Some Factors Influencing Shear Strength and Compressibility of Compacted Soils

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•THE GREAT majority of state highway departments are presently using dry density as the principal criterion for judging the quality of compacted earthwork. This criterion implies that increased dry density produces improved engineering properties in the material. Although the use of dry density for field control can be easily accomplished, particularly with the increasing use of nuclear devices, its value as a usable criterion is only valid insofar as the dry density does, in fact, indicate the engineering properties of the material. The two most important and generally applicable properties that concern the highway designer are the shear strength and the compressibility characteristics of the compacted materials. However, for certain soils and in many geographic areas the shrinkage and swell potential and the frost susceptibility may be of greater concern to the highway designer than the shear strength and compressibility characteristics.

The major purpose of this paper is to present a review of the presently available (1966) literature concerning some of the factors, in addition to the dry density, that affect the engineering behavior of compacted soils. Because of space limitations only shear strength and compressibility will be dealt with; for clarity of presentation, cohesionless and cohesive materials will be discussed separately.

SHEAR STRENGTH OF COHESIONLESS MATERIAL

Major Factors

The shear strength of cohesionless materials is essentially controlled by five factors: (a) mineralogical composition, (b) size and gradation of the individual particles, (c) shape of the individual particles, (d) void ratio or dry density, and (e) confining pressure. Assuming that the shearing resistance can be expressed by the Coulomb failure criterion with zero cohesion, the first four factors mentioned affect the angle of internal friction, whereas the fifth factor controls the normal stress. The first three factors are properties of the material and therefore the choice of material should be based on a consideration of these properties. The confining pressure is prinicipally governed by the amount of overburden that exists above the compacted material. Increased confining pressures for a given cohesionless material will not only produce larger shearing resistance but will affect the stress-strain behavior of the material. The magnitude of the confining pressure also affects the dilation characteristics and consequently affects the shearing resistance. It is, therefore, only the dry density or void ratio that can be significantly changed during the compaction process. The first four factors will be discussed briefly in the following sections.

Size and Gradation Effects

Holtz and Gibbs (1) performed a series of triaxial tests in order to study the effect of the maximum particle size on the shearing resistance of a sand-gravel mixture.

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For a 20 percent gravel and 80 percent sand mixture there appeared to be a slight increase in shear strength when the maximum size was increased from ¾ in. to 3 in. For the same materials with a 50 percent gravel and 50 percent sand mixture there was essentially no difference in shearing resistance as the maximum size was increased.

Kolbuszewski and Frederick (2) performed shear tests using different sizes of glass beads. For the rather limited range of median size of 0.48 mm to 0.86 mm, it was found that with increasing grain size the shearing resistance first decreased and then increased in strength over most of the relative porosity range.

Kirkpatrick (3) performed triaxial shear tests on a sand of very uniform particle size, ranging from 0.3 mm to 2 mm. Microscopic examinations were performed to insure uniformity of shape and mineralogy, and the sand was fractionated into six sizes. The results indicate that for equal relative porosities the angle of internal friction decreases as the mean particle size increases, when no energy correction is applied to the data. If, however, the angle of internal friction is not determined from the peak point on each stress-strain curve but rather at the strain where the sample attains a minimum volume, then the frictional component of the angle of internal friction thus obtained appears to be essentially independent of grain size. These data imply that the effect of grain size is to modify the stress-dilation characteristics rather than the actual frictional resistance of the material. This is consistent with Skempton's (4) hypothesis that the contact stresses that exist in a stressed mass of soil approach the yield strength of the grains. Therefore, the contact stresses should be independent of the grain size and the frictional component of the shearing resistance will be independent of the size of the grains. However, for practical considerations the work required to cause volume change must be considered together with the work required to overcome frictional resistance.

Considering all of these data, it appears that the effect of grain size on the frictional resistance has not been definitely established, although it appears that the effect on the dilation characteristics causes variation in the shearing resistance.

The principal influence of gradation characteristics is the effect it has on the limiting porosity of a given material. A more well-graded material will have a lower minimum porosity and, because shear strength is inversely related to porosity, a more well-graded material will have a larger shear strength for any relative porosity than a more poorly-graded material. The direct effect of gradation can be obtained by replotting Kirkpatrick's data for these sand mixtures in terms of absolute porosity vs angle of internal friction. Although the variation in gradation is not very large it appears that the better-graded material exhibits a slightly lower angle of internal friction than the more poorly-graded material. However, for similar compaction procedures a well-graded material will obtain a smaller porosity than a poorly-graded material and will, therefore, exhibit a larger shearing resistance.

Shape and Surface Texture Effects

The shape of individual particles has long been recognized as a factor influencing the shearing resistance of a granular material. Terzaghi and Peck (5) have indicated that for a granular material with round, uniform grains the angle of internal friction varies from about 28.5 deg with material in a loose state to about 35 deg for the same material in a dense state; the corresponding values for angular, well-graded soils are 34 and 46 deg respectively. The range of these values is so well accepted in practice that the effect of angularity is generally used to estimate approximately the limiting values of the angle of internal friction for a given relative density.

Data by Holtz and Gibbs (1) on an angular quarry material and a river deposit material at the same relative density (70 percent) exhibit angles of internal friction of 40 and 38 deg respectively. Holtz (6) states that a reasonable range of angle of internal friction might be 22 to 45 deg for rounded sandy soils at low and high relative densities and 27 to 52 deg for angular gravelly materials at low and high relative densities. Morris (7) presents some interesting data on a ⅞-in. maximum size crusher-run basalt. An attempt was made to separate shape effect from surface texture effects. These data indicate that merely rounding the particle shape without altering the texture results in an increase in shear strength, and smoothing the surface texture without altering the particle shape results in a reduction in shear strength. Unfortunately, density data are not presented and therefore it is quite possible that modification to the material resulted in density changes that affected the data. In general, however, naturally occuring rounded material will also exhibit a smooth surface texture and angular material will have a rough texture so that it is not usually necessary to consider these factors separately.

Void Ratio or Dry Density Effects

As previously stated, for a given material it is only the void ratio or dry density that can be modified by the compaction process. For a given cohesionless material it appears that the shear strength is directly related to the density but is independent of the compaction process used to obtain this density. Data presented by Means and Parcher (8) indicate that for a particular granular material the angle of internal friction is inversely related to the void ratio. The change in the angle of internal friction with a change in void ratio appears to differ somewhat depending on the soil being tested—varying from 2 deg for silty sands to about 6 deg for uniform gravels for a 0.1 change in void ratio. Zolkov and Wiseman (9) have presented similar data on dune and beach sands that indicate an increase of about 4 deg for a decrease in void ratio of 0.1.

Wu (10) investigated the effect of initial void ratio on the angle of internal friction by using uniform sands with mean diameters of 0.15, 0.44 and 1.00 mm. The angle of internal friction for a given void ratio was different for each material; however, the change in the angle of internal friction increased by about 2 deg for a 0.1 decrease in void ratio. When these same data are plotted in terms of the angle of internal friction vs the compacted relative density, the relationship collapses to a unique association independent of grain size. The angle of internal friction increases about 1 deg for a change of 0.1 in relative density. These data are consistent with the previous data with the exception that the mean grain size appears to affect the angle of internal friction at a given void ratio.

COMPRESSIBILITY OF COHESIONLESS MATERIAL

The compressibility characteristics of compacted cohesionless materials are primarily influenced by the same factors that influence the shear strength, namely, the mineralogical composition, size and gradation of the particles, shape of the particles, void ratio and confining pressure. In general, the compressibility decreases with increasing gradation, decreasing as-compacted void ratio, decreasing angularity, and increasing confining pressure.

The mineralogy of the individual particles contributes to the compressibility characteristics by influencing other properties such as the size, shape, cleavage planes, elasticity, etc., of the particles. Compression tests on sand-mica mixtures performed by Gilboy (11) showed that compressibility increases as the percentage of plate-shaped particles increases. McCarthy and Leonard's (12) investigation on micaceous sands and silts also indicated that the compressibility is significantly affected by the percentage of mica that is present in the material. The presence of plate-like particles, such as mica, produces two effects that influence the compressibility. First, the surface properties of these layer-latticed minerals are probably smoother than the massive-shaped minerals and therefore can be more easily densified. Second, the introduction of these flat particles produces a decrease in the compacted density which also contributes to an increase in compressibility.

Wu (10) has presented data to indicate that decreasing grain-sized material will exhibit increasing compressibility. These data are for samples with mean diameter from 0.51 to 1.00 mm. Using the same method of compaction, the initial void ratio increases with decreasing grain size; however, the initial relative density increases with decreasing grain size. Therefore, at a constant relative density, the increase in compressibility would be even more pronounced than indicated. Burmister (13), working with materials ranging from gravelly sand to silty fine sand, also found that at constant relative density (40 percent) the compressibility increased with increasing fineness of the material.

The influence of relative density on compressibility is similar to the effect of relative density on shear strength; that is, increasing relative densities for a given material will cause decreasing compressibilities. Gardner (14) presented such data on Atlantic City beach sand for a range of initial relative densities from 27 percent to approximately 100 percent and over a stress range from $1/8$ ton/sq ft to 55 ton/sq ft.

Schultze and Menzenbach (15) have presented data on 25 clean dry sands indicating that compressibility increases with increasing initial void ratio. These data also indicate that the compressibility increases for a given initial void ratio as the void ratio between the maximum and minimum states increases. These increasing compressibilities are due to the properties of the material such as grain shape and grain-size distribution.

The grain shape appears to have two effects. First, more angular grain shape decreases the compacted density that can be obtained and second, it decreases the stress required to cause crushing of grains. The crushing of grains causes degradation of the material and nonelastic densification of the materials.

SHEAR STRENGTH OF COHESIVE SOILS

The shearing strength of a compacted cohesive soil is primarily affected by the water content, gradation, dry density, soil structure, thixotropy and the normal effective stress acting on the failure plane. The water content that influences the shear strength is not only controlled by the molding water content, but includes any changes in moisture conditions that occur after placement. The dry density is controlled by the amount of compactive effort expended during compaction, the water content at which compaction takes place, the method used to compact the soil and any density changes that occur after initial compaction. The soil structure[1] is controlled by the method of compaction used and the water content relative to the optimum water content. The thixotropic effects for a given soil depend upon the time allowed for strength changes to occur and the strain level at which strength is defined. The effective stress that acts on an element of soil is produced by external pressure, such as overburden, and internal pressure exerted by the apparent negative pore water pressure. The overburden pressures on subgrades are quite small; therefore, the major contribution to the effective stress would be the internal pressure.

Influence of Effective Stress

The shear strength of compacted cohesive soils can be interpreted in terms of effective or total stresses in the same manner as saturated soils; however, the determination of the effective stress in a compacted soil is complicated because of the three-phase nature of the system. Because of this complication the shear strength of compacted soils is generally investigated in terms of total stress unless the test specimen is soaked prior to testing and pore pressures are measured during shear. Nevertheless, it is the application of an effective stress and not a total stress that causes an increase in shearing resistance of a compacted cohesive soil.

The shear strength of a compacted cohesive soil cannot, in general, be determined from the well-known Terzaghi equation because the pressure in the gas and water phases of the soil may be considerably different. Bishop (17) proposed the following expression for defining the effective stress in an unsaturated soil:

$$\bar{\sigma} = \sigma - X u_w' - u_a (1 - X) \tag{1}$$

[1] Lambe (16) defines soil structures as "the arrangement of particles and the electrical forces acting between them."

where

$\bar{\sigma}$ = effective stress;
σ = total stress;
u_a = pore air pressure;
u_w = pore water pressure; and
X = a factor depending primarily on the degree of saturation, but which may also be influenced by stress history, wetting or drying sequence, and soil types.

The solution to this expression requires a knowledge of X, u_a and u_w. The pore air and pore water pressures can be determined using modifications of the pressure plate procedure (18). The determination of the X-factor requires the testing of duplicate samples of saturated and unsaturated specimens and the assumption that the angle of internal friction remains constant upon saturation.

Assuming the Bishop equation adequately describes the effective stress, it is possible to obtain a qualitative estimate of the change in effective stress along a compaction curve. On the dry side of optimum water content the air permeability is high and therefore the pore air pressures produced by compaction should be rapidly dissipated. At optimum and slightly wet of optimum, although the air permeability is quite small, the X-factor is large and therefore the term u_a (1 - X) should be small compared to u_w X in Eq. 1. Assuming the u_a (1 - X) term can be neglected, Eq. 1 degenerates to

$$\bar{\sigma} = \sigma - Xu_w \qquad (2)$$

For a constant value of total stress, the effective stress becomes a function of the X-factor and u_w. Assuming the X-factor is only related to degree of saturation and the pore water pressure is related to the water content similar to the data presented by Lambe (19), Bishop and Blight (20) and Olson and Langfelder (21), Figure 1 schematically represents the relationship of dry density, X-factor and pore water pressure to the molding water content.

Figure 1 shows that on the dry side of optimum, u_w becomes less negative as molding water content and dry density increase but X continuously increases; therefore the effective stress may either decrease or increase depending on the interaction of these two factors. This implies that increased dry density does not necessarily result in increased effective stress.

On the wet side of optimum, the degree of saturation is essentially constant beyond optimum water content and thus X is essentially constant. However, u_w continues to be increasingly less negative as molding water content increases. This implies that the effective stress must decrease on the wet side of optimum.

To estimate the change in shear strength along a compaction curve requires a knowledge of the change in frictional

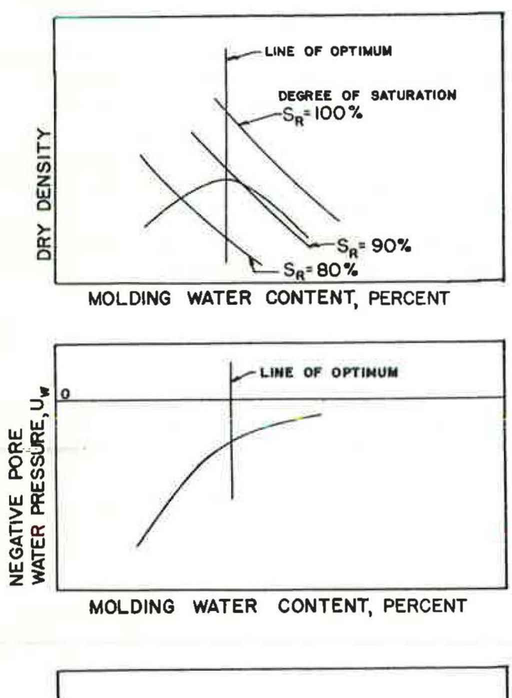

Figure 1. Relationship of dry density, pore water pressure, and X-factor to molding water content.

resistance as well as the change in the normal effective stress on the failure plane. This change in frictional resistance will vary along the compaction curve and therefore it is not possible to establish the change in shearing resistance along the compaction curve from a consideration of effective stress alone.

Effect of Molding Water Content and Soil Structure

Varying the molding water content of a compacted cohesive soil will have an effect upon (a) the initial soil structure, (b) the magnitude of the initial pore water pressure, (c) the dry density of the material, (d) the swelling characteristics, and (e) pore water pressures developed during shear. Each of these factors will, in turn, influence the shear strength of the material.

The initial soil structure of a compacted cohesive soil is governed by the molding water content and the method of compaction. It has been shown (22) that on the dry side of optimum the soil structure will generally be flocculated regardless of the compaction method, but on the wet side of optimum water content the compaction methods producing large shearing strains will produce dispersed soil structures. Increasing degrees of dispersion at water contents wet of optimum are produced by the static method, dynamic method and kneading method respectively. This relationship has been so widely accepted that it is common to associate a dispersed soil structure on the wet side of optimum water content with kneading compaction, and a relatively flocculated soil structure on the wet side of optimum water content with a static type compaction. It appears that a cohesive soil with flocculated soil structure will exhibit a higher as-compacted shear strength than a soil with dispersed structure because of the more rigid nature of the soil skeleton and the reduced pore water pressure developed at low strains.

The influence of induced soil structure on the resulting shearing resistance is also evidence by the behavior of as-compacted soils at different strain levels. At small strain levels the initial soil structure still influences the shearing resistance and therefore the flocculated structure that occurs on the dry side of the optimum water content produces larger shear strength than if the material had a dispersed soil structure. At large strain levels the initial soil structure is essentially destroyed and does not affect the shear strength.

Because the soil structure is an extremely difficult property to measure for clay-sized particles, it is usually the practice to infer the soil structure from other measurable properties. For example, Mitchell, Hooper and Campanella (23) have shown that for essentially the same water content vs dry density curve there is a distinct difference in water permeability on the wet side of optimum water content for different compaction methods. Seed, Mitchell and Chan (22) have presented similar data in terms of shear strength and stress-strain relationships for dynamic, kneading and static-type compaction. The soil structure at low water contents is flocculated because of insufficiency of the water available for formation of the double layer and the absence of interference of the adsorbed water films, and the attraction of the negatively charged surfaces of the clay for the positively charged clay edges and any other cations present. As the water content increases, there is a tendency for greater interference of the water films and if an opportunity for particle rearrangement exists, the soil will tend toward a more dispersed structure. Kneading and dynamic methods of compaction provide this opportunity for particle rearrangement. Therefore, as the molding water content is increased it should be expected that the shear strength should decrease based upon only a change in structure.

As previously noted, an increase in molding water content will produce a less-negative value of pore water pressure which, at least on the wet side of optimum water content, will cause a lower effective stress because of the increased degree of saturation and, hence, the X-factor is essentially constant for increasing water contents on the wet side of optimum. This decrease in effective stress should produce a decrease in shear strength providing the other factors that influence the shear strength are held constant.

The dry density of a compacted cohesive soil is, of course, greatly affected by the molding water content at which the soil is compacted. The dry density is a factor

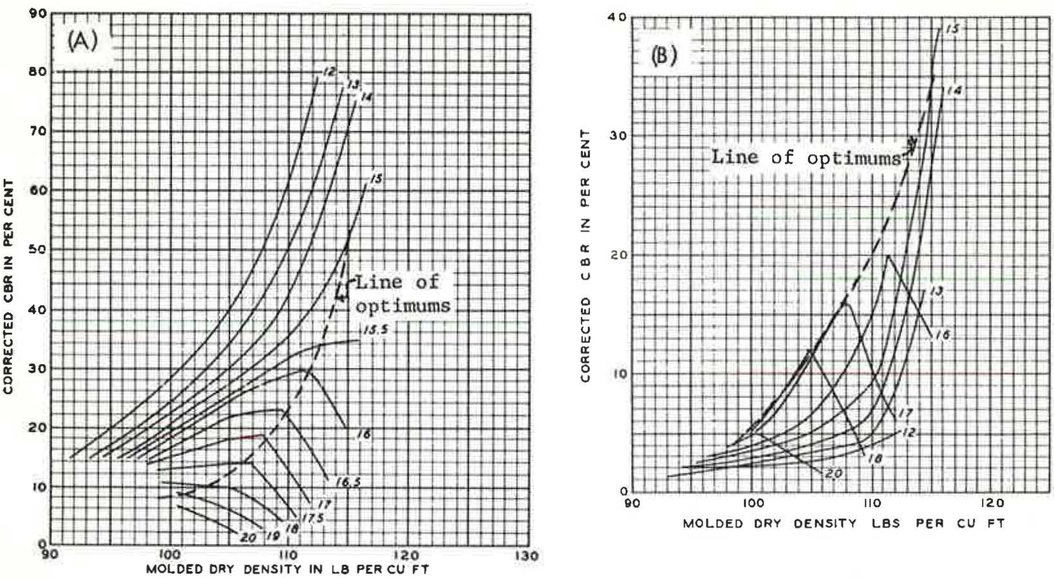

Figure 2. Relationship of molding water content, dry density and strength; (A) unsoaked, (B) soaked (after Turnbull and Foster, 1958).

influencing the shear strength of a cohesive soil, although, as will be shown subsequently, the available data appear to indicate that increasing the dry density will not always produce an increased shearing resistance. Various compaction theories (24, 25, 26, 27) have attempted to define the mechanism by which the molding water tends to affect the dry density that can be obtained by a specific compaction technique. Although these investigators have approached the question from different viewpoints, it is generally agreed that the addition of water to a dry cohesive soil first allows the particles to be more easily packed (up to optimum). After optimum water content is reached, the addition of more water acts to displace soil particles. For soils that exhibit distinct double peaks, Olson (27) suggests that the mechanism producing the first and lower peak may be different from the mechanism producing the upper and most generally recognized peak.

Considering the as-compacted state of a cohesive soil, all the available data indicate that for any constant value of dry density the shear strength will decrease with an increase in molding water content. In fact, CBR data from a series of Waterways Experiment Station publications (28, 29, 30) indicate that for water contents up to approximately 10 percent dry of optimum the strength in almost all cases decreases or remains essentially constant with increasing molding water content, even though the density increases with increasing water content on the dry side of optimum. These data imply that if increased strength is the primary engineering property sought it would be advantageous to compact the soil well dry of the field optimum water content. This would be particularly the case where the natural water content is less than the optimum water content and water must be added.

The available data on the shear strength of compacted cohesive soils that are soaked prior to testing indicate that soils compacted well dry of optimum do not retain high shear strength upon soaking. The soaking of a compacted cohesive soil not only increases the degree of saturation and water content, but may also decrease the dry density of the soil unless a sufficient confining pressure is applied to counteract the possibility of swelling. Seed, Mitchell and Chan (22) have presented data to indicate that for a sandy clay the amount of swelling that takes place because of soaking decreases as the as-compacted water content increases. These data indicate that upon soaking, the final water content is at a minimum and, therefore, the final dry density is at a maximum for a sample that had an initial water content slightly wet of optimum. Data (Fig. 2) presented by Turnbull and Foster (31) for a lean clay indicate that there is a considerable reduction in CBR values, particularly on the dry side of optimum water content after soaking with a surcharge equivalent to the expected overburden pressure. This type of soaking will, in general, allow swelling to occur during the soaking period. The maximum soaked CBR value for any given dry density occurs at approximately optimum water content.

Seed and Chan (32) have presented data on a silty clay (Fig. 3) and an expansive sandy clay both soaked under a low (1 psi) surcharge and tested unconsolidated-undrained in a triaxial apparatus at 1 kg/cm^2 confining pressure. For the silty clay, it appears that the soaked strength is essentially independent of the initial water content for strength defined at large strains, but is dependent on initial water content for strength at low strains. The soaked strength for the expansive sandy clay, for any given density, increases with increasing molding water content at both low and high strains. This difference in the effect of the initial water content on the strength after soaking can be attributed to the swelling potential of the different soils and the strain level at which the strength is defined. Initial flocculated structure that occurs at smaller water contents produces larger swelling potentials than those associated with dispersed structure occurring at high water contents. The effect of the molding water content on the soaked strength of a cohesive soil depends on whether the increased strength at low strains caused by a flocculated soil structure is sufficient to counteract the decrease in strength caused by a greater amount of swell and, therefore, the larger void ratio. For the silty clay, the swelling potential is small and, therefore, there is not a greater tendency for swelling on the dry side of optimum water content than on the wet side of optimum water content. Thus, the influence of the initial soil structure causes the strength at low strains to be larger on the dry side of optimum water content for a given dry density. At large strains, the soaked strength of the silty clay is essentially independent of initial water content because the initial soil structure is destroyed. For the expansive sandy clay, the soaked shear strengths at both small and large strains are dependent on the initial water contents. This is caused by the fact

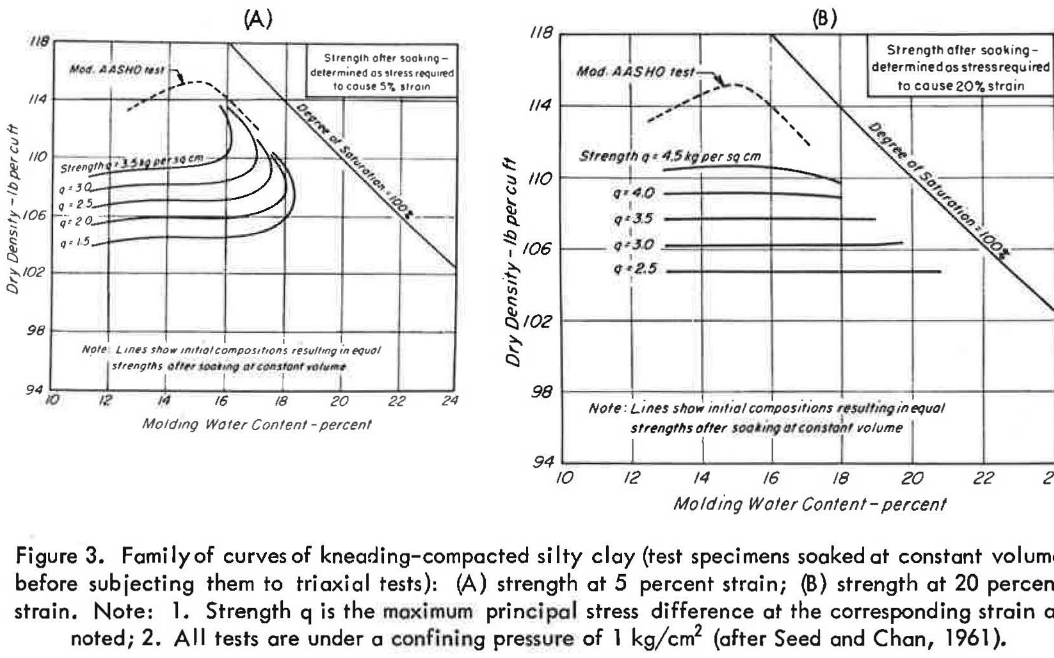

Figure 3. Family of curves of kneading-compacted silty clay (test specimens soaked at constant volume before subjecting them to triaxial tests): (A) strength at 5 percent strain; (B) strength at 20 percent strain. Note: 1. Strength q is the maximum principal stress difference at the corresponding strain as noted; 2. All tests are under a confining pressure of 1 kg/cm^2 (after Seed and Chan, 1961).

that the greater tendency of the flocculated structure to swell counteracts the increased strength associated with a flocculated structure.

If the surcharge during soaking is sufficient to prevent swelling then it appears that the maximum strength at a given dry density occurs at approximately optimum water content. This is consistent with the fact that the shear strength of a compacted cohesive soil at large strains is inversely related to the void ratio.

The development of pore water pressure during the application of a shearing stress will also depend on the molding water content because of its influence on the soil structure. For cohesive soils compacted dry of optimum, the flocculated structure will develop smaller positive pore water pressures at low strains than the small soil compacted wet of optimum. At large strains the initial flocculated structure is destroyed and the pore pressures tend toward the same value. Other factors being equal, this equalization of pore water pressure will cause the soil to exhibit approximately the same shear strength at large strains.

Effect of Dry Density

The changes in shear strength that are produced as a function of changes in dry density alone can be determined by using several different compaction energies and comparing the strengths at a constant value of molding water content. This procedure assumes that there is no effect of possible changes in soil structure as the optimum water content decreases with increasing compaction energy. As previously noted, this assumption should be valid if the strength is measured at large strains; however, if the strength is measured at low strains, the influence of changes in soil structure should not be neglected. In considering the influence of dry density on shear strength it is also necessary to make a distinction between soaked and unsoaked strengths. Finally, it

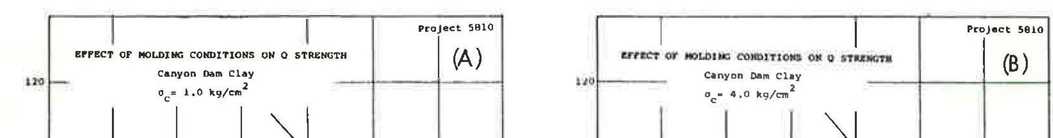

Figure 4. Family of curves for kneading-compacted Canyon Dam Clay (unconsolidated-undrained tests on as-compacted specimens); (A) confining pressure = 1 kg/cm^2; (B) confining pressure = 4 kg/cm^2 (after Casagrande and Hirschfeld, 1962).

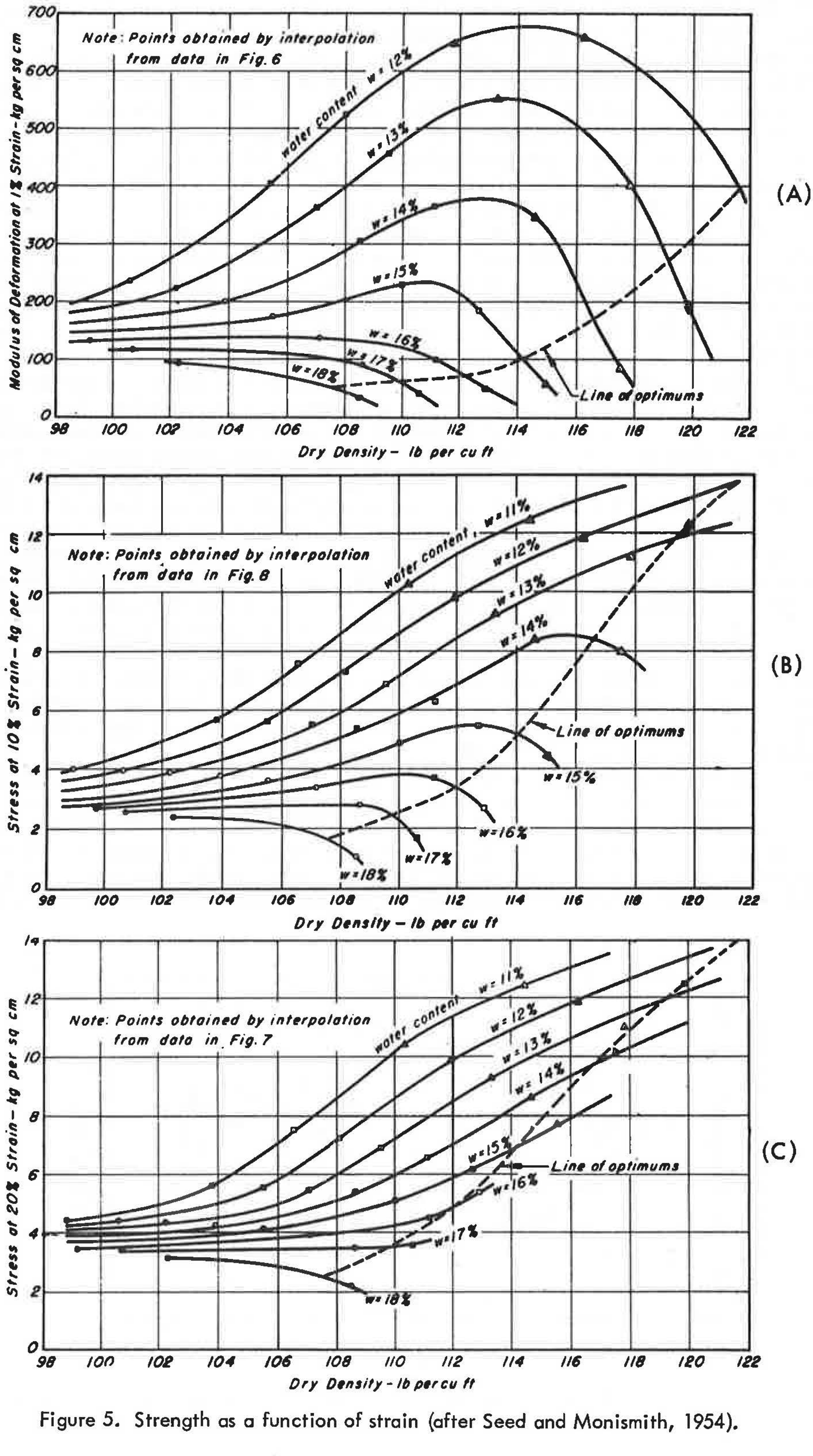

Figure 5. Strength as a function of strain (after Seed and Monismith, 1954).

appears that the method of compaction influences the response of the shear strength to change in dry density at constant molding water content.

Seed and Monismith (34), Seed, Mitchell and Chan (22) and Casagrande and Hirschfeld (35) all have presented data on the relationship between dry density and shear strength at different molding water contents. All these data indicate that an increase in dry density will cause an increase in shear strength for a given water content, provided the shear strength is defined at both large strains (Fig. 3B) and moderate confining pressure (Fig. 4A). In general, the rate of increase in shear strength with an increase in dry density is largest for the lowest value of water content. As the molding water content increases the increase in shear strength is smaller to nonexistent, depending on the soil being investigated. If the stress mobilzed at low strains is plotted against dry density for constant values of water content on soils compacted by different methods of compaction, it can be shown that the relationship between stress and dry density depends on the water content and the method of compaction. For a moderate confining pressure (1 kg/cm^2), statically compacted samples exhibit an increase in shearing resistence with density regardless of the strain level at which the strength is defined. However, for kneading-compacted samples there is a marked change in the relationship between dry density and developed stress as the water content increases. Figure 5 shows data by Seed and Monismith (34) for unconsolidated undrained triaxial tests at 1 kg/cm^2 confining pressure for kneading-compacted Vicksburg silty clay. These data are somewhat typical for kneading-compacted soils and indicate the effect of water content and strain level on the relationship between dry density and developed stress. It can be seen that the decrease in stress for the higher densities with an increase in dry density is most pronounced for the 1 percent strain data and, except for the very wettest water contents, nonexistent for the 20 percent strain data. This is consistent with the conclusions presented earlier, that kneading compaction will produce a flocculated structure on the dry side of optimum water content and a more dispersed structure on the wet side of optimum, and that the flocculated structure is more rigid than the dispersed strucutre. At the lower strain levels the initial structure still influences the strength, whereas at the larger strains the initial flocculated soil structure is essentially destroyed.

It is interesting to note that both field (sheepsfoot or rubber-tire rollers) and laboratory compacted CBR data exhibit relationships between strength and dry density similar to the relationships found at low to medium strain levels for kneading-compacted specimens tested in the triaxial apparatus. Figure 6 shows data reported by Turnbull and Foster (31) for a lean clay compacted by rubber-tired roller and tested using a CBR piston. It can be seen that at approximately the line of optimum for this soil there

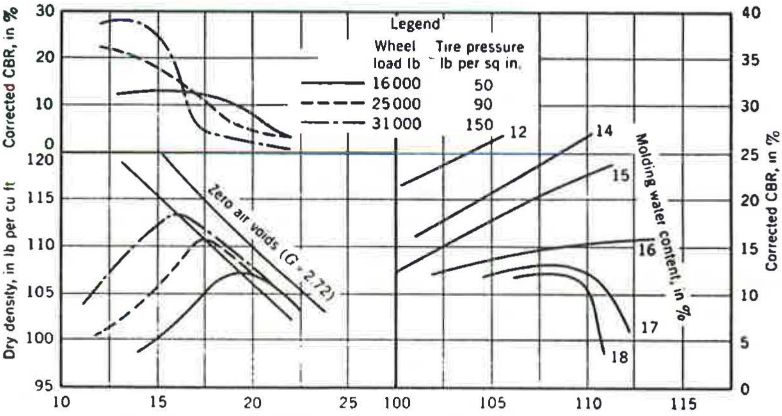

Figure 6. Relationship of CBR, density, and water content for lean clay test fills, 4 coverages, rubber-tired rollers (after Tumbull and Foster, 1958).

is a change from an increase in strength to a decrease in strength for increasing dry densities.

Casagrande and Hirschfeld's (35) unconsolidated undrained strength data on as-compacted clay tested under a large confining pressure indicate that the strength is dependent on initial water content, but is essentially independent of the dry density except at very low degrees of saturation. The difference between these data and the data at moderate confining pressure is that for these tests the confining pressure that was applied was sufficiently large to cause essentially complete saturation of the soil except at the very low degrees of saturation. Therefore, the material essentially behaved as a saturated clay and the shear strength merely depended upon the water content.

The relationship between the shear strength after soaking and the initial dry density depends on the amount of swelling that takes place during the soaking, the compaction method used, and the soil type. Seed and Chan (32) have shown, however, that the soaked strength of a compacted cohesive soil will increase with an increase in initial dry density, regardless of the compaction method, soil type (although the soils investigated were limited), amount of swelling during soaking and strain level. An exception to this conclusion is if strength is defined at low strain and the soil is compacted by a method that produces large shearing strains. For this condition it is possible to obtain a decrease in strength with increasing dry density. The standard laboratory CBR test is performed on a dynamically compacted specimen and the CBR value is obtained at what appears to correspond to a low strain level. Decreases in CBR values for increasing densities at constant water content have been reported extensively in the literature. This same condition also may exist in the field where a subgrade has been compacted by sheepsfoot roller and then soaked during spring thaw, and only small deformations are tolerable before loss of support to the pavement causes a failure.

Thixotropic Considerations

The process of strength changes with time at a constant water content is generally referred to as thixotropy in soil mechanics literature. This property is important when attempting to predict field strengths at some time after compaction from laboratory tests that are generally performed soon after compaction or soaking has been completed.

Mitchell (23) has hypothesized the cause of thixotropy as being the creation of a new equilibrium condition resulting from the cessation of external compaction forces. In order to obtain increases in shear strength with time it is necessary that the final equilibrium condition be conducive to a flocculent structure and the structure immediately after compaction be a relatively dispersed structure. This condition can be produced in certain soils by using kneading compaction methods even up to water contents slightly wet of optimum. In conjunction with this change in soil structure it was found that the initial pore water decreases during aging and also the pore water pressures developed during shearing are smaller for aged samples. It is quite likely, therefore, that there is an increase in strength in terms of total stress but the strength remains constant in terms of effective stress.

In addition to the influence of the molding water content on the amount of strength gain, the strain at which failure is defined also determines the measured amount of strength increase. This is consistent with the previous discussions that indicated that the flocculated soil structure is destroyed at large strains. Therefore, the change in structure, with time, from dispersed to flocculated which produces the larger strengths (either because of a more rigid structure or decreasing pore water pressures, or both) is not effective in producing increased strengths at large strains.

Methods for predicting thixotropic strength gains from index-type tests are not available at the present time. Furthermore, it does not appear to be satisfactory to extrapolate thixotropic behavior of field-compacted soils using laboratory compaction procedure because of possible differences in the soil structure produced by these different compaction methods. However, an awareness of the phenomenon will lead to a better understanding of the behavior of the field-compacted materials that possess this characteristic.

COMPRESSIBILITY CHARACTERISTICS OF COMPACTED COHESIVE MATERIALS

The compressibility characteristics of cohesive materials are significantly influenced by soil type, molding water content, dry density, degree of saturation, and the compaction method. The amount of compressibility for a given range of pressure is influenced by the combined effect of these factors. In general, the compressibility increases with increasing liquid limit, increasing molding water content, decreasing dry density, increasing degree of saturation, and compaction procedures that produce large shearing strains during the compaction process. It is evident, therefore, that the compressibility characteristics of cohesive soils are much more complicated than the compressibility characteristics of cohesionless materials whose behavior is controlled primarily by the relative density and gradation characteristics. Furthermore, the time rate of compression is an important factor in cohesive soils, whereas in cohesionless materials the rate of compression is generally rapid enough to eliminate the consideration of time rate of compression. The influence of these various factors will be discussed in the following sections.

Void Ratio vs Pressure Relationships Between Saturated Undisturbed Cohesive Materials and Compacted Cohesive Materials

The void ratio-pressure relationships of compacted cohesive materials are quite similar to the void ratio vs pressure relationships for undisturbed natural clays providing the sample is not saturated at some intermediate confining pressure. Leonards (36) observed that the compression index decreased for statically compacted clays that were soaked prior to consolidation with a decrease in the as-compacted void ratio. These data do exhibit a rather distinct break in the slope of the void ratio vs logarithm of pressure relationship similar to the change in slope at the preconsolidation pressure observed in undisturbed clays. The pressure at which the change in slope occurred was found to increase with a decrease in the as-compacted void ratio. It may be reasoned that this change in the slope of the void ratio vs logarithm of pressure curve, which is similar to preconsolidation pressure for natural clays, is caused by the built-in soil structure produced by the compaction process. This built-in soil structure is influenced not only by the compaction procedure but also by the ability of the soil to respond to this compaction process. It has been shown previously that the soil structure produced by various compaction procedures is essentially the same for a soil when it is being compacted on the dry side of optimum. However, when the material is being compacted on the wet side of optimum, it has been shown indirectly that the structure would depend on the compaction process. Based on data presented by Seed, Mitchell and Chan (22), it can be seen that the ratio of secant moduli for different compaction procedures varies significantly on the wet side of optimum (Fig. 7). It is, therefore, obvious that the compressibility characteristics for materials that are compacted on the wet side of optimum will be greatly influenced by the compaction procedure used to compact the soil. In general, it appears that the compressibility will increase for a soil compacted by static, vibratory, impact, and kneading compaction methods, in that order. That is, the statically compacted specimens should be less compressible than the specimens that are compacted using kneading methods for the same water content and dry density on the wet side of optimum; however, on the dry side of optimum the compressibility should be approximately the same regardless of the compaction method used.

Yoshimi and Osterberg (37) have presented compressibility data on Vicksburg silty clay prepared by kneading methods. These data also exhibit a distinct break in the slope of the void ratio vs logarithm of pressure relationship similar to saturated undisturbed materials. It is interesting to note from these data that the change in slope that is similar to the preconsolidation pressure occurs at a consolidation stress slightly less than the compaction stress used to prepare the compacted samples. It might be reasoned that the increase in compressibility at values in excess of the compaction pressure is caused by an additional breakdown in the structure of the compacted material once the compaction pressure has been exceeded. Based on this reasoning it may be concluded that if the stresses that will act on a material during its service

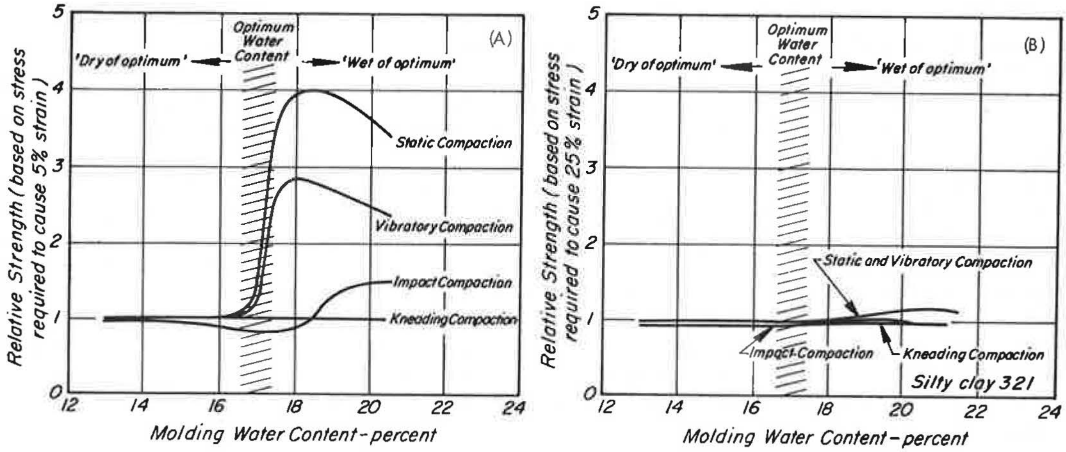

Figure 7. Relative strength at different strain levels for different methods of compaction: (A) performance at 5 percent strain; (B) performance at 25 percent strain (after Seed et al, 1960).

history are lower than the compaction stress, then the compressibility will be minimized; however, if the stresses that will act on the material are in excess of the compaction stress it might be assumed that the compressibility will be much larger.

The reasons for differences in the compressibility characteristics of a material on the wet side and dry side of optimum have been explained by Lambe (26) on the basis of a change in the soil structure that occurs as the material is compacted on the dry side, at optimum, and on the wet side of the compaction curve. These arguments are similar to those proposed by Seed et al based on the secant modulus at low strains. For a fairly small consolidation pressure range it appears that the samples that are compacted wet of optimum will experience a larger change in void ratio than when the material is compacted dry of optimum. However, for a large pressure range it appears that the total change in void ratio or compressibility is essentially independent of the initial conditions. This may be attributed to the fact that at sufficiently large consolidation pressures the soil structure of the material compacted either wet or dry of optimum water content will become highly dispersed and essentially independent of the initial soil structure and, therefore, the overall compressibility will be essentially the same.

Effect of Saturation on Compressibility

The previous section dealt with samples that were tested in the as-compacted state or samples that were saturated prior to testing. In the field, however, the material is generally compacted and then saturation may occur at a later stage when a confining pressure will exist on the material. The effect of saturating the material under various confining pressures was investigated by Jennings and Burland (38). This change in void ratio upon soaking can be quite large and may in fact be of the same order of magnitude of void ratio change that occurs during a large increase in externally applied pressures. For soils that appear to be subject to this collapse phenomenon it appears that increased compaction which produces a decrease in the void ratio will significantly aid in reducing the amount of void ratio decrease that will occur upon saturation of the material. The amount of collapse may also be reduced by increasing the degree of saturation of the material during the compaction process; however, this increase in degree of saturation and/or water content will lead to greater compressibility caused by external pressures.

Correlation of Soil Type With Compressibility

In fully saturated natural soils, it is well known that certain index properties may be used to indicate compressibility characteristics of cohesive materials. For example, the relationship between the liquid limit of a low to medium sensitivity material can be used to estimate the compression index of that material. For compacted cohesive materials, the problem becomes more difficult because not only are the properties of the materials involved but also the effect of the compaction process which is used to compact the soil. Regardless of the compaction procedure, however, certain conclusions can be drawn concerning the relationship between material properties and the compressibility of the material. Investigations by Gould (39) on rolled fill material indicate that the compressibility is significantly influenced by the plasticity of the fines in the soil. It was observed that fine sand and silt with little or no plasticity, when placed dry of optimum, have low compressibility, whereas clays of low to medium plasticity compacted dry of optimum exhibit higher compressibility. It was found that, in general, the compressibility increases in the following order: (a) gravel and sands with silty fines, (b) silts of low plasticity, (c) gravel and sands with slightly plastic fines, (d) sands with clayey fines, (e) mixtures of gravel sands and silts with clay, and (f) clays of low to medium plasticity. Gould concluded that this trend emphasized the importance of the plasticity of the fine fraction on the compressibility compared to gradation or grain size characteristics. Recent laboratory investigations by Matyas (40) provide additional evidence of the fact that compressibility is significantly influenced by the type and amount of fines and also by the molding water content.

It may be concluded that soil type is undoubtedly one of the basic factors influencing the compressibility characteristics of a compacted cohesive material, but additional factors such as the method of compaction, molding water content, and degree of saturation will also have significant effects upon the compressibility characteristics.

CONCLUSIONS

The available data in the literature indicate that dry density alone is not always a reliable index of shear strength and compressibility of compacted materials. Several other factors also play an important part in determining engineering properties of these materials. The following conclusions may be drawn from a review of the literature on shear strength and compressibility of compacted materials.

1. The shearing resistance of compacted cohesionless materials is related to properties of the material and the density obtained by compaction. The most important factors that will produce increasing shearing resistance are increasing angularity of the particles, increasing surface roughness and improved gradation. Improved gradation and possibly increasing amounts of larger-grained material mainly increase the amount of dilation during shear, which leads to increasing shearing resistance.

For a given cohesionless material the shear strength is inversely related to the void ratio or directly related to the dry density obtained by compaction. This relationship is valid regardless of the compaction method used and any strain up to peak strength.

2. The compressibility of a compacted cohesionless material is influenced by the same factors that influence the shear strength. In general, the compressibility decreases with improved gradation and decreasing as-compacted void ratio. Unlike the effect on shear strength, increasing angularity will produce increasing compressibility.

3. Based on effective stress theory, it can be shown that the initial effective stress may either increase or decrease with increasing water content along a compaction curve on the dry side of optimum, but that the effective stress will always decrease with increasing water content along the compaction curve on the wet side of optimum.

4. Cohesive soils are found to have differences in shear strength that are caused by differences in soil structure. A flocculated soil structure is more rigid and produces smaller initial pore water pressures during shear than the same soil with a dispersed soil structure. This leads to increased strengths, particularily at low strains. The soil structure that is produced by compaction is governed by the soil type, the molding water content, and the compaction method.

5. The as-compacted shear strength of a cohesive soil for a constant dry density will always exhibit a decrease in shear strength with an increase in water content. In fact, most data indicate that the as-compacted shear strength will decrease over the entire range of water contents usually investigated, even though there is an increase in dry density with an increase in water content on the dry side of optimum water content.

6. The as-compacted shear strength of a cohesive soil, for a constant water content, will exhibit an increase in shear strength for all water contents with an increase in dry density only when the strength is defined at large strains. At low strain levels the strength may increase or decrease with dry density depending on the water content and the method of compaction.

7. For soaked conditions, the resulting shear strength is determined by the combined effect of swelling during soaking, initial water content, and as-compacted soil structure. For CBR-type tests that allow swelling to take place it appears that the maximum soaked shear strength occurs at approximately the as-compacted optimum water content.

8. The strength of a compacted cohesive soil may change significantly with time after compaction because of thixotropic effects.

9. Compressibility of compacted cohesive materials is influenced by soil type, molding water content, as-compacted dry density, initial degree of saturation and compaction method.

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