# SOIL COMPACTION AND COMPACTION EQUIPMENT

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Scope of Study: The purpose of this report is to study soil compaction in both the field and the laboratory. The main part of this report is a discussion of soil compaction from the construction point of view, including discussion of field compaction equipment and factors affecting the compaction of soil in earthwork construction.

Findings and Conclusions: Compaction of soil is a subject quite vast and complex. It depends upon many variables including soil type, moisture content, amount and nature of compactive effort, and the degree of compaction specified. So it is nearly impossible to offer a solution to all its problems. The final determination of these factors must be based upon the results of laboratory tests with the judgment and experience of the engineer or the contractor.

ADVISER'S APPROVAL E. L. Bidwell

SOIL COMPACTION AND COMPACTION EQUIPMENT

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TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

## LIST OF FIGURES

| Figure | | Page |
|---|---|---|
| 1. | M.I.T. and B.S.I. Particle-Size Scale | 14 |
| 2. | Rubber Balloon Density Apparatus | 18 |
| 3. | Sand Cone Density Apparatus | 19 |
| 4. | Tube Sampling Apparatus | 22 |
| 5. | Relationship Between Number of Passes of 9.5 Ton Steel Roller and Dry Unit Weight of Sandy Clay Soil | 34 |
| 6. | Relationship Between Dry Unit Weight of 6 Inch Compacted Sandy Clay and Number of Passes of 47 Ton Pneumatic-Tired Roller | 37 |
| 7. | Relationship of Number of Passes of Sheepsfoot Roller and the Dry Unit Weight of Sandy Clay Soil | 40 |
| 8. | Typical Relationship Between Unit Weight and Number of Passes With the Vibratory Roller. Granular Material in 8 Inch Lifts | 42 |

# CHAPTER I

## INTRODUCTION

In the United States, hundreds of millions of dollars are spent each year to keep up the old roads network. For example, in Oklahoma the total maintenance costs of the roads for the year of 1959 was $38,505,000. This is about 25.6% of the total disbursements for the highways of the state during that particular year. [29] Improper compaction of subgrades is a basic cause. The construction contractor of the past was not so much guilty of short-cutting as he was of not really knowing all the compaction techniques. The supervising engineers were equally at fault for not understanding these fundamentals and explaining them to the men on the job.

The purpose of this report is to study some of the compaction problems from the construction point of view. It will discuss compacting equipment, their effect on different types of soil, and different methods of compaction to achieve the specified results. The rest of this chapter will be devoted to the explanation of compaction, covering its meaning, and its history from the earliest eras to the present time. The function or the requirement of this compaction will also be discussed.

Definition: Generally, compaction may be defined as the more or less rapid reduction in the voids of soil produced by mechanical means during construction processes.

In every natural mass of soil, there is a certain amount of voids. By means of compaction this amount of voids is reduced, increasing the density of the soil. Usually no water is expelled from the voids during compaction.

## History of Compaction

The earliest known records of intentional compaction date back to the great road construction eras of the Babylonian (Iraq), Pharaonic (Egypt), and Roman Empires. Huge cylindrical shaped stone rollers drawn by slaves, were used to compact earth embankments, or successive layers or lifts of smaller stones. Many of these roads are still in existence today and some even in use.

Later on, at about the start of the 19th Century, men in the United States and England drove sheep, cattle, and goats across the fields several times in order to attain compaction.

From the era of the Babylonian Empire until the present, rollers in many forms, sizes, and weights have been used to compact soils, stones, and asphalt.

The evolution of the power of one of these pieces of compacting equipment, the self-propelling power roller, began by being slave and oxen drawn, evolved into the steam powered, then to the gasoline drawn and finally to a self-contained gasoline or diesel engine power unit of today.

Modernization also includes power steering, adequate brakes, sprinkler system, operator's cab, and electric lights and starter.

## Compaction Requirement

The basic requirement for the compaction of soil is to have the shearing resistance or friction between the particles of soil reduced to a point where the superimposed loads can then press the particles closer together. By means of compaction engineers try to improve the soil from the standpoint of shear strength, resistance to settlement under future loading, and watertightness.

Satisfactory compaction is a function of four major component elements: Specification, materials, methods, and equipment. More discussion about these elements will be in the following chapters.

## CHAPTER II

## SPECIFICATIONS

In any construction project where compaction of fill is required, the owner wants the most dense and stable earthwork obtainable at the lowest possible price. The contractor strives to achieve the most economical method available in order to meet the minimum requirments in the shortest time, and thereby make the greatest profit. Owners accuse contractors of poor performance, and the contractors feel the owner wants to squeeze out perfection from a pittance while while trying to harness them with restrictions.

Most of these differences could be reduced by an understanding of what is actually desired by both sides. Reasonable specifications, as uniform as possible for the soil types involved, are basic to the realization of this goal.

Specifications are written to reduce these problems between owners and contractors giving the correct procedure of operations in order to achieve the best results.

Specifications are written after considering such factors as the specific soils at the site, the fill material obtainable within economical hauling distance, the difference between laboratory and field moisture-density relations, the various types of available equipment for preparing the fill, the height of lifts, and the speed and number of passes of the equipment.

There are four possible ways to write a specification so that the owner may have satisfaction at a reasonable price and the contractor can complete the job with pride and still make a reasonable profit. These methods are: method only, end result only, method and end result, and suggested method and specified result.

I. By Method Only:

This type of specifications describes in detail how the compaction is to be done. It states the maximum height of lift allowable, the required moisture content, and minimum number of passes allowable for specific equipment. The disadvantage to the owner, may be that he does not get the best results for his money. He can only be reassured that the job has been done as specified. It may force the contractor to buy or rent equipment he does not have at the moment to use on soils, where other equipment, which is not specified would be more efficient in achieving the specified results.

II. End Result Only:

This type of specification is becoming more popular, and there is a trend toward its more frequent use. A typical specification of this type might say: "The contractor may use any type of compaction equipment he deems necessary to obtain the specified density."

Result specification include one of the following:

1. Required degree of compaction, with
    a. a high degree specified for all soils, or with
    b. a degree specified which varies with the compaction characteristics of the soil.

There is little in favor of (1a.) except that it tends to be conservative in a number of cases. This approach does not recognize the fact that some soils are inadequate in performance even when compacted to peak or optimum densities. On the other hand, other soils are quite competent at levels significantly below the maximum. Method (1 b.) is based upon a recognition that soils may be classed upon the basis of compaction characteristics. Inherently strong materials have high optimum densities, where weak ones have low optimum densities. Accordingly, the former are adequate in performance at lower degrees of compaction than the later.

2. Required density, with

   a. reference to the penetration resistance of the compacted soils, or with

   b. reference to the relative values of saturation moisture content, liquid limit, and plastic limit.

The method of (2a.) was suggested by Proctor, and the numerical value selected for the control was one based upon experience. In this method a Proctor needle penetrometer is used to measure relative densities. The needle is pushed into the soil both in the mold and in the compacted fill. If the resistancesto penetration are reasonably close in both cases, then it is assumed that the desired results have been achieved. If they are not, then the field results and procedure must be changed.

The method of (2 b.) was suggested by Woods with reference to the consistency of remolded clayey soils at the liquid limit and plastic limit. At the liquid limit the remolded material has essentially no strength, while at the plastic limit the material is relatively strong.

It was reasoned that under the most unfavorable moisture condition, the moisture content should lie rather close to the plastic limit and rather removed from the liquid limit. The matter of how close to the plastic limit or how far from the liquid limit is a matter of judgment, as well as obviously depending upon the size of the moisture range for the plastic state.

3. Required density within a limited range of moisture contents

Such a specification takes recognition of the wide variability in properties which is possible when only a density level is specified, and that the contractor may be able to achieve this density at any reasonable water content by varying his compaction procedures. Under most favorable circumstances the density-moisture range specified is known to produce a compacted product with good in-service properties. The numerical values specified are known through experience and/or through a testing program. This is probably the best present type of compaction for end result specification.

At a conference on Increasing Highway Engineering Productivity held in Boston, in a symposium on "Need for Improving Construction and Contract Procedure," E. D. Moore of the Lane Construction Co. said, "Much of the confusion and added costs resulting from varying specification requirements could be eliminated if specifications were written to require only end results, leaving the construction methods to the ingenuity of the contractor." [17]

Some engineers believe that the specifications should emphasize the end result rather than the method to be followed. They reason that if a competent contractor is able to use a different compaction method and thereby still obtain the required result for less money, he should be permitted to do so. These savings should then be reflected in the contractors bid price.

It must be emphasized that specifications calling for end results in term of a standard must also be specific as to the number, type, and description of tests used to obtain these standards.

III. Method and End Result:

This type of specification is a combination of the above methods. It is not preferable because it leaves nothing to the contractor's resourcefulness. In some soil types it may be difficult to follow the specified procedure and still deliver the required results.

Its disadvantage to the contractor is that, if the specified procedure does not accomplish the result, the contractor and the engineer must reach a decision on a revised procedure which may cost the contractor extra money.

The following is an example of what can happen when a method and end result specification is used: [17]

On an airfield job, an end result of 95% Proctor was specified. Also specifications were 12 in. lifts compacted by a 12 ton steel-wheel roller. The contractor was losing money, and it was difficult to get the required densities all the way through the lift. The material was such that the dumping and spreading equipment required a push tractor to keep them moving in the loose soil.

An experience consultant reasoned and demonstrated that in this specific case, by building only 3 in. lifts, the dumping vehicles could move right along without needing the pushing tractor. This smaller lift also allowed lighter rolling equipment to obtain 97% compaction throughout. This reasonable change made the operation faster, gave a better end result, and resulted in economy for all involved.

The U. S. Bureau of Reclamation (Bu.Rec.) claims it finds the method and end result specification practicable in one situation. In its standard specification used in the construction of earth dams, the amount of compactive effort to be applied and the moisture density relation is specified. [17]

IV. Suggested Method and Specified End Result

This method of specification seems the most reasonable method. It allows the experienced contractor to use his experience, while it gives a guide to the less knowledgeable contractor. At the same time it insures for the owner the desired finished product.

Stephen M. Olko, a New York consulting engineer who is a compaction expert, believes that in most cases "A performance specification is superior to a methods specification. It is important, however, to provide guidance. This permits the contractor to select his own equipment. And it results in more competitive bids at reduced costs particularly for large projects." [17]

The author of this report believes that the suggested method and specified result specification is better than the end result method, because the former gives a guide to the less knowledgeable contractor, while the latter does not.

## CHAPTER III

## MATERIALS AND TESTS

The contractor must examine the job site carefully before bidding any earth work contract. He also must obtain information about such site conditions as: the types of soil at the job site; will they hold the overburden of a fill? If they will not, what is to be done so they will? Are they suitable for compacted embankment? If they are not, how far to the nearest acceptable borrow? Where is the bed rock? Where is the water table at both the site and the borrow? Is the water table permanent or seasonal? Will there be flooding and runoff at either place?

By investigating these questions, the contractor can predetermine the proper equipment, and this will allow him to bid with more certainty. It usually is not necessary for the contractor to spend a lot of money or time to obtain this information on his own. The owner agency may have most of the information available as many of them make accurate subsurface studies for planning and design before calling for bids. Since the contractor is responsible for the accuracy of these records, it is important that he verify the facts before making his bid.

There are several methods by which the contractor can get the necessary information about the job site before bidding. For example he can look at air photos and U.S. Coast and Geodetic Survey or Agricultural Soil Survey maps. He can walk it on foot, taking samples from many points of the area, by cutting soil chunks in proper size, wrapping them in aluminum foil to preserve the nature moisture, and carrying them to the laboratory for future study.

The contractor needs to know the behavior of the soil, in order to select the proper equipment and method of compaction operation; therefore, it seems necessary to discuss soil sampling and soil types.

## Soil Types

Before going into detail about soil types, a brief discussion about the formation of soil may be useful. Most soils have been derived from rock. Soil is formed from rock by mechanical disintegration or chemical decomposition, or both. Disintegration is related to freezing and thawing, the action of running water, and glaciation. Decomposition is associated with oxidation or hydration. The combined mechanical and chemical process is called weathering [12]. Decaying plant and animal matter sometimes contribute organic material to the soil.

Residual and transported soils are constantly undergoing changes in physical and chemical properties as a result of weathering. Freezing and thawing and the leaching of the topsoil through the removal of soluble salts and colloids, and the deposition of these materials in the subsoils, tend to develop layers and horizons.

To engineers the five most important soil types are: gravel, sand, silt, clay, and organic matter.

## Gravel

Gravel may be defined as rock material having a particle diameter more than 2 millimeters. The particles varying between approximately 15 and 22 centimeters in diameter are usually called stones, and those single particles larger than 22 centimeters in diameter are referred to as boulders.

Generally, gravels have good bearing capacity but they are unstable and unworkable. In using gravels for compaction other materials, such as sand and clay, may be added to increase stability and workability. More discussion about this point will be done under soil mixing.

## Sand

Sand may be defined as those particles of soil having a mineral grain size below 2 millimeters and above 0.06 millimeters. The size of particles in coarse sand will be in the range of 2 millimeters to 0.6 millimeters; medium, in the range of 0.6 millimeters to 0.2 millimeters; fine, in the range of 0.2 millimeters to 0.06 millimeters.

In general, sand particles have little attraction for each other, and there is little stability due to the internal friction. In using sand for compaction, usually clay is needed as a binder material and to increase workability.

## Silt

Silt is a very fine granular soil that presents no grainy appearance to touch or sight. When pure, it will settle out of muddy water. The size of particles are in the range of 0.06 millimeters to 0.002 millimeters, but it is still considered granular material. Silt is a permeable material, and it compacts very poorly as there is little internal friction between the particles. It is easily pulverized when in dry lumps.

## Clay

Clay is the finest size soil material. It consists of microscopic colloidal particles, which give clay its plastic properties. In water, clay colloids remain in suspension and settle very slowly. Its particles have much attraction for each other. so clay is a cohesive material. It has a high dry strength, good workability, and it compacts readily. But in clay there is little internal friction, so it is subject to slides. It also has low permeability.

## Organic Matter

Organic matter is partly decomposed vegetable or other living matter. This type of soil can be identified by its gray to black color, by the presence of undecomposed vegetable matter or shells, and by its odor, since in many instances it may contain gases that are released when the soil is excavated. It appears as peats, organic silts or organic clays. Organic materials should not be considered for fill material since they may decompose further, leaving voids, and this then reduces plasticity and dry strength.

Figure 1 shows the Massachusetts Institute of Technology and British Standards Institute scale of particle size distribution of soil [4].

| Clay | Silt | | | Sand | | | Gravel |
|---|---|---|---|---|---|---|---|
| | Fine | Medium | Coarse | Fine | Medium | Coarse | |

0.002 0.006 0.02 0.06 0.2 0.6 2.0

millimeters

Figure 1. M.I.T. and B.S.I. Particle Size Scale

The values of maximum unit weight obtained under a given compaction effort may differ widely with different soil types, depending on the shape of the soil grain, their size distribution, specific gravity, and their plastic properties.

When compacted under standard effort (AASHO Method T 99), some clayey soils of volcanic origin may have maximum unit weights of the order of 60 pounds per cubic foot or less. Other heavy textured clay soils may have maximum unit weights of the order of 90 to 100 pounds per cubic foot or more. Poorly graded (uniform size) sands may also have unit weights of less than 100 pounds per cubic foot.

The unit weight for a given compaction effort can be increased by improving the distribution of the grain sizes. This can be done by increasing the sand content and by keeping silt and clay components in proportion so as to fill the voids in the sand.

## Soil Tests

Testing and control for compaction are necessary, and cannot safely or economically be over-looked. Tests are the only way to determine which soil at hand is usable, how it is to be used, and if it is being used to its best advantages. Soil tests are divided into two parts: laboratory tests and field tests.

### 1. Laboratory Tests

The purpose of these tests is to find the relationship between the moisture content and the density for a particular type of soil. The standard tests, generally used and accepted by all states and by the Corps of Engineers are the Standard Proctor Test, which is denoted by AASHO as T 99-57 or ASTM as D 698-58T, and the modified AASHO Test (AASHO T 180-57 or ASTM D 1557-58 T).

#### a. Proctor Test [14]

The purpose of this test is to determine the relationship between water content and dry density or void ratio of a soil compacted in a standard manner. It also determines the optimum moisture content for the soil.

The apparatus consists of a standard brass cylinder mold, 4 inches in diameter and having a volume of 1/30 cubic feet. A removable extension fastens to the top of the mold to hold the soil during compaction. The soil is compacted in three lifts by use of a standard hammer having a circular face 2 inches in diameter and weighing 5.5 pounds. The compaction is done by compacting each layer with 25 uniformly distributed blows of the hammer dropped freely from an elevation one foot above the surface of the soil in the mold. The sample is prepared by drying the soil and taking the part passing a No. 4 sieve. The first trial should be done on a sample having a 5 to 10 per cent moisture content (below optimum). The moisture content of the soil is increased by adding water after each trial (usually it is increased by one to two per cent) until the weight of the compacted sample is less than that of the previous trial. This lower weight indicates that the density of the compacted soil is decreasing with increased water content and that the optimum moisture content has been exceeded.

Next the moisture content and the dry unit weight of each sample is determined. Using these results, a graph is plotted for the dry unit weight (pounds per cubic foot) vs moisture content (per cent), from this graph the optimum moisture content and the maximum dry density can be determined. This test is not used for soil under heavy compaction effort, but rather the Modified AASHO is usually used in this case.

### b. Modified AASHO Test

The purpose of this test is the same as that of the Proctor test, but the Modified AASHO Test is used to study the properties of a soil under a greater compactive effort than that provided by Proctor test. This test is made in the same manner as the Proctor test, except that the hammer weight is increased to 10 pounds, the falling distance is 18 inches instead of 12 inches, and the number of layers of the sample is increased to five.

Sometimes the mold diameter is increased to 6 inches and three layers are used with 56 blows per layer, or the sample is prepared by taking the material passing a 3/4 inch sieve and compacted in a 4 inch mold, with 25 blows per lift.

## 2. Field Tests

The purpose of these tests is to determine the density and the water content of compacted fill in order to compare the results with what has been specified.

To determine density in place, four methods are currently popular, these are:

a. Liquid Test,

b. Sand Test,

c. Nuclear Test, and

d. Tube Sampling Test.

### a. Liquid Test

In this method, the volume occupied for a known weight of material is determined by filling the space with a liquid. As shown in figure 2, the apparatus consists of a graduated glass cylinder, 8 inches in diameter and 18 inches high, a rubber membrane "balloon" attached to the cylinder, a base plate with an opening in the center, and a rubber tube attached to the other end of the cylinder for applying air pressure.

To use this apparatus the surface of the soil must be smoothed, the base plate is put on the surface, the cylinder and the balloon are placed over the base plate, then air is pumped into the cylinder until the balloon is completely deflated against the surface of the soil in the opening, the volume of the water is read on the graduated cylinder. Then the cylinder is removed from the plate and a hole is excavated through the opening. All loose material must be saved in an airtight container for future drying out to determine the dry weight and the moisture content of the soil. The cylinder is again placed over the plate and air is pumped into the cylinder, forcing the balloon into the hole. A new reading must be taken, and the difference between the final and the initial readings is the volume of the hole. In the office the dry unit weight is determined as follows.

$$\gamma_w = \frac{\text{Weight of the wet soil}}{\text{Volume of the hole}}$$

$$\gamma_{dry} = \frac{\gamma_w}{1 + \frac{w}{100}}$$

where

$\gamma_w$: wet unit weight

$\gamma_{dry}$: dry unit weight

w: moisture content.

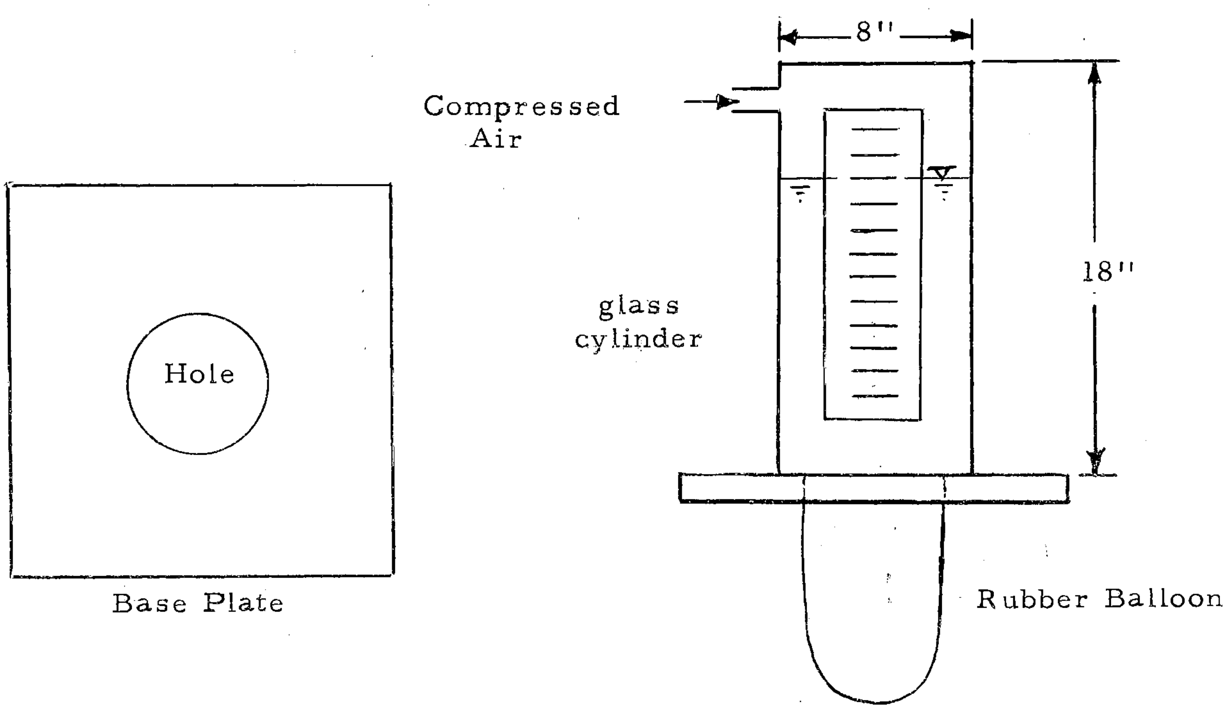


Figure 2. Rubber Balloon Density Apparatus [14]

The liquid method is not preferable for large particles of soil because the balloon may not completely fill the hole but instead bridge over small pits and corners in the surface. It is, therefore, preferable to use this test in soil consisting of samll particles.

b. Sand Test

Instead of using water, as in the previous test, sand is used to determine the volume of the hole. As shown in figure 3, the apparatus consists of a steel plate with an opening in the center, a hollow cone which fits over the opening, and a one gallon jar connected above. Between the cone and the jar there is a valve which allows the sand to run from the jar into the cone below.

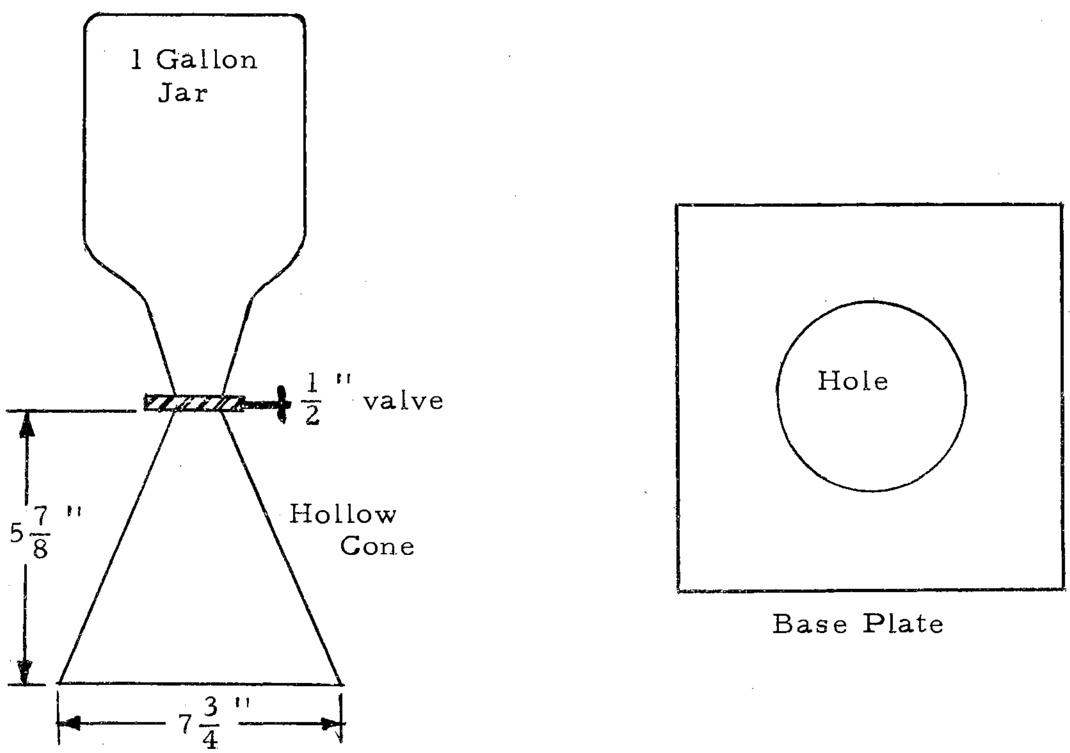


Figure 3. Sand Cone Density Apparatus [14]

Standard Ottawa sand, all of which passes the No. 20 sieve and is retained on the No. 30 sieve, is most commonly used. The surface of the soil should be smoothed, the plate placed over the surface and a hole excavated through the opening in the plate. The hole should be about 6 inches deep. The excavated soil must be saved in an air-tight container for future weight and moisture content determination. Place the jar and the cone over the hole and let the sand fill the hole. The difference between the original weight of the sand and the weight of the remaining sand in the jar and the cone is the weight of the sand filling the hole. The volume of the hole is calculated by dividing the weight of the filling sand by its density.

The dry unit weight and moisture content of the soil are determined in the same manner as that described in the liquid test. If ordinary sand is used and if the density of the sand is susceptible to change between the time of its determination in the laboratory and its use in the field, the method prescribed in this test procedure will give an inaccurate volume for the hole.

The sand test method is relatively slow, but it can be used on any type of soil.

c. Nuclear Test

The latest advance in testing for place density and moisture content is with radioactive materials. A new nuclear instrument capable of determining both density and moisture content during earth compaction has been developed by the Michigan State Highway Department. The nuclear gauge incorporates radium D beryllium in a stainless steel casting, which measures about 10 inches by 10 inches by 2 inches thick, and rests on the ground surface.

The device radiates gamma and neutron rays into the ground where they are partially absorbed and partially reflected. The amount reflected depends upon the density, the greater the density, the more rays are reflected. Reflected rays pass through Geiger-Muller tubes in the surface gauge. Counts per minute are read directly on a reflected ray counter gauge and are related to density and moisture by calibration curves.

The advantages of this method of field test are:

1. It does not disturb either the sample or the compacting surface.
2. It reduces the personal error element that is involved in conventional test procedures, thereby increasing the consistency of density and moisture test results.
3. It provides a method of performing density tests on large size aggregate base courses which are difficult to handle by other test methods, and
4. It increases the speed of testing a particular area.

Its disadvantages are the high initial cost and the presence of a potential source of radiation exposure to the operator.

### d. Tube Sampling Test [14]

In this method, the sample is taken as nearly as possible to its original state by using a sharpened cylinder of known volume, as shown in figure 4.

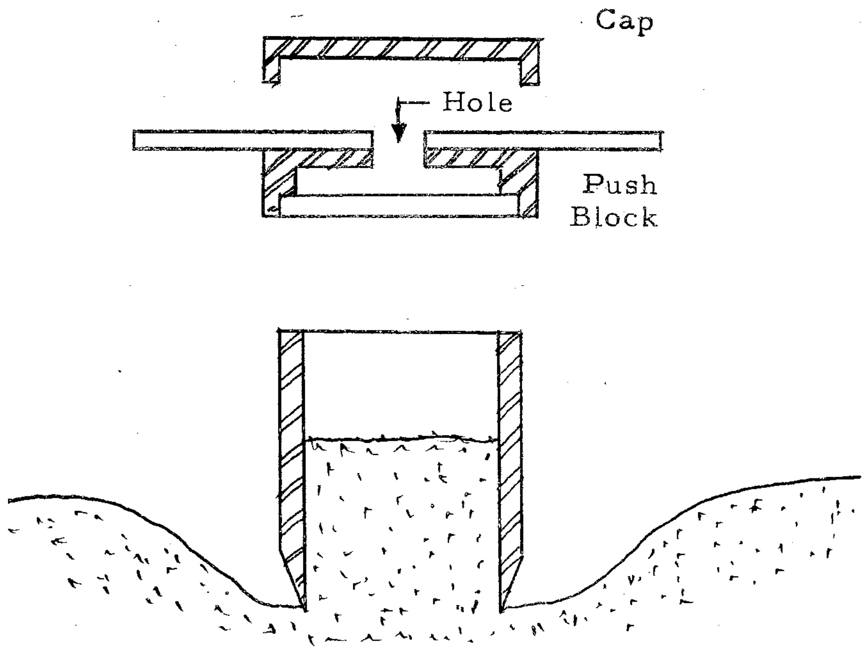


Figure 4. Tube Sampling Apparatus

The cylinder is carefully pushed a short distance into the soil and then the soil excavated around the outside to the bottom of the cylinder. Next the cylinder is pressed a further short distance into the soil and the soil again excavated to the bottom of the cylinder on the outside. This is repeated until the soil protrudes out from the top of the cylinder. The excess soil is struck off with a steel straight edge and the top of the cylinder covered with a smooth flat plate, preferably in the form of a cap which remains in place when the cylinder is turned upside down. The cylinder can then be lifted out by inserting a shovel beneath it. The cylinder is then turned upside down and struck off to a smooth plane surface. The soil in the cylinder can then be emptied into a clean container and sealed with an airtight cover to prevent the evaporation of moisture. The soil will be dried out, and the density and moisture content can be determined.

This method is convenient and quick, it works best on soft, cohesive soils, and cannot be used on stony or non-cohesive soils.

## CHAPTER IV

## COMPACTION METHODS

Generally, the method of compaction is considered the most important element in the operation of compaction. Even in an ideal situation where the specifications are just right for the contractor, the soil conditions are the best, and the equipment selected is correct and in top mechanical shape, the job still could physically and financially fail if he does not use all the three elements in the most advantageous way. To select the best procedure for compacting a specific earth fill, all the factors which influence the operation of compaction must be taken in consideration. Some of these factors are, moisture content, soil mixing, lift height, compaction speeds, number of passes, and weather.

In the following paragraphs each factor will be discussed in some detail.

### Moisture Content

Optimum moisture content is the amount of water needed in a given soil for compaction to maximum density. When cohesive soil is in the range of optimum moisture, it is plastic, pliable, and compacts readily. When it becomes too wet, it becomes soupy, weak, and unworkable. When it becomes too dry, it may compact well, but after a rain it will soak up morè water than soil compacted at optimum moisture content does, and thereby lose strength, possibly flowing out or sliding.

Generally, proper control of moisture is necessary to achieve a successful compaction. Too little moisture means there will be insufficient lubrication for the soil particles and, therefore, too low a density. Too much moisture makes the material soft and unworkable. With proper moisture control light compaction equipment may give results better than those obtained from much heavier equipment where moisture control is poor.

The difference between the optimum moisture content specified and the moisture in the borrow material will tell whether this material must be dried or wetted. If the material is to be dried, scarifying or spreading the soil in thin layers will reduce the moisture by evaporation. If the material is to be wetted, water can be added either on the fill or at the borrow pit. At the borrow pit, the necessary water can be added either by sprinkling or by ponding. In either case, enough time must be allowed before excavation for the water to penetrate and moisten the borrow material uniformly. Usually the material must be over wetted, because some of the water will evaporate when the soil is dug, hauled, and spread on the fill. When water is added to the soil after it is placed on the fill, it is usually done with tank trucks fitted with spray bars. This water must be worked into the soil by graders, cultivators, or harrows before actual compaction begins.

Sometimes, before the hauling trucks leave the pit, water is added to the hauling material. This allows water to penetrate during hauling time. If the hauling time is not enough for complete penetration of the water, a wetting agent may be added. This is essentially detergent soap, and acts as an agent to increase the penetration velocity of the water.

## Soil Mixing

Mixing of soils consists of blending two or more types of soil in order to achieve a mixture which is easy to compact. Actually best results do not come from soil of any one predominate type but from good sensible mixtures of several different soils. Mixing of soils is done either at the borrow or at the job site. Usually in either case mixing is done in the presence of moisture which makes the mixing operation easier and helps in achieving a uniform mixture.

In a coarse grained sand, for example, fine grain sand should be added to improve the maximum density. The smaller grains will shift themselves between the large grains, and thereby increase the density by reducing the amount of voids. Clay may also be added as a binder which makes the mixture easy to work.

In every clayey material granular soil should be added to provide good internal friction and to prevent slides. Generally, gravel and stones have good bearing capacity (the average load per unit of area required to produce failure by rupture of a supporting soil mass). They are unstable and may injure some compacting equipment (they may tear or damage the tires of the pneumatic-tired rollers, or damage the smoothness of wheels of the steel- wheel rollers).

By taking the best materials of each type of soil discussed earlier and mixing them together in special proportion, a mixture of good bearing capacity, workability, and stability can be achieved. A uniform mixture must be produced before compacting. This can be achieved by mixing the soils, and the mixing is usually continued until the mixture is uniform in color.

It is not practical to put the different types of soils in alternate layers because the failure of the earthwork may occur within the weakest layer.

## Lift Heights

The lift is the height of a layer of fill and must be specified as before or after compaction. Deep lifts (12 to 24 inches) might appear to be the best way to make a fill of 40 feet or more, but not all compaction equipment can handle such lifts economically. The top of the lift may be crusted while the bottom may remain loose. If deep lifts are chosen, the compaction equipment must be of a heavier and larger type in order to obtain the required density in the lower part of the lift as well as the top.

When using deep lifts sometimes a push-tractor is needed to help the earthmoving units move through the uncompacted material. In some cases the shallower lifts (3 to 5 inches) are recommeded, hauling units can dump at high speed without extra help, and more volume of material can be placed per unit of time. Better pulverization of fill material is also achieved, and lighter compaction equipment can get complete penetration for more uniform density at greater speed. But the costs of the labor, fuel, equipment ownership, and maintenance are also important when considering each job in determining the most economical height of lift for each soil. Some contractors suggest that a lift of 6 to 8 inches is best in most cases.

### Number of Passes and Speed

For a given roller, the number of passes required to achieve the specified density varies with the type of soil, the height of lifts, the amount of moisture present, and the weight of the roller. Some engineers and contractors believe that the first pass of a compacting machine is the most effective, subsequent ones have less effect, and the effect of any more than eight is negligible. Others say each additional pass helps that much more.

Generally, if good compaction isn't achieved in a reasonable time, continued coverage becomes uneconomical and a reason should be found. It could be too much or too little moisture, too high a lift, inadequate processing, or wrong choice of equipment.

Rolling speeds are closely associated with the number of passes. Only field testing can determine the combination that gives the best results. Slower speeds consume more fuel and time, but they get deeper effect in plastic materials. Faster speeds are recommended on sand in thin lifts, higher speed also may be helpful in keeping the loose material from flowing laterally.

Depending on field conditions, the usual towing speed for the roller is in the range of 1.5 to 4 miles per hour. Two or three miles per hour is generally a safe recommendation. To compact high lifts to high density, low rolling speeds are preferable, but no general rules can be given for towing speed and number of passes.

## Weather

There is a great effect of climatic conditions upon compaction operation. Compaction seldom should be done in the rain because the moisture content will change. Snow, like rain, will effect the results. Work on frost susceptible materials in cold weather is uneconomical, because the effort required to compact granular soils properly at temperatures below freezing is several times that necessary to get the same results when the soil is thawed. Proper compaction of cohesive soils that freeze into clods is very difficult.

However, in colder climates, many contractors on large jobs find it is economical to stockpile fill material near the job sites during the winter months when compaction is impractical.

## Test Embankments

Most earthwork specifications for large projects require the contractor to first build some part of the final emankment as a "test embankment." Even if it is not specified, a test embankment often can save money in the long run. From this test embankment, the specified density can be achieved by varying many factors such as moisture content, height of lift, placement method, compaction equipment, and compactive effort.

These test embankments may also lead to more efficient inspection by the engineer, as he knows what moistures and field operations will produce the required results. They also lead the contractor to a more efficient operation, and allow for his scheduling of equipment with minimum delay. For example there is no need to require eight full passes with a piece of equipment when four will do.

# CHAPTER V

## COMPACTION EQUIPMENT

To achieve good results in a compaction operation, care should be exercised to select adequate compaction equipment. In any event, it is not practical to depend on the action of earth hauling equipment to achieve proper compaction, as truck drivers try to follow the path of the vehicle ahead of them.

Today there are available well over one hundred different types of commercial machines or tools especially designed for compacting earth. There is some device built to satisfy nearly any job conditions. There is a trend toward units that are self-propelled. Regardless of how it is powered or propelled, compaction equipment does its job in one of four principal ways, or combinations of these ways,

I. Static weight,

II. Kneading action,

III. Vibration, and

IV. Impact.

### I. Static Weight

Static weight compactors are surface rollers of either the smooth steel wheel or pneumatic-tired type.

## A. Steel-Wheel Rollers

Steel-wheel rollers have long played an important part in earth compaction, and they are considered to be the oldest form of mechanical compaction known. Present models range in size from 1.5 to 18 tons. Steel rollers can be applied on all types of soil; however, loose sand may not support the heavier rollers. Steel rollers are most effective on soils of more granualar nature, because the crushing effect of their static weight can be best employed. Steel-wheel rollers are divided into two classes: Three-wheel rollers and tandem rollers.

### 1. Three-Wheel Rollers

They have one wide front steering wheel and two narrow rear wheels. The three wheels are actually steel drums that can be filled with ballast to increase their weight. If a roller is described as "10-14 tons," it means that the minimum dead-load weight of the machine is 10 tons and that the wheels can be ballasted with water or wet sand to produce a maximum total weight of 14 tons. The three wheel roller is quite maneuverable but tends to leave deep ruts in granular soils due to the concentration of load in the narrow wheels. Three-wheel rollers range in size from 1.5 to 18 ton.

### 2. Tandem Rollers

Tandem rollers are those with two or three steel wheels in line. The wheels can be ballasted either by water or by wet sand to increase the total weight of the roller.

Tandem rollers range in weight from 1 to 14 tons for the two wheel type and from 12 to 18 tons for the three wheel type. It should be kept in mind that although total weight of tandem rollers can be greater than three-wheel roller, the tandem type roller gives less compaction per ton of weight, because it spreads the weight over more surface than the three-wheel roller.

The lighter tandem rollers are generally used on small jobs or for maintenance purposes. Both classes of steel-wheel rollers have rather slow running speeds (up to 14 m.p.h.), and have questionable safety near the edges of high, steep-sided fills.

There is no standard requirement of number of passes of each machine, but rather the requirements vary with (a) soil type, (b) moisture content, (c) wheel load, (d) lift thickness, (e) contact unit pressure, and (f) specified unit weight.

Figure 5 shows the effect of number of passes of a 9.5 ton steel roller on a unit weight of sandy clay soil at optimum moisture content. The figure shows that the first eight passes are the most effective, while after this number of passes the curve straightens. The steel roller's compactive effort is lessened in plastic granular material, because the heavy rollers create crusting at the top of the layer, with diminishing effectiveness down to the lower parts of the lift, even for shallow thicknesses.

For very plastic material, steel rollers tend to have a bridging effect. This means that the roller will squeeze and crust the material at the top of the lift and so this crusting will reduce the effect of the roller to the lower parts of the lift. Steel rollers also have a plowing

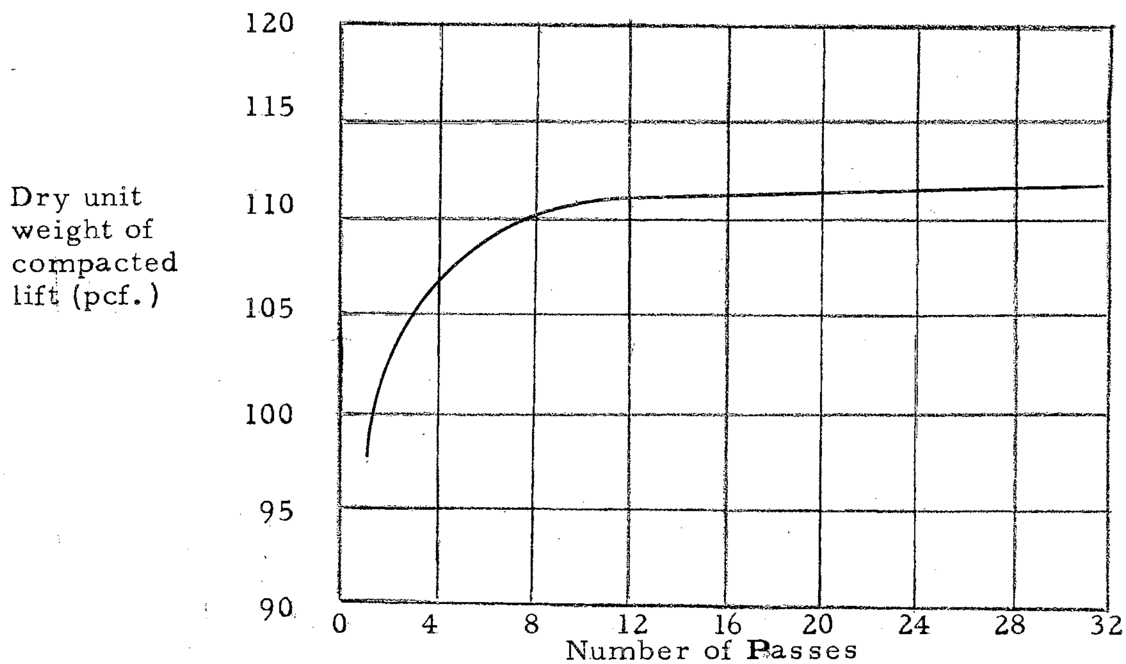


Figure 5. Relationship Between Number of Passes of 9.5 Ton Steel Roller and Dry Unit Weight of Sandy Clay Soil [9]

effect. This creates plastic waves ahead of the rolls and also results in a springing up of materials behind them. Steel rollers can be used effectively to smooth surfaces after sheepsfoot rollers have done their work.

Usually the required compression produced under the wheels runs from 275 to 300 pounds per inch of roller width. Some drums are made with extra wall thickness, so as not to disturb the smoothness of the wheel surface when used on the larger pieces of very hard gravel or rock.

### B. Pneumatic-Tired Rollers

Pneumatic-tired rollers are surface rollers, which also apply the principle of kneading action. These rollers have ballast boxes which can be filled with the cheapest materials available to increase compaction load. Water and/or sand are most frequently used, but for the heavy and super-heavy types, pig iron is used to achieve maximum load.

Pneumatic-tired rollers are either self-propelled or drawn. They are divided into three weight classes: medium, heavy, and super heavy.

The medium class is considered to include rollers up to 13 ton in total weight. Generally, the rollers in this class have two tandem axles with four to nine wheels each. The wheels are arranged so that the rear ones will run in the space between the front ones with a small overlap, thus, 100 per cent coverage is assured on each pass of the roller. This class of tandem rollers is used for compaction in shallow lifts up to 6 inches. Since medium class rollers are most generally used for compaction in the shallow lift range, the secondary action of the roller wheels is also important. This action is wheel oscillation which provides each wheel with an up and down motion, allowing the roller to follow the cross section of the ground contour closely, and thereby roll out voids and soft spots. Besides this, some rollers also have a wobble-wheel action which provides a weaving and kneading action under the wheel.

Rollers in the medium class provide the same unit surface pressure as the other two classes, but with less overall weight on the material being compacted. They do not push the material before them, or cause lateral displacement. They also offer more maneuverability with less motive power. On the other hand, they have poor flotation in loose materials, and there is slipping of the self-propelled units in very wet soil. Medium class rollers obtain efficient and satisfactory compaction while being moved at speeds up to 15 m.p.h.

The heavy class includes rollers with weights ranging from 13 to 50 ton, while the super-heavy rollers are those weighing between 50 and 200 ton.

These two classes work on all types of soils. They cover a bigger unit pressure area and have a deeper effect on soil than do the medium rollers. They can handle higher lifts (up to 24 inches), and obtain deeper penetration of compressive force. Since they require large tractors to pull them, their operation is quite expensive.

Pneumatic rollers should not be over loaded with ballast or moved at excessive speeds. Even though this operation would give more coverage, it also results in extra tire and bearing wear, thus increasing maintenance costs.

There are four ways used in expressing the compacting effectiveness of pneumatic rollers. They are: (1) gross weight of the roller, (2) wheel or tire load, (3) weight per inch of tire width, and (4) tire inflation pressure.

The problem is complex because rubber tires, unlike the steel rollers, are flexible, and therefore, low tire air pressure allows an oval surface contact area to enlarge. This diminishes the effect of load by giving larger weight distribution and, consequently lower unit ground pressure. Accordingly, gross-weight ratings mean little unless the number of wheels, tire size, and flotation pressure are known.

The number of passes required for pneumatic-tired rollers depends on (a) the tire widths and spacing of the wheels, (b) the contact unit pressure, (c) the wheel load, (d) the lift thickness, (e) the soil type, and (f) the moisture content.

Figure 6 shows the relation between the number of passes of a 47 ton pneumatic-tired roller and dry unit weight. The soil is sandy clay with a lift thickness of 6 inches.

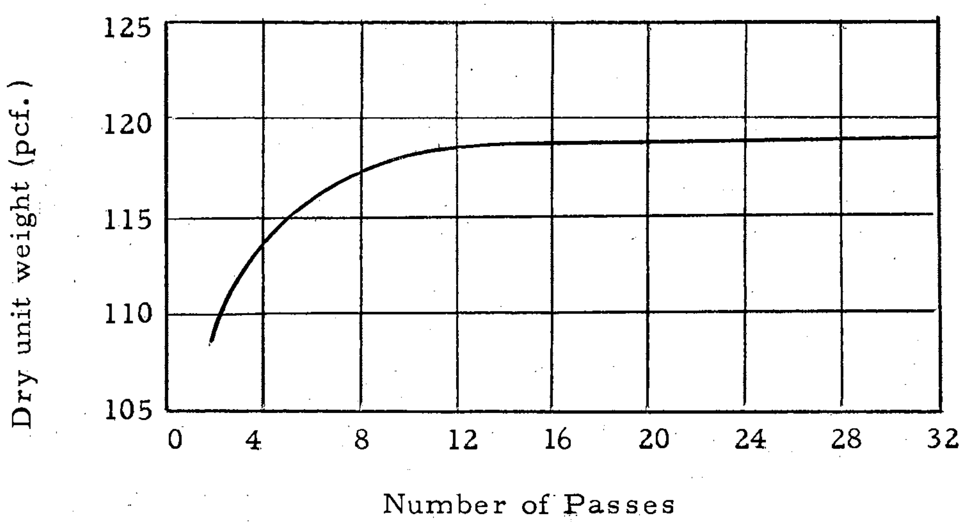


Figure 6. Relationship Between Dry Unit Weight of 6 Inches Compacted Sandy Clay and Number of Passes of 47 Ton Pneumatic-Tired Roller [9]

## II. Kneading Action

Kneading action compactors are primarily tamping rollers of the sheepsfoot type, grid roller, and steel roller with segmented pad drums.

A. Sheepsfoot Rollers

Sheepsfoot rollers are the most common type of compaction equipment being used today. They are manufactured in diameters from 40 to 72 inches ranging in weight from 6,000 to 60,000 pounds. The drum is hollow and ballastable to increase the load. The rollers can be towed in pairs, or four block pairs, or other arrangements. Usually, the feet are from 7 to 12 inches in length and have various shapes: round, pie-segmented, clubfoot, elliptical, or diamond. There has been little research on which is best, but it has been found that the compacting surface should be 5 to 10 square inches.

Sheepsfoot rollers are used only on cohesive materials (clay and silty clay). They produce kneading action on the soil, and can compact loose lifts up to 10 inches.

In a loose lift and during the first pass of a sheepsfoot roller, the feet penetration is nearly to the bottom of the lift. But as additional passes are made, the density of the soil will increase, and thus the bearing capacity of the soil increase. The tamping feet will then penetrate less and eventually do what is known as "walk out" when the specific density is reached. It is not necessary that the roller drum touch the surface, since the total load is transmitted to the soil by the feet in small areas of high concentrations.

In some cases sheepsfoot rollers bridge over the soil at the outset, but this bridging effect will break down with additional passes. This type of roller also exposes more soil surface to air and therefore, causes more evaporation of moisture and subsequent crusting. On the other hand, they work well by causing lateral particle movement beneath the surface, thus blending coarse and fine materials more thoroughly.

The contact pressure of the tamping feet determines the amount of compaction which will be obtained by the sheepsfoot roller. This contact pressure can be found by dividing the drum weight by the total area of one row of tamping feet. Usually the contact pressure is between 100 and 550 pounds per square inch.

The number of passes required to achieve a specified density depends on (a) the contact area of each tamper foot, (b) the contact unit pressure, (c) the drum weight, (e) lift thickness, (f) soil type, and (g) moisture content.

Figure 7 shows the relationship between the number of passes of a 5 ton clubfoot type sheepsfoot roller and dry unit weight of sandy clay soil when compacted in 9 inches loose layers at or just above its optimum moisture contents.

Some manufacturing companies make different variations of the sheepsfoot rollers. For example, Hyster Co. (Peoria, Illinois) replace the rear wheels of a caterpiller DW 20 prime mover with steel drum wheels fitted with sloped-pad tamping feet.

Another Hyster vatiation is the "grid" roller. Here the DW 20's rear wheels are replaced by wheels whose perimeter is made up of an open mesh of 1.5 inches wide steel bars on 5 inches square spacing. These grid rollers pulverize subsurface lumps and work well in gravel and rocky fill.

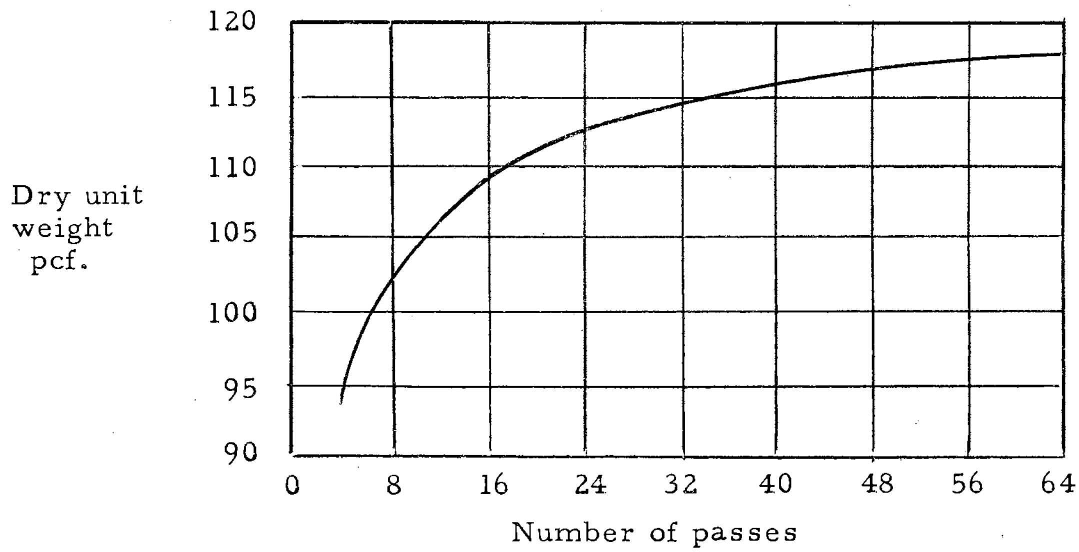


Figure 7. Relationship of Number of Passes of Sheepsfoot Roller and the Dry Unit Weight of Sandy Clay Soil [4]

III. Vibratory Rollers

Vibratory compaction is one of the most economical means for compacting embankments of sand or natural layer of loose sandy silts. Sand and sandy silts are granular materials, and their soil particles stack by nesting in the void spaces between other grains. When shaken or vibrated they will shift themselves into the tightest or closes arrangement, producing maximum density. Clay and silt soils are spongy and resist compression. As a result, when a static weight is applied they compress, but as soon as the weight is relieved they spring back almost to their original density. To achieve the required density under these conditions, the static weight roller must apply its compression force time and time again to overcome the resiliency of the soil. This requires many passes and much time-- which ties up costly equipment. Because of the nature of clay and silt soils, effective compaction demands that the soil be "sheared" and "driven" with sufficient force to overcome the tendency to return to its previous state. High impact force (by vibrated sheepsfoot roller) is applied to both shear and compress these soils. They can be made to reach specified density in much less time with much fewer passes.

In vibratory compaction a mechanical oscillator is employed to set up the vibrations in the soil mass. Here the oscillator furnishes a sustained dynamic force that causes some of the underlying soil to respond by moving with the vibrator.

Vibration is a complex phenomenon, in that a number of factors individually and collectively influence its nature. Some of these factors that determine the nature of vibratory compactors are as follows:

1. The frequency, which is the number of revolutions per minute (usually referred to as cycles per minute or cycles per second) of the oscillator.

2. The amplitude (displacement), which is the vertical distance through which the impulse travels, measured in parts of an inch.

3. The dynamic force, which is the energy from each impulse created by the centrifugal force of the oscillator (usually measured in pounds per inch).

4. The dead (static) weight which is the weight of the portion of the machine that vibrates.

5. The relationship between the dynamic force, and the dead weight, expressed as the force weight ratio.

6. The shape and size of the area of the vibrator contacting the soil.

The foregoing items are all inherent in the design of the vibratory compactor and determine the nature that the vibrations impart to the soil. In addition, the operation of the machine in terms of speed and number of passes, thickness of lift, type of soil, and moisture content have a large influence on the results obtained by the vibratory compaction.

Figure 8, shows the typical relationship between the number of passes of the vibratory roller and the unit weight of granular material in an 8 inch lift.

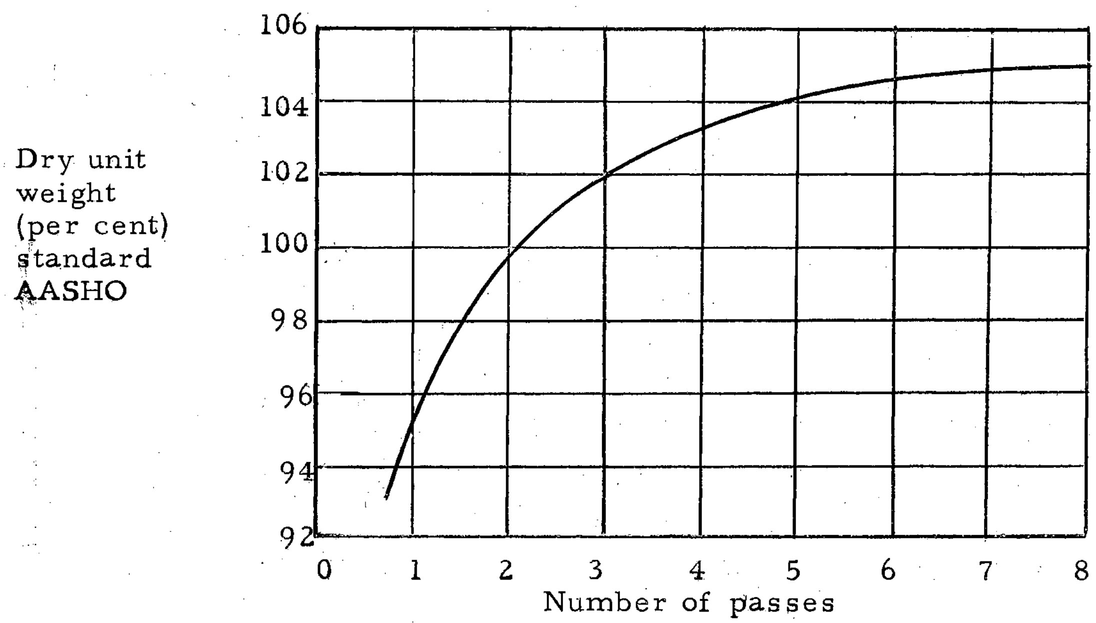


Figure 8. Typical Relationship Between Unit Weight and Number of Passes With the Vibratory Roller. Granular Material in 8 Inch Lifts [30]

In compacting granular material, the combination of frequency and amplitude of vibrations gets varying results with varying soils, depending on grain size distribution and moisture content. Each soil has its own frequency rate which is called the resonant frequency. Vibrations vary from 100 vpm in some compaction machines to 5000 vpm in others, and it is more economical to use a machine that will vibrate at the soil resonant frequency.

Tampo Manufacturing Company has recently introduced a self-propelled vibratory roller with vibrating frequency variable up to 2200 vpm. Although it weighs only 4 tons, the compacting power of this machine is reported to be equal to that furnished by a static roller of 16 to 20 ton capacity. Tampo has also introduced a meter for measuring the resonant frequency of materials being compacted; it is called a vibra-meter. This dashboard-mounted device allows the roller operator to read the resonant frequency point on a dial and make roller adjustments accordingly for alleged full compaction efficiency.

Vibratory compactors are generally divided into two classes; rollers and plates. Rollers impart vibration to the soil through a steel drum or rubber-tired wheels and thus, in effect, serve a double action. They vary in size from 1.5 to 50 ton.

Plates generally are mounted on wheels, but they apply their vibrations directly to the ground through skids or shoes. These skids or shoes are individually vibrated by eccentric devices driven electrically, hydraulically, or mechanically. The eccentrics shake the plates both ways in all three directions (a six-way), or just up and down. Shoes are generally about 2 feet by 3 feet in contact surface, and are mounted on some self-propelled frame in two to six rows. Smaller vibrating plate type units of various sizes, guided individually by hand, are suited for compacting bottoms of trenches, confined areas, and steep slopes.

Usually, vibratory compaction keeps the compacted surface fairly well sealed against evaporation of internal moisture and also against entrance of new water.

Sometimes the static and vibratory compaction principles are combined in the same unit to serve a double function. For example, Buffalo-Springfield Manufacturing Company developed a three-axle tandem roller with vibration on the middle roll. The vibratory roll is retractable, which allows the roller to be used as a two-axle tandem unit.

In the same field of combining both static and vibratory principles in the same unit, other companies attach vibrating plates to their regular steel wheel rollers. Others have combined vibratory compaction with large-rubber-tire rolling. Some companies have added vibrators to towed sheepsfoot rollers to make units that are effective in clays with high sand or silt content.

## IV. Impact Compactors

These machines have both vibrating and kneading action. Generally, they are hand-held or machine mounted, and are used in small areas and confined spaces.

Barco Manufacturing Company makes a hand operated rammer with a self-contained gasoline engine. The entire unit jumps up and down and weighs about 210 pounds. Other companies make different types of impact compactors in various sizes, weights, and with different methods of use.

The hydro hammer is a self-propelled impact machine working very much like a piling hammer in a set of leads. The given impact is obtained by raising a ram of specific transfers area and weight to a given distance in the leads and then releasing. The variable factors in this type of machine therefore, are the weight, the transfers area of the ram, and the ram's falling distance in the leads.

The intensity of the impact may be increased by either decreasing the transfers area of the ram, or increasing the weight of the ram, or increasing the fall distance in the leads.

The hydro hammer's main use is in confined areas, where standard compaction equipment is difficult or impossible to operate. Long narrow ditches and confined areas near the buildings may be a good example for its use. Extreme care must be taken in using this piece of equipment directly over vitrified clay or cast iron utility services, as the impact shocks may break or damage these materials.

## Special Rollers

Sometimes rollers are made in such a way that they serve special purposes.

### A. Retractable Wheel Roller [30]

The retractable wheel roller is a tandem roller, usually weighing from four to six tons, with an attachment having two pneumatic-tired wheels arranged so they can be used to carry the weight of the roller; and so it can be easily towed from place to place without loading it on a trailer or truck. When these transporting wheels are raised or retracted, the roller is immediately ready for use.

B. The Trench Roller [30]

The trench roller is designed to compact materials which are applied above or below the adjacent surface of a street or roadway, i.e. in a trench. Trench rollers have one or sometimes two large diameter wheels with comparatively narrow steel tires. Usually self-propelled by gasoline engines, the chassis with operator's seat is carried on pneumatic-tired wheels which ride on the existing surfaces. The compaction rolls may or may not be ballastable. This compaction roll axle is so constucted so as to allow for varying trench depths. These special rollers are used mostly to compact the material used on road and street widening jobs, primarily where the area is not accessible to other types of rollers.

Finally, there are combinations of the previous types, that cannot be classified under any of the above classes, or it can be said that they are neither bird nor mouse and must be classified as bat.

## Equipment Selection

The final goal is to build stable, acceptable earth work in the shortest time at the least cost. Whether the contractor gains or loses, generally depends upon the equipment he selects to do the job.

There are no pat rules to make this choice a routine matter. The variations in specifications, soil types, machines available, and operational methods make the equipment selection even more complex.

There are some basis for reasonable judgment in selecting a piece of equipment, however, such as special tables that give simplified general outlines of what to take into account. (These tables give, for example, compactor type, soil best suited for, maximum effect in loose lift, density gained in the lift). By combining information from these tables with suggestions given previously, the range of field equipment can be narrowed down for consideration. Full-scale field trials should then be made under conditions expected to be in the job and on the basis of comparative results, final choice of proper equipment should be made.

# CHAPTER VI

## SUMMARY AND CONCLUSION

Soil compaction is the process whereby soil is mechanically compressed through a reduction in the air voids. In the construction of roads for example, good compaction is needed in the building of embankments and for subgrades, bases, and subbases. In an enbankment subsequent settlement can be minimized, thus enabling a permanent road structure to be placed on it immediately after its completion. Compaction of fill increases its stability and resistance to water absorption.

In order to reduce the problems which usually occur between the owner and the contractor, four possible methods of specification are given for controlling the operation of compaction. Each method is discussed with its advantages and disadvantages and where it might be used.

Moisture plays an important function in compaction. For a given compaction effort all soils have an optimum moisture content at which a maximum dry density is obtainable; even though moisture slightly above the optimum appears to give the best results. The effect of type of soil, amount of compactive effort, and height of lifts is also discussed.

Descriptions are given of laboratory tests used to determine the compaction characteristics of soil. Also four field methods of measuring the dry density and moisture content of compacted fill are described, and factors affecting their use are discussed.

For modern earthwork construction there are many types of compaction equipment. The effectiveness of each type of equipment varies with type of soil and the specified density. Some of the factors which have an influence on the compaction of soil are: lift thickness, the number of passes and the speed of the equipment, contact pressure, tire pressure of pneumatic rollers, contact area of the rollers, wheel load, and frequency of vibration in vibratory compactors. All these factors and others inherent in the soil, should be studied carefully by the engineer working for earthwork compaction.

Soil compaction is a wide and complex subject,and depends upon several variable factors. One would be a fool to pretend to offer a solution to all its problems. This report will be successful if it helps the reader to understand some of these dependent functions and how to attempt to cope with many of the problems that occur in the course of normal job operations.

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