250 to 450 psi, and by increasing a rubber-tired wheel load from 20,000 to 40,000 lb with constant contact pressure. In the case of a lean silty clay, increasing a sheepsfoot roller from 250 to 500 and to 750 psi resulted in no increase of maximum density; and by increasing a rubber-tired wheel load with constant contact pressure from 10,000 to 20,000 and to 40,000 lb small increases in maximum density were obtained. For the lean silty clay it was found that, relative to the laboratory compaction curve, the field compaction curve was shifted toward the zezo air voids line for types of compaction equipment. This finding held for the clayey sand to a very minor degree.

-o-o-o-o-o-o-

IX b 16

AIR ENTRAINMENT IN COMPACTED EARTH EMBANKMENT

CHRISTOPHER F. HEISELMAN

Engineer in charge, Soils Laboratory, Merriman Dam, Board of Water Supply,
City of New York

INTRODUCTION

The following data relates to the plastic condition which resulted from the surface compaction of earth fill at moisture contents in excess of the optimum content, as observed, from time to time, during the placement of several million cubic yards of rolled earth embankment for the Merriman Dam under construction by the Board of Water Supply at Lackawack, New York. This phenomenon was investigated by means of laboratory compaction tests, supplemented by visual and photographic examinations of soils compacted in both the laboratory and field at various moisture contents. Considering the approximate mechanics of dynamic compaction it is concluded that the plastic, weaving behavior observed on the fill surface resulted from a temporary reduction in the relative shearing resistance of the soil, which in turn, was caused by the expansive pressure of entrapped air in the voids of the soil. Evidence is presented which indicates that intensive compactive effort expended while the soil is in this state does not produce additional densification.

MAIN TEXT

Soils for rolled fill purposes were obtained from a borrow pit located in a lateral moraine of glacial origin. Upon excavation, the materials were processed in a screening plant to remove stones larger than 5 inches, and thence hauled by truck to the embankment. This structure consists of a central relatively impervious core designated herein as "A," flanked by wide sections of materials not necessarily impervious, designated herein as "B."

Certain variable characteristics between A and B areas are as indicated below:

Area	Depth of Layer Before Compaction	Depth of Layer After Compaction	Passes of Tamping Roller	General Criteria for Soil Properties
A	7"	5"	14	To secure water-tightness
B	8"	6"	8	To secure slope stability

The tamping rollers, 60 inches in diameter and length, were of the two drum, articulated type, and exerted static pressures between 430 and 535 pounds per area inch of tamping foot, depending upon the loading of the drum.

Frequent sampling of the existing strata in the borrow with distribution by loading shovels, determined from early laboratory experiments, developed an average mixture of existing borrow materials for the A section, as follows:

Grain Size Distribution - Less Than 1/4 Inch
(U. S. Bureau of Soils)

Fine Gravel	7%
Coarse and Medium Sand	32%
Fine and Very Fine Sand	33%
Silt	18%
Clay	10%

Atterberg Limits

Liquid	15%
Plastic	12%
Shrinkage	12%
Flow Index	4%

The permeability coefficient, pertinent to a dry density for the "A" material of 125 pounds per cubic foot, was measured as 8 feet per year, and a value of 33° was obtained for the angle of internal friction in direct shear tests of dense, saturated soils.

Due to an abundance of materials having "A" characteristics in the borrow there was some overlapping into portions of the "b" sections adjacent to the core. An opportunity, therefore, was afforded to observe densification and general soil behavior as a function of the amount of roller compaction employed in the two areas.

Fill moisture ranged between 7% and 10%, averaging 9.5% while the most favorable or optimum contents for 8 and 14 passes of the roller were about 8.8% and 3.2% respectively.

Two distinct types of soil behavior were observed during and subsequent to rolling. When the fill moisture was equal to or less than the related optimum content, the material compacted to a dense state in which it was hard and unyielding under traffic, and a high degree of shearing resistance was evidenced by the negligible amount of weaving or rutting under the wheels of conveyors with capacities from 13 to 24 cubic yards.

However, when soil moisture exceeded the related optimum, by more than 1 per cent, the fill developed plastic characteristics evidenced by -

1) A standing wave similar in appearance to a small mud wave which preceded and followed the travel of equipment over the fill.
2) Progressively deeper rutting along the paths followed by wheeled equipment.
3) Variable checking and cracking of the fill surface.
4) Expulsion of soil moisture at drainage points below the elevation of the fill surface.

The degree to which these four conditions were evidenced appear related to the moisture content of the material with the rate of placement contributory to the amount of weave. The compaction of material as placed for both the A and B sections averaged 3 per cent less than laboratory tests at optimum moisture content. A single specimen sample of approximately 0.2 cubic feet in volume was extracted from the compacted fill for each consecutive 2,000 cubic yards placed in the A section and in the B one sample for each 4,000 cubic yards. As brought out by sampling the soil in a plastic state, virtually identical densification was obtained in both A and B areas when grain size distribution and moisture content were comparable. Considering the fact that the compactive effort of rolling in area A was 75% in excess of that in B, it would appear that when the moisture content of the material exceeds the optimum by more than 1 per cent, rollings in excess of eight passes do not appreciably increase the unit density.

The surface flexing under the wheels of conveyor units developed when placement progressed at a fairly continuous rate. In this connection it was observed that if a layer of the embankment which had weaved to a marked degree reposed undisturbed for a period of approximately one week, depending upon weather conditions, the weave disappeared, and the fill surface became stable and unyielding as in the case where initial fill moisture was less than the optimum. Subsequently when additional material with a moisture content in excess of optimum was placed in layers to form an addition of about four feet similar surface weaving developed.

Undisturbed specimen samples of similar grain distribution removed from the borrow, when tested in the laboratory, were found to have densities comparable to specimens extracted from the embankment layers. In view of the fact that the soil had been stable and unyielding under heavy truck traffic in the borrow, its plastic behavior on the fill may be summarized by stating that the rapid transition in soil density, from the loose state as spread, to one tightly compacted, resulted in a reduction in the relative shearing resistance of the soil, and that such resistance was gradually recovered in the vicinity of the fill surface, provided a sufficient rest period was allowed.

As a result of the wide differences observed in soil behavior in the fill layers of variable moisture content, certain particular compaction tests for moist soils were progressed in the laboratory, as follows:

A representative sample of area A embankment, less than the 1/4 inch size, was brought to a moisture content of about 6 per cent and compacted in a heavy metal cylinder, 4 inches in diameter and 4 1/2 inches in length. Densification, per 2 inch layer of soil, was obtained by dropping a 5 1/2 pound hammer, 2 inches in diameter, through a vertical distance of 18 inches. Raising of the hammer and rotation of the cylinder for the spacing of consecutive blows were performed mechanically. The dry soil density was obtained by a moisture determination and, following this, an increment of moisture was added to the soil and the above procedure repeated. From 8 to 10 such tests were performed on a given sample, the number of blows per 2-inch layer of soil being identical in each test. In all, 8 such groups of tests were performed on representative portions of the same soil, the number of hammer blows per 2-inch layer for the respective groups being 15, 25, 35, 45, 55, 65, 75, and 85.

The density obtained thereby is shown by the family of curves in Figure 1, where dry density appears as a function of moisture content. It will be observed that a given amount of compaction produced a gradual increase in density as moisture was added to the soil until the optimum was reached, after which the density decreased with additional moisture increments. Also, it may be seen that a straight line can be drawn, as was done in the Figure, as the locus of all the points of each test group lying on the wet sides of the respective optimum moisture contents. Such a line, therefore, might be called an envelope of density for the given soil, as a function of the specific conditions created by the test procedure. It is of interest that lines to the left of the respective optimum content are spaced in approximate logarithmic proportion to the various number of hammer blows. The significance of the socalled density envelope becomes clearer when the test data are arranged as in Figure 2. Herein it is shown that maximum densification, at a given moisture content was obtained by given amount of compaction, after which additional compactive effort resulted in an unchanged or static density.

Static density is by no means peculiar to the materials heretofore described. This has been observed in tests for different types of soils, including graded sands, and compaction tests reported by others indicate similar behavior. In general, therefore, it appears that any soil at a given moisture content can be compacted to a static density and the cause of these phenomena appears simple enough if one is satisfied with an approximate interpretation involving the mechanics of compaction.

It is generally agreed that every particle in a damp soil mass is coated, wholly or in

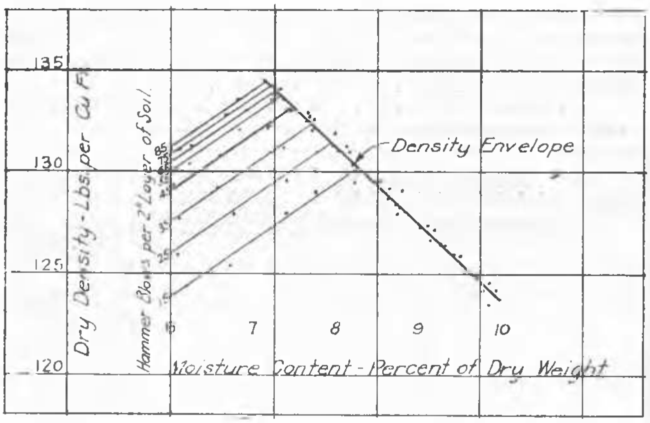

FIG. 1

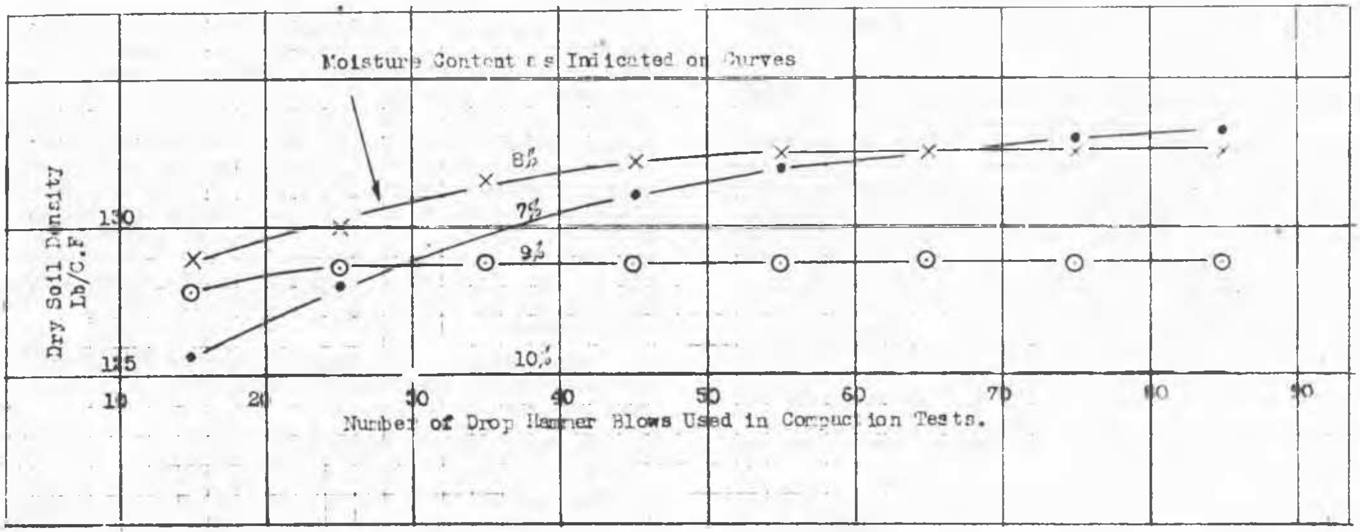

FIG. 2

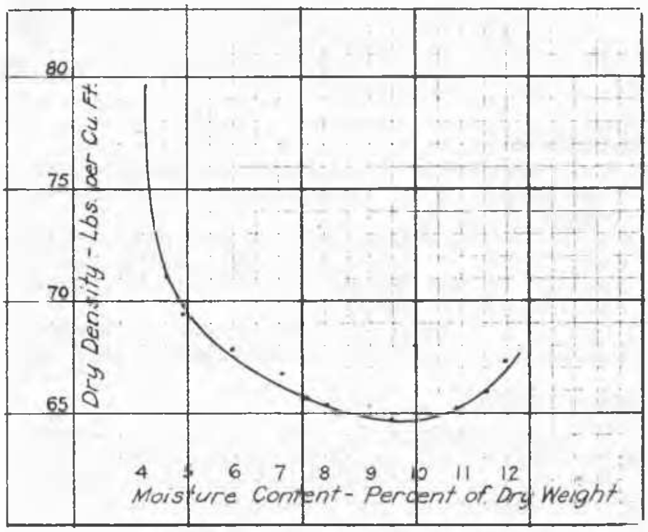

FIG. 3

part, with a thin water film of considerable tensile strength which may be illustrated by pouring such a material in a container at different moisture content and measuring densification obtained thereby. The results of such experiments performed on the soils are shown in Figure 3, where the wide density range may be explained by assuming that the tensile strength of the water film was sufficient to resist greater dencification.

In dynamic compaction, as illustrated in Figure 1, the soil particles are jammed together under a relatively tremendous impact, and the water films engage each other through the instantaneous development of tension and prevent a springing apart of the particles. From Dr. Karl Terzaghi's explanation of soil shrinkage, in which the tensile strength of water film retreating within a saturated soil is likened to the action of a compressing spring, it is recognized that the force which compacts a damp soil compresses the spring, after which film tension maintains it in equilibrium.

There is, however, an additional internal force at work during dynamic compaction, as may be illustrated by comparing the volumes of a damp soil in the loose and dense states. For example, let us say that a soil contains 9 per cent moisture when spread on the embankment, and that its dry density is 100 pounds per cubic foot. By referring to Figure 1, it is seen that the soil attains a density of 127.3 pounds per cubic foot when compacted dynamically at this moisture. If the absolute volumes of soil particles, water and air, which together comprise the soil mass, are examined for these two states, as in the following table, it will be seen that the volumes of soil particles and water are respectively identical for both states, and it then appears that densification is obtained by a reduction of the air volume initially present in the void spaces of the loose soil.

Absolute Values of a Soil in the Loose and Dense States

Dry Density Lb/CF	Soil Particles CF	Water in Void Spaces CF	Air in Void Spaces CF
100	0.69	0.14	0.26
127.3	0.60	0.14	0.05

It may be assumed that the void spaces before compaction were interconnected with each other and with the atmosphere, hence air pressure (above atmospheric) in the soil was negligible. Conversely, it may be assumed that the instantaneous volume change resulting from either laboratory or field compaction does entrap and compress a part of the initial volume of air.

On this basis, static density is explained by stating that during the densification of soil, a progressively closer arrangement of the particles increases entrapped air pressure until such pressure is numerically equal to the water film tension. These two forces being directly opposed, further mobilization of film tension is physically impossible, and the soil density will remain constant as long as the moisture content is unchanged. In such a case, additional densification can be obtained only by the application of an external static load, such as the weight of an embankment above a horizontal plane through its cross-section.

Judging from the curves in Figure 2, the expansive pressure of entrapped air reached its maximum value with the least amount of compaction when the soil moisture was relatively high, indicating, in a general way, that the volume of air so entrained was a function of moisture content.

In order to verify the above hypothesis, a simple experiment was performed as follows:

Three specimens of a well graded soil were compacted in the metal cylinder heretofore described such that the density range was less than 3 per cent. The compaction characteristics of the soil had been previously determined, and an amount of water, therefore, was added to Specimen A prior to compaction, which would result, theoretically in the formation of a relatively thin water film thus enabling the rapid escape of air during compaction. Specimen B contained enough moisture to place it in a border-line state, with respect to air entrainment, between A and C, whereas the latter specimen was sufficiently moist to fall within the static density range, as described graphically in Figure 2.

After being oven-dried at 105°C., the specimens were broken apart and examined with a hand lens. Specimen A, moisture content 6 per cent, consisted almost entirely of a dense, homogeneous arrangement of soil particles in which the voids were so finely divided as to be invisible. Here and there, however, were scattered a few small, crater-like holes which had obviously been filled with trapped air when the soil was in a moist state.

In Specimen B, moisture content 8 per cent, the sizes of the air holes were appreciably larger, and the shapes of some were relatively long and narrow with the major axes roughly parallel to the plane of compaction. Numerous trapped air voids were plainly visible to the unaided eye in Specimen C, moisture content 10 per cent, as indicated in Figure 4, which is a view of the specimen interior. To obtain this plate, the sample was first impregnated with a binder and ground to a plane surface and then photographed under an oblique light, so as to cause the trapped air pockets to appear as black areas on the above print.

Figure 4, it is believed demonstrates that air entrainment does occur under certain conditions in densely compacted soils, and comparison of all three specimens, as described above, indicates that the magnitude of such entrainment is a function of soil moisture, other things being equal.

Subsequent to the experiment heretofore described, many small chunks of compacted soils were recovered from the rolled embankment and examined visually for relative volumes of entrained air. As with the experimental specimens, soils compacted at less than optimum moisture content contained little evidence of entrainment, whereas, overmoist soils resembled the plate in Figure 4 to a degree depending upon moisture. On this basis, it may be judged that the mechanics of compaction in the laboratory and on the fill were similar to the extent that the curves in Figure 2 reflect the behavior of the latter.

In summary, the results of our field observations and laboratory experiments permit conclusions as follows:

A) Air entrainment occurs in compacted soils as a function of moisture content.

B) The presence of expansive air pressure in the void spaces of a soil definitely limits the density to which it can be dynamically compacted at a given moisture content.

C) Air entrainment reduces the relative shearing resistance of a given soil for a period of time which is dependent upon a number of factors, including initial moisture content and rate of fill placement.

REFERENCES

1) R.R. Proctor - "Fundamental Principles of Soil Compaction," Engineering News-Record, August 31, 1933.
2) U. S. Waterways Experiment Station, Vicksburg, Miss., "The California Bearing Ratio as Applied to the Design of Flexible Pavements for Airports." July, 1945.
3) Dr. Karl Terzaghi - "Principles of Soils Mechanics," McGraw-Hill Publishing Co., 1926.

ACKNOWLEDGMENT

Acknowledgment is made to Paul H. Bird, Senior Geologist, Board of Water Supply, City of New York, for preparation and photography of soil specimens, particularly for his preparation of specimen B and its photograph Figure 4.

-o-o-o-o-o-o-

IX b 17 LABORATORY SOIL COMPACTION METHODS, PENETRATION RESISTANCE MEASUREMENTS, AND THE INDICATED SATURATED PENETRATION RESISTANCE

R. R. PROCTOR

Field Engr., Water System, Dept. of Water & Power,
City of Los Angeles

SYNOPSIS

The methods for laboratory soil compaction developed and presented by the author in 1930-33 1) and described further in 1944 2) are still in use substantially as presented. However, published literature regarding the use of these methods by other organizations describes procedures that fall short of the objective intended in 1933, particularly in the use of 90 and 95% of the many "optima" soil dry weights secured by various combinations of a 12 or 18 inch drop of 5-1/2 or 10 lb tampers on one or two inch soil layers in compaction cylinders of 1/20 or 1/30 cu ft capacity, rather than the use of the penetration resistance of soils when saturated (Indicated Saturated Penetration Resistance), selected originally 1) as the standard for evaluating the measured density of natural or compacted soils. The author believes that many engineers have the impression that