Compaction Variables and Compaction Specification

A. G. Altschaeffl and C. W. Lovell, Jr.
Associate Professors in Civil Engineering
Purdue University

PURPOSE OF COMPACTION

Compaction is a mechanical process in which an earthen material is made more dense. The densification occurs as a direct result of the mechanical loading, and is essentially complete at the end of the loading. Volume changes are incurred as a result of a reduction in the quantity of air voids—water content remaining constant. Since it is impractical to squeeze out all the air, the as-compacted condition is a partly saturated one.

While compaction is densification, the achievement of high unit weight is not the direct objective. Rather, the intent is to produce a soil structure which will exhibit and retain a requisite level of integrity throughout a design service life. The properties which must be imparted to the soil vary with the project, but such descriptors as strength, compressibility, and flexibility are commonly involved.

Thus, densification is merely a means to an end. Where improvement in soil properties is directly related to increase in unit weight, the use of simple correlations between the two is highly satisfactory. In a few cases the relation is an inverse one, while in many cases, other variables are of much importance. Such difficulties in determining how soil properties can be improved are pronounced in the fine-grained soils, and this discussion focuses primarily upon the behavior of compacted clays.

Following a brief review of the compaction variables, both as-compacted and in-service behavior are discussed. Since the reader is most probably involved in highway-oriented problems, the property considered is that of resistance to shear . . . loosely termed "strength." All of this is intended to shed light on one of the most important and difficult judgements required of the materials engineer—what compaction to specify.

INITIAL CONDITION OF THE SOIL

Most soils can be used in compacted highway embankments. Exceptions are those which are highly organic or which are highly susceptible to frost, swelling, or remolding (sensitive). Soils which are otherwise suitable may be encountered in states of poor workability, i.e., frozen or with high water content. Wet clays may be sticky, slippery, and impossible to densify appreciably. Wet silts are even more treacherous, and may become "quick" under the loading of construction equipment.

Not only does the water content of fine-grained soils exercise an important influence on their response to rolling, but it also governs in large degree the subsequent behavior of the compacted mass. Since only small changes in water content can normally be accomplished by wetting or drying of clays on the grade, it is advisable to seek natural moisture conditions which are rather close to those believed optimal for the field compaction process. A good rule of thumb says that the natural water content should approximate the plastic limit of the clay. In general, the water content is the most important initial condition variable.

COMPACTION VARIABLES

The more important independent variables in the compaction process are the soil type and its degree of aggregation, method of application of the compactive energy, magnitude of compaction energy, water content, and temperature. The foregoing combine to produce the principal dependent variables of dry unit weight and some measure of "strength." In addition, the service environment causes changes in the as-compacted characteristics, and these must be included in considerations of behavior.

It is very expensive to investigate many levels of the foregoing variables with field studies. This was recognized some 35 years ago by R. R. Proctor when he initiated systematic laboratory examination of certain of the compaction variables, viz., water content, soil type, and dry unit weight. He selected a convenient, if arbitrary, kind of compaction, and he selected a compaction energy which produced dry unit weights achieved by field equipment of that time—if moisture conditions were favorable. Both the standard AASHO and the Modified AASHO (higher effort level) tests are adaptations of the Proctor approach. All state highway departments use these tests to define the reference curves of dry unit weight as a function of water content used for specification and construction control purposes.

It is vital to recognize that the relationships generated in standardized laboratory tests are valid for arbitrary single levels of other potentially important variables. For example, the results of an AASHO compaction test relate to a particular soil disaggregated to a specified level, subjected to a selected level of a special kind of energy input, and at the ambient temperature. Varying the compactive effort produces a regular three-variable relation of the kind illustrated in Figure 1.[1] The locus of points representing maximum compacted dry unit weights, and hence optimal water contents, is termed the "line of optimums."

Holding the compactive effort constant (at the level of the standard AASHO test) and varying soil type yields relationships of the type shown in Figure 2. If a smaller range of soil parent materials is used, with statistically derived typical curves, an even more orderly functional relationship is generated. A primary example is the set of Ohio typical moisture-unit weight curves—Joslin (1958).

Variations in the kind of compaction, viz., the type of laboratory test or field roller, can also significantly influence the effect of water content and compactive effort on unit weight. Figure 3 shows lines of optimums for three types of laboratory tests, as well as a general range of field compaction results. The use of laboratory control tests based upon a compacting action different from common field equipment introduces difficult correlation problems. Figure 4 illustrates differences between results of the AASHO-type test and those of several rated pneumatic rollers. Despite such evidence, it is seldom judged economically practical to generate the particular job compaction relationships by field experiment.

BEHAVIOR OF COMPACTED SOIL

In the preceding section attention was focused on dry unit weight as the major dependent compaction variable. While unit weight is an excellent pragmatic choice for specification and construction control, it must be correlated with the soil's behavior characteristics. Establishing the relation between unit weight and as-compacted strength is merely a first step. The influence of the in-service environment imposed by both nature and man must also be predicted, and the strength which remains after the interaction of all influences must sustain the highway structure in an adequate manner.

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[1] Note that in this illustration and others that follow, specific examples are used. Since the functional relations between compaction variables vary widely, it is sometimes deceptive to use generalized representations.

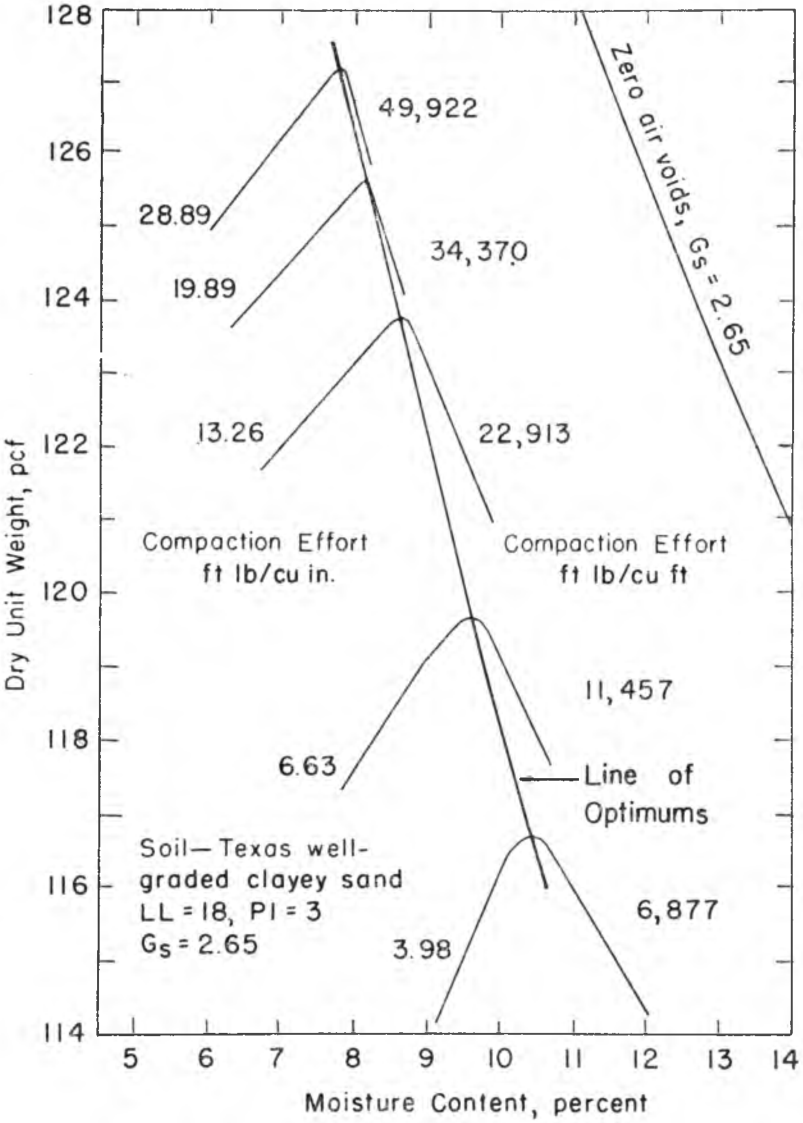
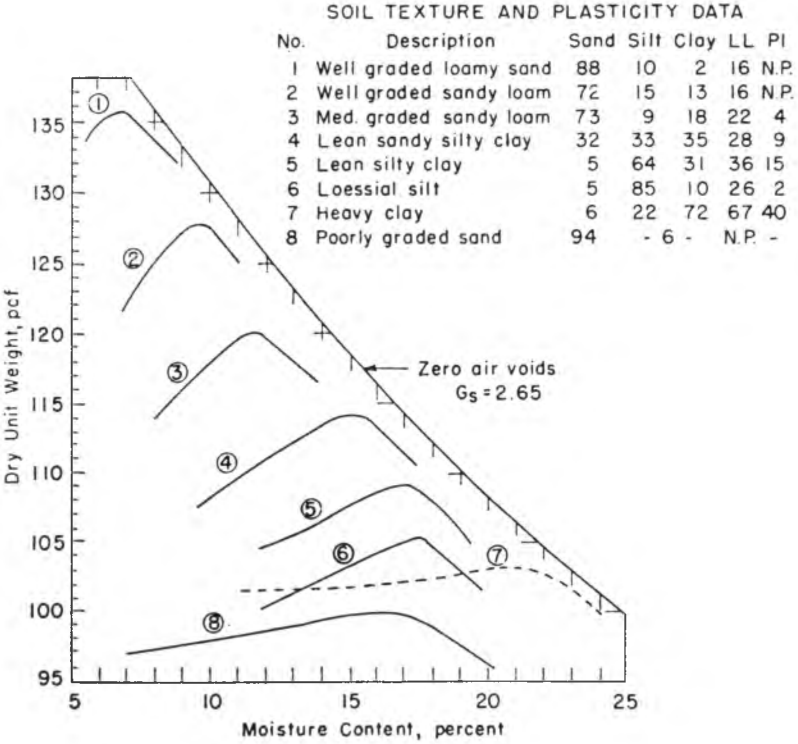


Fig. 1. Effect of compaction effort on moisture-unit weight relations for a clayey sand. Note—the compaction effort for Standard AASHO Method T 99-57 is 12,375 fp/cf and Modified AASHO is 56,250 fp/cf (55,986 fp/cf for AASHO Method T 180-57 using 1/13.33 cf mold). From Johnson and Sallberg (1960).



SOIL TEXTURE AND PLASTICITY DATA

No.	Description	Sand	Silt	Clay	LL	PI
1	Well graded loamy sand	88	10	2	16	N.P.
2	Well graded sandy loam	72	15	13	16	N.P.
3	Med. graded sandy loam	73	9	18	22	4
4	Lean sandy silty clay	32	33	35	28	9
5	Lean silty clay	5	64	31	36	15
6	Loessial silt	5	85	10	26	2
7	Heavy clay	6	22	72	67	40
8	Poorly graded sand	94	- 6 -		N.P.	-

Fig. 2. Moisture content-unit weight relationships for eight soils compacted according to AASHO Method T 99. From Johnson and Sallberg (1960).

While field observations and accumulated experiences are invaluable to the engineer, controlled laboratory experiments play an indispensible and economic role in validating concepts and in developing the key relationships. Accordingly, the relations which are discussed below were developed from laboratory tests.

The reader is reminded that the term "strength" is here used rather loosely to include everything from an ultimate stress to stresses induced at low deformation levels, as well as CBR relations.

As Compacted

It is customary to plot both dry unit weight and strength as a function of compaction water content, understanding that all other variables including the method of interpreting strength are held constant. Figure 5 is an illustration, where three levels of compaction energy are considered. Both measures of strength decrease with an increase in com-

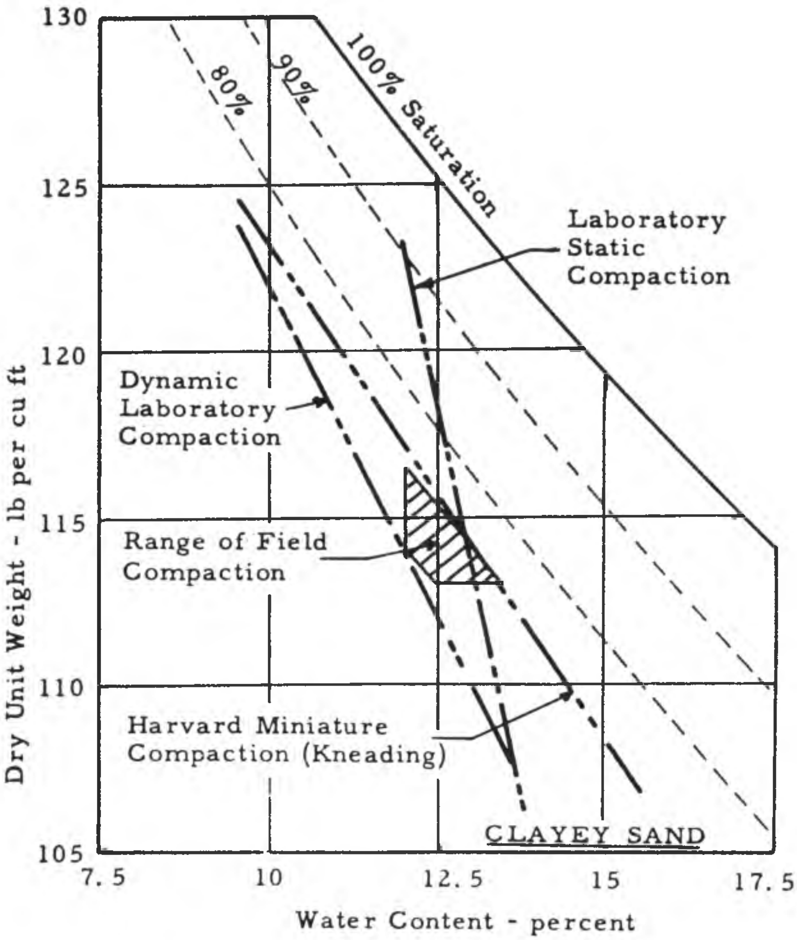
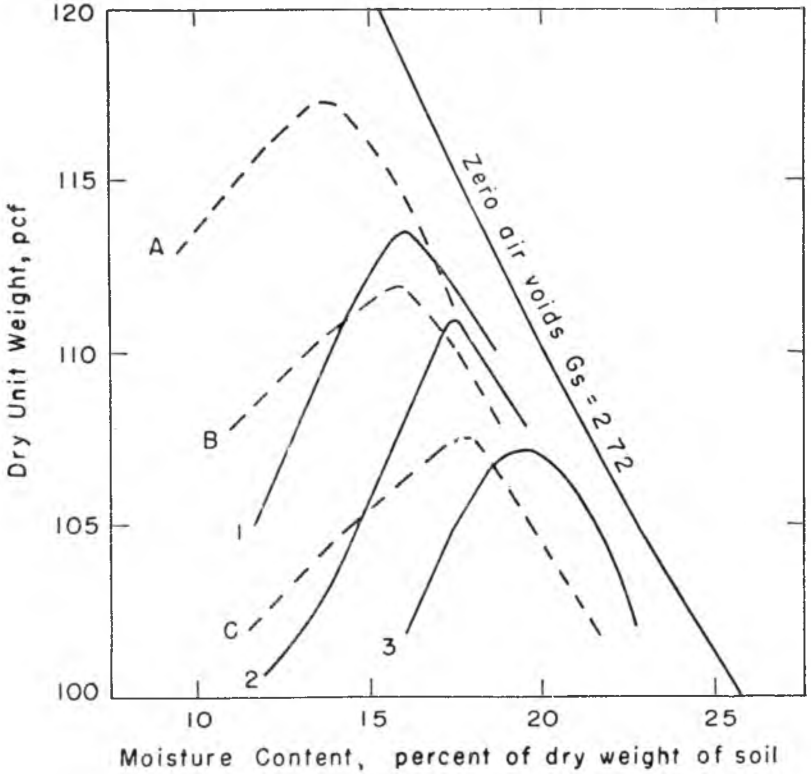


Fig. 3. Effect of type of compaction on peak points of moisture-density curves. From Wilson (1952).

paction water content and with a decrease in compactive effort—with minor exceptions at low strains.

The importance of method of compaction is demonstrated in Figures 6 and 7. The former compares AASHO and kneading types of compaction, while the latter shows relative strengths for four laboratory methods. The type of compaction is shown to be particularly significant for wet-side compaction. Seed and Chan (1961) explain these observations in terms of the relative shear strains induced in the compaction process, viz., the more the soil is deformed during compaction, the smaller is the strength at low strains.



COMPACTION EFFORT

A-Modified AASHO,* 5 layers, 55 blows per layer, 10-lb hammer, 18-in. drop, 56,022 ft lb/cu ft

B-Intermediate,* 5 layers, 26 blows per layer, 10-lb hammer, 18-in. drop, 26,483 ft lb/cu ft

C-Equal to AASHO,* 5 layers, 12 blows per layer, 10-lb hammer, 18-in drop, 12,223 ft lb/cu ft

1-Four coverages,† 31,250-lb wheel load, 16.00 x 21-in. tire, inflation pressure 150 psi

2-Four coverages,† 25,000-lb wheel load, 18.00 x 24-in. tire, inflation pressure 90 psi

3-Four coverages,† 15,875-lb wheel load, 18.00 x 24-in. tire, inflation pressure 50 psi

* 6-in. diam. x 4.5-in. high mold.

† Four coverages require 8 passes of roller.

Fig. 4. Comparison of laboratory compaction curves (dashed lines) and pneumatic-tired roller compaction curves (solid lines) for a lean clay soil (LL = 36, PI = 15). From Johnson and Sallberg (1960).

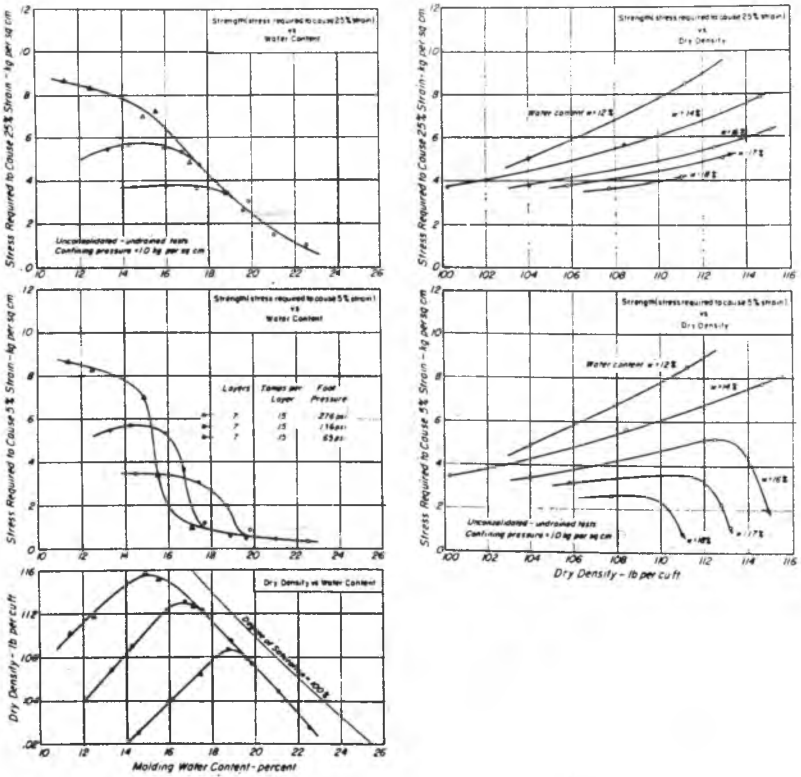


Fig. 5. Relationship between dry density, water content and strength as compacted for samples of silty clay—kneading compaction. From Seed and Chan (1961).

Although not specifically illustrated, soil type also has a major influence on the as-compacted strength.

In Service

Many things happen to an element of compacted soil following the "last pass" of the roller. These could include: (a) increase in stress and compression caused by the overlying weight; (b) increase in moisture content and either compression or swelling,[2] depending primarily on the compaction water content and the confining pressures; (c) shrinkage caused by decrease in water content; and (d) freezing expansions and thaw consolidations. Such complex changes can be simulated in practical laboratory testing in only a highly simplified fashion.

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[2] Bishop and Henkel (1962) observe that swelling can be expected for clays compacted at about optimum water content even under loads representing 20 or 30 feet of fill.

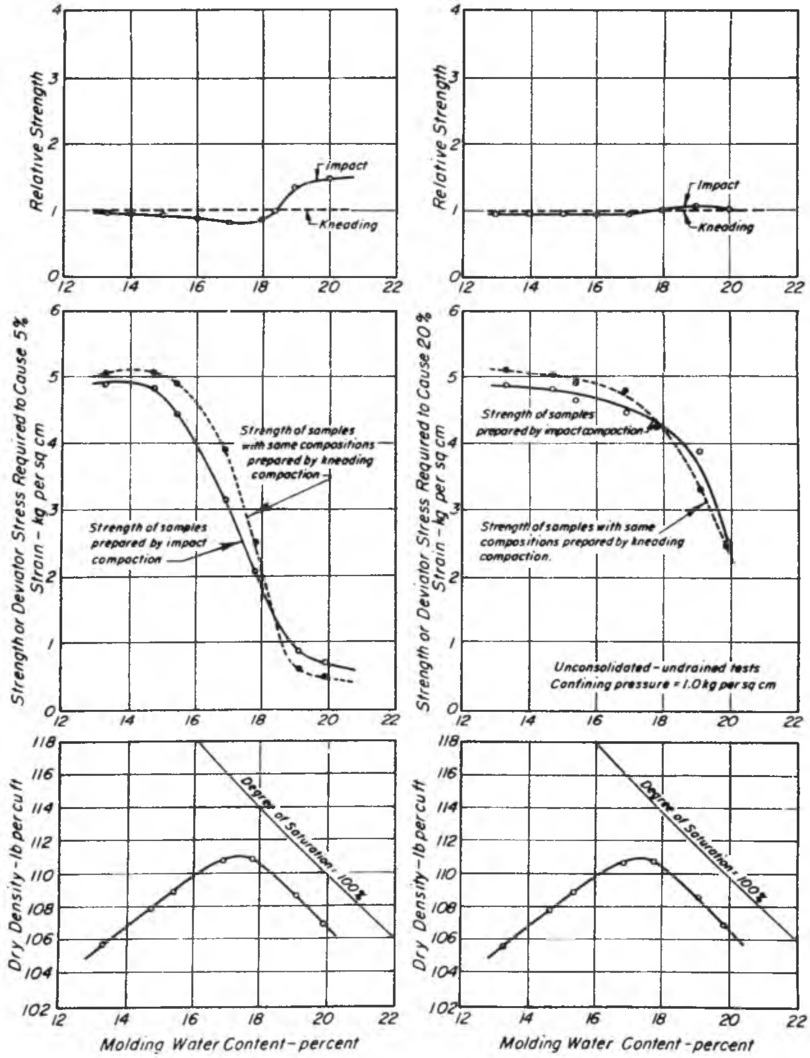

Fig. 6. **Comparison of strengths of silty clay samples prepared by kneading and impact compaction. From Seed and Chan (1961).**

In a climate like that of Indiana, it is reasonable to assume that the compacted soil will at times be essentially saturated. The changes in water content which can occur are shown in Figure 8, where the relative swelling of the soil is explained in terms of a flocculated or dispersed soil microfabric. The maximum residual dry unit weight is observed for the soil compacted near the optimum water content for the particular kind and level of compactive input.

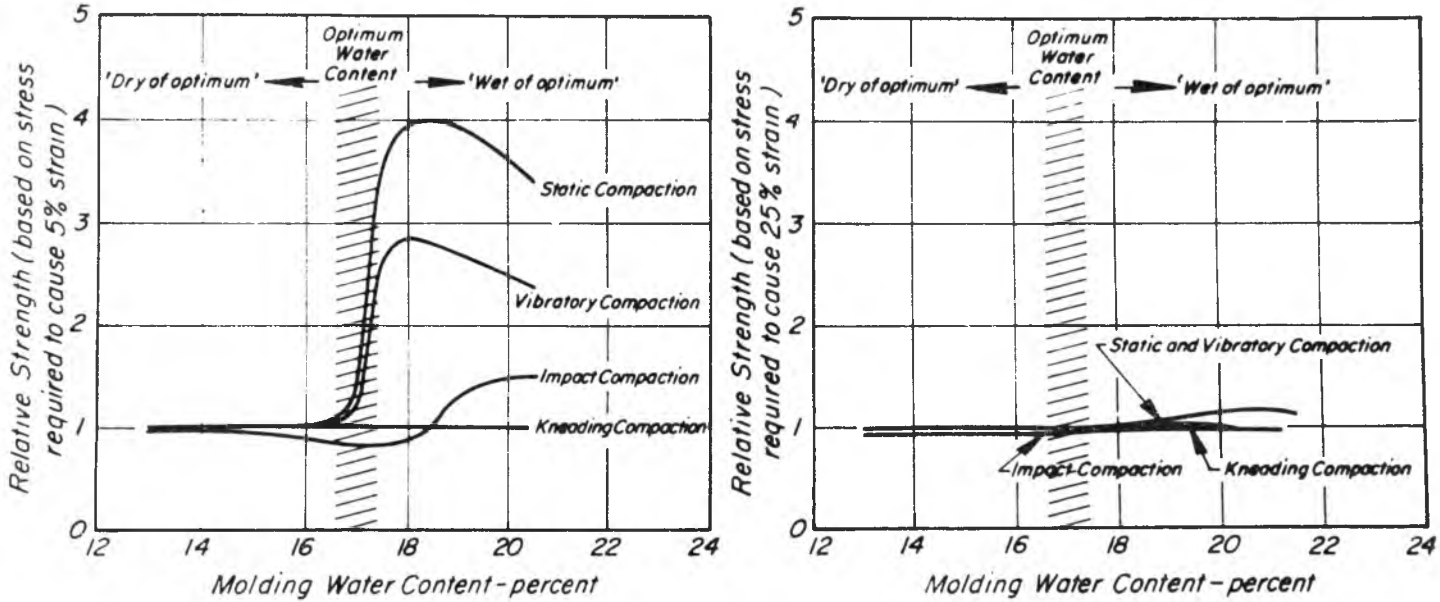

Fig. 7. Influence of method of compaction on strength of silty clay. From Seed and Chan (1961).

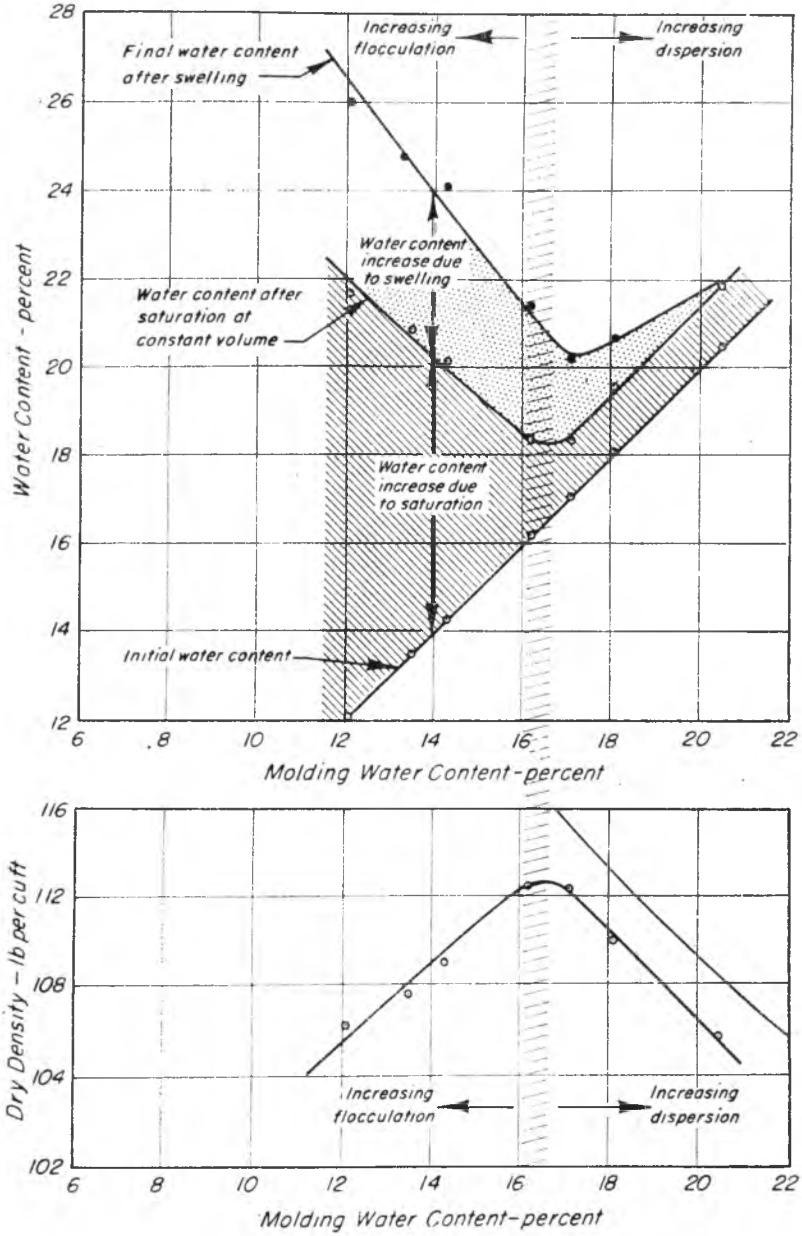

Fig. 8. Influence of molding water content and soil structure on swelling characteristics of sandy clay. From Seed and Chan (1961).

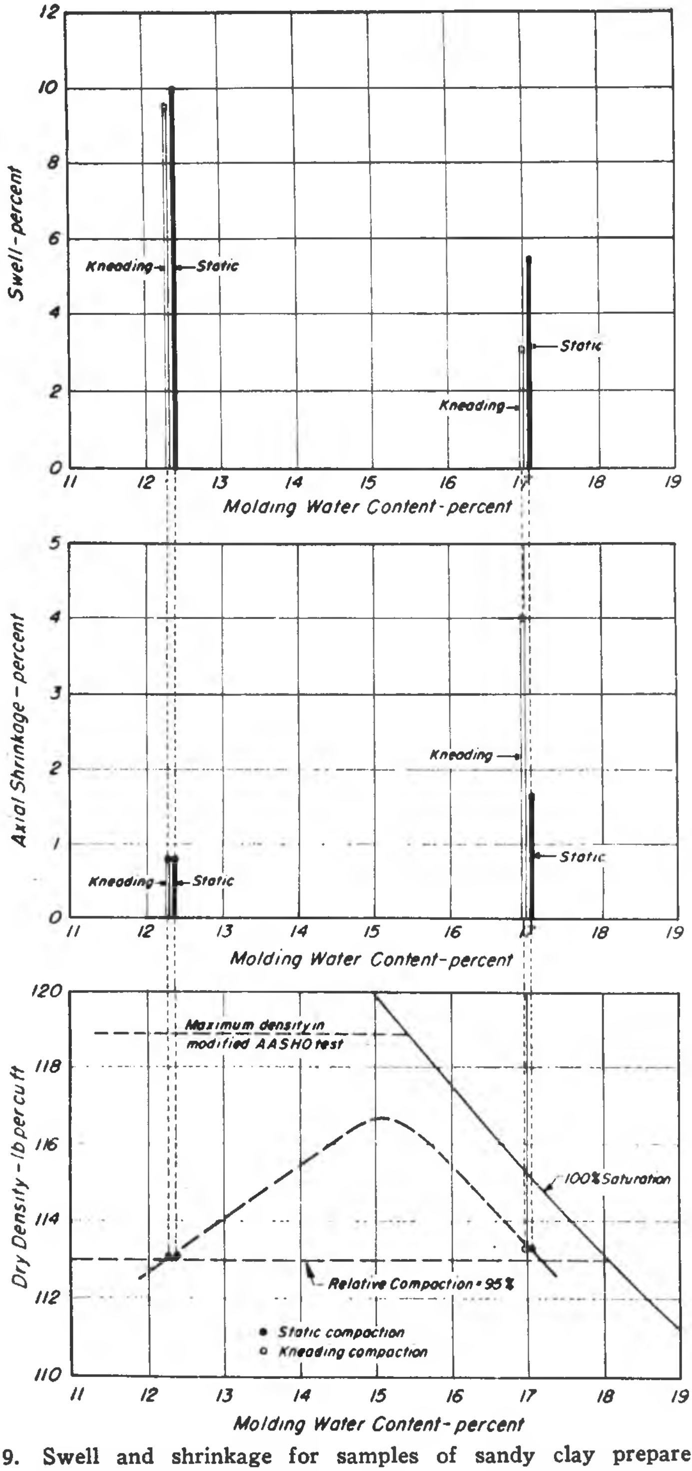

Fig. 9. Swell and shrinkage for samples of sandy clay prepared by kneading and static compaction. From Seed and Chan (1961).

The swelling potential also varies with the kind and amount of compaction. Figure 9 shows that swelling (or shrinkage) is more sensitive to differences in method of compaction when the soil is wet of optimum. Figure 10 shows a linear increase in swelling pressure with static compaction pressure. Swelling is also accentuated when quantities of montmorillonitic and illitic clay minerals are present in the soil.

To define the relations for in-service conditions, compacted samples are placed in contact with free water while realistic confining pressures are applied. When the samples have reached equilibrium under the above conditions, they are tested for strength in an undrained condition. Strength numbers (Figure 11), strength parameters (Figure 12), CBR values, and the like may be used to describe the results. Figure 11 can be compared with Figure 5 to show the reduction in strength due to soaking under moderately high confinement. Maximum low-strain soaked strengths occur in this example at compaction water contents

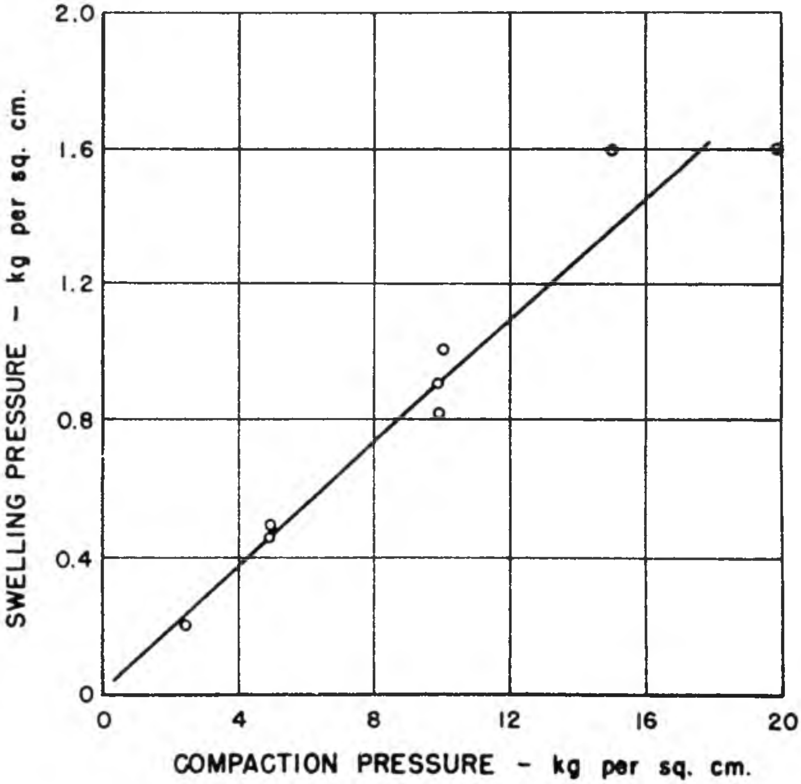

Fig. 10. Swelling pressure versus compaction pressure. From Wilson (Leonards) 1952.

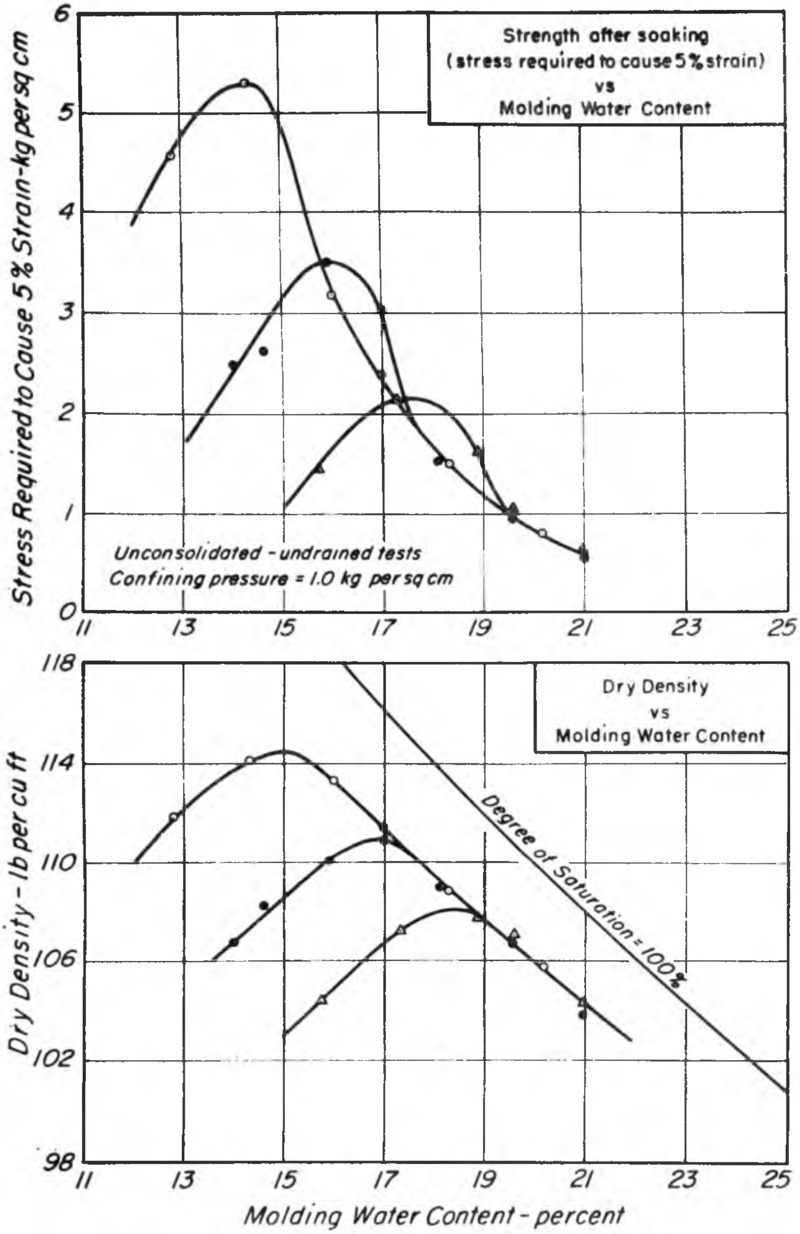

Fig. 11. Relationship between initial composition and strength after soaking at constant volume for samples of silty clay prepared by kneading compaction. From Seed and Chan (1961).

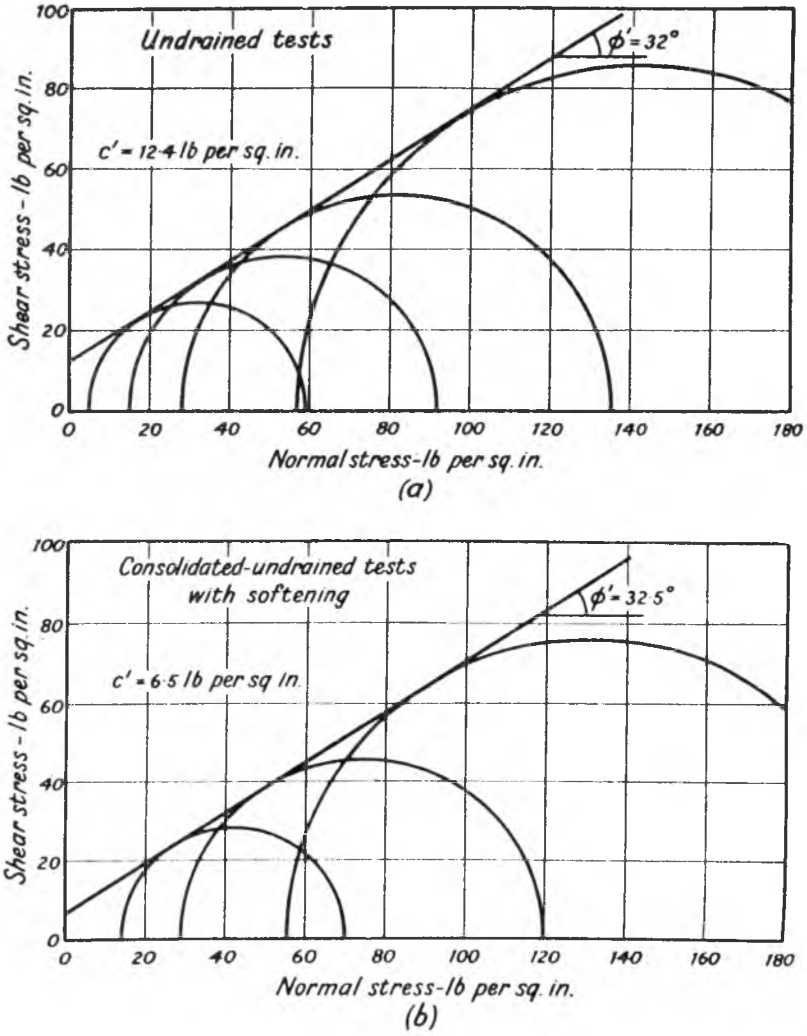

Fig. 12. Comparison between the Mohr envelopes for a compacted clay obtained (a) in undrained tests, and (b) in consolidated-undrained tests in which softening has been permitted. From Bishop and Henkel (1962).

slightly dry of optimum. On the other hand, effective stress parameters change with soaking as shown in Figure 12, viz., Φ' is essentially the same as for the as-compacted condition, while c' is reduced.[3]

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[3] This agrees with experimental evidence that the as-compared c' varies inversely with compaction water content, while Φ' is essentially invariant.

COMPACTION SPECIFICATION

The compaction specification is framed in terms of a procedure to use, an end result to obtain, or a combination of the two. There are great difficulties in writing a specification which can be readily checked, and yet which insures an economic serviceable soil structure.

The formulation of sound economic compaction specifications requires a thorough understanding of the sensitivity of the compacted soil to all the major variables. The effects produced by differences in compaction water content are probably the most important in such formulations.

Many end result specifications omit direct control of compaction water content; they usually require only that a certain unit weight level (percent compaction) be reached. Such a specification can be met over a wide range of water contents by adjusting the kind, rating, and use of common rollers. Thus, the compacted product can have a wide range of behavior, even though the compacted unit weight is the same. In the study illustrated by Figure 13, a number of laboratory samples were (a) compacted to the same unit weight by various levels of kneading effort; (b) soaked at a moderately low confinement; and (c) tested undrained in a triaxial kind of test. Compaction water content is shown to be very important for both measures of strength. The soaked strength at large strains is highest when the soil is compacted at the optimum water content for the effort being used. If the confining pressure were increased, the soaked strength would increase (see the lower half of Figure 12).

To achieve a specified unit weight at low moisture contents requires high efforts, and yet the compacted product may be inferior and more costly than that produced by lesser efforts at different water contents (Figure 13). This is presumedly due to the higher swelling potential imparted to the soil by the high energy-low moisture combination (Figure 10). Accordingly, we have an example of *overcompaction,* i.e., lesser efforts could have yielded a superior product at presumably lesser cost.

Compaction water content is also very important in implementing procedural specifications. Johnson and Sallberg (1960) present numerous examples of the sensitivity of unit weight increases to the rolling water content, i.e., the compaction achieved by a given use of a rated roller is much dependent upon the moisture condition.

There is little reason to doubt that, in the long term, compaction specification will become more restrictive in controlling procedures and end results. This can reduce the current level of uncertainty as

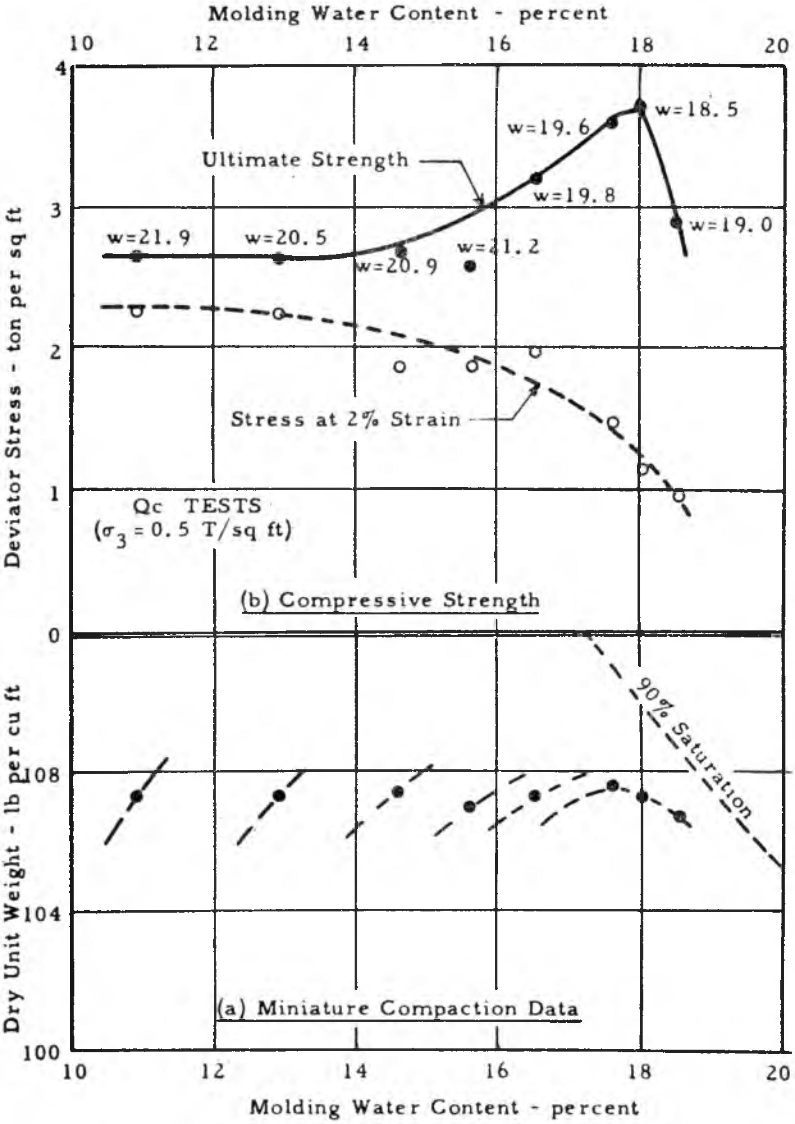

Fig. 13. Compressive strength versus molding water content for compacted silty clay. From Wilson (1952).

to the in-service capabilities of compacted soil structures. However, such changes must be based upon a clear understanding of the interrelations of the pertinent variables. Available experimental laboratory and field data are also required.

Finally, the authors believe that the primary focus in compaction studies should be directed toward the quality of the specification proper rather than the quality of the compliance with the specification. It is their hope that this discussion aptly illustrates the influences which must be considered when a specification is being developed. The elements of the specification are vitally important in producing a high quality compacted soil.

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