ESSENTIALS OF SOIL COMPACTION*

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SYNOPSIS

Two tests have been described by R R Proctor in his "Principles of Soil Compaction" A compaction test in which samples of soil, at different moisture contents, are tamped in a small brass mold, and a stability test in which the compacted samples are penetrated by a load-indicating needle The tests disclose the two basic relations of compacted samples that for each soil there is an optimum moisture content at which maximum density can be obtained, and that stability drops off rapidly as the moisture contents are increased above the optimum, and increases as the moisture contents fall below the optimum Higher stabilities of soil compacted below the optimum moisture content, however, are retained only if the soil is not wetted

Before compressed soil samples become completely filled with water, they undergo four distinct stages of wetting hydration, lubrication, swelling and saturation These specific phases of soil performance are a useful tool in the intelligent selection of soils whenever compaction is a factor

The chemical composition of the soil particles, the kind of ions absorbed in their surfaces, and admixtures having electro-chemical properties influence the thickness of adhesive films and therefore affect the densities to which soils may be compacted Control curves have been drawn to illustrate these phenomena Changes in film characteristics may provide a reasonable explanation of a number of phenomena which have been attributed to the purely physical effects of surface tension, arrangement of the soil particles, and the like Also it is possible that free water released from adsorbed films may account largely for stability loss when soils in their natural state are manipulated

In the Fall of 1936 the Engineering News-Record published a series of articles on the "*Principles of Soil Compaction*," by R R Proctor of the Los Angeles Department of Water Works Two tests were described: a compaction test in which samples of soil, at different moisture contents, are tamped in a small brass mold, and a stability test in which the compacted samples are penetrated by a load indicating needle, (See Fig 1)

The tests shown in Figure 2 disclose the two basic relations of compacted samples The density-moisture content curve, (left) shows that for each soil there is an optimum moisture content at which maximum density can be obtained. The curve on the right shows the stability of samples compacted at different moisture contents For the sample represented by the data the optimum moisture content is about 16 5 per cent, the maximum density, 111 8 lb per cu ft and the corresponding stability, 795 lb per sq in

Stability drops off rapidly as moisture contents are increased above the optimum, and becomes greater as the moisture contents are decreased below the optimum However, the higher stabilities of soil compacted below the optimum moisture content are retained only if the soil is not wetted At every density less than the maximum there is a moisture content below the optimum corresponding to one above the optimum which the soil can attain under wet conditions without changing in volume

Thus for the same dry weight density (108 pounds per cubic foot) the moisture content (Figure 2) may be either 13 7 per cent with an indicated stability of 1900 pounds per sq in , or 19 3 per cent

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at which the stability is only 270 pounds per sq. in.

Compacted Soils Undergo Four Stages of Wetting. When the moisture contents are expressed as percentages of the combined volumes of soil solids and moisture, the density-moisture content relation

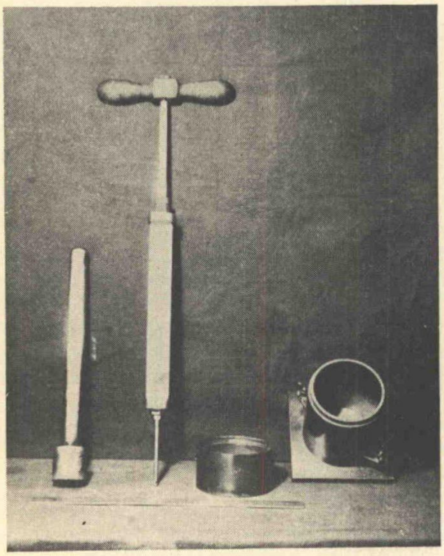

Figure 1. Proctor Apparatus

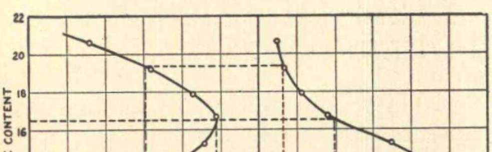

Figure 2. Compaction Relations

becomes a series of straight lines with different slopes as shown by the solid line in Figure 3. The broken line, Figure 3, shows the relation the density would have to moisture content if the samples contained no air. At any density, the difference in moisture contents indicated between the solid and broken lines represents the percentage of moisture, by volume, required to replace the contained air.

The moisture contents at which the straight lines intersect indicate the limits of four distinct stages of wetting which the compressed samples undergo before their pores become completely filled with water.

Wetting, up to a moisture content of 20.7 per cent, may be termed the stage of hydration. During this stage part of the contained water is absorbed by the soil particles and the remainder, adsorbed on their surfaces in the form of cohesive films. The maximum moisture

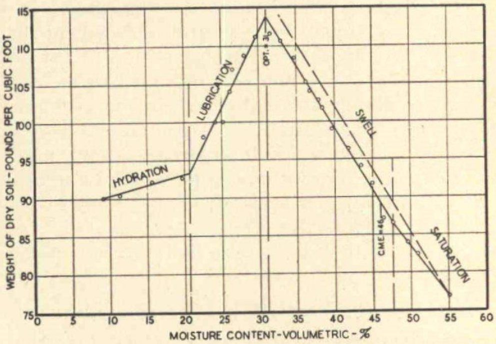

Figure 3. Density-Moisture Content Relation

content of this stage of wetting is termed the hydration limit.

Moisture contents ranging from 20.7 per cent to 31.1 per cent indicate the stage of lubrication. Part of the contained moisture now acts as a lubricant to facilitate the rearrangement of particles being compacted into closer association without, however, excluding all the air. The maximum moisture content of this stage of wetting may be termed the lubrication limit. It is the optimum moisture content at which maximum density is attained.

Water in excess of 31.1 per cent causes the soil mass to swell, although the air contained at the optimum moisture content is not appreciably decreased until the swell limit, a moisture content of 47.7 per cent in this case, is reached.

Moisture contents between 47.7 per cent and the saturation limit, 54.3 per cent in this case, represents the stage of saturation. During this stage practi-

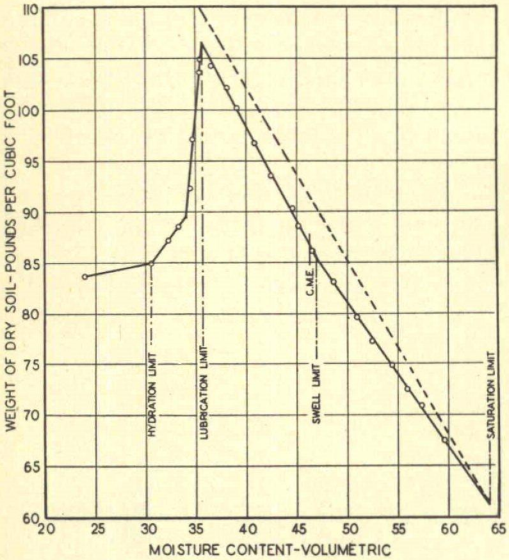

Figure 4. Density-Moisture Content Relation

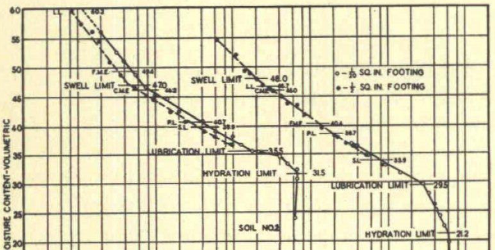

Figure 5. Moisture Content-Stability Relations

cally all the air is displaced and the soil becomes truly saturated.

Some soils have an additional stage of wetting between the hydration and the lubrication stages as shown in Figure 4.

From the foregoing, the stability-moisture content relation would be expected to be a series of straight lines also. Figure 5 shows that this is true if the moisture contents (by volume) are plotted against the logarithms of the penetrometer readings.

In the work at George Washington University, the stabilities are obtained by means of an improved penetrometer

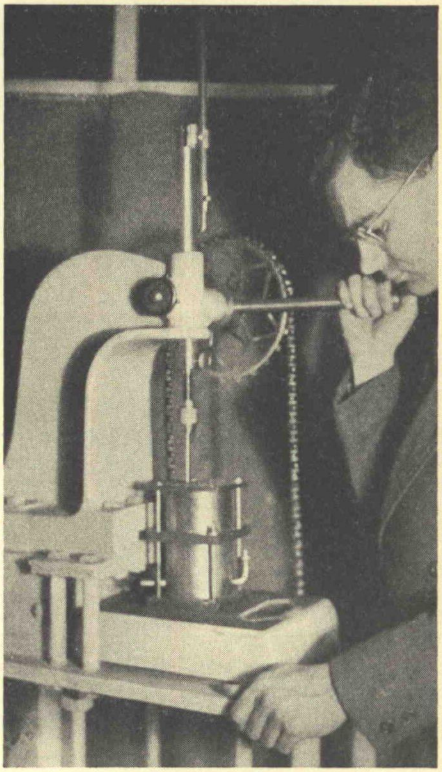

Figure 6. Combination Testing Apparatus Stability Determination

which was described in detail at the 1936 meeting of the American Society of Testing Materials. (See Figure 6.)

Moisture films vary in character during different stages of soil compaction. The Bureau of Public Roads has suggested that a small clay particle in a very wet soil-water mixture is encased in a film of adsorbed or adhesive water which in turn is surrounded by free water as shown in

Figure 7. The innermost layer of the adsorbed films is more nearly like ice than water and the entire film has a higher boiling point, a lower freezing point and is more glue-like than ordinary water in bulk. This conception helps to visualize the mechanics of wetting and compacting soil.

Simple mathematical calculations, involving assumptions not strictly true but valid enough for the illustrative purpose at hand, can be used to estimate the surface area of the soil particles in a given

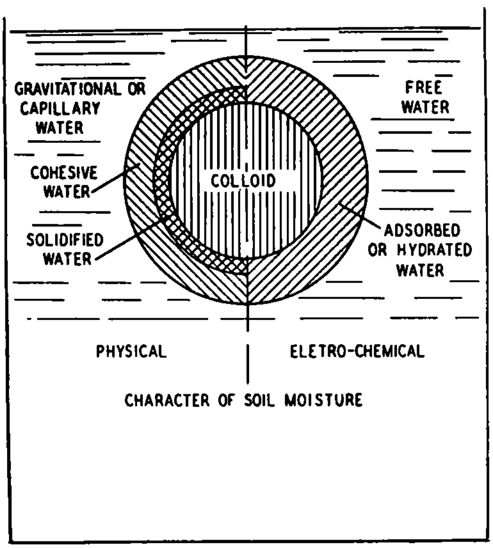

Figure 7. Clay particles in suspension

mass. The soil (Figure 4) consists of 44 per cent sand, 12 per cent silt, 11 per cent clay, and 33 per cent colloids. The estimated surface area, at the hydration limit, assumed to be 30.6 per cent, is 235,000 sq ft per cu ft of soil mass. If the water and air were distributed uniformly over the entire surface of the soil particles, the average thickness of water film would be about 11 millionths inch and of the air film 12 millionths inch. A thickness of about 5 millionths inch represents the hygroscopic moisture contained in the air dried sample.

In like manner the thicknesses of the moisture films at the lubrication swell and saturation limits may be estimated to be about 14 millionths inch, 22 millionths inch and 46 millionths inch, respectively.

Films differing several millionths of an inch in thickness might seem of little import on a sand or gravel particle. On a clay particle as small as one millionth of an inch (.0025 mm) in diameter, however, such small differences in film thickness become controlling influences on performance of the soil containing the clay. The diameter of such a particle is compared with the thicknesses of surrounding film in Figure 8. During the

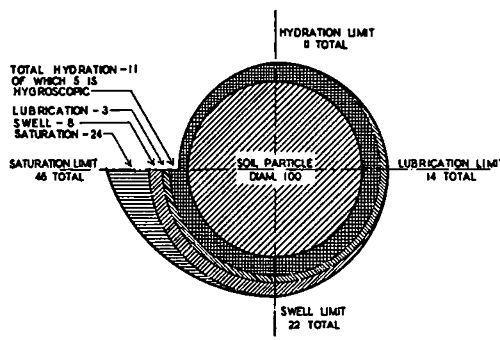

Figure 8. Relative diameter of particle and average thicknesses of moisture films in millionths of an inch

stage of hydration, the moisture film, more viscous and glue-like than free water, increases in thickness to a maximum of 11 millionths inch.

During the stage of lubrication, the water film increases in thickness to 14 millionths inch, the excess of three millionths inch above the hydration film acting more like free water to facilitate compaction of the particles. Correspondingly the air content is reduced to about 3 per cent by volume (1.5 millionths inch, equivalent thickness).

During the stage of swell, the water films increase in thickness to 22 millionths inch, the air content of the soil remaining fairly constant. Moisture in films of this thickness and less is possibly attracted more strongly by the soil particle than by gravity It would then coat the soil particles as shown in Figure 9 without filling the air voids between the outer surfaces of the films

Moisture in excess of the swell limit possibly is free water attracted more strongly by gravity than to the soil particle surfaces Consequently, the moisture gradually replaces the contained air until the soil becomes completely saturated at an equivalent film thickness of 46 millionths inch in this case Hydrostatic uplift may not be fully effective until the saturation limit, indicative of saturation, is reached

In the centrifuge moisture equivalent the films adhere to the soil particles so strongly that 1000 times the attraction of gravity fails to remove them The estimated thickness of film in the soil shown in Figure 4 at the centrifuge moisture equivalent is about 23 millionths inch

In computing the average thicknesses just mentioned the effect of size of grain was disregarded As a matter of fact films on sand grains may be many times as thick as on clay particles

The average diameter of sand grains passing the No 10 sieve and retained on the No 270 size is 041 in At a centrifuge moisture equivalent of 3, the estimated film thickness is 560 millionths in. Bulking of sand can be attributed to film phenomena At 6 per cent moisture where considerable "bulking" of the sand occurs, the estimated thickness of film is 1120 millionths inch This would increase the diameter of the average sand grain about 5 4 per cent If each dimension of a cube of dried sand were increased by 5 4 per cent, the total volume would be increased 17 per cent, an increase commonly observed due to the bulking of damp sand

Static pressures produce uniformly compacted samples If the moistened samples are compacted by static loads instead of by tamping, moisture content-density

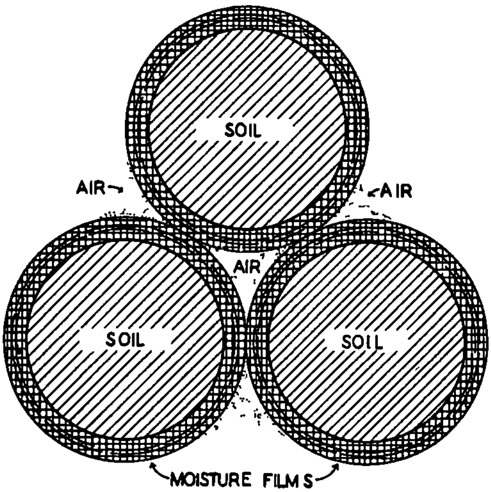

Figure 9 Entrapped air

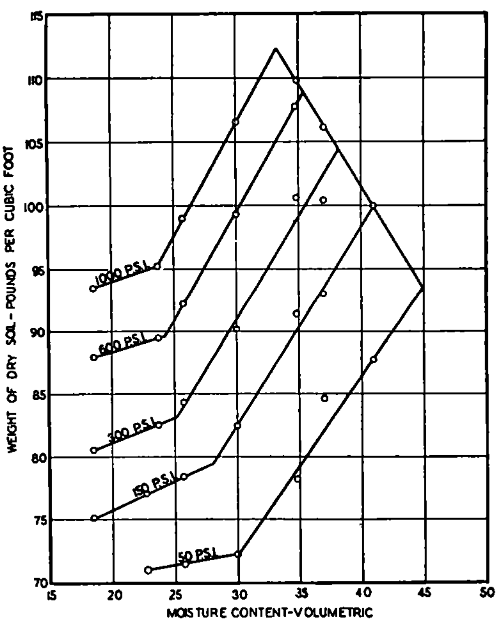

Figure 10. Density-moisture content relations for different static loads

relations such as shown in Figure 10 may be obtained for each soil These curves show the optimum moisture contents, the hydration limits and the lubrication limits for pressures ranging from 50 lb. per sq in to 1000 lb per sq. in. The densities at about 300 lb per sq in pressure on this soil equal those furnished by the standard tamping method

The relations of the optimum moisture contents to pressure, density and stability shown in Figure 11, are the control data for use in embankment construction For the compactive pressure to be provided by a given type of equipment the corresponding optimum moisture content, resulting density, and plasticity needle readings are shown by the curves. Likewise for any desired embankment density, the equivalent pressure which must be furnished by the rolling equipment is disclosed

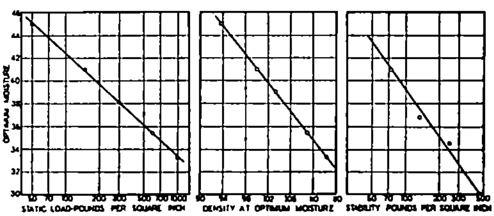

Figure 11. Control curves, sample A

To illustrate, let it be assumed that the Proctor equipment, exerting a compactive effort equivalent to 300 lb static pressure, is to be used Then the soil (Fig 11) should be compacted at a moisture content of 38 2 per cent (22 9 per cent by weight of weight of dried soil), the resulting density should be 104 4 lb per cu ft, and the plasticity needle reading, 117 lb per sq in

If, on the other hand, the embankment is to be constructed at an optimum moisture content equal to, say the plastic limit, (41 4 per cent by volume), the soil should be compacted at an equivalent of 130 lb per sq in static pressure The resulting density is 99 2 lb per cu ft, and the plasticity needle reading, 69 lb per sq in

Effect of soil character and admixtures is disclosed by the control curves. The chemical composition of the soil particles, the kind of ions adsorbed on their surfaces, and admixtures having electrochemical properties influence the thicknesses of adhesive films and therefore affect the density to which soils may be compacted

It is well known that soils with a relatively high silica content are not likely to become so dense under equal pressures as these composed principally of iron and alumina, that at equal pressures clays saturated with lithium ions are likely to have higher moisture contents than soils saturated with potassium ions, and that road soil mixtures containing *calcium chloride* become denser under traffic than

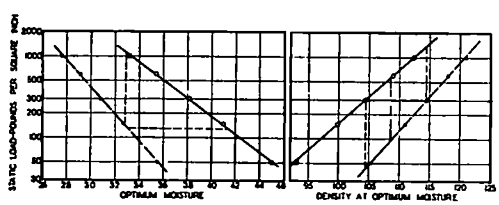

Figure 12 Control curves, A and B

similar soil mixtures without this electrolyte

Figure 12 illustrates how the control curves may serve to explain these phenomena The full lines were furnished by tests of one kind of soil, A, and the broken lines by tests of the same soil treated with calcium chloride, B The curves at the left show that at the same pressure 135 lb per sq in the optimum moisture content of soil A is 41 2 per cent as compared with only 33 0 per cent for soil B, also that to have same optimum moisture content of 33 0 per cent, soil A requires a pressure of 1,100 lb per sq in and soil B a pressure of only 135 lb per sq in

The curves to the right (Figure 12) show that to attain the same density of 104 4 lb per cu ft, a pressure of 300 lb per sq in is required for sample A as compared with 42 lb per sq in for sample B, and that at the same pressure of 300 lb per sq in soil A attains a density of 104 4 lb per cu ft, as compared with 114 5 lb per cu ft of soil B

Such control curves may serve in the same manner to disclose the effect of changing the acidity or alkalinity of soils or otherwise changing the metallic ions with which the soils may be saturated, also the effect of changing the electrical fields around the particles by means of treatment with electrolytes in solution

Compaction Limits Assist in the Selection of Suitable Materials The hydration, lubrication, swell and saturation limits as indicated by both the density and the stability curves agree within the range of experimental error ($1\frac{1}{2}$ per cent moisture content, maximum) This demonstrates that they truly disclose the end moisture contents of definite and specific phases of soil performance Therefore, they become a tool for use in the intelligent selection of soils in all cases where compaction is a factor

The centrifuge moisture equivalents of the two soils shown on Figures 3 and 4 are slightly less than the swell limits No other test constants seem to be indicative of any of the compaction limits

If high density is to be attained soil must be compacted at moisture contents above the hydration limit and as nearly as practicable at the lubrication limit When the difference between hydration and lubrication limits of a soil is smaller than the variation in moisture contents likely to occur under the best of control in the construction of embankments, the soil is obviously not suitable This is true in the case of the soil of Figure 4 The soil of Figure 3, on the other hand, represents material which was used satisfactorily in an earth dam constructed by the U S Forest Service near Gainesville, Ga, under the supervision of R E Pidgeon, Regional Engineer

With efficient control, the moisture content of soil during embankment construction may vary up to a maximum of about 5 per cent This would mean a variation from 2 5 per cent below to 2 5 per cent above the optimum when the soil is to be compacted at the optimum moisture content or lubrication limit as is the case when suitable materials are used

The soil shown on Figure 3, the suitable material, has a density of 109 lb per cu ft at a moisture content of 2 5 per cent below the optimum, 114 0 lb per cu ft at the optimum and 110 1 lb per cu ft at 2 5 per cent above the optimum, making the maximum variation in density, 5 lb per cu ft Under the same conditions the densities of the soil on Figure 4 are respectively 88 5, 106 5 and 101 5 lb per cu ft, causing the maximum variation to be 18 lb per cu ft

If the Figure 3 soil is compacted to 109 lb per cu ft at 2 5 per cent moisture below the optimum, the stability will drop to 380 lb per sq in at equivalent density above the optimum The stability of the Figure 4 soil will, under the same conditions, drop to 54 lb per sq in

However, if the only material available were such as that represented on Figure 4, it should be compacted at a moisture content above the optimum, the actual amount being determined from the slopes of the density curves in the lubrication and swell stages and at such moisture content that equal densities will result at the maximum variation of 5 per cent in moisture content In the case of this soil the moisture content which satisfies this requirement is 37 4 per cent instead of 35 7 per cent, the optimum Under these conditions the densities will vary between 98 5 and 105 5 lb per cu ft, the minimum stability being 200 lb per sq in

Field Conditions Affect Control Curves The characteristics of films on soil particles may be varied by manipulation of the soil and the manner in which it is wetted or dried Thus the control relations of a soil being gradually dried from a wet state may vary from those of the same soil when gradually wetted from a dry state Also the data furnished by tests performed on a thoroughly pulverized material may vary somewhat from those furnished by tests of the same soil in which the natural structure has not been so thoroughly destroyed Dried and powdered soils should be used only for laboratory research and identification tests For control purposes in embankment construction the soil should be tested as it comes from the borrow pit, manipulated as necessitated by the laboratory technic, with the natural moisture content gradually increased and decreased Otherwise the densities obtained by test are likely to differ from those produced by equivalent pressures during embankment construction This fact was reported by Mr Frank B Campbell, Engineering News-Record, Jan 30, 1936, and by the author in the same publication March 26, 1936

Change in film characteristics may provide a reasonable explanation of a number of phenomena which have been attributed to the purely physical effects of surface tension, change in the arrangement of soil particles, and the like

The data now available indicate that for soil wetted above the lubrication stage, increase or decrease in volume is due largely to film properties and not to any rearrangement of the soil particles Likewise it is possible that free water released from adsorbed films may account largely for the drop in stability, which has been frequently observed when soils in natural state are manipulated or remolded