

# Compaction Procedures, Specifications, and Control Considerations

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This paper provides a review of soil compaction principles and practice. The nonlinear relation of compaction energy to resulting density is shown. The need to consider the effect of change in moisture from the as-compacted state is pointed out. Factors that influence the reference test for specifying compaction are discussed to show the uncertainty in the resulting maximum dry density and optimum moisture content. Factors that influence field compaction are also described, and the possibility of a large variation in compaction results with field conditions is demonstrated. The need for more awareness of the effects of methods of preparation and uniformity of procedures is indicated. Limitations of density as a method of specifying compaction are pointed out. The type and magnitude of compaction measurement errors are defined and implications for compaction control are discussed. Finally, because knowledge of compactor performance in combination with observation of field procedures is a meaningful basis on which to judge compaction, some basic principles of compactor performance evaluation are described.

The purpose of this paper is to review and evaluate methods of specifying, achieving, and controlling field compaction. Although compaction is an important part of all earthwork projects, it is often treated casually. Present practice does not reflect the knowledge gained from the extensive past studies of compaction. Many basic principles are either not understood or not applied. Furthermore, discrepancies often exist between compaction expectations and reality.

## BASIC CONCEPTS

Compaction is the process of soil densification by mechanical manipulation (1). Densification is achieved by reduction in volume of the air voids. Thus, during compaction the moisture content remains unchanged, in the absence of wetting and drying caused by weather conditions, and the percentage of saturation increases. Consolidation, in contrast, is the process of volume reduction in saturated soils that takes place gradually as pore water is expelled (1). Unfortunately, the terms compaction and consolidation are often interchanged erroneously in practice.

The obtaining of a greater unit weight of soil is not a direct objective of compaction. Instead, the reason for compacting is to improve soil properties such as increasing strength, decreasing compressibility, decreasing permeability, and reducing swelling and shrinking. However, density is the most commonly used parameter for specifying the desired amount of compaction and for determining the state of compaction. This is primarily a consequence of historical tradition and convenience. An increase in density implies an improvement in the other parameters. However, a given density, or even a given percentage of compaction, does not produce the same magnitude of strength and compressibility properties for all soils. The use of density specifications causes this fact to be deemphasized.

If we exclude certain soils, such as relatively clean sands and gravels, the most common density reference tests for compaction specifications are AASHTO T99 (ASTM D698) and AASHTO T180 (ASTM D1557). In these tests, soil is compacted by the impact of a dropped weight. The compactive effort per unit volume  $E$  for this type of test is computed as follows:

$$E = WhNn/V_m \quad (1)$$

where

$W$  = impact hammer weight,  
 $h$  = hammer drop height,  
 $N$  = number of drops per layer,  
 $n$  = number of layers, and  
 $V_m$  = mold volume.

Thus, for the AASHTO T99 test,  $E = 12\,300 \text{ ft-lb/ft}^3$ , and for the AASHTO T180 test,  $E = 56\,100 \text{ ft-lb/ft}^3$ .

As indicated in Figure 1, the density achieved is neither proportional to the compactive effort nor linearly related to it. Thus, an increase in the amount of compaction from 95 percent AASHTO T180 to 100 percent AASHTO T180 might require a 500 percent increase in effort. This is an important fact to consider when attempting to achieve additional compaction in the field.

The general relations of dry density and strength to moisture content produced by the reference compaction tests are shown in Figure 2. These trends have been well established and are representative of most soils. The individual curves in Figure 2 are obtained by applying a constant compactive effort to samples of soil prepared with different moisture contents. The maximum dry density (MDD) occurs at a particular moisture content known as the optimum moisture content (OMC). When soil is compacted at both higher and lower moisture contents than optimum by using the same effort, the dry density achieved is less than the maximum. As the effort is increased, MDD increases and OMC decreases. The maximum as-compacted strength occurs at a compaction moisture content lower than optimum. At moisture contents well above optimum, the as-compacted strength is low, and an increase in compactive effort may actually produce a lower strength.

An important consideration, not always remembered, is that the relation in Figure 2 represents behavior of soil when the moisture content remains at the value during compaction. The equilibrium moisture content that develops in the field after compaction as a result of environmental factors may be very different from the moisture content chosen for compaction and may vary with time. Any such changes will alter the strength and density by an amount that depends not only on the magnitude of moisture change but also on the relation of the as-compacted moisture content to optimum. Consideration of this factor is an essential part of proper earthwork design.

## Factors That Influence Reference Test Results

Many factors influence the values of MDD obtained with the AASHTO T99 and T180 reference tests. These have been described in detail by Johnson and Sallberg (2). In summary, these factors are as follows:

1. Size and shape of mold--Test standards fix values for these so that their influence on MDD should be consistent.
2. Mold support--Variations in this can cause up

Figure 1. Relation of density achieved at optimum moisture content to compactive effort for several soil types.

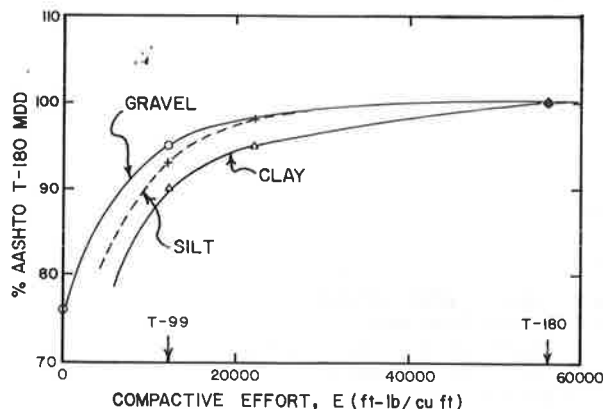
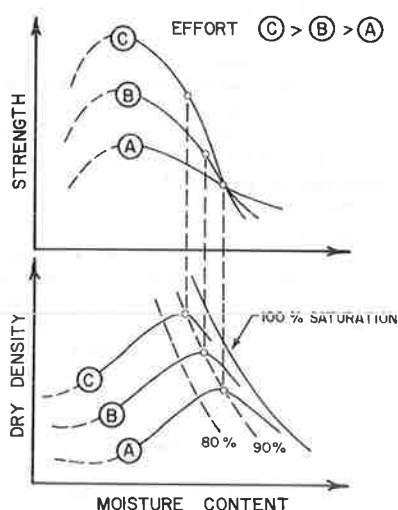


Figure 2. Moisture-density-strength relation for cohesive soils.



to 2 lb/ft<sup>3</sup> change in MDD. Not only is a solid base needed, but the mold bottom and base surface must be flat to ensure solid contact.

3. Sample preparation--This includes (a) whether or not soil is reused for the different compaction moisture contents, (b) whether the soil is oven-dried before mixing with water, (c) length of absorption time after adding and mixing water, and (d) how the water is dispersed into the soil during mixing. These factors can cause a change in MDD of up to about 5 lb/ft<sup>3</sup>.

4. Type, magnitude, and distribution of compaction effort--These are fixed by the test standards. A major limitation is that the impact type of compaction from the falling weight is not representative of any common field method. Thus, the magnitude of compactive effort per unit volume of soil, the moisture-density relations, and the efficiency of compaction are not likely to be the same in the field as in the reference tests.

5. Temperature--Temperature decrease, even when the soil remains unfrozen, can cause a reduction in MDD. The effect can be as much as 1/4 lb/ft<sup>3</sup> decrease per °F temperature decrease in clayey soils (2,3).

6. Layer thickness--This is fixed nominally in the reference tests by defining the height of the compaction mold and the number of layers. However, even with the same soil, control of layer thickness, particularly maintenance of constant layer thickness

for different moisture contents and compaction efforts, is not feasible with present test procedures. The value of MDD can be significantly influenced by this factor.

7. Degradation of particles--Gravel particles in soil can be broken by the impact of the compaction hammer. Thus, the compaction characteristics can be altered. This fact must be considered in interpreting the reference density test results for field use.

The above indicate that MDD from the reference test may vary significantly, even within the constraints of the standard test specifications. Furthermore, the reference test may not be representative of field compaction conditions. The main advantages of the AASHTO T99 and T180 reference tests appear to be that (a) they are relatively simple and inexpensive to conduct; (b) they can be performed with low cost, portable apparatus; and (c) they have been so widely used that they form the basis for most of the past empirical correlations between compaction specifications and performance experience. Although these are important advantages, they do not emphasize the fundamental technical objectives.

#### Factors That Influence Field Compaction Results

Many factors affect the amount of compaction achieved in the field. Although most of these have been documented in the past, for example by Johnson and Sallberg (4), their influence has not always been taken into account in earthwork construction.

That MDD and OMC vary with soil type is well known; however, less well appreciated is that soil type affects field results in a manner different from the reference test because of its influence on effect of methods of soil preparation and efficiency of types of rollers. The large effect of changing compaction water content on the resulting dry density is also well known. Chemical additives such as lime or cement, which are used to stabilize the soil by modifying its properties, will also change the compaction characteristics.

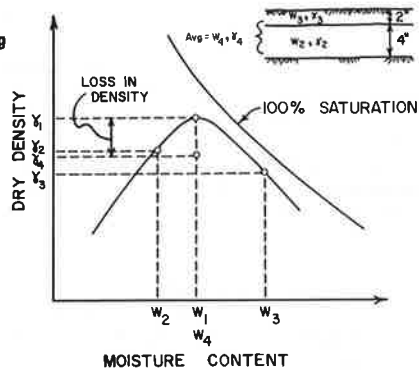
The remaining factors that influence field compaction are given in the following sections.

#### Method of Preparation

The method of soil preparation prior to compaction is an important factor whose influence is not adequately appreciated. This factor includes a means of excavating, transporting, and spreading the soil. It also includes a means of adding water or, conversely, of drying the soil. The blending of soil to get homogeneous composition and moisture content within a placed layer is especially important. This task is generally done poorly because it is expensive and difficult to achieve, particularly in cohesive soils. As shown in Figure 3, if the moisture is not evenly dispersed, even though the compactive effort and average moisture are correct, the density results will not be satisfactory.

Blending of the soil can be started during excavation. If water must be added, doing this at the borrow area is better than waiting until the soil is spread at the compaction site. Some mixing will occur during excavation, and additional time for water absorption will be provided. Additional mixing at the fill area may also be needed. Commonly used methods are dozer, disk harrow, and pulverizing mixer. The pulverizer does the best job, but it is expensive, and hence primarily reserved for adding stabilizing chemicals. The disk is ineffective for mixing water into cohesive soils. Thus, the contractor can only sprinkle the surface and hope that the water will seep into the soil.

Figure 3. Illustration of effect of poor mixing on compaction.



#### Uniformity of Procedures

Nonuniformity in construction procedures is probably the biggest cause of density variation in the field. Soil is never homogeneous in its natural state, and it is unfeasible to blend it so that large zones in an embankment are uniform in composition. However, the manner of excavation and spreading can affect the homogeneity significantly in the horizontal direction within any layer without substantially changing the earthwork cost. The thickness of placed soil layers varies widely (often more than by a factor of two) in typical construction because it is not carefully controlled, except perhaps for layers such as the base course beneath a pavement. The roller coverage pattern is also often widely variable. Inadequate attention is given to uniformity in construction procedures, even though these cause a large variability in the end product, which can be reduced with little increase in cost.

#### Environmental Influences

In cold regions moist gravel and crushed stone have, of necessity, been compacted in subfreezing temperatures. With this possible exception, compaction should never be attempted with frozen soil. Although this fact is generally appreciated, the influence of low temperature (above freezing) is not. The reference MDD is usually obtained at ambient temperatures around 70°F (21°C), but field temperatures may vary by at least ±30°F (±17°C) from this value. However, more critical environmental influences are those that cause drying or wetting of the soil during the earthwork operations. Although these influences are recognized, the magnitude of their effect may not be.

#### Type of Roller

A variety of soil compaction machines are available. Classification of these by distinct type is not always possible. The most common groups, excluding the small machines, used for the compacting element, are as follows:

1. Smooth steel wheel,
2. Pneumatic tire,
3. Sheepsfoot or tamping foot,
4. Segmented pad or grid, and
5. Vibratory smooth-drum.

The principles of compaction with vibratory rollers are more complex and less well understood than those associated with other types of rollers. A discussion of this subject may be found elsewhere (6-8). As indicated by Johnson and Sallberg (4), with few exceptions, no one type of roller is markedly superior

in its ability to achieve a desired density in any soil. However, the efficiency and economy will vary with the combination of soil and compactor used.

#### Compactive Effort

For any type of roller the effort can be changed by varying the magnitude of such parameters as weight, width, tire pressure, and vibration frequency. Obviously, some of these can be changed on a particular machine and others are fixed, unless a different machine of the same type is used. The value of compactive effort applied by field equipment, in comparison with the reference test effort, is generally unknown.

The total effort per unit volume of soil applied with a roller is also a function of the number of roller coverages given to the soil surface. For most rollers, the effectiveness in achieving density is largely dissipated within the first 8 coverages (8). Although measurable changes can often continue up to 16 coverages, the efficiency is low. If compaction is not achieved within 4-8 coverages, then a different roller or compaction condition should be considered.

#### Underlying Layer

As in the reference test, the nature of the support under the layer being compacted has an influence on the layer compaction. In general, the stiffer the underlying conditions, the higher the density that will result, other conditions remaining constant. However, this is not always the case. For example, in compaction of an overlay of asphalt concrete on a Portland cement concrete pavement with vibratory rollers, the stiff layer may cause excess pounding of the asphalt, compared with that experienced with softer underlying conditions, unless vibratory forces are diminished.

#### Lift Thickness

The lift or layer thickness significantly affects the density achieved. Generally, the average density decreases as the lift thickness increases. For example, field tests (8) have shown density decreases of 6-8 lb/ft<sup>3</sup> as layer thicknesses increase from 6 to 12 in. However, there are some exceptions to this trend. The maximum density with vibratory rollers is not always at the surface (9). Also, sheepsfoot rollers tend to leave the top part of each lift uncompacted.

As each layer is placed and compacted, some additional compaction of underlying layers may also occur. Field tests have shown (10) that when compacted layers are 6- to 12-in thick, which is typical of many projects, the placing and compacting of two to six additional layers still produces measurable compaction in the first of these layers. This additional compaction is not usually considered in compaction-control decisions.

#### Rate of Compaction

Soils are strain-rate-sensitive materials, especially clays. However, the rate of compaction as controlled by the roller travel speed, within the normal range of values used in construction, is important only for vibratory rollers. With vibratory rollers, unlike all other types, productivity is generally improved by decreasing the travel speed. The reason is that the number of drum oscillations and, in general, the compaction per drum oscillation, increases with decreasing travel speed.

Within the range of values of the above factors

that influence field compaction, an enormous range in the results can be achieved. The only reliable way to determine the effect of any combination of these factors is by field trial. More information on these effects can be found in many publications, (i.e., 4,8,11).

#### FIELD METHODS OF MEASURING COMPACTION

Density of soil is by far the most widely used method for measuring the results of field compaction. This is true even though density is only an indirect measure of the desired effects of compaction. Among the reasons why density testing is still the principal approach are probably (a) density can be measured by simple and inexpensive equipment (even though more expensive equipment may be better); (b) a lower bound specification can be used for density without defining moisture content (even though this may not be best), whereas other parameters such as strength or stiffness have their maximum values at too low a moisture content; (c) the density approach can be applied to almost all soil conditions; and (d) construction requirements have been established based on experience with density specifications and control procedures, which makes a change difficult to implement.

Other parameters that can be used to measure field compaction include seismic velocity, California bearing ratio, penetration resistance, and plate bearing modulus. Examples are given elsewhere (12-15). Each method will be seen to have particular advantages and limitations. Although density methods are likely to continue to be the most common in the future, other methods ought to be given serious consideration. New methods need to be tried so experience can be gained for their implementation.

#### Compaction Variability

Examples of the interpretation of relative density measurements, considering random and systematic sources of error, may be found in Selig and Ladd (16). Many references are available that provide a comprehensive discussion of measurement error theory. Thus, the subject will not be considered in detail in this paper. However, several basic concepts will be reviewed to provide the background needed for evaluating compaction specifications and control procedures.

All measurements have some error. These may be categorized as random, systematic, or mistakes. Mistakes must be avoided. This is done by careful work, adequately checked. Systematic errors are those that are consistently of the same sign and magnitude for repeated measurements. Examples are weighing scales out of adjustment or incorrect equipment calibration factors. Random errors are those that vary in magnitude and sign with repeated measurement. Examples of sources of random error in density achieved by compaction are soil inhomogeneity and variations in layer thickness, coverage pattern, and moisture distribution. Sources of random error in density measurement methods include reading precision and soil surface preparation effects. Random errors have the characteristic that the error in the measured parameter approaches zero when a sufficient number of repeated measurements are averaged. In contrast, the average of repeated measurements that all contain a systematic error will also have the same error.

Accuracy is defined by the difference between the average of a set of repeated measurements and the true value. The difference is a measure of the systematic error. Precision is defined by the repeatability of a measurement, as determined by the ran-

dom sources of error. A small amount of scatter in a repeated set of measurements indicates high precision. However, the average measurement will be inaccurate if a large systematic error exists. Whereas precision can be determined by repeated measurements, accuracy cannot. Unfortunately, if the systematic errors are not known, the accuracy of the measurement is not known.

Random errors in compaction measurements often follow a normal distribution. Thus, the set of repeated measurements can be characterized by a mean, which is the estimate of the true value, and a standard deviation, which is a measure of the scatter or precision. Systematic errors shift the mean value away from the true value (i.e., cause inaccuracy without altering the scatter or precision). In compaction work, these two types of errors must be distinguished to evaluate the results properly.

Information that indicates the magnitude of the errors in the reference compaction test and in field density measurements are given in a number of references (2,4,16-19). Based on data such as these, the values in the table below were established as an indication of the magnitude of the random and systematic errors for these two situations. Knowledge of these errors is essential for writing meaningful specifications and for evaluating compaction results.

Test Measurement	Systematic	Random, 1 SD
Reference		
MDD (lb/ft <sup>3</sup> )	2-10	<1
OMC (%)	1-5	<1
Field		
Embankment dry density (lb/ft <sup>3</sup> )	2-4	5-8
Embankment moisture (%)	<2	2-3
Base course dry density (lb/ft <sup>3</sup> )	1-3	2-5
Base course moisture (%)	<1	1-2

#### Compaction Specification and Control

Three questions need to be answered in order to prepare compaction specifications and establish control procedures for a job:

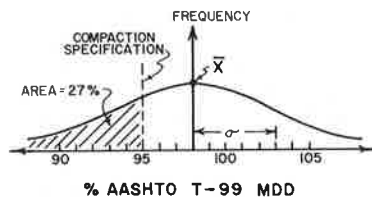
1. How much compaction is needed?
2. How should compaction be specified? and
3. How should the results be verified in the field?

#### How Much

Normally, the required level of compaction is determined from past experience. For example (20), 95 percent of AASHTO T99 MDD is commonly required in embankments below a depth of 1-6 ft from the surface, and a higher level of compaction (i.e., 100 percent AASHTO T99 MDD) is required in the top zone of the embankment or the subgrade, where the traffic-induced stresses are greater. Granular bases are generally required to be compacted to at least 100 percent AASHTO T99 MDD or 95 percent AASHTO T180 MDD, the latter usually being greater. However, 100 percent T99 for granular bases produces much greater strength and stiffness than 100 percent T99 for most subgrades and embankment materials.

Specification of the amount of compaction in any terms other than a level of density relative to some standard test value is unusual. The assumption is that if the required density is achieved with materials acceptable for the situation, then performance will be satisfactory. The limitation of this approach is that performance will vary widely among the acceptable soils when compacted to the same den-

Figure 4. Variation of field density in relation to compaction specification.



sity specification. Thus, for equal performance, the compaction requirements should be a function of soil type for the same application. This refinement is not usually made. Furthermore, if density is to be used as the primary basis for specifying compaction, then the required amount should be obtained by correlation of density to desired properties such as strength or stiffness. However, this approach appears to be implemented only rarely in practice.

Another, perhaps more serious, limitation of present compaction specifications is that variability is not usually recognized or considered. Thus, when a given level of density is requested, no indication is given whether this is intended to be an average, so that 50 percent of the samples can have a lower value, or a minimum, so that 100 percent of the samples must exceed the specification, or whether some other allowable percentage below the specification is intended. Since variability is an established fact, interpretation of the specification cannot be made without resolution of this issue.

#### How to Specify

The two basic categories of specifications are (a) method and (b) end result. The first specifies how the compaction should be done; for example, the equipment type, maximum layer thickness, minimum number of passes, and, perhaps, the moisture content of the soil. This method is considered too restrictive to the contractor. The second specifies the required characteristics, usually a minimum dry density within a range of acceptable moisture content. This approach assumes that suitable procedures exist and will be used to check the end result.

In reality, reliance on just checking the end result has been found to be unsatisfactory. This situation derives in part from the errors in the reference test and in the field test and the variability of field densities. But, in addition, the number of reference and field measurements is generally far too few. Thus, in practice, a combination of method and end result specification is generally used. Such a specification, for example, might require approval of the compactor or specification of the acceptable compactor characteristics, then specification of a maximum layer thickness, a minimum number of passes, and a minimum required density. Restrictions would be placed on the acceptable range of moisture content relative to optimum.

Wahls and others (3) provide examples of specifications used in highway practice based on an extensive survey completed in 1968. All of the specifications are of the combination type. A distinction is made in the requirements for embankments, subgrades, backfilling of trenches, and structural backfill.

#### How to Control

The first step in controlling the results is to obtain a representative sample of the soil for performing the reference density test. The purpose of the reference test is to obtain a value of MDD and

OMC for the soil. However, a representative sample is impossible to obtain in advance of construction. Tests are needed not only for each new soil type encountered but also for composition variations within the same soil type. Thus, samples should be taken periodically during construction to provide a continuing series of reference tests. A reference test can be justified for each field density test, although this frequency is not always essential.

The field density is measured during construction and compared with the reference value to determine whether the results comply with the specifications. To accomplish this task, the inspector must decide where to conduct the field tests and how many tests to perform. But, perhaps, more critical questions are, How appropriate is the reference value and what percentage of the compacted soil zone can be permitted to have a density below the reference value? The answers require determination of systematic errors in the reference tests relative to the field tests. Sources of these errors include the effects of soil preparation and type of compactive effort, even assuming that the samples are representative.

What happens if the results of the field test fail to meet the specified value? Remember that the purpose of the test is to check compliance. Thus, if the test does not pass, some action must be taken and a retest done until compliance is achieved. In practice, common solutions, in order of probable application, appear to be the following:

1. Rerun the field test, assuming an error in the first test. If this test passes, accept the compaction. If not, try step 2.
2. Require the contractor to do more compaction, then retest. If still unsatisfactory, try step 3.
3. Consider whether a different compactor is needed. If so, try it and then retest. If unsatisfactory, go on to step 4.
4. Rerun the reference density test. If the field test still does not pass, go on to step 5.
5. Scarify soil or remove and replace it, then recompact and retest. If the test still does not pass, go to step 6.
6. Request owner to accept a lower standard than previously specified.

The effects of compaction variability and specification interpretation on the acceptance decision can be illustrated with the following example. Assume that the specified compaction requirement is 95 percent of MDD from the AASHTO T99 reference test. Assume, too, that the variability of compaction is represented by a standard deviation of 5 percent compaction. Even though the statistical meaning of compaction specifications is unknown in general, it is reasonable to assume that at least the average density is intended to exceed the specified value. Thus, assume in this example that the average achieved is actually 98 percent.

The density distribution in relation to the specification value in this example is illustrated in Figure 4. This figure shows that 73 percent of the soil would have a density greater than the specified 95 percent MDD, and 27 percent has a lower density.

Consider three possible decision plans for compaction control.

1. Conduct a density test at a random location. Accept the compaction if the test result equals or exceeds 95 percent MDD. If the test fails, then discard it and take a second test at another random location. If this test result equals or exceeds 95 percent MDD, accept the compaction. If it fails, reject the compaction.

Plan 1 implies that the average compaction is intended to equal or exceed the specified value. If the average just equals the specified value, the probability of the first test passing is 50 percent and the probability of either the first test or the second test passing is 75 percent. Thus, the probability of plan 1 resulting in acceptance of this compaction is 75 percent (i.e., three out of four times the plan should result in the intended decision). For the example in Figure 4, the probability is even higher, specifically 93 percent, that the compaction will be accepted under Plan 1. Thus, if properly used, this simple plan can be very effective.

2. Conduct three or four compaction tests. Accept the compaction if three out of four (or 75 percent) of the tests exceed the specified value. If more than one of four tests fails, reject the compaction.

Plan 2 implies that 75 percent or more of the compacted soil is required to have a density greater than the specified value. The case illustrated in Figure 4 approximately represents this situation. For this case, plan 2 should produce the correct decision about 70 percent of the time.

3. Assume that every test must give a density that exceeds the specified value. Thus, some remedial action will be required if any test fails.

Plan 3 implies that 100 percent of the soil should exceed the specified compaction. The case in Figure 4 does not comply with this goal. If only one test is required to make a decision, then 73 percent of the time the wrong decision will be made. If two tests are required, then the wrong decision will be made 53 percent of the time. For this plan to be effective, the inspector must choose the spots that appear to be lowest in density and test at one of these. If the test passes, then the compaction should be accepted. However, this plan is unnecessarily severe because it forces the average compaction to be much higher than the specified value.

An alternative to these simple plans is a more rigorous statistical sampling plan with control charts. Examples are given elsewhere (3,19,21-23). According to Beaton (23), the reasons that such statistical control procedures have not been used generally are as follows:

1. Construction engineers and inspectors are unfamiliar with the concepts and terminology of statistical quality control,
2. Departures from the specifications are frequently needed because of changed job conditions,
3. Present specifications have not been written for use with random sampling or statistical control, or
4. Construction costs will increase unnecessarily if present quality is adequate.

All of these arguments can be circumvented by proper training and proper specifications. If compaction is generally adequate, then it is only necessary to define it unambiguously in specifications and develop an appropriate inspection plan to check it.

#### COMPACTOR PERFORMANCE EVALUATION

Knowledge of compactor capability is valuable for judging adequacy of compaction. Because suitable equipment specifications do not exist, this knowl-

edge has to come primarily from field experience. To assist in interpreting field experience and in correlating the extensive range of possible conditions and rollers, a method was developed to quantify ratings of compaction equipment in terms of

1. Compaction effort per unit of soil volume,
2. Productivity in volume compacted per unit of time, and
3. Power required for compaction.

The details of the method are given elsewhere (24), and examples of application is found in Hussein and Selig (11).

In its simplest form (Figure 5), the compactor may be represented as a smooth roller of width  $B$  and weight  $W$  that requires a towing force ( $F$ ) to pull it over a layer of compacted thickness ( $t$ ) at a travel speed ( $S$ ). The compactive effort ( $e$ ) (force  $\times$  distance) is given by

$$e = FLP \quad (2)$$

where  $L$  is the distance traveled per roller coverage and  $P$  is the number of roller coverages or passes.  $F$  may be related to the roller weight ( $W$ ) by

$$F = fW \quad (3)$$

where  $f$  is the coefficient of compaction or rolling resistance. Thus,

$$e = fWL P \quad (4)$$

The volume compacted ( $V_c$ ) is

$$V_c = LBt \quad (5)$$

The compactive effort per unit soil volume ( $E$ ), analogous to the parameter used in the AASHTO T99 and T180 tests, is

$$E = e/V_c = fWP/Bt \quad (6)$$

The compaction time ( $T$ ) is

$$T = PL/S \quad (7)$$

The productivity ( $R$ ) thus is

$$R = V_c/T = BtS/P \quad (8)$$

Finally, the required power ( $H$ ) is

$$H = C_1 RE = C_2 fWS \quad (9)$$

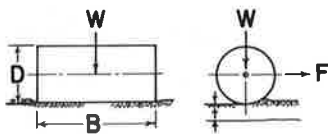
where  $C_1$  and  $C_2$  are constants for unit conversion.

A study of compactor performance by using this model has demonstrated that compactor weight, by itself, is an unreliable indicator of expected performance. This conclusion is illustrated by the observation that the 10-lb hammer used in the AASHTO T180 reference test can produce densities that are difficult to achieve by even the heaviest rollers available. The advantage of the heavy roller in this case is much higher productivity. Of course, heavy rollers, properly configured, can produce higher densities than lighter rollers, if other parameters such as layer thickness and coefficient of compaction are constant. However, if lighter rollers are matched in compactive effort per unit volume to heavy rollers, by appropriate selection of parameters, the heavy roller will only have a higher productivity instead.

To illustrate this point, compare two machines.



Figure 5. Simplified compactor model.



One is a self-propelled smooth steel-wheel roller that weighs 10 000 lb and has an effective rolling width of 3.5 ft. The other is a towed pneumatic tire roller that weighs 50 000 lb and has an effective rolling width of 7.1 ft. The number of coverages with both rollers is arbitrarily taken as five, but, in consideration of the weight differences, the layer thickness is designated as 4 in for the steel-wheel roller, and 10 in for the pneumatic roller. The coefficient of compaction is assumed to be the same in both cases, although, in reality, this is only approximately true.

According to Equation 6, the ratio of  $E$  for the steel-wheel roller to  $E$  for the pneumatic roller will be

$$E_{SW}/E_{PN} = (10\,000/50\,000)(7.1/3.5)(10/4) = 1.$$

Hence, both rollers in this case produce the same compactive effort per unit volume of soil compacted. However, according to Equation 8, and assuming that both travel at 3 mph, the corresponding ratio of productivity is

$$R_{SW}/R_{PN} = (3.5/7.1)(4/10) = 0.2.$$

Thus, the pneumatic roller has five times the productivity of the steel-wheel roller.

If, instead, the layer thicknesses were kept the same, say at 6 in for both rollers, the ratio of  $E$  would be

$$E_{SW}/E_{PN} = (10\,000/50\,000)(7.1/3.5) = 0.4;$$

that is, the pneumatic roller would produce greater compaction. The pneumatic roller would also achieve its higher amount of compaction with greater productivity because

$$R_{SW}/R_{PN} = (3.5/7.1) = 0.5.$$

#### CONCLUSIONS REGARDING PRACTICE

Observations of compaction practice over the past 20 years have led to the following conclusions.

1. Variability of density from point to point in the field is sufficiently large that compliance of 100 percent of compaction tests with a specified compaction requirement is unfeasible and unreasonable to expect.

2. Variability is significant, a typical standard deviation of density scatter is 4 to 6 lb/ft<sup>3</sup>. This means that the range of test values could easily exceed 20 lb/ft<sup>3</sup> for a particular job.

3. Moisture content around optimum is generally required, but modification of moisture content during construction is rarely observed. Thus, we could logically conclude that soil naturally exists at its optimum moisture content. However, it is more reasonable to assume that the tolerance allowed in field moisture is very much wider than normally specified. In fact, modification of moisture content is rarely required unless density results are unsatisfactory. If this practice does not produce an inadequate end product then, rather than change the practice, the specifications should be modified to be consistent with it.

4. If an inspection report indicates that all or most measured field densities are in excess of the specified value, then the average of these reported values is not likely to represent the average for the compacted zone of soil. The reason is that the lower end of the density distribution must be missing for this situation to occur, assuming a normal density distribution and reasonable compaction requirements.

5. Earthwork construction productivity has greatly increased in the last several decades, but procedures for compaction inspection have changed only to the extent that nuclear instruments have been perfected for determining the field results. No really new approaches have been introduced.

6. The percentage of total compacted soil sampled in inspection is infinitesimal. Thus, most of the compacted soil must be accepted by judgment of the inspector without testing.

7. As normally practiced, testing is insufficient for reliable judging of compaction. Thus, the primary value of conducting compaction reference tests and field density measurements is either to document compliance for the record or to guide the inspector's judgment.

8. Reliable compaction evaluation requires the services of an experienced and knowledgeable inspector. However, this task is often delegated to someone in a low-level position on the staff.

9. Given the limitations of present practice and the realities of field conditions, the most reliable way to assess the adequacy of compaction is to have a knowledge of roller capabilities and then observe the construction procedures. Field density testing, as currently practiced, is no substitute for experienced observation.

10. Improvement of compaction operations in the field will require more meaningful specifications, more appropriate testing apparatus, and a better understanding by contractors and engineers of the factors that influence compaction results.

11. Alternatives to density specifications should be encouraged.

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## Embankment Compaction and Quality Control at James Bay Hydroelectric Development

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Construction of 220 dams and dykes at the La Grande Complex, James Bay hydroelectric development involves several types of materials (till, sand and gravel, and rockfill) and construction procedures and equipment that must yield embankment zones of desired characteristics. Experience and design requirements, as well as the schedules, economic, and climatic restraints, have led to a general standardization of the specified material placement techniques and conditions. This paper deals with some of the practical aspects of the specifications that are developed with a suitable balance between the procedure and product specifications and reviews the relative importance placed on visual inspections and various control and verification tests. The difficulties encountered with the quality control and verification testing procedures are discussed and comments are made regarding the relative accuracy and suitability of these tests. Typical properties of the embankment materials based on extensive tests carried out on 160 Mm<sup>3</sup> of materials are also included.

The La Grande Complex (phase 1) of the James Bay hydroelectric development involves construction of about 220 earth and rockfill embankment dams and dykes that have a maximum height of 160 m. The complex covers a territory about 800 km long and 400 km wide and is located about 1000 km from Montreal in northern Quebec (Figure 1). Construction of these embankments at the five main project sites, namely

La Grande 2 (LG2), LG3, LG4, Eastmain-Opinaca (EOL), and Caniapiscau, began in 1973 and is scheduled to be completed in 1982. The work procedures specifications and the quality control requirements and methods have been developed from the experience acquired at the Manicouagan-Outardes Project in Quebec and the Churchill Falls Project in Labrador, with almost similar geological and climatic conditions.

### PROJECT DESCRIPTION

The complex lies within the Canadian Shield, a glaciated peneplain developed on a precambrian basement complex of igneous and metamorphic rocks (1). The project sites are underlain mostly by granitic rocks that range in texture from massive to gneissic. Glacial and fluvio-glacial sediments cover some 80 percent of the region. Glacial till is widespread in the form of ground moraine, locally including some drumlin deposits, and forms an excellent source of impervious material for embankment construction. Eskers and kames constitute the principal source of granular materials for filters, transitions, and