Influence of Clod-Size and Structure on Wetting-Induced Volume Change of Compacted Soil

Amy B. Cerato[1]; Gerald A. Miller[2]; and Jumanah A. Hajjat[3]

Abstract: Volume changes due to wetting may occur in naturally deposited soils as well as earthen construction (e.g., compacted fills or embankments). Depending on the stress level, some soils exhibit increase in volume upon wetting (swell) while others may exhibit decrease in volume upon wetting (collapse). The work described in this paper focused on wetting-induced volume changes in compacted soils. Motivation for this work stemmed from observations of earthen structures that exhibit problematic behavior under wetting conditions, even though soils were compacted to engineering specifications (i.e., at or above minimum density and within moisture content ranges). Not only is this problematic behavior a concern but also the laboratory tests used to predict settlement of constructed facilities may not properly model the actual behavior of soil compacted under field conditions. For example, settlements experienced by compacted fills may be different from settlement predictions based on one-dimensional oedometer tests. These differences are partly related to the variations in the soil structure in tested specimens that arise because soil clods compacted in the laboratory are smaller than soil clods compacted in the field. The term "soil structure" includes the combined effects of soil fabric and interparticle forces. "Fabric" generally refers to the geometric arrangement of particles, whereas interparticle forces include physical and physicochemical interactions between particles. The soil structure in this case is associated with specimen preparation methods and is influenced by several factors including soil composition (including pore water chemistry), compaction method, clod sizes, initial moisture condition of clods, dry density or void ratio, and compaction moisture content. A laboratory research study was conducted to investigate the influence of variations in clod-size and structure on one-dimensional volume change, with emphasis on wetting-induced volume change, for nine different fine-grained soils. The results of the study suggest that the influence of structure in one-dimensional oedometer tests depends on soil type and nature of the clods in the compacted soil. Clayey soils appear to be influenced more by differences in structure, whereas silts or clayey sands of low plasticity ($PI < 10$) do not appear to suffer as much from structure effects in one-dimensional oedometer tests. This is attributed to more extensive clod development in clayey soils. Furthermore, the moisture condition of clods appears to have an important influence on volume change behavior.

DOI: 10.1061/(ASCE)GT.1943-5606.0000146

CE Database subject headings: Volume change; Soil structure; Soil compaction; Soil water.

Introduction

Volume changes due to soil wetting may occur in naturally deposited soils as well as engineered soils (e.g., compacted fills, embankments). Depending on stress level, some soils exhibit increase in volume (swell) upon wetting while other soils exhibit a decrease in volume (collapse) upon wetting. Most compacted clayey soils will experience swelling under low confining stress and collapse under higher confining stresses; the degree of which depends on soil type and state. In general, all soils are susceptible to wetting-induced collapse when inundated with water under sufficient confining pressure. Precipitation, capillary water from foundation soils, and flooding may cause changes in the moisture content of soils leading to collapse (e.g., Lim and Miller 2004). Several factors influence the amount of collapse potential: initial moisture content, initial dry density, soil type, and confining pressure (e.g., Booth 1975; Lawton et al. 1989; Basma and Tuncer 1992; Noorany and Houston 1995; Lim and Miller 2004). Generally, the factors influencing collapse potential in the field are taken into consideration when 1D oedometer tests are performed in the laboratory to predict settlement behavior of a soil. However, to achieve relevant settlement information from 1D oedometer tests, it is important to test the actual specimens from the field. This creates a dilemma in that compacted soils are generally evaluated in the laboratory prior to field construction. Thus, the engineering behavior of compacted fills in the field can be different from the engineering behavior predicted by laboratory tests due to differences in soil structure. These differences arise mainly due to differences in clod sizes, initial moisture conditions, and difference in compaction methods. Therefore, soil structure is an additional factor that should be considered in 1D oedometer based predictions of compacted soils constructed in the field.

Soil structure has been shown to influence the behavior of compacted soils (e.g., Barden et al.1969; Barden and Sides 1970; Booth 1975; DiBernardo and Lovell 1980; Benson and Daniel 1990; Lawton et al. 1992). Consequently, evaluation of the soil

---

[1] Assistant Professor, Univ. of Oklahoma, 202 W. Boyd St., Room 334, Norman, OK 73019 (corresponding author). E-mail: acerato@ou.edu

[2] Professor, Univ. of Oklahoma, 202 W. Boyd St., Room 334, Norman, OK 73019. E-mail: gamiller@ou.edu

[3] Formerly Graduate Research Assistant, Univ. of Oklahoma, 202 W. Boyd St., Room 334, Norman, OK 73019. E-mail: jumanah.hajjat@ou.edu.

Note. This manuscript was submitted on February 9, 2008; approved on May 11, 2009; published online on October 15, 2009. Discussion period open until April 1, 2010; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Geotechnical and Geoenvironmental Engineering***, Vol. 135, No. 11, November 1, 2009. ©ASCE, ISSN 1090-0241/2009/11-1620–1628/$25.00.

structure and its changes as a result of loading is important in the field and the laboratory to truly understand the behavior of the soil. The term “soil structure” includes the combined effects of soil fabric and interparticle forces. “Fabric” generally refers to the geometric arrangement of particles, whereas interparticle forces include physical and physicochemical interactions between particles. The soil structure, in this case, is associated with specimen preparation methods and is influenced by several factors including soil composition (including pore water chemistry), compaction method, clod-size distribution at compaction, dry density or void ratio, and compaction moisture content.

Of particular importance, and a strong motivation for research described in this paper, is the fact that clod sizes compacted in the lab can be significantly different from the clod sizes compacted in the field. Clod sizes less than 4.75 mm (No. 4 sieve) or 2 mm (No. 10 sieve) are typically used to perform one-dimensional (1D) oedometer tests, whereas in the field, the clods may be 76 mm or larger.

Research described herein was focused primarily on the influence of soil structure on 1D behavior observed during oedometer tests for several natural soils from Oklahoma. The primary objective of this research was to examine the influence of clod size, and to some extent, sample preparation method on collapse potential, swelling index, and other engineering properties derived from oedometer curves. Understanding these influences and how they can potentially impact predictions of fill behavior is important to appreciate long term performance of earthen structures. Furthermore, this knowledge may impact the approach to design and quality control for important earthen structures.

Background

Observations of soil volume change in the field may be different from predictions provided by 1D oedometer tests, even when the initial moisture content, initial dry density, soil type, and confining pressure are kept the same (e.g., Miller and Cleomene 2007). Therefore, the soil behavior under loading should be studied with consideration given to differences in soil structure between laboratory and field-compacted specimens. It was found previously that the soil fabric strongly affects the collapsibility of soils (Rizallah and Keese 1989). However, some soils such as fine cohesionless silty sand (ML) may not be as susceptible to fabric induced variations in collapse behavior (e.g., Miller and Cleomene 2007).

Based on the compaction moisture content, there are two general modes of soil fabric. When the soil is compacted at a moisture content lower than the optimum value, the soil fabric is aggregated; consequently, the soil exhibits more of a clod structure. On the other hand, when the soil is compacted at a moisture content higher than the optimum value, the soil fabric tends to be homogeneous and exhibits little to no clods (e.g., Benson and Daniel 1990). Since soil is often compacted in the field in a dry of optimum moisture condition (OMC), and since this condition yields the largest clods, the current paper focuses on the dry of optimum conditions. The soil clods compacted in the laboratory are often smaller than the soil clods compacted in the field. So, an important question arises: is it acceptable to predict volume change of compacted fills from standard 1D oedometer tests?

Prior to the current study, Cleomene (2005) conducted research at the University of Oklahoma to examine differences in the 1D volume change behavior of laboratory versus field-compacted soil. Four soils from Okla. were used; three lean clays (CLs) and one ML. Two compaction procedures were used to prepare standard oedometer samples in the laboratory: (1) air-dried soil passing a No. 4 sieve was mixed with water, compacted in a standard Proctor mold, and then trimmed directly into a 60-mm oedometer ring and (2) air-dried soil passing a No. 10 sieve was mixed with water and then compacted (tamped) directly into a 60-mm oedometer ring. For comparison, soil was collected from field sites just prior to field compaction, sealed in 0.018-m^3 buckets, brought to the laboratory, and compacted using a simulated field compaction method into a large 560-mm diameter oedometer ring. Additional large samples were prepared from which smaller oedometer samples were trimmed. Details of the simulated field compaction and testing can be found in Cleomene (2005) and Miller and Cleomene (2007). A limited number of samples from soil trimmed directly into the large rings in the field were also tested. The purpose of the study was twofold; first to examine the influence of sample size and second to investigate the influence of soil structure on the resulting 1D behavior.

In general, the results of the study by Cleomene and Miller indicated that for the relatively fine-grained soils tested, the size of the oedometer sample did not cause differences in the 1D behavior. However, the sample preparation methods, including significant differences in maximum clod size, did seem to affect the behavior in some cases, even though the samples had nominally similar dry density and moisture content. This was particularly true for the clayey soils, whereas the fine sandy soil behavior was much less affected. The study showed that the differences in the soil structure created during field and laboratory compaction could result in differences in the oedometer test results but since only four soil types were tested, the results were somewhat inconclusive. Thus, the current study was developed to provide additional information on the influence of soil structure for a wider range of soil types. Furthermore, the current study involved standard sized oedometer specimens to avoid the practical difficulties with large oedometer specimens and because the study by Cleomene (2005) suggested that specimen size was not an issue for fine-grained soils.

Methods of Investigation

Nine natural soils collected from Oklahoma were used in this work, including seven clays (five CL, two CH), one ML, and one clayey sand (SC). After ensuring field samples were properly processed to maximize soil homogeneity, all test soils were subjected to classification and physical property tests according to ASTM standards (ASTM 2005): Atterberg limits (ASTM D4318-00), grain size distribution (ASTM D422-00), specific surface area (Cerato and Lutenegger 2002), carbonate content (Dreimanis 1962), cation exchange capacity (Rhoades 1982), and standard Proctor compaction (ASTM D698-00) tests. Properties of the test soils are listed in Table 1.

To create oedometer samples with potentially different structure, two different methods of sample preparation were used in this study: (1) soil samples compacted directly into 63.5-mm diameter oedometer rings with a nominal maximum clod size (prior to mixing with water) of 2 mm and (2) samples trimmed from soil compacted in a 101.6-mm diameter compaction mold with a nominal maximum clod size of 38 mm. The latter, while not the same as field-compacted soil, is more representative of larger clod sizes associated with field compaction. It was expected that if differences were observed in the behavior of soil prepared using these two methods then even greater differences may be possible between the lab and field tests, where clod sizes can be consider-

Table 1. Properties of the Test Soils

Soil No.	Soil name	AASHTO classification	USCS classification	LL (%)	PI (%)	Fines (%)	Clay size (%)	$\gamma_{d\max}$ (kN/m^3)	OMC (%)	Total SSA (m^2/g)	External SSA (m^2/g)	Internal SSA (m^2/g)	CEC (meq/100 g)	Activity (*A*)	Carbonate content (%)	Dolomite content (%)	Calcite content (%)
1	Kirkland and Pawhuska complex	A-7-6 (25)	CL	44	26	93	38	17.0	17.4	102	54	48	26.3	0.68	5.7	3.0	2.7
2	Teller soil	A-6 (12)	CL	31	14	92	29	17.0	16.8	99	48	51	20.4	0.48	8.4	6.3	2.0
3	Burford-Vernon complex	A-6 (15)	CL	36	17	91	36	17.0	17.3	92	29	63	23.6	0.47	3.9	0.5	3.5
4	Normangee loam	A-7-6 (40)	CH	63	35	97	65	14.3	27.2	241	46	195	33.6	0.54	2.4	0.3	2.1
5	Ashport and Grainola complex	A-6 (9)	CL	31	14	77	28	18.0	15.5	50	19	31	22.6	0.50	8.2	6.6	2.7
7	Devol soil	A-4 (0)	ML	—	NP	80	7	17.6	14.7	54	10	44	16.5	—	5.2	1.6	3.6
8	Devol soil	A-4 (1)	SC	25	9	47	14	19.2	12.2	63	29	34	19.5	0.64	4.4	1.8	2.6
9	Kirkland and Pawhuska complex	A-6 (13)	CL	37	16	81	29	16.9	17.5	57	33	24	50.6	0.57	8.6	3.0	5.6
10	Hollywood soil	A-7-6 (45)	CH	65	43	93	61	15.2	24.0	220	44	176	51.9	0.70	4.0	0.9	3.1

Note: LL=liquid limit; SSA=specific surface area; and CEC=cation exchangeable capacity.

ably larger than 38 mm (limited to 75 mm by specification but larger chunks are common). All specimens in this study were prepared with the same curing time (e.g., time between the addition of water to the soil and compaction of the soil) and aging time (e.g., time between compaction of the specimen and initiation of testing). The curing time was 16 h; afterward, the soil was compacted into the rings and testing commenced immediately (aging time=0 h).

Samples Compacted Directly in Oedometer Ring

Soil samples prepared for oedometer tests were thoroughly air-dried, pulverized, and then passed through a U.S. standard No. 10 sieve (2 mm). Water was thoroughly mixed into the soil to the specified water content (2% dry of OMC from the standard Proctor test, ASTM D698) and soil was placed in a humid chamber for 16 h to promote moisture equilibrium. The soil was then compacted into the oedometer ring in two layers to achieve the required dry density (95% of $\gamma_{d\max}$ as determined from the standard Proctor test, ASTM D 698). Laboratory compaction consisted of tamping with a 19.2-mm diameter metal rod to achieve approximately uniform application of compaction energy to the top of each layer. Smooth stainless steel oedometer rings were used with 63.5-mm diameter × 19.1-mm height for both sample preparation and oedometer tests. Samples prepared in this fashion are referred to as "ring-compacted" (RC) in this paper.

Samples Trimmed from a Proctor Compacted Specimen

Soil samples were partially air dried to a moisture content below the target value, then clods were broken to a maximum diameter of 38.1 mm. Water was thoroughly mixed into the soil to achieve the desired water content and soil was placed in a humid chamber for 16 h. Then the soil was compacted in three layers to achieve the required dry density (95% of $\gamma_{d\max}$ as determined from the standard Proctor test, ASTM D698). A standard Proctor rammer was used, however, the drop height and number of blows was adjusted to achieve the target density. The soil was then extruded from the 101.6-mm standard Proctor mold and trimmed to a diameter slightly larger than the diameter of the oedometer ring (63.5 mm). The cutting ring was carefully pushed into the sample while trimming the soil. The top and the bottom of the specimen were trimmed with a straight sharp cutting edge. Samples prepared in this fashion are referred to as "Proctor-trimmed" (PT) in this paper.

Oedometer Testing Procedures

All soil samples were subjected to single- and double-oedometer tests. The single-oedometer method was performed in general accordance with ASTM D 5333 "Standard test method for measurement of collapse potential of soils." It consists of incrementally loading a test specimen at its "as-compacted" water content, up to a target stress level followed by inundation with water. Each loading increment is maintained for 1 h or until no further significant deformation occurs. The sample is then inundated with water to induce collapse at a vertical stress of approximately 200 kPa. The collapse potential is determined when there is no more noticeable deformation in the specimen, which generally occurs overnight. The collapse index, I_e, is the collapse potential or vertical strain change due to wetting the test specimen at an applied vertical stress of 200 kPa.

The double-oedometer test method (Jennings and Knight 1957) involves testing two nominally identical samples. One sample is tested at its as-compacted water content (unsaturated) using the standard incremental loading procedure. The other sample is initially inundated with water under a 5-kPa seating load and allowed to swell until primary swelling is complete (the vertical strain measured after the inundation process is called the free-swell value, F_s). Then the sample is loaded using the standard incremental method. The load increments are the same for the two tests but the duration of load is typically longer for the inundated sample to allow for completion of primary consolidation. The comparison between the stress-strain behavior for unsaturated and saturated samples gives an indication of the potential swelling and collapse behavior over the range of stress levels used in the test. In the current study, the double-oedometer results were used to determine the free-swell potential and characteristics of the as-compacted compression behavior.

All soils were prepared at 95% relative compaction (standard effort, ASTM D 698) and at 2% dry of the OMC. Relative compaction of 95% and 2% dry of the OMC are often the lower limits for construction of embankments found in typical DOT specifications. These lower limits were chosen because they represent the worst combination of dry density and water content for wetting-induced collapse allowed by specifications. Furthermore, the dry of optimum condition was expected to produce samples with significant clods. The collapse potential or collapse index was determined at 200 kPa for all soils. In some cases, multiple tests were conducted to examine repeatability and/or investigate unusual results.

Repeatability and Experimental Variability of Oedometer Tests

Multiple single-oedometer collapse tests and double-oedometer tests were conducted to investigate the repeatability of selected oedometer test results. The corresponding properties and characteristics of both RC and PT specimens, including the initial moisture content (w), initial dry unit weight (γ_d), collapse index (I_e), free-swell index (F_s), preconsolidation stress (P_c), recompression ratio (RR), and compression ratio (CR), were used to examine the experimental variation. The average values of these parameters were used as a basis for determining whether results from the RC and PT specimens were significantly different and whether differences in soil structure were influencing volume change behavior.

The values of RR, CR, and P_c were determined from unsaturated compression curves obtained as part of the double-oedometer test. These values are assumed to be the most meaningful in terms of the actual fill behavior and wetting sequences expected under field conditions. That is, it is expected that, in most cases, self-weight compression will occur under unsaturated conditions in the field and not following complete inundation with water. The large change in void ratio associated with free swelling at the beginning of the saturated oedometer test for some soils greatly affects the subsequent compression behavior (i.e., RR and CR) and is not representative of actual field soil conditions. For this study, the RR was determined as the slope of the initial linear portion of the ε_v-log σ_v curve between 12 and 60 kPa. The CR was determined as the slope of the linear portion of the ε_v-log σ_v curve between 800 and 1,600 kPa. The preconsolidation stress (P_c) was determined from the Casagrande construction method. To investigate repeatability, two different types of soils were used; Burford-Vernon complex (Soil No. 3) CL and Normangee loam (Soil No. 4) CH.

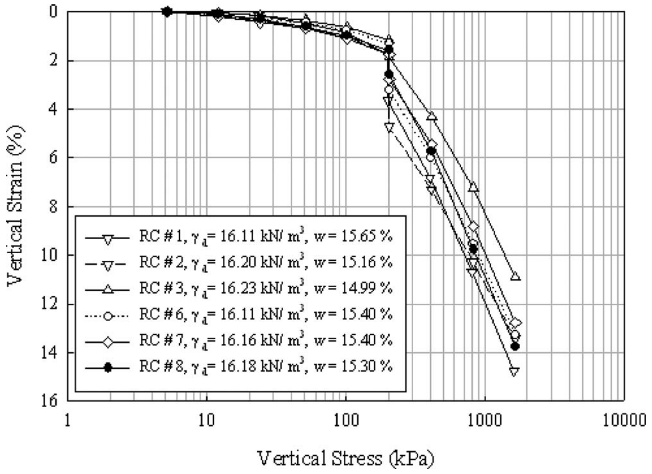

Fig. 1. Soil No. 3— single-oedometer collapse tests (RC specimens)

Results of Repeatability Study

Repeatability of Single-Oedometer Collapse Tests

Single-oedometer collapse tests for Soil No. 3 are presented in Figs. 1 and 2 for RC and PT specimens, respectively. As shown in Fig. 1, the range of water contents and dry unit weights are 15.0–15.7% and $16.1\ \text{kN/m}^3 - 16.2\ \text{kN/m}^3$, respectively, for six samples compacted in the oedometer ring. Two trials, tests 4 and 5, were removed from this study because the water contents and densities fell outside of what was considered an acceptable range (e.g., 13.7 and 16.7%, 16.4 and $16.0\ \text{kN/m}^3$). Despite the small differences in water content (0.7%) and density ($0.1\ \text{kN/m}^3$) of the six samples, the collapse index range is 0.7–2.9%, which is significantly large. This variation may be due to slight variations in initial moisture content and density of the sample prior to inundation with water, variations in compaction using the manual tamping procedure, and/or sample heterogeneity. Every effort was made to achieve nominally identical samples but differences in laboratory humidity and temperature during sample preparation and testing may have led to slight differences in moisture content and density prior to wetting.

The average compression curves of single-oedometer collapse tests for both RC and PT specimens are compared in Fig. 3. While

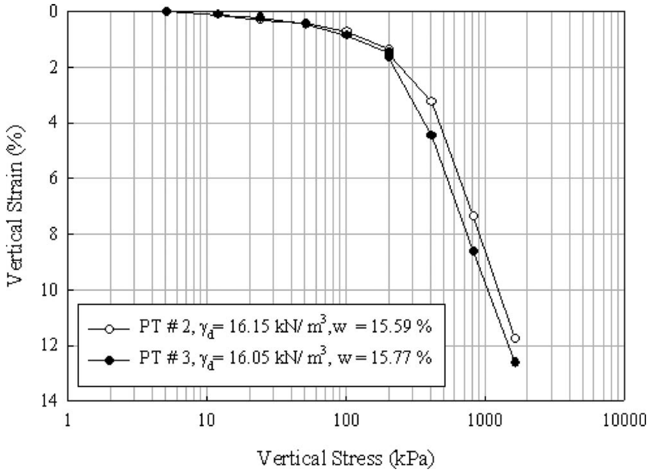

Fig. 2. Soil No. 3—single-oedometer collapse tests (PT specimens)

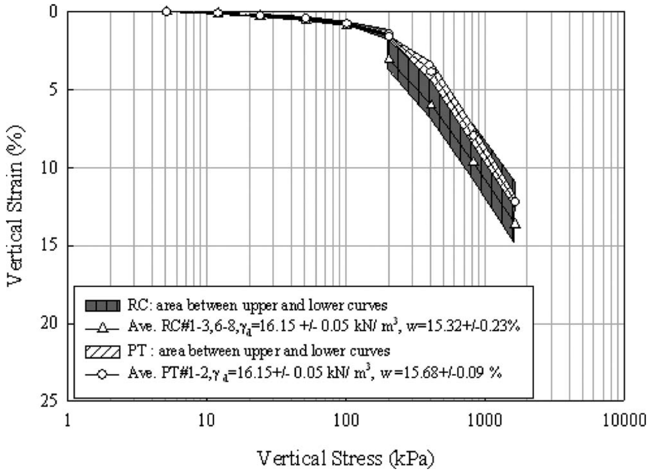

Fig. 3. Soil No. 3—comparison of single-oedometer collapse test results from RC and PT specimens

there is some overlap in the data ranges, it is clear from this figure that the RC specimens showed significantly more tendency for wetting-induced collapse than PT specimens. This is further emphasized in Fig. 4; the difference in collapse index between RC and PT specimens is significantly large (1.4%) and indicates that differences in soil structure may be important to the collapse behavior for Soil No. 3.

Repeatability was similarly investigated with Soil No. 4 using four RC and two PT specimens. The average and range of oedometer curves are shown in Figs. 5 and 6. While the distinction between PT and RC specimens is not as clear as for Soil No. 3, there appears on average to be slight differences in behavior, as shown in Fig. 6. Since the average collapse index for the PT specimens is closer to the average of the RC specimens for Soil No. 4, it appears that the differences in soil structure between RC and PT specimens are not as significant compared to Soil No. 3. It was expected that the more plastic soil (Soil No. 4) would exhibit more dependence on clod structure. However, as discussed later, another important factor to consider is the initial moisture content of the soil at the time of sample preparation, especially with regard to behavior of PT samples.

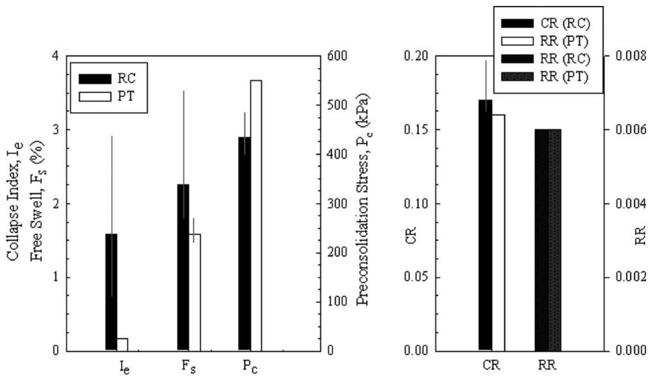

Fig. 4. Soil No. 3—comparison of collapse and swell indices, preconsolidation stress, RR and CR from RC and PT specimens (uncapped error bars indicate range of values)

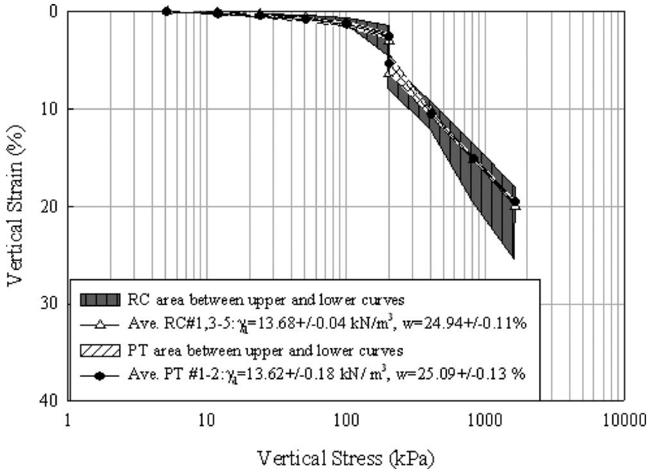

Fig. 5. Soil No. 4—comparison of single-oedometer collapse test results from RC and PT specimens

Repeatability Study of Double-Oedometer Tests

Repeatability was also examined using six RC and two PT saturated oedometer tests, as well as three RC and one PT unsaturated tests for Soil No. 3. As shown in Fig. 4, the range of free-swell index for the PT specimens from saturated oedometer tests falls below the range of the free-swell index of the RC specimens. Results of unsaturated oedometer tests indicate significant differences in preconsolidation stress, being considerably higher for the PT specimen. However, recompression and virgin compression slopes were not significantly different, as reflected by RR and CR. In addition, RR and CR were highly repeatable between tests (hence the lack of range bars in Figs. 4 and 6).

Similar to wetting-induced collapse behavior exhibited by Soil No. 4, it seems differences in soil structure between RC and PT specimens are less important to the results of double-oedometer tests for Soil No. 4, as shown in Fig. 6.

Although RC and PT specimens exhibited experimental variability in oedometer tests, there are consistent differences between both the RC and PT specimen test results. The initial moisture contents and dry unit weights for oedometer specimens were carefully controlled throughout the test program, showing relatively low coefficients of variation of <0.1. Therefore, meaningful comparisons between RC and PT specimens were expected. Furthermore, in a subsequent analysis of test results from

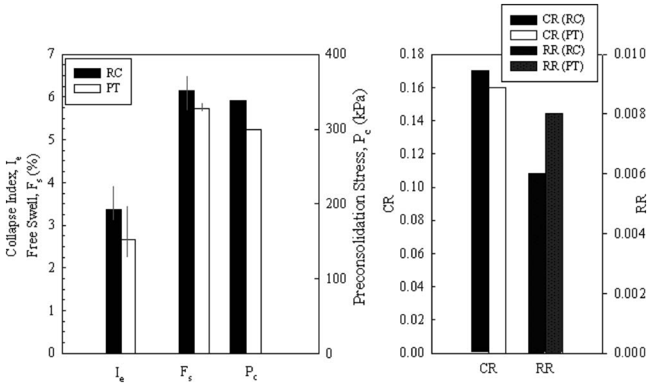

Fig. 6. Soil No. 4—comparison of collapse and swell indices, preconsolidation stress, RR and CR from RC and PT specimens

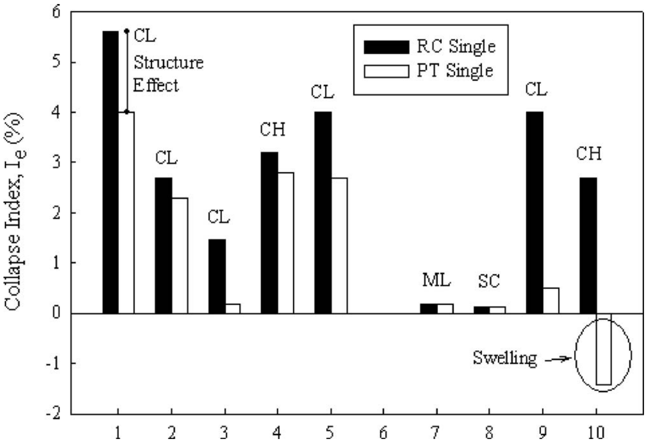

Fig. 7. Comparison of collapse index from single-oedometer collapse tests for all RC and PT specimens

all nine soils, statistically significant trends are presented that lend credibility to the experimental methods and results.

Oedometer Tests Results for All Soils

Results of Single-Oedometer Collapse Tests

To investigate the structure effect on 1D compression behavior, the average results of the RC specimens (clod size ≤ 2 mm) and the PT specimens (clod size ≤ 38.1 mm) were compared. Values of collapse indices from the single-oedometer collapse tests are presented graphically in Fig. 7 while a tabular summary of all results is presented in Table 2. A few important observations may be made from this figure.

1. Collapse indices from single-oedometer tests are consistently greater for RC compared to PT specimens with an average percent difference of 47%, except for Soil Nos. 7 and 8, where minimal difference was noted.
2. Consistent with previous observations (e.g., Lim and Miller 2004), generally clayey soils exhibited more collapse potential than sandy and silty soils of low plasticity ($PI < 10$).
3. The differences between single-oedometer collapse indices for RC and PT specimens are not strictly related to soil type. However, the greatest difference is observed for the soil with the highest plasticity index (PI) (Soil No. 10). The lowest differences observed were for the low plasticity soils (Soil Nos. 7 and 8).
4. The PT results for Soil No. 10 (CH) indicate that swelling occurred following inundation. This was the only soil that experienced swelling during the single-oedometer collapse test. Soil No. 4, the only other inorganic high plasticity, fat clay (CH) soil, did not exhibit this behavior.

The differences observed between PT and RC specimens are largely attributed to differences in the soil structure. These differences are most pronounced for soils in this study classified under the AASHTO A-6 and A-7-6 groups or unified soil classification system (USCS) CLs and high plasticity CHs. For the same moisture content and dry unit weight, the structure of the specimen compacted in a Proctor mold is different from the structure of a specimen compacted directly in a small ring. This is due to the different clod sizes, pore size distributions, moisture content distribution and suction within the clods, and resulting interparticle forces, which depend in part on applied stress and stress induced during compaction.

Compacted soil can be thought of as a dual porosity material having a large pore network between clods (interaggregate pores) and much smaller pores within clods (intra-aggregate pores). Generally, there are more and smaller clods in RC specimens than in PT specimens. Therefore, it is expected that the RC specimens will have a more extensive interaggregate pore network than the PT specimens. It appears that the differences in the clod size and extent of interaggregate pores may help to explain why in some cases the wetting-induced volume change behavior is different between RC and PT specimens.

One possible explanation is that when the soil is inundated the water quickly penetrates the interaggregate pore network leading to a rapid loss of matric suction and associated collapse. On the other hand, the water penetrates the intra-aggregate pores in individual clods more slowly. This may give clay particles within these clods time to swell and further impede water penetration into the clod. Thus, the volume change behavior of an individual clod may be positive or negative depending on the matric suction in the clod, swelling potential and rate of water penetration. Furthermore, it is expected that water will penetrate larger clods associated with PT specimens more slowly than small clods associated with RC specimens. The initial moisture content and suction within a clod will depend heavily on the size of the clod, initial moisture content prior to mixing the soil to the compaction water content, and length of time permitted for water to distribute within the specimen following mixing. This may explain why Soil No. 10 exhibited swelling in the PT sample during the single-oedometer collapse test as the initial water content (Table 2) was quite low compared to Soil No. 4, for example, which had a relatively high initial moisture content prior to mixing. Following

Table 2. Soil Collapse, Preconsolidation Pressure, and Free-Swell Parameters in Comparison with Change in Water Content from Initial to Target and PI

Soil No.	OMC (%)	PI (%)	Initial w_i (%)	Target w_f (OMC-2%)	I_e RC (%)	I_e PT (%)	P_c RC (kPa)	P_c PT (kPa)	F_s RC (%)	F_s PT (%)
1	17.4	26	11.8	15.4	5.56	3.96	425	550	3.53	1.84
2	16.8	14	15.0	14.8	2.67	2.25	433	545	3.06	2.63
3	17.3	17	14.5	15.3	1.47	0.17	433	550	2.25	1.58
4	27.2	35	23.0	25.2	3.37	2.66	338	300	6.14	5.73
5	15.5	14	14.0	13.5	4.01	2.71	243	313	2.53	1.03
7	14.7	0	11.2	12.7	0.12	0.12	350	350	0.08	0.17
8	12.2	9	10.9	10.2	0.12	0.12	219	263	0	0
9	17.5	16	12.3	15.5	4.02	0.50	427	500	4.08	2.72
10	24.0	43	8.8	22.0	2.73	−1.42	300	500	10.47	9.50

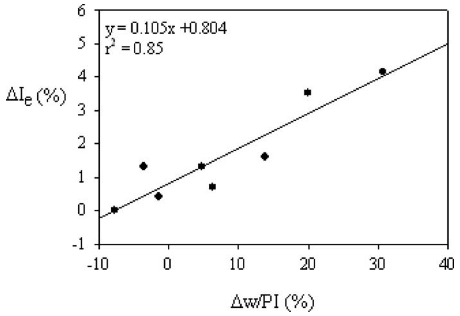

Fig. 8. Relationship between collapse index and the amount of water added from the initial water content to the target water content (OMC-2%) and PI

mixing, the interiors of the clods in Soil No. 10 were likely in a relatively dry state, which may have led to the significant swelling. Furthermore, with less moisture penetrating the clods during mixing there is more moisture distributed in interaggregate pores around the clods. This will lower the matric suction in the interaggregate pores and potentially reduce the collapse behavior. Regarding the RC specimens, the smaller clods are likely closer to the target (mixing) moisture content at the time of testing compared to larger clods in the PT specimens and therefore less prone to swelling.

It is clear that the soil type, clod size, and initial moisture content are important factors influencing the wetting-induced response. To emphasize this further, the PI, and change in water content during mixing (Δw) are combined in a single parameter and compared to the difference in collapse index (ΔI_e) between RC and PT specimens for all nine soils in Fig. 8. The change in water content (Δw) is the difference between the target water content (OMC-2%) and the natural water content of the soil prior to mixing (see Table 2). The relatively large coefficient of determination exhibited by the linear relationship in Fig. 8 provides strong empirical evidence of the importance of soil type and initial moisture content relative to the influence of clod size and soil structure on collapse behavior.

In this study, the results showed that the PT specimens from AASHTO A-4 group (e.g., Soil Nos. 7 and 8), which have low PI ($PI < 10$) and low clay-size fraction ($CF < 15\%$), exhibited similar collapse indices to those of the RC specimens. It appears that collapse index is less affected by the initial specimen condition, clod size, and compaction method; probably due to clod breakdown in PT specimens, which results in soil with similar structure to the RC specimens.

As mentioned previously, differences in the compaction process may be partly responsible for the differences between RC and PT specimen behaviors. While the samples had similar moisture content and dry unit weight, the stresses induced during compaction in the ring and Proctor mold are likely different because of different contact stresses between the rammers and soil in each case. Therefore, the resulting differences in stress history cannot be ruled out as a contributing factor to variations in the observed comparisons of RC and PT behavior. This has important implications with regard to differences in compaction stress history under field and laboratory conditions.

Results from Double-Oedometer Tests

Results from saturated and as-compacted oedometer tests showed some differences between behaviors of RC and PT specimens.

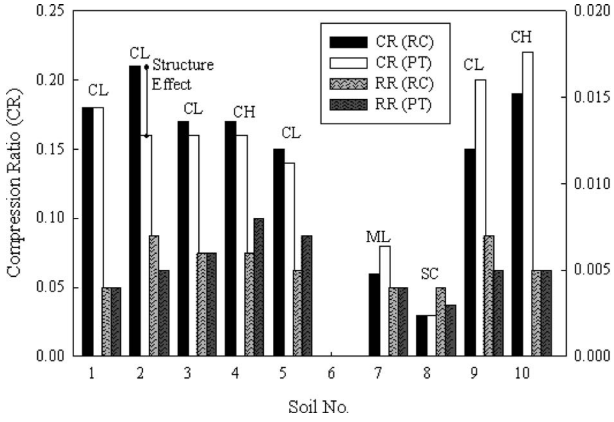

Fig. 9. Comparison of CR and RR from unsaturated-oedometer tests for all RC and PT specimens

There were differences in RRs and CRs, preconsolidation stress, collapse potential, and free swell. The most consistent difference between the two appears in the values of preconsolidation stress, where PT test values are consistently higher than for RC tests.

Values of RR and CR show some variation between RC and PT samples as presented in Fig. 9. Most of the CL soils have a higher CR in the RC samples than in the PT samples, except for Soil No. 9, where the reverse is true. The CH soils are split; Soil No. 4 shows a higher CR in the RC sample and Soil No. 10 shows a higher CR in the PT sample. The ML Soil No. 7 has a higher CR in the PT sample. While the RR values show some variation, no strong visible trends can be seen in the data. The average percent difference of CR is 14% while RR is 17%.

For RC specimens and PT specimens, preconsolidation stress results determined from the unsaturated oedometer tests are presented in Fig. 10. For all soils except Soil No. 4 (CH) the preconsolidation stress appears slightly higher for the PT specimens than those of the RC specimens, with an average percent difference of 27%. The preconsolidation stress is a 1D yield stress and is known to be closely related to several factors including the stress history. It is important in settlement computations to separately analyze recompression and virgin compression behavior. The compaction process, being different for PT and RC specimens, is expected to be one factor possibly responsible for the observed

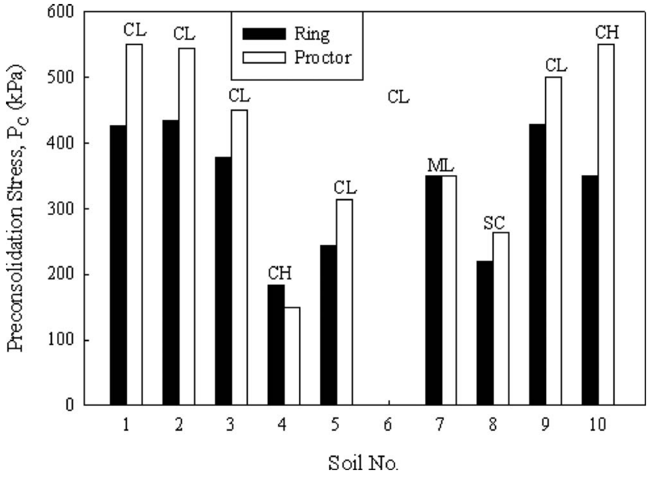

Fig. 10. Comparison of preconsolidation stress from unsaturated-oedometer tests for all RC and PT specimens

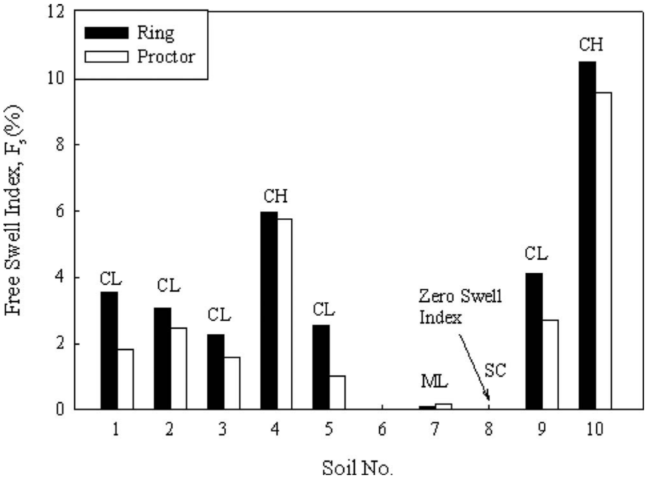

Fig. 11. Comparison of free-swell index from saturated-oedometer tests for all RC and PT specimens

differences in preconsolidation stress. However, the data suggest that the presence and state of clods in each sample is also largely responsible for the observed differences.

For example, consider test results for Soil Nos. 4 and 10 discussed previously. In many ways, these soils are similar yet they represent the extremes in observed differences between PT and RC specimens. Soil No. 10 showed the largest difference between preconsolidation stress of PT and RC specimens, with the PT specimen having a much larger value. On the other hand, Soil No. 4 exhibited relatively little difference between PT and RC specimens with the RC specimen actually having a slightly higher value of preconsolidation stress. The main difference between these soils was the initial moisture content of the soil prior to mixing with water (Table 2). In fact, these soils also represent the extremes of initial water contents of the soil samples. It appears that relative to RC specimens, the softer clods in the Soil No. 4 PT specimens resulted in a soil with lower yield stress (i.e., preconsolidation stress) compared to the stronger clods in the Soil No. 10 PT specimens. As discussed previously, following mixing with water, it is unlikely that the water fully penetrated these relatively large clods before compaction and testing, which resulted in a more stable structure in the case of Soil No. 10.

The swelling behavior from the saturated oedometer tests for the RC and PT specimens are presented in Fig. 11. Generally, the higher plasticity soils exhibited some differences between RC and PT free-swell values with RC specimens typically exhibiting larger free-swell indices than those of the PT specimens, with an average percent difference of 35%. It appears that the differences in structure, distinguished by clod size and pore size distribution, between the RC and the PT specimens may lead to differences in the free-swell indices in the two cases.

Soils with low PI ($PI < 10$) and low clay-size fraction ($CF < 15\%$) did not exhibit significant structure effects in 1D compression tests. These soils were classified under AASHTO A-4 group and USCS ML and SC groups. As mentioned previously, this is most likely due to clod breakdown that results in soil having similar structures, although two different sample preparation methods were used.

Conclusions

In this study, oedometer specimens were compacted using two different methods to produce samples with different soil structure but with similar dry density and moisture content. RC samples were produced by tamping soil directly in an oedometer ring where the maximum clod size in the soil was about 2 mm. The PT specimens were produced by using a standard proctor mold and rammer where the maximum clod size was limited to about 38 mm. Based on the comparison of results from RC and PT oedometer tests for nine fine-grained soils, the following conclusions can be drawn:

1. The soil type can be used for preliminary assessment of the potential importance of soil structure on 1D volume change behavior of compacted soils. Generally, clayey soils seem more prone to the influence of soil structure on volume change characteristics in 1D compression and wetting tests. In particular, the wetting-induced collapse potential, preconsolidation stress, and free-swell index showed the most significant differences between RC and PT specimens.
2. In general, in addition to soil type, it appears the collapse potential and swell index of the soils depend largely on the interaggregate and intra-aggregate pore size distribution resulting from different clod sizes and the moisture condition (and suction) within and between clods. Soils with a greater number of smaller clods (RC specimens) showed more collapse and swelling potential than soils with larger clods (PT specimens). The difference between RC and PT specimens was more pronounced when the initial moisture content of clods prior to mixing and compaction was relatively low and the plasticity was high.
3. For clayey soils tested in this study, generally, collapse potential and free-swell index were lower and preconsolidation stress was greater for PT than RC specimens. The primary factor responsible for differences in behavior observed between RC and PT specimens appears to be the size and state of clods in the compacted specimens. For two similar highly plastic clays, test specimens prepared from field soil samples at a relatively low moisture content (Soil No. 10) showed considerable differences in volume change behavior for RC and PT specimens compared to specimens prepared from samples initially at a relatively high moisture content (Soil No. 4). It appears that when clods are initially in a drier state, the water content in mixed and compacted samples is less uniform overall and lower within the clods. This results in clods that are stronger with a higher yield stress (preconsolidation stress) and an overall soil structure that is less prone to wetting-induced collapse.
4. Cohesionless and low plasticity soils ($PI < 10$) did not seem to be affected by sample preparation and compaction method (i.e., Soil Nos. 7 and 8). Two such soils exhibited similar collapse and free-swell indices in the RC and PT specimens, which indicate that there was no appreciable structure effect. This is attributed to the breakdown of the clods during compaction and relatively similar moisture distribution in both RC and PT specimens for low plasticity soils ($PI < 10$).
5. The CR and RR of unsaturated specimens exhibited some differences between PT and RC specimens. However, the differences were inconsistent from one soil to the next and overall, generally, not as significant as other volume change parameters.
6. Results of this study indicate that for some soils, particularly clayey soils, volume change behavior of compacted soils in the laboratory may be significantly different than field behavior and erroneous volume change predictions are possible if the clod-size distribution and moisture state of the clods in the field is not considered. In answer to the question posed

earlier, under certain conditions, it would not be acceptable to predict volume changes of compacted fills using standard 1D oedometer tests. Further study will be required to determine ways to adequately match soil structure characteristics in laboratory samples to the soil structure that results from various methods of field compaction. This requires understanding of how field and laboratory compaction procedures and other factors affect the final structure.

Acknowledgments

The writers are grateful for the financial support of the Oklahoma Department of Transportation.

References

ASTM. (2005). "Soil and rock (I)." *D 420–D 5611*, West Conshohocken, Pa.

Barden, L., Madedor, A. O., and Sides, G. F. (1969). "Volume changes characteristics of unsaturated clay." *J. Soil Mech. and Found. Div.*, 95(1), 33–51.

Barden, L., and Sides, G. R. (1970). "Engineering behavior and structure of compacted clay." *J. Soil Mech. and Found. Div.*, 96(SM4), 1171–1200.

Basma, A. A., and Tuncer, E. R. (1992). "Evaluation and control of collapsible soils." *J. Geotech. Engrg.*, 118(10), 1491–1504.

Benson, C. H., and Daniel, D. E. (1990). "Influence of clods on hydraulic conductivity of compacted clay." *J. Geotech. Engrg.*, 116(8), 1231–1248.

Booth, A. R. (1975). "The factors influencing collapse settlement in compacted soils." *Proc., 6th Regional Conf. for Africa on Soil Mechanics and Foundation Engineering*, Vol. 2, South African Institute of Civil Engineers, South Africa, 57–63.

Cerato, A. B., and Lutenegger, A. J. (2002). "Determination of surface area of fine-grained soils by the ethylene glycol monoethyl ether (EGME) method." *Geotech. Test. J.*, 25(3), 315–321.

Cleomene, E. (2005). "Scale and fabric effect on one-dimensional compression behavior of compacted soils." MS thesis, Univ. of Oklahoma, Norman, Okla.

DiBernardo, A., and Lovell, C. W. (1980). "Dependence of compacted-clay compressibility of compaction variables." *Transp. Res. Rec.*, 754, 41–46.

Dreimanis, A. (1962). "Quantitative gasometric determination of calcite and dolomite by using Chittick apparatus." *J. Sediment. Petrol.*, 32(3), 520–529.

Jennings, J. E., and Knight, K. (1957). "The prediction of total heave from the double oedometer test." *Transactions of a symposium on expansive clays*, South African Institute of Civil Engineering, South Africa, 13–19.

Lawton, E. C., Fragaszy, R. J., and Hardcastle, J. H. (1989). "Collapse of compacted clayey sand." *J. Geotech. Engrg.*, 115(9), 1252–1267.

Lawton, E. C., Fragaszy, R. J., and Hetherington, M. D. (1992). "Review of wetting-induced collapse in compacted soil." *J. Geotech. Engrg.*, 118(9), 1376–1394.

Lim, Y. Y., and Miller, G. A. (2004). "Wetting-induced compression of compacted Oklahoma soils." *J. Geotech. Geoenviron. Eng.*, 130(10), 1014–1023.

Miller, G. A., and Cleomene, E. (2007). "Influence of fabric and scale effect on wetting-induced compression behavior of compacted soils." *Proc., GeoDenver: New Peaks in Geotechnics*, ASCE, Reston, Va., 1–10.

Noorany, I., and Houston, S. (1995). "Effect of oversize particles on swell, and compression of compacted unsaturated soils." *Geotech. Spec. Publ.*, 56, 107–121.

Rhoades, J. D. (1982). "Cation exchange capacity." *Methods of soil analysis. Part 2*, A. L. Page, ed., 2nd Ed., American Society of Agronomy, Madison, Wis.

Rizkallah, V., and Keese, K. (1989). "Geotechnical properties of collapsible soils." *Proc., 12th Int. Conf. on Soil Mechanics and Foundation Engineering*, A.A. Balkema, Rotterdam, Vol. VI, 101–104.