ROLE OF COMPACTION OF SOILS FOR EARTH DAMS

A Dissertation

Submitted in partial fulfillment of the requirements for the

DEGREE OF MASTER OF ENGINEERING

in

WATER RESOURCES DEVELOPMENT

By

G.N. SUBRAMANYAM

WATER RESOURCES DEVELOPMENT TRAINING CENTRE
UNIVERSITY OF ROORKEE
ROORKEE (INDIA)

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1967

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This is further to certify that he has worked for a period of 9 months from October 1966 to July 1967 in connection with the preparation of this Dissertation.

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Continued in next page

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ROORKEE

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S Y N O P S I S

Compaction of soils has an important role in earth dam construction. It has engaged the attention of several research workers and field engineers in this country.

This dissertation presents a detailed review of the upto-date literature on the subject.

A general introduction is made by specifying the compaction characteristics of soil and by tracing out a brief history of the development of the subject. The existing theories of compaction have been reviewed. Methods of laboratory tests in vogue and the new trends are also discussed. The study includes the precautions essential for a correct qualitative estimation of compaction characteristics. The engineering properties of soil are found to alter with the various factors affecting compaction. A detailed study is made to enable the design engineer to decide the best method to attain desired properties. The different kinds of equipment available for use and their relative behaviour for compacting the soil is also discussed. Due to the hetrogenuity of soils in nature, Compaction methods are to be modified to suit the individual characteristics. This study would be useful to decide the best mode of compaction to give desired results economically. All the same it is essential that a proper quality control is exercised during execution to attain these properties. Methods of quality control are discussed. New methods that are being developed to overcome the shortcomings of the existing ones are mentioned. An analysis of the characteristics of individual

groups of soils with particular reference to Madhya Pradesh soils is made. For Madhya Pradesh soils, few correlations and generalisations of compaction characteristics are attempted.

General conclusions and scope for further work are given at the end.

CHAPTER 1

COMPACTION OF SOILS AND ITS CHARACTERISTICS

1.1. From an Engineer's view point soil is a material by means of which and on which a structure is built. In earlier days the design and construction was based on empirical methods. With the advancement of soil science a well reasoned out design, better construction and a realistic estimation of the post construction behaviour of structure is possible. This soil science termed soil mechanics though of recent origin is developing at a rapid rate. This necessitates a need for perfect understanding of the subject to keep pace with modern methods.

1.2. CONCEPT OF COMPACTION OF SOILS

Soil mass, as is well known consists of a skeleton of solid particles, enclosing interspaces filled with air or water or both. It has thus three phases. In granular soils due to massive individual grains volume of voids is relatively small. In soils with honey combed or flooculant structure greater voids do exist. In a denser state the soil has greater strength lesser permeability, lesser shrinkage in addition to greater weight per unit volume than in the normal state. These are the pre-requisites for a good construction particularly in case of earthen embankments. The process of achieving this dense state is thus of greatest significance and is termed COMPACTION.

1.3. COMPACTION OF SOILS

Compaction of soil is thus an artificial process of reduction of voids to increase its density. The soil particles are constrained to pack more closely together through a reduction in the air voids. This increases the electro-static forces of attraction between the particles at their bonding.

Thus the cohesion and the overall shearing strength of soils is enhanced.

1.4. O.M.C. & M.D.D.

Compaction of a soil depends fundamentally on the resistance offered by its clods to break into finer particles so that they can be rearranged to a compact state. A certain amount of moisture is found essential to coat individual particles for readjustment. With higher moisture, soil particles are kept far apart from each other and hence densification is not possible. With very little moisture, soil forms into clods and again it is not possible to compact fully.

Thus it is seen that during compaction of soil the density is less at little moisture. But with higher moisture, density of soil goes on improving. After a certain stage, with further moisture the density is further lessened. The moisture content (which is the bulk weight of water expressed as a percentage of weight of dry soil) at which the maximum density is achieved is termed as the OPTIMUM MOISTURE CONTENT (O.M.C.). The dry density achieved at this O.M.C. is known as MAXIMUM DRY DENSITY (M.D.D.).

1.5. CHARACTERISTICS OF COMPACTION (38, 77, 78, 31)*

1. In the process of compaction it is not found practicable to remove all air. At lesser air contents, water and air in combination tend to keep particles apart and prevent any further decrease of air content. A limiting degree of saturat-ion is thus reached. Some air particles are entrapped and left surrounded by pore water. No further compaction can improve the degree of saturation. The dry density moisture curve thus approaches the

* Figures in parenthesis indicate the corresponding reference

saturation line but never reaches it. The drooping side of the curve is thus almost parallel to saturation line. (Fig.1)

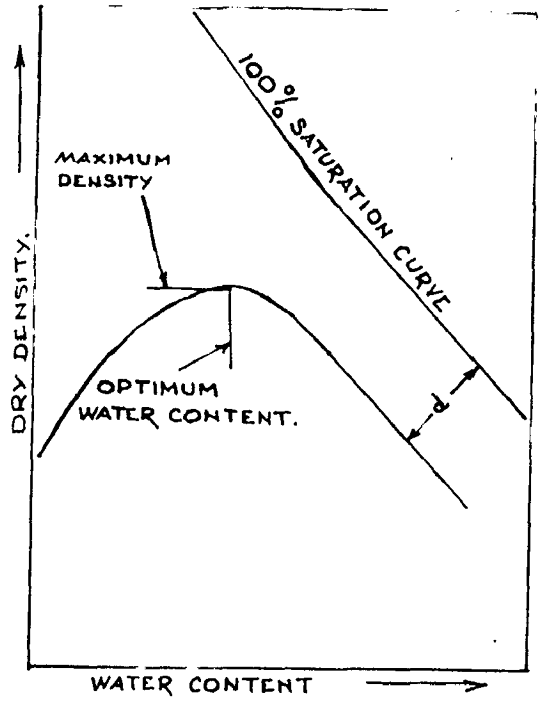
2. The O.M.C. is generally found to vary as much from 4 % to 30 % and M.D.D. from 140 to 70 lbs/cft for coarse to finer soils respectively. O.M.C. is generally about 2 to 5 % less than the plastic limit.

3. An increase in the compactive effort would naturally bring the particles more closer even with less moisture. Thus as compactive effort is increased the maximum dry density is increased but the optimum moisture content is decreased.(FIG.2)

4. To obtain higher density, it is better to increase compactive effort than to increase the number of repetitions during compaction of the same compactive effort. This is particularly more effective on the dry side of the O.M.C. (Fig.3) as on wet side for different compactive efforts, the density does not vary much.

5. The curve joining the points of O.M.C. for different compactive efforts is found to be parallel to zero air void curve and all the compaction curves are found to be of similar shape. The distance of the compaction curves on wet side of O.M.C. to the zero air void curve indicate the amount of entrapped air. (Fig.4).

6. Due to the coarser gravel particles the density is improved from that of finer fraction only. (Fig.5). With increasing coarser material (+3/16" material) density increases till it reaches a percentage of 70 to 80 % and then starts decreasing. Hence a theoretical upper limit of the percentage of gravel does exist.



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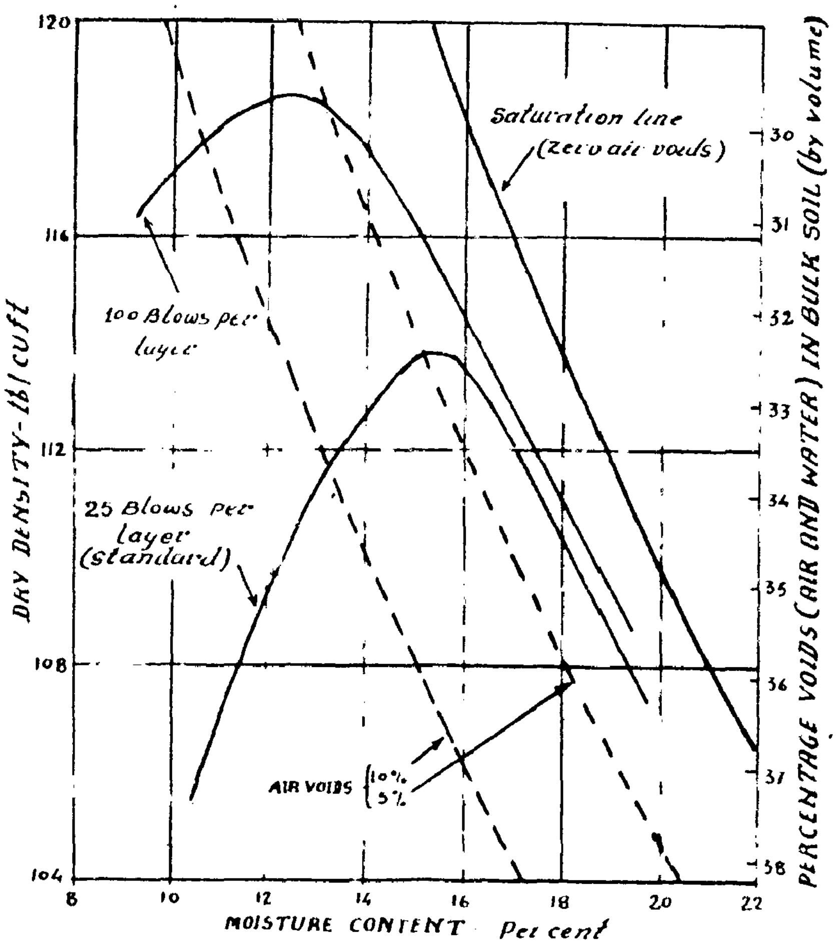

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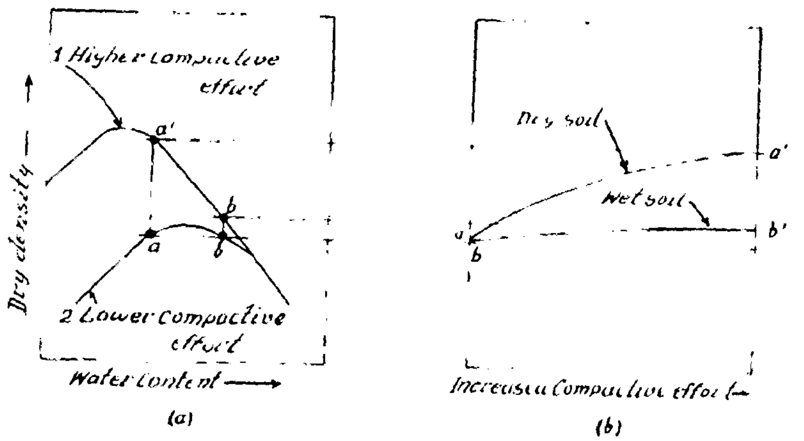

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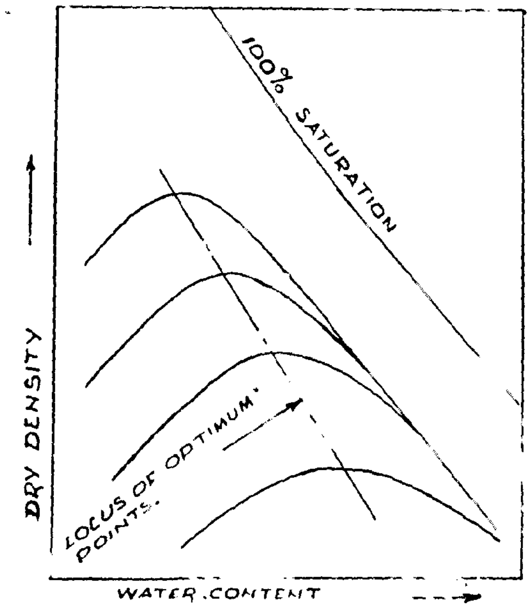

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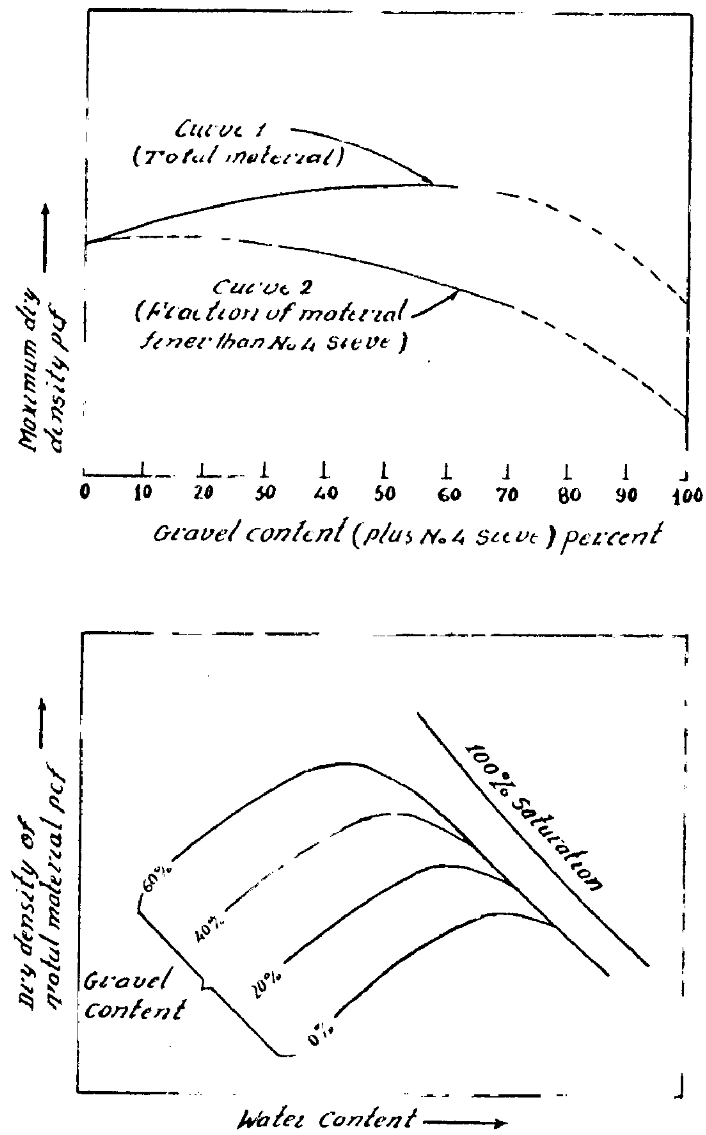
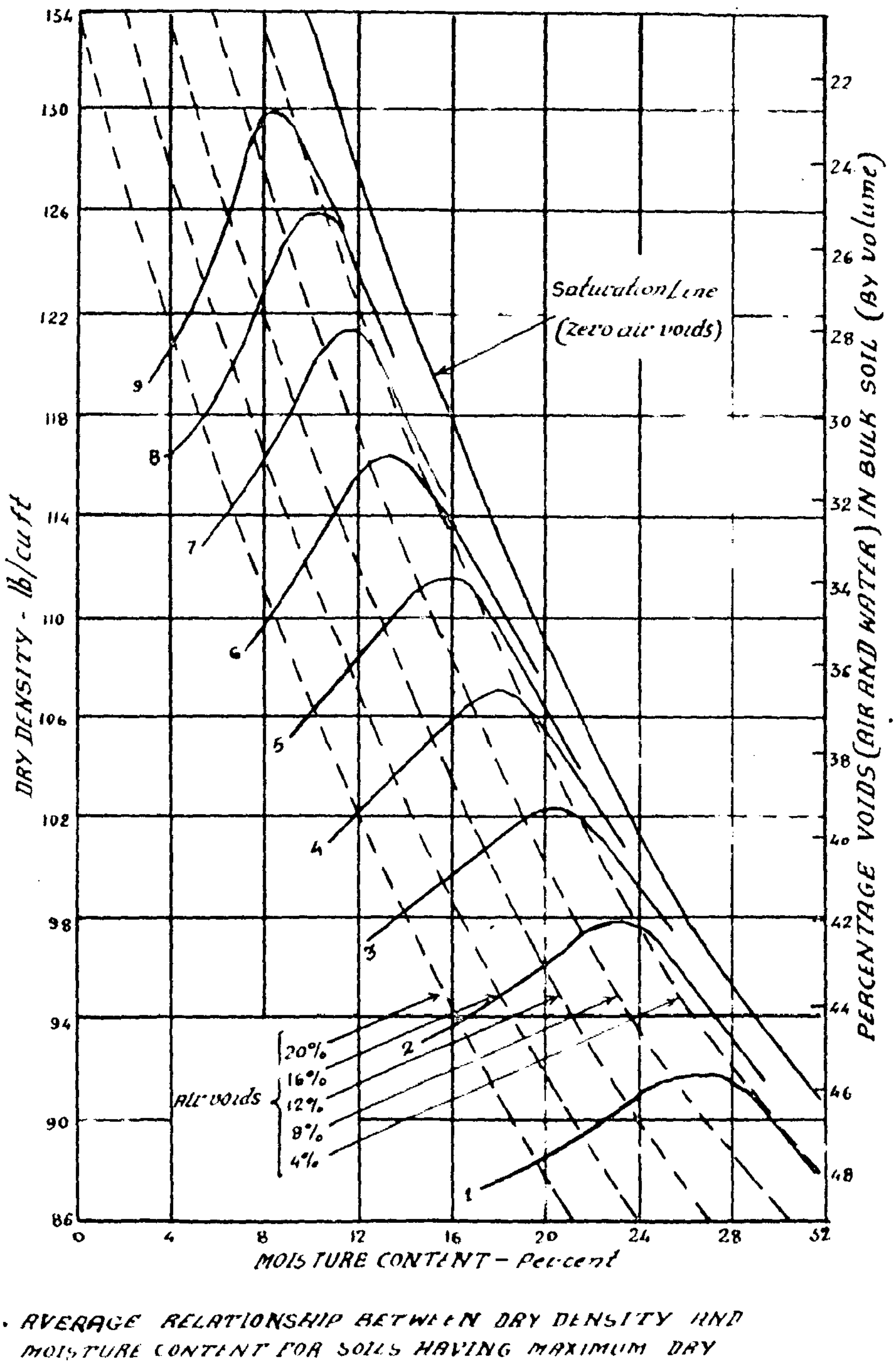


5. Relationship between density and gravel content for course, impervious soil with single compaction effort.



6. AVERAGE RELATIONSHIP BETWEEN DRY DENSITY AND MOISTURE CONTENT FOR SOILS HAVING MAXIMUM DRY DENSITIES DIFFERING BY 5 LB /CU FT

7. For uniformly graded soils, a flat curve and for well graded soils a compaction curve with well defined peak is observed.

8. Typical dry density moisture curves from the average test results on 1383 Ohio soils by K.B. Woods are indicated in Fig.6. It is generally seen that the peaks of curves are at about 5 % air voids.

1.6. COMPACTION AND CONSOLIDATION

The compaction is thus an artificial process of eliminating air voids to increase density by dynamic loading or by kneading or by static loading. After compacting the soil voids are filled with entrapped air and water. When this soil is subjected to a superimposed load continuously, the soil starts consolidating. The moisture in the soil would cause pore pressure. If drainage is possible, the water with entrapped air escapes gradually reducing the pore pressure and causing an increase in effective pressure on soil grains. Finally at infinite time the soil takes up the entire load with reduction of pore pressure to zero. This natural process of expulsion of entrapped air and water slowly due to the static load from soil mass is known as consolidation of soil as compared to the compaction process of increasing density by expulsion of air by artificial means. By the process of compaction, the void space in the soil mass is reduced to a minimum. This densification leads to optimum values of shear strength parameters, C & ϕ for the given soil. However, the shear strength depends on intergranular stress - and the process of compaction of moist soil together with superimposition of subsequent layers of earth work develops considerable pore pressures in the soil mass and reduces effective pressures. The process of consolidation takes place gradually leading to the dissipation of these pore pressures and increased shear strength in the soil.

1.7. BRIEF BACKGROUND OF HISTORY OF COMPACTION OF SOILS

Earth dams are constructed and used since the early ages of civilisation. The most ancient dams are supposed to have been built in India but the methods adapted are not easily traceable. A 40' to 90' high dam was completed in Ceylon in 1200 A.D.

The earliest record of the old dams (90) is in Wegman's "Design and Construction of Dams " *wherein it is described that old dams are simply large mounds of argillaceans earth which was brought in baskets to the site of the dam and was compacted by the tread of army of workmen engaged on work.' 15' to 30' high embankments were constructed at about 500 B.C. In 1789, a 150' high dam was constructed in Spain requiring 34 years for work.

At the end of 19th century James D. Shuyler writes in "Reservoirs for Irrigation Water Power and Domestic Supply" that "In building earth dams of any type, the earth should be moist in order to pack solidly and if not naturally moist, should be sprinkled slightly until it acquires proper consistency. An excess of moisture is detrimental. It should be thoroughly rolled or tamped and the surface of each layer should be roughened by harrowing or mixing before next layer is applied. Droves of cattle, sheep or goat are often used with success as tamping machines for earth embankment. They are led or driven across fresh made ground and the innumerable blows of their sharp hoofs pack the soil very thoroughly". In 1901 a Committee of Consultants had given the conclusion," the maximum height to which an earth embankment, with its top 20 feet above the water line and with outside slopes 2:1 can be built with safety is 70'." The following list of dams constructed (43) indicates the pace of development:-

Name of the Dam	Height in Feet	Year of Construction
Madduk -Masur Dam	108	1500
Druid Lake Dam	119	1871
Terrace Dam (Colorado)	180	1909
Tienton Dam	230	1925
Winsor Dam	295	1940
Anderson Ranch Dam	455	1950
Trinity Dam in U.S.A.	537	1960

Oroville Dam (in U.S.A.) (730' high) and Nurek Dam in U.S.S.R. (990' high) are now reported under construction.

With the development of automobiles in the early 20th century, the necessity of compaction for roads to prevent excessive settlement of uncompacted fill, was keenly felt. The increased activity of earth dam construction provided an additional incentive for development of compaction methods to satisfy the requirements economically and efficiently.

In 1906, the tamping feet of a flock of sheep crossing a scarified, oil treated road in Southern California provided the idea for a sheeps foot roller for compacting soil. In 1912, the first S.F. roller with a unit pressure of 75 lbs/□" was brought to use. The Echo Dam (1928) on Weber River was the first dam to be completely compacted by a sheep foot roller. The necessity of an investigation of the process of compaction gave rise to R.R. Proctor's theory. The first laboratory test for qualitative estimation was also then advocated. The moisture density relation came to prominence. Since then there has been tremendous progress on investigation of compaction of soils.

Some research workers have tried to correlate the compaction characteristics with other engineering properties. New types of equipment particularly heavier equipment posed many more problems of cost and efficacy of use to the engineer with the advantages they possessed. Even in 1948 Terzaghi & Peck (84) mentioned that "the relations of the moisture content at the time a fill is placed, the degree of compaction and the physical characteristics of the fill throughout its period of service are still very imperfectly understood." Several theories of compaction have been profounded. New testing procedures evolved to suit different soils and conditions. The effect of compaction on engineering properties of soils and consequently on the stability of the fill is studied in detail. There are much improvement in compaction equipment and in the methods of use. New and better methods of quality control have been evolved. This is paving way for modern economical designs of structures which could not be thought off in earlier days.

This Science of soil compaction deserves more attention with the increasing earth work involved in all the development projects

A detailed review of this subject to the present stage should be of immense use to every practising engineer.

CHAPTER 2

THEORIES OF COMPACTION

2.1. Most engineering works necessitate excavation, transportation and placing of soil. As soil, if dumped, is weak, compaction is essential. A clear conception of the effect of moisture and the changes in soil during process of compaction would be of utility in interpreting the results. The main purpose of a theory of compaction is to account the effect of moisture on compacted dry density. Several theories are in vogue for explaining the compaction phenomenon of fine grained soils.

2.2. THEORIES

Prominent among the theories are Proctor's theory (1933) based on capillarity and lubrication, C.A. Hogentogler's theory (1936) based on Viscosity of water , B.N. Bannerjee and Dhawan's explanation by theory of thermodynamics, Lambes theory (1960) based on surface chemical theories and of Roy Eolson's theory (1963) based on effective stress considerations.

2.3. PROCTOR'S THEORY

R.R. Proctor contends (59) that moisture has a dual effect of both capillarity and lubrication. Water when added lubricates the soil particles thus reducing interparticle friction and hence shear strength. The particles slide over one another due to this loss of strength thus coming closer and increasing in density. By capillary action the moisture surrounding the soil is held by surface tension. When the water filaments come closer they are attracted due to capillary force causing a high frictional resistance between them. This gives rise to high shear strength to resist further densification after a certain stage when moisture is at O.M.C. When water content is further increased the water capillary tension is reduced and hence lesser strength and lesser density is achieved. Thus density goes on increasing till a particular stage (O.M.C.) of water content and further density reduces.

2.4. HOGENTOGLER'S THEORY

This theory of compaction is based on viscosity of water. Hogentogler (65) believes that the water is absorbed by the soil particles. The first layer closest to grain surface is highly cohesive, the subsequent layer less cohesive and finally the last layers mingles with free water in the pores. At low water content the high viscosity between contact points increases the shear strength but reduces dry density. At higher water content due to increased absorbed layers, soil is less cohesive. Greater density is achieved. Free movement of particles for densification is possible. After a certain stage (supposedly O.M.C.) the water acts as a lubricant resulting in displacement of solid materials with consequent reduction in density.

2.5. LAMBE'S THEORY

As per Lambe's theory (42) based on the physico-chemical reaction at low water content, the electolyte concentration in pore water is high and this decreases the double layer. Thus osmotic repulsion is reduced and hence particles flocculate causing lesser density due to low degree of inter particle repulsion. With increased water, expansion of double layers and reduction of electolyte concentration occurs. This reduces the degree of flocculation. This causes a better orientation and higher density. Further increase of moisture content helps in the expansion of double layer and reduction of net attractive forces between particles is observed. The added water dilutes the soil particles per volume and hence lower densities are again obtained.

2.6. DENSITY WITH INCREASED PRESSURE

B.N. Chatterjee and Dhawan (11) have applied the law of conservation of energy in interpreting the stress and strain in the process of compaction. The work done on a system is equal to the change of total energy of the system plus the heat transferred. According to the above, pressure applied for compaction = Increase in density of soil mass + the energy spent to overcome the frictional resistance of soil particles. This indicates that with increased pressure increased densification (higher density) is possible with reduced frictional resistance as no energy is ever destroyed from law of thermodynamics.

$$-W = \Delta E + (-Q)$$

Where $-W$ = Work done on the mass

$-Q$ = Heat transferred from soil mass in the shape of frictional resistance

ΔE = Change in total energy of the system due to increased density of soil mass

Energy applied may be wasted if rearrangement of particles fails to densify the soil due to complete failure of soil mass or may be superfluous if reduction in void is less compared due to excessive frictional resistance.

Soil with a slight moisture will be under influence of surface tension giving rise to high frictional resistance. Hence out of total energy applied, very little is utilised for increasing density. Low density results. With increasing moisture, the surface tension is lost. Frictional resistance is much less and hence density increases.

With further increase in moisture, there is loss of frictional resistance. Thus local failures take place. Further, pore fluid now consisting mainly of water with some entrapped air cannot be expelled by short period loading. In fact part of the roller load is supported by excess pore pressure, and thus a smaller pressure is actually applied to the grains. Hence it is only at a particular moisture content (O.M.C.) that frictional resistance is minimum which is sufficient to withstand applied pressure. At this stage M.D.D. is achieved. Moisture control is thus considered main factor in controlling compaction. The authors suggest optimum compacting pressure and O.M.C. to be investigated before undertaking construction.

2.7. EFFECTIVE STRESS THEORY

Roy.E.olson opines (65) that effective shear stresses on contact surface between particles resist compaction during the process and when applied pressure is less than the effective shear, further densification does not take place.

In the initial stage the soil mass is loose with a low shearing strength. When an external force is applied for compacting the soil, shear stresses developed between particles reach the shear strength of contact surface. Failure occurs in the form of particles sliding over each other. Proper orientation takes place. The density is increased. Simultaneously total pressure and pore pressure in soil increase but the increase of pore pressure is less than that of total stress as the soil is not saturated. The effective stress of the soil is thus increased before the application of next blow of dynamic compaction. Deformation and increase in effective stress continues till soil attains sufficient strength to resist compaction. When the pressure is released during the process, the vertical load reduces to zero thus tending the soil to expand in a vertical direction. This expansion reduces the total lateral stress. The expansion of soil is resisted by development of negative pore pressure. The reduced lateral stress and the negative pore pressure cause sufficient effective stress of compression to maintain the density condition. This process continues with the application and withdrawal of compacting force eventually making the soil strong enough so that no particle further yields on further application of force. The stage of M.D.D is achieved then.

With smaller moisture content, there is shallower foot penetrations during compaction. This is similar to a shallow footing where bearing capacity is about six times the shearing strength of the soil. When moisture content increases then the foot penetrates deeply into the soil. It stimulates the action of a deep footing where the bearing capacity is greater. Hence soil can resist the same foot pressure and hence no further densification is possible.

2.8. DISCUSSION

These current theories do not fully account for the compaction phenomenon of moisture density relationship. The concept of capillary induced stress giving higher shear strength to resist compaction (as in Proctor's theory) is seen in the effective stress theory also. For Proctor's theory on principles of lubrication, it is shown that a non-lubricant like carbon tetrachloride also gives a regular moisture density curve. Against the viscous water theory of Hengentogler it is shown that high viscosity beyond first few layers is not observed in experiments on clay in 1955 (65). If Lambe's theory based on electrolyte concentration is to hold good, then a fluid with a low dielectric constant like benzene should not have given a regular moisture density curve. Mc Rae and Turnbull (November 1963) discussing the effective stress theory do not agree with the development of negative pore pressures during compaction. All this only suggests that a comprehensive theory is yet to be established.

The theories do not have general applicability as compaction is achieved these days by different methods namely by kneading by static loads and by dynamic force. Use of coarser materials like gravels and cobbles are quite common and the theories will not suit to the larger sized particles.

CHAPTER 3

LABORATORY TESTING FOR COMPACTION OF SOILS

3.1. The compaction characteristics of the type of soil is a pre-requisite for the design and execution of an embankment. This involves study of the soil in the investigation stage to arrive at an economical design. It was in 1933 that Proctor published the first test procedure for compaction. The fundamental purpose of a laboratory test is to determine the optimum moisture content and the resultant maximum density possible for particular compactive effort correlated to the proposed mode or modes of compaction to be used in the field. With the advancement of the types of construction equipment, different modes of testing are evolved regularly. The critical question always asked about the laboratory compaction test is how well does it represent the field compaction. The prevailing methods of testing is reviewed to understand the present standards. Brief description of tests is given below (3, 31, 41, 71, 86)

3.2. COMPACTION TESTS FOR COHESIVE SOILS

1. PROCTOR'S TEST

The first type of test recommended by Proctor termed as PROCTOR'S TEST (Or B.S. COMPACTION TEST) has been adopted by American Association of State Highway Officials and American Society of Testing Materials. It is hence also known as STANDARD ASTM TEST OR STANDARD A.A.S.H.O. TEST. A cylindrical mould 4" in diameter and 4.6" high with a capacity of 1/30 ft is used. Soil (to be tested) is mixed with a certain quantity of water and is compacted in the mould in each of the 3 clayers by 25 blows of a 5½ lbs standard rammer falling freely from a height of 12". The moisture content and dry density is worked out. With varying moisture contents the experiment is repeated and a plot of moisture VS density plotted to get the M.D.D. and corresponding O.M.C. (the ordinates of the peak of curve).

2. MODIFIED A.A.S.H.O. TEST (1943)

With the advent of heavy compacting equipment the Proctor's test was improved. Heavier compaction by 25 blows of a hammer of 10 lbs falling from a height of 18" on 5 layers of soil is adopted. The increased compaction energy is 4½ times the standard test to suit new equipment.

This test known as Modified A.A.S.H.O. has now come into greater prominence.

3. CALIFORNIA LOAD COMPACTION TEST

This test developed in 1935 by O.J. Porter makes use of a 6" dia - 8" high mould. Dried soil is mixed with varying moisture contents each time and is compacted in a hydraulic press under a load of 2000 lbs/sq". By measuring the reduction in volume, the density is worked out. A plot of moisture VS density gives the required results.

4. DIETERT TEST

Soil with changing moisture percentages in each test is compacted in a 2" cylindrical mould. Compacting energy is indirectly applied by dropping a weight of 18 lbs through a height of 2 inches through a piston. Moisture and density plots are made from the results.

5. U.S.B.R. TEST

The Proctor's test is modified in this case by having a 1/20 cft mould and allowing a free drop of 18" instead of 12" of the

$5\frac{1}{2}$ lbs rammer.

The state of California Department of water resources have modified for the same purpose the modified A.A.S.H.O. test by having mould of 1/20 cft cylinder and compacting the 5 layers by 18 blows instead of 25 blows.

6. HARVARD MINIATURE COMPACTION APPARATUS

A miniature compaction device with a mould of 1 5/16" inside diameter and 2.816 inches long was suggested by S.D. Wilson (ASCE 1950). The tamper has a prestressed spring inside the handle which controls the applied force. 5 to 10 tamps/layer would give a homogeneous mass. The advantage is of reducing the time for test and also the quantity of sample needed (2 to 4 lbs).

7. IOWA COMPACTION TEST

To avoid the elaborate procedure of the standard Proctor's and Modified A.A.S.H.O. tests the Iowa Engineering Experimental Station have evolved a simpler method (69). A 2" dia x 5" long mould is made use off. The frame is connected to vertical rods which are joined together by a cross member with a slot to guide the hammer. The hammer blows are given indirectly by a drop of 12" through a lever arrangement. Both sides are separately compacted by 5 blows of the 5 lbs rammer for the standard test and rammer of 10 lbs for the modified A.A.S.H.O. test. This method known as Iowa bearing value method has the advantage of using less soil, consuming about 45 minutes for each test instead of the normal 2 to 3 hours. It is shown from tests on 40 samples (16) that it is suitable for all soils except clays of high plasticity. Even in such soils the error in M.D.D. is not more than 3 lbs/cft than the standard test.

8. ABBOT'S APPARATUS

A compact device for the test consists in the cylinder of 2" dia wherein a known quantity of oven dried soil is mixed with different percentages of water and compacted by a rammer giving a certain fixed number of blows. The soil plug is removed and the height measured. The usual moisture density curve is drawn. The number of appliances and quantity of soil needed are reduced.

9. DORMI TEST (U.S.S.R. STANDARD)

This test is similar in principle to the Proctor's test. The soils is tamped by 25 blows of a ram weighing 4.5 Kg and falling from a height of 30.5 cms. The contact area of ram is the same as that of the cylindrical mould.

3.3. ANALYTICAL STUDY OF THE TESTS

It is seen that there are too many methods prescribed for testing of soils for compaction. This leads one to think in terms of their limitations and advantages. It may well generally be stated here that any test that corresponds to the proposed field compaction would be the ideal one. General limitations of these tests may be mentioned as below:-

(1) Coarser particles (+4 fraction) are not generally taken up for testing and a gravel correction, (This is explained further in the quality control method) needs to be applied when the coarser particles exist.

(2) These tests are not suitable for cohesionless soils. (The U.S. Army Corps of Engineers suggest that even such soils can be compacted in a saturated state in the modified A.A.S.H.O. test to get the density for

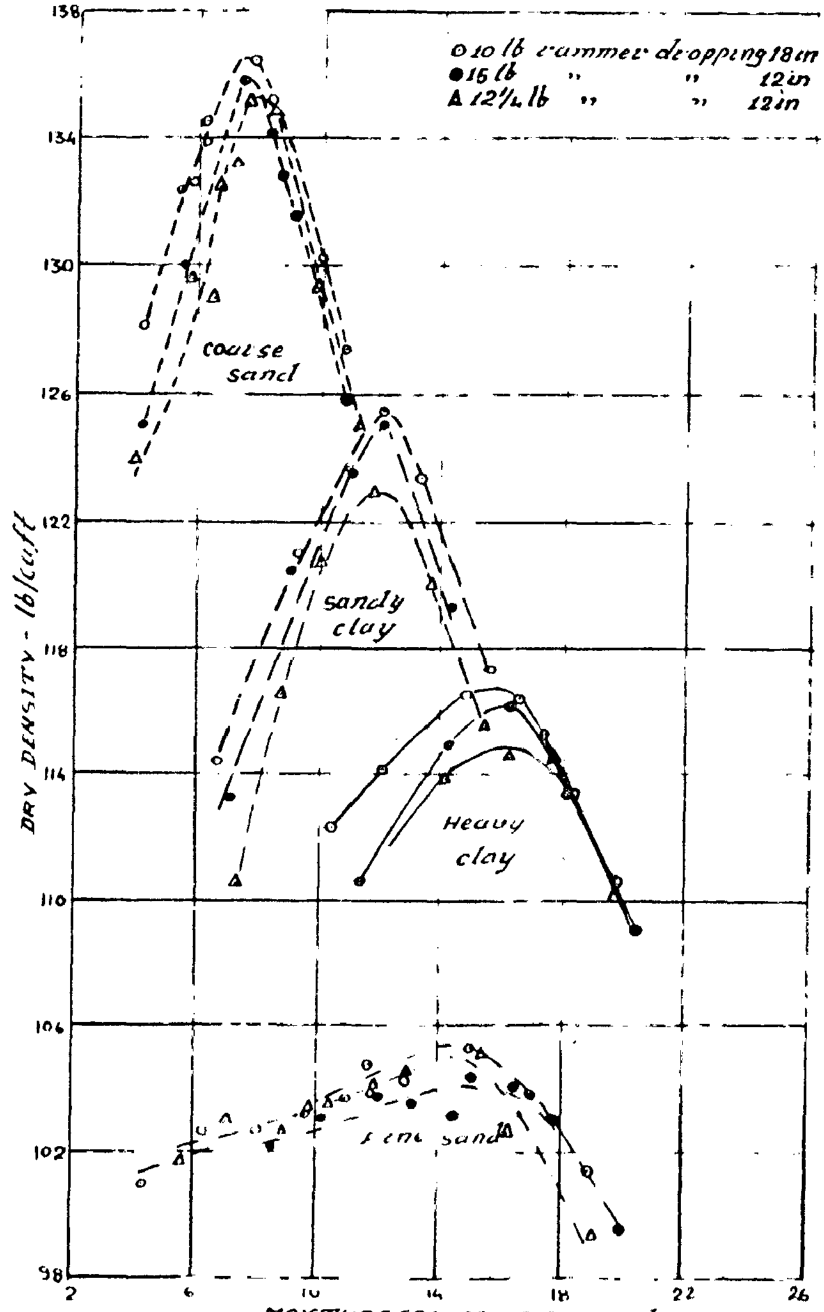
field control).

(3) The different test procedures correspond to different energy per unit volume and hence each test is suited for a particular mode of compaction. Table 1 gives the energy/unit volume of different tests in vogue.

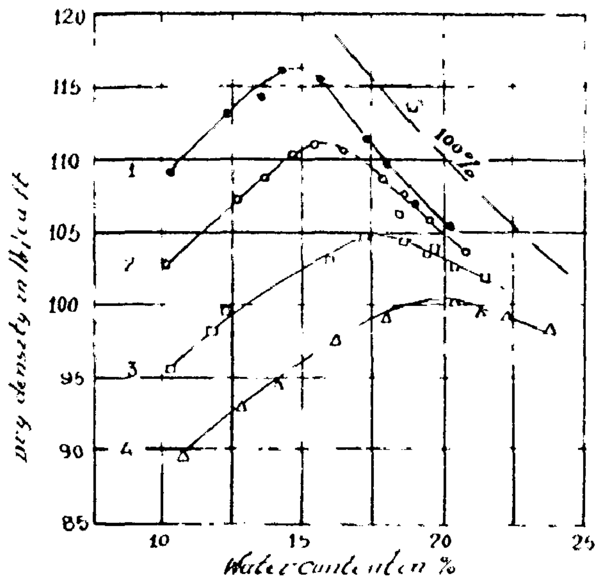
TABLE I

No	Type	Mould Size	Weight of rammer in lbs	Height of fall in inches	Energy applied ft lbs /cft	No of Blows
1	Standard Proctor's Test	4" dia 4.6" Ht	5.5	12	12375	25 Blows in 3 layers
2	Modified Proctor	4" dia 4.6" Ht	10	18	56250	25 Blows in 3 layers
3	C.B.R. Compaction Test	6" dia 5" Ht	5.5	12	12375	61 blows in 3 layers
4	Dietert Test	2" dia & of varying height	18	12	16501	10 Blows on both sides
5	U.S.B.R. Test	28" dia 6" Ht	5.5	18	12375	25 Blows in 3 layers
6	Abbot's Apparatus	2" dia & of varying height	5.5	12	22700	15 Blows in one layer
7	Iowa Compaction Method	2" dia 2" Ht	5	12	13750	5 Blows on each side (Total 10 Blows)

Fig.7 & 8 indicate the trend of compaction curves for the different energies of compaction by static and dynamic methods (31,71) For adopting a particular type of test, the compaction energy



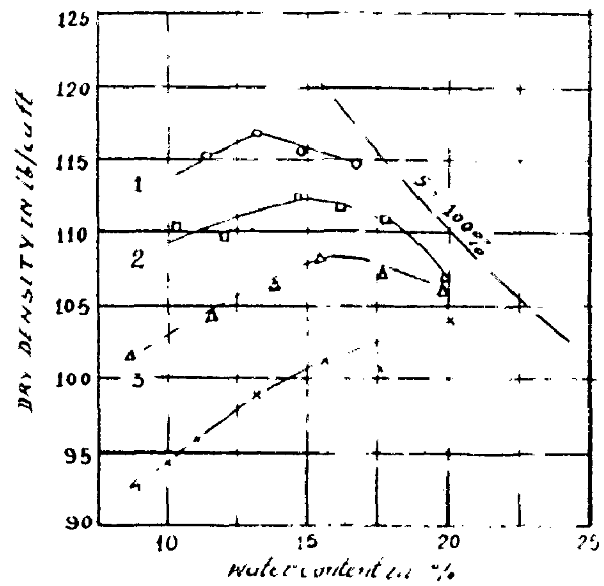
7. DRY DENSITY/MOISTURE CONTENT RELATIONSHIPS FOR FOUR SOIL TYPES USING RAMMERS OF DIFFERENT WEIGHT DROPPING THROUGH DIFFERENT HEIGHT



Dynamic compaction curves for a silty clay
(From reference V-11)

No	Layers	Blows per Layer	Hammer Weight	Hammer Drop
(1)	5	35	10 lb	18 in (mod AASHO)
(2)	5	26	10	18
(3)	6	12	10	18 (std AASHO
(4)	3	25	5 1/2	12

Note - 6 in dia. mold used for all test.



Static compaction curves for a silty clay
(From reference V 11)
(1) 2000 - psi static load
(2) 1000 psi static load
(3) 500 psi static load
(4) 200 - psi static load

Note - Compaction on top of soil sample

FIG. 8.

proposed to be given in the field needs to be represented in the laboratory test also. It is desirable to conduct tests for different compactive energies and work out the economy by alternatives for major structures.

(4) The compaction can be achieved by either static loading or dynamic loading or by kneading action. The conventional laboratory methods depend on the dynamic type of compaction whereas in field a combination or any of the above type may be applied (The common sheep foot roller compaction produces the kneading effect whereas a rubber tyred roller gives a static load compaction). Any of the above types or a combination may be adopted for field compaction. As such it is imperative to verify whether the compaction achieved by the above different processes in the field corresponds to laboratory test. From experiments it is seen that the standard Proctor's test or the Modified Proctor's test do tally with the results of field compaction. The effect of compaction by static loading studied by Hongentogler (31) is similar to that by dynamic loading as shown in Fig.9.

(5) Commenting on the control of embankment material by laboratory testing F.C. Walker and Holtz (93) mention that theStandard Proctor's method gives slightly higher M.D.D., lower O.M.C. and higher penetration values than in the field as the material

is confined during testing. The comparison of the standard test of impact compaction with the compaction by S.F. roller has been investigated and found agreeable.

As the standard test was recognised not suitable for cohesionless soils, the relative density test is recommended for cases when casing is thick. In smaller casing zones the effect is not considered great as satisfactory stability would exist and consolidation could be tolerated.

3.4. PROBABLE ERRORS IN TESTING

The test results are found to vary on the following. They need to be therefore carefully attended to

(1) Personal errors in compaction are very likely. To avoid these errors in compacting in the mould uniformly and to get accurate results, use of electrically operated automatic compactors with a counter are made use off. They assure uniformity of compaction to the exact required degree.

(2) P.N. Ray and Chapman (64) mention of the effect of sub-base on which mould is placed in the compaction test. A concrete floor or a wooden platform would change the O.M.C. depending on the effective mass of the mould, base plate and sub-base mass. A sub-base of concrete of 400 lbs or of 2" base steel plate of 63 lbs on wooden base is recommended. A.S.T.M. specifies a minimum mass of 200 lbs. This needs to be adhered to.

(3) Mixing of water is another factor greatly affecting results. To prevent small modules of hard clay existing as aggregates it is suggested that for soils with a plasticity index greater

than 20 a certain maturing period should be allowed. With improper mixing a variation of O.M.C. upto 1½ % and of M.D.D. of 1½ lbs/cft could be anticipated. By soaking the soil before test higher M.D.D. is observed. Sufficient care needs to be exercised.

(4) The sleeve around the mould prevents the rammer striking the soil at surface. Hence a standard test is felt essential. 15 % of surface area thus escapes direct compaction.

(5) The use of the same soil repeatedly for the trials during test affect the results. Higher densities may be achieved by remoulding the compacted sample to a higher water content. This needs to be avoided.

(6) Raymond Dawson (16) has made specific useful observations after conducting several standard A.S.T.M. Laboratory Tests. Studies on the effect of type of rammer, weight and free fall of rammer, hand and automatic compaction, non-homogenety of soil in the mould, shape of mould on results of A.S.T.M. standard test are made. The salient observations are:-

(a) Automatic compactors are found to give lesser densities than that with hand compactor. The advantage is in the speed and the uniformity attained for each test.

(b) Variation of size of mould from 4" to 6" is not found to make difference. Larger size of mould is advocated for soil with aggregate.

(c) A 10 lbs rammer with 18" drop is found to be suitable when higher densities are required.

(d) Sector head rammer and round rammer are found to give same results.

(e) Densities in the compaction mould is found to be greatest at bottom and least at top of mould. With a round head rammer the interior portion of soil at same depth is found to have greater density than at the exterior. With sector head rammer no such deviation is observed.

(f) For clayey soils an average of 3 to 4 results are recommended as greater variation anticipated in each case. With a single test the uniformity of mixing with water is not definite.

(7) Holtz and Merriman (16) state that with an automatic compactor the compactive effort is less than the ball indentation method of hand compaction. As such to attain same values as hand compaction addition of extra weight (about 1.05 lbs) is suggested.

(8) G. Tamez (75) of University of Mexico has mentioned of the following probabilities of errors keeping in view field conditions.

(a) If in field, material from borrow area is compacted without remoulding, as is normally done, the laboratory test should not involve, use of previously compacted soils.

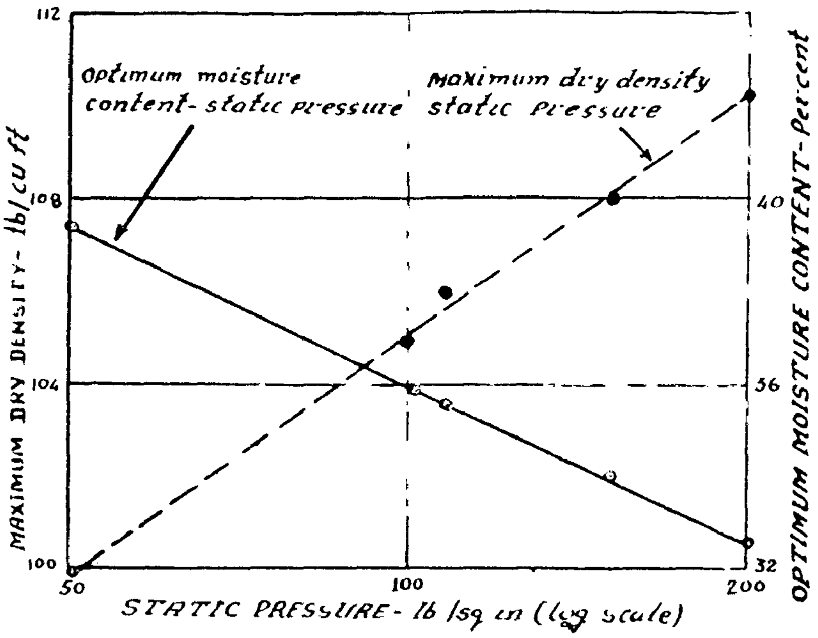
(b) The distribution of moisture in laboratory test should conform as much as possible to the field conditions. This is found to have a greater importance in fine soils.

(c) In miniature moulds as long as the ratio of thickness of layer to tamper diameter is maintained same, results are found same with the same compaction pressure per unit volume.

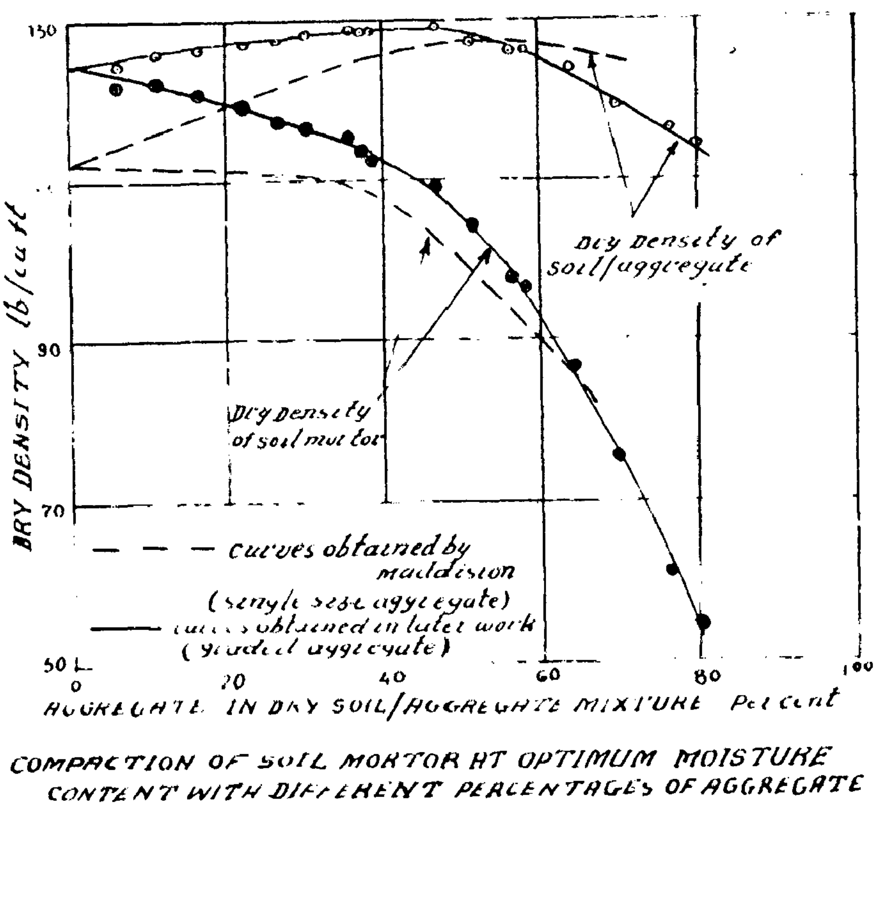
(9) During tests on clay for Sasuma Dam, S. Serota of Britain has compared the effect on M.D.D. of increasing moisture to O.M.C. from an air dried sample and of reduction of moisture of a wet sample to O.M.C. during the test. Lower densities are reported for the latter case than in the former. Heavier compaction energy was found essential to obtain the higher densities possible at O.M.C. from an air dried sample when the borrow material wetter than O.M.C. was dried to O.M.C.

(10) Maddison and others of the Road Research Labotory (31) have conducted A.A;S.H.O. tests on single sized aggregates and the results are indicated in Fig.10. 25 % of stones of one particular size when in admixture indicated maximum density at about 60 % of aggregate. Later using graded aggregates, it is shown that the density of the mixture reduces and a maximum is reached at 50 % aggregate.

W.G. Holtz and A. Lowitz (33) have made large number of tests on gravelly soils (1957). About 106 large scale field compaction tests of the combined soil were made in a 291 sq. in mould where soil is filled in 3 layers of 9" and compacted with a 185.7 lbs rammer of cross sectional area 70.9" sq.in freely falling by 18" to give the energy/cft of 12,135 lbs. Slight variations from theoretical density were observed. Higher values than proctor's test values were obtained due to size of apparatus.



9. EFFECT OF STATIC PRESSURE ON MAXIMUM DRY DENSITY AND OPTIMUM MOISTUR CONTNT (BY VOLUME) OF SOIL



10. COMPACTION OF SOIL MORTOR AT OPTIMUM MOISTURE CONTENT WITH DIFFERENT PERCENTAGES OF AGGREGATE

UNIVERSITY OF ROORKEE
ROORKEE

REPORT ON THE DISSERTATION SUBMITTED BY SRI S.N. SUBRAMANIAM FOR THE AWARD OF MASTER OF ENGINEERING DEGREE IN (W.R.D.)

* * * * * * * * * * * * * *

The dissertation has been written well and bears a practical bias. I appreciate the effort of Sri Subramanyam, as he has given alomost all the information on the subject, particularly discussion of the theories of compaction and bringing out their limitation. The chapter 4 on strength development of compacted soils needs special mention as nearly all the work on strength properties has been covered. The chapters 5 & 6 regarding compaction equipment and compaction techniques are of great practical utility. The author's mention of the work on the Madhya Pradesh soils may be useful and instructive for practicing engineers in that area. The chapter 9 points out areas where research work is wanting and has been usefully appended. However the chapter on Quality control could have been more elaborate giving details of various steps that are needed. The utility of a field test section and the effect of clay mineral structure and exchangeable bases could have found place in the dissertation.

Sd/- B.N. GUPTA
External Examiner

UNIVERSITY OF ROORKEE
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No. Ex/. /-139 Dated December , 1967.

Copy forwarded for information to:-

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ABBREVIATIONS USED

(a) Jn. of I.N.S. of S.M. & Fn. Eng - Journal of Indian National Society of Soil Mechanics & Foundation Engineering

(b) A.S.T.M - American Society of Testing of Materials

(c) Proc. of Int. Conf. on S.M. & Fn. Eng - Proceedings of International Conference on Soil Mechanics and Foundation Engineering

(a) It is shown that density of total material containing river gravel becomes less than theoretical density. Existence of gravel reduces the compactive effort for finer particles with particle interference. Maximum density of total material is achieved with 60 to 80 % gravel content. With higher gravel, fines would be insufficient to fill the voids and density drops rapidly with further increase in gravel content.

(b) With better gradation of gravel increased density is achieved.

(c) The effect of angular and subangular gravel particles were found to be same.

(d) The results of large scale tests mentioned above were found to correspond to roller compaction at Cachuma Dam but it is observed that the theoretical density at higher gravel content were achieved also with heavy U.S.B.R. sheep foot roller giving the required kneading action.

Sherard (71) mentions that for material with gravel upto 30 % the effect of gravel on compaction of fines is negligible. With 30 to 50 % gravel, compaction of fines is effected giving lesser M.D.D. and greater O.M.C. than that if no gravels were present. It is observed that higher the plasticity of fines, greater would be the quantity of gravel it can tolerate before the finer fraction is influenced.

3.5. MODERN TREND IN TESTING SOILS FOR COMPACTION

Proctor's fundamental studies established the basic relation between moisture, compactive effort and dry density achieved. It is now repeatedly objected that these dynamic impact tests of proctor do not stimulate the effect of the field compaction by different modes.. Hence modification of Proctor's methods and also new methods based on relation between stress and porosity of soils are being (58) thought off:-

(a) Kneading compaction was stimulated in the apparatus of Wilson (1950) namely Harvard miniature compaction apparatus This is found to give a higher degree of saturation and the densities are closer to S.F. Roller Compaction.

(b) Odeometer test analysis was propagated by Myslivec . (1936) & (1957), This is based on the fact that soil compacted in the fill to a density corresponding to the void ratio obtained in a confined compression test would not further settle by consolidation under increasing load. Based on this Rajcevic of Yugoslavia (1953) and Breth of Germany (1953) have suggested methods for compaction adopted in dams of their countries (58). As moisture content and density corresponding to surcharge of respective layers in dam are suggested, lesser compaction than the maximum are considered sufficient, saving compaction cost. The advantages posed by this are not as many for an immediate switch over as the Rossa Lauptin Dam of Germany though compacted on this basis is supposed to have undergone considerable settlement. Economy in compaction cost would not much matter when compared to the advantage of the Proctor's method giving a characteristic moisture density relation so useful in deciding the placement condition. With the recent advancement in study of strength characteristics of compacted soil by calculating the pore pressure and shear strength under different placement conditions, the Proctor's test and A.A.S.H.O. tests still have the importance.

(c) Myslivec of Czechoslavakia in his paper (55) in 1957 has enunciated that soil should be compacted at every part of embankment as per the maximum pressure which are expected to act. Embankment clays when compacted upto 100 % modified proctor's density were found to be free from settlement up to a height of 110 metres and these compacted to 90 % safe upto heights of 8 to 11 metres. From the standard compaction procedure soils at top levels in high embankment are over compacted and those below are under compacted as vertical loads are lesser at the top and much greater below.

The method suggested is to consolidate the soil sample in a odeometer or a triaxial machine with pressures corresponding to that in embankment. The height of sample is measured. The load is reduced and height measured. The unloading represents the sampling done in field. Knowing the dry and moist weights of specimen the density for different pressures worked out. This is termed as equilibrium density. It is found that

$$\gamma d = (\gamma d - 1) + (A \log_{10} P)$$

Where $(\gamma d - 1)$ = dry density after unload-ing a spcimen consolidated to P = 1.0 Kg/cm

A = constant (about 1.1 to 1.75)

P = Pressure in Kg/cm.

Soil is to be compacted to support without further settlement the maximum pressure. O.M.C. is determined according to specific pressure acting below roller and according to the dry density to be attained and this is preferably found in the field by determining the least number of passes by available compaction machine to achieve the density. This method has more significance in high dams with soils conducing to heavy settlement.

This density is termed as stable density (21) by C.L. Dhawan & J.C. Bahri. The ultimate density of soil depends on its overburden to which it is subjected. Due to the different nature of soils doubt is expressed about soils compacted to M.D.D as per Proctor's method getting into unstable conditions when overburden is insufficient to maintain this density.

3.6. COMPACTION TESTS FOR NON-COHESIVE SOILS

None of the testing methods so far mentioned do not lend themselves well to study of compaction characteristics of coarse soils. Density of sand is not a significant function of water content as that of fine grained soils due to the negligible effects of lubrication, viscosity, or surface tension on the coarse grained soils.

In case of non cohesive soils, compaction is indicated by the term relative density which is expressed as a percentage on the basis of void ratios as follows. (86)

$$D_d = \frac{e\ max - e}{e\ max - e\ min} \times 100$$

where e = inplace void ratio

Converting in terms of the dry density it is expressed as

$$D_d = \frac{\gamma_{d max}\ (\gamma_d - \gamma_{d\ min})}{\gamma_d\ (\gamma_{d\ max} - \gamma_{d\ min})} \times 100$$

Where $\gamma_{d\ max}$ = greatest dry density of soil as obtained by the laboratory procedure

γ_d min = least dry density of soil as obtained by laboratory procedure described.

γ_d = the dry density in place

Brief review of the testing methods is made below:-

1. U.S.B.R. METHOD

The experimental procedure consists in finding γ_d max and γ_d min (Details are given in designation E/2 of U.S.B.R) Minimum density or zero percent relative density obtained by filling a certain quantity of soil (as per specified procedure) loosely in a cylindrical vessel. Volume is worked out by the quantity of water at 21^{o}C required to fill it. The density obtained would give minimum density. The maximum density is obtained by filling saturated soils into the vessel and vibrating the same. The moisture content is also worked out and maximum density computed.

The insitu density is obtained by a density test as in compacted fill (explained under Quality Control)

Maximum density may be found also by using vibratory table either by dry method or wet method.

2. A.A. Wagner has suggested (3) that for soils containing more than 25 % larger than No.4 sieve size upto a maximum of 3" size, the size of mould needs to be increased than in the standard D-698 of A.S.T.M. A 20" dia mould, 15" high with a metal rammer of 186 lbs with detachable shoe guide rod and adjustable block having a 9½" dia circular face is recommended. Free fall of 18" at rate of 12 blows/min by an electrically powered, rotating double arm cam is suggested.

3. The density of cohesionless soils is found to be much influenced by the sand grading (34). Kolbuszewski showed in 1948

that density is effected by sand grading due to the internal structure. Further Shockley and Garber in 1953 and Durante and others in 1958 have shown that a relation between sand grading and limiting density does exist. Bruce Hutehinson and David Townsend (34) have suggested some improvement in test procedures from an analysis on 12 samples. For finding maximum density Air dry sand is filled in a 1/30 cft compaction mould. Each layer is vibrated for 15 minutes by an electric vibratory hammer of 50 lbs at 1800 vibrations. The hammer face covers the complete cross sectional area. The method of Kolbuszeswski did not specify hammer weight and compaction was done under water. It was found that for Cu of 2.5 to 5.0 densities obtained were 2 to 7 lbs/cft lower with saturation than that in air dry condition.

4. The A.A. S.H.O. test (1955) of finding density as in case of cohesive soils by 25 lbs of hammer is found to give density varying from 5 to 6 lbs for uniform sand (Cu = 1.4 to 2) and 8 to 9 lbs/cft for well graded sand (Cu $\nless$ 3.5 to 5). Minimum density tests of Kolbuszesuki is found to give 2 to 3 lbs/cft lower than the U.S.B.R. test for uniform sand and greater values for well graded sand.

5. Some experimental study has been conducted in Japan on compaction of sandy soils (76). Kichie Tanimoto reports that with increase in number of blows, dry density increases at a faster rate initially and more slowly later. Higher free fall would give the final stages of compaction earlier.

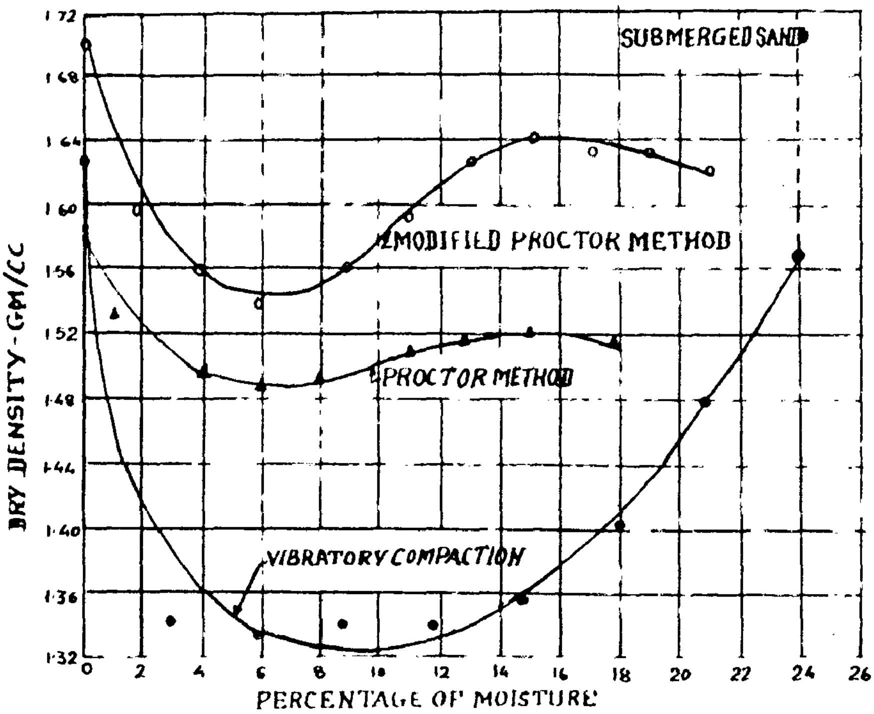
6. The effect of moisture, static loading and vibration on the compaction of sands has been investigated by T.K. Natarajan and R. M. Palit (57). Standard Proctor's test, modified proctor's

test and vibratory testto a frequency of 4000 R.P.M. and 3/16" amplitude and the vibratory compaction with static load wa-s conducted on 4 samples. It is concluded that the dry state gives maximum density and the minimum density is obtained at 6 % moisture. With further increase of moisture upto 15 % there is an increase of density which more or less remains constant further. With vibration the density in the submerged case is also found to give as high or even higher values of densities than when dry. But the intermediate moisture contents are found to give a low densities. An optimum static load is found to give improved values with vibration. The details of results are reproduced in Fig.11. These observations relate to compaction by internal vibration where by the interparticle bond is broken entirely. This concept is more useful in compaction under water as in coffer dams. For compaction by dynamic loading or surface vibrators the normal concept of O.M.C. does hold good. By blasting and vibration, the densities can be increased depending on charge and depth. Hence the maximum density would also mean the economical maximum density.

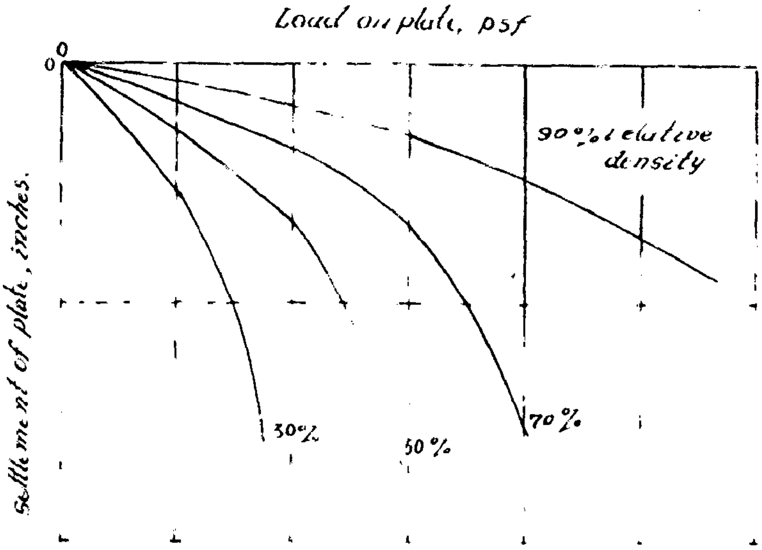
7. As precise laboratory tests cannot be conducted for relative density, the plate bearing test at field is gaining prominence. The settlement of a loaded plate would depend primarily on the relative density. By conducting tests on a standard section, load settlement curves to different relative densities can be plotted and made use off to check relative densities at other sections by interpolation. (Fig. 12).

3.7. CONCLUSION

A detailed analysis for a soil is essential to decide the placement moisture content, economical mode of



11. Density moisture relationship for different types compaction, Yamuna sand.



12. Family of load settlement curves which can be used for estimating relative density of clean sand and gravel embankment sections from plate bearing tests

compaction and to have a qualitative estimation for the design purpose. Test procedures to suit a particular energy of compaction needs to be adopted. Methods are also found to vary with different countries with slight modifications but the fundamental test of proctor is still prominent for cohesive soils. With the existence of coarser fraction in soil, application of gravel correction or use of large size moulds for the test are essential. For noncohesive soils like sand the relative density test is essential.

From experiments on several samples, research workers have made observations to obtain accuracy. These facts need to be taken into account in tests for compaction. It is essential that in all tests, the conditions to occur in field are properly represented in laboratory tests also.

There is tendency to advocate compaction to a stable density corresponding to the overburden pressures to reduce settlement. Consolidation tests are suggested. This may gain favour only in such cases where settlement is a serious problem. The practice in this respect is yet to be established.

The Proctor's test has the decided advantage for the to help in deciding placement moisture conditions to control all other properties for a stable structure. It only needs to be ensured that the field compaction corresponds to particular laboratory test adopted to ensure proper design assumptions are made.

CHAPTER 4

STRENGTH OF COMPACTED SOILS AND PLACEMENT MOISTURE CONTENT

4.1. The fundamental aim in compacting the soils is to promote the best possible strength characteristics essential for the safest possible structure with use of available materials. The moisture content and density variations in compaction of different soils are found to have important effects on the engineering properties of soils. The shear strength, consolidation characteristics, permeability of the material, shrinkage and swelling characteristics, pore pressure in the soil are found to alter with compaction.

4.2. The Engineer should know well the requisites for a safe and economical structure. The general requisites for an earth dam as a water retaining structure are as below:-

(1) Water barrier zone to be homogeneous and free from potential paths of seepage or piping through the zones or foundations or its contact.

(2) Soil mass to be sufficiently impervious to prevent excessive loss of water.

(3) High compressibility of impervious material undesirable from stand point of pore water pressure development during construction and reservoir drawdown, in addition to possible loss of free board during primary consolidation.

(4) Maximum possible shear strength from available material is essential.

(5) Soil is not to ~~be~~ soften on saturation.

(6) These conditions are to be satisfied by simple, practical and economical operations

It is not correct to specify that a fill compacted at O.M.C. to maximum density would have the ideal qualities. Knowing the design requirements and available materials a study will have to be made as to how best the design requirements can be satisfied economically.

Behaviour of compacted soil depend on

(a) Soil type and interaction with adjacent soil type

(b) Type and amount of compactive effort

(c) Confining pressure

(d) Presence or absence of source of water

(e) Nature of applied load

(f) Strength, stiffness of the soil

But the quantitative effects are not well known. All the same Moisture at compaction is found to have a predominating influence.

Hence a study of how the engineering properties change with compaction would hence help in arriving at the best placement moisture to obtain the desired properties. The variation of properties by compacting the soil with moisture at dry of O.M.C. and wet of O.M.C. is now analysed.

4.3. COMPACTION AND SHEAR STRENGTH

The strength of the soil is an important criterion for economical and safe design and construction of embankments. Primarily, increased density gives increased shear strength for the soil. J.W. Hilf (29) has stated that the presence of air at higher densities would reduce pore pressure. Consequently higher undrained strength would be developed. This leads to the idea of compacting to M.D.D. with moisture dry of O.M.C. as air content would be more in such a case. This would involve a higher compactive effort to achieve this condition.

The same views are expressed by T.W. Lambe (42) as follows:-

(1) Increased compactive effort, dry of optimum gives increased strength

(2) For same compaction effort and same compacted density, dry side compaction gives higher strength than that on wet side of O.M.C.

(3) Increased compactive effort, wet of optimum can result in gain or loss of strength (which is small in either case)

C.R. Foster (24) has clarified that it is not correct to consider always that increase of density gives added strength. As long as compaction is such that no significant pore pressures develop, increase in strength is possible. But when pore pressure increases naturally the undrained strength reduces. The pore pressure increase is definitely greater for soils compacted wet of O.M.C. to higher densities with a larger compactive effort. Hence the undrained strength is lower though density is high. From Laboratory tests (29) it is shown that the limiting moisture content is 1.5 % to 1.7 % wetter than the O.M.C. by modified A.A.S.H.O. test. Generally it can be said that due to pore pressure build up, the undrained strength is less when compacted at wet of O.M.C.

G.A. Leonards (44) makes an interesting observation from the fact that the critical factor that controls strength is void ratio at failure. For a given initial water content reduction in void ratio achieved through a process of consolidation gives better strength than that possible under similar conditions by compaction. Consolidated soils have no pore pressure whereas pore pressure build up is considerable in a compacted soil.

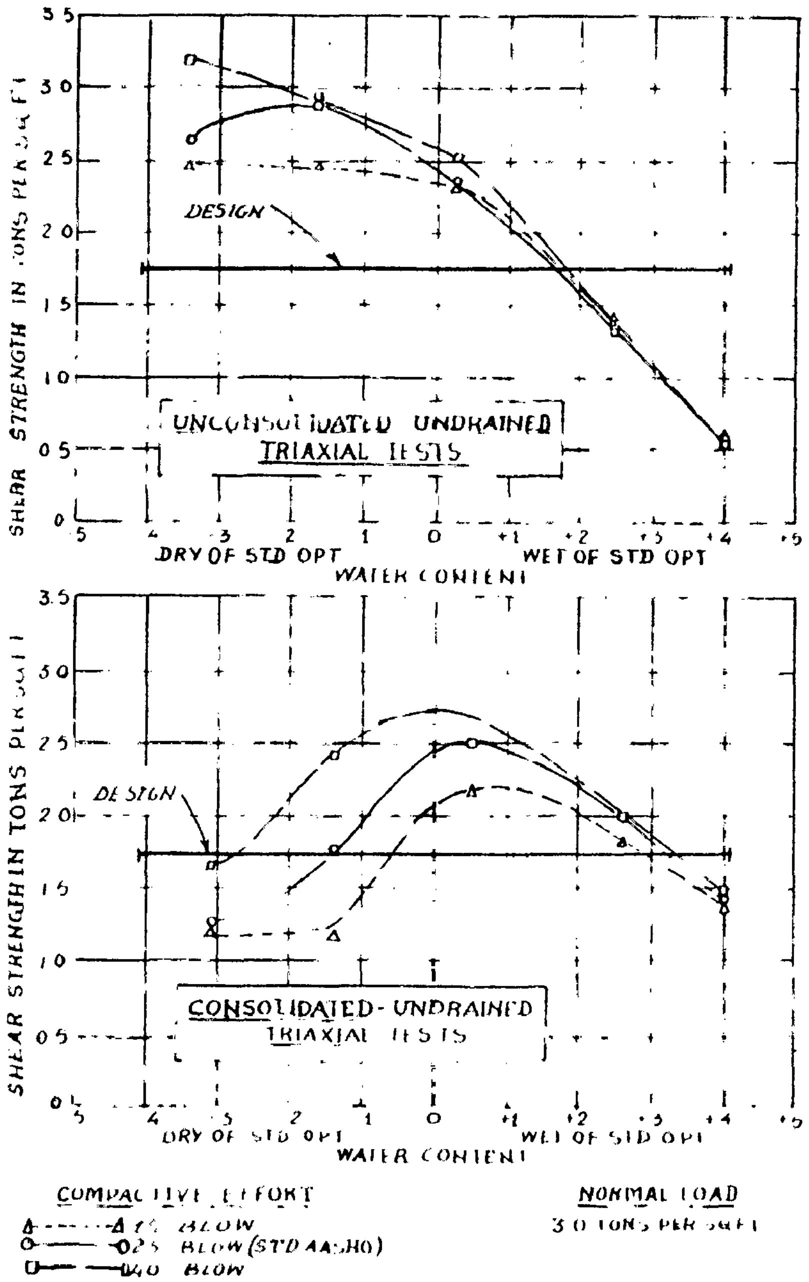
Turnbull and Shockley (82) have reported investigations of the laboratory tests on a clayey sand (Details are given in Fig. 13). The results confirm that the compaction dry of O.M.C. is preferable and that higher compactive efforts are helpful only on dry side of O.M.C.

Seed and Chan have made detailed analysis (67) of the influence of soil structure on all the properties. Compaction of soil dry of O.M.C. produces a flocculated arrangement giving higher undrained strength.

There is thus an abundant proof, as will be explained later also, that compacting dry of O.M.C. induces a high undrained strength. With drainage, the consolidated strength with compaction on the drier side of O.M.C. is found high. Increase of compactive effort for the compaction dry of O.M.C. is observed to produce high values of strength.

4.4. COMPACTION AND PORE PRESSURE IN SOIL

For the stability of embankment in the initial stage of service, the unconsolidated strength is of importance and hence the pore pressure needs to be controlled. It is only for long term stability that the consolidated strength characteristics come into play



13. *Effect of compaction effort and water content on shear strength of clay sand. Effet de l'effort de compactage et de la teneur en eau sur la résistance au cisaillement du sable argileux*

A.W. Bishop (9) mentions of a high pore pressure build up in dam if compacted wet of O.M.C. unless drainage is possible during the construction of the dam. Provision of special drainage arrangements would help in reducing the increase of pore pressures when further layers are laid.

Reduction of pore pressure by reducing placement moisture is possible. Greater air would be present at dry of O.M.C. The limitation would be that too low a moisture would consolidate greater on saturation. Hence lower limit is defined as that lowest placement moisture content (93) at which saturation will have no effect on consolidation. The upper limit is fixed on basis of the tolerable maximum pore pressure permissible which does not reduce the undrained strength appreciably.

Pore pressures existing in compacted clay (40) have been measured by Lambe. After compaction at moisture dry of O.M.C. the soil is observed to have negative residual pore pressures. It is concluded that:-

(1) Higher placement water content would give lesser negative residual pore pressure

(2) Higher compactive effort would give higher residual pore pressure.

(3) Kneading compaction is found to give higher residual pore pressure than impact compaction for higher compacting effort for same moisture and density.

(4) If soil was wetter than moulding water content, residual pore pressure are greater.

(5) Compaction if done at lesser temperature higher residual pore pressure are observed.

J.W. Hilf (29) mentions of clays compacted dry of O.M.C. to have negative pore pressure resulting in higher intergranular stresses and hence higher strength. In this condition moisture is insufficient for the formation of double layer of soil colloids. Water is attracted by the soil colloids and in the process capillary menisci develop. These transfer water tension into intergranular compression.

An interesting study of negative pore pressure in compacted cohesive soils is reported in four earth dams of Brazil by Silva Fransico. P. The water tension was found to increase with increasing load application to a certain value. This behaviour is observed for low degrees of saturation. Approaching 100 % saturation, positive pore pressures appear once the air paths are not inter-connected.

Irrigation Research Institute, Roorkee, U.P. has conducted studies on two similar dams and pore pressure is shown to be greater at M.C. wet of O.M.C.

TABLE 3 (A)

Name of Dam	Embankment Material	Placement Moisture	Pore Pressure Ratio	Dissipation Factor	
Nanak Sagar Dam	CL. ML. CL	1% Wet of OMC	1.1	1/7	Computed by tractor drawn
Moosakhad	CL ML CL	3% dy of OMC	0.8	1/4	S.F. rollers

R. Little (47) has given some observations of pore pressures with reference to compaction moisture content

TABLE 3 (B)

Name of Dam	Height	Placement Moisture	Pore Pressure
Dear Dam	130 ft	2.1 % dry	zero
Usk Dam	110 ft	2.2 % wet	100 % at end of construction
Tai Lam Chung Dam	85 ft	0.3 % wet	Small
Foxcote Dam	30 ft	1 % wet	30 %
Serre Pon Con Dam	430 ft	2 % wet	Nearly 100 %

Turnbull and Shockley (80) indicate, that the U.S. Corps of Engineers do not consider less than 100' high dam as dangerous from pore pressure consideration. Turnbull and Foster suggest that it is not good economy to desigh steeper slopes by suggesting compaction dry of O.M.C. for the fear of pore pressure. The greater danger of cracking may develop at moisture content dry of O.M.C.

This leads us to conclude that compacting with moisture at dry of O.M.C. is definitely beneficial from the view point of pore pressure and increased undrained strength. The caution indicated by Turnbull and Shokley (mentioned above) merits consideration.

4.5. COMPACTION AND PERMEABILITY

Permeability has an important bearing for a water retaining structure from considerations of seepage loss. It has great influence in increasing strength of soil by reducing pore pressures by proper drainage. Consolidation is also hastened.

Kozeny has shown in 1942 that permeability is a function of void ratio. Void ratio of a soil also indicates the compaction of soil. They are hence closely inter-related.

Kozeny Carman equation (42) gives

$$K = \frac{1}{K_oS^2} \times \frac{e^3}{1 + e}$$

Where K_o is a constant depending on pore shape and tortuosity of flow, S denotes specific surface and e void ratio. During process of compaction the soil particles re-adjust. The constant K_oS^2 takes this into account. When compacted dry of O.M.C. random orientation exist causing greater permeability. Larger the individual pores for any given total pore area, greater is the flow since K varies as a function of opening size. At O.M.C. a parallel arrangement of the particles causes reduced permeability.

R.L. Dhawan has conducted tests (17) to show reduced permeability values wet of O.M.C.

Buchman concluded from his tests that higher compactiv effort reduces the permeability.

Lambe (42) explains the reduction of permeability at higher moulding water content as that due to repulsive electrical forces between particles during compaction. The experimental graph by Lambe for a clay sample indicates the lowest permeability with compaction at about 3 % wet of O.M.C.

Compaction at moisture wet of O.M.C. is explained (5) to produce a low permeability resulting in low seepage velocity. Hence it precludes piping.

When compacted dry, particularly in a homogenous embankment, the soil deflocculates on wetting. This causes the clay particles to break into fines. These are capable of moving in suspension under seepage flow in this relatively porous strata and finally out of dam. This may culminate in a macrofailure by piping.

Bjerrum, Hudes and Bernell (42) have conducted tests to find out variation of K with moisture content. The rate of change of K is found to depend on the clay content. Even for clays compacted at 2 % dry of O.M.C. permeability is reported to be 50 times greater than that compacted at O.M.C. If K is less than 10^{-5} cms/second (10 ft/year), it is supposed to control piping failures while K = 10^{-4} cms/sec. may give a velocity sufficient to remove particles of 0.5 micron.

Hence control over permeability is possible by varying the compaction moisture content within permissible range.

Permeability of material is reduced either by increasing the water content during the compaction to wet of O.M.C. or increasing the compactive effort.

In North Catamount Dam, 200' high increasing the compactive effort for the embankment material is reported to have made (71) the soil 100 times more impervious.

Discussing the permeability of Mudmountain Dam core material, Allen S. Carry & Others (2) have mentioned that with same numerical void ratio and density, if the voids are of uniformally small size with higher water content, low value of K is obtained. At low water content varying sizes of openings gives higher permeability value. Thus the numerical value of void ratio alone cannot indicate the variation of K near about O.M.C. as nature of voids also effects the K value. It is reported that only in larger ranges a relation could exist between K and e.

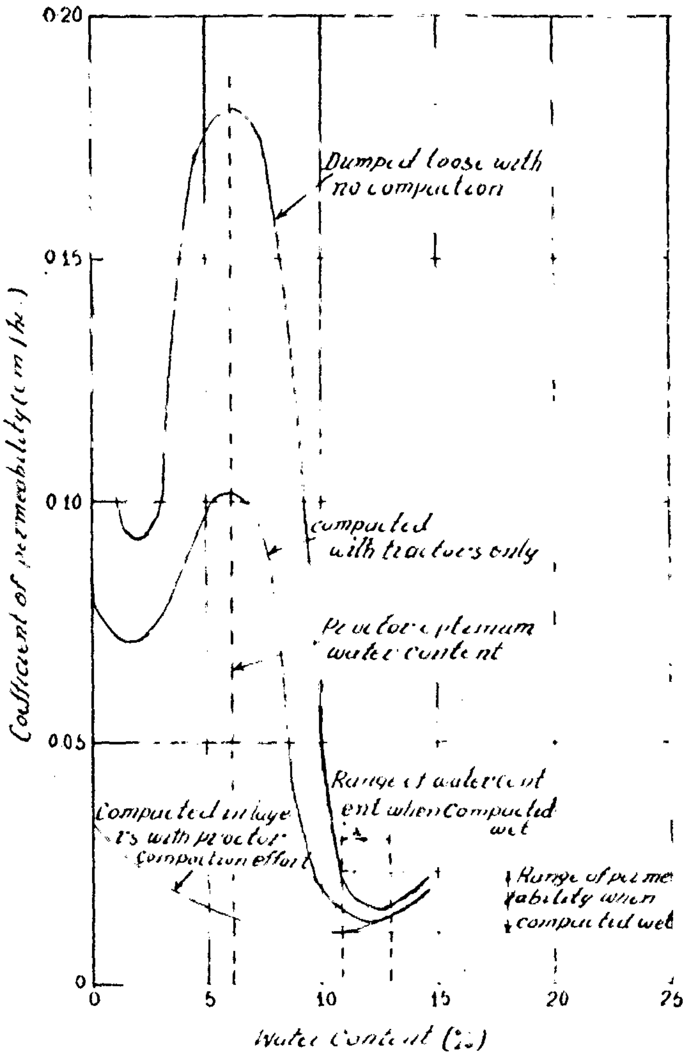
W.P. Creager also states that at dry of O.M.C. moisture is not well distributed and material is lumpy. Fraction of material may have little water and some material more water. The soil which has little water/swells on saturation increasing voids and also permeability. At moisture higher than O.M.C. distribution is uniform and as such swelling and permeability are reduced. Variation of K for a sandy soil with changes in compactive effort and moisture is shown in Fig.14.

Hence it can be concluded that with the variation of moisture content and compaction effort, permeability can be very well controlled to the required properties by proper investigations.

(1) Moisture greater than O.M.C. during compaction reduces the permeability. This would help in semipervious soils being used for cores in dams. Similarly compacting impervious soils dry of O.M.C. self draining properties can be induced and material used for casting.

(2) Higher compactive effort would reduce permeability and vice-versa.

(3) For fine grained soils, permeability is a function of the size of the opening, distributio as well as of the void ratio. For coarse



14. Influence of compaction effort and water content on permeability of typical sandy medium used for [illegible] in sweden. (after swedish state power Board, Ref [illegible])

grained soils, it is primarily a function of void ratio.

4.6. COMPACTION AFFECTING SHRINKAGE AND SWELLING CHARACTERISTICS

The shrinkage and swelling characteristics account for the settlement and formation of cracks in earthen dams. These may also give rise to piping failures. These depend considerably on the moisture content during compaction and on the overburden pressure. The shrinkage and swelling are particularly great in the undraining clayey soils.

At low pressures, if soil is compacted wet of O.M.C. greater settlement are observed as particles readjust easily and no work is needed. But if compacted dry of O.M.C. when getting saturated floocculated structure is formed. Work would be needed to cause settlement. Due to low pressure settlements are less.

With high overburden pressure, a greater volume change is possible. It is only essential that for any significant volume change the pressure should exceed the preconsolidation load of the soil.

Allen's experiment in 1938 showed that increased compactive effort during compaction reduces the settlement.

J.P. Gould's (27) observations of rolled fill dams indicate as below:-

Compaction at dry of O.M.C. causes settlement increasing with added stress.

Compaction at wet of O.M.C. causes a higher initial settlement and there is lesser settlement with added stress.

John A. Fotch Jr. (79) has expressed the possibility of highly plastic clays failing by plastic failure when compacted wet of O.M.C. and possible swelling when compacted dry of O.M.C. causing serious cracks. Failure of Trenton Dam was found to be due to compaction by heavy compaction effort in clay soil wet of O.M.C

G.A. Leonards (44) views that a clayey soil compacted wet of O.M.C. will have a higher degree of saturation and is more compressible. In case of earth dams subjected to differential settlement compaction at dry of O.M.C. is advocated for easy adjustment for settlement without cracks. Though pervious, higher strength and hence economical slopes are possible. If soils are of low plasticity, compaction dry of O.M.C. may involve excessive leakage and dangerous cracks

Bishop has confirmed from consolidation tests (9) that soils compacted dry of O.M.C. ensure lesser compressibility and lesser softening on saturation. A criterion for treatment of volume change given by U.S.B.R. is indicated in Fig.15.

Lambe (42) making a detailed study mentions that compacted clay when subjected to alround pressure with drainage possibility, compresses primarily due to re-arrangement of particles in an orderly array. Volume changes caused by such readjustment is not recoverable. The decrease in size of micille would also contribute to compaction.

Substantive studies on the flexibility of clay and cracking of earth dams have been made by Dr. Jagdish Narain and G.A. Leonards (43). Increase of moisture content for compaction from 2 to 3 % dry of O.M.C. to O.M.C. is found to give appreciable flexibility whereas further increase to 3 % wet of O.M.C. may not affect much particularly if settlements are likely. Near about O.M.C. increase in compactive effort would also reduce the flexibility. Generally highly plastic clays are more flexible than clays of low plasticity. Steep abutments and low moisture content at compaction and construction material of silts, clayey sand and silts are given as reasons for cracking by J.L. Sherard.

E. Tamez, Springall, R.J. Marshall further clarify the effects of settlement caused by volume changes in embankment and that due to compaction or consolidation of foundation. The desirable practices mentioned are:-

(1) Use of fine silty sand, clayey silt and silty clay in homogeneous dams and cores is to be avoided if possible.

(2) Discontinuities in slope of embankment and closure of sections are to be minimised.

If the foundation material is compressible, compaction wet of optimum is recommended. When foundation soils are likely to collapse on wetting remoulding or pre-wetting or preloading is recommended.

If the use of shrinking clays cannot be avoided construction of substantial zones of well graded sands and gravel are suggested.

Following possibilities are indicated from studies (43) and the relative importance of moisture density control for different soils given:-

TABLE 4.

Relative Importance of Moisture Control	Classification of Soil	Liquid Limit	Plasticity Index	Effect of inadequate moisture control during compaction
I	ML- ML-CL ML-SC ML-SF	10-45	0-10	High probability to failure by cracking & piping. (Particularly uniform sand with P.I. $<$ 6)
II	ML CL	20-50	15	Most likely to fail by cracking and may fail by piping
III	SF GF	10-30	0-8	Most likely to fail by piping and may possibly fail by cracking
IV	ML CL	20-50	15	May fail by cracking or piping only in severe condition
V	SC SF GC GF	20-50	8-15	-do-
VI	CH CL-CH	40	25-40	Least likely to fail either by piping or cracking

Highly plastic clays exhibit the behaviour of swelling and shrinkage with variation of moisture.

Clayey soils compacted at less than O.M.C. and allowed to saturate swell more than when compacted at wet of O.M.C Lambe (42) also remarks that high swelling characteristics and swelling pressures are observed of clay compacted dry of O.M.C.

Effect of moisture and density on the expansive characteristics of clay is indicated in Fig.16. This is from results of work done by H.B. Seed (68) of U.S.B.R. It indicates that on dry side of O.M.C. swelling would be much higher than at wet of O.M.C.

Swelling of soil (44) is found to increase with degree of compaction at a given confining pressure in presence of water in the soil.

Thus it is seen from above study that for clayey soils

(a) Settlement is greater with compaction wet of O.M.C. particularly when the overburden pressure is high. Plastic failure needs to be averted.

(b) Increased compactive effort reduces settlement by a certain extent but reduces flexibility with moisture content near about O.M.C.

(c) Cracks are lessened when compacted wet of O.M.C. as easy adjustment for differential settlement is possible.

(d) But swelling is greater for clayey soils compacted dry of O.M.C. If foundation soils are compressible compaction wet of O.M.C. has the advantage of settlement without cracks due to better flexibility.

Hence a greater care is essential in dealing with clayey soils for homogeneous embankments. Detailed studies of individual soils are desired.

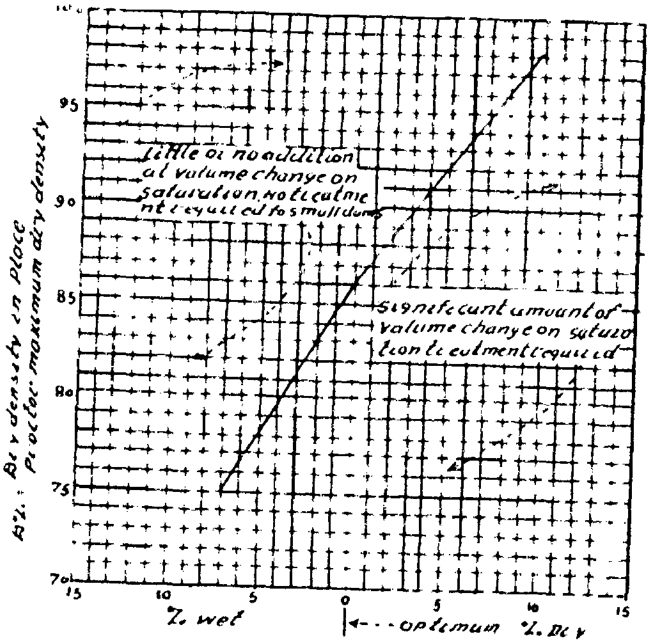


Fig No 15 Criterion for treatment of relatively dry fine-grained foundations. 101 D 246

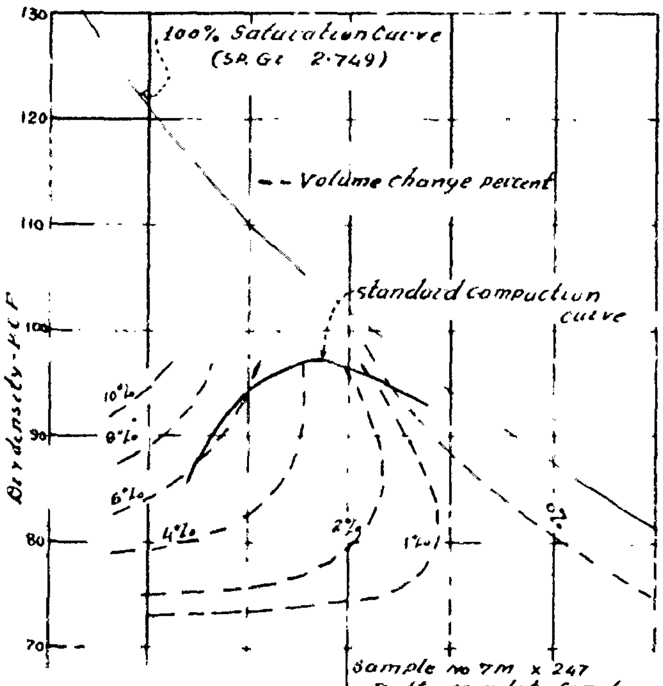


Fig No 16 Effect of moisture and density on the expansive characteristics of a clay. 101 D 207

4.7. EFFECT OF GRAVEL ON THE ENGINEERING PROPERTIES OF SOILS

The tests conducted are mostly on the -4 fraction and the effect of the coarser particles on the overall behaviour of soil needs to be studied in detail. Walker & Holtz (29) have made certain studies. The following general conclusions can be drawn.

(a) Higher densities are achieved upto about 60 % of +4 fraction.

(b) Compressibility of the combined material is less. Hence reduced pore pressures seen giving higher undrained strength.

(c) As permeability would be higher consolidation is hastened giving quicker consolidated strength. The value of angle of internal friction (ϕ) is increased due to gravel content. But increased permeability would involve higher seepage.

(d) The shrinkage and swelling characteristics are less. From studies it is reported (29) that the relative volume change under load for a GM soil was in particular case 0.9 % to about 4 % of initial volume in case of CL soils.

(e) Compaction at dry of O.M.C. is found to give a rugged surface preventing local shear failures.

Qualitative estimation of the variation is being studied by several research workers. The details are not included in the present analysis.

4.8. MODE OF COMPACTION AFFECTING SOIL PROPERTIES

The mode of compaction changes the strength and stress deformation characteristics of compacted soils. It depends on whether a continuously increasing stress or a repetitive stress of varying magnitude is applied. The effect of confining pressure needs to be accounted for also. Varying results are observed in individual cases.

Sowers (73) mentions that the rate of improvement of soil properties becomes smaller as compactive effort is increased for a given moisture content. It is mentioned that the lateral pressures developed by soil compaction are retained and cause deflections in earth retaining structures. These residual pressures are found to be greater with higher compactive effort and lesser with increased moisture content for clayey soils. In sandy soils no major variation in residual pressures with compactive effort or moisture content is observed. Passage of time is found to reduce these lateral pressures for clayey soils and time is not effective for sandy soils.

The utility of different modes for different soils is discussed later. However, from construction view point, use of materials dry of O.M.C. is found to be preferable for the facility of travel of equipment. The upper limit of moisture control can be based on the trafficability of equipment.

Prevention of piping failure by moisture control during compaction or post construction control by addition by chemical is advocated. Compaction at wet of O.M.C. is considered the critical factor to prevent dam failures by piping.

4.9. PLACEMENT MOISTURE

Knowing the desired properties from detailed soil investigations for the particular structure, the placement moisture for compaction in construction needs to be decided. This important aspect would help in achieving the desired design properties in the field. The effects of compaction at wet or dry side of O.M.C. should be well known in individual cases before any decision can be made. T.W. Lambe (42) has generalised the properties of clay for variation in moisture content at compaction as follows:-

(A) STRUCTURE

(1) Particle arrangement - Dry side more random orientation than at wet of O.M.C.

(2) Water deficiency - Dry side more deficient Hence imbibes more water and swells more. Lesser pore pressures observed.

(3) Permanence - Dry side structure is sensitive to changes

(B) PERMEABILITY

(1) Magnitude - Dry side more permeable

(2) Permanence - Dry side permeability reduced much more by permeation.

(C) COMPRESSIBILITY

(1) Magnitude - Wet side more compressible in low pressure range and dry side in high pressure range

(2) Rate - Dry side compaction helps in more easy consolidation.

(D) STRENGTH

(i) At moulding water content

(a) Undrained test values - Dry side higher

(b) Drained test values - Dry side somewhat higher.

(ii) At Saturation

(a) Undrained test values - Dry side higher if swelling is prevented. Wet side can be higher if swelling is permitted.

(b) Drained test values - Dry side about same or greater by a small value.

(iii) Pore Water Pressure at Failure - wet side higher. From these considerations soils with a high clay content have a very low permissible range and hence diligent and precise control is mandatory.

Ervin E. Nonveiller in the general report on "Compaction Methods and Moisture content for material used in the construction of earth core and supporting fill for earth and rockfill dams" (58) has analysed vividly the importance of placement moisture content giving a review of the opinions of the various soils scientists as below:-

In 1953, Middlebooks, Walker, Little, Penman and Terzaghi mentioned the advantages and disadvantages of the dry and wet placement of soil. Deformability of foundations, characteristics of the material and time schedule of work do affect the decision.

Peterson and Iverson (1953) have reported failures of low homogeneous dams at first filling of the reservoirs wherein material was placed dry of O.M.C. The saturation caused a sudden reduction of volume subsidence and subsequent failure by piping. Terzaghi (1953) has suggested use of proper filter layers by side of cores to avoid chances of piping. If soils placed wet of O.M.C. the effect of pore pressure needs to be accounted in design (as has been explained in Bishop's work in 1953, 1957).

The limits of placement condition is based on the subsidence on saturation at lower limit to the practicability of use of machinery on the higher side.

In areas where the natural moisture itself is great and adverse climatic conditions exist where drying cannot be done, compaction is done wet ofoptimum itself taking care to dissipate pore pressure by slow construction. Bernell of Sweden and Kawakani of Japan indicate such situation in their areas. De Luccia cites the example of 512 ft high Swift Dam where due to heavy number of rainy days wet compaction was adopted. It is felt that when soils containing sandy gravel little silt and clay are used, compacting wet of O.M.C. can give a rational design as higher shear strength quicker pore pressure dissipation is possible.

Embankment of most fine grained soils are stiff and brittle when compacted dry of O.M.C. but the same can take up considerable deformation without cracking.

Discussing the limits for the placement moisture in high rolled earth dams W.G. Holtz (32) states that placement moisture at O.M.C. is not correct for a high dam. With higher moisture, pore pressures increases reducing the strength. The reduced permeability also delays consolidation and causes higher pore pressure. Hence the upper limit is to be based on the tolerable pore pressure.

With lesser moisture, on saturation further consolidation occurs. The limit at which saturation will have no effect on consolidation is considered.

The placement moisture should not be so dry that additional consolidation will take place when the soil mass becomes saturated when fill load is considered.

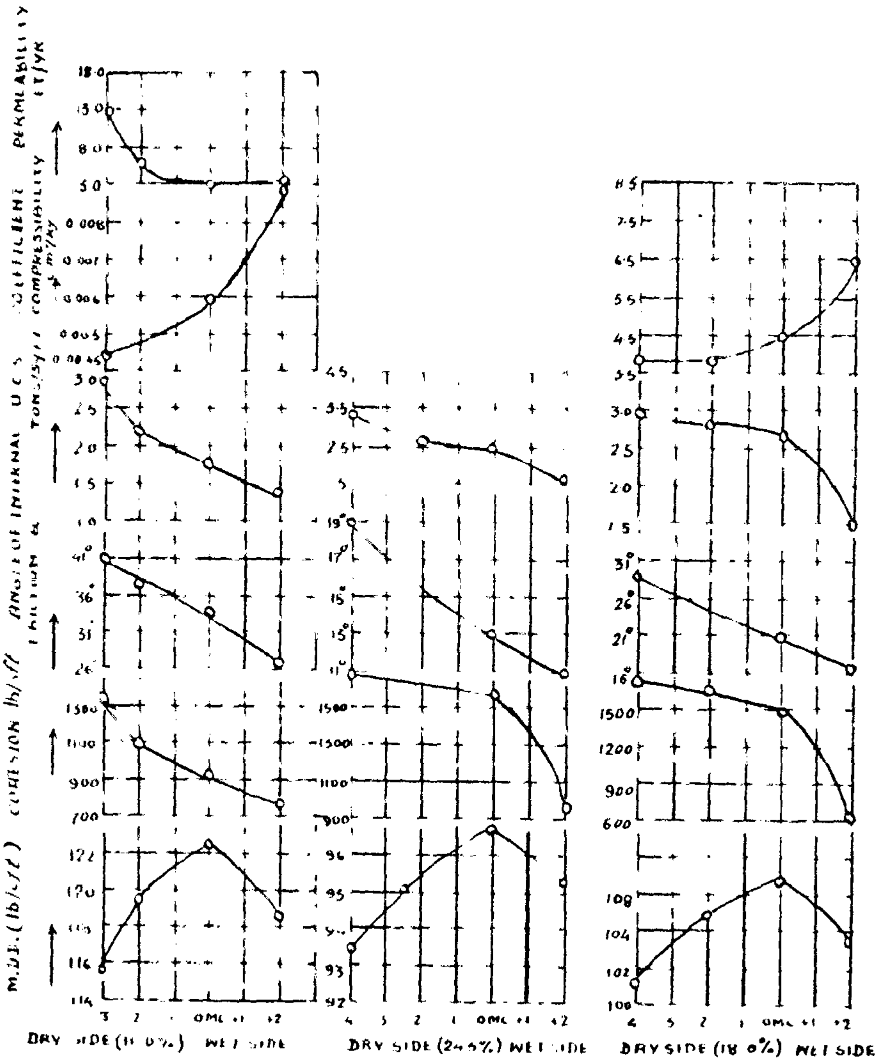
The U.S. Army Corps of Engineers consider the serious problem of cracking and find it proper to compact wet of O.M.C. taking care of pore pressures separately. The U.S.B.R. Engineers prefer to compact it on the dry side taking care of cracking and also saving the cost of pore pressure control and having steeper sections.

R.L. Dewan has conducted studies (17) for placement moisture in earth dam construction. The practical difficulties in bringing the soil to a particular moisture content in the field due to severe wet season and the tropical heat is found to involve not only expense but also hamper the progress. Hence a range of permissible moisture is found essential. Tests on three different types of soils clay, clay loam, sandy loam (CH, SM, SC) have been made. The effect of variation of moisture on the engineering properties is indicated in Fig.17. The results indicate a preference for compaction dry of O.M.C. for clayey soils. Hence a moisture range - 4 to 1 % of O.M.C. is advocated. For sandy soils - 3 to -2 % O.M.C. may be recommended. The percentage increase in compactive effort to attain the M.D.D. may vary from 50 to 100 % for 4 % below O.M.C. and 25 to 50, for 2 % above O.M.C. Similar studies on soil for Hirakud were made (90) and results shown in Fig.18. This indicates that at each site individual studies as above would be found very beneficial.

The placement moisture has therefore to be decided on individual merits knowing the limitations and accounting them for design. Careful consideration of the construction techniques, time schedule for works and also the climatic conditions needs to be made. No definite recommendations except classifying the advantages and disadvantages can be made as a general rule. It is essential under staking individual studies as the economy achieved would be worth the investigations.

4.11. CONCLUSIONS

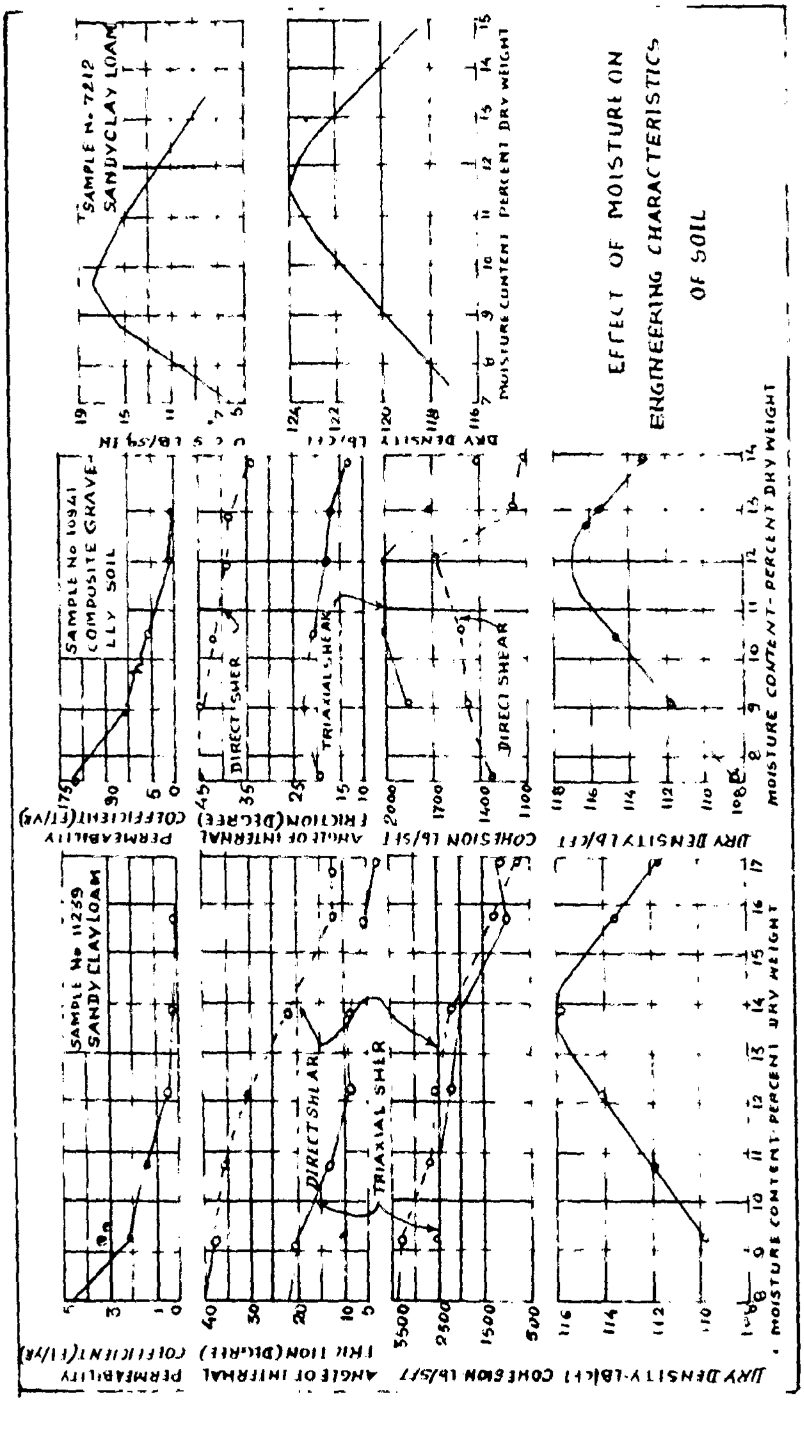
A study of the soils at site regarding the changes in engineering properties with variation of moisture content, compactive effort is essential. From a scrutiny of all the results only can a decision be taken regarding the placement moisture and other allied factors of compaction. In general



17. Showing variation of soil properties under standard proctor's compaction at different moisture conditions
Hatia soil (H 7) sandy loam

Showing variation of soil properties under standard proctor's compaction at different moisture conditions
Hatia soil (H 5) Impermeable

Showing variation of soil properties under standard proctor's compaction at different moisture conditions
Hadua soil (H 3) · clay loam.



18. *Influence de l'humidité sur les caractéristiques du sol* for homogeneous dams of clayey soils greater care is essential. A reasonable range of moisture variation needs to be fixed for quality control. The trend of changes in properties has been discussed individually to arrive at reasonable conclusions.

CHAPTER 5

MODES OF COMPACTION EQUIPMENT AND THEIR RELATIVE BEHAVIOUR

5.1. INTRODUCTION

Selection of the most efficient and economical mode of compaction is an important criterion. In the dams constructed before the advent of machinery, compaction was achieved only by the movement of human and animal labour engaged on the work. Since then there has been a great development in the modes for compaction and a lot of research work has shown the advantages of compaction with machinery. For achieving particular design properties for particular soils at minimum cost, there are generally one or two alternative methods available. A study of the various modes and the factors involved for best compaction would assist in making the correct decision.

5.2. METHODS OF COMPACTION

Compaction of soil in the field is possible by applying pressure in any of the following three ways or a combination of them.

(a) Dynamic action

(b) Static pressure application

(c) Kneading action

The equipment used for compaction is classified under three sub-heads namely

(a) Pressure rolling

(b) Impact ramming

(c) Vibration

Pressure rolling is achieved by the sheeps foot roller, smooth wheeled rollers and pneumatic tyred rollers.

Compaction by sheeps foot rollers provide a combination of the static pressure application and kneading action. The slow speed of the heavy equipment and the varying pressures during the process of compaction respectively give the static effect and the kneading action. With smooth wheeled rollers and pneumatic tyred rollers with a slow speed, an effect of static pressure application is produced. When the speed is great a dynamic effect also is combined.

Impact compaction by various types of rammers provide a dynamic action for compaction. Different types of rammers are in use.

Vibration of the soil for densification is possible by vibratory equipment or by blasting or by new modes of vibration like vibro-floatation. Vibration gives a dynamic effect but with an overburden a static load would also act giving a combined effect.

It will be thus seen that the methods of compaction in field is not necessarily of the dynamic type as adopted in the laboratory. It may be of any one type or a combination. The laboratory test results need to be correlated to the effective compaction results of the field.

5.3. PRESSURE COMPACTION

The different types of rollers in use are discussed below:-

5.3.1. SHEEPS FOOT ROLLERS

The idea of a sheeps foot roller, initially was obtained by the efficient compaction achieved by flocks of sheep which while moving was found to knead the soil into a denser mass. It was in 1905 in California that the first roller of wooden log

3' dia and 8 ft long with rail road spikes (71) was used. In 1912 rollers with feet of 7" long and 4 sq. in cross section were evolved to give unit pressures of 75 p.s.i. Higher unit pressure of 170 lbs/sq inch was achieved in 1928 in the Weber Dam Construction. During 1928-38, 15 U.S.B.R. dams were compacted with unit pressures upto 434 lbs/sq.inch. The weight of roller was increased from 1178 to 2900 lbs/foot length of the drum. Further study led to the idea of loading the drum by ballast for particularly cohesionless soils. Sand and water were used for loading the rollers.

The standard design of an U.S.B.R. sheeps foot roller specified in 1959 is as follows (33)

(1) Tamping rollers must have drums not less than 5 feet in diameter and between 4' to 6' long with space between adjacent drums of 12" to 15".

(2) Each drum to be free to pivot about an axis parallel to direction of transit.

(3) One tamping foot to be provided for every 100 sq. inches of drum surface.

(4) Spacing between the tamping feet must be equal to or greater than 9".

(5) Cross section of feet to be equal to or less than 10 sq. inches at a distance of 6" from surface of drum. It has to be equal to or greater than 7 sq. inch but not greater than 10 sq. inches at a distance of 8" from the surface of the drum

(6) When filled with sand and water, the weight is not to be less than 4000 lbs/ft length of the drum.

(7) Pressure relief valve to be provided on each drum.

(8) The space between tamping feet to be clear of soil that would interfere with compaction.

This equipment commonly used is rugged and is generally suitable for all soils. This is a two drum unit in a hinged frame. When fully ballasted it has a weight of 41500 lbs giving a unit pressure of 490 lbs/sq.inches with 5 % of the area in contact with earth at any time.

These heavy S.F. rollers assist in proper mixing of soil and use of other special equipment for the purpose can be eliminated. Better homogenuity is achieved. These produce rough surfaces for proper bonding. They eliminate local shear failures or slickensides preferably with moisture at dry of optimum. Due to mixing action of feet and roller passes, uniformity of moisture in the material is well achieved.

The economy of use of a heavy S.F. roller is doubted by C.Y. L.I. and Jack Hodge. The effect of the higher effort of compaction decreases very rapidly with increase in moisture content. The results achieved by increased compaction may not compensate for increased cost.

The common type of S.F. roller in use in England (31) was having two hollow cylinders 4' wide, 3'-6" diameter. The steel drums were welded to a steel frame and mounted with projected feet 8" long on its surface in different shapes. Taper foot or club type rollers are the two major types depending on the size and shape of projecting feet. Club foot roller with 4" x 3" feet gives 115 p.s.i./sq.inch pressure with a gross weight of 5 tons ~~p.s.i.~~ A taper foot roller with $2\frac{1}{4}$"x $2\frac{1}{4}$" feet produces 250 p.s.i. pressure with roller weighing $4\frac{1}{2}$ tons.

New types are being evolved by Modifications to the projecting feet in different ways to suit requirements. "Elephant foot type roller" is evolved at Ukai Dam in Gujarat by providing much flatter feet to the rollers for efficient compaction of finer soil./ Fundamentally, compaction by S.F. Roller depends on the foot pressure and the coverage of ground obtained per pass. The gross weight of the roller, the area of each foot, the number of feet in contact with ground at any instant account for the foot pressure. They are essentially towed by any of the types of tractors (commonly cra-wler type) with easy manoeuverability and at a speed of about 4 miles per hour.

The tamping feet of the S.F. roller first penetrates the loosely spread layer. Initially the soil takes up the load of roller but the lower layer is compacted by the tamping feet. On successive passes the top layers also get densified thus reducing the penetration of the tamping feet. Finally the roller drum lifts off the surface which is termed as "the roller walking out". About 100 to 500 cu. yards of soil may be compacted per hour by a double drum roller.

Special type of self propelling S.F. rollers (71) are being produced to accelerate compaction rate. U.S.B.R. have used a four drum self propelled roller in Twitchel Dam in California in 1958. The possible higher speed of 6 miles/hour and the easier operation and movement in both directions have resulted in a uniform compaction with saving in time.

5.3.2. SMOOTH WHEELED ROLLERS

The smooth wheel roller may be the three wheel roller type of 1½ to 18 ton weight or tandom rollers of 1 to 14 tons or the heavier three axle tandom rollers weighing 12 to 18 tons. By ballasting the roller or by adjustment of sliding weights the pressure on soil can be adjusted.

The smooth wheeled rollers apply the pressure at the surface and compaction is achieved by repetition of the load.

The smooth wheeled rollers are replaced by heavier and more efficient pneumatic tyred rollers where higher unit pressures are possible and better manoeuverability is achieved. Smooth wheel rollers are common in road embankments in the country and for minor works where better equipment involves cost. A variation of the smooth wheel roller recently introduced is the grid roller. A heavy mesh replaces the steel wheel. It is particularly useful where some degradation of the coarser material is required during compaction (23).

5.3.3. PNEUMATIC TYRED ROLLERS

Initially during 1930s, the small rubber tyred roller of 6 to 8 tons came to be used. The rubber tyred rollers also apply the pressure only at the surface (though it sinks slightly in the initial few passes because of the tyres). The unit pressure depends on the air pressure in the tyres. The gross weight of roller is a secondary factor.

The usual type of a pneumatic roller consists of a box or platform mounted between axles. The front axle is made to have one wheel less than the rear and the wheels are so arranged that rear wheels do not travel on the tracks of the front wheels. A slight tilt is given to the wheels which causes a kneading action and this principle is adopted in Wobble wheel rollers.

A 12 ton roller with 4 front and 5 rear wheels giving a tyre inflation pressure of 36 lbs/□" was in common use in England. A 50 ton heavy roller is commonly adopted now in U.S.A. for compacting earth fills. The first major dam constructed with this roller was in 1949 (Look out point dam, Oregon). The roller (71) had a minimum 4 wheels with pneumatic tyres capable of operating at air pressures varying from 80 to 100 p.s.i. under full wheel load. The body is segmented in such a way that it can be ballasted to atleast 25000 lbs/wheel. With heavy rubber tyred rollers, the density of embankment may be increased in deeper layers by repeated passes. S.F. roller weighing 4000 lbs/ft is found to compact to a depth of 3 feet but a rubber tyred roller weighing 15000 lbs/ft compacts to much greater depth. The rubber tyred rollers are found to compact 500 to 1000 cyds/hr depending on roller speed which is about 2 - 4 m.p.h when driven by a crawler tractor or about 8 m.p.h. when towed by a pneumatic tyred tractor.

5.4. IMPACT COMPACTION

Wherever the space is limited for the convenient roller compaction, impact compaction has to be resorted to. Connection between abutments or masonry structures with the earth work or trenches of small width need impact compaction. Earth work in steep rocky slopes are possible to be compacted by impact methods. Though a slower and costlier process, it is useful in such situations.

The most primitive of this type was the compaction by wooden rammers, worked by labourers. The use of dropping weight as for piles is of recent origin for earth dam construction. Modern types of rammers are of pneumatic or internal combustion type. From rammers weighing ½ ton with a base diameter of 2'-5" is found to give the maximum dry densities as from standard Proctor's test in 2 to 4 passes. This is found to compact 40 to 100 cubic yard/hour. Compressed air tampers, light or heavy wheeled tractors with tamping feet, are also adopted for impact compaction.

5.5. VIBRATORY EQUIPMENT

Vibration as one of the means for compaction was initiated by Germans. Providing vibration to a soil mass produces a densification. These vibratory equipment are found to be essential for gravelly soils inspite of their cost. Great improvements are anticipated by research and competition. Vibratory equipment may be surface vibrators or internal vibrators. Surface vibrators used in earth fill may be classified as flat plate vibrators or roller vibrator. Flat plate vibrators are used effectively for compacting cohesionless soils. The depth of compaction is reported to be equal to twice the width of vibrator base. For cohesive soils, the maximum is found to be half this value.

Roller vibrators have the advantage of speed and are easily manoeuverable. But the depth of compaction is shallow and their speed may be too great to develop resonant action between the soil and roller.

Studies on vibratory equipment were conducted in 1958 by Road Research Laboratory in Middlesex (45). As the vibratory rollers are much lighter than conventional dead weight rollers the economy of their use for all types of soil was studied. The table No.2

indicates the type of rollers and their performance in field tests Following conclusions are drawn from the study of the vibratory rollers and vibratory plate compactors:-

(1) M.D.D. is found to increase with additional static load O.M.C. is decreased. A 2½ tons vibrating roller was found to have the efficiency of the 8 tons smooth wheel roller.

(2) The vibratory roller requires greater amount of passes than vibratory plate compactor in the ratio of 10:3

(3) Plate compactors are more efficient in compacting to greater depths and the state of compaction increases with higher weight. Heavy compactors are found efficient on cohesive soils also.

(4) Frequency range of 2200 - 2400 cycles/minute in the 2¾ tons roller was found to give greatest efficiency.

(5) Vibratory rollers are gaining importance even in U.S.A in recent times. Vibratory attachments to either smooth steel drum rollers or rubber tyred rollers are made e.g. Naraj Dam (1959) Newjersey Dam (1961).

The use of heavy vibrators of as much as 24 tons weight is made in Germany. This vibrator mounted on tractor is found to compact layers of sandy soils of 7' feet thick at the rate of 5000 sq. ft. per hour. The practice in U.S.A. is also to use frog rammers of bottom dia 9.5 inches raising 14" in air producing a compaction energy of 240 lbs/sft. In Scandinavia, a vibrating sledge which imparts blows at frequent intervals by the rotation of an imbalanced wheel mounted on it, is used (8).

Vibratory Rollers	Sl. No.	Total weight in tons	Power/Fuel	Average speed during compaction in ft/min	Length & width of vibrating plate	No of Passes needed	Depth of compacted layer in inches	Cutput in Cyd/hr
VIBRATORY ROLLERS								
Vibration by single rotating shaft having an cut of balance weight mounted within Vibrating roller	1	0.21	1.3(petrol)	30	21 x 24	8	3	3.5
	2	0.34	2.7 -do-	60	22½ x 28	12	6	11
	3	0.97	5.5 -do-	67	26 x 32	4	6	41
	4	2.4	10.0 -do-	42	30 x 32	4	6	26
	5	3.8 (Towed)	36 (Diesel)	120	48 x 72	6	10	180
	6	3.8 (Tandom)	25 -do-	73	35 x 39½	4	7	57
VIBRATING PLATE COMPACTOR								
Two counter rotating shafts each having one or more out of balance weights	1	0.2	4.5(petrol)	28	19 x 15	3	6	11
	2	0.66	6.0(Diesel)	53	27 x 24.5	4	6	33
	3	0.70	6.0 (petrol)	42	24 x 24	2	6	39
	4	1.5	10.0 (Diesel)	25	32x5x30	2	12	58
	5	2.0	8.0 -do-	27	50 x 34	2	12	71

The machine is assumed to operate 50 min/hour. The 3¼ ton vibrating roller is found to be the best.

5.5.2. COMPACTION BY BLASTING

Compaction by blasting is suitable for sandy soil foundations. The loose material is detonated by buried changes of explosives causing disturbance and hence densification. From Laboratory tests the density required is initially fixed. The material consolidates due to the vibratory forces during blasting.

Charles E. Hall (10) of International Engineering Coy has arrived at some conclusions to decide the mode of blasting from several field tests.

(1) Repeated blasts are more effective than a single large blast or several small charges blasted simultaneously

(2) Each blast should be small enough not to rupture the sand surface.

(3) The top layers are left without densification and small charges are effective for the top layers.

(4) Compaction gained by repetition of the blast more than 3 times is small.

(5) Compaction of 85 to 96 % of modified A.A.S.H.O. values are possible. The void ratio can be reduced from 0.9 to 0.7 and relative density increased from 50 to 80 %

The recommended procedure for blasting sands under water is as follows:-

(a) The sand fill is dewatered to a level 5' below top.

(b) Charges are to be placed by jetting at 20' spacing horizontally in 3 tiers at about 15' height.

(c) Size of charges may be 8 lbs of 30 % special gelatine For top layers 3 to 5 lbs is considered sufficient.

(d) The lower tier is detonated first followed by middle and top tiers.

(e) The second coverage is done with single layer placed midway between the middle & bottom tiers.

(f) Tests are conducted for settlement, density by penetration tests by a 2" core pointed at end.

(g) Compaction considered satisfactory when surface settlement is 5 % depth of sand. Penetration test should not reveal any soft layer. Density should be more than the required value.

Explosive sticks $1\frac{1}{8}$" x 8" weighing an average of 0.42 lbs with the dynamite wrapped in bundles is lowered through a 3" casing pipe fitted into sand. The bottom bundle is provided with electric primer. Casing pipe is withdrawn after dynamite is tamped and then back filled with wet sand.

The blast will cause the surface layer to rise by 6" initially and then rest with concave appearance. Gas and water will come out after a minute for about 30 minutes.

It is agreed by C.E. Hall and W.J. Turnbull that this method though not very popular for cohesionless soils is particularly suitable for under water compaction. Fears are expressed by W.H. Gotolski and Zolkov (26) about decreased strength and liquefaction due to sudden shear deformation causing high pore pressure.

The compaction by blasting is successfully achieved at Kingsley Dam in Nebraska, at Franklin Falls Dam in New Hampsshire, at Karanfauli Dam 200' high under construction in Pakistan. Dennison Dam and Almond Dam

A.K.B. Lyman (48) mentions the advantage of reduction in horizontal permeability. Saturation of soil is considered to be conducive to better results. Explaining the liquefaction occuring just after blast it is clarified that this causes water to escape to surface facilitating rearrangement of particles. No limitations of depth are considered except that for less than 30 ft deposits, one tier considered satisfactory. At Franklin Falls Dam, the optimum compaction is reported with charges of 8 lbs of 60 % dynamite at a depth of 15' from surface.

The cost of compaction is found lesser than that of vibrators or pile driving or the alternative replacement of material. This is found to give extra strength with increase in the value of angle of internal friction.

5.5.3. VIBROFLOATATION METHOD

Vibrofloatation is another modern method of compacting cohesionless soils in foundation. S. Steurman (31) of Germany developed this method for compacting soils at great depths. The first field test was done by T. Mogami in Japan in 1954. It was adapted for large scale construction in 1957. The vibrofloat is driven inside by forcing water into surrounding sand. The vibrator is jetted into required depth. The vibrofloat compacts the soil during the upward movement combined with the action of water jets (84).

The grain size of the soil is found to be an important factor. Vibrofloats are developed to suit individual site condition. Details of one such vibrofloat given by Watanabe (91) is as below:-

Length 8 to 10 metres

Diameter about 22 cms

64960

Number of jet Nozzles	3 at bottom
	3 at top of vibrator
Electric motor	7.5 H.P.
Number of Revolutions	1750 r.p.m./60 cycles
	1450 r.p.m./50 cycles
Eccentric load	12 to 15 Kg
Eccentricity	About 3 cms

Total weight of Vibrofloat = 1 ton

Spacing of penetration was 1.2 to 1.5 metres in triangular pattern. The amount of water used for penetration was 300 - 350 g/minute and for compaction 250 - 300 g/minute. Compaction is performed in 50 cm depths in about 1.5 to 3 min/step. Volume of added material during compaction was 10 to 20 %.

Compaction was found to be proportional to the product of eccentric moment and cycle of vibration.

$$S \propto MW$$

Where S = Settlement

M = Eccentric moment

W = Cycle of vibration

The method is most suitable only for clean sands. The results are considered disappointing when clays and silts are combined with it.

Dr. G. Viering (88) has analysed the process of compaction by vibration. The effect of acceleration on compaction is found to depend on static pressure. Upto a certain value of acceleration the same degree of compaction is supposed possible. The process of compaction is initiated only after a certain critical value of acceleration is exceeded.

D'Apdlia and others have studied (14,15) sand compaction by vibrofloatation. Following conclusions may be drawn.

(1) Compaction of a single vibrofloat does not increase relative density above 70 % at points more than 3 feet away from the vibrofloat.

(2) Overlapping effect of vibrofloat spaced further than 8' apart is small.

(3) Superimposing the effects of compaction is possible.

(4) Spacing of vibrofloats at 6' or less are recommended for efficient compaction.

Vibrofloatation compacts sands by two motions. An impulsive radial movement that pushes sand and another due to vibratory motion.

Compaction of sand at resonant frequency (13) is shown to give 90 to 95 % of compaction of modified A.A.S.H.O. test values. It is concluded that:-

(1) The operation of vibrator at resonant frequency is the key to problem of obtaining maximum compaction of sandy soil.

$$\text{Frequency of vibrator in cycles/sec} = \frac{1}{2\pi}\sqrt{\frac{Kg}{W}}$$

Where K = Spring modulus lb/in

W = Weight of vibrating body

g = Acceleration due to gravity

(2) With a proper oscillator design the compaction is achieved to a depth of twice the width of oscillator.

Terzaghi & Peck (84) mention that if frequency of vibrations is equal to critical frequency of soil the settlement due to compaction is 20 to 40 times greater than by a static load equivalent to pulsating force.

5.5.4. Compaction by driving piles is suitable for loose sand foundations. The surface settles reducing porosity of the soil. The cost involved is high and is not suitable for the top 6 feet layers. Short stubby piles in small areas are found to increase the density of the soil to the safe value of relative density of about 70 %. For providing designed foundation, bearing piles are designed and they are driven until the necessary resistance or the designed depth is obtained. They are driven by gravity or steam or air hammers or even gasoline driven hammers. Detailed sub-surface investigations are essential to study possible heavy settlements due to weaker layers existing in the pressure bulb. Negative skin friction may develop. Piles are more useful for soils above water table and their zone of influence is limited depending on depth.

5.6. RELATIVE BEHAVIOUR OF MODES OF COMPACTION

The most common method of compaction is by rollers. The possible compaction depends on the following factors (71)

(a) Roller type and weight

(b) Thickness of compacted layer

(c) Number of roller passes

(d) Roller speed; &

(e) Soil water content

The specification should include other important factors namely uniform spreading, proper blending of moisture with the soil and good bonding with subsequent layer. Auxillary equipment like dozers, water tankers, scarifiers, harrows and the like are essential to satisfy the requirement.

The Road Research Laboratory, England and the Army Vicksburg Experimental Station have conducted research work on different types of rollers to decide the layer thickness, number of passes and the effect of speed on various soils.

5.6.1. COMPACTION BY SHEEPS FOOT ROLLERS

Sheepsfoot rollers are rated generally in terms of the pressure exerted by the feet assuming one row of feet in contact with the embankment. Generally a 6" layer of soil compacted with 6 to 12 passes give the required density. With a little extra rolling slightly higher density and better uniformity is possible. Hence 10 to 12 passes are generally recommended. Though S.F. rollers do give an additional compaction to about 3' depth, 6" layers are desired. Lower the water content greater is the influence of compacting to depths. The effect of speed of rollers does not have any great effect on density. The normal speed of 4 m.p.h. is adhered to when driven by crawler-type-tractors. The advantage of higher speed or the self propelled rollers is in the saving of time with slightly better uniformity.

Turnbull and Foster (79) have made studies on test embankments to find out the effect of size of sheepsfoot and roller passes on the density and optimum moisture content. Tests were conducted on silty clay with sheepfoot rollers of 4000 lbs, 28000 lbs 42000 lbs weight giving 250 p.s.i. pressure. The roller was of 60" dia x 66" long drum with 120 sheepfoot in 30 rows. Fig.19 and 20 indicate the results. The following conclusions may be drawn.

(1) Increasing the foot size increases M.D.D. and reduces O.M.C.

(2) With number of passes density increases with reduction in O.M.C.

Road Research Laboratory, England have conducted work on four different types of soils by two types of sheep foot rollers. The 5 ton club foot roller gave 115 p.s.i. pressure and the 4½ ton tapered foot roller produced 250 p.s.i. pressure. Following conclusions are observed:-

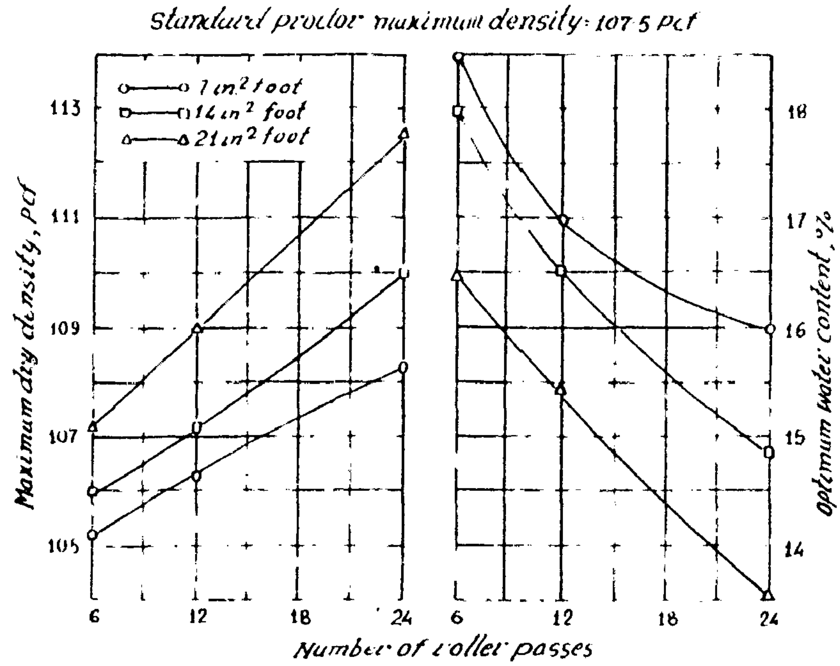
(1) The density goes on increasing with compaction by club foot roller upto 64 passes. In case of heavy clay a maximum density was achieved after about 32 passes (Fig.21)

(2) A tapered foot roller was found to give higher densities with lesser number of passes for all soils except heavy clay. 64 passes were needed to achieve the density as obtained by club foot type in 32 passes (Fig.22)

(3) The effects of variation of moisture and the number of passes of the tapered foot roller on density for a heavy clay is shown in Fig.23 The O.M.C. of 21 % is found to give maximum densities within 16 passes. O.M.C. was found to reduce to 16 % for 64 passes of the roller.

A general relation of the compaction curve for four different soils for compaction by 64 passes of a 4½ ton taper foot S.F. roller is shown in Fig.34.

S.J. Johnson and Shokley (37) suggest that the selection of sheepfoot rollers should be made by regular field tests. The effect of roller foot pressure and size of feet on different



19. Influence of number of roller passes and foot size of sheepsfoot roller from test embankments on silty clay. In all cases the roller foot pressure is 250 p.s.i. (after Turnbull and Foster, Ref 402)

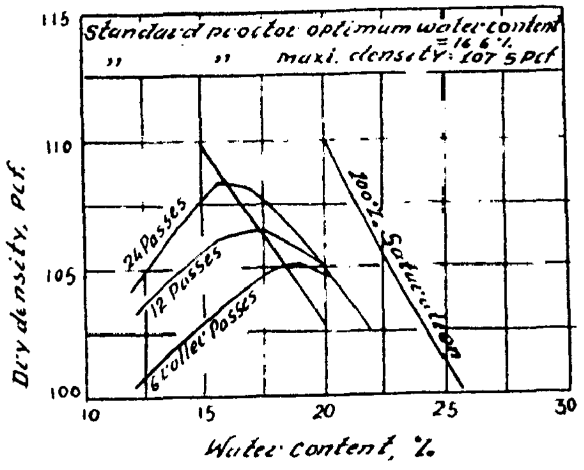


Fig N 20. Water content density curves for 250-P.S.I. Sheepsfoot roller from test embankments on silty clay (after Turnbull and Foster, Ref. 402)

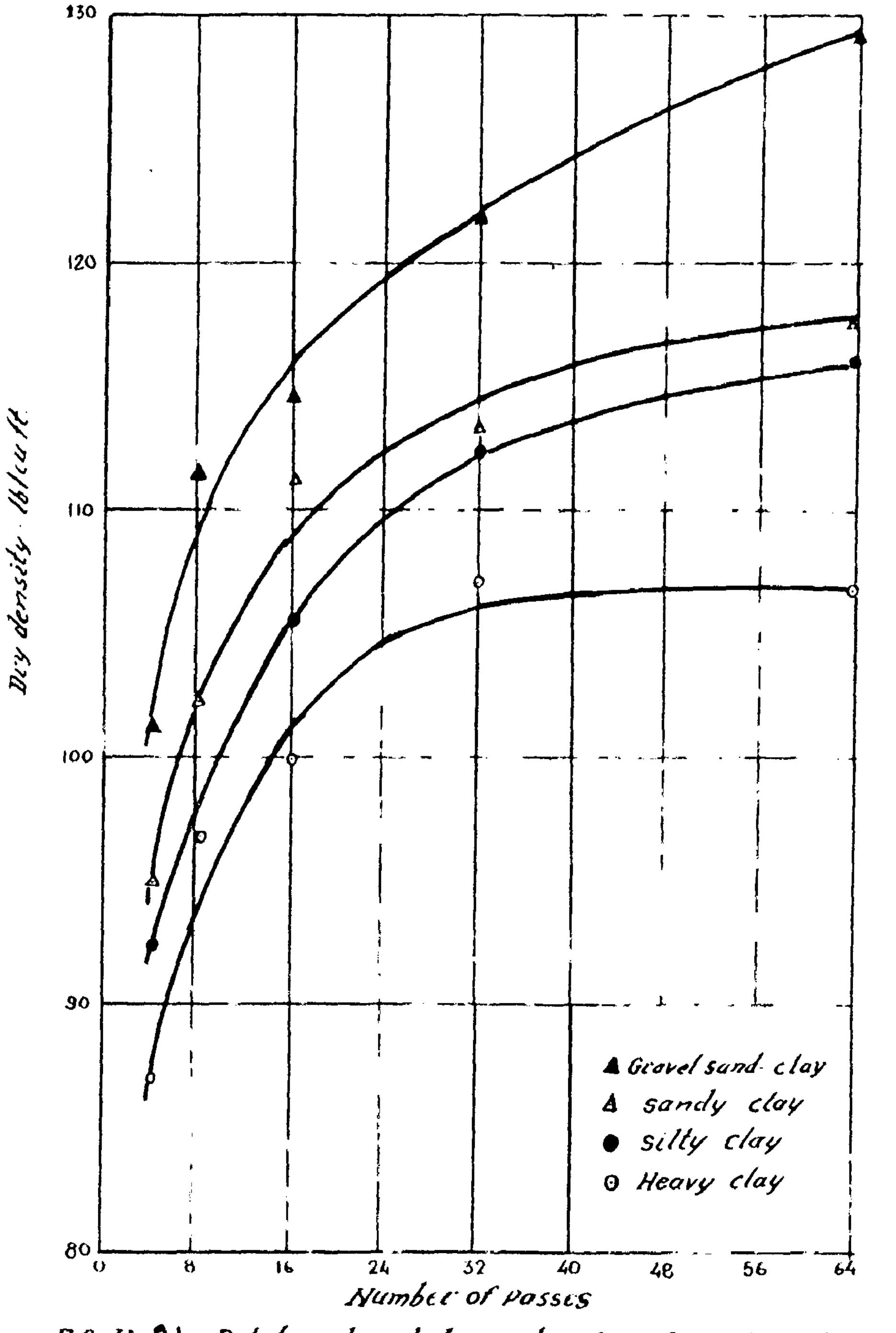


Fig No 21. Relationships between dry density and number of passes of the 5 Ton club foot sheepsfoot roller for four different soils when compacted in 9 in. Loose layers at or just above their optimum moisture contents for roller compaction.

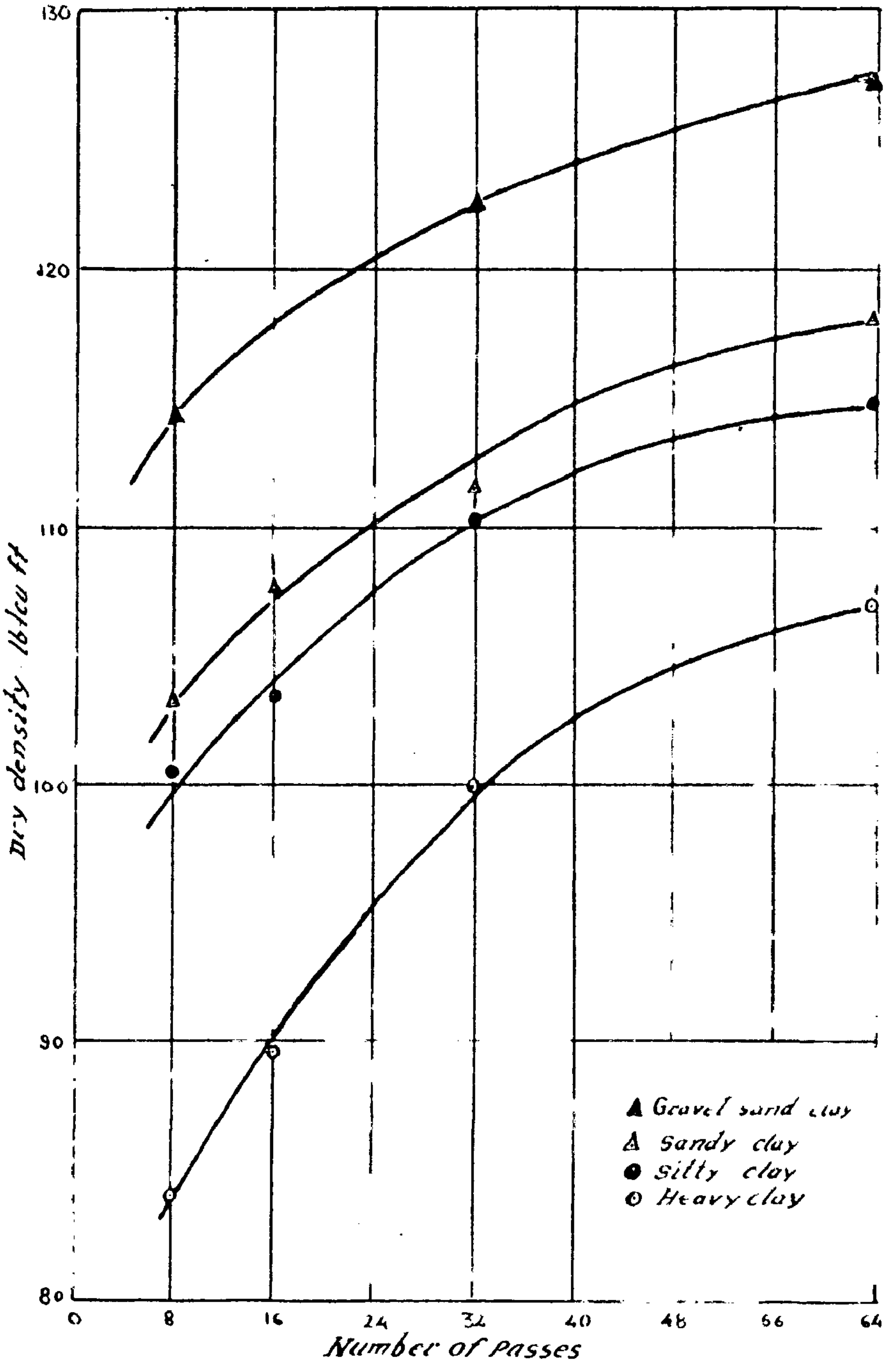


Fig. No 22 Relationships between dry density and number of passes of the 4½ Ton taper foot sheepsfoot roller for four different soils when compacted in 9 in. Loose layers at or just above their optimum moisture contents for roller compaction

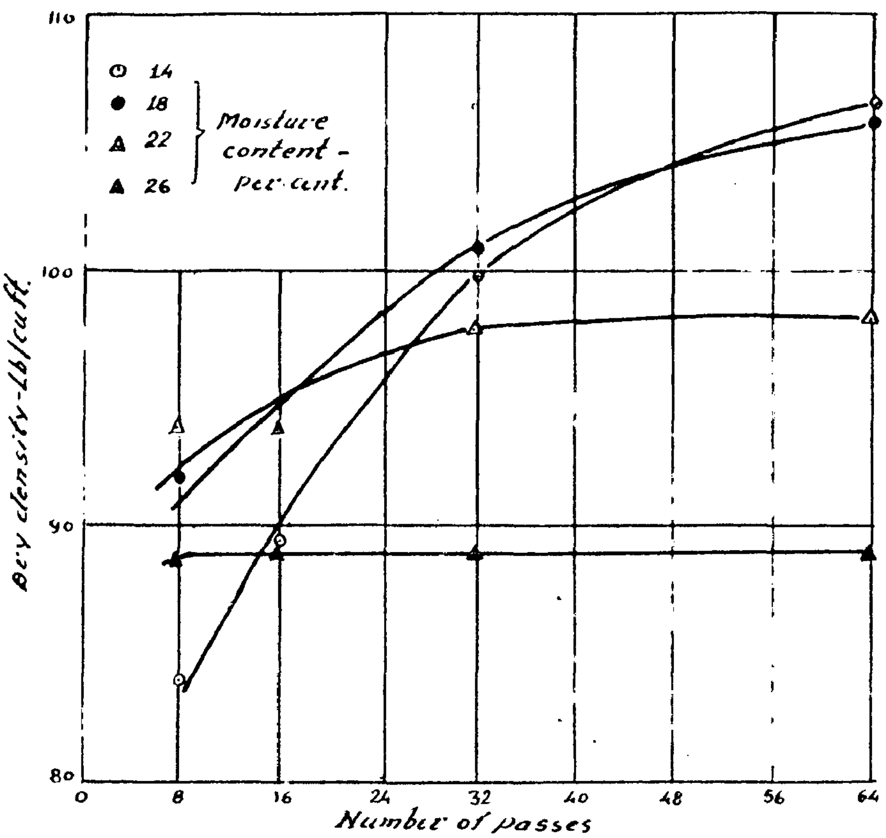


Fig. No 23 Relationships between dry density and number of passes of the 4 1/2 Ton taper-foot sheepsfoot roller for a heavy clay when compacted in 9 in. Loose layers at different moisture contents.

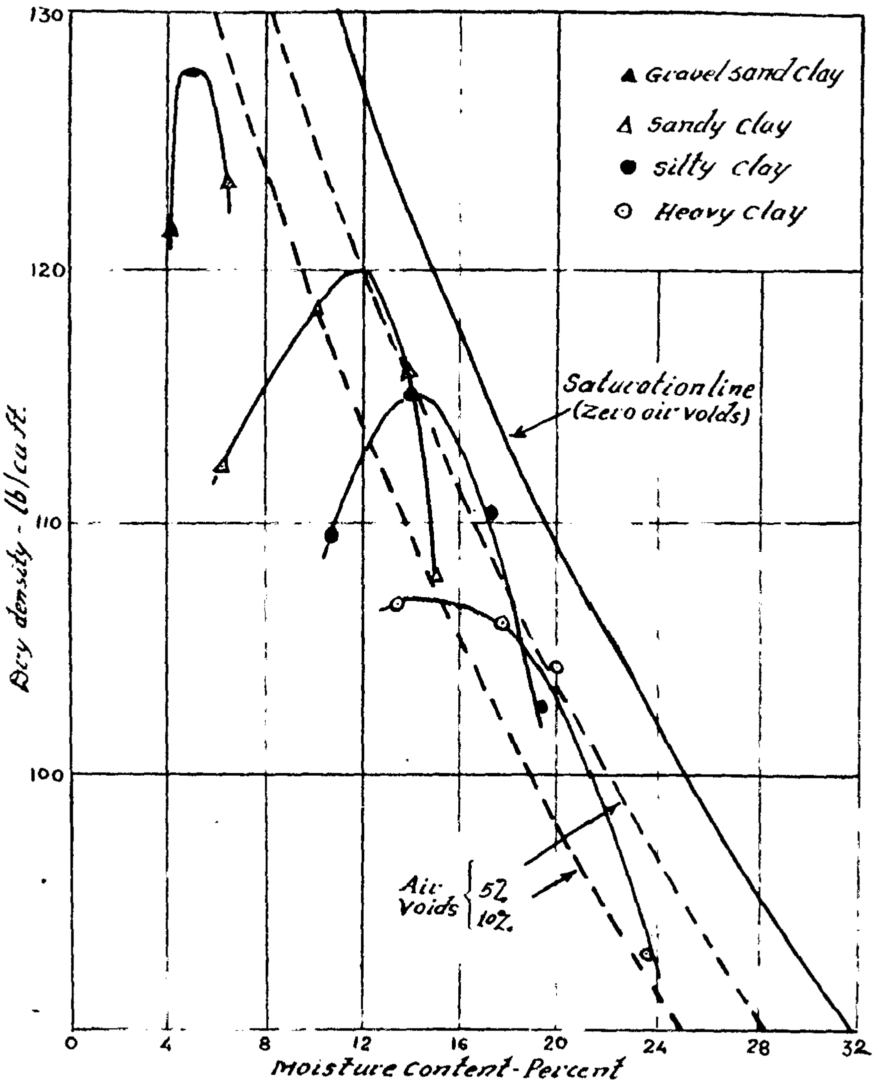


Fig No. 24. Relationships between dry density and moisture content for four different soils when compacted in 9 in. Loose layers by 64 passes of a 4½ Ton taper-foot sheepsfoot roller soils vary in individual cases.

J.W. Hilf (29) has mentioned that if the feet penetrated on an average atleast 4" less at the 12th pass than that initially the roller was considered to walk out. If the reduction in penetration is less than 2" walk out is reported to have not occurred. The walk out is not considered a means of the measure of compaction. The advantages of a walk out are

(1) More effective construction control is possible

(2) The roller can be pulled more easily

The disadvantages are:-

(1) There is no evidence to indicate that the walking out increases overall density as a lighter roller may walk out without full compaction.

(2) Determining proper weight, area of feet for each type of soil moisture condition will be time consuming if quality control is to be based on the roller walking out.

Field tests have been conducted by W.J. Turnbull and Shockley (81) on compaction of lean clay soil by sheepfoot rollers and pneumatic tyred rollers. It is concluded

(1) The sheepfoot roller with 14 sq. in size is ideal.

(2) Increase of tyre pressure from 50 to 150 p.s.i. resulted in substantial increase in density and reduction in moisture content.

(3) Increase in number of passes is found to give a pronounced increase in density in case of S.F.

(4) Variation of sheepfoot size with the same pressure is found to have no significant effect on density.

(5) Rollers are found to walk out on soils only at or dry of field O.M.C. and not at wet of O.M.C.

5.6.2. COMPACTION BY PNEUMATIC TYRED ROLLERS

Pneumatic tyred rollers are coming into prominence since about 1930. Rubber tyred rollers range in size from small wobble-wheel rollers of 6 to 8 tons capacity to the heavy 200 ton rollers. Tyre pressures vary from 30 p.s.i. to 150 p.s.i. The contact pressure between the tyre and the soil can be easily varied in this case. An increase in contact pressure gives an increased compactive effort.

Tests have been conducted (71) by Army Vicksburg Waterways Station on a silty clay by compacting with 50 ton rubber tyre roller in 9" layers. A summary of field densities and O.M.C. is indicated below:-

TABLE 5

Lab. value from Proctor's Test
O.M.C = 16.6 % M.D.D. = 107.5 lbs/cft

Roller Passes	150 p.s.i. Tyre Pressure		90 p.s.i. Tyre Pressure		50 p.s.i. Tyre Pressure	
	O.M.C.	M.D.D	O.M.C.	M.D.D	O.M.C.	M.D.D.
4	16.0	113.5	17.7	110.5	19.7	107.0
8	15.3	115.0	17.2	111.2	19.0	107.5
16	14.7	116.5	17.0	111.5	18.8	108.0

The compaction curves with 8 passes of roller is shown in Fig.25. The effect of variation of moisture content on density with varying passes is indicated in Fig.26.

Turnbull and Foster (79) conclude from the above test results as follows:-

(a) Air pressures in the tyres have a major influence. The 50 ton roller with a tyre pressure of 90 p.s.i. provide more or less Proctor's test values.

(b) On the dry side of O.M.C. there is an increase in density with tyre pressures and coverages but on the wet side of O.M.C. the increase is little.

Turnbull & Foster (82) mention that for compaction of soil with rubber tyred roller the increase of tyre pressure within practical limits is more effective than increasing number of passes. An increase of pressure from 50 to 150 p.s.i. is found to produce an increase in density of about 8 lbs/cft for about 16 passes. The field O.M.C. for rubber tyred roller is higher than the laboratory value slightly with heavier compactive effort and more at lower effect

5.6.3. COMPACTION OF SHEEPS FOOT ROLLER AND PNEUMATIC ROLLER COMPACTION

The Army Vicksburg waterways experiment station have made studies as detailed earlier on both types of rollers on a silty clay. It is probable that the general relationship is same for all fine grained soils. From the results it can be concluded that (71)

(1) The field O.M.C. for both sheep foot roller and rubber tyred rollers correspond generally

to the laboratory values of standard Proctor's test.

(2) The sheepsfoot roller compaction was found to give a less saturated mass than the rubber tyred roller (Fig.27). Optimum conditions for S.F. roller was achieved at 80 % saturat-ion whereas for rubber tyred rollers 90 % saturation gives the optimum.

(3) Increasing the number of passes has the same effect as increasing compactive effort. O.M.C. is reduced and M.D.D. increased.

(4) Roller speed does not materially change the density. Lesser passes at slow speed would give same results as greater passes at higher speed. The saving in time may not compensate the cost involved.

The main advantages of compaction by sheep foot roller are as follows:-

(1) Larger chunks are more easily broken.

(2) Adjustment of moisture content, either wetting or drying is possible during compaction.

(3) Better fusion with the next layer is possible as the top surface is loose. Scarifying would not be separately needed.

(4) Work can be done even when the soil is at a greater moisture content.

The rubber tyred rollers are having the following advantages:-

(1) Quicker work is possible saving time and money due to lesser passes needed for compaction.

(2) Regular maintenance during compaction of gravelly soils as for sheepfoot roolers is eliminated.

(3) Better compaction at junctions of concrete structures with embankment is possible.

(4) 9" thickness of lifts may be adopted with heavy pneumatic tyred rollers particularly for cohesionless soils.

(5) Construction work during rains is possible as the surface does not get slushy as with S.F. roller compaction.

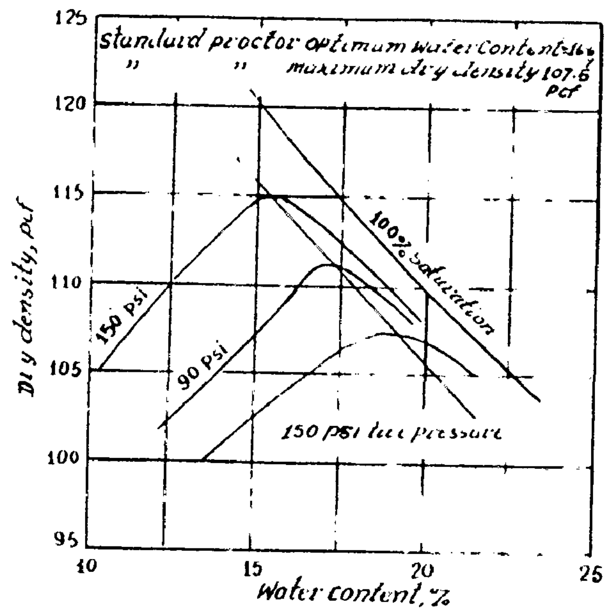
The relative advantages need to be studied in particular cases. Rubber tyred rollers generally are more useful for soils containing large cobbles and rock pieces. A combination may also be used with advantage.

5.6.4. COMPACTION BY OTHER MODES

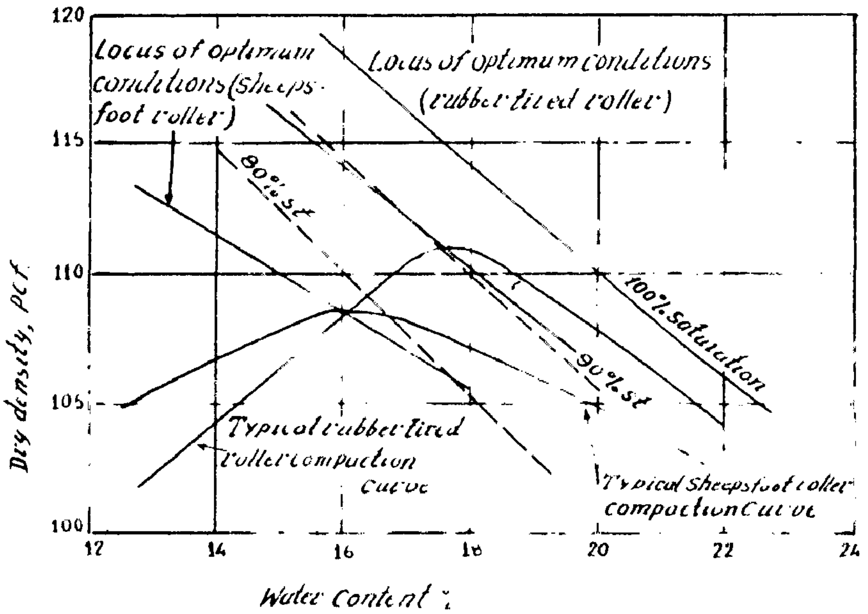
A study on five different soils was made by the Road Research Laboratory Middlesex (31) to study the effect of variation of passes for compaction by different modes. The grain size curves of soils studied is shown in Fig.28.

Compaction by 8 ton and $2\frac{3}{4}$ ton smooth wheel rollers indicate an increase in density for the first 8 passes (Fig.29) with a gradual increase for further passes. Similar results are obtained for compaction, by pneumatic tyred rollers (Fig.30).

Compaction by a Frog rammer of $\frac{1}{2}$ ton weight is found to give maximum densities with only 2 to 4 coverages (Fig.31).



25. Water content density curves for eight passes of rubber tired roller with different tire pressures from test embankments on silty clay (after Turnbull and Foster, Ref. 415)



27. Relationship between sheepsfoot and rubber tired roller compaction from test embankments on silty clay (after Zeyatra, Ref 564)

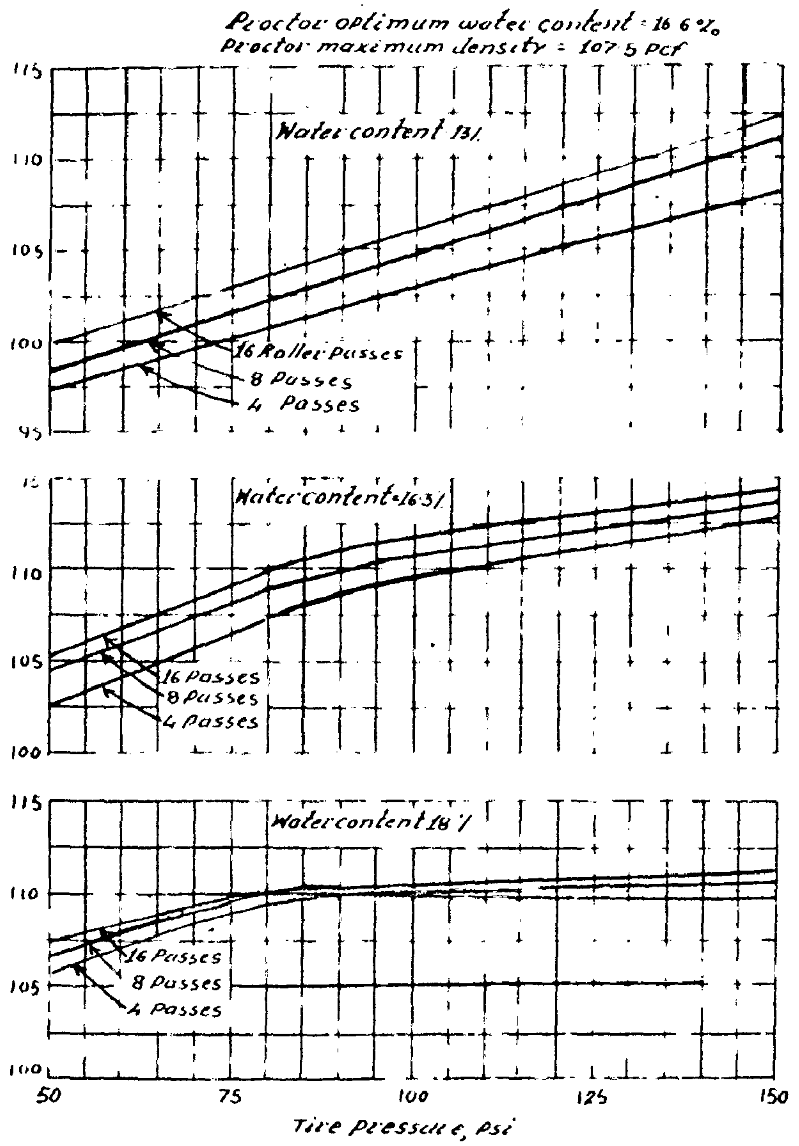
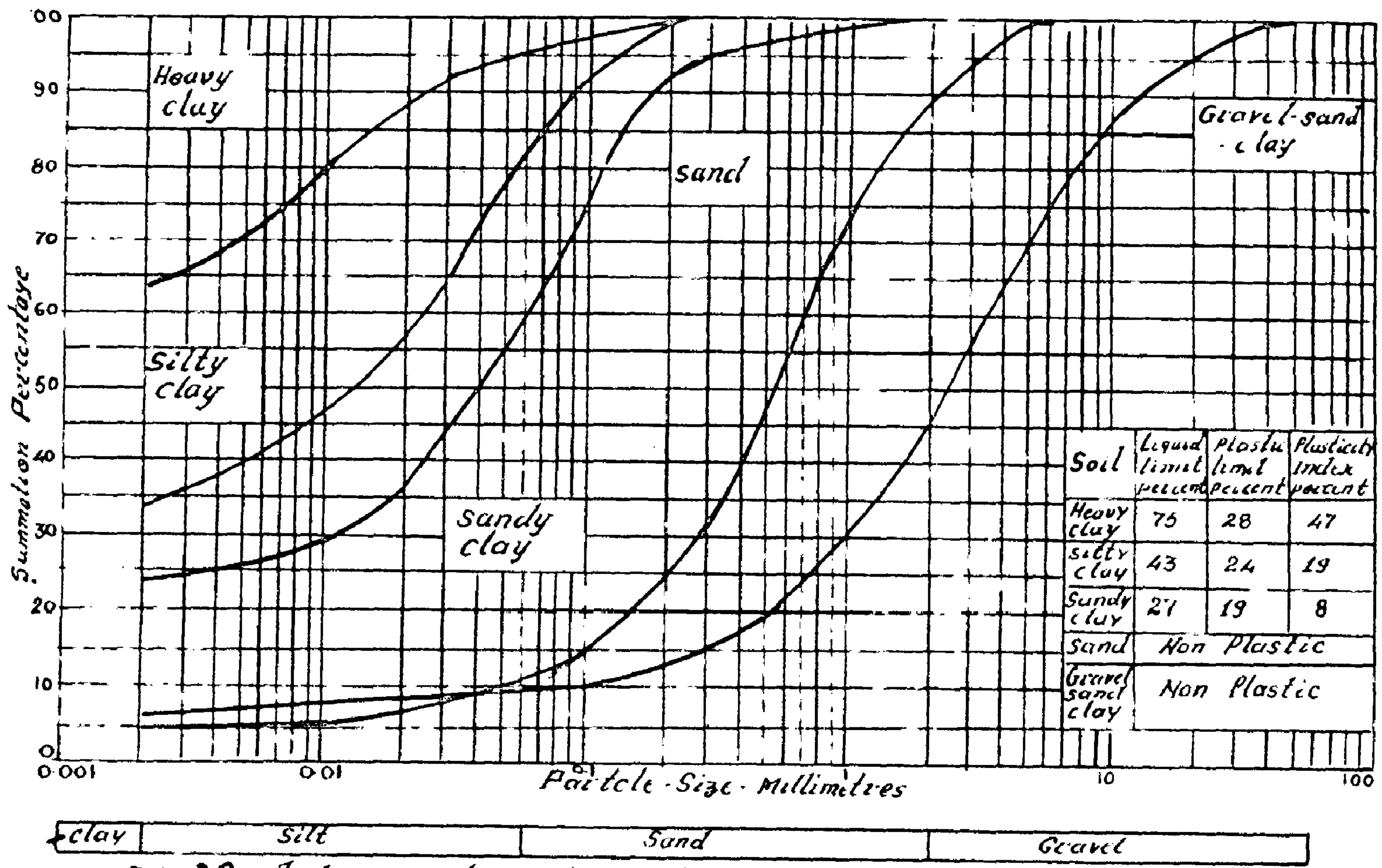
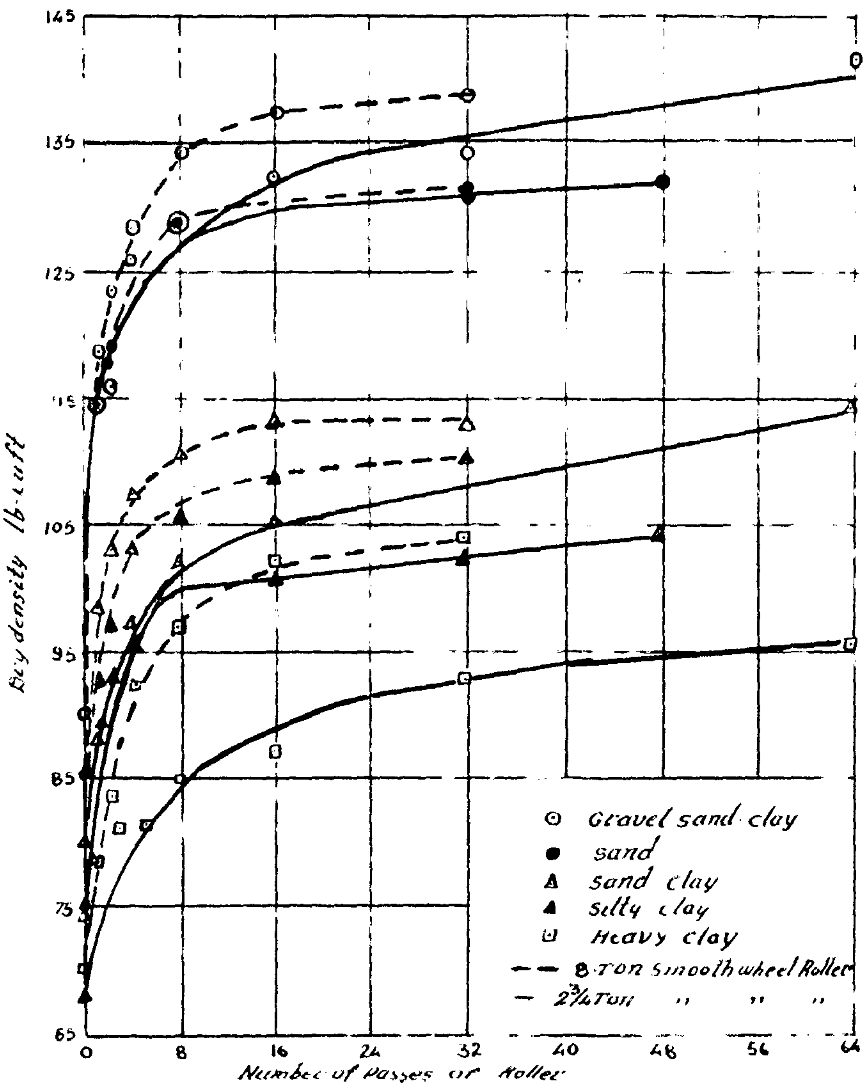


Fig No 26. Influence of tire pressure and number of roller passes on dry density of silty clay (after Turnbull and Foster, Ref. 415)



Soil	Liquid limit percent	Plastic limit percent	Plasticity index percent
Heavy clay	75	28	47
Silty clay	43	24	19
Sandy clay	27	19	8
Sand	Non Plastic		
Gravel sand clay	Non Plastic		

Fig. No. **28.** Index properties and particle size distribution of soils used in covered track



29. Relationships between dry density and number of passes of the 8 ton and 2¾ ton smooth wheel rollers for five different soils when compacted in 9-in. Loose layers at or just above their optimum moisture contents for roller compaction

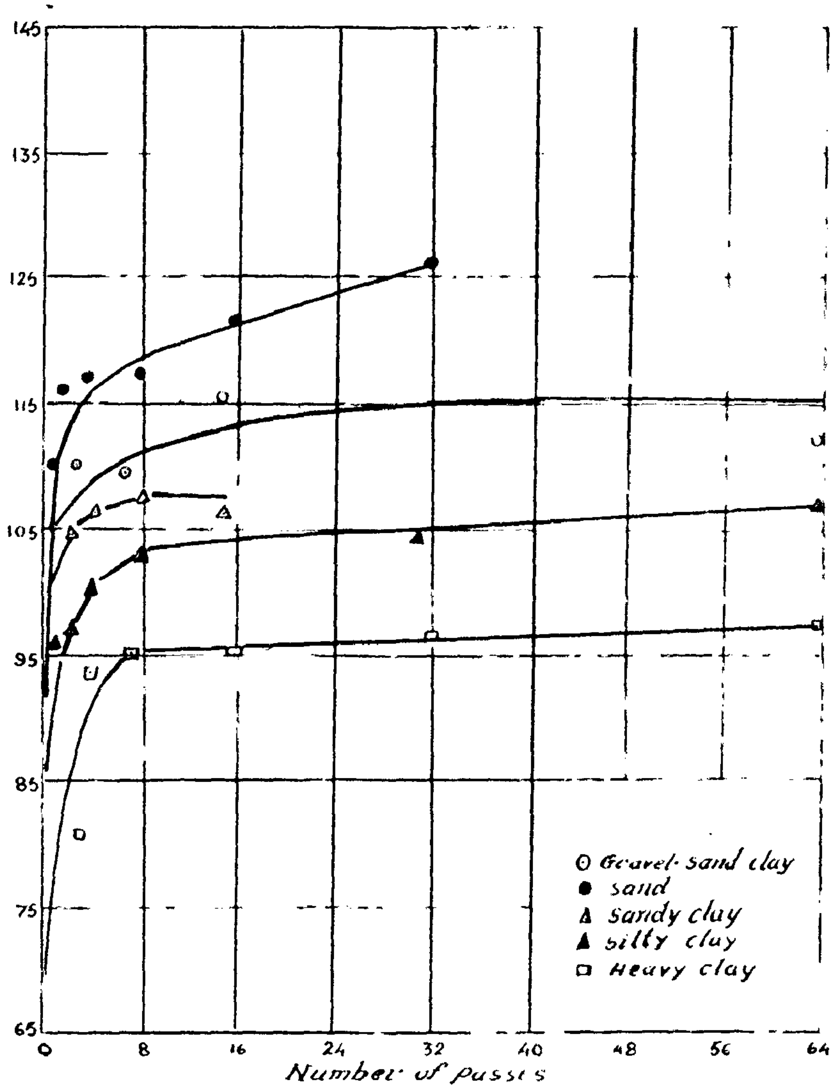


FIG No 30. Relationships between dry density and number of passes of the pneumatic-tyred roller for five different soils when compacted in 9in. Loose layers at or just above their optimum moisture content for roller compaction.

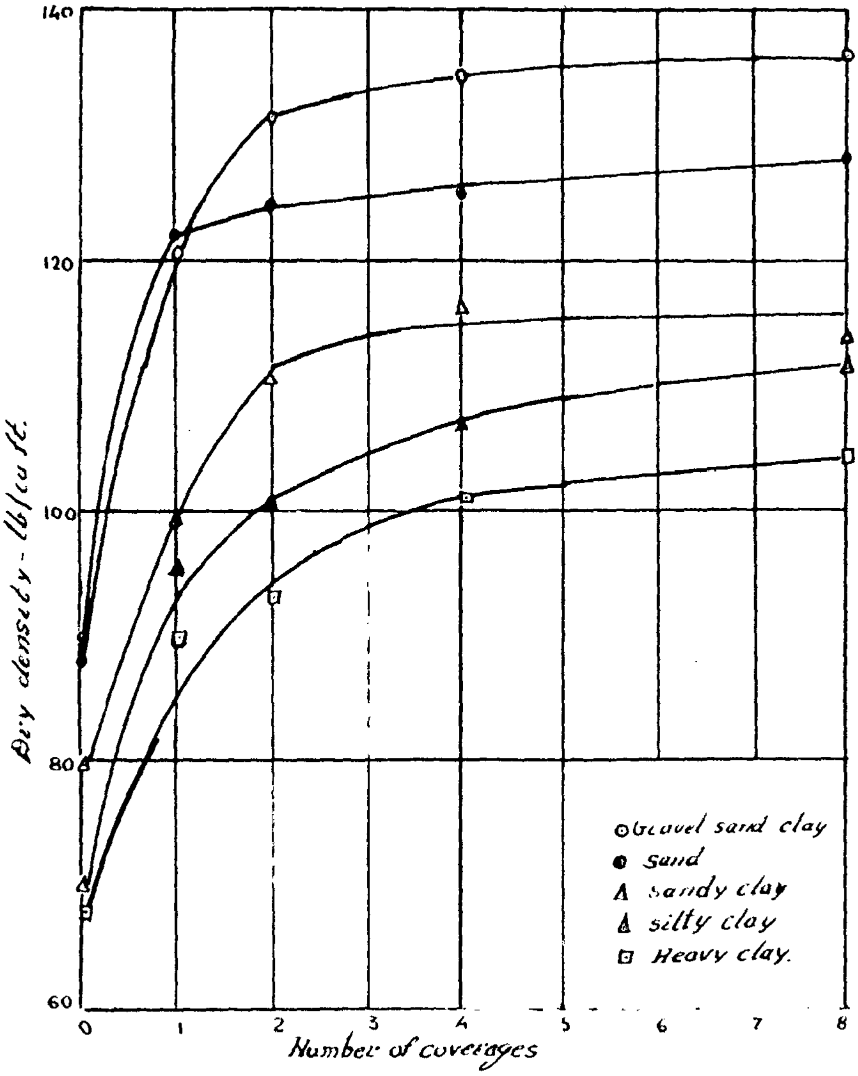


Fig. No 31 Relationships between dry density and number of coverages of the ½ ton frog rammer for five different soils when compacted in 9 in. loose layers at or just above their optimum moisture contents for compaction with the frog rammer.

(d) Rolling is found difficult with layer thickness exceeding 12" because of ruts formed from first pass.

Edmund J. Zegarra commenting on the above paper mentions that each type of compactive effort evidently produces compaction by a unique arrangement of particles in soil mass which has an ~~undermentioned~~ undetermined effect on shear strength. The data from the field is notoriously scarce and yet this is precisely where significant observations are possible. It is felt that it is only that heavy and not light or medium rubber tyred rollers that can produce compaction comparable to the values of laboratory from a modified A.A.S.H.O. test. The use of heavy machinery for compaction o soils at moisture content wet of O.M.C. is shown to be detrimental as undrained strength is reduced. L. Pruske (60) advocates use of lighter equipment. He analyses that by plotting change of density with compaction work, the work which may result in adequate increase of density economically can be made known. After certain compaction the soil almost gets saturated and the use of heavy machinery is not at all useful.

A.C. Whiffin has in his study (92) discussed the pressures generated in soil by compaction equipment.

(1) Peak pressures generated at a given initial depth per pass of compacting machine increases with number of passes to attain a maximum value.

(2) The density and pressures generated are inter-related.

(3) This relation depends on the type of soil and moisture content and is not effected by the compacting machine and duration of pressure pulse generated in soil.

(4) The number of passes needed for achieving different percentage of compaction is given from experiments on five types of soils.

The following table would illustrate the results:-

TABLE 6

Compacting Equipment	Number of passes needed														
	Heavy Clay			Silty Clay			Sandy Clay			Sand			Gravel Sand Clay		
	90 %	95 %	100%	90	95	100	90	95	100	90	95	100	90	95	10
$2\frac{3}{4}$ ton smooth wheel	14	31	a	3	7	48	12	38	68	1	2	3	2	4	9
8 ton smooth wheel	3	5	7	1	3	5	2	5	32	1	2	3	1	2	3
Pneumatic Tyre	1	2	46	1	3	10	11	14	a	13	13	a	20	a	a
Frog $\frac{1}{2}$ ton	1	2	3	1	2	3	2	2	4	1	1	1	1	2	2

W.A. Lewis has conducted work on impact compactors (46). It is mentioned that the impact pressure is a function of kinetic energy/unit area of rammer for a given size of rammer.

$$P = \text{Pressure generated at surface} = \sqrt{\frac{W}{g} \cdot \frac{k_s}{2} \cdot \frac{V^2}{a}}$$

Where W = Weight of rammer

V = Velocity of rammer on impact

K_s = Dynamic modulus of deformation

A = Area of rammer base

K_s is inversely proportional to square root of loaded area and hence $K_s = C/\sqrt{A}$

$$P = \sqrt{\frac{W V^2}{g A \sqrt{A}} \times \frac{C}{2}}$$

The height of drop or the impact velocity is found to have little effect on the pressures developed.

A Myslivec (55) suggests field tests for the particular compactive effort to fix up the field O.M.C., number of passes for obtaining the density.

5.8. CONCLUSIONS

New modes of equipment developed since about 40 years pose before the engineer the problems of a proper selection. Sheepfoot rollers and heavy rubber tyred rollers are prominent among them. The use of vibratory equipment is considered a necessity for cohesionless soils.

Sheepfoot rollers are particularly amenable for impervious soils and are suitable for all other soils also. The pneumatic tyred rollers have the advantage of economy and quicker work except for clays. Vibratory plate compactors are considered more efficient than the vibratory rollers. New vistas are open for foundation compaction by methods of blasting and vibrofloatation Impact rammers come in handy in small areas where rollers cannot work.

The variation of compaction effort, layer thickness number of passes depend on type of soil and mode of equipment.

For compaction by sheepfoot roller,

(1) Increase in foot size or increase in number of passes gives the same effect as increase in compactive effort of increasing M.D.D. and reducing O.M.C.

(2) A club foot roller for clays and tapered foot roller for other soils are found suitable.

(3) With increased moisture maximum density is achieved with lesser number of passes.

10 to 12 passes of the roller on 6" layers are considered minimum. Sheepfoot roller of 14 sq. in area are considered ideal.

Heavy pneumatic tyred rollers are found to give the required densities with lesser number of passes. It is found more effective to increase tyre pressure than increase the number of passes. A 50 ton roller imparting a tyre pressure of 90 p.s.i. is found to correspond to standard proctor's values. The rubber tyred rollers provide a more saturated soil after compaction. Fewer passes at slow speed give the same results as more passes at higher speed. 9" thick layers are permitted as compaction is achieved to greater depths.

Vibratory equipment is gaining an importance. Qualitative studies are difficult. Modes to suit individual condition to be decided on the basis of merits and demerits. Details of procedure have been discussed earlier. In general there is a gradual improvement in the methods of ~~equipment~~ compaction from the older methods of compaction by movement of labour on embankment or by wooden rammers or by steam road roller. What are the advantages of the new method ?

(1) Better and more uniform compaction is possible. Strength of soil is improved.

(2) The progress is very much quickened with reduced number of passes by increased effort of compaction. Thus economy is also achieved.

(3) Different modes to suit individual types of soils are evolved to give efficient compaction.

(4) New modes of compaction have helped in constructing higher dams which were once considered impossible.

CHAPTER 6

COMPACTION TECHNIQUES FOR DIFFERENT SOILS

6.1. In nature, different types of soils are found with varying properties. Compaction procedure to be adopted has to take into account the type and condition of soil. Any method suitable for one type may not be so far the other as each would pose different problems. As compaction of soils is to be achieved efficiently and economically a study of compaction procedures for different soils and different conditions would be essential.

Broadly the soils may be classified for this purpose as:-

(1) Clays
(2) Moderately cohesive soils
(3) Non-cohesive soils
(4) Special soils

Compaction procedure to be adopted has also to take into account the climatic conditions and time available for work, and Conditions like natural moisture content of the soil. A study of the same is made.

6.2. COMPACTION OF CLAYS

Clays, because of their cohesion have their particles interlocked. The problems arising in compacting clays would be as below:-

(1) When excavated they are obtained in chunks which needs to be broken during compaction.
(2) The soil would not be amenable for moisture changes after excavation.

With such soils deposited in chunks, void ratio cannot be reduced either by the pressure for short duration applied by rolling or by vibration even. The space between the chunks can be only reduced. Sheep foot rollers are considered most efficient for the purpose.

Compaction of clays at moisture content dry of O.M.C is advocated to prevent differential settlement and higher initial strength. Compacting clayey soils wet of O.M.C. with heavy compaction effort would be detrimental.

New devices for compacting clayey soils like the steel mesh cylinder, segmented roller and grid rollers are suggested but their use is still limited.

The U.S.B.R. practice is to use heavy S.F. rollers for compaction with a high foot pressures for better homogenity and less of stratification.

The U.S. Corps of Engineers recommend either a sheep foot roller with 250 - 600 p.s.i. pressure or heavy rubber tyred rollers with wheel loads from 18000 to 25000 lbs and 80 - 100 p.s.i. inflation pressure.

The cohesive soil in 115' Sasuma Dam in Kenya is reported by Dixon (22) to have been compacted in 6" layers by a 20 ton sheepsfoot roller, then by a 20 ton rubber tyred roller and finally by a 45 ton rubber tyred roller. The combined use of three roller types was felt necessary in that case as soil was very much wetter than O.M.C. The ~~natural~~ optimum moisture content was 50 % and M.D.D. 70 lbs/cft only. The natural moisture content was above optimum.

A.L. Little (47) mentions of dams with use of clayey soils where only construction traffic has been relied upon for compaction. The following table would illustrate the point.

TABLE 7

Name of Dam	Height	Year of Completion	Mode of Compaction
Daer Dam	135	1955	Construction traffic with flat track crawler tractor
Usk Dam	109	1954	Construction traffic with 4 ton smooth roller for finish
Hong Kong Dam	85	1956	Construction traffic with tractor with steel tyres and loaded with ballast and a roller for finish

In general it can be well said that clayey soils can be compacted with heavy sheepfoot rollers in thin layer of 6" with well controlled moisture content. It is always preferable to add the required quantity of moisture at the borrow area for uniform distribution in soil to O.M.C., rather than adding at site. In cases where soils exist at wet of O.M.C. other precautions to dry the soil, or account for the reduced values of strength due to higher pore pressure needs to be taken. Highly plastic clays are not suitable for use due to their shrinkage and swelling tendencies with variation of moisture. They do have very poor densities and low shear strength. When such soils are to be used unavoidably sufficient precaution of moisture control is essential. Compaction wet of O.M.C. produces high pore pressures, compaction dry of O.M.C. gives chances of high volume changes, on saturation.

Compaction at about O.M.C. is desirable. Pore pressure are taken into account and possible reduction of pore pressure by drainage arrangement essential.

Similarly highly precompressed clays in foundation are dangerous due to possible volume changes on saturation. Low undrained strengths are achieved. Pore pressures are high. Removal of such poor soils and replacement by better material is advocated. If the removal is uneconomical the strength needs to be improved by providing drainage arrangement in the form of sand drains. This would very much help in early consolidation and thus good strength. It is also suggested to remove material to that depth where the insitu density is about 95 % of the Proctor's density. In Balimela Dam of 230' height in Orissa, similar treatment is being studied (28) on the basis of works of same nature at Boundary Dam of Canada 516' high Goschemenalp dam of Switzerland, Arkabutle Dam and others.

6.3. COMPACTION OF MODERATELY COHESIVE SOILS

In this category a further distinction of plastic and non-plastic soils would be useful.

6.3.1. For non-plastic soils like ML, CL, SM, GM soils (i.e. L.L. less than 50) rolling in layers would be effective. Pneumatic tyred rollers can compact 6" layers to the requirement with 8 to 10 passes. Moisture content slightly dry of O.M.C. at compaction is found to give the optimum strength.

However, smooth wheel rollers are not considered good for gravelly and sandy soils due to the poor strength of unloaded surface of such cohesionless fills. Rubber tyred rollers are more suitable on account of its flexibility.

J. Salva (66) gives example of Sarno dam of 100' height where a 16 - 27 ton vibratory rubber tyred roller was not found satisfactory for compacting G.M. (Silty gravel) of 25 cms thick layers but a S.F. roller of 6 ton capacity producing pressure of 340 p.s.i. was found successful.

6.3.2. For plastic soils with moderate cohesion like clays and silts of medium plasticity (CI and ML) sheepfoot rollers are preferable. A 17 ton roller of 5' diameter, 8' length with feet extending to 6" to 9" with surface area of feet of 7 to 12 sq. inches give contact pressures of 300 to 600 lbs per sq.in. is found useful. This would be suitable for major works and for minor works 8 ton rollers would be sufficient. About 8 to 12 passes on layers of 10" to 12" can compact to the required density if accurate moisture control is maintained. These soils have a marked variation in strength and swelling with changes in moisture. A.C. Shah (70) has made studies on three types of soils to conclude that to achieve minimum swell and higher strength it is advisable to compact slightly wet of O.M.C. and achieve density of about M.D.D. For clays of intermediate plasticity moisture higher than O.M.C. is advocated. Either sheepfoot rollers or rubber tyred rollers or a combination of them is found to be suitable for all the ranges of soils between cohesive and non-cohesive soils.

6.4. <u>COMPACTION OF NON-COHESIVE SOILS</u>

It is the non-cohesive soils which are not easily amenable for analysis. The soils themselves (as reported under Laboratory Testing of Soils) do not exhibit a marked O.M.C. Much research is in progress regarding compaction of these sandy soils. The problem is more so in compacting foundations where sand exist. Compaction of sand is based on the principles of vibration, shock and static compaction in the order of efficiency.

If the frequency of vibrations equal the natural frequency of soil maximum effect is obtained. Submerging the soil produce conditions conducive to the free movement of particles to stable positions and hence better compaction.

Rollers are found to be the least effective in compaction but the same when drawn by heavy crawler mounted tractors, the engines of tractors transmit their vibrators to sand.

When the pervious soils (G.W; G.P., S.W., S.P.) are selected for use in embankment, heavy crawler tractors are specified for compaction. The contamination of soil by fines (-200 fraction) to be less than 3 to 5 %. Water content considered sufficient if free moisture appears in the crawler tracks after it passes over the layer. The tractor operating at the highest practicable speed is conducive to greater vibration and thus compaction. The rollers by themselves are ineffective.

The methods of compacting sand and gravel in order of decreasing efficiency are vibration, watering and rolling (15) A combination is generally adapted. The frequency of vibration for best efficiency varies depending on resonant frequency. Watering process compacts by breaking down unstable grains. This is found to be less effective. About 1.5 cyd of water per cubic yard of sand is reported generally essential.

When foundation material is of sandy soil with low relative density removal of material is advocated if economical.

Otherwise foundation needs to be compacted to the required density by any of the methods of blasting, vibrofloatation or vibratory rollers or plate compactors. Economy would be the main criterion to decide the mode as no qualitative estimation is possible in general.

6.5. COMPACTION OF OTHER TYPES OF SOILS

Some special soils do need greater care in compaction because of their peculiarities.

6.5.1. Residual soils or some soils become finer by break down during the process of excavation, spreading or rolling (71) At the initial stage though sufficient moisture is added, after a few passes of compacting unit, the soil may appear dry. With each pass, the O.M.C. of the soil increases. Hence in such cases it is essential to add moisture by sprinkling during the process of compaction.

6.5.2. Such materials as shales, mudstones, siltstones chalks or badly weathered rock might be suggested for random zones in embankments. Such soils may initially be blasted or stripped in the borrow area. Thin layers may be taken up for work and well watered allowing it to stake. Then they are rolled in dams by heavy rollers with spikes.

6.5.3. Compacting a soil under water is found to cause lot of difficulties. Such problems are encountered in coffer dam constructions or in compacting in cut off under sub-soil water. Compacting sands under water may be done by vibratory methods explained in previous chapter.

The Andhra Pradesh Research Laboratory have made some studies for Srisailam Project Coffer Dam (62). Laboratory tests are made to find the efficiency of the different modes by which soil could be filled for compaction. Deposition of soil in a 10 feet column of water through a tremie in a pipe of 6" dia was found to give higher density by 10 % than other methods. It is not possible to achieve the standard densities when compacting under water.

The variations for one samples by all methods is indicated below:-

TABLE 8

Method of Filling	Moisture Content %	Dry Density lbs/cft	'K' Permeability Cms/Sec x 10^{-6}
1. By Proctor's Test on Soil	24	100	0.49
2. In Slurry State	49.9	73.5	728.0
3. Soil put into water from just above Proctor's mould	46.3	72.0	203.0
4. Soil deposited in water by tremie/ high in Proctor's mould	48.7	68.8	1455.0
5. Soil put in water column 10' high (6" pipe)	46.9	71.0	-
6. Soil put in water through tremie in 10' column of water (6" pipe)	41.7	77.4	-

6.5.4. Black cotton soils have to be compacted such that swelling pressures are a minimum. S.R. Mehra and H.L. Uppal (51) have analysed from about 300 tests the effect of density on the swelling pressures. Cylinderical blocks 2.8" high and 2.5" diameter were compacted at Optimum Moisture Content to dry bulk densities of 1.35 to 1.75 gms/C.C. The blocks were allowed to get saturated. Maximum swell pressures were observed at higher densities and minimum at 1.35 gms/c.c. Hence compaction to higher densities are found disadvantageous. Compaction wet of O.M.C. reduces swelling.

6.5.5. Loessic soils formed by wind deposit are loose soils likely to have very poor properties particularly after saturation. In works on platter river in Central Nebraska such soil was compacted at 2 % above O.M.C. After saturation had taken place under dams and settlement started, sides were drilled on upstream and downstream slopes and silt injection method adopted for stabilisation. The insitu density of sample if less than 80 lbs/cft is found to be highly susceptible for settlement. A minimum of 85 lbs/cft is insisted upon. Such soils are not recommended for use due to poor strength, If occuring in foundation are to be preferably removed.

6.6. COMPACTION OF WET SOILS

Compaction of soils existing in borrow area, at moisture content wet of O.M.C. pose certain difficulties.

If the natural material is available only at moisture content wetter than O.M.C. the problem is of drying the soil before compaction. Such situations are quite common. Coarser and non-plastic soils can dry up early but the fine soils cause delay. If there are same regular drizzles drying takes too much time. The two choices in such cases would be (71) :—

(1) Using conventional methods to dry the soil at the cost of delay in construction.

(2) Using the material at its high moisture content and adopt the corresponding properties in the design. In Swedish & Norway this is reported to be a common problem

Methods of drying would be by:-

(a) Lowering the water table at borrow area by drainage.

(b) Ripping, ploughing or aerating the soil to a depth of several feet at borrow area.

(c) Providing surface drainage in burrow area to prevent infiltration

(d) Ploughing or discing before rolling at embankment

(e) Using heavy rubber tyred rollers to provide hard surface.

(f) Sloping the construction surface to drain out water

A few examples of dams and the methods of drying adopted are mentioned below:-

(1) Mud mountain Dam (Washington) 1940 - Soil dried in rotary kilns and a huge canvas tent was erected for protection from rains over construction surface.

(2) Beachwood Dam (Candda) 1955 - Aggregate Drier used.

(3) Dorena Dam (Oregon) 1949 - Aggregate drier used

(4) Yale Dam (Washington) 1953 Asphalt surfacing was given to borrow area to prevent infiltration.

(5) Swift creeks dam (Washington) 1958 - Constructional precautions such as quick compaction, good drainage, grading and compacting the burrow area were made.

Compaction of wet fills is achieved in Sweden and Norway by the following method. The material is dumped on surface and pushed to position by dozers. Crawler type tractors are made to move fast 8" layers compacting the soil. The density achieved is definitely less than M.D.D. This process of wet compaction is suitable for silty, gravelly sand. The consequent changes in strength, settlement characteristics, high pore pressure are all accounted for in design. Examples of such dams are

(1) Tustervatn Dam (Norway) 1956-57

(2) Årstaddalen Dam (Norway) 1962-63

(3) Messaure Dam (Sweden) 1958-62

(4) Hill Creek Dam (Oregen) 1959-60

Construction problems are posed by the existance of fines in the material, as sufficient water is retained to ma-ke the construction surface too soft and slushy to support the equipment. This is particularly so when the material from borrow areas below subsoil water is used with the percentage of fines passing 200 sieve greater than just 4 %. During compaction the fines are worked up to cause heavy slushiness. Such difficulties in compacting wet soil with silty fines are reported in Wanship Dam in Utah, Tutle creek dam in Kansas. Dewatering borrow pit, limiting the rate of construction and removal of silty fines by dredging had to be adopted.

(1) If the material is better graded, though higher densities are possible, there would be problem of the fines causing trouble.

(2) When the borrow area consists of sandy and gravelly soils underlain by clay and silt, the excavation under water cannot prevent contamination of the fines.

(3) Stock piling of the saturated sand and gravel and allowing it to drain is found to be helpful.

(4) Another solution would be to place alternate layers of wet material and dry material and then blending them together by a dozer before compaction.

Similar studies on compaction of wet cohesive soil was undertaken at the Public Works Research Institute, Japan (25). It is felt that compacting soils at O.M.C. to M.D.D. would involve waste of time and energy as the wet soils in nature has to be dried at high cost. A more convenient standard for compaction in terms of the degree of saturation is advocated. An "Optimum Zone" of compaction is fixed. It can be to restrict either degree of saturation to 85 % to 95 % or permissible air voids to 5 % or 10 % or economical upper limit of moisture content on the basis of providing stable embankment. The upper limit of moisture has to take into account the easy trafficability of equipment in addition to the compressibility requirement to prevent harmful settlement.

The specification of Ministry of Transport and Civil Aviation England for road embankment specify that "Compaction shall be continued until a dry density corresponds to not more than 10% of air voids". This would also agree to this concept of optimum zone.

L. Prusk (60) mentions of the maximum degree of saturation occuring after a certain compaction after which further additional work is not useful. In such cases use of lighter machinery is found sufficient and the higher cost due to heavy machinery avoided.

F. Kawakami (39) explains the difficulty of moisture control in Japanese works where climatic conditions keep the soil wet of O.M.C. It is shown that with decreasing M.C. to O.M.C. the same M.D.D. is not possible as with increasing moisture to O.M.C. A 4 ton tamping roller provided with feet of 60 sq/cms C.S. area exerting 284 p.s.i. pressure is commonly used. This is found to effectively compact layers of 20 - 25 cums. It is concluded that drying of soils to O.M.C. was not possible.

6.7. SUITABILITY OF MODES OF COMPACTION

Comparison of maximum dry densities and optimum moisture contents obtained with different compaction units and in laboratory tests is reproduced for general guidance (31) in Table 9.

TABLE 9

Soil Type	Heavy Clay		Silty Clay		Sandy Clay		Sand		Gravel-Sand-Clay	
	M.D.D	O.M.C	M.D.D	O.M.C	M.D.D	O.M.C	M.D.D	O.M.C.	M.D.D.	O.M.C.
B.S. Compaction Test	97	26	104	21	115	14	121	11	129	9
Modified A.A.S.H.O. Test	113	17	129	14	128	11	130	9	138	7
Dietert ~~Computation~~ Compaction Test	102	23	109	17	116	14	119	11	-	-
$2\frac{3}{4}$ ton smooth wheel roller	95	21	110	17	114	16	127	10	134	8
8 ton smooth wheel roller	104	20	111	16	116	14	132	8	138	7
Pneumatic tyred Roller	98	25	104	20	108	19	127	11	126	7
S.F. Roller (Club Type)	107	16	116	14	119	12	-	-	129	6
S.F. Roller (Tapered Foot)	107	15	115	14	120	12	-	-	128	5
$\frac{1}{2}$ Ton Frog Rammer	107	17	110	15	116	13	128	10	136	7

The following table given by G.F. Sowers (74) gives the general compaction characteristics and suitable mode of equipment for different soils

TABLE 10

	Class	Compaction Characteristics and suitable mode of compaction	General Values M.D.D. lbs/cft	O.M.C. in %
1.	GW	Good - Rubber Tyred Rollers Vibrators	125-140	4-12
2.	GP	"	115-125	4-14
3.	GM	Good - Rubber Tyred/or light S.F. rollers	120-135	8-13
4.	GC	Good - Rubber Tyred or S.F. Rollers	115-130	8-15
5. 6.	SW) SP)	Good - Rubber Tyres or Vibrators Rollers	100-120	6-16
7.	SM	Good - Rubber Tyred Rollers or Light S.F. Rollers	110-125	10-18
8.	SC	Good - S.F. Rollers or Rubber Tyres	105-125	10-20
9.	ML	Fair to poor S.F. rollers or Rubber Tyred Rollers	90-120	12-28
10.	CL	Good to Fair Rubber Tyred or S.F. Rollers	90-120	12-28
11.	OL	Not suitable for dams	80-100	20-35
12.	MH	Poor-Rubber Tyres or Light S.F. Rollers	70-95	25-40
13.	CH	Fair Heavy Sheep Foot Rollers	75-105	18-35
14. 15.	OH) PT)	Not suitable for dams	65-100	25-50

6.8. STABILISATION OF SOILS

Stabilisation of soils by use of chemicals is advocated by investigations by C.A. Hogentogler (4). Use of calcium chloride is found to improve density of gravel roads by 11 %. Use of electrolytes on cohesive soils gives an increased density of 5 to 10 %.

G.E. Johnson (36) has made some studies on the stabilisation of soil by the silt injection method to increase the density of coarse grained soils. The requirements for the program is mentioned below:-

(1) Soil to be porous enough to serve as a filter to allow excess water to move out under pressure

(2) The slurry to be pumped in to be also sufficiently porous to allow water to move under pressure through slurry.

(3) Slurry must have sufficient fines to lubricate the mixture well so that it can be pumped in plac

(4) Sufficient water is provided to liquify the mixture and the injection to be made at sufficien depth to ensure consolidation.

A mixture of 5 % bentonite and 95 % porous Loessic soil can be mixed with 40 % of water into a slurry and pumped at 125 to 150 p.s.i.

6.9. CONCLUSIONS

Compaction techniques for various types of soils are different to suit the individual characteristics.

Clays are compacted best by sheepfoot rollers as the clods need to be broken during compaction. Compacting at wet of

O.M.C. and taking pore pressure into account is advocated.

Moderately cohesive soils, commonly used in dam construction may be compacted by either sheepfoot rollers or pneumatic tyred rollers. Sandy soils are more amenable to pneumatic roller compaction.

Non-cohesive soils when used in the embankment are compacted by vibratory rollers or heavy pneumatic rollers. Saturating the soil before compaction would yield good results. Residual soils which crumble on saturation need constant sprinkling of water during compaction for the best results. Soils like shale, silt stone and badly weathered rock are well compacted by heavy rollers with spikes.

Foundation of clay, sand and loessic soils do need compaction in dam construction when removal is uneconomical.

Soft clays are to compacted to an insitu density of about 95 % of the proctor's values so that differential settlements are avoided and better strength properties are attained. Provision of sand drains improve the soil properties.

Sandy foundations are to be compacted to a safe relative density. Methods of blasting, vibrating the soil by internal vibrators or vibrofloatation method is commonly adopted.

Loessic soils with poor density exhibit very poor strength on saturation. Saturating the soil to allow full settlement or stabilising the soil by silt injection method is recommended.

Compacting of soils under water needs detailed study. The degree of compaction achieved varies with the methods of placing soil under water. Static loading or internal vibrators or blasting would assist in getting good densities though the Proctor's values cannot be achieved.

In places of wet climate, soil is naturally found to be at moisture very much wetter than O.M.C. Different methods of drying process needs to be utilised or if uneconomical soil may be compacted at insitu moisture accounting for the varied properties.

The advantages of field tests in all cases needs an emphasis as the results help for future correct decisions.

CHAPTER 7

QUALITY CONTROL OF COMPACTION

7.1. The importance of controlling placement of soil for the embankments has increased considerably with the increasing knowledge of the factors controlling the stability of the structure. An entirely safe and substantial design may be ruined by careless and shoddy execution and the failure of the structure may very possibly be the result. Careful attention to the details of construction is therefore as important as the preliminary investigation and design. For earth dams, the designer must provide sufficient latitude in specifications for construction engineer to achieve the designed properties as the properties of soil varies from place to place and the dimension of the structure is large. But at the same time the persons incharge of construction are to be well aware of the design criteria so that the same can be achieved with the knowledge, experience, judgement, responsibility and authority with them. It is worth quoting Karl Terzaghi who states (83) "If the Engineer incharge of earth work does not have the required geological training, imagination and commonsense, his knowledge of soil mechanics may do more harm than good. Instead of using soil mechanics he will abuse it." Whatever benefits are to be derived from use of soil mechanics is nullified by improper supervision and control in the construction phase of a project. Hence the necessity of quality control.

7.2. SPECIFICATIONS

The quality to be achieved and controlled would be the designed properties to be attained with the minimum cost.

so that strict adherence to the same would give desired results. Specification may be either of the performance type where the ultimate result is aimed or of the procedure type where the best economical method to get the best result is decided. Without getting into the details it may be mentioned that the specifications must include the salient points mentioned below as far as it relates to compaction.

(1) Preparation of foundation which may involve entire removal or compaction if the soil is poor.

(2) Formation of a good bond between embankment and foundation.

(3) Use of selected ~~approval~~ soil satisfying design criteria.

(4) Mode of achieving uniform moisture in soil for compaction within allowable range.

(5) Fixing up the mode of compaction, layer thickness and number of passes to attain desired density most economically.

(6) Field control tests to check up the efficiency of the work done.

(7) Further modifications needed, if results are unsatisfactory.

7.3. GENERAL CRITERIA FOR QUALITY CONTROL

Quality control at field is to ensure that the design criteria is satisfied. The best results are to be economically achieved. The personnel engaged for the purpose have thus an important duty to perform. They have to ensure that the required density is achieved by compacting soil at field placement moisture content. The judgement and the experience will prove handy as ~~one~~ reliable conclusions can be drawn from visual observations and a few simple tests. It is essential to fix up before hand the layer thickness and number of passes for a particular type of equipment and soil.

Water content should be controlled and proper mixing ensured before compaction.

Various criteria for quality control have been propose(On the basis of compaction of 44 cohesive soils and 18 cohesionless soils, the U.S.B.R. has suggested a criteria for quality control as indicated below:-

TABLE 11

U.S.B.R. CRITERIA FOR CONTROL OF EARTH EMBANKMENT

Type of Material	Percentage of +4 fraction by dry weight	Percentage based on - 4 fraction: For Dams less than 50' high — Minimum Density acceptable	Desirable Average	W_o-W	Dams > 50' high — Minimum acceptable Density	Desirable Average	W_o -
Cohesive soil controlled by Proctor test	0-25	D = 95	D = 98	~~Dz~~-2	D=98	D=100	
	26-50	D=92.5	D = 95	to+2	D=95	D=98	+2 to 0
More than	50	D=90	D = 93		D=93	D=95	
Cohesionless soil controlled by relative density test	Fine Sands 0-25	D_d=75	D_d= 90	Soil	D_d=75	D_d=90	Soil should be
	Medium sands 0-25	D_d=70	D_d= 85	to be	D_d=70	D_d=85	very wet
	Coarse sand and gravel	D_d=60	D_d=80	very	D_d=65	D_d=80	

Note

(1) $W_o - W_t$ is the difference between O.M.C. and fill water content in percent of dry weight of soil.

(2) D is $\frac{\text{fill density}}{\text{Maximum dry density}}$ in percentage indicating degree of compaction.

(3) D_d is relative density of cohesionless soils.

(4) For high earth dams special instructions on placement moisture limits will ordinarily be prepared.

The adequacy of the compaction needs to be checked before allowing further work. A regular record is essentially maintained of the day to day work.

The study of the record and analysis of the same would give a clear picture of the final work and the performance can be anticipated. Statistical methods are increasingly used these days.

Such records would be useful for other projects from similar soils. It also serves as a proof of the work having been done to the tolerance ranges of design criteria.

7.4. FIELD TESTS FOR COMPACTION CONTROL

7.4.1. The field tests during the construction of an embankment are to take little time so that the progress of work does not suffer. Field tests of a minimum of one for every 2000 cyds of earthwork is specified by the U.S.B.R. for their works. Extra tests are essential where degree of compaction is doubtful. Location where filling operations are concentrated and in places near about embedded instruments, greater care is essential.

Doubtful conditions may specifically be expected where

(1) Rollers turn during rolling

(2) Junction of mechanical and roller compaction area

(3) The thickness of layer is great or the roller passes are less.

(4) The rollers which are clogged are used.

On smaller dams more samples are to be tested to ensure reliability.

Fields tests involve

(1) Moisture determination

(2) Measurement of inplace wet or dry density.

7.4.2. TEST FOR MOISTURE DETERMINATION

The standard method for moisture determination would be to take out a representative sample and dry it in an oven at a temperature of about 110°C for atleast 24 hours. But the delay of 24 hours in test would affect the progress. Hence several methods of rapid moisture determination devices are in vogue these days. A rapid method of moisture determination is by the use of proctor needle, known as penetration needle. A representative soil sample of about 20 to 25 lbs is selected either in the spread layer or from the face of excavation in borrow pit. The material is sieved through No.4 sieve to obtain about 10 lbs of the soil. A portion of the soil is utilised for conducting the laboratory test adopted in design. The soil is compacted in the mould and the penetration resistance observed. It is compared with the standard value or the permissible range of resistance for that quarry soil for acceptable moisture ranges.

If greater variation is observed corresponding modification is made in the moisture before compaction. The results are not accurate for coarse grained soil. The normal methods of testing moisture would involve time thus giving chances for moisture to evaporate. The use of penetration needle would not involve any such error. The degree of penetration of needle (88) depends on:-

(1) Physico mechanical properties of soil.

(2) Moisture content

(3) Wet density

For a particular soil the ratio of penetration effort of needle with constant area and wet density of soil is found to vary within small limits for any given moisture content. The method is not useful when gravel content exceeds 20 %. The correlation between the variables involved has been defined as below:-

$$W = e^{-a\, P/\gamma}$$

Where a = Constant depending on soil properties

P = Penetration resistance in Kg.

γ = Wet density

W = Water content of soil

For particular soil a graph of W Vs P/γ can be prepared from laboratory tests. In field from undisturbed samples wet density is found. P is read off on the dynamometer scales. Average of 3-4 readings are taken. Knowing P/γ the value of W is read from the curve which is a straight line on a semi-log plot. This is reported to have given an accuracy to ± 1.5 % on being used at two projects. The time taken in this case is only ten minutes.

The use of open pan or hot plate to dry the sample at site would also reduce the time for moisture determination. This method is common. The time to which the soil is to be heated needs to be fixed up by experiments. The rapid moisture meter (method using calcium carbide to generate acetylene in a closed container) and alcohol burning method are in use to provide quicker means of drying and save time.

Mogami and Kawasaki (53) have devised a portable dyer. It consists of a high frequency oscillator and electrodes. The soil sample of 30 m.m in diameter and 5 m.m in thickness could be dried in less than five minutes, by placing the soil in between and passing the high frequency current.

7.4.3. METHODS OF DETERMINATION OF FIELD DENSITY

The common method is to remove a known weight of soil from a hole in the compacted embankment and measure the volume of soil taken by the calibrated sand method or by water filled rubber baloons or by filling the hole with oil. An important source of error may occur as the compacted material adjacent to the hole may squeeze into the hole. This accounts for a reduced volume to be measured and higher densities to be recorded (71) Use of about 100 lbs of clean, air dry uniformly graded sand passing No.16 sieve and retained on No.30 sieve is recommended for the sand replacement method.

A standard steel template with a circular hole of 4" diameter is used for forming a hole in the embankment of 6" to 12" diameter. The adjoining area is not to be disturbed. The material is gently scooped out. Sand of known density is gradually filled by a sand funnel apparatus. The weight of sand used is obtained by knowing initial and final weights. An average of several trials would give greater accuracy. The volume of the sand used to fill the hole is calculated. The weight of this volume of soil is obtained by measuring the scooped out material. Wet density of the soil can then be worked out. After determining moisture content by any of the drying process the dry density is calculated. This standard procedure in common use is designated E-24 in the U.S.B.R. Manual wherein complete details are given. (Similar details are given in section B of Sub-Committee D-18 of A.S.T.M.)

This procedure is suitable for soils with -3/16" fraction. The results obtained can well be compared with the M.D.D. of the standard test wherein -3/16" fraction is utilised for test.

Details of the method of determination of dry density of soils in place by the sand replacement method is explained by the Indian Standard Committee (35).

Use of rubber ballon method is recommended by L.D. Hicks for test holes of 0.025 to 0.050 cft capacity for material with particle size not greater than ½".

A volumeter which is a calibrated vessel is used to measure volume of the hole by tilting a liquid contained in thin flexible membrance.

In dam construction, coarse soils containing a good percentage of materials retained on No.4 sieve (+3/16" material) are used. The standard laboratory tests are made on -4 fraction of the soil. As such the influence of the coarser particles on compaction is to be known. The density obtained is to be corrected for gravel by a gravel correlation. The maximum density of a rock soil mixture is possible when the fines are just sufficient to fill up all voids of the coarser particles. The limiting percentage of the +4 fraction of material is about 60 to 75 %. For soils containing less than 30 % of coarse particles, compaction of fine grained soil is not found to get affected. With lesser percentage of coarse particles, the amount of moisture required for the finer particles for achieving maximum density would be quite high. Sherard (71) mentions of the Hill Creeks Dam where the moisture content needed was near about the liquid limit of the fine soil due to presence of coarse particles. When such material is used Field density controlled by testing the fines and applying gravel correction or by using large scale moulds for the total material.

Gujarat Research Institute (70) has suggested use of 8" dia and 6" high mould for tests on total material consisting +4 fraction. Wagner of U.S.B.R. has suggested moulds of 20" dia and 15" high with metal rammer of 18 lbs weight with 9½ diameter base. Rammer is dropped from 18" to give impact at a rate of 12 blows/minute.

Gravel correlation can be applied by knowing the percentage of coarse material by the formula given below:-

$$D_t = \frac{1}{P/D_r + \frac{1 - P}{DS}}$$

Where D_t = Dry density of combined soil & rock mixture

D_r = Density of rock fraction

Ds = Density of soil fraction

P = Percentage of +4 fraction (expressed in decimals)

W.Mcleod has worked out the following relations (50) for O.M.C. for combined material.

O.M.C. = PAo + OC

Where P = Percentage of material in decimal of oversize particles (+4 fraction)

O = Percentage in decimal of finer particles (-4 fraction)

Ao = Percentage of water absorbed by the oversize

C = O.M.C. of the finer fraction

The value of Ao is very low. This value of water absorption can be measured by immensing it in water and finding out the quantity absorbed.

The volume of +4 fraction of the mixture is obtained by separating the -4 and +4 fraction by sieving after knowing the wet density of total mixture. The weight of +4 fraction is determined after removing the little moisture adhering to it. Volume can be found by displacement of water in a can. The density is worked out.

To avoid all these elaborate calculations, tests of the rock soil mixture can be made in a larger compaction mould initially and the O.M.C. and M.D.D. obtained. The rock soil mixture can be tested in the field also with the larger mould.

The density of sand is determined by the use of a penetrometer. A steel shaft 3/4" diameter tapered to a driving point is driven in the sand fill by blows of an 8.2 lbs weight from a height of 8.5". This probing device is sensitive to changes in sand density. Calibration is made for the equipment originally by penetrating in a uniform dense mass of sand in a steel cylinder 13 inches diameter and 36" deep. Average density of sand is made known by knowing the weight and volume of cylinder.

The U.S.B.R. Practice is to use a sounding rod with a conical tip with apex angle of 60°. Sounding rod is of 42 m.m diameter and is driven by a 60 Kg hammer with a drop of 0.8 meters. No casing is needed. The number of blows for sinking one meter is correlated to relative density.

As undisturbed sampling of sand is difficult by normal method, method of freezing is adopted for the purpose. The soil is freezed and sample taken out. It is found that water saturated sands do not change density on freezing.

7.4. REVIEW OF LITERATURE ON QUALITY CONTROL

The importance of a close watch of work is essential as at times even though the fill satisfies the moisture density requirements, it may have stratified layers or pockets or lenses substantially different from remainder of the zone (73). Not only a knowledge of the material and foundation conditions is essential but also the behaviour of treated embankment and foundations in satisfying the multitude of design details should be known. Proper control of these factors ensures a structure from failure.

P.T. Bennett (7) has mentioned of the experience of the U.S. Corps of Engineers in their dams. The use of random fills downstream of impervious zone is advocated for economy. Field tests are suggested for developing construction procedures. In construction control once the moisture is found to be in order, the wet density of inplace and the wet density of the compacted embankment is compared. With an increase within 10 lbs of the original wet density, the minimum density requirement is considered as satisfied. This method of density control named "One point modified proctor test" provides rapid and effective check.

Turnbull and Shockley (80) have detailed the procedures of the U.S. Corps of Engineers in their dams. The aim of quality control is to achieve the end product visualised in the designed structure. This is accomplished mostly by moisture density control which is supposed to give the other engineering properties. Visual observation of roller and fill behaviour by an experienced field engineer could form the basic control of the compaction. Laboratory tests on the undisturbed samples are specified at every 1000 to 3000 cu.yds of material in field. If after several passes a rubber tyred roller ruts excessively or sheepfoot roller continues churning the construction surface showing no signs of walking out the moisture content is considered high. But with low moisture even after 3 or 4 passes the S.F. rollers walks out or a rubber tyred roller provides a hard and smooth surface.

Sowers (72) has stressed the importance of field test particularly in case of gravelly soils where the ordinary apparatus is not of use. Explaining one such test for a 300' high earth dam, it is indicated how an area of 80' x 100' can be utilised to check up the effect of different modes of equipment and layer thickness. This would help in deciding best mode of equipment and the thickness of layers.

In recent years, new method of quality control are being suggested to overcome the elaborate procedure and time consumed. A few novel devices suggested by research work are mentioned below.

7.5. NUCLEAR METHODS FOR QUALITY CONTROL.

Use of gamma radiation and neutrons for measurement of insitu density and moisture is gradually developing. The method was first applied in 1941 for oil well digging for qualitative estimation. In 1950, Belcher evolved methods for the use of the radio-isotopes for quality control. A symposium of the use of the nuclear methods was held at Ohio in 1952 to discuss its merits and demerits.

The methods in vogue (52) are based on the fact that intensity of transmitted radiation depends on the density of soils. Gamma rays interact with matter in three ways depending on the energy of gammas. Cromption scattering of the medium energy of gammas is simple and suitable for density measurements. The inter-relation is given as

$$I = I_o \ e^{-\mu x}$$

Where I = Transmitted intensity of energy beam

I_o = Original intensity

x = thickness of absorber

μ = Total linear absorption coefficient

The essential components of a density measuring system are a source, a detector of gamma rays and a device to count or record pulses from detector.

Sources may be cobalt 60 with half life of 5.3 years or radium 226 with half life of 1590 years or cacsium 137 with half life of 33 years.

Gamma detector may be a Geiger Muller tube or Boron-tri-fluozide proportional counter or scintillation counter or electro-meter dosimeter. Geiger Muller tube is commonly used due to its low cost.

Counting and sealing units have to amplify the impulses from the detector and then count individually. Popular type of Dekatron scaler is used.

The general method of constructing the system may be

(1) Source and detector arranged so that principally scattered gammas are measured (Back scatter method). This is suitable for deep holes.

(2) Source can be embedded in the medium and detector placed some distance away either at surface or buried (Attenuation method). This method is suitable for surface measurement.

From the surface gamma rays transverse the matter and residual energy is measured. The quantity of absorbed energy is greater for dense soils due to higher absorption coefficient. From a standard calibration chart density is obtained.

Moisture determination is based on Neutron interaction. Source of fast neutrons is placed on one side and a counter of slow neutrons on the other side of the wet soil. Fast neutrons penetrate and are scattered on its atomic neuclii and slowed down on hydrogen nuclii. Dry soil shows less slowing than wet soil.

The source may be radium berillium or polynium berillium. The detector of neutrons commonly adopted is Boron-tri fluoride tube enriched with Boron 10 isotopes. Amplification and counting is done by special amplifiers with amplitude discriminator.

A compact density and moisture measuring equipment (18" x 18" x 12") was devised by A.C. Meigh in 1957. The following difficulties are encountered

(1) Probable calibration error

(2) The scalers are sensitive to shaking and transportation to sites difficult.

(3) Errors are found when the three batteries used do not run down at the same rate. The change in voltage causes variation in counting rate.

(4) The use is costly.

As an improvement, use of thimble chambers instead of the scalers is advocated. This essentially consists of well insulated condenser charged to known potential. When gamma rays traverse the chamber, the air is ionized and the condenser discharged. The drop of potential is proportional to the transmitted radiation. A sensitive electrometer is used to measure the variation.

The thimble chamber encloses a chamber of 1 C.C. with walls of mixture of graphite and bakelite with outer diameter 1.5 cms and length 2.5 cms. The field equipment evolved is in the form of a fork. Two brass tubes 100 cms long with outside diameter 3 cms and wall thickness 0.2 cms are fastened together with steel sheet at 30 cms apart. At the lower end a form of shallow tail is provided with sharp edge for easy penetration. The top is provided with attachment for drill rods. Containers of the source cobalt 60 and container with thimble chambers are inserted in the tubes and exposed. The variation of potential measured from calibration charts. The required results are obtained.

A Radio active fork has been evolved in U.S.S.R. for controlling soil densities. It has two metal tubes 1.8 cms in diameter and 50 cms long rigidly connected through a hollow union to a duralumin rod. One tube is provided with the source and the other detector. The ionization current is fed to a pulse amplifier mounted in the union and then to pulse recorder.

Thus it is seen that the methods are developing gradually and are particularly useful for sandy soils and soil under water where undisturbed sampling is difficult.

7.6. REVIEW OF OTHER METHODS FOR QUALITY CONTROL

"Porosimeter", an instrument evolved by R.L. Dewan (18) is supposed to give fairly reliable determinations of density and moisture content. Mathematical relations are made use off to work out the results in a quick time. The Dalton's law of partial pressure is made use off. The process yet needs to be adopted in actual field work.

R.L. Dewan and others (19) have explained that most of the methods in vogue are very elaborate, time consuming thus affecting progress of work. The new modes using gamma rays and the like involve costly machines and high technical skill which is not possible to be provided at each individual site. Much simpler methods are felt essential.

The use of statistical method for analysis has been propagated early in 1953 by F.J. Davis (20). The following detailed record is suggested in high dams for analysis

(a) Separate analysis of each borrow area

(b) Separate analysis of (a) above for different periods of time.

(c) Elimination of all doubtful tests

(d) Importance of representative sampling

Variation of O.M.C. & M.D.D. in individual tests recorded and statistical analysis by frequency graphs, normal distribution graphs is suggested.

The working out of arithmetical averages does not indicated the scattering or range of occurence. A statistical distribution would indicate more details.

An interesting statistical study of the records of portugese dams made by M. Rocha (63) is shown below:-

TABLE 12

Name of Dam	Number of Tests	$W_t - W_{proct}$		% Compaction $\frac{\gamma_f}{MDD} \times 100$	
		Mean	S.D.	Mean	S.D.
Campilhas	50	0.5	1	99	4
Silves-core	50	-2	2	94	3
Marahao-core	50	-3	2	101	3
Montargil					
(a) Core	43	-4	3	96	4
(b) Upstream fill	52	-3	3	92	7
(c) Downstream fill	44	-3	3	92	8

W_t = Field moisture content

W_{proct} = O.M.C.

S.D. = Standard deviation

γ_f = Field density

Such studies are useful in all cases. Hilf's method of 'Rapid control' based on statistical formulae (30) is gaining importance in the U.S.B.R. dams. The results are obtained in an hour or less. The method (DES-E25) essentially consists in compacting soil with the fill water content in a standard compaction cylinder and finding wet density. Wet density is found for two other moisture contents

Field tests are essential at a minimum of every 2000 cyds of earthwork. More tests are needed in doubtful areas. A statistical record of all work is to be maintained.

Moisture measurement by the normal method of oven drying takes much time. As further work would be hampered quicker methods are evolved.

Use of hot plate, penetration needle or rapid moisture meter are generally adopted these days.

Measurement of field density is made by scooping out the material from embankment and weighing it. The volume is found by either the sand replacement method, rubber ballon method or oil filling method. As laboratory tests are done on - 3/16" fraction gravel correction needs to be applied for soil containing coarser particles. Density of sand may be found out by calibrated probing device.

Modern methods of quality control by nuclear devices is gradually coming into importance though the methods are costly and are highly technical. These have great scope in future. The U.S.B.R. are adopting in recent days Hilf's method of rapid control. These new methods avoid the elaborate procedure and save time.

different research workers.

8.2. REVIEW OF CORRELATIONS ATTEMPTED

8.2.1. R.R. Proctor (61) gave a scientific approach to the process of compaction in 1932. The Swedish Scientist A. Atter Berg at the same period indicated methods for measuring plasticity characteristics of soils. Woods and Litchison made the first attempt in 1937 to correlate the Atterber's limits with standard proctor's compaction values.

In 1948, Rowan and Graham worked out a relation of O.M.C. and M.D.D. with the combined effect of plasticity characteristics and gradation of soil on the basis of tests on 10 soils. The relation is:-

$$\text{Density} = \frac{6250}{S(B/A - 1) + 100/R}$$

$$\text{and O.M.C.} = S\,(B/A)$$

Where S = Shrinkage limit

A = Percentage of soil passing U.S. No.4 sieve

B = Percentage of soil passing U.S. No.40 sieve

and R = Shrinkage Ratio

Within a year in 1949, Davidson and Gardner modified the relation to obtain more reliable values as below:-

$$\text{Density} = \frac{6250\,K_1}{S\left(\frac{B}{A}\right) + 100\,R}$$

$$\text{and O.M.C.} = S\,(B/A + K_2)$$

$$\text{Where } K_1 = \frac{312 - 2\,(PI)}{300}$$

$$K_2 = \frac{PI}{3} - 4$$

Where PI = Plasticity index

In recent years, in 1962, Ring Salisberg and Collins have evolved the P.R.A. equation (Public Road Authorities) on the basis of linear regression analysis by computer studies on 600 results. It gives

$$O.M.C. = 0.8151 + 0.1358\ (w_1) + 0.529\ (WP)$$

with a standard error of ± 2.15 %

Where W_1 = Liquid limit

WP = Plastic limit

Hungarian Academy of Science has published in 1963 the variation of ranges for O.M.C. and M.D.D. for Hungarian soils in relation to plasticity values.

Plasticity Index	O.M.C.	M.D.D. in gms/c.c
5 to 10	9 - 13	1.90 to 1.98
10 to 15	10 - 14	1.85 to 1.95
15 to 25	11 - 17	1.75 to 1.92
25 to 45	14 - 20	1.65 to 1.80

In 1963, Rajoria(61) has worked out a relation by testing 50 soils of the Indo-Gangetic Plains in U.P. and black cotton soils of Madhya Pradesh with liquid limit between 20 to 60 and plastic limit between 10 to 40. The final recommended relation is:-

$$O.M.C. = 3.962 + 0.218\ (WL) + 0.252\ (WP)$$

Relation between compaction values and plasticity characteristics has been tried by P.L. Narayana Murthy by a study of 121 soils of Bihar (56). Two parameters NP and N_O named as plasticity factor and O.M.C. factor are utilised.

Np is defined as $= \sqrt{\frac{W_1 \quad W_p}{P_I}}$

WP =
Where ∠ Liquid limit

WP = Plastic limit, and

PI = Plasticity Index

and $N_o = \sqrt{\frac{0 (W_1 - 0)}{PI}}$

Where 0 = O.M.C.

From analysis it is shown that

$N_o = 0.28 + 0.495\ Np$

Hence it is observed that the compaction characteristics are related to plasticity values.

8.2.2. The grain size distribution in soil was shown to affect the O.M.C. value and corresponding M.D.D.

Mohammed Saiid Youssef of Cairo (54) has the following conclusions to connect O.M.C. with the gradation.

(1) O.M.C. is found to be same for soils of given degree of fineness whatever the grading may be as long as compactive effort is same. M.D.D. is found to vary.

(2) As temperature increases, O.M.C. is found to decrease slightly. This is due to decreased viscosity. A temperature correlation to O.M.C. would thus be necessary where field temperatures are very different from those of laboratory tests.

(3) As compactive effort is increased, the density moisture curve changes to give lesser O.M.C. and greater M.D.D. The line joining the peak of curves namely ~~to~~ line of optimum is found to satisfy the relation as below:-

$$y - C_1 C_2 y x = C_1$$

Where Y = Value of D.D.

X = Moisture content

C_1 & C_2 are constants.

C_1 & C_2 needs to be established by a set of tests.

8.3. SOILS OF MADHYA PRADESH

8.3.1. Different authors have indicated the generalised properties from their studies for the different classes of soil. This serves as a good guide for preliminary investigation. Such analysis for individual areas would prove beneficial and very handy. Similar studies for soils of Madhya Pradesh were thought off.

The U.S. Corps of Engineers (87) have made an engineering use chart (Extracts given in Table 13) indicating the properties and suitability of compaction units for particular groups of soils as per unified soil classification system.

The U.S.B.R. in their publication "Design of Small Dams" (85) have analysed the properties of soil groups. It is on the basis of analysis of laboratory tests on 1500 samples conducted at Denwer Laboratory. Although sampling was done in the 17 Western Districts of United States it is reported that the results are insensitive to geographical distribution. The 90 % confidence limits are also indicated.

G.F. Sowers has also analysed the soil properties for individual soil groups of unified soil classification system. The values of O.M.C. and M.D.D. are given in Table 13.

Such studies were undertaken to study properties of compaction for prominent soils of Madhya Pradesh. Tests are conducted as per details given by Lambe (14) for standard proctor's test. From test results sampling was made by author to include soils of different districts, soils having minimum and maximum of O.M.C., M.D.D., Liquid Limit and Plastic Limit. Averages of O.M.C. and M.D.D. for individual groups were worked out. Standard deviations have been calculated. The values have been incorporated in the Table 13, along with the results of other authors to give a comparative idea. It shows that the ranges fixed by other authors and particularly by U.S.B.R. is too small. The maximum dry density cannot be defined to be almost within 4 lbs/cft of any one value for any soil group as there can be easily greater variation. Similar is the case with optimum moisture content. The averages worked out for Madhya Pradesh soils for M.D.D. gives a maximum range of 28.4 lbs/cft for GM soils and a minimum of 12.6 for GC soils. The ranges are practical and reasonable.

It is very essential that the results obtained are checked to find out how they suit greater number of test results. Such check was exercised by the author on more than 2000 samples and results tabulated in Table 14. It will be seen that about 80 % reliability is obtained for non-plastic soils and 66 % for plastic soils.

Group	Permeability compacte	U.S.B.R. n of Small Dams) D.	O.M.C.	As per Studies of Results of Raipur Laboratory M.D.D.	O.M.C.
(1)	(2		(18)		(19)
GW	Pervious		13.3	-	-
GP	Very Pervi		12.4	-	-
GM	Semi-pervi pervious		14.5	108.9±142	18.4± 7.8
GC	Impervious		14.7	109.7±16.3	18.7 ± 8.5
SW	Pervious		13.3 ± 2.5	-	-
SP	-do-	2	12.4 ± 1.0	-	-
SM	Semipervio Impervious	1	14.5 ± 0.4	104.8±13.5	20.3 ± 8.2
SC	Impervious	1	14.7 ± 0.4	114.7±12	14.6 ± 6.2
ML	Semi-imper Impervious	1	19.2 ± 0.7	105.2±10.8	17.4 ± 4.7
CL	Impervious	1	17.3 ± 0.3	110.5±7.0	15.8 ± 3.2
OL	Semi-imper Impervious		-	-	-
MH	Semi-imper Impervious	4	36.3 ± 3.2	92.1±7.9	27.7 ± 5.6
CH	Impervious	2	25.5 ± 1.2	85.3 ±11.2	27.8 ± 8.2
OH	-do-		-	-	-

Note:- Columns of abbreviations used is indicated below:-

C = Cra

TABLE 13

Group	Permeability when compacted	Shearing Strength	Suitable Compaction Units	Compressibility	Unit Dry Wt/Cft Lbs as per U.S. Corps of Engineers	General Characteristics as per Sowers & Sally		As per U.S.B.R. (Design of Small Dams)		As per Studies of Results of Raipur Laboratory	
						M.D.D.	O.M.C.	M.D.D.	O.M.C.	M.D.D.	O.M.C.
(1)	(2)	(3)	(4)	(5)	(6)	(7)		(8)		(9)	
GW	Pervious	Excellent	C.R. St.	Negligible	125-140	125-140	4.12	119	13.3	-	-
GP	Very Pervious	Good	-do-	-do-	110-130	115-125	4.14	110	12.4	-	-
GM	Semi-pervious to pervious	Good	RS	-do-	120-145	120-135	8-13	114	14.5	108.9±142	18.4± 7.8
GC	Impervious	Good to Fair	RS	Very low	120-145	115-130	8-15	115	14.7	109.7±16.3	18.7 ± 8.5
SW	Pervious	Excellent	CR	Negligible	110-130	110-135	6-18	119+5	13.3 ± 2.5	-	-
SP	-do-	Good	CR	Very low	100-120	100-120	6-16	110±2	12.4 ± 1.0	-	-
SM	Semipervious to Impervious	-do-	RS	Low	105-135	110-125	10-18	114±1	14.5 ± 0.4	104.8±13.5	20.3 ± 8.2
SC	Impervious	Good to Fair	RS	-do-	105-130	105-125	10-20	115±1	14.7 ± 0.4	114.7±12	14.6 ± 6.2
ML	Semi-impervious to Impervious	Fair	RS	Medium	100-125	90-120	12-28	103±1	19.2 ± 0.7	105.2±10.8	17.4 ± 4.7
CL	Impervious	Fair	RS	Medium	90-105	90-120	12-28	108±1	17.3 ± 0.3	110.5±7.0	15.8 ± 3.2
OL	Semi-impervious to Impervious	Poor	RS	Medium	90-105	80-100	20-23	-	-	-	-
MH	Semi-impervious to Impervious	Fair to Poor	S	High	80-100	70-95	25-40	82±4	36.3 ± 3.2	92.1±7.9	27.7 ± 5.6
CH	Impervious	Poor	S	High	90-110	75-105	18-35	94±2	25.5 ± 1.2	85.3 ±11.2	27.8 ± 8.2
OH	-do-	Poor	S	High	80-105	65-100	25-50	-	-	-	-

Note:- Columns 1 to 6 are taken from the "Engineering Use Chart" of U.S. Corps of Engineers. The details of abbreviations used is indicated below:-

C = Crawler type tractor S = Sheepsfoot roller

R = Pneumatic type tractor St = Smooth wheel roller

TABLE 14

RESULTS OF CHECK TO FIND OUT RELIABILITY OF THE RANGES FIXED

S.No	Type of Soil	No. of Samples consider-ed for analysis	Values of O.M.C. & M.D.D.		No. of results checked	No. of results not agree-ing for O.M.C. values	No. of results not agree-ing for M.D.D. values	No. of results not agreeing for both	No. of Test Results Satisfying ranges of OMC & MDD	Percentage of Reliability
			O.M.C.	M.D.D.						
1	GM	19	18.4+7.8	108.9+14.2	80	2	7	10	61	76
2	GC	32	18.7+8.5	109.9+6.3	310	29	15	6	260	84
3	SM	18	20.3+8.2	104.8+13.5	178	12	9	26	131	73
4	SC	34	14.6+6.2	114.7+12	395	10	8	31	346	88
5	ML	18	17.4+4.7	105.2+10.8	298	26	4	13	255	85
6	CL	18	15.8+3.2	110.5+7.0	144	14	4	9	117	80
7	MH	13	27.7+5.6	92.1+7.9	62	9	4	8	41	66
8	CH	18	27.8+8.2	85.3+11.2	273	12	57	24	185	66
9	CI	30	19.6+4.3	103.9+4.7	421	25	31	31	337	80
Total		200	Total number of results utilised for check		2166					

8.3.2. N.P. Wadhwa and others (89) have made the initial studies of correlation of soil properties of lateritic soils of south western Madhya Pradesh. From work on 18 samples it is indicated that these soils have an accurate relation of M.D.D. = 195 - 71.5 log O.M.C. No relation has been reported possible between O.M.C. and clay percentage or between O.M.C. and plasticity index.

Correlation of O.M.C. with M.D.D. for the selected samples of Madhya Pradesh soils was attempted by the author from data available from the Raipur Laboratory. Several trials were made and finally correleation between M.D.D. and log O.M.C. has been established for different individual groups of soils. The method of least squares has been used for obtaining the best fit curves. Test results correspond to standard proctor's test. M.D.D. is in lbs per cft and O.M.C. percentage.

Group	Number of samples considered for analysis	Best curve fit for the values
CL	18	$MDD = 220 - 118 \log OMC + 22 (\log OMC)^2$
GC	32	$MDD = 284 - 142 \log OMC$
ML	18	$MDD = 483 - 309 \log OMC$
CH	18	$MDD = 186 - 70 \log OMC$
GM	20	$MDD = 126.5 + 24.5 \log OMC - 31 \log (OMC)^2$
SC	18	$MDD = 141 - 20 (\log OMC)^2$

M.D.D. is in lbs/cft and O.M.C. is %.

A generalised solution was also obtained as indicated below:-

$$M.D.D = 209 - 83 \log O.M.C.$$

From these equations the results were checked for 130 samples. For 10 samples results varied by more than 10 % and for 5 samples between 5 to 10 % of the maximum dry density 90 % reliability is established. Correlation can thus be generally utilised.

8.3.3. As clay percentage plays a predominant part in deciding the O.M.C. of soil, correlation was tried, between clay % and O.M.C.

From an analysis of 7 samples in each group the relation for individual groups was obtained as below:-

CL	Clay % = 2.24 OMC -4.93
CI	Clay % = 2.17 OMC -5.92
SC	Clay % = 1.20 OMC +6.37
CH	Clay % = 2.15 OMC -12.97
MH	Clay % = 0.65 OMC + 9.54
ML	Clay % = 0.38 OMC +11

On checking, the variation in case of coarse grained soils was found to be large and hence no correlation was considered feasible.

For fine grained soils, a general relation was obtained as below:-

$$\text{O.M.C.} = \frac{(\text{Clay } \% + 6.8)}{2.12}$$

From check for 104 samples only for 58 samples O.M.C. was within $\pm$ 3 % of theoretical O.M.C.

Calculation of a second degree equation was attempted. The relation obtained is

$$\text{Clay } \% = 54.6 - 4.84 \text{ O.M.C.} + 0.17 \text{ (OMC)}^2$$

This relation was slightly better. From checking for 104 samples the actual O.M.C. for 63 samples with within $\pm$ 3 %

theoretical O.M.C. The relations thus do not indicate full reliability. It was concluded that no relation of clay percentage with O.M.C. was possible.

8.4. CONCLUSIONS

Research workers have attempted for correlations o compaction characteristics by studies of several test results.

The process of arriving at the correlations is a long process involving careful selection of samples, statistic analysis of the values and a thorough check to find out the accuracy. Only an attempt was made for such correlations for Madhya Pradesh soils. Detailed studies would give more rel results.

From the studies made the general range of O.M. and M.D.D. for different groups have been established. The results have about 80 % reliability except for the highly plastic soils. The range prescribed by other authorities is small and a larger variation does occur. The values worked can ~~have~~ serve as a general guide.

Relation between O.M.C. and M.D.D. was attempte for Madhya Pradesh soils. M.D.D. was found equal to 209 - 8 O.M.C. This relation has a 90 % reliability and can be used

Attempt was made to correlate the optimum mois content with clay percentage and plasticity index. Reliabl results could not be obtained. When such correlations are attempted, it is better to select smaller geographic zone the type of soils do not vary much. It was felt from exp that by selecting large area such as the entire state of Pradesh, reliability is reduced.

CHAPTER 9.

CONCLUSIONS AND SCOPE FOR FURTHER STUDY

9.1. In the present study, a review of the uptodate literature on the subject of compaction has been made to arrive at the following conclusions and indicate scope for further study.

9.2. CONCLUSIONS

9.2.1. The well known general characteristics of compaction are enumerated in article 1.5. It is seen that increase of compactive effort reduces the O.M.C. and increases M.D.D. To achieve a higher density increase of compactive effort is needed. Each soil is thus shown to have a certain specific compaction value of O.M.C. and M.D.D. for a particular compactive effort. The review of history indicates a gradual increase in compactive effort to achieve economy and efficiency.

9.2.2. Several theories of compaction based on lubrication, viscosity of the liquid, surface chemical action and effective stress considerations have been promulgated. As discussed under 2.8 none of them still completely explains the phenomenon of compaction of increasing density of a soil upto a certain moisture content and decrease in density with moisture beyond the optimum value.

9.2.3. Testing of soils for compaction is possible in many ways. But the original standard proector's test or the modified proctor's test is still in vogue as none of the other methods provide special advantages for a change over. Use of Harvard miniature compaction test comes in handy when only a small quantity of material is available for test.

It is true that the laboratory dynamic test does not represent the field condition where compaction by the combined effect of static, dynamic, and kneading action is achieved. But the results are shown to tally well with the actual field values. Precautions that are essential to get a correct estimation of compaction values from laboratory are as follows:-

(a) Varying the compactive energy in tests to correspond to the field values.

(b) Use of large size moulds when combined material containing +4 fraction is to be tested or else gravel corrections needs to be applied.

The possible errors in testing enumerated in 3.2 only stress the importance of adhering to the specifications. Salient points to be followed are:-

(a) A sub-base of concrete of 400 lbs or a 2" steel plate on wooden base is essential uniformly for all tests.

(b) Uniform mixing of moisture in soil is to be ensured.

(c) Remoulding of the same soil for different trials should be avoided.

(d) As soil at top of mould would have slightly lesser densities, it may be worthwhile adopting these values for a conservative design

(e) With clayey soils averages of 4 to 5 tests is desirable as there may not be uniform and proper distribution of moisture in fine soils.

A new method of testing soils for finding compaction effort needed is by consolidation tests. This is to minimise settlement of compacted soils. It is still under study. This method will have value when soils are to be compacted only to prevent settlement.

Density of cohesionless materials are to be based on relative density test as these materials do not exhibit a marked O.M.C. as cohesive soils. Plate bearing tests at field may give more reliable results but are suitable for foundations. An optimum static load is found to give improved values of compaction by vibration. For internal vibration of sand, the dry state is found to give maximum density but for other modes the saturation of sand would result in better densities.

9.2.4.(a) The most important study is regarding the variation of strength of compacted soils with compaction. The strength variation clearly indicates the necessity of quality control to ensure specified moisture and density in field to get required results. Only from a careful study of the strength characteristics of compacted soil with tests at different moisture content at compaction, the placement moisture is to be decided. Following conclusive points are indicated from the review of literature.

	Compaction wet of OMC	Compaction dry of OMC
Settlement	Less	Greater
Swelling	Less	Greater
Plastic failure of clays	Greater chances	Less
Permeability	Less	High
Shear Strength	Low	High

	Compaction wet of O.M.C.	Compaction dry of O.M.C.
Cracking	Less	Great
Piping chances	Low	Great
Seepage velocity	Low	Greater
Pore Pressure	High	Low (Even negative pore pressures in clays are reported)
Consolidation	Lesser	Better
Trafficability of machines	Poor	Better

(b) It is thus seen that soils compacted wet of O.M.C. have low shear strength due to high pore pressure. Consolidation is also poor in addition to the difficulties in movement of machinery. Permeability is low. As such the permissible upper limit of moisture is to be fixed on the basis of trafficability of equipment and permissible pore pressure.

On the other hand if compacted dry of O.M.C., swelling characteristics and settlement are greater though higher strength is possible. Due to greater permeability of soil consolidation would be better. But the chances of failure by piping or cracking due to differential settlement is also greater. The lower limit may be based on permissible settlement. 100 % compaction to achieve M.D.D. increases swelling characteristics. Hence in clay embankments compaction to lesser than M.D.D. at or slightly wet of O.M.C. is desirable. Clayey soils compacted wet of O.M.C. prevent piping and settlement. Shrinkage would be less. Proper account of pore pressure and strength is to be taken. Accurate moisture control is needed. Clayey soils in foundation or in embankment do need special study.

Increase in compactive effort would cause better particle orientation giving higher density. It reduces flexibility Resistance to piping is improved as permeability is reduced but chances of failure due to cracking are not avoided. Higher pore pressure would develop. Better strength by compaction at dry of O.M.C. is possible but wet of O.M.C. there may be a little less or gain in undrained strength due to higher pore pressure build up. Consolidation would also be poor. The rate of improvement of soil properties with heavier compaction is considered small.

Gravel content in embankment material gives the following advantages:-

(1) Increased density is obtained.

(2) Greater strength is achieved due to increase in angle of internal friction.

(3) Permeability is greater and hence better consolidation is possible.

(4) Pore pressures are reduced.

(5) Compressibility is less.

All the above points need due consideration with reference to available material and equipment for deciding placement moisture content.

It is clearly seen that engineering properties can be changed in the desired direction by moisture control.

9.2.5. The different modes of compaction available for use have increased much since the early days when human labour or animals were utilised for compaction. Heavy compaction units are a pre-requisite for an important construction to achieve economy and speed in execution . There will be the added advantage of proper mixing and good bond between layers.

The sheepfoot rollers are still predominently used with the growing importance of heavy pneumatic rollers. These can give better progress of 500 to 1000 cyds/hour as compared 100 to 500 cyds/hour of the former. The intricate foundation problems of soils has resulted in advancement of vibratory modes of compaction. Vibratory rollers, methods of blasting, compaction by vibrofloatation are gaining importance though the details are not fully known. Study for individual site conditions are essential to select the best mode.

The thickness of layers and number of passes of rollers have a great significance. Field tests would give the correct idea of the most economical lifts and number of passes depending on type of soil and moisture content. In general a 6" layer for sheepfoot roller and 9" for rubber tyred rollers are specified though Heavy S.F. rollers do have effect of compaction to about 3 feet and the latter much more. Depending on the number of passes and compacting pressure, the soils indicate a particular field OMC and MDD which is adopted.

Increasing number of passes reduces field O.M.C. and increases density. A limiting number of passes for efficiency for individual type of soils and type of equipment is shown to exist. Increasing the passes further are not found useful. Vibratory rollers are found to need more number of passes than plate compactors. The increase of tyre pressure for a pneumatic roller is better than giving higher number of passes with the same compactive effort. Similarly the variation of size of sheepfoot varies density and a 14" sq.in size of foot is considered most suitable.

9.2.6. It is seen that method of compaction suitable for one soil may not suit the other. In clayey soils, the clods need to be broken and it is also found that varying the moisture content after excavation from borrow area is difficult. Watering the borrow area is recommended for uniform moisture and greater working space. Sheepsfoot roller is considered the best for compaction. Greater moisture control is very essential.

Moderately cohesive soils can be compacted well by rubber tyred rollers or smooth rollers. A proper combination of either the S.F. roller and pneumatic rollers can be used for compaction depending on the individual characteristics found out by field tests.

Noncohesive soils like sands need greater attention. These sands are being used these days for dam construction and are generally found in foundations. Compaction of foundation by blasting or vibrofloats or by any method of vibration is desired. Embankment soils can be compacted by vibratory rollers or by heavy tractors to achieve required relative density.

Soils as residual soils, loessic soils, shales, silt stones require special treatment to suit individual properties.

In wet climates where the soil in nature is at a moisture content wetter than O.M.C., drying may be done by any of suitable modes given under 6.5.5. The other alternative is to compact soil at its existing moisture content. The corresponding strength characteristics needs to be accounted for. With fines greater than about 4 % construction difficulties are observed due to the fines working up and causing slushiness.

Suitability of different modes for individual types of soils are generalised under 6.7.

9.2.7. All the studies on compaction indicate fully the importance of quality control. The design assumption made should be satisfied by checks exercised in the field. This is ensured by control of field moisture and density. A permissible range needs to be fixed up in design as at field one has to deal with different climatic conditions, materials, equipment and their behaviour for compaction.

Quality control is to be a combination of visual inspection, sound judgement, field laboratory tests and their analysis. Rich experience is a guiding factor for visual inspection of the moisture content and study the performance of rollers. Field laboratory tests for every 2000 cyds are essential for moisture and density check.

The prevailing standard test procedures involve time. The wet density is found out by testing undisturbed samples from compacted embankment. It needs to be oven dried to get results of field moisture. Rapid methods of field test are evolved to dry the sample in quicker time. For moisture control penetration needle is commonly used for fine soils. Hilf's method of "Rapid control" is fast gaining importance, particularly in U.S.B.R

With coarse soils, gravel correction needs to be applied or a degree of compaction which accounts for gravel percentage (as fixed by U.S. Army Corps of Engineers) may be adopted. Large size moulds are used for testing the total combined material. The relative density of sand can also be found by cone penetration tests.

There is the modern trend to use nuclear methods for quality control. Apart from the fact that these methods are costly the difficulties in calibration and adaptation of these to varying field conditions has delayed its use on large scale quality control.

Maintenance of detailed records and a statistical analysis of field tests is recommended. It is helpful for future projects and would serve as a proof to show that the work is done to required standards.

9.2.8. A study of the variation of the compaction values for different soils and an inter-relation with other soil properties has been attempted by several authors. Such correlations would enable forecasting of compaction characteristics with considerable accuracy without detailed tests. These are particularly useful where testing facilities are not available. It is seen that the correlations made at a particular place may not suit for all places. Many correlations are based on scanty data which again give rise to errors. It is deemed essential that the correlations should be checked up with some standard values before being used to prevent errors. Only a guiding information can be obtained from them.

The moisture content and density have been correlated to the grain size distribution of soils in 1949 and to Atterberg limits in 1962.

From a study of soil samples of several districts of Madhya Pradesh the variation of O.M.C. and M.D.D. have been worked out by the author for individual soil groups and are indicated in Table 13. A good check is exercised to indicate the percentage reliability.

A correlation of O.M.C. with M.D.D. has given a relation,

$$M.D.D. = 209 - 83 \log O.M.C.$$

Trials were made for correlating O.M.C. with clay percentage. The results indicate poor reliability even for fine grained soils. For coarse grained soils there is much deviation for any possible correlation.

9.3. SCOPE FOR FURTHER STUDY

9.3.1. A great deal of intensive study and standardisation of the subject of compaction on scientific lines is still needed.

9.3.2. It is only recently in 1963, that the effective stress theory of soil compaction has been enunciated after disproving the theories that existed earlier. A thorough investigation of study of pore pressure build up during the process of compaction can only establish this theory. Doubts have been expressed regarding creation of negative pore pressures in the process. A comprehensive theory is yet to be enunciated.

9.3.3. Several methods of laboratory tests have been evolved but still the standard proctor's test is most commonly adopted. To account for increased compactive effort, the modified A.A.S.A.O. test has come to stay. Field compaction is found to produce satisfactory results comparable to the dynamic compaction tests. Different tests though in vogue do not have specific advantages.

sts on soils from different methods can give good ~~compaction~~ comparison of
liability of each test.

With increasing utilisation of the gravelly soils, ndardisation of test procedures for relative density test deemed essential. A simpler method of finding relative density sand would be useful. This may be on the lines of the etration test as obtaining undisturbed samples of sand or vel to find insitu void ratio is not easy.

.4. Regarding the strength characteristics of compacted ls, no amount of research would be complete. A general guide e of the quantitative variation of properties for different so: ıps with variation in placement moisture for compaction is an ediate need. This may involve a series of tests on soils at 'erent moisture content and is worth the purpose. It is well ı that only from moisture and density adjustment, all the r properties can be changed as desired. This analysis would f greate~~r~~ utility.

5. Considerable work on the different modes of pment in use and their efficiency has been made. The effect of 1 of movement on compaction needs to be worked in detail. increasing earthwork and need for quicker progress the ibilities of adopting thicker layers may be great utility. types of equipment for further economy are expected. Vibratory rs have a large scope for use on different types of soils mically and efficiently. The details are to be studied and ardised.

. Different types of soils ...

sandy soils. It is preferable to have one type of equipment to suit all categories of soils. The field engineers would prefer to have a stastical analysis of the effects of compaction on different types of soils by different modes to decide its merits and demerits.

9.3.7. Quality control assumes greater importance with construction of higher embankments. Rapid control method needs to be standardised for an easy understanding of the Inspector in charge of quality control. Simpler Gadgets for moisture and density determination may solve the problems in a very simple way. The process is still cumbersome and time consuming. New methods are still highly technical. Rapid moisture meter has a promising future.

The permissible relaxation in specifications for dams of smaller heights should be studied and the criteria for the same determined. It does not stand to reason that the same standards of quality control that apply to a 400' dam should apply to a 40' high dam. Even assumptions of reduced values of strength in design with relaxed quality control may be worth the change as it would avoid strict quality control.

9.3.8. Study of soil properties with their relation to compaction values is of assistance to minor schemes where the cost of testing could be eliminated if results are satisfactory. A word of caution is that the correlations when worked out should be specific and accurate. Good and reliable tests needs to be chosen for individual areas.

9.4. It is hoped that in the years to come the subject of compaction will achieve much greater importance inviting soil scientist to dwell more into the subject. There is a bright future with the urgent need for ~~the~~ economical earth dams in large number for full utilisation of the water resources for the development of man-kind.

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