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Generalized Hydraulic Behavior of Compacted Clays

by

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Introduction

The important role of compacted clays in geotechnical structures has led several investigations to focus on their hydraulic behavior. Since the original studies conducted by Lambe (1958a, 1958b), Seed and Chan (1959), and Mitchell, et al. (1965), increased use of compacted clay in hydraulic barriers has prompted several recent investigations (Boynton and Daniel, 1985; Day and Daniel, 1985; Mitchell and Madsen, 1987; Benson and Daniel, 1990; and Shackelford and Javed, 1991; among others). The hydraulic behavior of compacted clays, unlike that of sands, is governed by a large number of parameters associated with their preparation. Prominent among them is the molding water content which greatly influences the structure of compacted clays. Based on the current necessity, much of the recent research has focussed on identifying the various factors affecting hydraulic conductivity such as method of compaction, physical and chemical properties of soil and permeant, and evaluating the differences between field and laboratory measured values. The variation of hydraulic conductivity with molding water content and dry density has been emphasized in all these studies. The intricate mechanisms involved in the hydraulic behavior of compacted clays make it difficult to develop a predictive tool on a theoretical basis. The complexity of these mechanisms is best illustrated in Fig. 1 which demonstrates the significant variation of hydraulic conductivity for four clays having approximately equal optimum molding water content and maximum dry density. Very few studies dealt with the problem of predicting the hydraulic conductivities of compacted clay. Earlier studies (Michaels and

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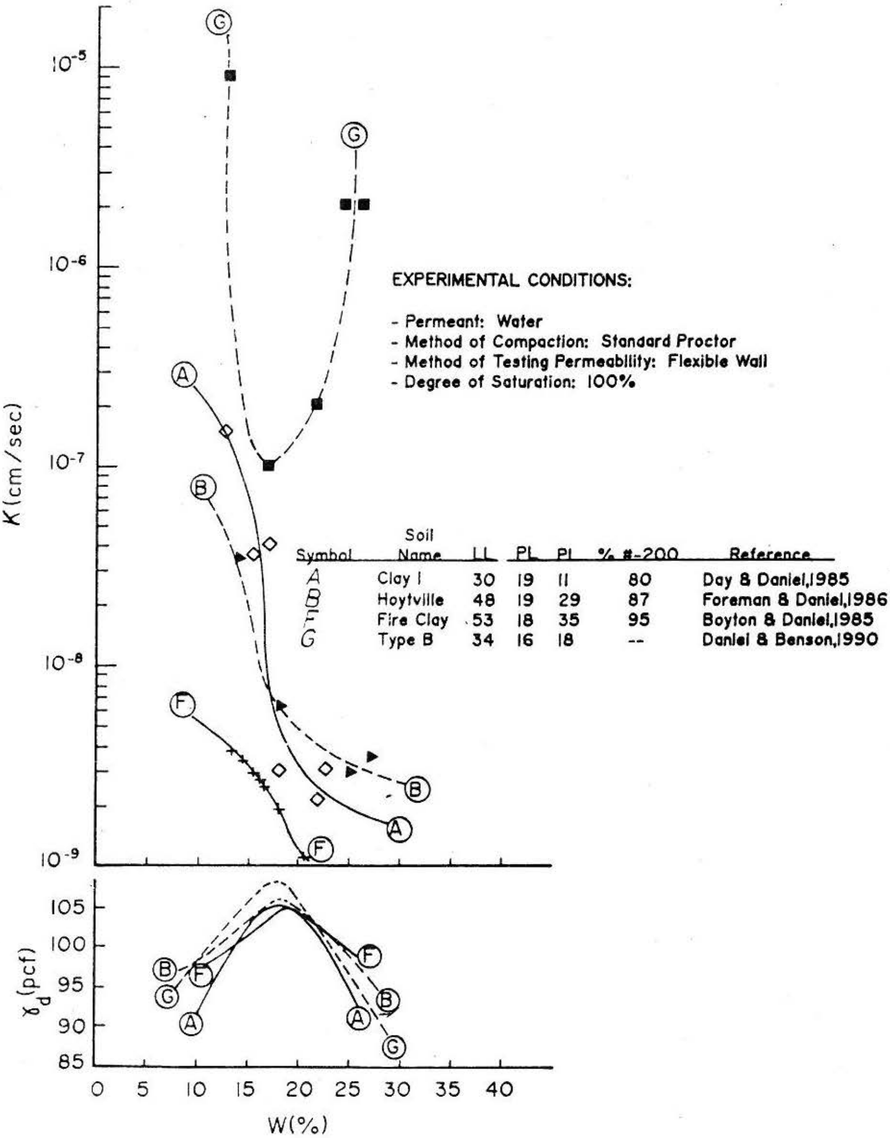

FIGURE 1 Variation of Hydraulic Conductivity with Molding Water Content for Four Clays having Approximately Equal OMC and Maximum Dry Density

Lin, 1954; Lambe, 1954; Olsen, 1962; among others) utilizing Kozeny-Carman equation have met with failure since the microstructure of clays is not considered in the equation. Experiments conducted by the authors (Lee,

1992) also show significant discrepancies between observations and Kozeny-Carman predictions. More recent studies (Kingsley H-W, 1985; Bogardi et al., 1990; for example) adopted regression techniques which are empirical in nature. These regression studies lumped both saturated and unsaturated behavior in one equation without considering their differences from a theoretical standpoint.

The purpose of this study is to draw generalizations in the behavior of compacted clays by decoupling their saturated and unsaturated behavior. Reference states of compacted clays are sought to normalize the saturated hydraulic conductivities. Although there have been numerous studies on hydraulic behavior of compacted clays, experimental data documenting systematic variations of saturated hydraulic conductivities due to various compaction parameters is rather scanty. This is due to the high costs involved in time-consuming testing of compacted clays. In this study, available data from various sources was made use of in developing and illustrating the generalization. The literature is even more limited in documenting the unsaturated characteristics of compacted clays. For porous media in general, Millington and Quirk (1961) pioneered the prediction of unsaturated hydraulic conductivity from their moisture retention functions. The earlier prediction methods for unsaturated hydraulic conductivity were later modified by Campbell (1974) and van Genuchten (1980). For the purpose of this study, the limited data available for compacted clays was used to study the validity of capillary theory over a range of molding water contents.

Saturated Hydraulic Conductivity

The primary reason for failure of Kozeny-Carman equation in predicting hydraulic conductivity of compacted clays is well established to be the dominant role of microstructure of clays which is ignored in the equation. Earlier studies by Lambe (1958) as well as subsequent studies qualitatively document the changes in structure from flocculated to dispersed due to compactive effort and molding water contents. Models attempting to predict hydraulic behavior of clays should therefore incorporate some quantitative parameters representing micro-structure of clays. However, these parameters are difficult to define let alone determine. The approach taken in this study is therefore, to find reference states of clay-water interactions against which the hydraulic conductivity at any other state can be normalized. The reference states have to be such that the microstructure of compacted clays is predictable at those states. The liquid limit state of compacted clays and the line of optimums shown in Fig. 2a, provide such reference states. The area bounded by the two reference states represents the flocculated structure of clays with increasing dispersion towards the line of optimums. Beyond the line of optimums, further increase of dry density with higher compactive effort results in the dispersed structure of clays. Figure 2b shows the

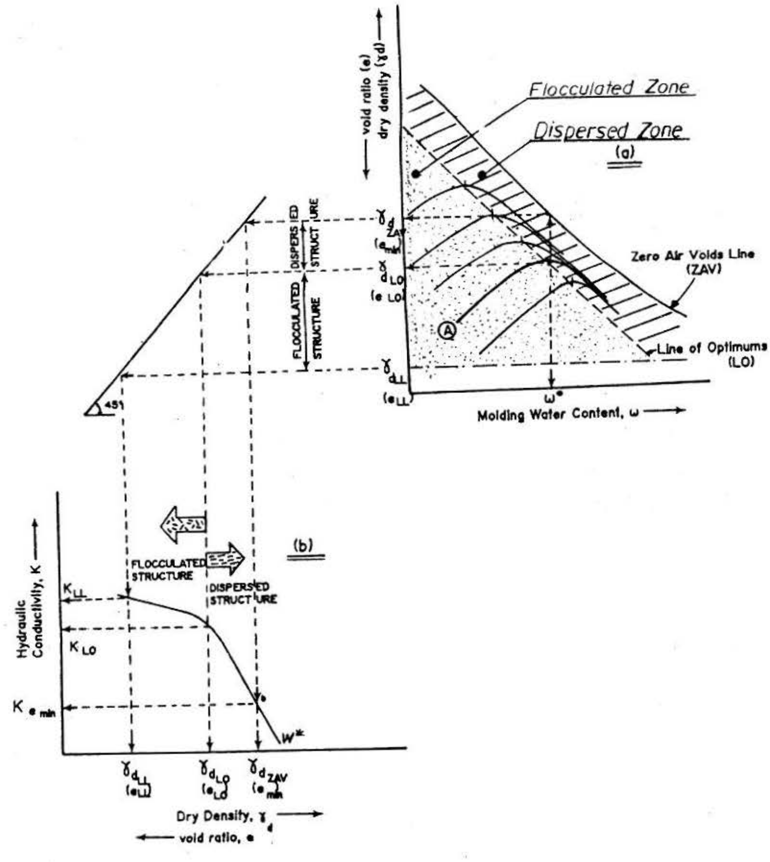

FIGURE 2 Definition of Reference States and Idealization of Hydraulic Behavior

idealized hydraulic behavior of compacted clays for a given molding water content, w*. In all studies to date (Mitchell et al. 1965; Day and Daniel, 1985; for example), the differences in K vs. γ_{dry} relationship are clearly brought out between the two structures of compacted clays. Figure 3 for instance, shows experimental data from one of the studies indicating differences in the slope of K vs. γ_{dry} thus supporting the idealization in Fig. 2b. In the dispersed zone, compactive effort plays more significant role than dry density resulting in a steep decrease in hydraulic conductivity (Fig. 2b and 3). Moreover in practice, it is impossible to approach the zero-air-voids curve irrespective of the compactive effort utilized. Due to these reasons, it was not possible to observe generalizations for hydraulic behavior in the dispersed zone. The present study aims at drawing generalizations in the

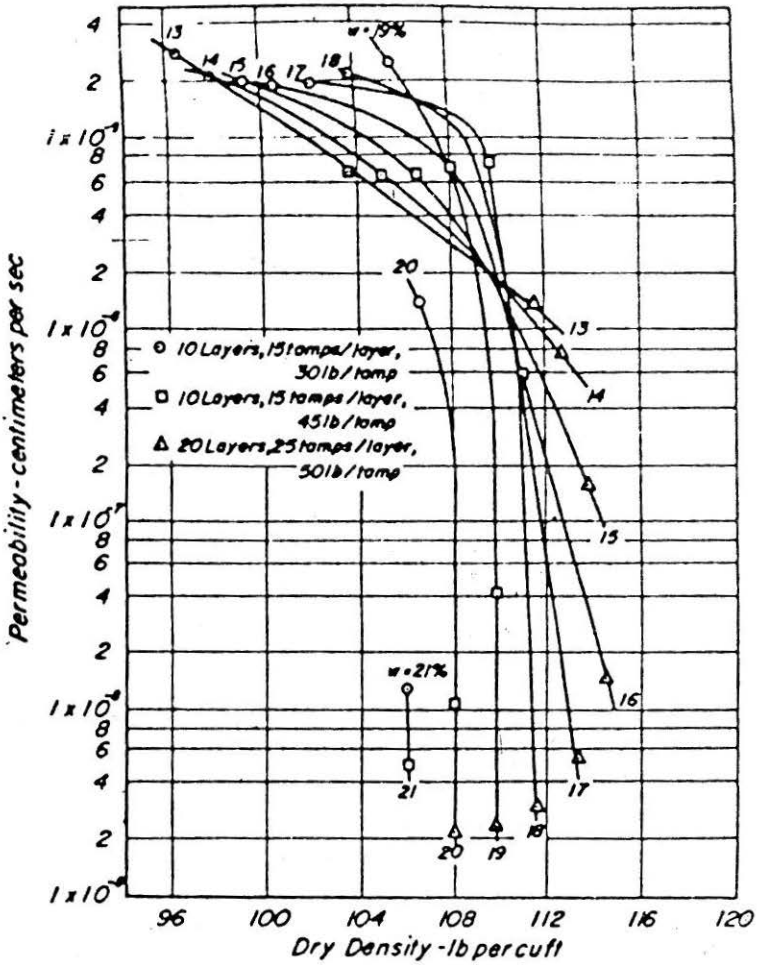

FIGURE 3 Saturated Hydraulic conductivity as a Function of Dry Density at Several Molding Water Contents (Mitchell et al., 1965)

hydraulic behavior for the flocculated zone only. The rationale for choice of the reference states chosen in this study and generalization of hydraulic behavior between these states are described in the following sections.

Liquid Limit

The definition of liquid limit offers a well-defined state of fine-grained soils at which the shearing resistance is of the same order (1.7 to 2.0 kPa)

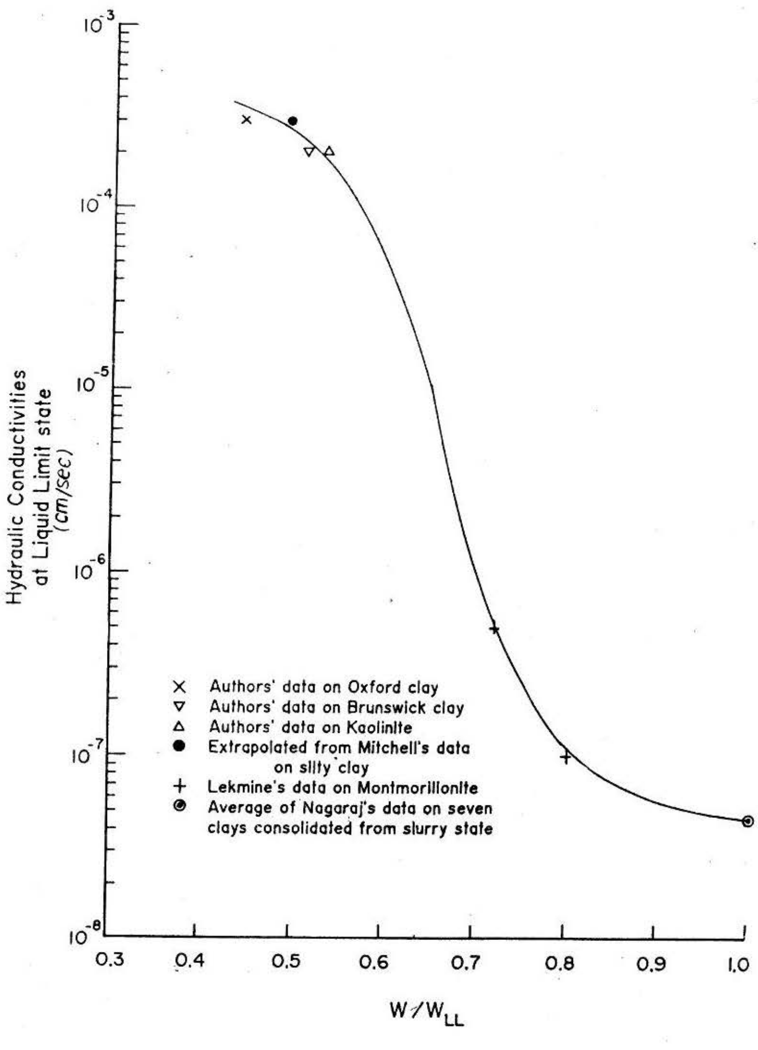

FIGURE 4 Variation of Liquid Limit State Hydraulic Conductivity with Normalized Molding water Content

and the pore water suction is 6 kPa (Wroth and Wood, 1978; Whyte, 1982). Detailed studies of the physico-chemical interactions at particle level at liquid state have recently been made (Nagaraj, et al. 1990a, 1990b). An important result of these investigations is that the hydraulic conductivity at liquid limit void ratios for several clays is nearly the same (4.5×10^{-7} cm/sec), although their liquid limits vary over a very wide range. These clays ranged from bentonite with a liquid limit of 330% to an ovendried marine soil with a liquid limit of 55%. This result implies that the micro- pore distribution irrespective of the particle orientations within clay clusters is of the same pattern.

Nagaraj's results on hydraulic conductivity at liquid limit state were obtained by compressing soils from a slurry state. In the context of compacted clays however, differences should be expected depending upon the molding water content of compacted clay from which liquid limit state is realized. For molding water contents wet of optimum, the microstructure at liquid limit state is likely to be similar to that of slurry consolidated state. Therefore, it can be assumed that for compacted soils at liquid limit state realized from liquid limit molding water contents, the hydraulic conductivities are of the same order as Nagaraj's results. For initial states dry of optimum which have a flocculated structure enclosing relatively large pores, the liquid limit hydraulic conductivites are expected to be higher than 4.5×10^{-7} cm/sec.

Available data from literature was used to evaluate the variability of liquid limit hydraulic conductivities with molding water contents. Figure 4 shows the variation of liquid limit state hydraulic conductivities available for various compacted clays against molding water contents normalized by their respective liquid limits (w_L). While Lekmine's (1991) and the author's data directly correspond to liquid limit void ratios, data from Mitchell et al. (1965) were extrapolated from Fig. 3. Although the data is limited, the variation is in accordance with the intuition that increased flocculation corresponding to low w/w_L yields high values of hydraulic conductivity at liquid limit. The liquid limit void ratio corresponds to an upper limit for hydraulic conductivities in the flocculated domain and will be taken as a reference state for each soil examined in this study. Whether the relationship shown in Fig. 4 is universal can only be judged with more experimental data.

Line of Optimums

The line of optimums is the locus of optimum dry densities corresponding to all molding water contents (Fig. 2a). This line is considered to represent the transition from flocculated to dispersed structure. However as discussed in the next section, this is only an approximate transition since the changes in structure of compacted clays are always gradual. The steep decrease of hydraulic conductivity as a result of the change in structure in the neighborhood of line of optimums corresponding to a given molding water content is illustrated in Fig. 5 which summarizes a number of investigations. In Fig. 5, only those molding water contents for which optimum dry densities were experimentally identified are chosen. All curves

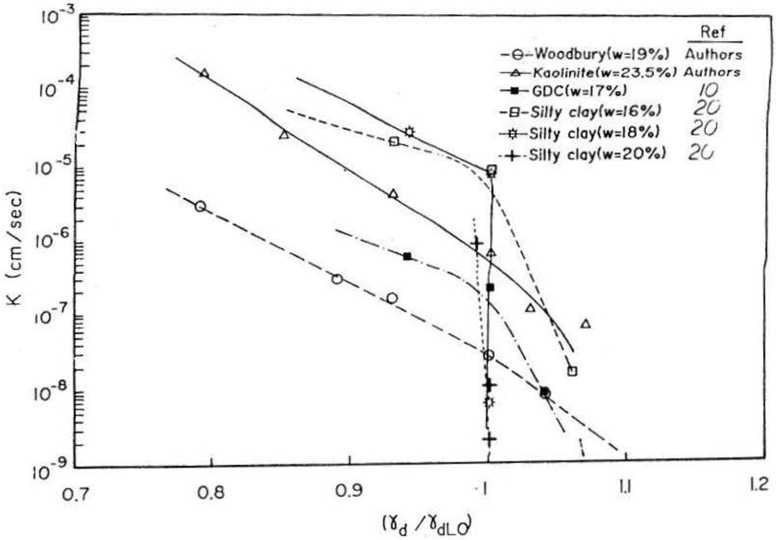

FIGURE 5 Hydraulic Conductivity as a Function of Dry Density in the Neighborhood of Line of Optimums

shown in Fig. 5 support that transition in the slope of K vs. γ_{dry} occurs at or within 10% of optimum dry density. Based on these results, it is assumed that the line of optimums serves as a good approximation for the upper bound of flocculated domain. In other words, the line of optimums is assumed to correspond to the lowest hydraulic conductivities in the flocculated domain.

Generalized Behavior

The dry densities corresponding to the two reference states described in the previous sections denote the range within which the structure of the clays is expected to be flocculated. The range decreases as the molding water content increases. In other words, molding water content governs the rate at which the structure of clay changes from liquid limit state to the line of optimums. To compare the rate at which the hydraulic conductivity changes between the two states, the experimental data from Mitchell et al. (1965) was normalized between the two states as shown in Fig. 6. Figure 6 shows the data for all the molding water contents for which data in the flocculated domain is available from Fig. 3. The dry densities in Fig. 3 were transformed to their respective void ratios. As can be seen in Fig. 6, the

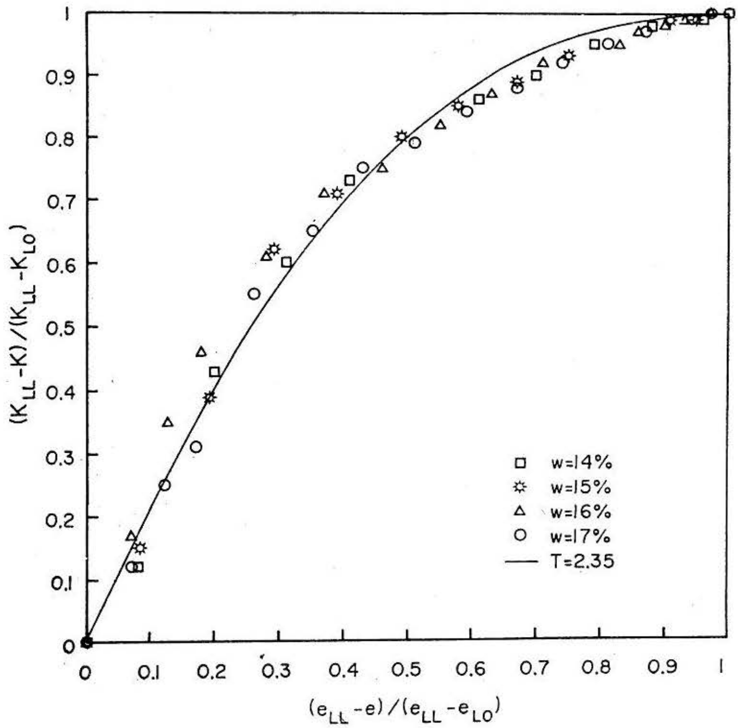

FIGURE 6 Variation of Hydraulic Conductivity with Void Ratio when Normalized between Reference States for Various Molding Water Contents (Data from Mitchell et al., 1965)

relationship between normalized K and normalized e is nearly the same for all molding water contents although Fig. 3 shows considerable variation in K vs. γ_{dry} relationships. This shows that the relative changes in hydraulic conductivity are same for all molding water contents for a given proportion of void ratio change in the flocculated region. In other words, the variation of K with e when normalized between the two reference states is independent of molding water contents. The variation is mathematically modeled using an empirical equation in the form

$$K^* = 1 - (1 - e^*)^T \qquad (1)$$

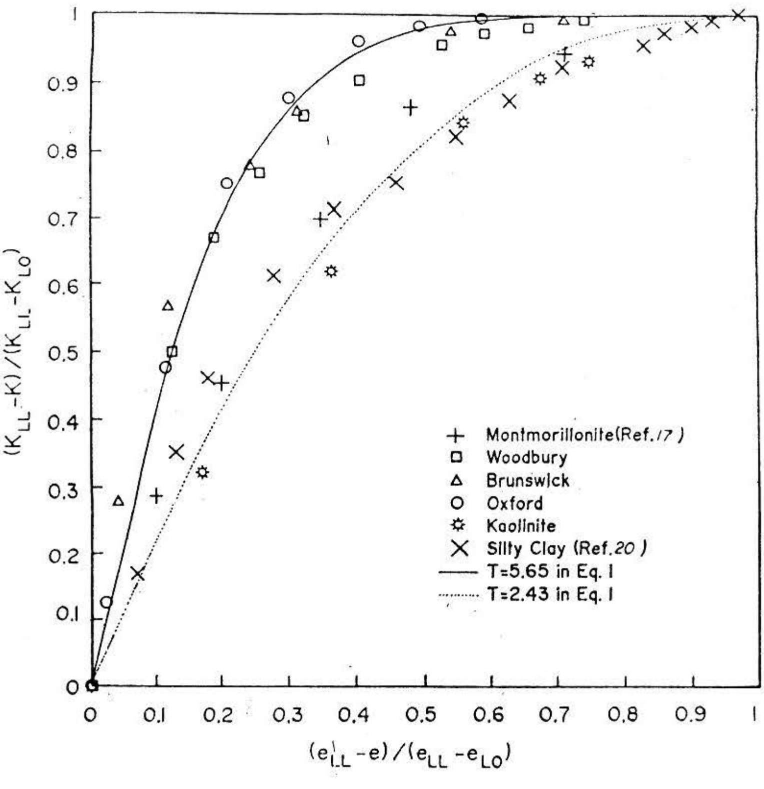

FIGURE 7 Variation of Hydraulic Conductivity with Void Ratio when Normalized between Reference States for Various Clays

where

$$K^* = (K_{LL} - K)/(K_{LL} - K_{LO})$$

$$e^* = (e_{LL} - e)/(e_{LL} - e_{LO})$$

K_{LL}, K_{LO} and e_{LL}, e_{LO} are hydraulic conductivites and void ratios corresponding to liquid limit state (LL) and line of optimums (LO), respectively, and T is an empirical constant. Equation 1 when fit to the data in Fig. 6 yielded a value of 2.35 for T.

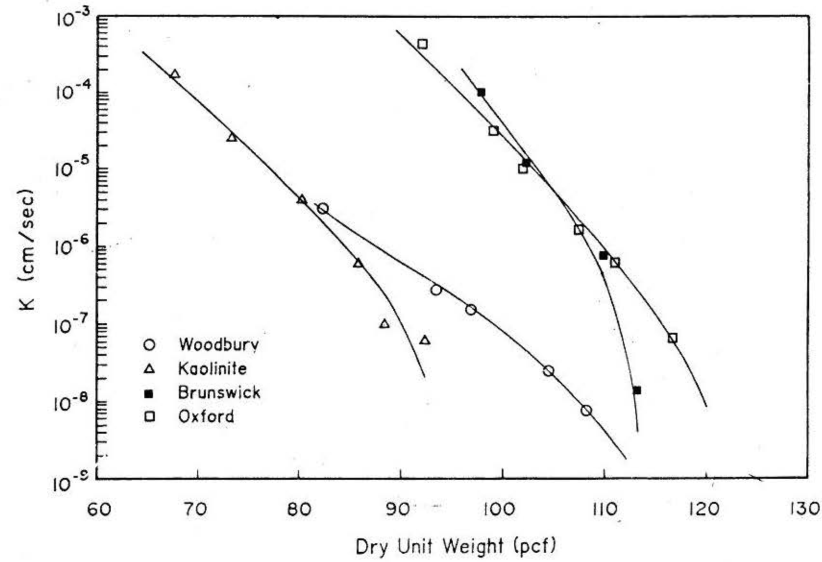

FIGURE 8 K vs. γ_{dry} Relationships for the Author's Soils at their Respective Optimum Molding Water Contents

To study this generality further, data from investigations on other soils was normalized between the two reference states. Figure 7 shows data from three different investigations normalized between their respective reference states. These investigations encompass a variety of soil minerals ranging from kaolinite to montmorillonite. The woodbury soil in the authors studies contains 36 percent of illite, 17 percent of montmorillonite, 9 to 15 percent of kaolinite and 17 percent of quartz. The brunswick soil is a reddish silty clay composed of 50 to 75 percent quartz and 15 percent of feldspars. The predominant clay mineral is illite with chlorite as a subordinate mineral. Both the authors's data and data from Mitchell et al. (1965) were obtained from similar testing procedures while the data from Lekmine (1991) was indirectly obtained from consolidation tests. The effect of normalizing can be seen by comparing Fig. 7 with Fig. 8 which shows individual K vs. γ_{dry} relationships for the authors's soils. The generalized relationships for the author's soils are nearly the same except for kaolinite. The value of T for all the author's soils except kaolinite was found to be 5.65 and the range of T encompassing all the soils studied was 2.43 to 5.65.

The differences among various soils exhibited in Fig. 7 can be understood based on a consideration of the behavior of individual minerals.

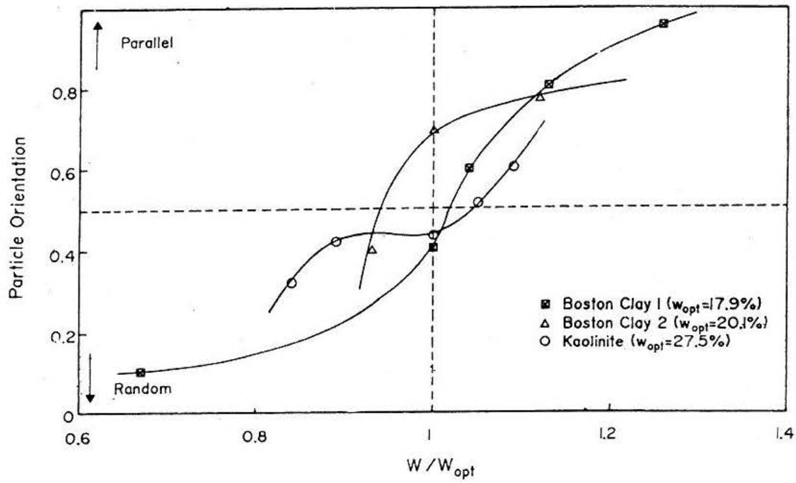

FIGURE 9 Change of Particle Orientation in the Neighborhood of Optimum Molding Water Content (plotted data of Seed and Chan 1959)

The line of optimums which was used as the second reference state only approximately denotes the onset of dispersed structure since the change of structure from flocculated to dispersed is always gradual in any soil. This was well illustrated as early as in 1959 by Seed and Chan who studies the particle orientation as a function of molding water content. Figure 9, which is a summary of these studies, shows that the parallel orientation (dispersed structure) does not always begin dominating at optimum water content. The onset of dispersed structure may well begin dominating at optimum water content. The onset of dispersed structure may well begin either dry or wet of optimum. This is expected to be controlled by the predominant mineral in the soils. Hence, in general, it is opined that differences in the onset of dispersed structure at the line of optimum along with differences in the testing method are responsible for the discrepancies in Fig. 7.

Unsaturated Hydraulic Conductivity

For a given set of void ratio and molding water content, degree of saturation creates an additional parameter of variability for compacted clays. In the flocculated region considered in the previous sections, the moisture retention characteristics of compacted clays can be modeled by capillary theory. Application of Kozeny-Carman equation to model unsaturated hydraulic conductivity (K_u) lead Mitchel et al. (1965) to conclude that K increases with cube of degree of saturation (S_r):

$$K_u = KS_r^3 \tag{2}$$

Theoretical considerations of water retention in soils have also been well researched in the area of soil physics. Campbell (1974) and van Genuchten (1980) provide two commonly-used expressions for the unsaturated hydraulic conductivity (K_u):

$$K_u = KS_r^{2b+3} \tag{3}$$

$$K_u = KS_e^{0.5}\left[1-\left(1-S_e^{1/m}\right)^m\right]^2 \tag{4}$$

where S_e is the effective saturation given by $(\theta - \theta_r) / (\theta_s - \theta_r)$, θ is the volumetric water content, θ_r and θ_s are the residual and saturated water contents, and b and m are empirical constants defining the shape of moisture-characteristic relationship.

It is to be noted that Eq. 3 and 4 are partly empirical since they assume different functions to relate suction pressures and moisture contents and partly theoretical since they consider pore size distributions within the soil. Unsaturated hydraulic conductivity studies on compacted clays are usually confined to relatively high degrees of saturation. To test the capillary theories expressed by Eq. 2 to 4, data from Ref. 20 for silty clay was again used (Fig. 10). Figure 11 shows the agreement between measurements and predictions using the three models. In obtaining the predictions, only those data from Fig. 10 for samples tested immediately after compaction were used. The range of 'b' in Campbell's relationship is taken to be 5.95-14.85 as suggested by Clapp and Hornberger (1978) for silty clays. Volumetric moisture content at retention (θ_r) in van Genuchten's relationship (0.25) and in m value (0.643) are chosen for typical clay materials used by Kool and Parker (1987). Figure 11 shows good agreement between observations and van Genuchten's predictions. The relatively poor predictions by Eqs. 2 and 3 should be expected since these relationships implicitly assume a power curve to represent moisture suction relationship which was shown to be inaccurate at higher degrees of saturation (Clapp and Hornberger, 1978). Also in several recent studies (Kool and Parker, 1987; Alessi et al. 1992; for example), Eq. 4 has proved to be reasonably accurate for a wide range of soils.

An important result displayed in Fig. 11 is that the capillary theory

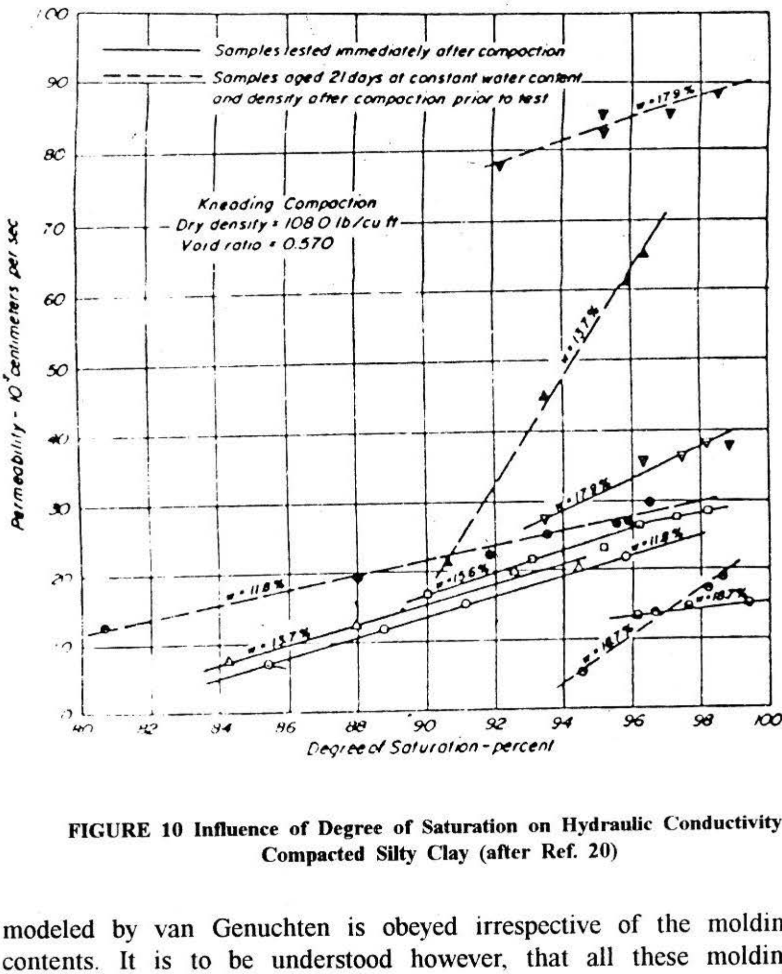

FIGURE 10 Influence of Degree of Saturation on Hydraulic Conductivity of Compacted Silty Clay (after Ref. 20)

modeled by van Genuchten is obeyed irrespective of the molding water contents. It is to be understood however, that all these molding water contents are dry of optimum for silty clay. For the one molding water content wet of optimum (w = 18.7%), the observations showed considerable deviation from the others (Fig. 10 and 11). Although the data for wet of optimum is limited, it should be expected in general, that water retention characteristics wet of optimum may not be governed by capillary theory but by double diffuse layer theory. This is because of the parallel particle orientation which violates the idealization of uniform porous tubes in capillary theory.

Summary and Conclusions

In this study, the hydraulic behavior of compacted clays has been

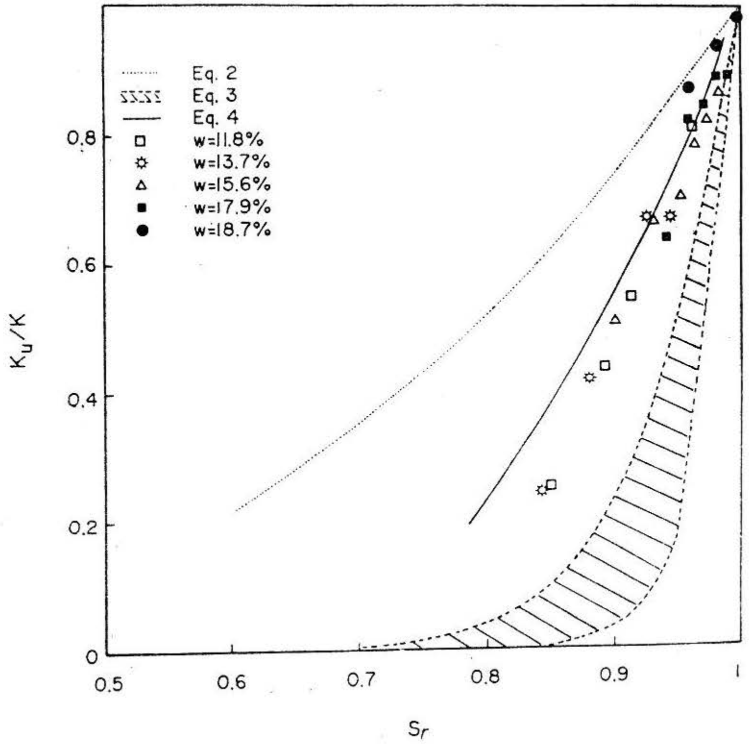

FIGURE 11 Comparison of Predictions and Observations on Unsaturated Hydraulic Conductivity of Slity Clay for Different Molding Water Contents (Data from Mitchell et al., 1965)

analyzed with the help of experimental data from several investigations. It has been possible to observe some generalization in both saturated and unsaturated behavior. These generalizations have been found in the flocculated zone of compaction bounded by the liquid limit state and the line of optimums. Saturated hydraulic conductivities when normalized between the two bounds exhibited a unique relationship with normalized void ratios. This relationship was found to be valid for all molding water contents for a given clay. The limited data available in literature on unsaturated hydraulic conductivities of compacted clays showed better agreement with van Genuchten's model than with models developed by Campbell and Mitchell et al. Capillary theory was found to be valid for compacted clays irrespective of molding water contents within the flocculated region.

The generalizations developed in the present study for saturated behavior of compacted clays should not be mistaken to be predictive models. They only emphasize the importance of microstructure of clays so that future investigations are oriented towards developing and incorporating structure-related parameters in their predictive efforts. It must be realized that the extension of these generalizations to serve as predictive models depends on how well the conditions at the two reference states can be identified for a given clay. Whether the relationship shown in Fig. 4 between the liquid limit hydraulic conductivity and normalized water content is relatively constant for a variety of clays merits detailed examination. Although the generalization is not affected by this constancy, existence of such a universal relationship would aid in predictive efforts. Considerable progress has been made in the recent years on qualitative understanding of micromechanistic behavior of clays; however, little is known on quantifying the structural changes during compaction. The generalized approach presented in this paper will be of great utility as a predictive model if these structural changes are quantified to identify a specific point of transition from flocculated to dispersed zone. This may involve a modification of the second reference state to reflect a true onset of dispersed structure (such as the dry density corresponding to 50% or greater parallel orientation of particles). Such a modification needs extensive testing for fabric structure in the neighborhood of line of optimums for a range of minerals and their mixtures. Whether the generalized relationship between the normalized K and e between the two reference states can serve as a universal predictive tool can only be judged from these tests. Finally, it should be borne in mind that development and success of any predictive model depend on experimental data for good quality. While there have been several experimental studies on the dispersed zone of compaction (in clay liner studies), data showing systematic influence of various parameters involved in flocculated behavior of compacted clays is still scarce. Future investigations may fill this need to further check the consistency of any generalized model such as the one developed in this study.

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Notation

b = empirical constant in Campbell's model;

e = void ratio;

e^* = normalized void ratio

K = saturated hydraulic conductivity;

K_u = unsaturated hydraulic conductivity;

K^* = normalized saturated hydraulic conductivity;

m = empirical constant in van Genuchten's model;

S_e = effective saturation;

S_r = degree of saturation;

T = empirical constant in generalized model;

w = molding water content;

w_{LL} = water content at liquid limit;

γ_{dry} = dry density;

θ = volumetric water content;

θ_r = volumetric water content at retention (residual water content);

θ_s = volumetric water content at saturation (porosity).