: Rigid moisture control has created several innovations, such as planned irrigation of borrow areas by flooding, with metering of the water to definite areas; planned excavation of areas after flooding; sprinkling of borrow areas; and sprinkling the face of cuts during excavation. Best results have been obtained where the borrow areas were processed to the desired moisture.

Where fills have been irrigated, numerous methods have been used, such as water-wagon sprinklers used on the spread layers, hose-and-nozzle spray on the soils as they are dumped from trucks, and sprinkling the dump before and during spreading.

In many cases where the soils have been irrigated on the fill, considerable difficulty has been experienced with uneven distribution of moisture. One job built a special-type tooth harrow for moisture distribution. Each tooth in the harrow was hollow and perforated, and the harrow carried a supply of water which was applied to the soil through the perforated teeth.

On the jobs where only a small amount of water is needed, the use of sprinkling wagons on the fill proper has proved satisfactory. On the other hand, if more than about four or five per cent moisture is required, the irrigation on the fill is usually a great source of trouble. Consequently, recent specifications require irrigation of the borrow material wherever possible.

The sheepsfoot roller has been almost universally accepted as the most efficient equipment for compaction and is used exclusively where operating space is available. Along abutments and structures where rollers cannot operate, mechanical tampers of the gasoline or air-hammer type are generally employed.

The sheepsfoot roller, in addition to efficient compaction, tends to give uniform density throughout the fill due to the mixing action of the feet. Furthermore, there are no noticeably smooth surfaces in the compacted mass, which is considered important for water-retaining structures.

Sheepsfoot rollers have been increased greatly in weight since 1934. Those used at present are specially designed and weigh about 9,600 lb. per drum when empty and 19,000 lb. per drum when fully ballasted with sand and water. The feet or knobs on these rollers are 10 in. long and have a face area of 7.07 sq. in. (3 in. dia.). These feet are staggered, forming a sort of spiral on the drum, and are spaced so that there will be about one foot for each square foot of developed area of the roller, computed along the bearing surface of the feet. The drums are 5 ft. long and 5 ft. in diameter. The ordinary roller consists of two drums set end to end and connected by a frame which allows each drum to oscillate in accordance with the ground surface. The rollers are equipped with adjustable cleaners, and the feet are slightly conical in shape, so that the cleaners will dislodge any rock sticking between the feet. The feet have face knobs of special hardened steel, which can be removed from the foot shank and replaced as they become worn. These rollers furnish a compacting pressure of about 270 to 340 lb. per sq. in. on the feet in bearing when empty, and, when fully ballasted with sand and water, the pressure is increased to approximately 540 to 675 lb. per sq. in. This is vast improvement on the commercial rollers of a few years ago, which, when fully ballasted, gave compaction pressure of around 70 to 100 lb. per sq. in.

Satisfactory compaction with the sheepsfoot roller is contingent on five factors: (1) spread thickness of layer to be compacted; (2) roller passes; (3) roller weight; (4) cleanliness of the roller; and (5) proper moisture for the compacting equipment.

The thickness of the compacted layer is usually set, by specifications, at about six inches. The construction man, after a few observations, can establish the proper thickness of spread layer to result in the specified thickness of compacted layer. The observations can be made in the following manner: Scrape off the uncompacted fluff, and place something such as a newspaper on the compacted surface; then cover with soil, and reference this point in so it can be found later. After a couple of layers are placed, the thickness can be measured and thickness of the spread layers adjusted to satisfy the desired conditions.

Observations have indicated that increased roller trips increase the density up to about 10 or 12 passes. For this reason, recent specifications have set the roller passes at 12 as a standard with a provision for extra pay, per trip-yard of compacted fill, for a greater number of passes and a deduction of a similar amount if the requirements are less than 12 passes. This item is included as a fixed rate set at approximately the actual rolling cost, and is included as a part of the bid on compacting fill. At the beginning of most jobs, a series of test sections are made as a part of the structure. These are rolled at various times, and the resulting density is measured and compared with the roller passes. From these data, the proper roller passes are determined.

In the event that roller weights are not set by specifications, the construction engineer is afforded an excellent opportunity to improve densities and construction conditions by requiring the roller weights to be increased.

Another method used to increase the compacting pressures has been to reduce the area of the compacting feet or to reduce the total number of the feet per drum, especially where the feet are closely space. Just how far either of these methods of change can be carried is extremely questionable. The general policy now is to limit the minimum size of feet to about 6 sq. in. and the maximum spacing between feet to about 15 in.

Stanton: Standard California practice requires that embankments be constructed and consolidated in layers not more then 8 in. thick before compaction and that each layer be consolidated by rolling to a relative compaction of not less than 90 per cent before subsequent layers are placed. By this method, combined with rigid control over the moisture content it has been found possible to construct embankments to any height without subsequent appreciable settlement.

On large grading projects one assistant engineer is assigned full time to compaction studies and he advises the other grading inspectors the amount of water that should be added to obtain the best results. The specifications require that water meters be maintained at each hose outlet and this permits the grading inspectors to control closely the quantity of water and correctly balance the output against the yardage handled. Experience has proven that the water must be uniformly distributed throughout the depth of each layer to procure best results and that this can usually be accomplished most readily by watering at the point of excavation or by bringing the embankments up in very thin layers of 4 or 5 in.

In many cases contractors handle work in this manner without any direct instructions from the engineer as they have found that they can obtain the degree of compaction specified with less rolling than when they attempt to construct a thicker layer with a water content that is not ideal throughout the total depth.

Embankments on many large grading jobs, particularly when the average haul from excavation does not exceed 1,000 ft. are built with the large capacity carry-all scrapers developed in the west. Such equipment is particularly adapted to constructing embankments in very thin layers and with many soils this method insures good compaction with very little rolling, as the normal distribution of the hauling equipment thoroughly consolidates a large portion of the area. Rollers or tampers are still essential, however, to compact adequately the inaccessible areas and other places where the haul is light.

Shovels and trucks are generally used where the average length of haul is great or where the cut material is sufficiently hard or rocky to require shooting and shovel excavation. The hauling with trucks, as in the case of the carry-alls, when well distributed over the width of the embankment, has been found to be very efficient in consolidating the material. Tests made on many projects during the past 7 or 8 years have clearly indicated that a density is often attained greater than under the standard test method on the portion of embankments subjected to a large amount of truck haul. On one project consisting of a lengthy fill approach to a bridge over the Kern River in Kern County, the fill consisted of a sandy loam soil and sufficient water was added at the point of excavation so that only a small amount of sprinkling was necessary at the embankment to replace normal evaporation. Each layer of the fill, varying between 6 and 8 in. thick before compaction, was rolled with a 12 ton roller and then smoothed up so that the trucks could be routed over a fill as it was built up. At the bridge end where the yardage of truck haul was smallest a relative compaction of approximately 93 per cent was secured, whereas at the point nearest the source of supply of the fill material the relative compaction was 102 per cent.

Except for the fact that the specifications provide that no adobe shall be placed in embankments above one foot below profile grade, there is no restriction in the California specifications regarding the nature of the material which can be used.

It has been found possible to secure relative compactions of 90 to 100 per cent with even the difficultly consolidated California adobe soils of the A-7 type, provided the construction procedure laid down in the specifications is rigidly followed. For that reason all material from excavation is permitted to be used in embankment subject, of course, to the precautionary construction measures fully set forth in the specifications.

While it is our practice to select or import suitable material for the upper one or two feet of embankments and subgrades, the fills on most of our heavy grading jobs must be constructed of materials from adjacent cuts. It is usually impracticable, from an economic standpoint, to import high quality materials for the entire fill, such as is apparently the practice on smaller fills in some other States and, therefore, it is necessary for us to use local materials and to determine the degree of compaction and treatment required with the type of material readily available.

Figure 14. Irrigating a Hillside Borrow Pit Location in Norton County, Kansas. The moisture penetrated to a depth of 12 ft. in this silty loam soil.

Johnson: *Preparation of Foundation:* Where foundation compaction is necessary, the grade is cleared, all stumps, rocks are removed and the foundation plowed to the depth to which compaction is deemed necessary. It is then rolled in lifts not to exceed 6 in. of compacted depth.

Adjusting Soil Moisture Prior to Compaction: No definite methods are prescribed in the specifications for mixing water with soil when necessary prior to to compaction. The following methods have been most widely used on construction projects in Kansas:—

Irrigation of Borrow Pits: This method has been used both on side-hill locations and on locations where the ground surface is flat. When side-hill locations are irrigated, contour ditches are cut by means of a blade grader, as indicated in Figure 14. Water is then pumped into the ditches until the desired depth of penetration is obtained. Borrow pit sites on flat upland and creek bottoms are diked and ponded.

Sprinkling: Sprinkling has been done on a few projects by means of hoses attached to pipe lines. However, on most of the projects where the sprinkling method has been used, it has been done by means of tank wagons equipped with gravity type spreader bars. Sprinkling has been carried on in the cut section prior to excavation, as well as on the soil after it has been deposited on the embankment.

The success or failure of the irrigation method has depended upon the type of soil being watered and the depth of penetration desired. The greatest success was obtained on sandy loams and silty loams which were sufficiently pervious to allow penetration and diffusion of the moisture into the soil in a reasonably short time. It has not proven successful on projects where dense, impervious clays were encountered. This method has been most used on projects involving large embankments, for example, on approaches to bridges and railroad grade separations, but has also been used on projects involving comparatively light fills. When rapid penetration has been obtained, very little additional mixing, after the material has been deposited on the grade, has been found necessary. Watering the soil after it has been placed on the grade has been the most widely used method for clay soils. This is especially true for clays which are finely structured and break down readily when manipulated.

A number of different types of equipment have been used in mixing to obtain uniform soil moisture. Heavy spring tooth harrows have been used with success on the loams, silty loams, and sandy loams of the A-2 and A-4 groups. "Wheatland" type one way disc plows have been used on a few projects where the clay loam groups of soils have predominated. Tractor drawn blades have proved most efficient on clay soils of the A-6 and A-7 groups. When very dry clay soils are wetted, the deposited soil windrows are spread, water is applied and a shallow cut is made with the blade. Water is again applied and bladed off, and the operation is repeated until the entire lift of loose material has been wetted. The wetted windrow is then bladed into position by making shallow cuts in the wetted soil.

The wetting of clay soils to a uniform moisture content has been found to be a very difficult problem; although many methods of mixing have been tried none has been completely satisfactory on dry, hard, cloddy, clay soils. Sprinkling by means of truck wagons and mixing by means of tractor drawn blades has given the best results.

Roller requirements for compacting ordinary soils are sufficiently broad to allow the use of all standard tamping type rollers. The use of three-wheeled power rollers is allowed if they weigh not less than 10 tons and provide a compression of not less than 300 lb. per lin. in. of roll.

Tamping type rollers providing a minimum pressure of 200 lb. per sq. in. are required for the compaction of shales and other materials which can be improved by compaction, but cannot be compacted under ordinary specifications.

Tamping type rollers are standard equipment on almost every earthwork project. Power rollers are available and have been used with success under some conditions.

The soil in embankment areas adjacent to structures, where it is not practicable to use a roller, is tamped with mechanical tampers to meet similar density and moisture requirements as are specified for the fill.

A trial and error method of determining the amount of rolling necessary has been used in the early stages of construction on a number of projects. In this method several parallel windrows of soil are spread to uniform thickness. A different number of trips over with the roller is used for each strip of soil. A number of density tests are then made on each strip. The least number of trips necessary to obtain compaction is then set up as the minimum for the existing soil type and soil moisture content. Attention is given to changes in soil type and soil moisture and changes in rolling procedure are made as construction progresses.

It has been found as was anticipated from laboratory studies that the number of trips necessary to obtain compaction is dependent upon soil type and structure, soil moisture, thickness of lift, size and shape of the tamping feet, number of and spacing of tamping feet and the pressure exerted by the tamping feet. The existence of these variables has naturally brought about a number of problems which were a source of some trouble when compaction was first done with tamping type rollers. In some instances it has been necessary to only partially load rollers having small tamping feet when rolling silty soils with poor binding qualities. In other instances it has been economical to use sand (with sufficient water to fill the voids in the sand) in filling the drums of rollers having large tamping feet to obtain compaction of clay soils when using the maximum allowable compacted lift thickness of 6 in. On other projects, sandy loams having plasticity indices from 0 to 7 have been compacted at less cost by using heavy smooth wheeled rollers on comparatively thin lifts. The maximum tamping foot pressures possible under loading have been necessary in some instances to break down and compact shales into a hard, dense and impervious state. Compaction of such materials by using light rolling equipment would have resulted

TABLE 3

Field Summary of Embankment Control Tests by Projects

From January 1, 1938, to August 1, 1938 (as Received)
Results of Field Data Obtained by Divisions and Compiled by Ohio State Highway Testing Laboratory

County	S. H. & Sec.	No. of Tests	Dry Weight Peak			Opt. Moist. Ave.	+ or − Opt.			Compaction %		
			Ave.	Max.	Min.		Ave.	Max. +	Max. −	Ave.	Max.	Min.
Adams	7-B & C (Pts.)	47	103.8	109.0	91.7	20.3	−0.7	5.8	4.3	98.7	109.9	87.5
Adams	7-D & E (Pts.)	104	104.4	117.8	94.6	20.0	+0.4	6.4	3.6	103.4	156[a]	74.1
Allen	127-M	62	111.0	114.5	104.7	16.5	+0.5	4.3	4.6	96.3	107.9	86.8
Ashtabula	2-M (Pt.) G. E.	5	126.0	126.0	126.0	10.2	−1.7	0.4	5.0	91.1	94.8	84.0
Ashtabula	2-Geneva & K (Pts.)	20	107.1	119.2	100.4	13.3	−3.8	..	7.7	95.8	103.0	77.8
Brown	7-X (Pt.)	16	105.1	111.7	102.5	19.5	+0.9	5.5	4.5	96.5	119.8	79.0
Butler	183-A (Pt.)	30	110.8	116.0	97.4	16.9	+1.5	5.5	3.1	98.3	109.1	88.5
Clermont	7-K (Pt.)	2	104.2	108.6	99.8	20.9	+5.2	5.3	0.1	100.7	106.0	95.3
Defiance	318-Defi. Br.	2	118.6	120.9	116.2	13.0	+4.0	5.0	...	95.9	99.3	92.5
Fairfield	10-Rushville (Pt.)	9[b]	114.9	121.2	109.4	14.6	+2.2	2.6		95.7	99.5	91.4
Greene	195-H & F (Pts.)	2	124.5	127.2	121.8	13.2	−1.8	0.6	2.4	99.9	100.0	99.8
Gallia	7-L (Pt.)	8	108.3	111.0	104.4	17.0	+2.2	3.8		94.6	111.6	79.7
Hamilton	8-M-Cincinnati	5	115.8	129.9	106.4	15.2	+2.9	5.4	3.2	97.7	99.5	95.4
Hamilton	39-N. College Hill	25	106.6	113.8	97.4	18.1	+1.4	6.3	3.6	98.0	109.5	92.4
Hamilton	43-Cincinnati	26	117.7	128.3	97.2	13.6	−1.4	0.6	3.6	95.4	109.3	87.6
Highland	259 R & Q (Pts.)	125	115.4	126.3	102.3	15.4	+0.7	3.6	4.9	97.1	103.1	81.7
Hocking	360-L (Pt.)	5	104.9	107.2	104.3	19.1	+1.7	3.5	0.7	93.4	96.1	91.5
Hocking	360-K (Pt.)	20	111.8	117.6	106.0	16.0	+0.5	4.5	3.0	95.5	101.9	86.0
Huron	267-Bellevue	16	112.6	116.2	97.5	15.0	−0.5	4.1	4.1	98.2	115.7	87.7
Knox	339-719 M&C (Pts.)	48c	110.6	116.5	106.8	16.3	+1.3	9.5[a]	3.0	97.5	99.9	93.6
Lawrence	7-D & Proctorville	34	113.6	118.8	105.3	15.0	+1.0	3.2	3.1	99.2	106.6	90.5
Licking	1-G-1	9	109.6	113.4	105.5	17.5	+3.1	4.7	.	99.1	105.6	95.4
Lorain	3-J (Pt.)	1	99.6	..	.	23.2	−4.6	...	4.6	91.9	...	.
Lucas	697-B & Waterville	20	113.6	124.2	109.0	14.8	+1.0	2.5	2.8	96.6	103.8	80.0
Montgomery	63-H & I	6	120.9	127.2	116.9	12.3	+1.3	2.7	1.0	98.6	103.2	96.7
Noble	391-I (Pt.)	44	111.4	113.8	108.9	16.8	−0.3	5.1	4.0	99.1	104.8	93.3
Perry	10-Somerset	46	110.5	118.5	97.8	17.4	+1.3	3.7	3.8	97.0	104.4	89.6
Portage	12-W (Pt.)	69	112.5	119.3	108.9	16.8	+0.6	4.8	4.7	94.3	111.8	70.9
Richland	338-Belleville Br.	1	No tests Material too Granular									
Stark	17-Q-2	56	118.8	124.3	102.4	13.0	+1.4	4.8	3.1	97.3	112.5	70.8
Summit	S. Main Gr. Sep. Akron	37	117.7	123.8	102.2	12.3	+1.3	5.4	3.3	94.1	99.4	82.6
Trumbull	80-P (Pt.)	27	117.6	120.6	111.6	11.8	+0.8	4.2	2.5	95.3	101.8	84.8
Van Wert	418-F & G (Pts.)	1	105.8		..	19.0	+4.4	4.4	.	100.0	..	....
Wayne	69-J & N (Pts.)	52	122.2	123.8	113.6	11.3	+0.9	4.8	1.1	93.5	97.9	86.9
Wood	282-E (Pt.)	41	110.0	125.5	105.4	13.2	−0.8	5.3	6.4	94.7	101.2	87.1

[a] Probably an Error.
[b] Only 6 Compaction Samples.
[c] Only 32 Compaction Samples.

in a pervious fill which would readily take water, soften and be in danger of failure by sliding.

Woods: In Ohio all embankment materials except rock are spread in successive level layers of not more than 8 inches. Rock may be placed in two-foot lifts, dumped in place, but must be reduced in size to 18 in. or less. Material dumped on the fill is usually spread by bull-dozers. During the dry summer months large quantities of water are used, which usually requires mixing.

Tamping or 3-E (10–15 ton) rollers are required for fill compaction excepting that the outer 5 ft. must be compacted with a tamping roller to insure good density on the side slopes.

Field Summaries of Control Tests

In May, 1938, the Ohio Bureau of Tests started checking field embankment control tests from all highway projects in the State, and accumulating pertinent information in connection with this field control. Table 3 shows typical results of the 2,754 field tests which had been checked to November 1. The summaries in general show the successful operation of the embankment specification in Ohio.

Inspection of the summaries shows the general type of soil used on each project as indicated by the dry weight peaks. Deviations from the optimum moisture content are shown as well as the average percentage of compaction. It is interesting to note that the average compaction on all projects is well above the former specification requirement of 90 per cent. The most significant point is the apparent ease with which the embankment specification works, and particularly in a state like Ohio where the soil types are decidedly complex and varied.

SPECIFICATIONS

(Excerpts)

California

In constructing embankments, the following California standard embankment specifications are followed:

"... the total width upon which the fill is to be constructed shall be lightly plowed, scarified and finely broken up in order to allow new fill material to bond with the old earth. If broken material is dry or forms hard clods it shall be watered to soften the clods so that they will crush and then rolled before placing embankment material.

"Where embankments are to be placed on plowed or cultivated ground or on lightly compacted soils, the ground surface shall be rolled before placing embankment material until a relative compaction of 90 per cent is reached in the upper 12 in. of the compacted soil.

"When embankments are to be made and compacted on hillsides or where new fill is to be compacted against existing embankments or where the fill is built one half width at a time, the loosely compacted slope of the original hillside, old or new fill, shall be cut into as the work is brought up in layers. Material thus cut out shall be recompacted along with the new fill at the Contractor's expense, unless the width of cut required exceeds 3 ft. in which case the excavated material will be measured and paid for as roadway excavation.

"Only suitable materials shall be placed in embankments. The best fine surfacing material shall always be saved for finishing. Clods or hard lumps of earth, over 6 in. in greatest dimension, shall be broken up before being placed in the fill.

"Large rocks or hard lumps, such as hard pan or cemented gravel, which cannot be broken readily shall be distributed throughout the embankment and filled around with fine material so as to secure a dense, compact embankment. No such rocks or lumps over 6 in. in size shall be placed in the upper one foot of embankments.

"When embankments are formed of stone, the material shall be carefully placed so that the large stones will be well distributed and the interstices shall be completely filled with smaller stone and earth, so as to form a dense, solid embankment.

"All adobe material placed in embankment shall be deposited at the bottom of the fill and no adobe shall be placed in embankment above a point 1 ft. below profile grade.

"In general, embankments shall be placed and compacted in layers as hereinafter specified, with the exception that where permitted by the Engineer, sidehill fills where the width is too narrow to accommodate compacting equipment, may be placed by end-dumping until the width of the embankment becomes great enough to permit the use of compacting equipment, after which the remainder of the embankment shall be placed in layers and compacted as hereinafter specified.

"The sides of embankments shall be constructed first and the center shall be brought up lower than the shoulders.

"Embankments built of earthy material or material consisting of gravel or small particles of rock or containing by volume less than 25 per cent of rock larger than 6 in. in greatest dimension shall be constructed in layers not exceeding 8 in. in thickness before compaction. Each layer shall be rolled with three-wheeled power rollers or tamping rollers until compacted in accordance with the requirements hereinafter specified.

"Embankment material containing by volume 25 per cent or more of rock too large to be compacted in layers 8 in. thick shall be placed in layers of a thickness not exceeding the maximum size of the rock present in the material, but in no case shall the thickness of the layers exceed 2 ft. Sufficient earth or other fine material shall be incorporated with the coarse rock as it is deposited in order to fill the interstices and to provide a dense, solid embankment. Each layer shall be compacted by routing the loaded hauling equipment over the entire width, supplemented by the use of rollers. Power rollers equipped with tamping studs shall not be used to compact rock fills.

"The relative compaction of the earthy material composing each layer of embankment shall not be less than 90 per cent as determined by the compaction test.

"Embankment material which does not contain sufficient moisture to compact in accordance with the above requirement shall be sprinkled with water in accordance with the directions of the Engineer. Material containing an excess of moisture shall be permitted to dry to the proper consistency before being compacted.

"Power rollers for use in compacting embankments shall not weigh less than 10 tons and shall provide a compression on the rear wheels of not less than 325 lb. per lin. in. of tire width. Tamping rollers shall consist of metal rollers, drums or shells surmounted by metal studs with tamping feet projecting not less than 7 in. from the surface of the roller, drum, or shell. Tamping feet shall be spaced not less than 6 in. nor more than 10 in. measured from center to center in any direction and the cross-sectional area of each tamper foot measured perpendicularly to the axis of the stud shall not be less than 4 nor more than 12 square inches. The weight of tamping rollers shall be such that the load on each tamper foot shall not be less than 50 lb. per sq. in. of cross-sectional area. The load per tamper foot will be determined by dividing the total weight of the roller by the maximum number of tamper feet in one row parallel to, or approximately parallel to, the axis of the roller.

"At least one three-wheeled or one tamping roller shall be provided for each 100 cu. yd. or fraction thereof, of embankment material placed per hour. The quantity of material placed per hour shall be determined by averaging the total quantity of material placed within any one day or one shift of operation, measured in excavation. When several fills, each of small area, are so isolated from one another that one roller or tamper cannot compact the areas satisfactorily, additional rollers or tampers shall be provided, as ordered by the Engineer."

Kansas

Type "A" Compaction of Earthwork: Minimum moisture requirement not less than 2 per cent above that required to obtain maximum density by the standard compaction test. The maximum moisture content is limited either to that which the soil will contain at 90 per cent of standard compaction or by its refusal to "build up" after repeated rolling with tamping type rollers. The latter limit governs in all instances where the soil becomes too wet before it is limited by porosity as governed by density.

This type of compaction is used on all expansive soils for subgrades for concrete pavements. The use of type "A" compaction is limited to cut sections, the depth depending upon local conditions, and to the upper 4 ft. embankments.

Type "B" Compaction of Earthwork: The minimum moisture requirement is 5 per cent less than optimum. The maximum moisture requirement is equal to the optimum moisture content as determined by the Standard Compaction test.

This range of moisture control is used in preparing subgrades for bituminous surfaces, base courses and similar construction where a minimum softening of the soil is desired.

Type "C" Compaction of Earthwork: The minimum and maximum moisture requirements are limited to those necessary to secure adequate density, except where soils are so wet that they will not "build up" so that the tamping feet ride the surface when compacted with tamping type rollers. As under type "A", the latter limit governs all instances where the soil becomes too wet under the required density limitations.

Type "C" is used in compacting fill foundations, (except under shallow fills for concrete pavements where type "A" moisture requirements are necessary) and for compacting the body of the embankment for all types of construction. It is also employed in the upper portion of fills except for the types of construction as noted above under types A and B.

The minimum density requirements for all types of construction is limited to 90 per cent of the maximum density obtained by the Standard Compaction Test.

Rolling and Tamping Supplemental Specifications: The system of compaction requirements described above is applied to all soils which can be compacted in the compaction cylinder and made to yield definite limits by which compaction can be controlled. Obviously a number of materials exist which can be used in embankment construction and which can be improved by compaction, but which cannot be compacted either in the laboratory or in the field to meet the standards described. Included among these materials are:—structured, bedded shales which do not break down sufficiently under compaction either in the field or in the laboratory to be governed by standard compaction; non-uniform rocks such as the Red Beds, portions of which break down under rolling; and extremely non-uniform gravel soil combinations which contain soil and gravel fractions ranging between limits too wide to be governed by standard specifications.

Materials of this nature are compacted under supplemental specifications designed to make the best use of the material peculiar to each location. Compaction is governed by lift thickness, minimum pressure for roller tamping feet and the number of trips necessary to cause the tamping feet to ride the compacted surface.

Ohio

Embankments shall be formed of satisfactory soil, granular material, shale, rock, or random materials.

Soil shall be considered as layers or deposits of disintegrated rock lying on or near the surface of the earth which have resulted from natural processes such as weathering, decay, and chemical action in which at least 40 per cent by weight of the grains or particles are smaller than a No. 200 sieve.

Shale shall be considered as finely laminated rock formed by the consolidation of soil including clay, silt, and fine sand.

Granular material shall be considered as natural or synthetic mineral aggregate such as broken or crushed rock, gravel, sand, cinders, or slag which can readily be incorporated in an 8-in. layer (loose depth), and in which at least 66 per cent by weight of the grains or particles are larger than a No. 200 sieve.

Rock shall be considered as broken sandstone, limestone, glacial boulders, etc., which cannot readily be incorporated in an 8-in. layer, and which after placing in embankment, contains insufficient material to fill the interstices between the stone particles.

Random materials shall consist of a mixture of any or all materials permitted for use in embankment such as soil, shale, granular material, old paving material, shattered rock, etc.

These materials when used in embankment shall be reasonably free of organic material such as leaves, coal blossom, grass, roots, sewage, and other objectionable material. Soil, granular material, shale, and random material shall be spread in successive level layers of not more than 8 in. in thickness (loose depth), unless otherwise specified, for the full width of the cross-sections or the full width between rock slopes.

Compaction of the outer 5 ft. of each layer measured horizontally from the face of slopes shall be obtained by a tamping roller. The balance of the fill may be compacted by a tamping roller or a Type 3-E (10–15 ton) roller.

For soil, each layer shall be rolled until its density is not less than the percentage of the maximum density prescribed in Table 4.

Soil, in addition to the above requirements, shall have a liquid limit of not to exceed 65 and the minimum plasticity index number of soil with liquid limits between 35 and 65 shall be not less than that determined by the formula 0.6 Liquid Limit minus 9.0.

Shale shall be placed in accordance with the requirements for soil if possible. Shale containing sufficient amounts of large particles to make checking of the compaction impractical, shall be broken down in placing by the use of a tractor and bull dozer unit, power grader, tamping roller, or other approved device, until at least 40 per cent of material passes a No. 4 sieve to fill the voids between the shale particles.

When rock and other embankment material are excavated at approximately the same time, the rock shall be incorporated into the outer portions of the embankment as rock fill and the other material shall be incorporated into the inner portion as rolled embankment. Rolled embankment adjacent to rock fills shall be held at substantially the same elevation as the rock, but always above the rock and of sufficient width to permit the proper compaction of this portion.

The top 3 ft. of all embankments shall be constructed of material other than rock according to the specifications for placing that material. In all cases where embankment material other than rock is superimposed upon rock, the top of the rock fill shall be sealed with spalls and granular material and rolled.

TABLE 4

Ohio Embankment Soil Compaction Requirements

Condition I Fills 10 ft. or less in height, and not subject to extensive floods		Condition II Fills exceeding 10 ft. in height, or subject to long periods of flooding	
Maximum Laboratory Dry Weight,* lb. per cu. ft.	Minimum Field Compaction Requirements, Per Cent of Dry Weight	Maximum Laboratory Dry Weight,* lb. per cu. ft.	Minimum Field Compaction Requirements, Per Cent of Dry Weight
89.9 & less	**	94.9 & less	***
90.0- 99.9	95	95.0- 99.9	100.0
100.0-109.9	95	100.0-109.9	100.0
110.0-119.9	90	110.0-119.9	95.0
120.0-129.9	90	120.0-129.9	90.0
130.0 & more	90	130.0 & more	90.0

* Maximum Laboratory Dry Weight is obtained as described in "Information from the Laboratory, No. 3, Sampling and Testing Soil for Use in Embankment."

** Soils having maximum dry weights of less than 89.9 lb. per cu. ft. will be considered unsatisfactory and shall not be used in embankment.

*** Soils having maximum dry weights of less than 94.9 lb. per cu. ft. will be considered unsatisfactory and shall not be used in embankment under Condition II requirements.

Embankment material which does not contain sufficient moisture to compact in accordance with the requirement shall be sprinkled with water in accordance with the direction of the Engineer. Embankment material containing excess moisture shall be permitted to dry to the proper consistency before being compacted.

Frozen material or sod shall not be placed in the embankment, nor shall embankment be placed upon frozen material.

Embankments in areas inaccessible to a roller shall be composed of embankment material which can readily be incorporated in a 4-in. layer, loose depth, placed and compacted in accordance with the following provisions. Acceptable embankment material shall be deposited in level layers not exceeding 4 in. in thickness, loose depth, and compacted by mechanical or pneumatic tamping devices to the required density, except that granular material may be deposited in water to a height not exceeding normal water level.

Field control shall consist of the following: Control during construction consists of maintaining an adequate moisture content. It also includes checking the per cent of compaction of the material being placed at approximately the optimum moisture content and regulating the amount of rolling so as to obtain compaction within the specification requirements.

The apparatus used for determining the moisture and per cent compaction shall consist of the following:

A cylindrical metal mold known as the density or Proctor cylinder, approximately four inches in diameter and four and one-half inches in height and having a capacity of $\frac{1}{30}$ cu. ft. This mold is fitted with a detachable base plate and removable extension approximately two and one-half inches in height.

A metal tamper having a striking face 2 in. in diameter and weighing 5½ lb.

A steel straight edge 12 in. long.

A penetration resistance device consisting of needles of known end areas and a spring balance.

A scale of 25 lb. capacity sensitive to 0.01 lb.

A post hole auger (4 to 6 in.).

Approximately one cubic foot of dry sand.

The method for determining the moisture content of the embankment soil shall be as follows:

Compact the wet soil in the density cylinder in the standard manner prescribed under "Information from the Laboratory No. 3, Sampling and Testing Soil For Use in Embankment." Weigh and compute the wet weight per cubic foot. The penetration resistance of the wet soil in the cylinder is determined. The wet weight per cubic foot and penetration resistance are compared with the values on the Laboratory wet weight density and penetration resistance curves for that soil and the corresponding moisture content selected. In case of a discrepancy the moisture content corresponding to the wet weight per cubic foot is used. If the soil is found to be below the optimum moisture content it shall be sprinkled with water sufficiently to bring the moisture content approximately to the optimum; if found to be above the optimum it shall be spread out on the fill in thinner layers and allowed to dry either before rolling or during longer rolling periods. Where it is desired and suitable drying equipment and scales of sufficient accuracy are available, the moisture content may be determined directly by drying a sample of soil to constant weight.

Checking Per Cent Compaction

Condition A. When the embankment material contains no stone retained on the No. 4 sieve. Approximately 15 lb. of material is taken from the rolled embankment with a post hole auger and weighed. Determine the moisture content as described above. These operations shall be performed without loss of time so that the sample will not lose moisture by drying. Then fill the hole with dry sand of known loose weight per cubic foot and compute the volume of the hole. Compute the wet weight per cubic foot of the compacted soil by dividing the wet weight of the soil removed from the fill by the volume of the hole. Determine the dry weight per cubic foot and the per cent compaction as follows:

Dry Wt. Per Cu. Ft. of Embankment =

$$\frac{\text{Wet Wt. Per Cu. Ft.}}{100 + \text{Moisture Content}} \times 100$$

% Compaction =

Dry Wt. Per Cu. Ft. of Embankment ÷ Wt. Per Cu. Ft. at Peak of Dry Wt. Density Curve × 100

Condition B. When embankment material contains from 0 to 40 per cent by weight of stone retained on the No. 4 sieve. Approximately 15 lb. of material is taken from the rolled embankment with a post hole auger and the stone retained on a No. 4 sieve removed. Weigh the remaining portion of the sample and proceed as in Condition I except that the stone removed from the sample shall be replaced in the hole as sand is poured in, in making the volume determination.

NOTES ON GERMAN PRACTICE

Casagrande: In constructing an embankment, the soil, which has consolidated perhaps for thousands or millions of years, is broken up and disturbed thoroughly. The best compaction often could not replace the original state of the earth, and it takes a long time before such a highway fill has come to a complete rest. In making a cut, one disturbs the equilibrium which again has been built up during a long period. Loading the ground with an embankment and pavement means applying additional forces, resulting in co-ordinating settlements or other movements. Another factor discovered by soil mechanics is that the word "homogeneous", applied to soil, does not exist. Even a soil deposit of great height which looks very homogeneous shows remarkable difference in its character when tested in the laboratory. But even if the properties should not be very different, it still would result in slight differential behaviour under the pavement.

Besides those two important facts there is a third, perhaps the most distinct phenomenon, the weathering of soil in its upper strata, influenced by air, temperature, and water. Neighbouring soils often disintegrate very differently under the same climatic conditions.

Considering those fundamental characteristics, one comes to the conclusion that not only could absolute rigidness of the pavement not be very well expected, but considerable movement of the surface must take place. Settlements were considered as being dangerous until Dr. Terzaghi showed that a certain amount of settlement need not be of any danger at all so long as it is equally distributed. Otherwise cracking of the building will result.

In exactly the same way, only more complicated, will a pavement behave which rests on earth as its foundation. Equal settlements, for instance, in a highway fill are of no danger, but the slightest differential movement causes unevenness or even total failure.

Highway fills were not compacted in Germany until a few years ago. They were simply dumped with a bit of rolling on the surface. Such fills, of course, were not able to bear the pavement satisfactorily. Therefore it was expected in advance that the pavement would have to be rebuilt after a certain time. This was taken for granted in just the same way as it was taken for granted that frost damages the pavement during wintertime. We realised—and everybody accepted it as an unavoidable fact—that repairs of pavements cost within a few years as much or even more than the original road surface.

Having at one's disposal good fill material, such as coarse sand or gravel, only compaction of the upper layer is necessary. On the other hand, fine-grained material, such as clay, loam, silt, etc., should never be used as an uncompacted core, but compacted in layers, depending on the type and weight of machinery used. When good material is available only to a certain extent, it should be placed between layers of the other material in order to allow better drainage and quicker consolidation of clay or whatever the fill may consist of.

In Germany different types of compacting machines have been developed, partly influenced by investigations carried out in our soil laboratories. Compaction of cohesive material (clay, loam, etc.) should be carried out by tamping or rolling. The most common types of tamping outfit are the derrick, with a heavy plate (generally 2 tons), being lifted and falling down from a height between 3 ft. and 6 ft., depending on the soil, and the frog built with weights of ½ ton and 1 ton.

The same machinery is used frequently also for cohesionless material, though better results are obtained by vibrating machines. Cohesive material is also frequently rolled by different types of rollers, such as the Koppisch machine, a common roller with a special attachment to prevent the roller from sinking in too much. Another type is the sheepsfoot roller, which was brought over recently from the United States with very good results, enabling compaction of even very wet clay or loam. While tamping allows 2 ft. and 3 ft. layers, rolling is only satisfactory with layers of not more than 1 ft. to 1½ ft.

Immediately after compaction each layer of fill should be rolled to prevent the accumulation of water on top. Nothing is worse for the stability of a fill than to let it soak. Depending on the soil, it may take years before such a softened fill consolidates and comes to rest.

Another weak point in fill construction is the shoulders. Since they cannot be compacted by heavy machinery, special care should be taken to compact the shoulders in smaller heights with light machinery, and this can easily be done.

Behind abutments the fill should be compacted in layers of less than 1 ft., in order to prevent settlements. Settlements of a few inches would not be harmful somewhere on the embankment; if they are evenly distributed they probably will stay unnoticed, but they must and can be prevented behind abutments.

A difficult problem with the construction of the Reichsautobahnen has been at first the crossing of swampy and marshy land with soft subsoil up to a depth of 60 ft. and more. This material has no bearing power and, even with very low embankments, causes heavy damage after a short period of traffic. We tried to avoid the removal of this soft peat material at first, but very soon came to the conclusion that for absolutely rigid pavements removal of the subsoil cannot be prevented. For secondary roads the old methods of part removal, fascine mattresses, etc., are still in use with satisfactory results. But for the construction of the Reichsautobahnen an economic method of total removal had to be found and soon was discovered in the American method of blasting. We adopted it for our needs and are now using this method with very good results. As probably known, it consists of dipping the embankment on top of the peat, of loading holes, brought down to the bottom of the soft material, with explosives and detonating. The force of explosion lifts up somewhat the sand overburden, whose weight presses the mud sideways

One embankment settled down 50 ft. to the bottom of the peat, displacing about half a million cubic yards of soft material.

To reduce the amount of blasting, the upper layer of the peat is first softened and disturbed with small charges of dynamite, thus allowing the embankment to settle to a certain extent. The holes for the charges are made by means of high-pressure water.

Whilst in the United States the explosives are brought in through drill holes, we developed a method of spilling in, by means of high-pressure water, large quantities of dynamite in the form of torpedoes containing up to 300 lb. Apart from the economical side of this method, work can be done this way in a quarter of the time needed by other methods. So far we have crossed many miles of peat with a displacement of a few millions of cubic yards.

MISCELLANEOUS

Stanton: *Correlation Between Test Values and Fill Service.* Three projects, constructed in 1929 in accordance with the California specifications have been under close observation for nine years.

The first project consisted of fill approaches to the Herndon Bridge in Fresno County. The embankments contained approximately 36,000 cu. yd. and ranged up to 30 ft. high. The material, consisting largely of a red claypan was wetted in excavation at night and hauled during the day and spread on the embankment in 4-in. layers, with carry-alls.

The relative compaction, averaged approximately 93 per cent for the entire embankment. The results varied between 90 per cent near the bridge where the material was compacted largely by rolling with a light tractor equipped with sheepsfoot tamping studs, and 95 per cent where the haul was concentrated and no rolling was done.

Careful levels, taken over the pavement immediately after construction and again in recent years, show an average settlement of less than $\frac{1}{8}$ in. and a maximum of $\frac{1}{4}$ in.

The second project, the approaches to the Rincon Overhead structure in Santa Barbara County, involved fills up to approximately 40 ft. high and required 100,000 cu. yd. of embankment. The material consisted of a soft, light weight clay-shale which pulverized readily during watering and rolling and showed a compacted dry density of 100 lb. at an optimum moisture content of approximately 18 per cent. The relative compaction, averaged about 90 per cent and varied between 85 and 95 per cent with the exception of those portions of the fills immediately adjacent to the structure where the hauling and compacting equipment did not efficiently process the material.

Pavement was placed over the embankments, with the exception of the first 50 ft. on either side of the structure and no appreciable settlement has occurred. The exceptions, where a relative compaction of only approximately 80 per cent was secured, were surfaced with crushed rock and bituminous macadam. A small amount of maintenance has been required to keep these portions up to grade.

The third project consisting of relocation of the main highway through Weldon Canyon near Newhall, in Los Angeles County, involved approximately 800,000 cu. yd. of roadway excavation. About one-half of this yardage was placed in a number of large fills, varying up to 110 ft. in height. The material consisted largely of very soft sandstone and silt stone which pulverized under the equipment, to a sandy loam and clay loam soil.

Extensive tests indicated that a moisture content close to the optimum was obtained throughout and that the fills were well consolidated to a relative compaction, ranging between 90 and 105 per cent, and averaging in excess of 95 per cent. This excellent consolidation is attributed to the careful moisture control and the fact that heavy buggies were used to transport the fill material from the shovels and spread it in uniformly thin layers over the fill. Most of the water was applied at the point of excavation.

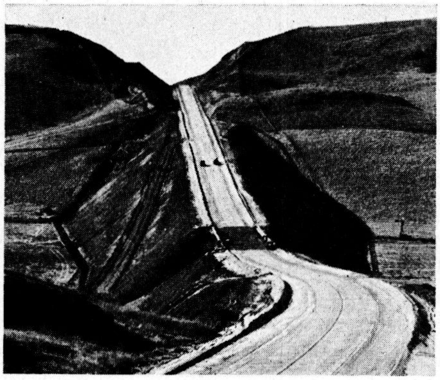

Figure 15. A 900,000 cu. yd. embankment, 80 ft. High, Constructed in 1933 and 1934 on the American Canyon Project in California. No appreciable settlement to date (November, 1938).

During nine years of service no appreciable settlement of these large fills has occurred.

A number of major projects, each with many large fill and embankment quantities totaling in excess of a million cubic yards have been constructed from material consisting largely of clay-shale of the A-7 soil type. Little trouble has been encountered with these heavy fills whenever the foundation was adequate. Figure 15 shows a fill on the American Canyon project in Solano County 80 ft. high and 2,500 ft. long and containing approximately 900,000 cu. yd. of material. This fill was constructed in 1933 and 1934 from blue clay-shale. Most of the material is of the A-7 soil type, but stability was obtained by consolidating to a high dry density of approximately 125 lb. per cu. ft.

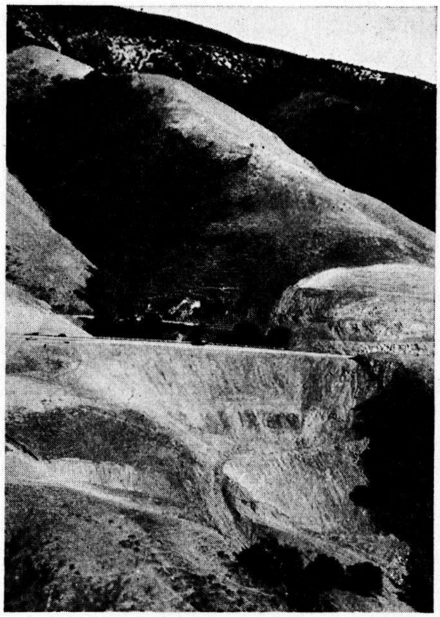

Figure 16. A 130 ft. Fill. Cuesta Grade Project near San Luis Obispo, California. Two toe support fills 50 and 100 ft. in width were used to flatten the average slope and reduce the high embankment and foundation stresses. The slope has recently been covered with 6 in. of top soil to promote plant growth for erosion protection. Constructed, 1937. No appreciable settlement to date.

Figure 16 shows a 130-ft. fill on the Cuesta Grade in San Luis Obispo County constructed in 1937. Material in this fill consisted largely of a colloidal shale of the A-7 soil type. Relative compaction in excess of 90 per cent and a dry density of approximately 125 lb. per cu. ft. were secured. Notwithstanding a severe wet winter subsequent to the construction of the fill, no appreciable settlement has taken place during the first year.

Johnson: *The Cost of Earthwork Compaction:* Average contractor prices for type "A" compaction for the fiscal year 1937–38 have been approximately 3 cents per cubic yard of embankment, the cost ranging from a minimum of 2 cents to a maximum of 7 cents per cubic yard.

Average contract prices for type "C" compaction have been approximately 2 cents per cubic yard, the cost ranging from a minimum of one cent to a maximum of 4 cents per cubic yard.

Rolling and tamping has shown an average cost approximately equal to that of type "C" compaction.

Bid prices for water for adjusting soil moisture content prior to compaction have ranged from $0.10 to $2.50 per thousand gallons with an average of approximately $1.25 per thousand gallons. Added to these unit costs is the cost of installing a pumping system which is entered in the contract as a separate bid item. Average bid prices for the installation of water systems has been approximately $350.00.

The soils which are encountered in Kansas range from tough waxy clays of the A-6 and A-7 groups in the southeastern part of the state, through the intermediate groups to the silty loams of the A-4 group and sandy loams and sands of the A-2 and A-3 groups of western Kansas. The clays are in many instances very difficult to handle through all phases of earthwork construction. They are difficult to blade into lifts of the required thickness. When they occur at moisture contents less than their plastic limits, they break out in large chunks during excavation. The addition of water for a uniform and adequate moisture content is a difficult problem even with the best of equipment. Compaction can be obtained without excessive rolling when moisture is adequate, but becomes difficult when the soil moisture is less than optimum. In contrast, the lighter soils in western Kansas are comparatively easy to compact, take water and can readily be mixed to a uniform moisture content.

CONCLUSIONS

Hamilton: The past few years have seen a marked development in the concepts of compaction and in the methods of control; yet there is much refinement to come. Soil laboratories can help a great deal in setting up theories and obtaining data to show the advantages gained through compaction and control, but the real checks must wait on years of correlation between laboratory and field work.

The one test that would probably do more to show the real advantages of compaction, is unfortunately, the very one that is still in a precarious stage of development; namely, the shear test.

The construction engineer has only four tools to work with in the construction of an earth fill; namely, selection of the soil, the soil, the compacting roller, and water. Regardless of the soil selection, the other three are vitally important, and it should be the aim of the engineer to develop an understanding of the effects of each and their relations one to another.

There are three problems which need further development of data rather than theories; namely, what are the advantages gained, what are the mechanics of the operation, and how shall it be performed and controlled to insure a stable and economic structure.

Johnson: There are a number of problems in compaction in need of solution. So far no researches have shown the limits of compaction necessary to accomplish what compaction is expected to do. Obviously the degree of compaction necessary to prevent settlement of a 5-ft. fill is not so great as that necessary to prevent settlement of a 65 ft. fill. If identical requirements are set up for both, one will be overcompacted and possibly the other will be undercompacted.

Safe heights of fills for various soils at different densities and different moisture contents have not been determined. The effect of climate, vegetative cover, surface drainage for different types of surfacing, and similar items on the state of permanency of the compacted soil are factors which are not fully understood. One of the difficult problems pertaining to soil compaction is that of setting up adequate and workable specifications which will fit the various soil types and soil conditions. No single set of specifications has yet been written which will adequately control compaction of all Kansas soils for all types of construction.

APPENDIX

The following case studies submitted by A. W. Johnson are appended to show the use of preliminary data in planning the design, as well as the methods and equipment used in construction.

Case Study No. 1

This project is located west of Medicine Lodge in Barber County in South Central Kansas. The project consists of 10.16 miles of earthwork, culverts, and bridges. The entire project lies in highly eroded hilly country.

The materials encountered are non-uniform in occurrence ranging from the sands of the Ogallala group, through the loam groups to the hard gypsum, and Red-Bed shales and rocks of the Permian System. A major portion of the sands and some of the sandy loam soils along the centerline contain insufficient binder for use as subgrade soils. However, sandy loams with suitable binder were available as borrow materials, and could be used in the top of the grade through a considerable portion of the project without excessive haul. A feature of the soils originating from Red-Bed shales on this project is that although not always well graded and sometimes having plasticity indices as high as 15, they are stable materials which do not swell and become soft upon absorbing water, and thus constitute excellent subgrade material.

Preliminary Soils Studies: Preliminary soils studies consisted of the centerline soils survey, identifying the various soils in the road profile and cross section; the location of borrow for fill material where necessary, and for use as subgrade material; and the testing of representative soils and shales in the laboratory. These studies formed the bases for the following recommendations, regarding the use of soils in the design of the road section and the methods of construction:

Use of Soil—Treatment of Sands: The stabilization of sands with asphalt, by the addition of binder soil or by topping them with available sandy loam soils from selected borrow locations, the type of treatment to depend upon the economy of the method and the nature of material.

Subgrading and Backfilling Shales and Rock: The depth of subgrading for each of the various materials. The depth in each instance was recommended on the basis of the method of construction which could be used and the manner in which the materials broke out during construction. Selected sandy loam soils were located for use as backfill material.

Compaction: Type "C" Compaction was recommended for all locations where soil predominated.

Supplemental rolling and tamping specifications were written for locations which contained considerable quantities of shales and rocks, since these materials could not be broken down enough to be compacted under the Kansas standard specifications. These specifications required, (1) the use of tamping type rollers having a minimum tamping foot pressure of 200 lb. per sq. in.; (2) the use of a maximum 6-in. compacted lift thickness except for locations where massive gypsum rock was encountered; (3) the use of enough water to obtain good bond in the compacted soil; and (4) rolling until the roller feet rode the surface of the compacted lift.

Foundation compaction was set out for shallow fill locations through cultivated areas and through cut sections.

Miscellaneous: Other recommendations included the placing of undesirable blue shales in alternate layers with suitable soils; erosion protection for backslopes and ditches; subsurface drainage and special foundation work where Gypsum caverns existed.

Contract Data: Earthwork was begun on September 1, 1938. The contract included 931,300 cu. yd. of common excavation and 135,500 cu. yd. of rock excavation. Common excavation was bid at $0.115 per cu. yd. and rock excavation at $0.44 per cu. yd. Compaction averaged $0.02 per cu. yd. and water costs were $0.50 per thousand gallons.

Equipment: The major construction equipment at the beginning of work consisted of:

1. Tractor drawn heavy "smooth faced" roller
1. Dual unit tamping type roller
5. RD 8 Caterpiller tractors
2. RD 4 Caterpiller tractors
1. 30 Caterpiller tractor
1. Bulldozer
4. 13 cubic yard carry-all scrapers
2. 12-ft. blades
4. Tank trucks

Construction Methods: The sandy soil encountered at the beginning of work was wetted in the cuts by means of gravity spray bars attached to tank trucks. Excavation and hauling was done by using two carry-all scrapers in tandem, a second tractor being equipped to push the rear scraper during loading operations. After the soil had been dumped on the grade, the slight amount of additional mixing necessary for the thin lifts was accomplished with a tractor drawn blade. Rolling of the thin lifts of sandy loam was accomplished by a single pass of smooth wheeled rollers having a roller pressure of approximately 200 lb. per sq. in. of contact area. The compacted lifts ranged from two to four inches in thickness. Due to the size of the project, and the variety of soils encountered, the methods were of necessity changed as construction progressed. A considerable portion of the soil existed at a natural moisture content adequate for compaction, and watering was unnecessary. The use of the tamping type roller is necessary on Red-Bed shales and on the finer textured soils. Certainly the project presented a number of problems and possible solutions as regards soil compaction.

Case Study No. 2

This project is located near Dodge City in Ford County in southwest Kansas. It consists of 5.335 miles of grading, culverts, and concrete pavement. Approximately two-thirds of the length of the project is located on alluvial deposits in the Arkansas River Valley. The remaining one-third is located in the hills adjacent to the river valley.

The alluvial soils are largely expansive clays and silty clay loams of the A-4 and A-7 groups. The upland soils consist of undifferentiated loess, sand and gravel of the Sanborn formation of the Ogallala groups of the Pleistocene age. These upland soils are non-uniform in occurrence ranging from A-4 clay loams, and A-2 sandy loams to A-3 sands. In addition to the natural soils, a considerable quantity of drifted soil containing a large portion of chaff was present in the side ditches along the existing traveled way.

Preliminary Soils Studies: The preliminary studies consisted of a field soils survey identifying the various soil types in the road profile, and cross section and the location of borrow where necessary, and laboratory tests on representative samples of soils. These studies formed the basis for the following recommendations regarding the use of soil and the methods of construction:

1. Removal and waste of undesirable drift soil containing excess organic matter.
2. Covering of undesirable subgrade soils with suitable soils.
3. Compaction of unexpansive sandy loams to 90 per cent or more of standard density without moisture control.
4. Compaction of expansive soils to 90 per cent or more of standard density at moisture contents of not less than the lower plastic limit minus 5 per cent.

Contract Data: Earthwork was begun November 12, 1935 and was completed May 23, 1936. The earthwork contract consisted of 198,593 cu. yd. excavation at a cost of 15½ cents per cubic yard, and 156,055 cu. yd. rolling and tamping at 4 cents per cubic yard. Water for adjusting soil moistures was considered as a subsidiary item to rolling and tamping.

Equipment: The equipment consisted of:

1. Elevating grader
2. Tamping type rollers
1. 70 Caterpiller tractor
10. 60 Caterpiller tractors
1. 30 Caterpiller tractor
7. 12 cu. yd. crawler tread dump wagons
2. blades
2. compressors and auxilliary mechanical tamping equipment
1. Lorain 75 B Shovel
1. Bulldozer
2. 75 gallon pumps
2. spring tooth harrows
1. wheatland disc plow.

Construction Methods: Soil was dumped in windrows and spread with tractor drawn blades Blading was limited to four trips to prevent excessive wheel tracking No blading was done after rolling began Water for compaction was obtained at depths of 12 to 14 ft from wells dug along the centerline and was delivered to the fill areas through a pipe line Water was applied to the bladed soil by means of hoses attached to the pipe lines Mixing was accomplished by means of spring tooth harrows which were found to be more effective than were the disc plows Five to eight passes were enough to obtain comparatively good distribution of moisture in the soil The shorter fills were compacted by a dual drum oscillating type sheepsfoot roller Two rollers in tandem were used on the long fills on the river terrace portion of the project An average of ten passes of a single roller were sufficient to result in satisfactory compaction