PAPER No. 257

# DENSIFICATION OF CANAL BANKS

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## Introductory

The lining on the Haveli Main Line has been the subject of some trenchant criticism in view of its failure in certain reaches, within a year of its construction. One of the main causes which led to this failure was considered to be inadequate compaction of the earth fill resulting in subsequent settlement and the formation of a plane of segregation behind the lining. To avoid the possibility of damage due to such settlement in the case of future linings, Mr. Haigh initiated experiments to secure control of the earthwork by rolling and by controlling the moisture content.

Before dealing, however, with these experiments and the scope of their application in the field, it would be worthwhile mentioning some of the physical properties of soils and the effect of admixture of water on the same.

## Physical Properties of Soils

*Classification of Soils.*—The solids of which a soil is composed are classified by the Bureau of Public Roads, U. S. A., according to particle size in the following groups* :

1. Gravel .. particles retained on the No. 10 (2 mm.) sieve.
2. Coarse sand .. particles passing the No. 10 sieve and retained on the No. 40 (0·42 mm.) sieve.
3. Fine sand .. particles passing the No. 40 sieve and retained on the No. 270 (0·05 mm.) sieve.
4. Silt .. particles between 0·05 and 0·005 mm. in diameter.
5. Clay .. particles finer than 0·005 mm. in diameter.
6. Colloids .. particles finer than 0·001 mm. in diameter.

*Density.*—The density of a soil is its weight per unit volume. As 1 c.c. of water weighs 1 gram, the density of water is 1 in the c.g.s. (centimetre-gram-second) system. A soil which consists of solids

*" Engineering Properties of Soil," by Hogentogler.

and pores has two densities, that of the mass termed 'bulk' density and that of the solids termed absolute density.

If Voids ratio, *i.e.* $\frac{\text{Volume of pores } (V_e)}{\text{Volume of solids } (V_s)} = e$

then Volume of soil bulk per unit of Soil volume, $V = 1 + e$ and

porosity E, expressed as a percentage $= \frac{e}{1+e} \times 100$

Moisture content required to fill the pores expressed as a percentage

of the weight of dried solids (W) $= \frac{100\ e}{G}$

(Where G is the specific gravity of solids.)
When the pores contain no water

Bulk Specific gravity $G_o = \frac{V_s \times G}{V}$ = Bulk Density $D_b$ in the c. g. s. system.

When the pores are filled with water

$$G_o = \frac{V_s \times G + V_e \times 1}{V} = D_b \text{ in the c.g.s. system.}$$

When the moisture content is w%,

$$D_b = \frac{V_s \times G\ \frac{(1+W)}{100}}{V}$$

The dry bulk density $\frac{V_s \times G}{V} = \frac{\text{Weight}}{V}$ is thus a true measure of compaction, as its value will increase proportionately with $V_s$ in a unit volume of soil.

*Soil Moisture.*—The soil moisture as far as it concerns adhesion to soil particles is of two kinds, adsorbed or free. All the contained moisture in a soil is arranged round the particles as films, with the interstices filled with air, till the condition of equilibrium between attraction of the soil particles for water and gravity is satisfied. Any further addition of water remains in a free state and flows through the interstices between the outer surface of the adsorbed moisture films. This free moisture serves as a lubricant causing soil particles to slide or be displaced under load instead of acting as a binder to hold the particles together as adsorbed or film moisture does.

When soil is added to water, the moisture content of the sediment is so high that it has all the properties of a fluid. This is the truly Liquid state, the minimum moisture content of which is the flocculation limit. The viscosity of the moisture is that of the water in this state. Reduction of moisture below the flocculation limit causes the formation of menisci and the mixture becomes more viscous, the minimum moisture content of this state being the true lower liquid limit.

Further decrease in the moisture content turns it into a plastic paste in which condition it remains until the ratio of lubricating to adhesive moisture is so much reduced that the adhesive water becomes the dominating influence on the performance of the soil and it becomes rigid. This point is termed the plastic limit. The numerical difference between the moisture content (percentage) at the liquid and the plastic limits is defined as the plasticity index and indicates the range in moisture content through which the soil remains plastic.

The moisture content is 'critical' at this stage and is equal to the plastic limit of plastic soils and approximately 75 per cent. of the liquid limit of non-coherent, fine-grained materials.

Further reduction of the moisture results in a shrinkage in volume until the 'shrinkage limit' is reached. At this point shrinkage ceases as the resistance of the soil to further consolidation equals the contractive effect of surface tension.

The soil is in a solid state below this limit. Further evaporation leaves only the very thin more or less solidified films coating the soil particles. These films become permanent at high temperature.

Moisture entering soils due to adsorption causes the soil mass to swell due to the separation of soil particles. Soils after being completely dried, when placed in air absorb moisture called the 'hygroscopic' moisture, which may cause a considerable increase in volume. In sands, the increase in volume at hygroscopic moisture content of 6 to 8 per cent. is termed 'bulking' and may be as much as 25 per cent.

Samples of compressed wet soil resist disintegration to a much greater extent if they are immersed in water in the wet state instead of first being thoroughly dried, as in the former state the whole is more or less a dense mass, impervious to the entrance of additional water.

## Soil Stabilization

*Methods adopted.*—The stability of a soil may be defined as the resistance to lateral flow of a soil when loaded denoting its structural strength which depends upon the shear strength representing the combined effect of internal friction of the soil particles.

Soil stabilization consists of treatments for influencing the ratio of free to adhesive moisture, the degree of adhesion of binder films, and the permanency of the joint between these films and the soil particles.

It may be noted that soil particles having a high affinity for water will collect thick moisture films. The outer portion of this thick film will be more like free water and so thin films are more desirable. The methods generally adopted to attain this are :

(*i*) Manipulation to acquire compaction, so as to increase the density. The granular consistency of the soil is also regulated sometimes by the admixture of mineral aggregates and soil constituents, so as to make the graded mixture stable. This is termed Mechanical Stabilization and includes compaction and densification.

The aggregates and constituents to be added, dependant on the particular requirements, are :

(*a*) gravel to furnish the strength and hardness required for resisting the abrasive action of traffic.

(*b*) Sand to provide interlocking of soil grains and thus increase the shear strength.

(*c*) Silt to act as a filler and to provide the capillary bond necessary for stability.

(*d*) Clay to retain the moisture adhesive films after the large films of capillary moisture have evaporated.

(*ii*) The use of various admixtures which include :

(*a*) Solutions of electrolytes to reduce the thickness of adhesive water films.

(*b*) Neutralizers such as limestone dust, slag, etc., to neutralize acid soils.

(*c*) Moisture retentive chemicals as calcium chloride and common salt to provide enough moisture to facilitate compaction by traffic.

(*d*) Water insoluble binders such as portland cement and Bituminous materials to furnish films more substantial than those of moisture alone and to destroy the colloidal properties of soils.

(*e*) Adhesives such as molasses, calcium silicate, etc.

(*f*) Primes and fillers such as soaps, stone dust and slag to increase the adhesion between the soil particles and chemical and bituminous admixtures.

(*iii*) Electro-chemical treatment, application of heat, etc.

It may be noted that the use of admixtures would be preferable, wherever practicable, in case of soils likely to undergo detrimental volume changes with the addition of moisture. Such soils generally have high plasticity, shrink considerably on drying and have a high field moisture equivalent which is defined as the minimum moisture content at which a drop of water placed on a smoothed surface of the soil will not be immediately absorbed but will instead spread out on the surface and give it a shiny appearance.

*Compaction and densification.*—Compaction is used to designate that type of consolidation where in the case of five-grained materials a load applied at the top causes further consolidation only of the portion immediately below. In this, neither the thickness of layers nor the moisture content is critical. Densification, on the other hand, connotes uniform consolidation throughout the thickness, without stratification. In this case, both the moisture content and density are predetermined by test.

When the soil is compacted to maximum density at optimum moisture content, the adsorptive attraction between water and soil particles is probably completely satisfied, so that the tendency for moisture to enter the soil and expand or soften the soil mass is eliminated to a great extent.

As the use of admixtures was considered to be too expensive to be of any practical application in the formation of canal banks involving large quantities of earthwork, the investigations carried out were concerned essentially with the densification of canal banks with the admixture of water only.

## Laboratory Tests

*Soil Analysis.*—The first preliminary before the optimum moisture content of a soil could be determined was its mechanical analysis.

The method adopted was that developed in the Punjab Irrigation Research Institute. The soil particles are originally found coalesced with one another and it is necessary to disperse them to estimate the percentage of clay, silt and sand present. A definite weight of sun-dried soil, 33 grams, is taken and suspended in water in a bottle. About 2 to 2·5 c.c. of NaOH is then added to make it alkaline above a pH of 10·8, in addition to 1 c.c. of $Na_2\,Co_3$ to remove the exchangable calcium. The soil is then made to 1,100 c.c. in a cylinder and thoroughly shaken for four hours, after which it is kept overnight. In the morning it is again shaken for one hour and then allowed to stand.

A chain hydrometer is inserted in the mixture and the time taken by the silt particles to pass just beyond its centre of gravity is allowed. At this stage all the particles of silt have passed below and the density of suspension is simply due to the presence of clay. The density is then observed and the percentage of clay computed considering the average density of soil to be 2·65.

For determining the sand percentage, the soil is dispersed as above, diluted and after shaking allowed to settle for the time calculated for the smallest sand grain (·05 mm. diameter) to settle to the bottom. The upper liquid is syphoned off and the process is repeated two or three times to drive off all the clay and silt which may be sticking to the sand particles. The sand is then dried and weighed.

The time of settlement of particles of different sizes was determined according to Stoke's formula

$$S^2 = \frac{30\,n}{g\,(G - G_1)\,V}$$

where S = diameter of particles in millimetres.
n = coefficient of viscosity of suspended medium.
g = gravitational constant (980).
G = specific gravity of particle.
$G_1$ = specific gravity of suspended medium.
V = Settlement velocity in centimetres per minute.

Substituting the following assumed numerical values :
n = ·0102 (viscosity of water at 67° F).
G = 2·65 (specific gravity of average soil solids).
$G_1$ = 0·9984 (density of water at 67° F).

We have $S^2 = \frac{V}{5290}$

or $V = 5290\ S^2$ cm. per minute
$= 173\ S^2$ ft. per minute.

A convenient method of showing the distribution of particle sizes in a soil is to plot grain diameters as abscissas on a logarithmic scale with the corresponding total percentage as ordinates on an arithmetical scale. The curve connecting the points so plotted is termed 'particle-size accumulation curve.'

*Compaction Apparatus.*—To test the compaction, with a view to determine the optimum moisture content, a compaction apparatus as devised by the Research Institute (Plate I), which is really a modification of the Proctor's Apparatus, was manufactured. It consists of a container $2\frac{3}{4}$ inches diameter and 7 inches long. This is equipped with a piston which is a loose fit in the cylinder and carries *via* a piston rod an impact table. The piston rod works in a guide which fits to the top of the cylinder. The falling weight is attached to a rod $\frac{3}{8}$ inches diameter which works in guides arranged to permit it to fall vertically over the cylinder and the lower guide acts as a stop to the weight. The guide is movable and can be screwed to the vertical pipes at any height. The weight used, including that of the M. S. bar attached to it, was $4\frac{1}{2}$ lbs.

Experiments were first conducted to determine the number of strokes and the distance of travel which would give the maximum compaction. A sample of earth, 200 gms. sun-dried, was taken. The moisture was varied from 4 to 20 per cent. and the height of stroke from 0·5 to 2 feet. It was noted that with a $4\frac{1}{2}$-lb. weight and a range of 2 feet, there was no decrease in volume after 10 strokes, irrespective of the moisture content.

*Optimum Moisture Content.*—Experiments were then conducted to determine the optimum moisture content of samples obtained from different sites along the Thal Main Line. The sample of earth was sun-dried till there was no further decrease in weight. 200 grams were then taken out of it and 4 per cent. water added. This was compacted in the compaction apparatus described already by giving it 10 strokes with a $4\frac{1}{2}$-lb. weight falling from a height of 2 feet. The final reading was noted and the dry bulk density of the sample calculated. This experiment was repeated after adding 2 per cent. water every time and the densities were then plotted against the respective percentages of water. The experiments were repeated by adding 10 to 50 per cent. sand. A typical graph obtained is shown in Fig. 1. It would be noticed that there is only one moisture content at which compaction is maximum for every soil.

In a few cases, the dry bulk density was plotted against the volumetric moisture content. For the sake of comparison, compaction was also tried with a lighter weight of one pound. A typical graph actually obtained is shown in Fig. 2.

It would be noticed that the density moisture content relation becomes a series of straight lines when the moisture content is expressed as a percentage of the combined volume of soil solids and moisture instead of the weights of soil solids. This relationship was first obtained as a result of work done at George Washington University, U.S.A. The relation between the two moisture contents is given by the equation—

$$W' = \frac{W}{W + \frac{100}{G}} \times 100$$

where $W'$ = moisture content by volume
and $W$ = moisture content by weight.

The four stages expressed by this graph are :

(*i*) Hydration, when the contained water is absorbed by the soil particles and the remainder adsorbed on their surfaces in the form of cohesive films.

(*ii*) Lubrication, when part of the moisture acts as a lubricant to facilitate a more compact re-arrangement of the particles, without, however, excluding all the air. The maximum moisture content of this stage, *i.e.* the lubrication limit, is the optimum moisture content at which maximum density is obtained.

(*iii*) Swell, when the excess water causes further separation of the soil particles.

(*iv*) Saturation, when all the air is displaced and the soil becomes truly saturated.

It would also be noticed from this graph that for a lesser compaction the optimum moisture content is more than that required for higher compaction. This point is of considerable importance when compaction in the field falls short of the value obtained in the laboratory.

*Determination of density of natural soil.*—To compare the compaction (dry bulk density) obtained with varying strokes in the compaction apparatus with that of the natural soil, it was necessary to note the volume of the specimen of natural soil in its undisturbed condition. This was done as follows :

The surface of the soil was cut away to give as accurate a flat level as possible. The soil specimen was taken in the shape of but slightly larger than the standard box used with its top level with the ground surface. This box which was in the form of an inverted wedge 6 inches square base and 8 inches height was then placed in the hole in position and was secured by nailing two wooden strips on the top projecting from the sides to rest on the sides of the hole. The space between the box and the sides of the hole was then filled with dry sand from a graduated cylinder so that its volume could be ascertained. The volume of the hole was thus the volume of the box plus that of the sand. The cylinder containing sand as well as the wedge was well vibrated so that the degree of compaction obtained in the two was the same. The whole of the specimen was then carefully dried and weighed and the density calculated.

It was noticed that while compacting with a $4\frac{1}{2}$-lb. weight with a 2-inch stroke, the density exceeded that of the natural soil even after one or two strokes. As the densities normally expected to be obtained in the field with rolling, were more or less of the same order as that of natural soil, it was felt that the results thus obtained would not be comparable with those in the field. A weight of 1 lb. with 1 foot stroke was accordingly adopted. The size of the cylinder in the compaction apparatus was also increased from $2\frac{3}{4}$ inches to $4\frac{1}{4}$ inches diameter and a 2-lb. weight used in this case.

*Penetrometer.*—A penetrometer was devised by Mr. Haigh for gauging the bearing value of soils of different types as shown in Plate I.

In this A is a graduated glass tube 15 inches long held in a vertical position by a wooden support.

B is a needle 3 inches long fitted with a guide at the top so that it is free to move up and down. The end of the needle is cylindrical in form with a flat end. It is of full thickness for a length of $\frac{1}{4}$ inch only from the bottom, the stem above this being thinner to obviate friction between the side of the needle and the hole.

C is a weight in the form of a cylinder fitting loosely in the tube with a thread attached to it for lifting it out. The test comprises determination of the number of blows of the weight, dropped a height of 1 foot, required to cause the needle to penetrate 1 inch.

This experiment was tried with different specimens and it was found that there is a change in slope in the penetration curve at the optimum moisture content and the same can thus also be determined by the Penetrometer.

A typical graph obtained with a sample which was compacted with 1 lb., 2 lbs. and 4 lbs. weights varying the moisture content from 4 to 20 per cent. is also shown in Fig. 3.

This indicates that the bearing value of soils, which depends on the extent of compaction, decreases very rapidly with increase in the moisture content. It may be noted here that for every density each soil has a particular stability, as determined by its resistance to penetration.

*Compaction and Penetration Tests on Artificial Mixes.*—To get some idea of the change in compaction and penetration in the range of soils likely to be met with generally, the main components of the soil, *viz.* clay, silt and sand, were separated artificially in the laboratory and mixed in 32 different proportions, as indicated by the encircled points in the trilateral chart shown in Fig. 4.

This chart was developed originally by A. C. Rose of the U. S. Bureau of Public Roads and shows the mechanical grading of the types classified according to texture.* The range of soils thus obtained covered different proportions of clay from 5 to 30 per cent. and sand from 30 to 90 per cent.

All these artificial soils were compacted with a 2-lb. weight in a $4\frac{1}{4}$-inch diameter cylinder to different densities with varying moisture contents, so as to find out the compaction obtained with different number of strokes. These were also tested with a penetrometer with a view to find out the strokes required with 1 oz. weight on $\frac{1}{4}$ inch needle dropped from 1 foot height to penetrate 1 inch in the soil. Over 500 readings were thus taken each for compaction and penetration, and the following formulæ were deduced :

(*a*) *Compaction*—

$$\log N = \left(\frac{K D}{W^{\frac{1}{6}}}\right)^4$$

where N = number of strokes with a 2-lb. weight dropped from 1 foot height in the compaction apparatus having a $4\frac{1}{4}$-inch cylinder.
K = constant for the soil depending on its constituents.
D = D. B. Density.
W = Moisture percentage by weight.

(*b*) *Penetration*—

$$\log N' = \left(\frac{K\sqrt{D}}{W^{\frac{1}{6}}}\right)^4$$

where N′=number of strokes with 1 oz. weight on a $\frac{1}{4}$-inch needle dropped from 1 foot height to penetrate 1 inch.
K = constant depending on the constituents of the soil. Its value is, however, different than that in the case of the compaction formula.

*"Engineering Properties of Soils," by Hogentogler.

A graph based on the above formula is given in Plate III.

These relationships apply up to the limit of optimum moisture content only. Densities corresponding to higher moisture contents can be easily determined by assuming that the rate of decrease in density beyond the optimum moisture is the same as the increase up to this limit. In other words, if the optimum moisture for a soil is 18 per cent., the density obtainable with 20 per cent. moisture would be approximately the same as that with 16 per cent.

It may also be noted that the above results and formulæ can be taken as accurate only within the extreme limits attained in the experiments. The results would naturally vary if the constituents in the soil have a different grading. The presence of salts in the soil would also affect these results considerably.

*Effect of grading on Compaction.*—The maximum densities obtained by compaction at optimum moisture content with a 2-lb. weight in the modified Compaction Apparatus with different soil constituents are plotted in the graph in Fig. 5. It would be seen that the maximum density of 2·025 is obtained when the sand content is 70 per cent., clay 10 per cent. and silt 20 per cent., and this would thus represent the ideal grading. The maximum densities obtained with 5, 20 and 30 per cent. clay are 1·73, 1·8 and 1·96, respectively. It can thus be seen that grading has a very important bearing on the maximum densities obtainable by compaction and it is preferable to have the sand content between 40 and 75 per cent.

*Effect of Temperature on Compaction.*—As water is more viscous in cold weather, the thickness of adhesive films is greater and so to obtain the same densities, more compaction is required at low temperatures. In other words, greater densities can be obtained at higher temperature with the same compaction.

It has even been noticed that soils compacted at low temperatures sometimes soften solely because of the water liberated by a rise in temperature.

*Shrinkage on drying.*—The artificial soils manufactured after having been compacted at optimum moisture content with a 1-lb. weight dropped from a height of 1 foot, were dried and the shrinkage obtained in the volume noted in each case. These results are plotted in Fig. 6 which clearly indicates that the shrinkage increases with an increase in the clay content and is about 7 per cent. when the clay content is 30 per cent. and the sand 30 to 50 per cent.

*Rolling.*—To test the approximate amount of rolling that would be necessary to attain the density of natural soil, two rollers were originally manufactured; one plain and the other with projections (toothed). The frame was made of angle-iron and ball-bearing plumber blocks were fitted so that these could be driven easily. The length of the roller was kept as 4 feet with an outer diameter of 2·87 feet and the thickness of concrete as ·4 foot giving a weight of about 1·3 tons. These were made hollow with a pipe fitted in the end so that, if desired, weight could be increased by the addition of water or sand. The concrete projections on the toothed roller were 6 inches diameter and 3 inches high, the sides being splayed at 60° slope. These were spaced 1 foot apart in each direction and each line staggered 3 inches behind the next as shown in plate II.

Rollings were tried with both in the original condition of soil as well as at optimum moisture content and it was found that the density of natural soil could only be attained by rolling with a toothed roller at optimum moisture content. As a section of such a roller is pulled forward over a layer of loose material the teeth penetrate the layer, driving some of the surface down and compressing it to such a density that it will support the weight carried. With successive trips the bottom compacted layer becomes thicker and the penetration of the teeth is reduced until they ride upon the surface. The teeth thus really knead from bottom upwards and give a more uniform compaction

For measuring the compaction in the rolled banks, brass containers 4 inches diameter and 4½ inches high with level edges were filled with natural uncompacted earth and buried in the bank in four rows of 3 each. Rolling was then started and after every three rollings one set of three containers was taken out and rolling continued on the remaining sets which were taken out after 6, 12 and 24 rollings. After removal, the upper face of the containers were cut off level with the top and the density of the soil was calculated, as the volume of the container was known and the weight of the soil was obtained after drying. As a further check, the compaction was also measured by using a wedge-shaped box, as described already, and it was found that the results obtained with the containers were about 7 per cent. less than the densities as directly measured by the wedge method. The latter method was accordingly adopted for all future measurements of density of the rolled bank.

*Ramming.*—Compaction was also tried by ramming in both 6 and 19-inch layers with a few samples of soil in which the clay content ranged from 13 to 19 per cent. and the sand from 28 to 50 per cent. The rammer used was square in shape with a weight of 16 lbs. The average height of fall being 1·25 foot, the pressure exerted per square foot was 20 ft. lbs. It was found that on an average, about 20 blows were necessary on a 6-inch layer to have the same average compaction as that of the natural soil.

## Hardness Allowance

This allowance had been paid arbitrarily in the past after judging the effort needed in actual excavation, and so an attempt was made to get a more scientific basis for the grant of this allowance. A statement (No. 1) attached shows the dry bulk density of the soil, as actually obtained, in a few reaches of the Thal Main Line. It would be seen that the hardness allowance was sanctioned when the dry bulk density ranged from 1·46 to 1·66, the latter being the maximum density of the natural soil met with on this canal. It can thus be safely inferred that a hardness allowance is needed where the dry bulk density of the soil exceeds 1·50, provided the sand content is not more than 60 per cent. A rate of Re. 0-12-0 0/00 c.ft. for densities ranging from 1·50 to 1·58 and Rs. 1-8 for densities above 1·58, would probably be suitable.

## Extent of Compactoin Required

As a result of tests carried out in Czechoslovakia* in connection with work on dams, it was observed that there was a definite relation between the pressure to which the soil was subjected and the volume of voids in the same. If all the voids in the soil are filled with water, the volume of voids for a given pressure is called the natural volume of voids and the volume of water is called the natural volume of water. The greater the pressure in the soil, the smaller the natural volume of voids in it and *vice versa*. Settling will take place, if the actual volume of voids in the soil is greater than the natural volume when the soil gets wet and apparent cohesion ceases. Consequently, the more permeable the soil, the sooner will it settle. The soil in a bank should thus be rolled to the natural volume of voids corresponding to the pressures which will be in the bank, to avoid future settlement.

The natural volume of voids can be determined by testing samples of the given soil saturated with water. The sample of soil is compressed by loading and the volume of voids corresponding to each pressure ascertained.

As the pressure in the soil, which would depend on the weight of the earth, traffic load and water pressure would be more in the bottom layers of the bank than near the top, a higher degree of compaction would be necessary in the lower layers. We can thus divide very high banks in three or four portions. The maximum pressure at any point in each portion can then be calculated and the rolling adjusted accordingly, taking a factor of stability of say 1·2.

The roller to be used should naturally be able to exert a greater pressure than the maximum pressure at any point in the bank.

## Compaction in the Field

*Selection of site.*—It was definitely established by the experiments detailed already that we can get the same compaction as that of natural soil by ramming as well as rolling by bullocks, if the moisture content is properly controlled. In cases where the work is to be done on a large scale, rolling would obviously seem to be a better proposition, as this would ensure a more uniform compaction at a lower cost. The real efficiency of the various types of rollers as well as the methods of controlling the moisture content could however be best tested only if the work was undertaken on a large scale in the field.

*Second Congress on large dams, 1936, Vol. IV.

It was, therefore, decided to make puddled banks in the reach R. D. 104,000 to 107,000 of the Thal Main Line, involving about 10 lakhs cubic feet of earthwork.

The reach selected covered a very wide range in the composition of soil, as the sand content varied from 11·7 to 96·3 per cent. and the clay content from 1·6 to 51·2 per cent. The tube-well was situated at a distance of about 2 miles and the watercourse had to pass through sandy *tibbas* before getting to the reach in question. Most of the length in this reach was such that a hardness allowance would normally be sanctioned for the same. The work taken up thus presented all the difficulties that could possibly have to be contended with in a work of this nature.

*Soil Analysis.*—Before starting the work, the soil was analysed every 500 feet apart in the centre as well as on either side of the area, which had to be excavated for obtaining the earth. All the samples were then compacted in the Laboratory with a view to determine the optimum moisture content and tests with penetrometer were also carried out. The D. B. density of the natural soil was also noted in each case. It was decided that the compaction to be aimed at should be not less than that of the natural soil, and about 90 per cent. of that obtained in the Laboratory.

Graphs connecting optimum moisture content W with the percentage of clay, silt and sand were plotted as shown in Fig. 7 on the basis of the above results. It would be seen that the curve connecting moisture percentage and the sand content S approximates more closely to the various observations. This curve thus dispensed with the need of taking further observations of optimum moisture content as the same could easily be determined from the formula deduced, *viz.*

$$W = 24 - 0{\cdot}14S$$

The optimum moisture content thus varies from 11 for 90 per cent. sand to 23 for 10 per cent. sand.

It would be interesting to note that these results compare very well with the compaction tests on the Coyote Dam in California*.

The optimum moisture content for maximum compaction in this case was found to be 24 for clay, 22 for silty clay, 15 for loam and 11 for fine sand and sandy gravel.

*Moisture Control.*—The first point to be settled on taking up the work, was the method to be adopted for the addition of water. This could be done either by sprinkling water over the loose earth spread on the bank, or by watering the area under borrowpits beforehand and allowing sufficient time to elapse till the average moisture content in the top one foot was equivalent to the optimum moisture content. Sprinkling was tried in a short reach to start with, but was not found to be very successful, as the mixing was not thorough and the moisture

*"Selection of materials for rolled-fill earth dams," by G. H. Lee.

content was thus not uniform throughout the layer. Moreover, it involved a lot of extra expenditure.

Some experiments were also carried out to determine the quantity of water needed for watering the borrowpits, to get the required moisture content. A typical graph showing the distribution of moisture in the soil after the addition of water is shown in Fig. 8. This distribution would depend, among other things, on the constituents of the soil, moisture content existing in the soil, temperature and depth of water-table. As the soil constituents varied considerably at every foot-depth and also from place to place, no general rules could be laid for the quantity of water that should be added in the borrowpit area.

The procedure as actually adopted, on the basis of experience gained on the work, was as follows :

The moisture content already in the soil was first determined and the additional quantity required to make up the optimum moisture content calculated, after making due allowance for the evaporation losses which were of the following order :

| | Per cent. |
|---|---|
| August .. .. | 25 |
| September .. .. | 17 |
| October .. .. | 12 |
| November .. .. | 10 |
| December .. .. | 8 |

The time that had to elapse between the watering and the excavation varied from place to place and required careful regulation. It was found that in some cases the borrowpits were fit for working after 24 hours, whereas in other cases no work could be done till after 3 days, due to the top layer not being sufficiently dry to be workable. The moisture content was checked before taking out the earth and spreading it on the bank. As some moisture was lost by evaporation during consolidation, the moisture content was kept up to the optimum by sprinkling, as necessary, its value being checked both during and on the completion of the rolling.

The watercourse carrying the water was run along the centre line of the canal and compartments were made on either side, their length being controlled by the labour strength available. While one compartment was thus available for watering, the adjoining one was ready for excavation. The borrowpit in which excavation was completed, was watered the same evening. Care was, of course, taken that the surface of the borrowpit area should be level, so that the added water may spread uniformly.

*Rolling.*—One of the main objects of the work undertaken in the field was to determine the best type of roller and the extent of rolling required to get the desired compaction.

The depth of the layers to be consolidated was restricted to 6 inches, as it was found that this should not exceed double the height of the teeth to avoid undesirable stratification.

A sheep's-foot and a tamping roller with knobs $4\frac{1}{2}$ inches high and a toothed roller with 3 inches teeth were at first tried in soils where the sand content varied from 30 to 60 per cent. and clay from 15 to 30 per cent. The results are shown in dotted lines in Fig. 9 which indicate that a tamping roller would give the best compaction in the above range of constituents.

The sheep's-foot, though better than the toothed roller, could not be of much practical utility, however, when rolling had to be done by bullocks as two pairs simply refused to move it even for a short distance and considerable difficulty was also experienced in turning it at the end of a run. This turning was essential as all the projections were inclined to one side and the soil was ripped up instead of being compacted, if the roller moved in the wrong direction.

Two pairs of bullocks also found it difficult to pull a tamping roller with $4\frac{1}{2}$-inch knobs and so their length was reduced to 3 inches, which was good enough for a 6-inch layer.

The original toothed roller was also modified. The size of the teeth, which was originally 9 inches diameter at bottom and 6 inches at top, was reduced to 6 inches at bottom and 4 inches at top, the depth being kept the same, *viz.* 3 inches. The spacing of the knobs was also reduced from 1 foot to 9 inches in this case, though the weight—1·3 tons—was kept unchanged.

A combination of the tamping and toothed roller having alternate concrete teeth $5'' \times 3''$ diameter and tamping iron knobs 3 inches high was also tried and the average results obtained by rolling in several soils where the sand content varied from 5 to 20 per cent. and the clay content from 50 to 75 per cent. is shown in Fig. 9.

It was found that a toothed roller was better than a tamping roller in this range of constituents and a toothed-cum-tamping roller was even better.

It was also found that a tamping roller would not be effective in clean sand, as heavy kneading in such soils made up of finely divided particles without any binder (clay), increases the film moistures content, thus keeping the soil particles further separated, resulting in less density.

While compacting with this roller in clayey soils, the bottom layers were not sufficiently consolidated to allow it to ride on their surface. This resulted in the knobs continuing to sink even after 10 to 12 rollings. The friction to be overcome thus increased with every rolling and the work became more difficult in the later stages. The layers also developed a pitted surface due to adhesion of the clayey soil to the surface of the tampers in this case.

The above results can thus be abstracted as follows:

| Per cent. content of sand in soil. | Type of roller which would give the best compaction. |
|---|---|
| 0—20 .. | .. Toothed. |
| 20—30 .. | .. Toothed or tamping. |
| 30—60 .. | .. Tamping. |
| 60—75 .. | .. Toothed or tamping. |
| 75—100 .. | .. Toothed. |

On the whole, therefore, taking into account the comparative difficulty of working a tamping roller, a toothed roller with teeth 6″×4″ diameter and 3 inches high would be the best where work has to be done by bullocks.

A toothed-cum-tamping roller could also be used with advantage in place of a toothed roller, where facilities for making iron knobs are available, as concrete knobs of this size are liable to be easily chipped.

A statement (No. 2) showing some of the results of the actual operation is attached. It would be seen that on an average 16 rollings with the toothed roller would give a density of about 1·5. Although this is appreciably less than the density obtained in the laboratory, it is in most cases better than the density of the natural soil and may thus be considered good enough to prevent any future settlement.

As a further check on the densities actually being obtained, the total quantity of earthwork in the banks as well as the excavation in the borrowpits was measured and it was found that the earthwork in banks was 6 per cent. less than the quantity obtained from the borrowpits, which indicated that the average compaction obtained in the bank was 6 per cent. more than that of the natural soil.

While working with these rollers, it was noticed that the end 2 feet of the bank could not be rolled properly, as the bullocks shied when taken too near the edge of the bank.

This portion had thus to be compacted by rammers, preferably having knobs. To avoid this ramming, a toothed roller was constructed in two parts, placed 5 feet apart with a connecting shaft. The roller wheels thus go outside the space over which the bullocks have to walk, and it becomes possible to roll very nearly up to the extreme edge.

The extent of compaction was generally measured by the wedge method, the centre of gravity of the wedge being kept at the centre of the layer of which the density was to be ascertained. This could also be determined by measuring the resistance of penetration of the soil layer in place, and comparing the values with the readings obtained when the same soil was compacted in the standard manner in the cylinder, as the penetrometer readings depend directly on the density. This test was, however, not tried much, as the direct measurement of density was also considered to be quite simple. It may be noted though, that the top 1 inch or 2 inches layer which gets dried up and has thus a lower moisture content than the optimum must be removed to get a true idea of the penetration in the field.

It was noticed in the reaches where the clay content was over 30 per cent. that the surface of the bank showed cracks about $\frac{1}{8}$ inch wide on drying, after 8 to 10 days. To overcome this, mixing of sand in varying proportions was tried by spreading a uniform thickness of sand on the borrowpit area before excavation. The mixing, however, could not be uniform, as the sand simply stuck outside big lumps of clay. This had accordingly to be discarded. Consolidation at a lower moisture content than the optimum was also considered, but was rejected, as this would have meant a decrease in the density. Spreading a layer of sand about 1-inch thick on the compacted bank was then tried. The sand was removed after a couple of days, when the cracks had got mostly filled up. This was found to be quite useful in cases where the compacted earth could not be covered by another layer within three or four days, resulting in the development of cracks.

The method generally adopted, however, was not to allow any layer to remain exposed to the direct rays of the sun for more than three days, so that it retained most of its moisture content, which was conserved by the addition of another layer on top.

It may be noted, however, that if the earth is well compacted, any small cracks do not represent a source of potential danger, as these would probably get filled up due to swelling of the soil mass when the channel is in flow and would not lead to any settlement.

*Cost of rolling*.—The present sanctioned schedule rate for puddling as actually paid on the Haveli and Thal Main Lines, is Rs. 4/-0/00 c.ft. extra over the schedule rate for earthwork. The rate actually arrived at for the work in question is as follows :

Two pairs of bullocks working one roller are on the average able to give 16 rollings to a bank 300′×20′, thus giving a daily progress of 3,000 c.ft.

Assuming 25 working days in a month, the progress per month would be 75,000 c.ft.

The establishment employed on the work was :

| | Rs. |
|---|---|
| 2 pairs bullocks at Rs. 40 per pair per month .. | 80 |
| 1 Earthwork Mistri at Rs. 22 per month .. .. | 22 |
| 3 mates for sampling, counting rollings and maintenance of watercourse at Rs. 15 p.m. .. .. | 45 |
| 5 beldars for maintaining watercourse, watering borrowpits, etc., at Rs. 12 p.m. .. .. | 60 |
| 1 chowkidar at Rs. 12 p.m. .. .. .. | 12 |
| Total .. | 219 |

∴ rate per 0/00 c.ft. = Rs. 2-15, say Rs. 3.

The rate would naturally go down if more than one roller is worked at one site.

This does not include the cost of running the tube-well, setting up of a laboratory, or having a laboratory Assistant for analysing the soil. Even including these, the cost would not work out to more than Rs. 4/- 0/00 c.ft. No hardness allowance was paid anywhere as the soil was softened by watering.

## Compaction by Tractors

In America and other countries compaction of banks is generally done by the use of tractors, which can spread the soil as well as roll it.

The writer had some experience of their working on the Rangpur Canal, where about one crore c.ft. of earthwork was done with the aid of caterpillar tractors. No attention was paid to the control of moisture content on this work, but the earth was spread in layers of about 6″ to 9″ and rolled every time by the tractor going over it. Even this ensured such an adequate compaction that a car could be easily taken over the bank while the work was in progress and as far as is known to the writer, no breaches have occurred on the Rangpur Canal so far in the reaches made with the use of tractors.

If the earthwork has to be done by tractors, it would involve working the following machines :

(*i*) Carry-all Scraper worked by a 95 H. P. Tractor for carrying and spreading earth.

(*ii*) Ripper worked by a 35 H. P. Tractor for loosening the soil to be excavated.

(*iii*) Dozer worked by a light tractor for rough dressing of the banks.

(*iv*) One or two rollers worked by a light Tractor.

The cost of working these would be as follows :

*Expenditure :*

| | |
|---|---|
| Assume : life of machines | = 20,000 hours. |
| Working hours per day | = 12. |
| Total cost of machines | = Rs. 80,000. |

(*a*) Fixed charges (per day) :

$$\text{Depreciation} = \frac{80{,}000 \times 12}{20{,}000} = \text{Rs. } 48.$$

Interest (6% on 60% of the total cost) = Rs. 7-14

Total = Rs. 55-14

(*b*) Operating expenses per day :

| | Scrapper | Ripper | Dozer | Rollers | Total | Rate | Cost |
|---|---|---|---|---|---|---|---|
| | | | | | | Rs. | Rs. |
| Diesel oil (gallons) .. | 68 | 15 | 9 | 15 | 107 | -/12/ | 80/4/- |
| Lubricating oil (galls) .. | 3.0 | 1.2 | .7 | 1.2 | 6.1 | 3/- | 18/5 |
| Grease (lbs.) .. | 2.0 | .66 | .66 | .66 | 4.0 | -/4/- | 1/- |
| Petrol (galls) .. | 1.0 | .5 | .5 | ·5 | 2.5 | 2/- | 5/- |
| Establishment .. | 10/- | 10/- | 10/- | 10/- | 40/- | .. | 40/- |
| Ropes, etc. .. | 30/- | .. | .. | .. | .. | .. | 30/- |
| | | | | | | Total | 174/9/- |

(*c*) Overhead charges :
Rs. 20 per day.

(*d*) Arrangements for watering area to be excavated = Rs. 10

∴ Total Expenditure per day = Rs. 55-14 + Rs. 174-9 + Rs. 20 + Rs. 10 = Rs. 260-7-0.

Average outturn = 25,000 c.ft. per day.

∴ cost = Rs. 10-6, say Rs. 10 0/00 c.ft.

The scheduled rate for earthwork 3 chains lead being Rs. 5/-0/00 the extra expenditure involved in working by Tractors would thus be about Rs. 5/-0/00 c.ft. against Rs. 3 0/00 extra for compacting by bullocks. It may be noted, though, that a much better compaction would be obtainable by Tractors, as these could easily pull heavier rollers.

The weight of the Tractor with its attendant vibration would also contribute materially towards attaining a higher compaction.

## Densification Methods for Small Works

In cases where work has not to be done on a large scale and the facilities of setting up a laboratory are not available or this is considered to be too expensive, the work could easily be done as follows :

(*i*) Measure the sand content in the soil by drying a specimen and passing it through No. 270 sieve.

(*ii*) Calculate the optimum moisture content in each case from the formula

$$W = 24 - 0.14\,S.$$

(*iii*) Use a 1·3-ton roller 4 inches wide having staggered teeth 3 inches high, as shown in Plate II (No. 2).

(*iv*) Roll at optimum moisture content in 6 inches layers, giving 16 to 20 rollings to each layer. The approximate number of rollings required to attain a certain density can be easily ascertained by referring to the graph in plate IV.

(*v*) Ram the side 2 feet which cannot be rolled properly, by 16-lb. rammers, preferably those having knobs, giving atleast 20 strokes per s.ft. over the whole area.

(*vi*) Check up the density actually being obtained by the wedge method to see that it is not less than that of the natural soil, subject to a minimum of 1·48.

**Acknowledgements**

The work described in this paper was initiated by Mr. F. F. Haigh, who took a keen personal interest in the experiments and without his help and guidance this paper would have never been written.

The author is also thankful to M. Ata Mohammed, Overseer, who showed both initiative and intelligence in carrying out the various experiments.

*STATEMENT No. 1*

STATEMENT SHOWING COMPOSITION OF SOME SOILS ALONG THAL MAIN LINE UPPER

| Situation | Depth below Natural Surface | Dry bulk Density | Soil Components | | | | Remarks |
|---|---|---|---|---|---|---|---|
| | | | Clay % | Sand % | Silt % | Kankar % | |
| R. D. 25,000 Main Line Upper. | 0 | 1·32 | 11·1 | 66·0 | 22·9 | .. | |
| | 1·0′ | 1·23 | 17·1 | 55·2 | 27·7 | .. | |
| | 2·0′ | 1·35 | 8·6 | 64·2 | 27·2 | .. | |
| | 4·0′ | 1·48 | 4·9 | 82·2 | 12·9 | .. | |
| | 8·0′ | 1·42 | 10·3 | 51·3 | 38·4 | .. | |
| R. D. 55,000 Main Line Upper. | 0 | 1·36 | 24·9 | 42·7 | 22·4 | .. | |
| | 1·0′ | 1·34 | 18·9 | 46·5 | 34·6 | .. | |
| | 2·0′ | 1·48 | 25·5 | 48·4 | 26·1 | .. | |
| | 4·0′ | 1·46 | 24·4 | 46·4 | 29·2 | .. | |
| | 8·0′ | 1·41 | 2·4 | 94·3 | 3·3 | .. | |
| R.D. 127,000 Main Line Upper. | 0 | 1·46 | 12·8 | 54·0 | 33·2 | .. | Hardness allowance sanctioned. |
| | 1·0′ | 1·46 | 20·3 | 48·9 | 30·7 | .. | Do. |
| | 2·0′ | 1·42 | 16·1 | 47·2 | 36·7 | .. | Do. |
| | 4·0′ | 1·64 | 31·1 | 59·4 | 9·5 | .. | Black soil. Hardness allowance sanctioned. |
| | 8·0′ | 1·56 | 25·4 | 53·4 | 21·2 | .. | Hardness allowance sanctioned. |
| R. D. 60,000 Main Line Upper. | 0 | 1·34 | 13·2 | 50·1 | 36·8 | .. | |
| | 1·0′ | 1·37 | 27·9 | 27·9 | 44·2 | .. | |
| | 2·0′ | 1·40 | 5·8 | 33·6 | 60·6 | .. | |
| | 4·0′ | 1·33 | 18·6 | 43·2 | 38·2 | .. | |
| | 8·0′ | 1·39 | 8·1 | 71·2 | 20·7 | .. | |
| R. D. 147,500 Main Line Upper. | 0 | 1·66 | 23·5 | 50·0 | 24·5 | 2·0 | Hardness allowance sanctioned. |
| | 1·0′ | 1·48 | 21·1 | 54·6 | 24·1 | 0·2 | Do. |
| | 2·0′ | 1·56 | 17·3 | 49·9 | 32·6 | 0·1 | Do. |
| | 4·0′ | 1·62 | 26·4 | 48·3 | 25·0 | 0·3 | Do. |
| | 8·0′ | 1·58 | 19·1 | 59·5 | 14·4 | 7·0 | Do. |
| R.D. 155,500 Main Line Upper. | 0 | 1·51 | 30·6 | 53·4 | 16·0 | .. | Do. |
| | 1·0′ | 1·53 | 48·4 | 47·7 | 3·7 | 0·20 | Do. |
| | 2·0′ | 1·51 | 17·7 | 49·1 | 33·0 | 0·20 | Do. |
| | 4·0′ | 1·61 | 24·3 | 63·4 | 11·7 | 0·60 | Black soil. Hardness allowance sanctioned. |
| | 8·0′ | 1·53 | 15·4 | 78·0 | 4·5 | 2·10 | Hardness allowance sanctioned. |

### *STATEMENT No. 2*

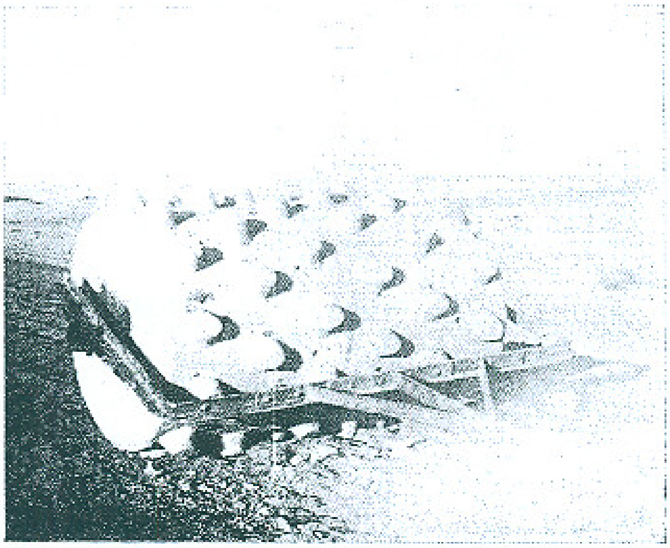
### DETAILS OF ROLLING THAL MAIN LINE UPPER R. D. 104,000—107,000

| Serial No. of Layer | Thickness of Layer | Particulars of N. Soil: Clay % | Silt % | Sand % | Dry bulk Density | Laboratory Tests: Optimum Moisture Content | Density obtained | Field Tests: Moisture Content at start | Moisture content at end | Type of roller | No. of rollings | Density obtained |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | *(R. D. 104,000 to 104,400 R).* | | | | | | | |
| 1 | 6″ | 61·0 | 20·4 | 18·6 | 1·52 | 20% | 1·75 | 21% | 21% | Tamping | 16 | 1·49 |
| 2 | 6″ | 57·8 | 29·7 | 12·5 | 1·53 | 20% | 1·79 | 21% | 19.5% | Toothed 6″×4″ | 16 | 1·53 |
| 3 | 6″ | 66·7 | 17·0 | 16·3 | 1·45 | 20% | 1·82 | 21% | 20% | Tamping | 16 | 1·47 |
| 4 | 6″ | 53·9 | 25·4 | 20·1 | 1·48 | 19% | 1·83 | 20% | 20% | Toothed 9″×6″ | 20 | 1·49 |
| 5 | 6″ | 52·8 | 23·2 | 24·0 | 1·47 | 17% | 1·78 | 21% | 19% | ,, 6″×4″ | 20 | 1·52 |
| 6 | 6″ | 65·2 | 27·3 | 7·5 | 1·48 | 24% | 1·73 | 24% | 24% | ,, 9″×6″ | 20 | 1·48 |
| 7 | 6″ | 75·1 | 19·6 | 5·3 | 1·49 | 24% | 1·75 | 24% | 24% | ,, 6″×4″ | 20 | 1·49 |
| | | | | | *(R. D. 105,100 to 105,300 R).* | | | | | | | |
| 1 | 5″ | 54·0 | 25·2 | 20·8 | 1·52 | 18% | 1·73 | 18% | 16% | ,, 6″×4″ | 16 | 1·54 |
| 2 | 6″ | 53·5 | 22·9 | 23·6 | 1·48 | 18% | 1·71 | 14% | 13% | ,, ,, | 16 | 1·51 |
| 3 | 6″ | 54·1 | 22·1 | 23·8 | 1·47 | 18% | 1·76 | 15% | 14% | ,, ,, | 16 | 1·48 |
| 4 | 6″ | 50·7 | 23·1 | 26·2 | 1·54 | 17% | 1·82 | 18% | 17% | Tamping | 16 | 1·52 |
| 5 | 6″ | 48·4 | 25·2 | 26·4 | 1·50 | 18% | 1·79 | 17% | 17% | Toothed 9″×6″ | 16 | 1·49 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 6 | 6″ | 47·5 | 23·2 | 29·3 | 1·49 | 17% | 1·78 | 19% | 19% | ,, | ,, | 16 | 1·48 |
| 7 | 6″ | 50·2 | 29·4 | 20·4 | 1·47 | 16% | 1·82 | 18% | 18% | ,, | ,, | 16 | 1·49 |
| 8 | 6″ | 39·7 | 20·8 | 29·5 | 1·50 | 17% | 1·85 | 20% | 20% | ,, | ,, | 16 | 1·47 |
| 9 | 6″ | 40·4 | 25·2 | 34·4 | 1·47 | 15% | 1·76 | 21% | 21% | Tamping | | 16 | 1·45 |
| 10 | 6″ | 39·6 | 26·3 | 34·1 | 1·46 | 16% | 1·75 | 17% | 17% | Toothed | 6″×4″ | 20 | 1·53 |
| 11 | 6″ | 52·9 | 23·1 | 24·5 | 1·48 | 16% | 1·77 | 16% | 16% | ,, | ,, | 20 | 1·52 |
| 12 | 6″ | .. | .. | .. | 1·50 | 17% | 1·82 | 18% | 18% | ,, | ,, | 20 | 1·55 |
| | | | | | (R. D. 104,800 to 105,000 L). | | | | | | | | |
| 1 | 9″ | 20·1 | 48·0 | 31·9 | 1·48 | 16% | 1·85 | 19% | 18% | ,, | 9″×6″ | 16 | 1·48 |
| 2 | 6″ | 19·4 | 49·2 | 31·4 | 1·49 | 16% | 1·83 | 18% | 18% | ,, | 6″×4″ | 16 | 1·55 |
| 3 | 6″ | 21·7 | 44·1 | 34·2 | 1·46 | 16% | 1·79 | 19% | 18% | ,, | ,, | 16 | 1·52 |
| 4 | 8″ | 22·0 | 45·2 | 32·8 | 1·54 | 18% | 1·81 | 20% | 19% | ,, | ,, | 16 | 1·49 |
| 5 | 6″ | 64·3 | 17·1 | 18·6 | 1·45 | 19% | 1·77 | 20% | 19% | ,, | ,, | 16 | 1·48 |
| 6 | 6″ | 55·0 | 26·5 | 18·5 | 1·48 | 17% | 1·70 | 21% | 19% | Tamping | | 16 | 1·44 |
| 7 | 6″ | 54·7 | 31·6 | 13·7 | 1·49 | 15% | 1·78 | 21% | 20% | ,, | ,, | 16 | 1·48 |
| 8 | 6″ | 64·8 | 19·5 | 15·7 | 1·55 | 18% | 1·73 | 19% | 18% | Toothed | 6″×4″ | 16 | 1·55 |
| 9 | 6″ | 55·4 | 20·7 | 23·9 | 1·49 | 17% | 1·75 | 18% | 18% | ,, | ,, | 20 | 1·52 |
| 10 | 6″ | 79·3 | 9·3 | 11·4 | 1·47 | 19% | 1·79 | 20% | 19% | Tamping cum toothed | | 20 | 1·56 |
| 11 | 6″ | 56·8 | 35·3 | 7·9 | 1·51 | 18% | 1·82 | 18.5% | 18.5% | Do. | | 20 | 1·54 |

TOOTHED-CUM-TAMPING ROLLER

TOOTHED ROLLER IN TWO PARTS
WITH A CONNECTING SHAFT



TOOTHED ROLLER

# DETERMINATION OF OPTIMUM MOISTURE CONTENT

## SOIL CONSTITUENTS

| DESCRIPTION | PERCENTAGE OF | | |
|---|---|---|---|
| | CLAY | SAND | SILT |
| NATURAL SOIL | 15·6 | 58·8 | 25·6 |
| 10 % SAND | 14·0 | 63·0 | 23·0 |
| 20 % SAND | 12·5 | 67·0 | 20·5 |
| 30 % SAND | 10·9 | 71·2 | 17·9 |
| 40 % SAND | 9·4 | 75·2 | 15·4 |
| 50 % SAND | 7·8 | 79·4 | 12·8 |

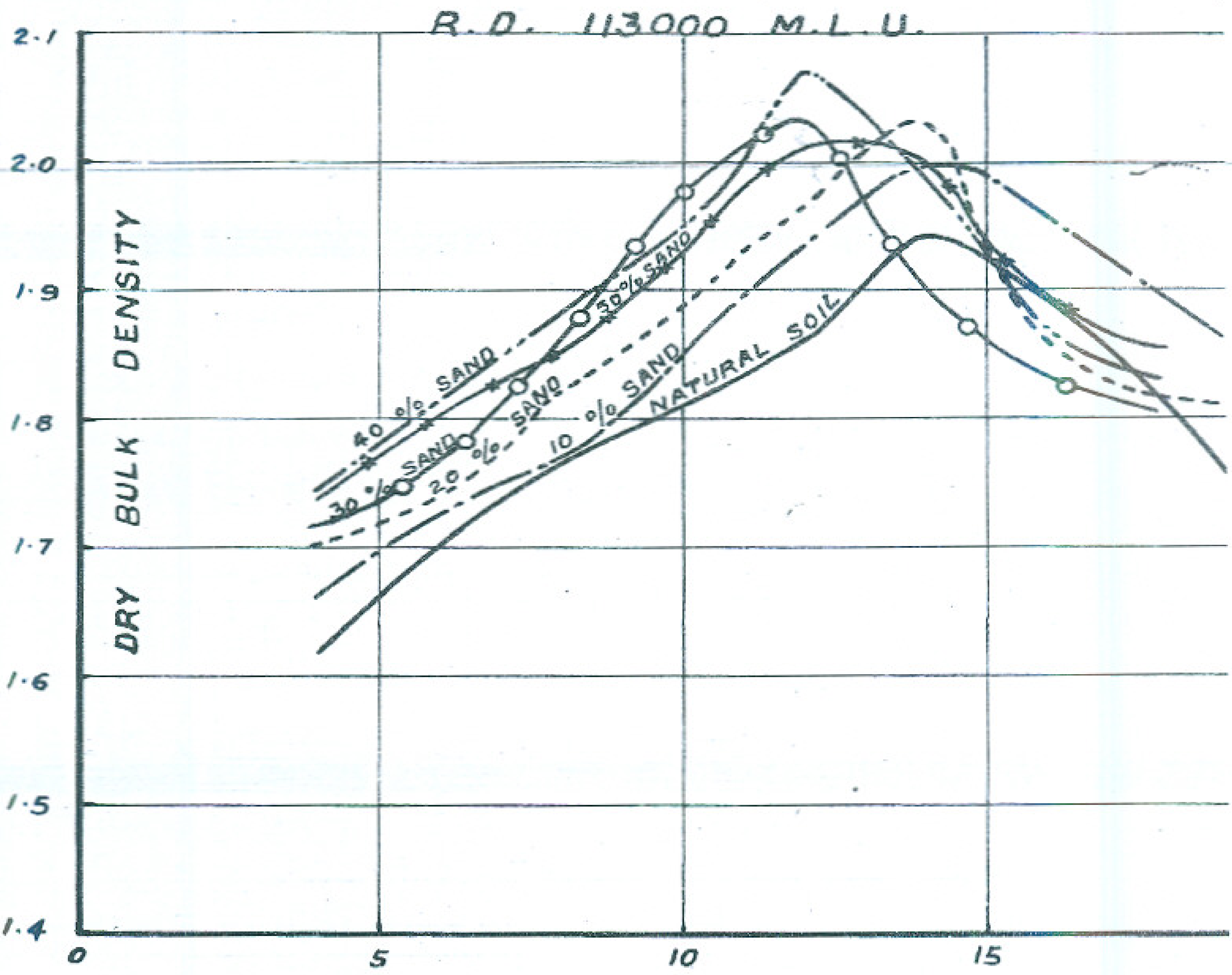



FIG (1)

# DETERMINATION OF OPTIMUM MOISTURE CONTENT

SOIL CONSTITUENTS

| | | |
|---|---|---|
| CLAY | = | 14·6 % |
| SAND | = | 73·3 % |
| SILT | = | 12·1 % |

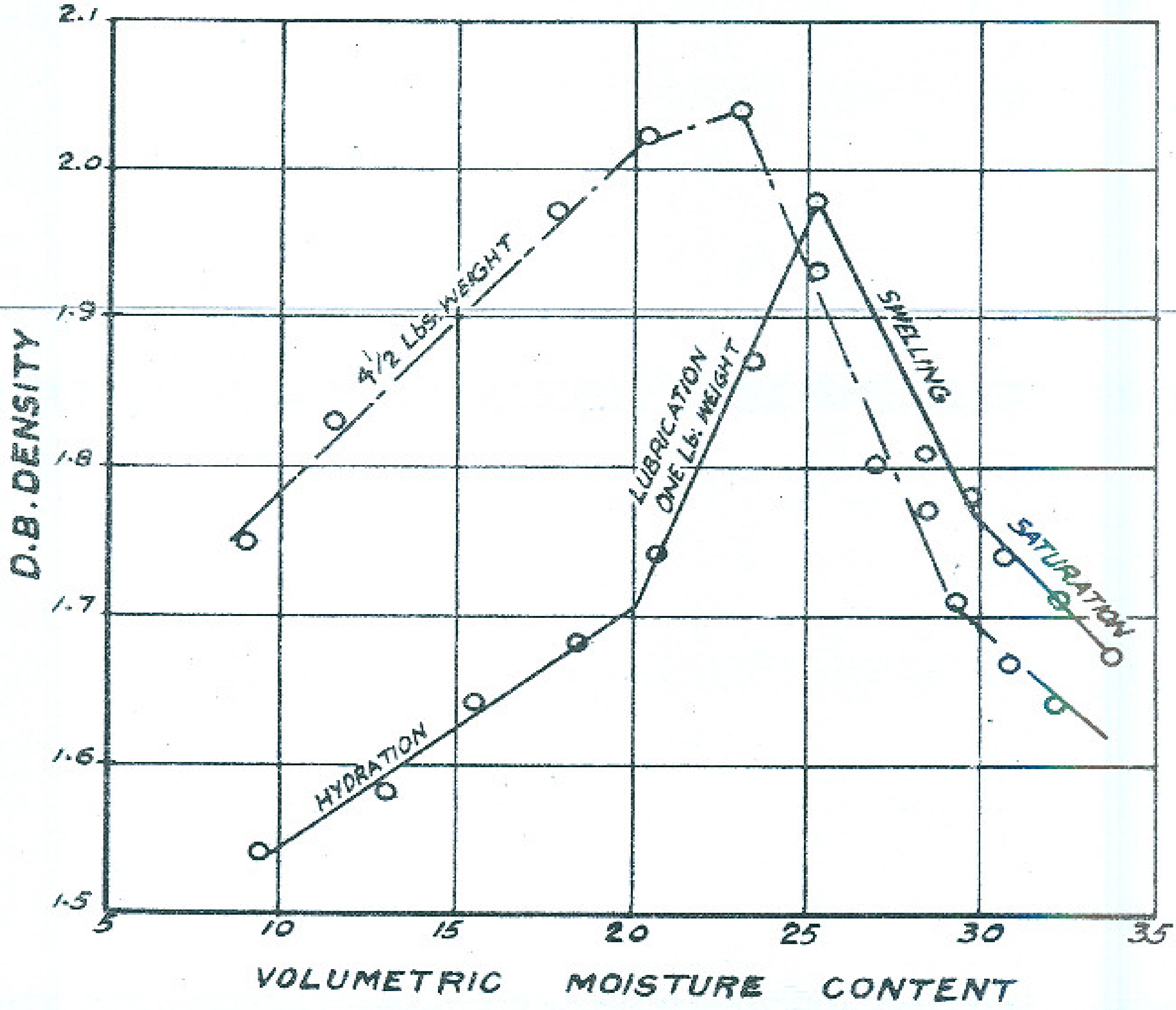



FIG (2)

PAPER

# PENETRATION TEST ON SOILS COMPACTED WITH DIFFERENT WEIGHTS

(1" PENETRATION WITH 1 OZ WEIGHT DROPPED FROM 1·0 HEIGHT ON A 1/4" DIA

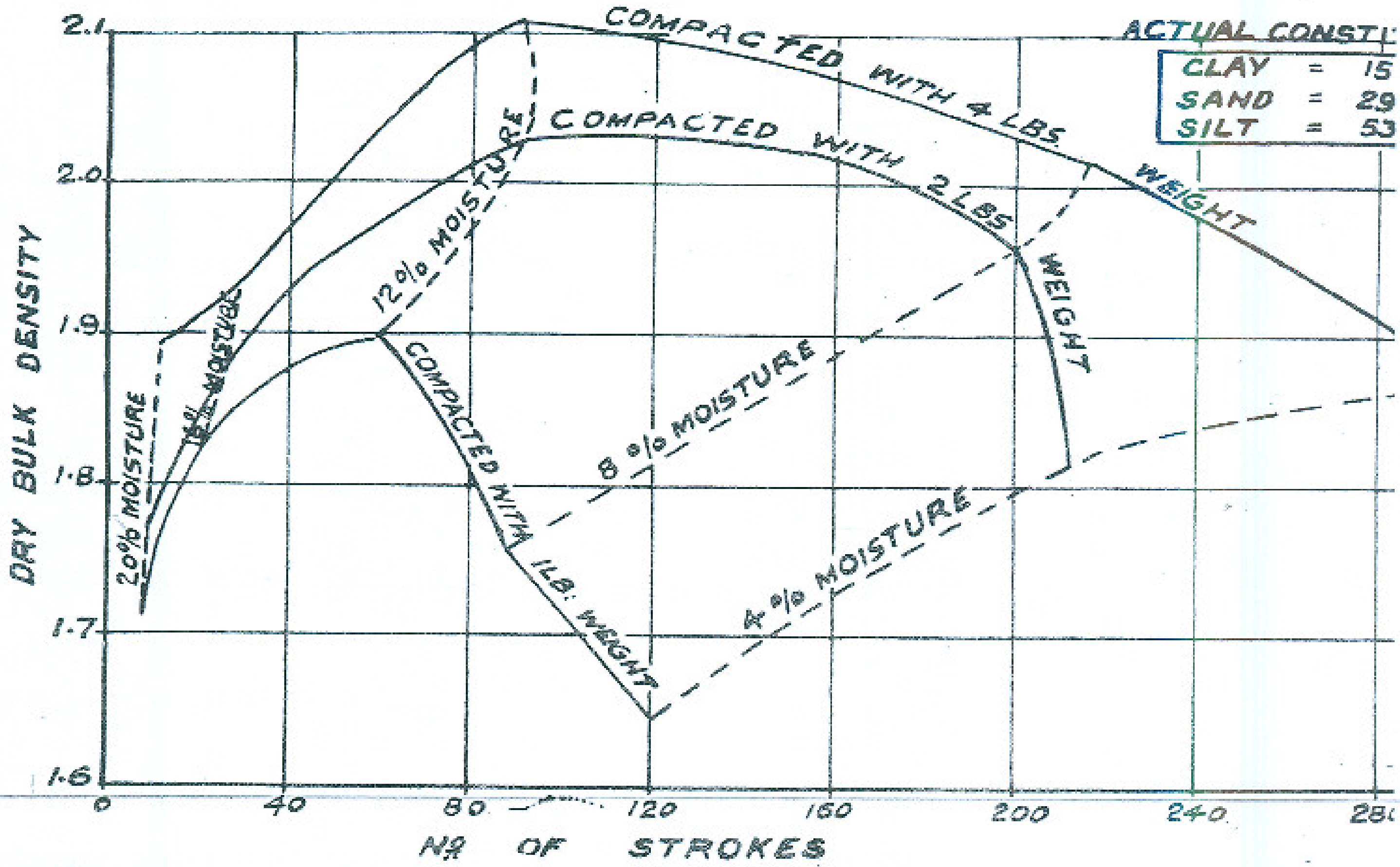
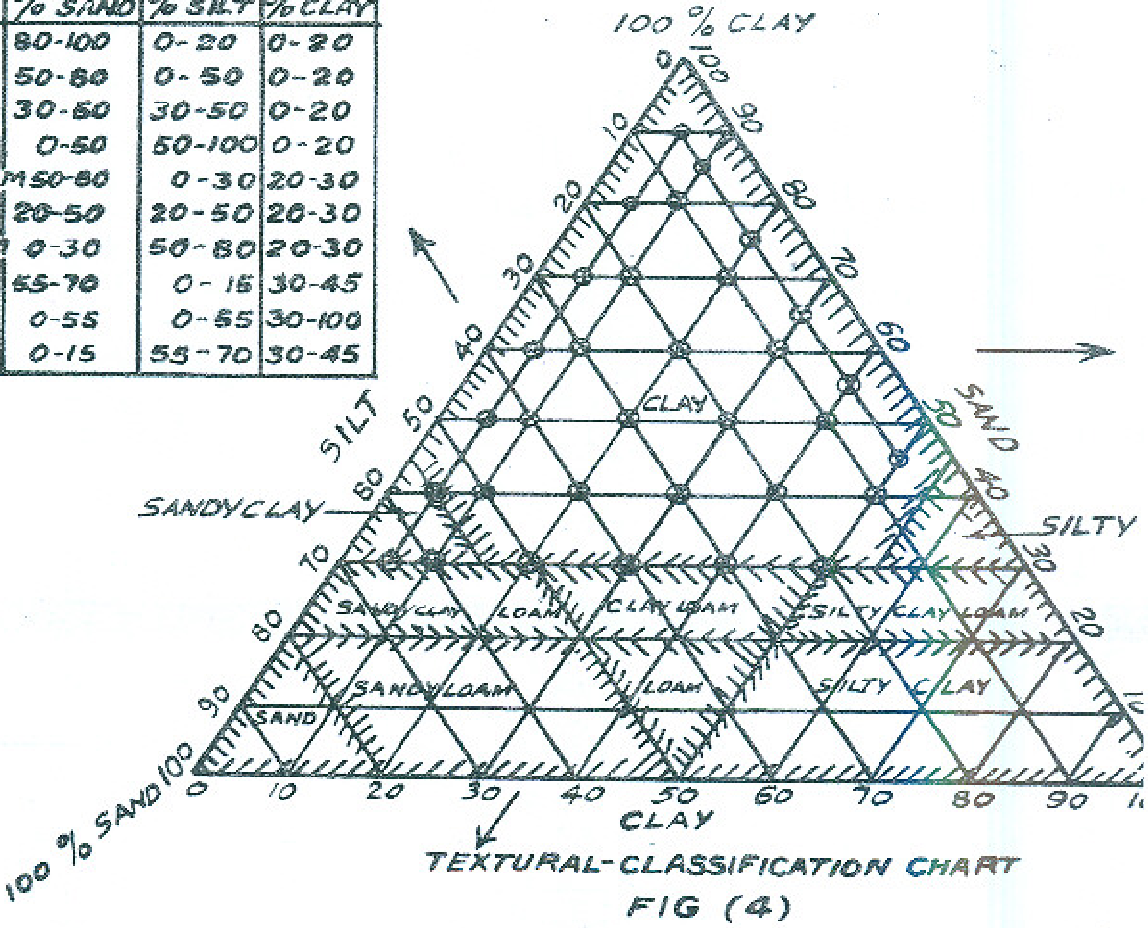



FIG (3)

| CLASS | % SAND | % SILT | % CLAY |
|---|---|---|---|
| SAND | 80-100 | 0-20 | 0-20 |
| SANDY LOAM | 50-80 | 0-50 | 0-20 |
| LOAM | 30-50 | 30-50 | 0-20 |
| SILTY LOAM | 0-50 | 50-100 | 0-20 |
| SANDY CLAY LOAM | 50-80 | 0-30 | 20-30 |
| CLAY LOAM | 20-50 | 20-50 | 20-30 |
| SILTY CLAY LOAM | 0-30 | 50-80 | 20-30 |
| SANDY CLAY | 55-70 | 0-15 | 30-45 |
| CLAY | 0-55 | 0-55 | 30-100 |
| SILTY CLAY | 0-15 | 55-70 | 30-45 |




TEXTURAL-CLASSIFICATION CHART

FIG (4)

(FIG:4 REPRODUCED FROM ENGINEERING PROPERTIES OF SOILS BY HOGENTOGL

PUNJAB ENGINEERING CO.

# EFFECT OF VARYING SOIL COMPONENTS ON DENSITY

(MAXIMUM DENSITIES PLOTTED AT OPTIMUM MOISTURE CONTENT)

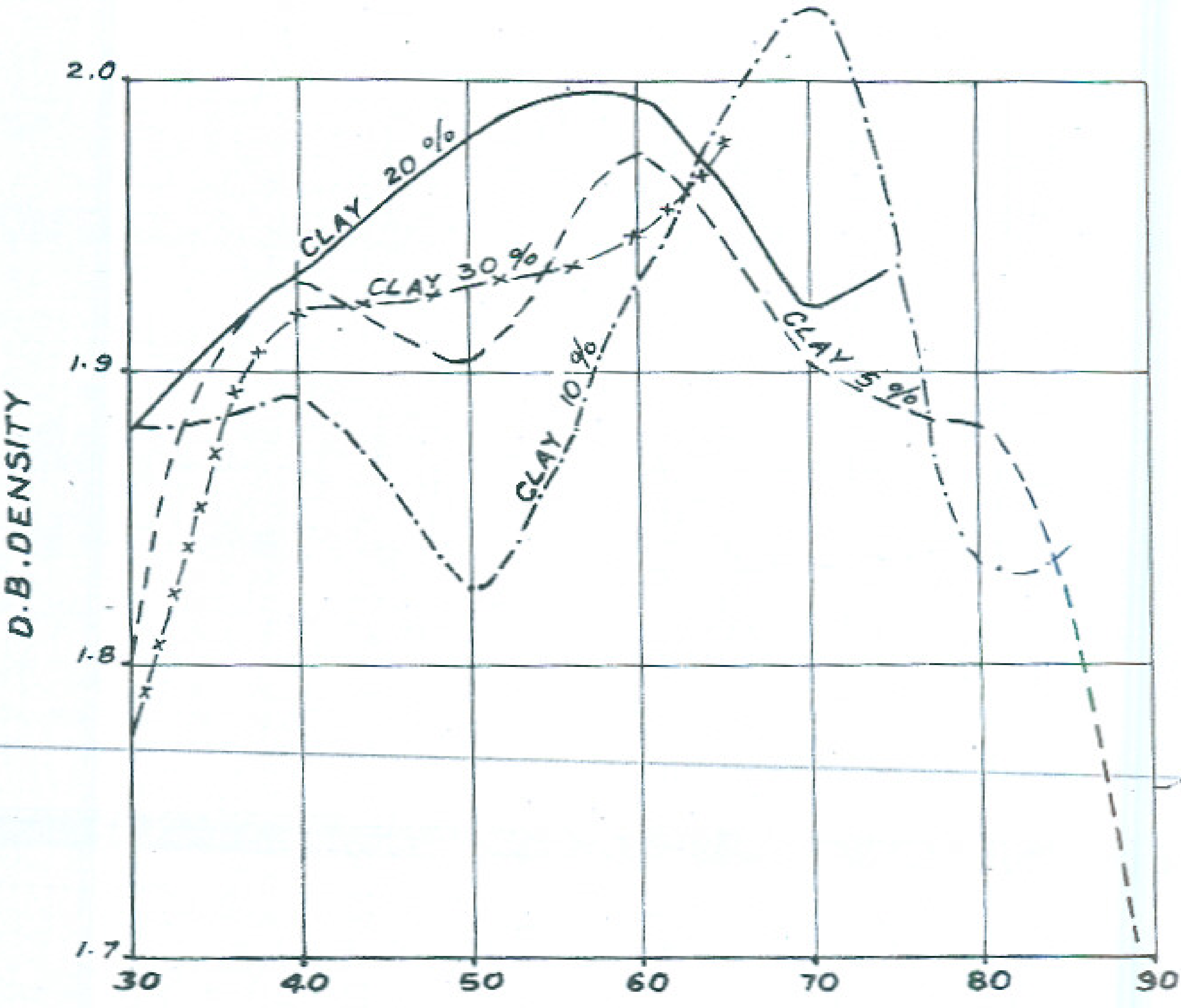



FIG (5)

# EFFECT OF DRYING SOILS

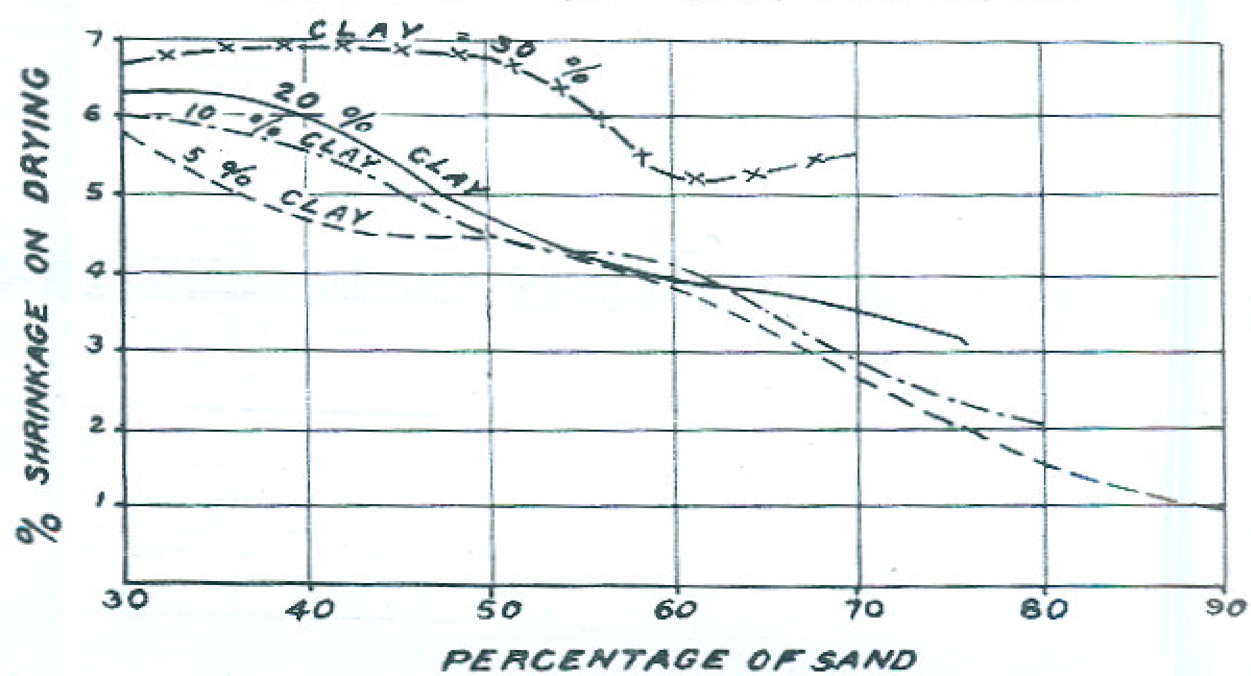



FIG (6)

# GRAPH SHOWING CORELATION BETWEEN OPTIMUM MOISTURE CONTENT & THE SOIL CONSTITUENTS

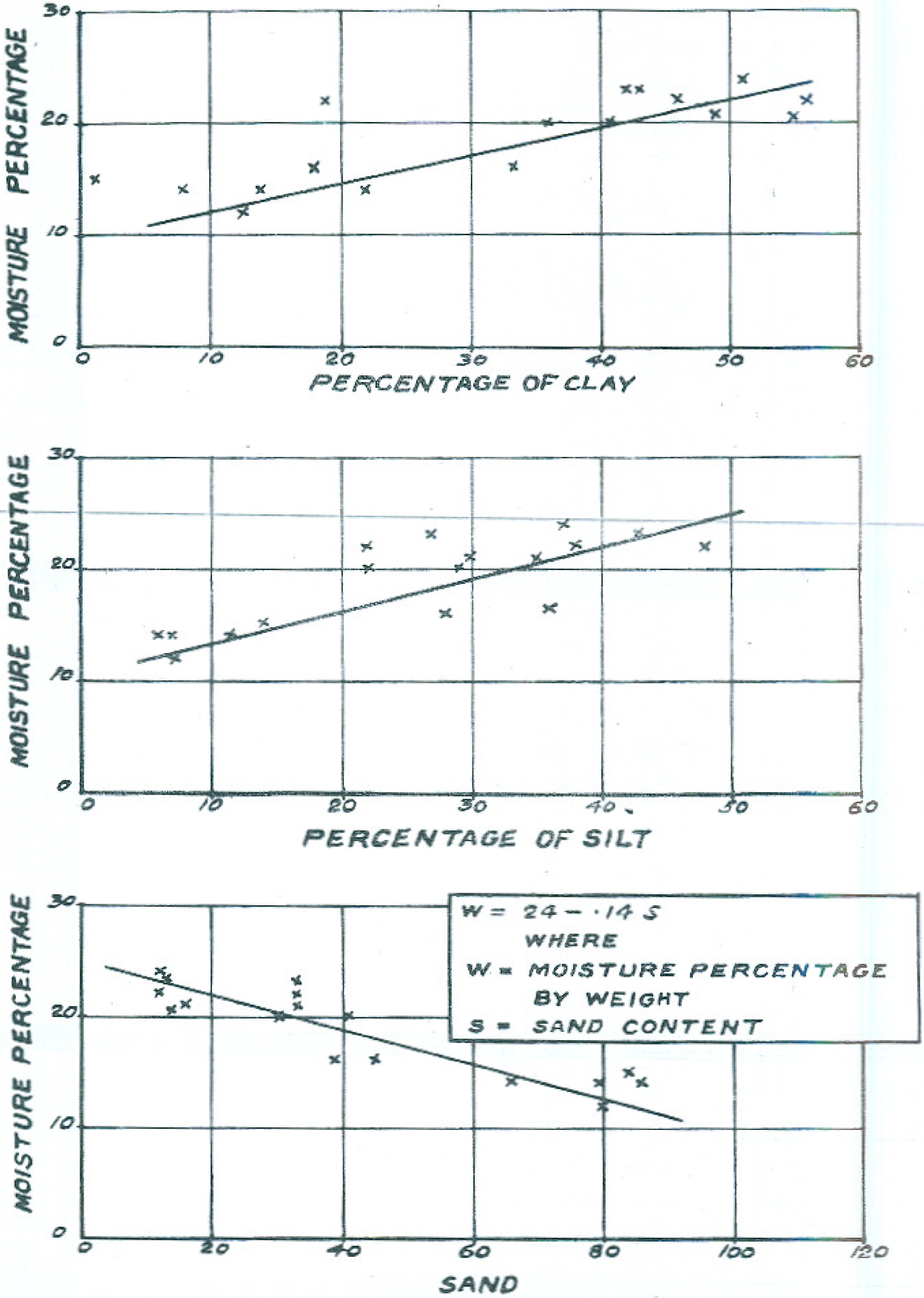



FIG (7)

# GRAPH SHOWING THE DISTRIBUTION OF MOISTURE IN THE SOIL

| DEPTH BELOW N.S. | CLAY | SAND | SILT |
|---|---|---|---|
| 0 | 20·2 | 50·7 | 29·1 |
| 1 | 5·7 | 84·3 | 10·0 |
| 2 | 10·5 | 69·9 | 19·6 |
| 3 | 19·2 | 46·8 | 34·0 |

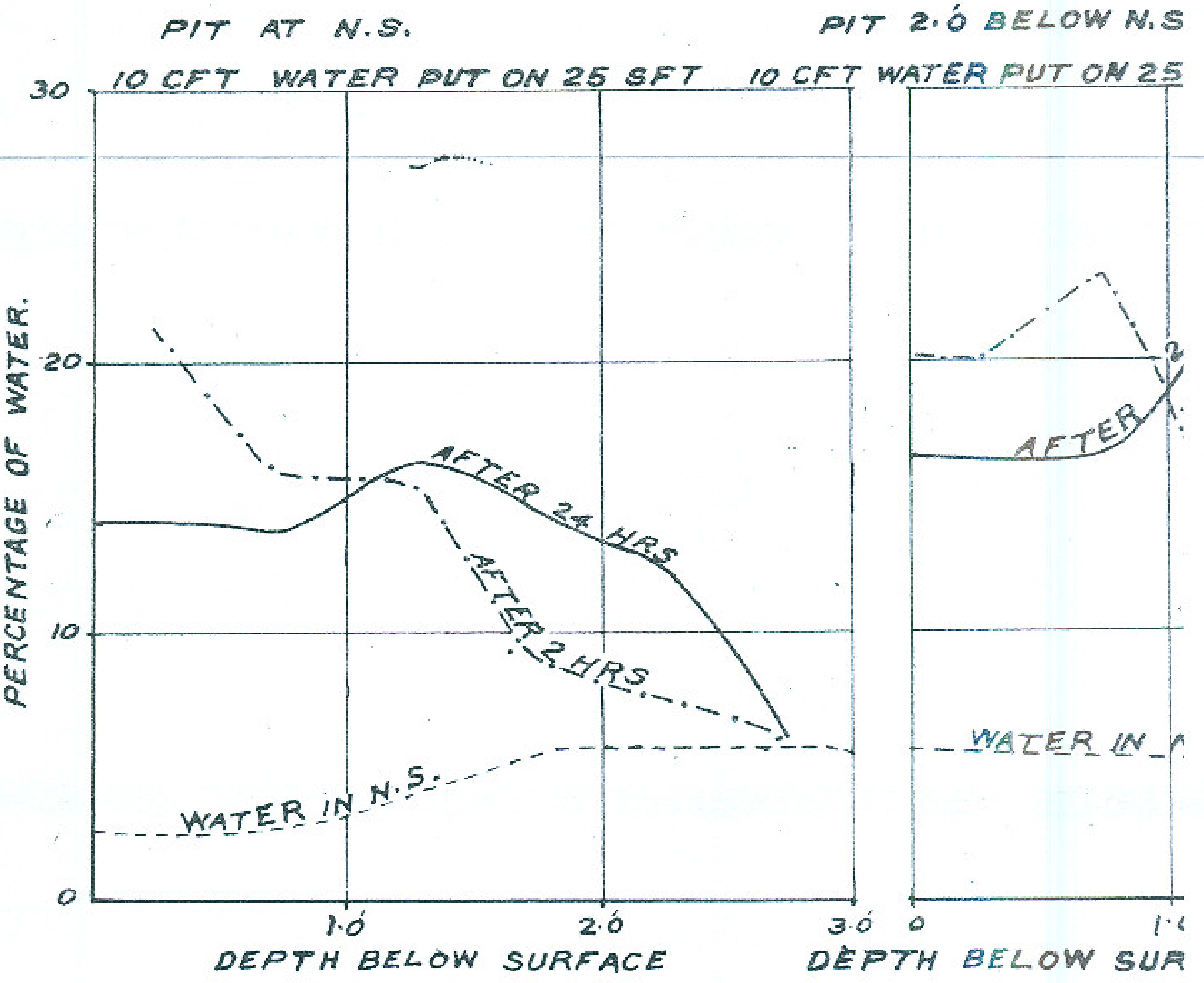



FIG (8)

# ROLLING 6" LAYER WITH DEFFERENT ROLLERS

SAND 30 TO 60% — CLAY 15 TO 30% - - - -

SAND 5 TO 20% — CLAY 50 TO 75% ———

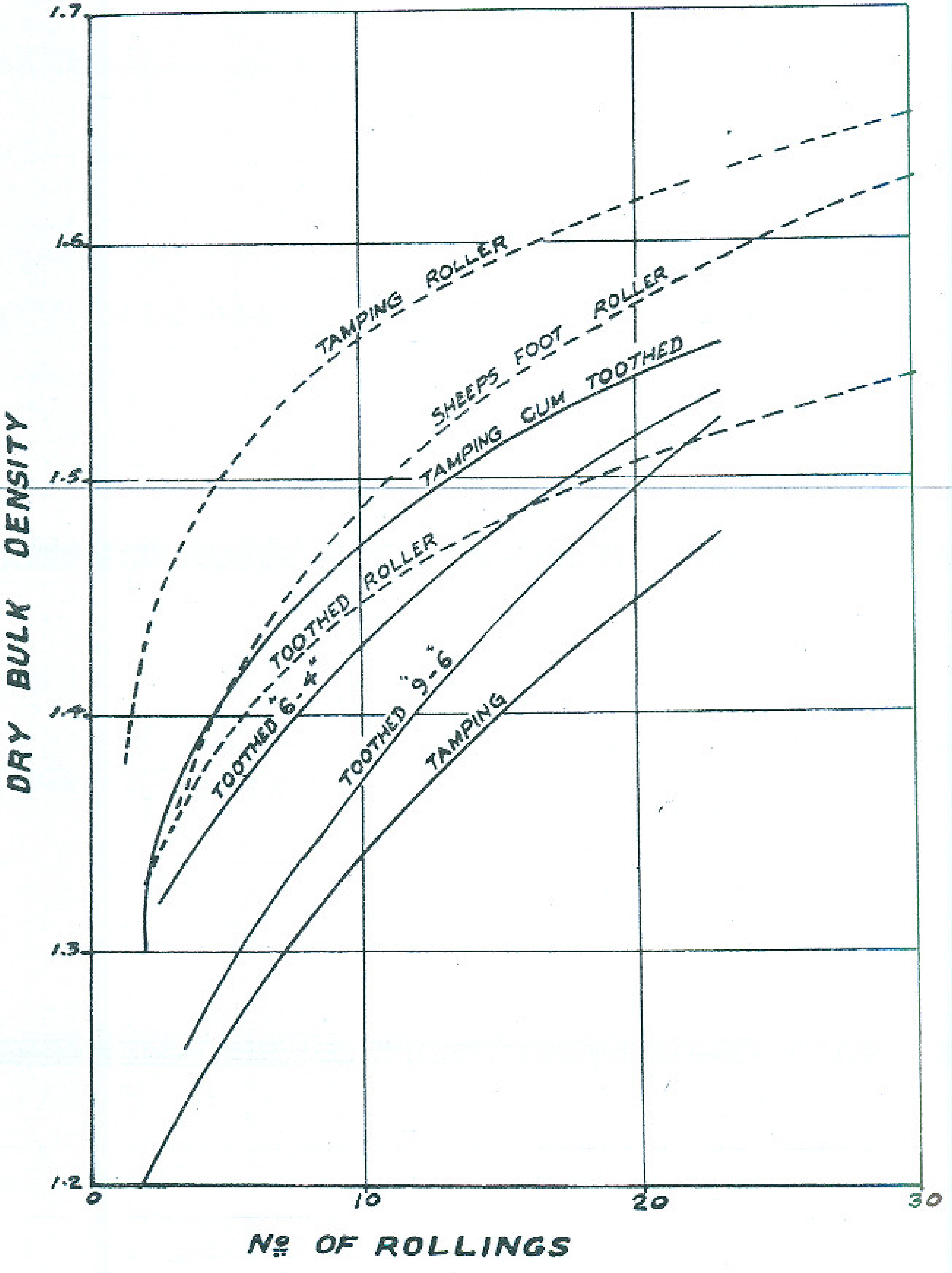
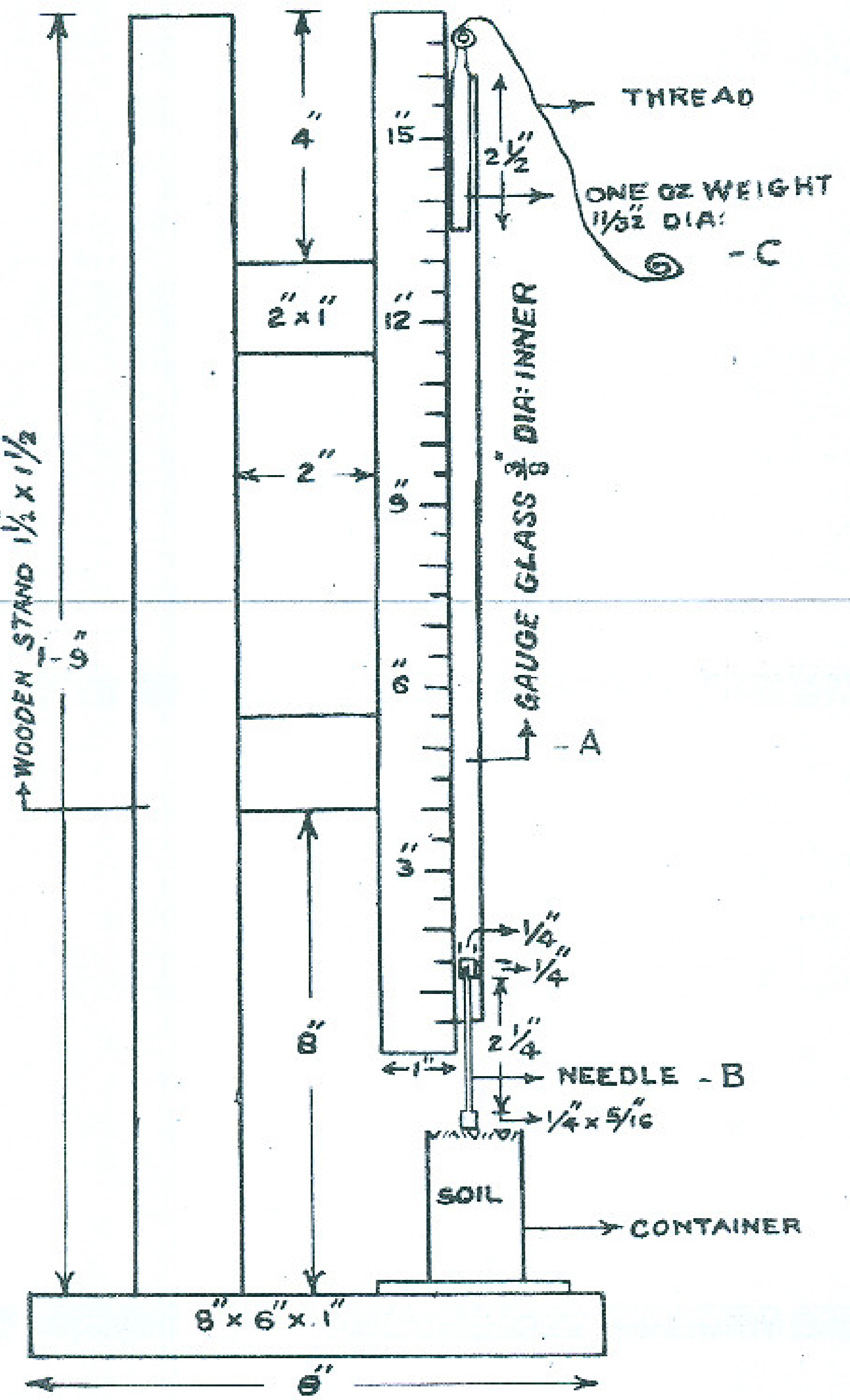
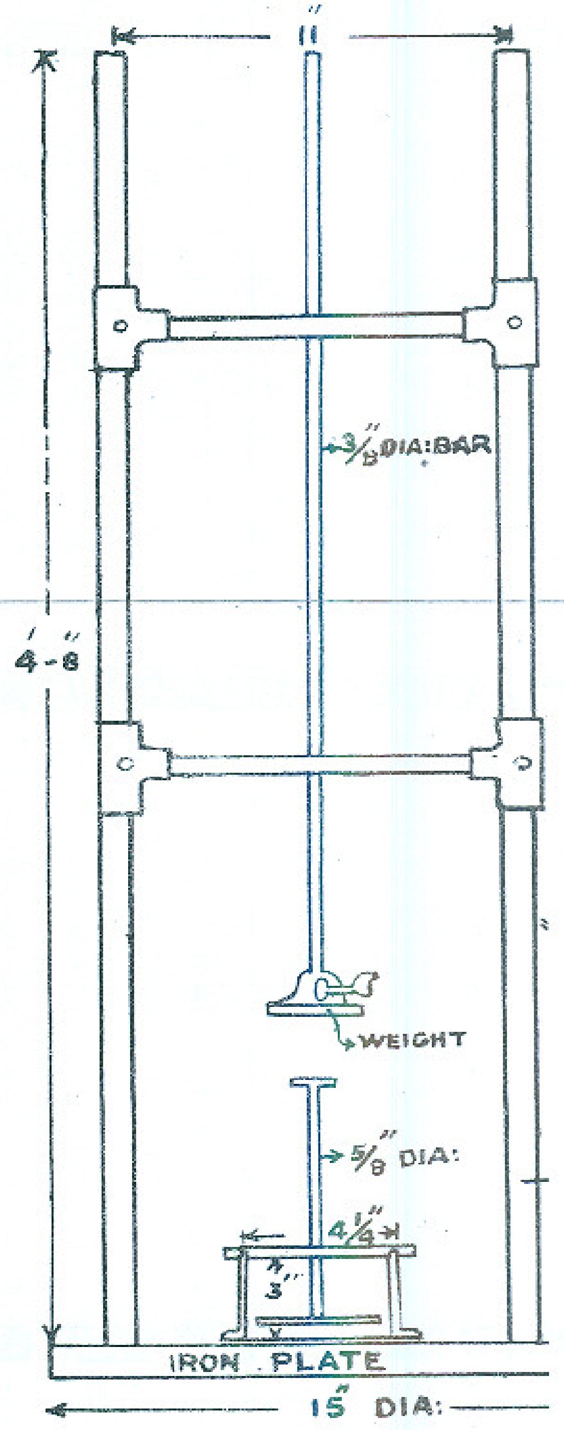



FIG: (9)




PENETROMETER




MODIFIED COMPACTION APPARATUS

PLATE II
PAPER No. 257

# DETAILS OF ROLLERS

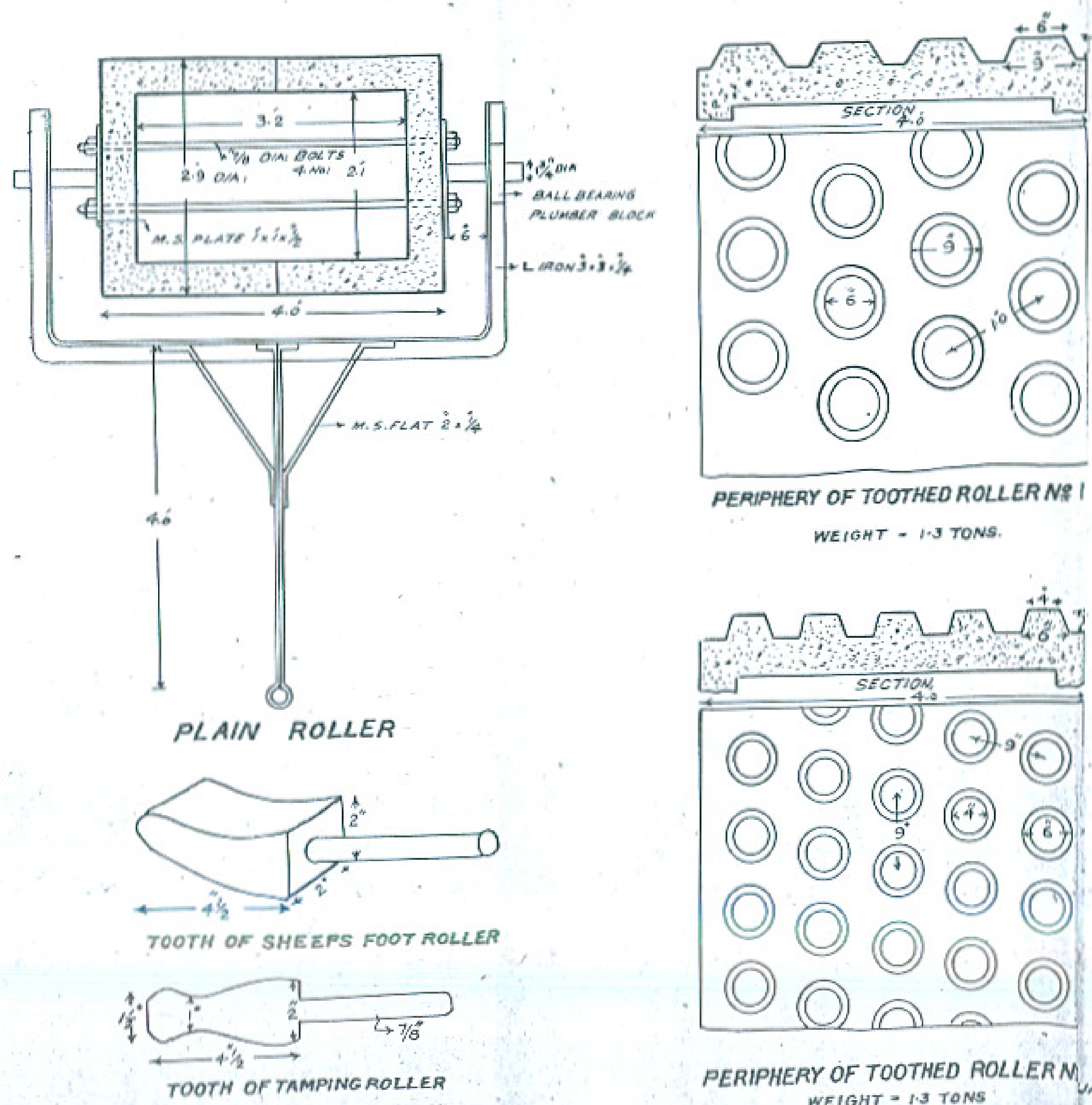



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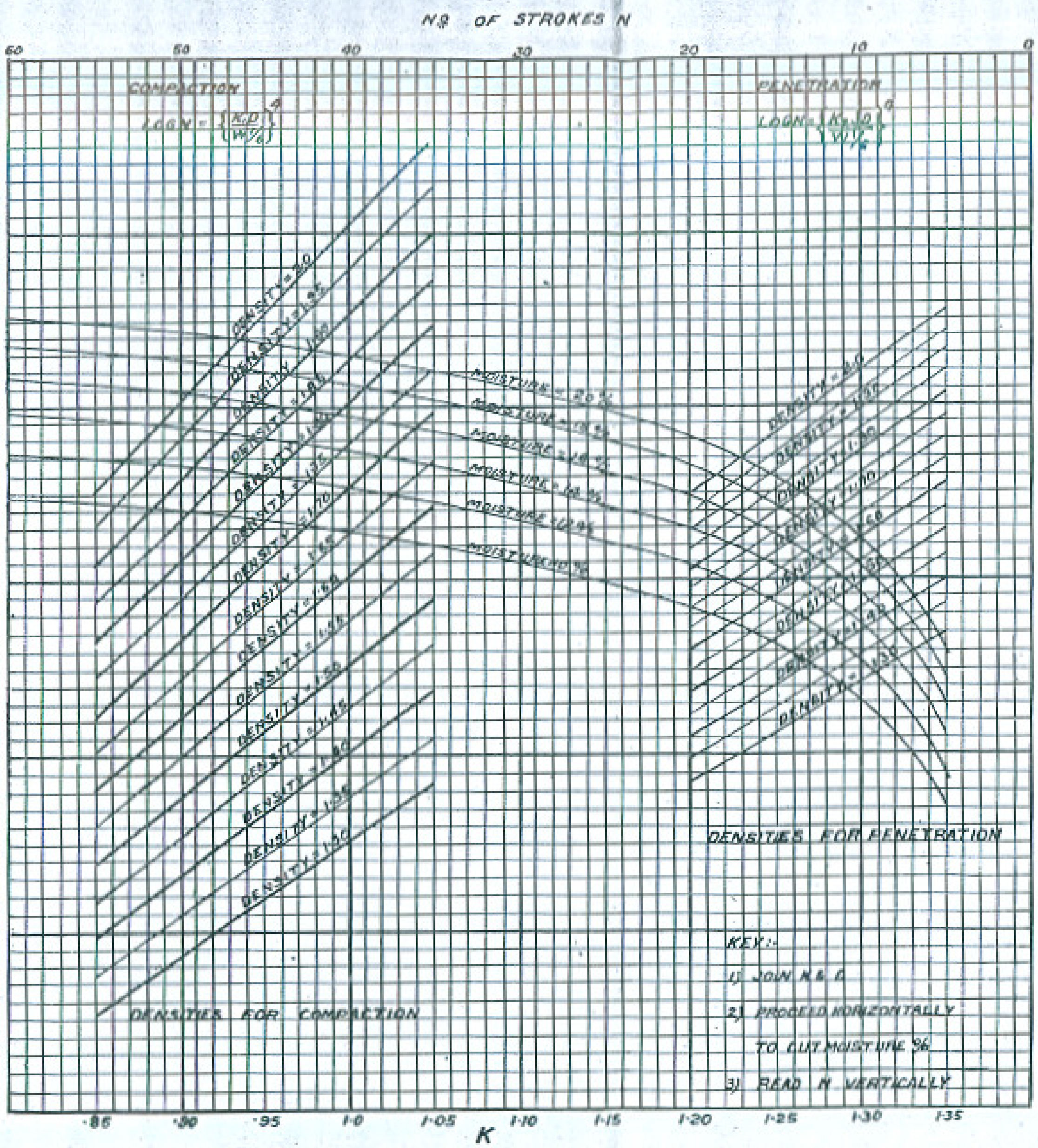
PLATE III
PAPER No. 257

# GRAPH SHOWING COMPACTION & PENETRATION OBTAINED IN THE LABORATORY

AREA OF CYLINDER 89 SQ C. M.
WEIGHT OF SAMPLE 600 GMS.




VALUE OF K

| CLAY % \ % SAND | | 30 | 40 | 50 | 60 | 65 | 70 | 75 | 80 | 85 | 90 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 5 | $K_1$ | ·96 | ·97 | ·89 | ·85 | | ·86 | | ·91 | | 1·00 |
| | $K_2$ | 1·25 | 1·32 | 1·295 | 1·27 | | 1·22 | | 1·22 | | 1·27 |
| 10 | $K_1$ | 1·0 | ·93 | ·95 | ·87 | | ·87 | | ·92 | ·92 | |
| | $K_2$ | 1·3 | 1·295 | 1·26 | 1·25 | | 1·25 | | 1·26 | 1·29 | |
| 20 | $K_1$ | 1·0 | ·93 | ·90 | ·88 | | ·91 | ·91 | | | |
| | $K_2$ | 1·3 | 1·26 | 1·25 | 1·24 | | 1·23 | 1·24 | | | |
| 30 | $K_1$ | 1·0 | ·98 | ·93 | ·93 | ·90 | | | | | |
| | $K_2$ | 1·3 | 1·28 | 1·27 | 1·25 | 1·255 | | | | | |

D = DRY BULK DENSITY
W = MOISTURE %
N FOR COMPACTION:-
No. OF STROKES WITH 2 Lbs. WT. LENGTH = 1·0
N FOR PENETRATION:-
No. OF STROKES WITH ONE OZ WT. DROPPED FROM 1·0 HT. TO PENETRATE 1" BY A 1/4" DIA: NEEDLE

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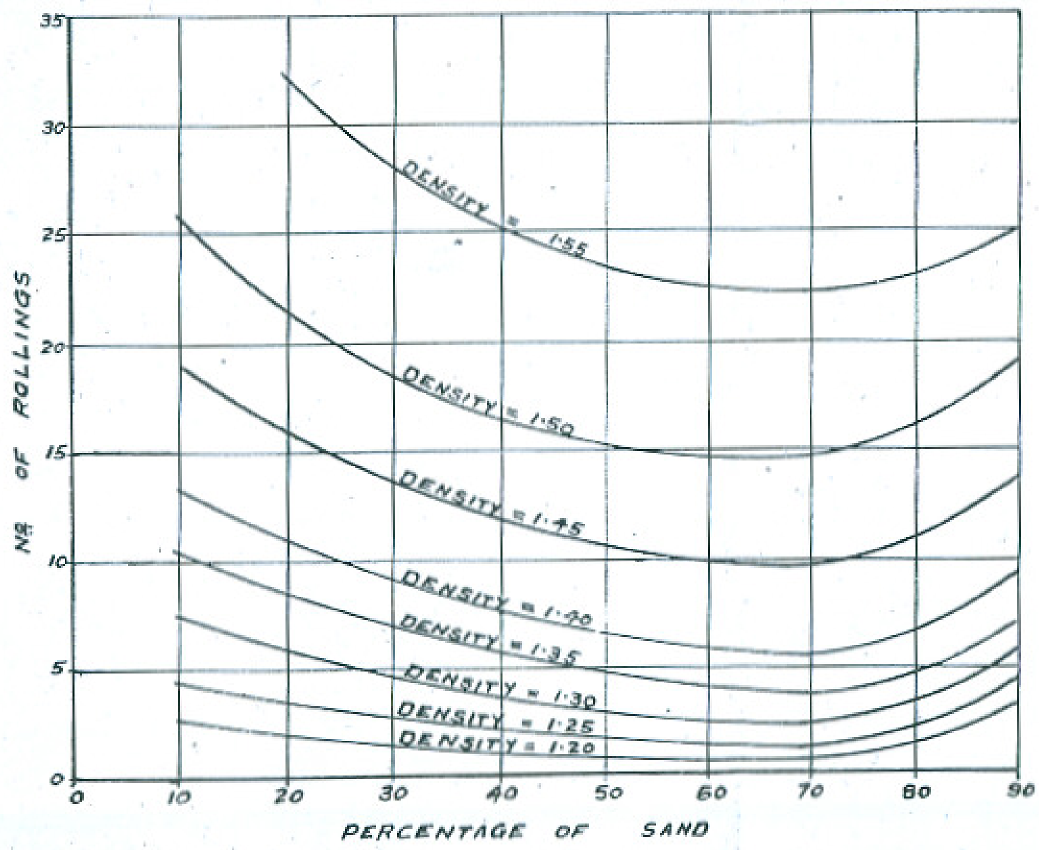
PLATE IV
PAPER No. 257

# EFFECT OF ROLLING

WITH A TOOTHED ROLLER 6"x4" KNOBS

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## DISCUSSION

The AUTHOR in introducing his paper remarked that the paper dealt essentially with the methods evolved for the formation of compact banks without the aid of mechanical tractors, which might not be easily available.

In general, compaction was dependent on—

(*a*) The nature of soil, and its grading;
(*b*) moisture content;
(*c*) thickness of the layers in which the earth was placed;
(*d*) The size, type and method of operation of equipment used in compaction; and,
(*e*) uniformity in the mixing of constituents, wherever this had to be done.

The grading of the soil had a very important effect on the densities obtained, as had been shown in the paper, but in the case of construction of canal banks, any selection in this direction might not be practicable.

The moisture content had, of course, a very important bearing. There was a definite optimum moisture content for every soil which varied slightly with the extent of compaction required. A simple formula had been evolved for its determination, which was based only on the sand content in the soil and thus afforded a rough and ready method of calculating the quantity of water to be added on to the borrow pit area.

In this connection, it might be observed that a popular notion for doing successful puddling was to allow water to a stand by making small dowels and dump earth in the same. This actually gave a very low density. Some puddling done on the Thal Main Line in this manner gave an average density of about 95 per cent. of the natural soil, whereas in the case of the experimental reach described in the paper, a density 106 per cent. of the natural soil was obtained by controlling the moisture content and adopting suitable compaction methods.

The thickness of a layer should not exceed twice the length of the teeth of the compacting roller to avoid undesirable stratification and a depth of 6 inches, as stipulated in the original I. B. Specifications, seemed to be the best.

The experiments described in detail in the paper showed that a 1·3 ton toothed roller, which could easily be pulled by two pairs of bullocks, would yield very good results under average conditions, and its adoption was accordingly advocated.

There were three generally accepted methods of compacting soils, *viz.* by the application of weight, impact and vibration. Of these, the application of weight was most suitable, where work had to be done by manual labour. In this connection the author mentioned a novel method of attaining compaction, which was still in an experimental stage, *i.e.* by the use of explosives. This, of course, had a limited application and was useful only in cases where a denser soil structure would be formed if the material was completely disturbed as in some saturated, loose deposits.

As a result of the experimental work done on the Thal Main Line, a set of graphs had been prepared to indicate the extent of rolling required in different soils for getting various densities. These, combined with the formula for optimum moisture content, should enable the methods outlined in the paper to be used, without setting up any expensive laboratories for all scattered jobs.

A scientific basis for deciding whether any hardness allowance should be paid in a certain reach or not, had also been indicated.

The presence of salts in the soil would naturally affect compaction considerably. Methods had been evolved by the Irrigation Research Institute for neutralising such salts, but these were naturally expensive and could be used only in the case of some highly important works, where cost might not be the primary consideration.

In his paper on soil stabilization, Mr. Mehra had advocated a 3-inch layer, of sand under the bank. Possibly a 6-inch layer would be better, but this would be useful only if the earth in the bank above the sand layer did not contain any salts.

A simple precaution that might be observed in the construction of banks in "kallar" soil, however, was not to use the top one-foot layer of earth, which had a comparatively higher concentration of salts.

Mr. F. F. Haigh stated that as he had already mentioned in his remarks on the Haveli Canal that morning, the idea of the experiments described so ably by Mr. Mahbub in his paper originated from experience on that work.

At the time of the Haveli construction the speaker was acquainted with Proctor's work in America and actually considered the possibility of using soil compaction methods on the Haveli Canal. The American technique, however, seemed to call for the use of heavy rollers operated by tractors and as it appeared that such equipment would be very expensive and impossible to obtain in time, he abandoned the idea.

When, however, the troubles due to settlement on the Haveli Canal became evident and the construction of lined channels on the Thal Project was contemplated, it seemed advisable to see if something could not be done on these lines to secure better work. For low canal banks, however, it was apparent that the high densities obtained in American dam construction were not necessary. A density equal to or slightly greater than that of the natural soil was considered sufficient for the purposes required and it was probable that this could be obtained by the use of light rollers drawn by bullocks such as could readily be obtained or manufactured in this country.

As a result, the experiments described in this paper were started and it would be agreed that they had been successful. Within certain limits of soil types, we were now in a position to produce a bank sufficiently consolidated for our purposes at a reasonable cost.

It had been said that a good deal of the work done in these experiments was very similar to work done in the Research Institute and elsewhere and was consequently unnecessary. His answer to that was that the details of previous experiments were not readily available and in any case, the repetition of the work was necessary to train the staff carrying out the work and equip them for further research.

Similarly, it might be said that much of the substance of the paper was not new, which was true, but Mr. Mahbub had, in such cases, acknowledged the source of the information. Much of this matter would, however, be new to many readers of the paper and its inclusion was justified in order to give a complete picture of the work and enable it to be understood.

Although the paper might be said to give a distinct advance in our knowledge of this subject, there was still plenty of scope for further research. The treatment of heavy clays and of salt bearing soils was particularly difficult. Practical methods of improving inferior soils by adding materials in which they are deficient were required. Mr. Mehra's paper gave some useful information on this, but the cost of his methods seemed to be high for canal work. The speaker hoped that research on these questions would be continued, both in the Research Institute, and by officers interested and that the results would become apparent in due course.

He trusted that members would find this paper as interesting as the work has been to those concerned with it.

R. B. Kanwar Sain, congratulated both Mr. Haigh and Mr. Mahbub for bringing forth this paper, before the Congress, on a subject which was so important in connection with the lining of canals. Starting with what had been done in America and in India in connection with roads, they had applied the methods to lining problem and had made suggestions which would be most useful in any earthen job of a big magnitude. Considering the importance of the problem, the paper might be classed as one of the best during this year.

After the Haveli lining had failed at a number of places during early 1940, the causes of such failure were investigated and a number of suggestions were made by various officers in the Department for further experiments to eliminate the possibilities of such failures in the future.

The speaker in July 1940 had noted as follows about the earth backing :—

Most of the trouble experienced on the Haveli Canal was due to faults in the backing. Any shrinkage or settlement of the backing must cause failure of the lining resting on it irrespective of the type of lining.

For compaction, experiments were necessary to determine the following :—

(*a*) Composition of the soil which would give a low coefficient of shrinkage and swelling.

(*b*) Critical moisture content for any particular soil.

During his visit of engineering works in America, the speaker had noticed that not a single big earth-work job was done without a Soils laboratory at site.

Moisture content was the most important to determine. He quoted from Hogentogler's "Engineering Properties of Soil", as follows :—

> "During shrinkage the contracting force increases as the volume decreases, but the friction between particles increases and causes the soil mass to offer greater resistance to further reduction in volume. Moisture helps to reduce this friction. When the resistance of the soil to further consolidation just equals the contractive effort of surface tension, a moisture content termed the 'shrinkage limit' is reached, at which shrinkage ceases.
>
> Below the shrinkage limit, the soil is in the solid state. Further evaporation causes the mobile moisture to recede in the pores, leaving only the very thin, more or less solidified films to coat the soil particles. The soil then changes in colour from dark to light but does not appreciably decrease in volume".

This emphasised the necessity of determination of optimum moisture contents, which could be done for each particular soil in the laboratory.

In America, in earth dams the practice was to consolidate with sheep's foot rollers which were power driven. He remembered along with Mr. Khosla having roughly calculated the pressure on the leg of a donkey and they came to the conclusion that the pressure exerted by the sheep's foot rollers was approximately equal to the pressure exerted on the foot of the loaded donkey. Thus any earthwork done in layers by means of donkey labour got the necessary compactions, provided it contained the optimum moisture and the donkeys were made to travel over the fresh earthwork.

It had not been possible for the speaker in the time at his disposal to subject the details in the paper to a critical study which a paper of this kind deserved. It could, however, easily be seen that the ground covered by the paper was exhaustive and the conclusions arrived at very valuable for Indian conditions.

The speaker suggested that a 'Soil laboratory' should be provided at site on every big earth work job where compaction was desired. He also recommended a careful study of the "Engineering Properties of Soil" by Hogentogler, to every Engineer who was interested in soil problems. The Author had followed in the paper the same nomenclature and relationships in general as had been used by Mr. Hogentogler. This made it easy to study the two side by side.

Mr. C. L. Handa observed that the subject of compaction of Soils with regard to the lining of canals or for bedding of concrete or masonry on earthen formation was most important and the paper embodied the results of pioneer experiments. There were a couple of points to which he invited attention. Firstly, the composition of the soil was a very important factor, and the speaker considered, that the problem of producing compacted banks in such cases, was more complicated than had been envisaged by the Author. For example, one could quote the reach near R. D. 2,15,000 of the Haveli Canal, where it was impossible to make the soil cohere in a homogeneous mass with any amount of moisture and "wriggling." On one occasion, it was required to produce puddle with this soil, and it was seen, that the little lumps of soil would not join together, even after two months' wetting and pugging. This was probably due to the salts in the soil composition, which prevented absorption of moisture. His second point was, that an artificial admixture of sand would not be a practicable proposition.

The speaker concluded by saying, that further field experiments on a large scale were necessary and desirable, and it was quite certain that specifications including compaction would lead to sounder work so far as lining of Canals was concerned.

Mr. G. R. Sawhney congratulated the Author on his great effort to solve one of our everyday problems. His vivisection of the soil with a view to determine mechanical stabilization including compaction and densification reminded him of a couplet :—

"Errors like straw upon the surface blow.
He who would search for pearls must dive below."

Reading the nomenclature and glancing at the first page of the paper, he thought here was some common sense and simple advice, but shock followed shock soon after turning over the first page and he then realised how complex and complicated the simplest problems of life could be made to appear when an ingenious mind got down to look into the pros and cons of the minute details concerning them

The conclusions arrived at about the moisture content at which compaction was the maximum for every soil and that for every density each soil had a particular stability were indeed very useful and also was the evolution of tooth and tooth cum tamping rollers.

He doubted, however, if all this probing into the dark was necessary, as the Author himself had to discard most of the conclusions derived from his experiments.

He presumed that for new excavations on the Thal Project, soil surveys had been done. He would like to know what would happen if the contractors challenged the rates given in their work orders when the soil was not in accordance with the actual densities of, the soil they had to dig.

Working on 6″ layers continuously and then waiting for the next layer to be put after the rolling had been done, was not going to be very congenial to the contractors who carried out the earthwork at Rs. 3/8/- per thousand cubic feet. Although it should be quite practical to do such densification for the banks of a reservoir or even for a short canal reach, the speaker very much doubted if long lengths could be so well done by men who in the past had not even been breaking clods. He was sure that for the quality of work that would be required in order to conform with the specification given by the Author very much higher rates would have to be paid.

Considering all these aspects, if densification of banks was to be done on a large scale then it would be more economical and satisfactory if the compaction were done by tractors, in the speaker's opinion.

The AUTHOR replied to the discussion and remarked that Mr. Haigh had explained why it was necessary to include a portion of the accepted theory on the subject in the Paper. This was intended to save members reading a lot of literature and also served as a background for a proper appreciation of the experiments conducted and the results obtained.

Mr. Kanwar Sain had emphasised the importance of having soil laboratories at site on every big earthwork job, where compaction seemed desirable. These laboratories would certainly be useful for analysing the soil and determining the optimum moisture content accurately. It might not, however, be practicable to have laboratories for isolated, scattered jobs and simple formulæ had accordingly been given, which would lead to a fair approximation.

Mr. Handa had invited attention to two points, *viz* :—

(*i*) The composition of the soil had an important bearing on the compaction obtained.

(*ii*) Artificial admixture of sand would not be a practicable proposition.

Of these, (*i*) had been dealt with under effects of grading on page 158 and (*ii*) was exactly what had been stated on page 165. No further comments on these would, therefore, appear to be necessary.

Regarding his having been unable to cohere the soil at R. D. 2,15,000, Haveli Canal, into a homogeneous mass with any amount of moisture, the Author considered that much better results would have been obtained if the optimum amount of moisture had been used and if rolling with toothed rollers had been adopted.

The Paper did not deal with the stabilization of soils and further experimental work was necessary in connection with the treatment of heavy clays and salt bearing soils by the addition of certain materials, as indicated by Mr. Haigh in his remarks.

Regarding Mr. Sawhney's remarks, the Author was sorry to learn about the shocks which he seemed to have received. It appeared that these shocks had made him unable to go through the whole of the paper, but if he had persevered and seen the last two pages, which described in a nut-shell how the results arrived at by the experiments could be used in a simple, straightforward manner to get denser banks without incurring any extra cost, possibly he would not have considered the subject to be so abstruse and complex.

Mr. Sawhney had expressed the opinion that higher rates would have to be paid if work were done by these methods. Actually, however, about 10 lacs cubic feet of earthwork has been done in a length of 4,000 feet at scheduled rates without any difficulty. As a matter of fact, the hardness allowance which would normally have had to be paid in this case, had been saved since no such allowance was necessary due to the soil having been previously moistened. Moreover, no clod-breaking had to be done by the labour as was necessary in the case of ordinary earthwork, due to the use of rollers.

Mr. Sawhney had also expressed the opinion that if densification had to be done on a large scale, it could be carried out more satisfactorily and economically by the use of tractors. That it could be done more satisfactorily was certainly beyond doubt, as had been mentioned in the Paper, but the main point was that it was not easily possible to arrange for tractors and the work done with these was also more expensive. As a matter of fact, one of the main ideas behind the work described in the Paper was the evolution of methods in order to secure proper consolidation without the use of tractors.