

Swelling Characteristics of Compacted B-Horizon Oklahoma Soils

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One of the critical field problems of compacted clay soils used as subgrades for pavement structures is related to the deformation and swelling that result from water absorption. This paper describes the swelling characteristics of five composite B-horizon soils belonging to the Renfrow series that are encountered throughout north-central Oklahoma. Unlike the C-horizon soils in this area, the soils reported on here are sufficiently weathered and not well cemented. This was verified by the fact that neither the clay-size portion nor the plasticity index of these soils increased substantially after ultrasonic degradation. Laboratory specimens compacted to maximum dry density at optimum moisture content were tested by using the constant-volume and free-swell methods. The volume increased with the logarithm of the time; the initial phases showed higher rates of moisture uptake than did the final stages. This and the other relationships among swelling pressures, volume changes, moisture uptake, and physicochemical properties were generally characterized by a band pattern that implied the existence of upper and lower limits of swelling response. In addition, the reaction potential, which serves as a good predictor of volume changes and swelling pressures for C-horizon soils, did not have the accuracy expected. Scanning electron microscopy data indicated that swelling pressure and volume increase in direct proportion to the void cross-sectional area.

The structural damage that results from the swelling of clay soils has been documented over the years by numerous authors (1). Studies have shown that the magnitudes of swell and swelling pressure are dependent on many factors and that they are different for undisturbed and compacted soils. For compacted clays of the type reported on in this paper, examples have been given by Means and coworkers (2, 3). Poor pavement performance manifested by heaving, cracking, and lateral expansion has been reported by Haliburton (4).

To thoroughly understand swelling (volume-change) and swelling-pressure phenomena in compacted clay soils it is essential to study compaction and the structure of clay minerals, the physicochemical aspects of soil behavior, current theories of swelling, and the mechanical (or physical) factors that affect the phenomena. The expansiveness of compacted clay is a well-documented topic (5-12), but the current literature (13-16) suggests that there have been no major changes in theory development or procedures for the investigation and testing of expansive clays in the past decade.

In this investigation, the swelling potential of B-horizon soils was measured by the use of swelling pressure and percentage swell and correlated with the unconfined compressive strength, adsorbed cations, and void cross-sectional area (as determined by scanning electron microscopy).

EXPERIMENTAL PROCEDURE

Soil Characteristics

The five B-horizon soils used in this investigation were obtained from north-central Oklahoma. They are residual soils developed in place from the underlying clay shale of Permian deposition. Their engineering properties, which were determined by standard American Association of State Highway Officials (AASHTO) methods, and their physicochemical properties are given in Table 1. That these soils are well weathered was verified by

ultrasonic treatment [which has been successfully applied to Oklahoma shales (17)]. As shown in Table 2, the differences between the raw and the treated soils are inconsequential.

Mineralogically, the soils are predominantly illitic, as shown by their X-ray diffraction patterns, being composed of a mixture of illite (I), kaolinite (K), and mixed-layer illite-montmorillonite (ML). The relative proportions of the clay minerals were estimated by using an area-under-the-curve method. The concept of the "reaction potential" (17, 18) was then used to calculate a composite parameter (see Table 3) that can be considered indicative of the clay expansiveness.

1. The reaction potential for each individual mineral was calculated by multiplying its average cation exchange capacity (CEC) (16, p. 189) by the percentage of it present in the soils.

2. The composite reaction potential was calculated by multiplying the sum of the individual reaction potentials by the percentage of clay (<0.002 mm) in the soil and dividing by 100.

Swell and Swelling Pressures

A laboratory testing program was carried out to determine the volume change (percentage swell) and the swelling pressure at maximum dry density and optimum moisture content conditions. The swelling pressure was determined by the constant-volume (1, 14) and free-swell methods (14, 19). The data are given in Table 4, and the volume change is shown in Figure 1.

DISCUSSION OF RESULTS

The relationship between volume change on absorption of moisture and time (Figure 1) follows an S-curve pattern that appears to reach a constant value after about 7 days (or 10 000 min). The initial low volume change is believed to be due to the time lag between the absorption of moisture and the accompanying swelling. As shown in Figure 2, the free-swell method gave a slightly higher swelling pressure than did the constant-volume method. It is of interest that the pattern of the scatter of data points suggests that the relationship between moisture absorption and swelling pressure is direct but falls within a narrow fan-type range.

Similarly, when the CEC (or the amount of exchangeable sodium ions) is plotted against the swelling pressure, a fan-type or band pattern is observed (see Figure 3). Conversely, there is a straight-line relationship between swelling pressure and activity index (see Figure 4), as shown by Seed and others (12). Although the formulation of the reaction potential is based on earlier experiences with C-horizon soils in Oklahoma (18), Figure 4 indicates that, for B-horizon soils, the reaction potential is inversely proportional to swelling pressure. An explanation of this inconsistency may lie in the fact that the C-horizon soils were predominantly montmorillonitic while the B-horizon soils studied

Table 1. Properties of B-horizon soils.

Property	Soil 1	Soil 2	Soil 3	Soil 4	Soil 5
Physical^{a,b}					
Location (county)	Oklahoma	Kingfisher	Blaine	Kay	Pawnee
Soil series	Renfrow	Renfrow	Renfrow	Renfrow	Renfrow
Depth (cm)	25-91	25-127	30.5-117	15-152	30.5-178
Liquid limit (%)	51	56	52	60	51
Plastic limit (%)	18	18	18	19	17
Shrinkage limit (%)	8	9	10	11	10
Plasticity index (%)	33	38	34	41	34
Textural composition (%)					
Sand (2 - 0.074 mm)	2	2	4	16	11
Silt (0.074-0.002 mm)	47	46	46	40	48
Clay (<0.002 mm)	51	52	50	44	41
(<0.001 mm)	47	47	46	40	38
Specific gravity	2.75	2.73	2.72	2.72	2.71
Activity index	0.65	0.72	0.73	0.93	0.83
Free swell (%)	65	50	60	60	50
Dry density (kg/m ³) ^c	1630.8	1632.2	1601.8	1600.2	1750.8
Optimum moisture (%)	21.9	21.5	20.0	23.0	19.3
AASHTO soil classification	A-7-6(36)	A-7-6(41)	A-7-6(35)	A-7-6(36)	A-7-6(31)
Unified soil classification	CH	CH	CH	CH	CH
Physicochemical					
pH	9	8.6	8.7	8.9	8.5
Carbonates (as CaCO ₃) (%)	0.620	0.432	1.124	2.330	0.796
Cation exchange capacity (meq/100 g)	26.36	20.54	31.04	28.97	25.39
Exchangeable cations (meq/100 g)					
Calcium	18.71	14.97	27.94	18.96	16.74
Magnesium	4.11	3.29	4.52	4.52	2.88
Potassium	0.25	0.13	0.25	0.25	0.13
Sodium	1.74	1.30	1.96	1.74	1.55

Note: 1 cm = 0.39 in; 1 kg/m³ = 0.062 lb/ft³.

^aDetermined by AASHTO 1974 test procedures and specifications.

^bResults (except for specific gravity, activity, dry density, and optimum moisture content) reported to nearest whole number.

^cStandard Proctor density [AASHTO T 99(A)] with soil-water mix seasoned approximately four hours.

Table 2. Index properties of raw and ultrasonically treated soils.

Soil	Type of Clay Mineral (Percentage)			Total Reaction Potential (meq/100 g)				Clay (<0.002 mm)	
	I	K	ML	I	K	ML	Sum	Percent-age	Reaction Potential (meq/100 g)
1	16.6	2.4	81.0	4.1	0.2	56.7	61.0	51	31.1
2	21.8	5.2	73.0	5.4	0.5	51.1	57.0	52	29.6
3	15.4	7.6	77.0	3.8	0.8	53.9	58.5	50	29.2
4	12.8	5.1	82.1	3.2	0.5	57.5	61.2	44	26.9
5	6.4	6.5	87.1	1.6	0.6	61.0	63.2	41	25.9

Table 3. Clay mineral composition and reaction potential.

Soil	Clay (<0.002 mm) (%)		Liquid Limit (%)		Plasticity Index (%)	
	Raw	Treated	Raw	Treated	Raw	Treated
1	44	51	51	58	33	37
2	52	44	56	60	38	34
3	50	53	52	54	34	30
4	44	41	60	56	41	37
5	41	37	51	48	34	32

Note: 1 mm = 0.039 in.

contain only traces of mixed-layer illite-montmorillonite. Consequently, it will be erroneous to apply the conclusions formulated for the C-horizon soils to the B-horizon soils.

Moisture absorption by soil implies, to some degree, moisture accommodation within the soil mass. Therefore, the void-domain characteristics of the soil may be important in determining the amount of moisture absorbed and the accompanying swelling or swelling pressure experienced. This question was studied in the following way: Electron microscopy was used to measure the void space per unit surface area (see Figure 5), and the unconfined compressive strength of samples molded at optimum moisture and near maximum dry density [Harvard miniature compaction at a diameter of 33.2 mm (1.31 in) and a height of 71.5 mm

(2.81 in)] was determined. As shown in Figure 6, the strength increased as the void cross-sectional area decreased, and swelling pressure increased as the void area increased. Admittedly, measurements on five soils may raise questions of statistical validity and, therefore, any quantified relationships inferred may be premature. The significance, however, lies in the trend established; namely, scanning electron microscopy can be used as a time-saving predictive tool to determine the swelling of these or similar soils.

CONCLUSIONS

For the five B-horizon Oklahoma soils studied, the following conclusions can be drawn:

1. Swelling pressures increase directly with moisture absorption, but the relationship has a fan-type scatter of points.
2. Swelling pressure is directly related to activity index.
3. The reaction potential, which is a good predictive tool for C-horizon soils, does not appear to apply in the case of B-horizon soils.
4. The void cross-sectional area, which can be determined by scanning electron microscopy, shows great potential as a predictive tool for determining swelling pressures; the higher the area, the higher the swelling pressure.

Table 4. Volume changes and swelling pressures of soils at maximum dry density and optimum moisture content conditions.

Soil	Compaction Characteristics		Determination of Volume Change				Determination of Swelling Pressure			
	Optimum Moisture Content (%)	Maximum Dry Density (kg/m^3)	Moisture Content (%)		Water Intake (%)	Volume Change (%)	Constant-Volume Method		Free-Swell Method	
			Initial	Final			Initial Moisture (%)	Swelling Pressure (kPa)	Initial Moisture (%)	Swelling Pressure (kPa)
1	21.9	1630.8	22.1	22.4	2.3	1.94	21.9	67.37	22.9	89.24
2	21.5	1632.2	20.7	24.9	4.2	2.13	22.1	72.17	20.7	128.46
3	20.0	1601.8	20.7	26.8	6.1	3.18	20.3	77.27	20.7	125.52
4	23.0	1600.2	22.1	27.1	5.0	4.21	22.0	111.50	22.1	143.17
5	19.3	1750.8	18.8	21.1	2.3	3.95	19.0	95.81	18.8	171.61

Notes: $1 \text{ kg/m}^3 = 0.062 \text{ lb/ft}^3$; $1 \text{ kPa} = 0.145 \text{ lbf/in}^2$.

Figure 1. Relationship between volume change and time.

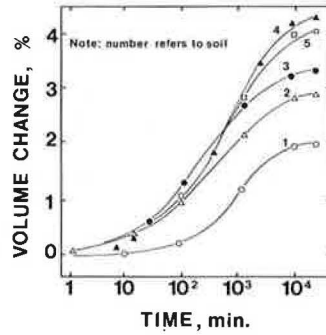


Figure 4. Effect of clay characteristics on swelling pressure.

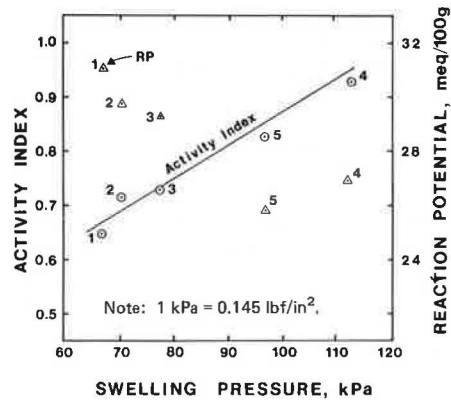


Figure 2. Relationship between moisture uptake and swelling pressure.

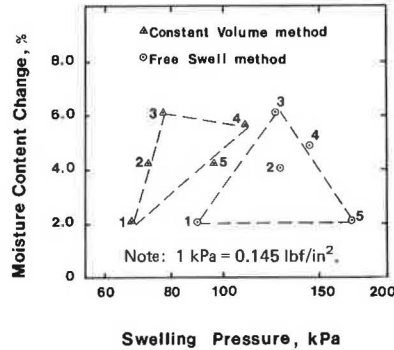
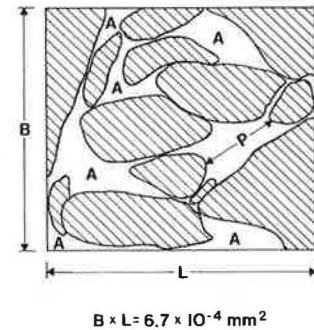


Figure 5. Schematic representation of void cross-sectional area in soil system.



$$\text{Void Cross-sectional Area, } V, \% = \left(\frac{\sum A}{B \times L} \right) \times 100$$

P = Longest Pore Intercept, mm.

Note: $1 \text{ mm} = 0.039 \text{ in.}$

Figure 3. Effect of cations on swelling pressure.

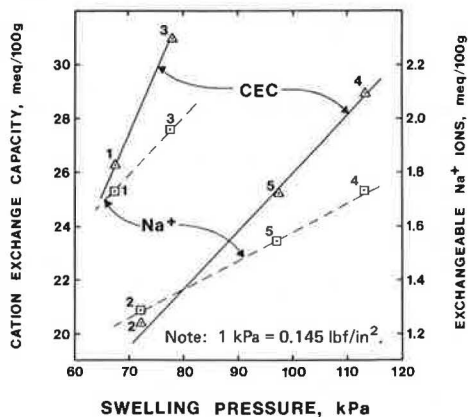
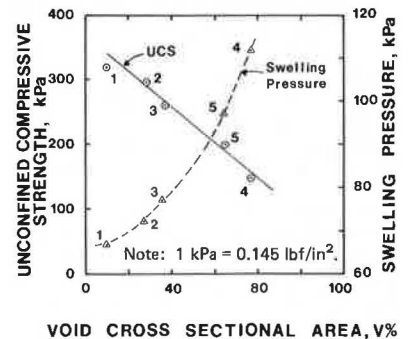


Figure 6. Effect of void cross-sectional area on unconfined compressive strength and swelling pressure.



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Soil Aggregates and Their Influence on Soil Compaction and Swelling

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Prediction of the characteristics and properties of compacted fine-grained soils is much aided by a physical soil mechanism or model. This model should, as nearly as possible, fit the observed soil conditions during and after compaction. This paper describes an extension to existing soil compaction models and uses it to explain the behavior of kaolinite compacted in the laboratory by static pressures under conditions of no lateral strain. The experimental investigation included an examination of the kaolinite aggregations at the compaction moisture content but before compaction. This was followed by the determination of the relationship between the net energy input during compaction and the compacted unit weight. Finally, constant-volume swelling-pressure measurements were made on selected compacted samples. The swelling pressures were monitored continuously after giving the samples access to water; the results are presented as swelling pressure versus time relationships. The experimental results confirm the appropriateness of a deformable-aggregate soil model to explain the compaction of kaolinite as prepared in the laboratory and then compacted statically. The model is also appropriate for understanding the constant-volume swelling-pressure pattern that develops on wetting the compacted soil.

was to develop a model and a mechanism that can adequately explain the achievement of compacted unit weight for kaolinite statically compacted in the laboratory. Such an explanation should be complete enough to explain the condition of the soil before compaction, the interactions within the soil mass during compaction, and the observed behavior of the compacted soil.

The model hypothesized was one in which the soil is made up of macroscopic aggregations of clay particles. During compaction, it is the interactions of these aggregates, their deformation characteristics, and their ability to fit together in a compact mass that determine the end result unit weight for a given type of compaction and amount of effort. It is this same compacted macrostructure—an assemblage of aggregates—that, to some extent, determines the engineering behavior of the compacted soil.

The experimental approach was to study certain of the properties of the soil aggregates before compaction, monitor the compaction effort, and then subject the

The objective of the research described in this paper