Effect of Fabric on the Swelling Characteristics of Highly Plastic Clays

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Abstract

This paper provides an assessment of the influence of fabric on the swelling characteristics of clays. Specifically, the evaluation involves clay specimens compacted wet and dry of optimum (to achieve a comparatively dispersed and flocculated structures, respectively). In addition, characterization involved specimens collected in the field using Shelby tubes driven into an expansive soil deposit. The clay specimens were moisture-conditioned to the same dry state after compaction and before testing using a centrifuge-based inundation approach. The results from moisture-conditioned specimens were compared against those from specimens that were initially prepared dry prior to inundation.

The results from specimens prepared to a dispersed structure show primary swelling of the same magnitude as those prepared to a flocculated structure. However, the specimens prepared to a dispersed structure took longer to reach the end of primary swelling. The results from field-collected undisturbed specimens show similar time response as the compacted, moisture-conditioned specimens, but reveal slightly higher swelling than specimens reconstituted to the same initial conditions. Overall, the experimental results show that the soil fabric of highly plastic clays affects primarily the time needed to reach the end of primary swelling but not the magnitude of swelling for laboratory reconstituted specimens.

INTRODUCTION

Expansive soils undergo significant volumetric changes due to changes in moisture content rather than changes in external loads. The effect of the initial conditions, namely the gravimetric moisture content (Chen, 1988) and dry density (Komine and Ogata, 1992), on the swelling characteristics of these soils has been extensively studied. However, while some studies have evaluated the effect of various compaction techniques on swelling behavior (Attom et al., 2001), few studies have evaluated the effect of the internal clay structure, or fabric, on the swelling characteristics of expansive soils.

Using microscopy and pore-size distribution tests, previous studies have shown that soils tend to have a more dispersed microstructure when compacted wet of the optimum moisture content as determined by ASTM D698 compaction tests. Additionally, soils tend to have a more flocculated structure, with large, interconnected macro-voids, when compacted dry of the optimum moisture content (Diamond, 1971). These microstructures have been reported to play a significant role in the engineering properties of clayey soils (Fredlund and Rahardjo, 1993). Because the microstructure affects several engineering properties, an evaluation of how the internal clay structure affects the swelling characteristics is useful to assess whether laboratory reconstituted specimens are representative of samples taken from the field at the same initial testing conditions.

MATERIALS AND METHODS

Three soils were used in this research study, all of which involving highly plastic clays that were sampled in Central Texas from various transportation projects. The first two soils, the Eagle Ford and Behring clays, were bulk sampled from excavated, bare soil deposits. The other soil involves portions of the Branyon clay collected in the field using Shelby tubes driven to a depth of 5 ft.

All three soils were tested for their Atterberg Limits and classified as highly expansive clays (CH) according to the United Soil Classification System (USCS). The bulk soil samples from the Eagle Ford clay and the Behring clay were tested for their specific gravity (G_s), maximum dry unit weight ($\gamma_{d,max}$) and optimum moisture content (ω_{opt}) as indicated by proctor compaction tests using standard effort, fines content from wet sieving of the crushed soil, and clay content from hydrometer analysis of soil that passed through the No. 200 sieve. A summary of these soil properties is shown below in Table 1.

Table 1. Summary of Soil Properties

Soil	Liquid Limit	Plasticity Index	Specific Gravity (G_s)	ω_{opt} (%)	γ_{dmax} (kN/m^3)	Fines Content (%)	Clay Content (%)
Eagle Ford clay	88	49	2.74	24.3	15.25	97	76
Behring clay	58	41	2.78	20	15.42	82	40
Branyon clay	74	46	-	-	-	-	-

To test the soils for their swelling characteristics, a newly developed centrifuge methodology, developed at the University of Texas at Austin and outlined in Zornberg et al. (2017), was used. The testing involves a setup similar to an odometer test from ASTM D4546. Soil is either compacted or trimmed into a cutting ring and confined vertically by two bronze porous disks, separated from the soil with filter paper. The cutting ring with soil is then placed into an acrylic permeameter cup which is in turn placed into a swinging centrifuge bucket. The buckets are then placed in a reconfigured general purpose centrifuge that utilizes LVDTs and a wireless data acquisition system for real-time monitoring of changes in the soil's height. These height changes correspond to one-dimensional strain of the soil. A view of the permeameter cup setup and of the centrifuge rotor prior to testing is shown in Figure 1.

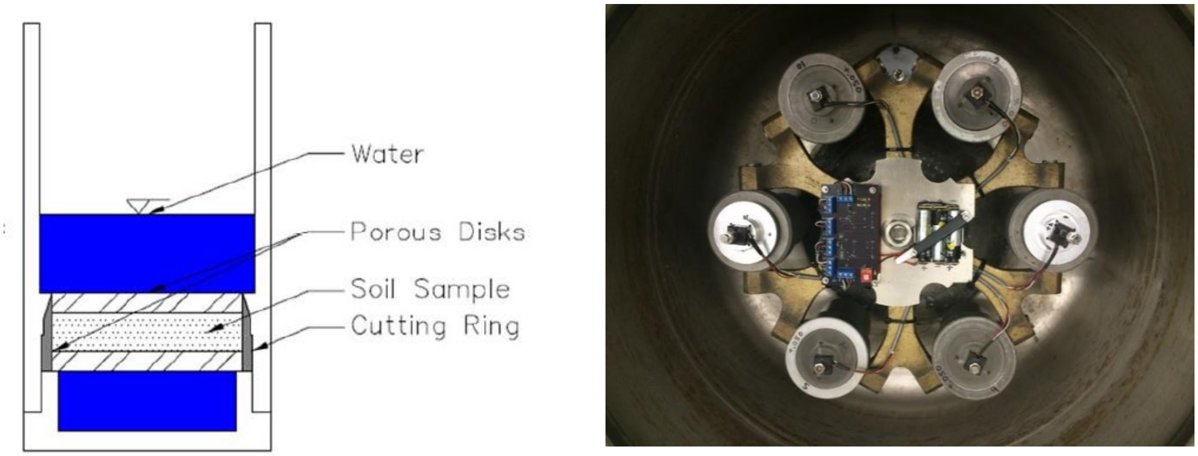

Figure 1. Side view of permeameter cup (left) and overview of centrifuge system (right)

The specimens undergo a compression cycle prior to testing. Water is then introduced, inundating the specimens, and the specimens are allowed to swell for approximately 48 to 72 hours. The centrifuge is subjected to a target RPM for an imposed artificial gravitational level on the specimen, which controls both the overburden stress and hydraulic head through the specimen. At the end of testing, the specimens are removed and measured for their final wet and oven-dried mass to determine the initial and final moisture content.

Soil preparation differed between the bulk-sampled soils and the Shelby tube sampled Branyon clay. The bulk-sampled soils (Eagle Ford and Behring clays) were air-dried, processed through a rock crusher, and sieved through the No. 10 sieve to remove granular particles from the processed soil. The soils were then rehydrated to both a wet of optimum and dry of optimum state for testing. For the Branyon clay, excess portions of the soil from the trimming of the Shelby tube samples were air-dried and underwent a similar method to process and rehydrate the soil.

Moisture conditioning was performed on the soils to isolate the effect of the initial fabric and prevent shrinkage cracking. This process involved the use of a glove box with a saturated salt solution, to control the relative humidity and rate of drying of the soil, and a scale to monitor the moisture loss through the specimens. The relative humidity was kept between 70% and 90%, depending on the amount of soils being dried at one time, to slow the rate of drying of the soil and prevent shrinkage cracks. A view of the glove box used for moisture conditioning is shown in Figure 2.

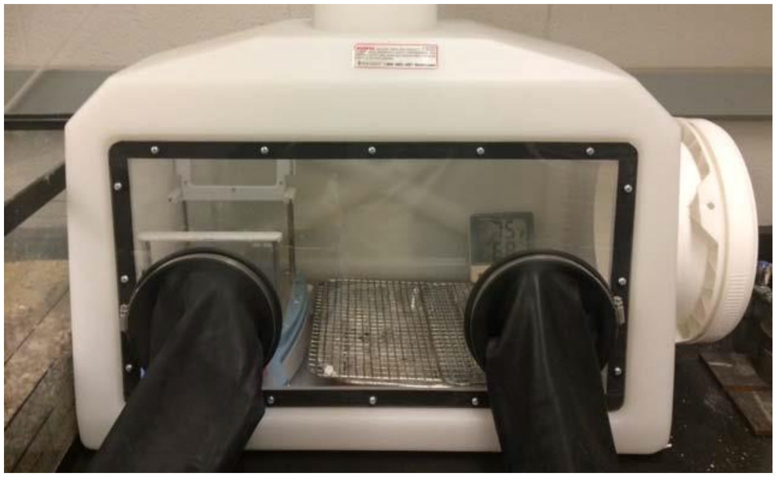

Figure 2. Environmental chamber for moisture conditioning of soils

The initial mass and gravimetric moisture content of the soil was taken prior to moisture conditioning, and a targeted mass was calculated based on a dry moisture condition that was 3 percentage points dry of optimum. For the Branyon clay, the optimum moisture content was estimated using the correlations from NAVFAC DM-7 (U.S. Navy, 1962).

After reaching the targeted weight, the specimens were wrapped in aluminum foil and allowed to come into a moisture equilibrium for 48 hours prior to testing in the centrifuge. This moisture equilibrium was employed to make a more homogenous distribution of moisture content throughout the sample.

To test the effect of fabric, the initial fabric of the soil prior to testing was controlled by the initial moisture content and mass of soil at the time of compaction for the reconstituted specimens and the sampling method for the Shelby tube samples. To create a more dispersed structure, the Eagle Ford clay was compacted at 3 percentage points wet of the optimum condition at the maximum dry unit weight, and the Behring clay was compacted at 5 percentage points wet of the optimum moisture content at the maximum dry unit weight. The clay structure for the field specimens was assumed to have a unique structure that can't be classified as either flocculated or dispersed due to cyclic wetting and drying.

Non-moisture conditioned soils were compacted at a state that targeted the dry moisture content and dry unit weight of the moisture adjusted soil prior to the compression phase in the centrifuge. Since this state was dry of the optimum moisture condition for all of the laboratory reconstituted specimens, the internal clay structure was assumed to be more flocculated.

RESULTS AND ANALYSIS

The testing program was grouped in two series. The first series involved testing laboratory reconstituted samples of the Eagle Ford and Behring clays at both moisture adjusted and non-moisture adjusted states. The second series involved the testing of both the field-sampled and laboratory reconstituted specimens of the Branyon clay. Results for these tests are shown as swelling curves in the void ratio versus time space. Additionally, testing data is shown in a table containing experimental data at three conditions: (1) initial conditions, including the gravimetric moisture content (ω_i), the dry unit weight ($\gamma_{d,c}$), void ratio (e_i), and volumetric moisture content at the end of the compression phase (θ_i); (2) experimental results at the end of primary swelling, including the void ratio at the end of primary swelling (e_p) and the time to the end of primary swelling ($T_{E.O.P.}$); and (3) experimental results at the end of testing, including the void ratio at the end of testing (e_f), the final volumetric moisture content (θ_f), and the testing stress (σ’). Primary swelling was defined according to ASTM D4546 as being the swelling at the intersection of tangents of the primary and secondary portion of the swelling curve. Strain was not used in this analysis as the initial conditions differed slightly between tests.

For testing on the reconstituted Behring clay, the samples were compacted at a 1 cm.-height prior to moisture conditioning of the soils. The trend results from one of these tests is shown below in Figure 3 with the testing conditions shown in Table 2.

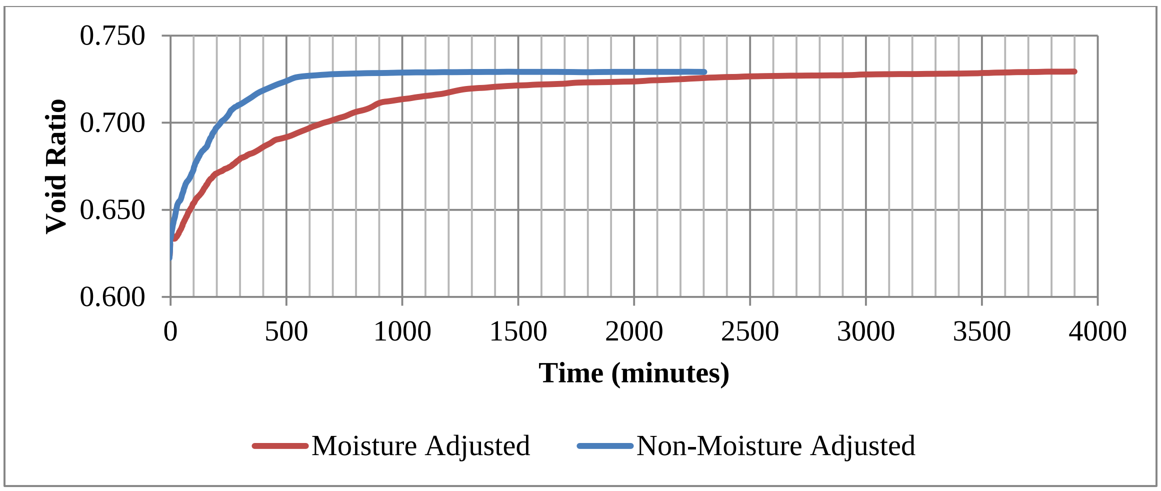

Figure 3. Swelling curves for the Behring clay tests

Table 2. Initial conditions for the Behring clay tests

Testing Condition	ω_i (%)	$\gamma_{d,c}$ (kN/m^3)	e_i	e_p	e_f	θ_i	θ_f	σ' (kPa)	$T_{E.O.P.}$ (min)
Non-Moisture Adjusted	17.8	16.8	0.622	0.727	0.729	0.3	0.422	11.3	604
Moisture Adjusted	17.5	16.8	0.627	0.72	0.73	0.307	0.422	11.7	1331

The moisture adjusted and non-moisture adjusted specimens resulted in similar void ratios at the end of primary swelling and at the end of testing. The time response of the different specimens differed significantly, with the moisture adjusted specimen taking approximately twice as long to reach the end of primary swelling. The increased amount of time to reach the end of primary swelling is hypothesized to have been caused by the lower hydraulic conductivity of the dispersed soil specimen. During the compaction process, the flocculated specimen will have a higher amount of macro-voids, allowing for moisture to infiltrate through the sample quicker than the dispersed specimen. Furthermore, this lower hydraulic conductivity is speculated to have caused the higher amount of secondary swelling in the specimen, as fewer regions of the soil had quick access to the moisture flowing in the specimen's macro-voids. Testing of the Behring clay indicated that the effect of fabric is primarily on the time characteristics, rather than the magnitude, of swelling.

For testing of the reconstituted Eagle Ford clay, soil specimens were compacted at a 1 cm.-height prior to moisture conditioning of the soils. The trend results from this test are shown below in Figure 4 with the testing conditions shown in Table 3.

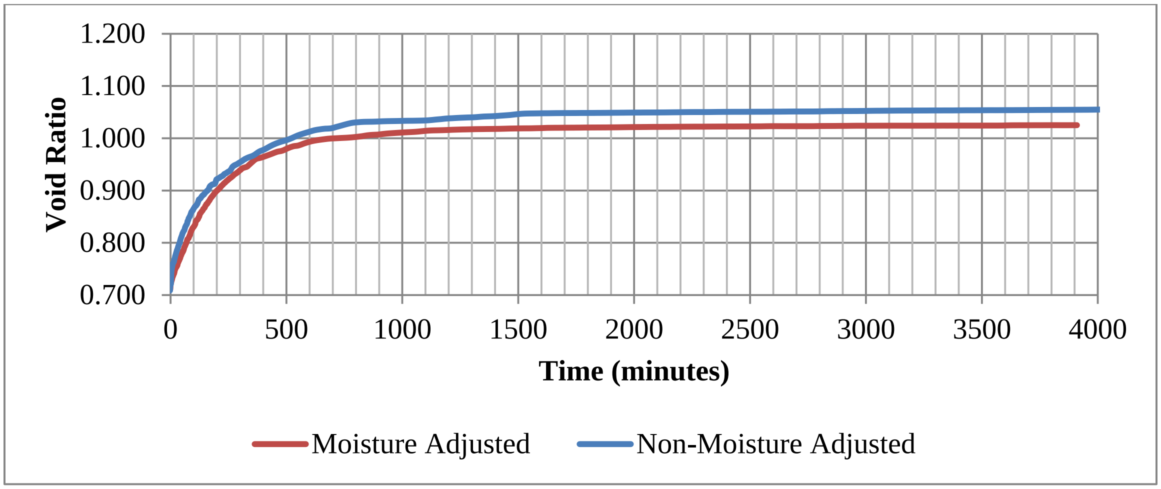

Figure 4. Swelling curves for the first Eagle Ford clay tests

Table 3. Initial conditions for the first Eagle Ford clay tests

Testing Condition	ω_i (%)	$\gamma_{d,c}$ (kN/m^3)	e_i	e_p	e_f	θ_i	θ_f	σ' (kPa)	$T_{E.O.P.}$ (min)
Non-Moisture Adjusted	19.7	15.7	0.711	1.028	1.063	0.317	0.515	11.0	764
Moisture Adjusted	19.4	15.7	0.709	1.011	1.025	0.312	0.506	12.8	1009

The results of this test were similar to those from the Behring clay tests. Both the moisture adjusted and non-moisture adjusted specimens reached similar final void ratios at the end of testing. There was a small difference in these void ratios due to a slight difference in the artificial gravitational level and corresponding overburden stress between the two specimens. However, the effect of fabric on the duration of primary swelling was not as significant for the Eagle Ford clay as for the Behring clay. In order to verify this result and overall trend, an additional test on the Eagle Ford clay was conducted. The trend results from this test are shown below in Figure 5, with the testing conditions shown in Table 4.

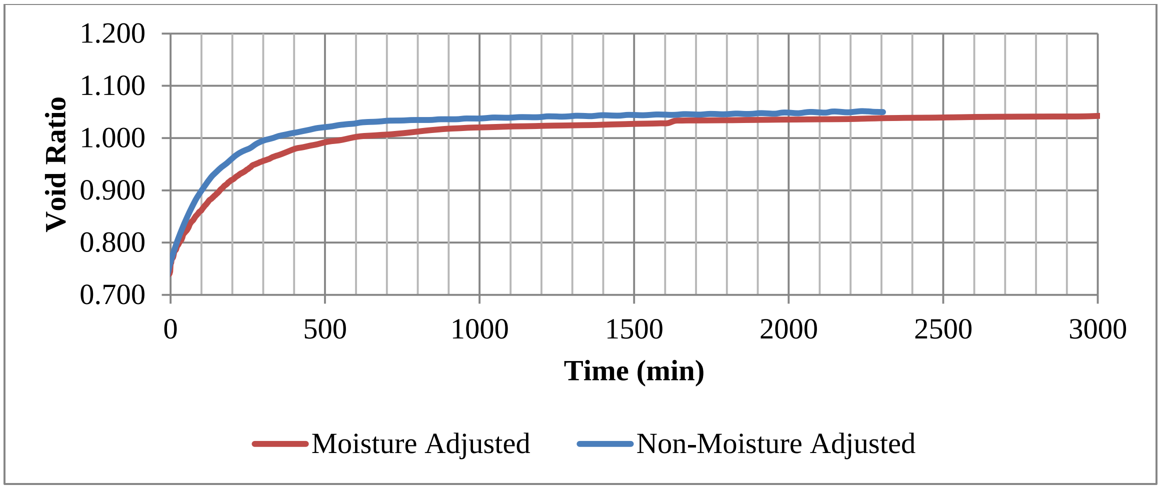

Figure 5. Swelling curves for the second Eagle Ford clay tests

Table 4. Initial conditions for the second Eagle Ford clay tests

Testing Condition	ω_i (%)	$\gamma_{d,c}$ (kN/m^3)	e_i	e_p	e_f	θ_i	θ_f	σ' (kPa)	$T_{E.O.P.}$ (min)
Non-Moisture Adjusted	20.4	15.5	0.736	1.026	1.055	0.323	0.513	11.8	524
Moisture Adjusted	19.1	15.4	0.742	1.021	1.051	0.301	0.513	11.8	1007

Note that there is a difference in the initial gravimetric moisture content with the non-moisture adjusted specimen being compacted wetter than the moisture adjusted specimen. Despite this, both tests have similar end of testing void ratios. Again, the trend where the more dispersed specimen takes a long time to reach the end of primary swelling is seen. This trend is seen despite the non-moisture adjusted specimen being compacted at a slightly more dispersed state than in the previous test. Overall, testing of the Eagle Ford clay reaffirmed the trend that the effect of fabric is primarily on the time characteristics, rather than the magnitude, of swelling.

For testing on the moisture adjusted field specimens of the Branyon Clay, two soil samples were cut from the extruded Shelby tube sample to a height of 2.5 cm. prior to moisture conditioning. After moisture conditioning, the soils were both trimmed into the cutting rings at a height of 2 cm. and tested in the centrifuge within 48 hours. The trimmings from various borings – all taken within a 400 ft.-section of the roadway and located in the same surficial soil deposit – were combined, air-dried at approximately 22°C, processed through a rock crusher, and rehydrated to create reconstituted specimens to compare against field samples. The reconstituted, non-moisture adjusted specimens were compacted to 2 cm. in 1 cm. lifts to match the height of the trimmed field specimen. The trend results from the first test are shown below in Figure 6 with the testing conditions shown in Table 5.

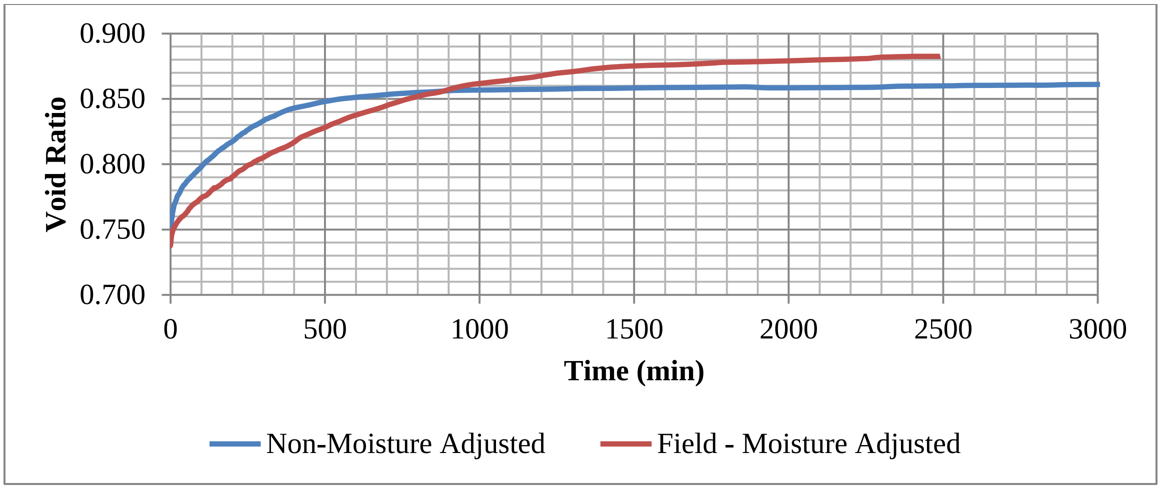

Figure 6. Swelling curves for the first Branyon clay tests

Table 5. Initial conditions for the first Branyon clay tests

Testing Condition	ω_i (%)	$\gamma_{d,c}$ (kN/m^3)	e_i	e_p	e_f	θ_i	θ_f	σ' (kPa)	$T_{E.O.P.}$ (min)
Non-Moisture Adjusted	21.3	15.3	0.737	0.85	0.862	0.333	0.463	14.8	553
Moisture Adjusted	21.9	15.2	0.743	0.876	0.88	0.341	0.468	12.1	1302

The field specimen had a higher change in void ratio and swelling, with a longer time to reach the end of primary swelling. The difference in the overall amount of swelling was attributed to local variations in soil particle distribution. An additional test was conducted to verify this trend. The trend results from the second test are shown below in Figure 7 with the testing conditions shown in Table 6.

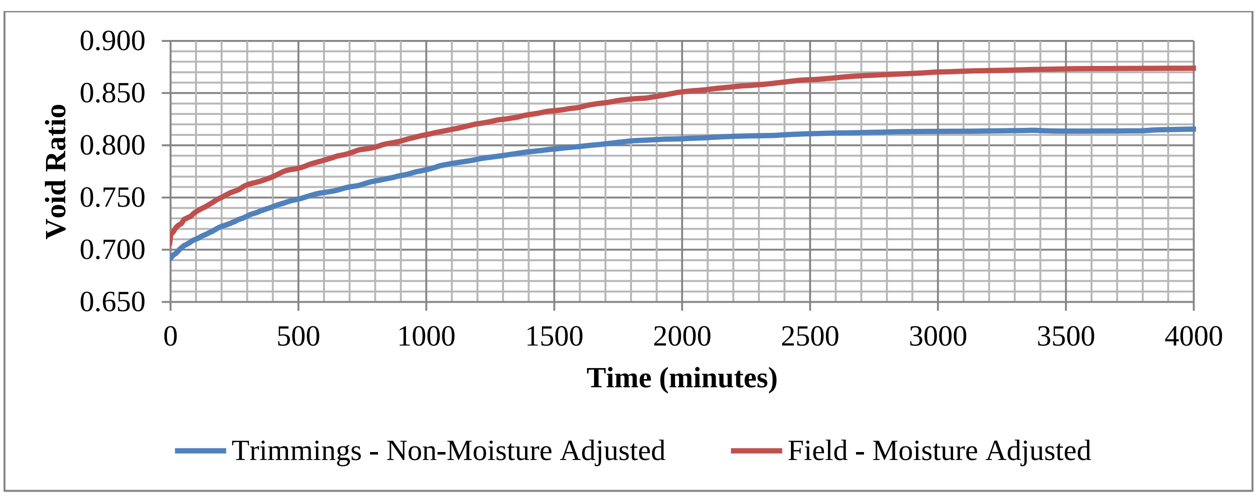

Figure 7. Swelling curves for the second Branyon clay tests

Table 6. Initial conditions for the second Branyon clay tests

Testing Condition	ω_i (%)	$\gamma_{d,c}$ (kN/m^3)	e_i	e_p	e_f	θ_i	θ_f	σ' (kPa)	$T_{E.O.P.}$ (min)
Non-Moisture Adjusted	21.4	15.7	0.692	0.81	0.816	0.342	0.449	13.3	1207
Moisture Adjusted	22.4	15.5	0.709	0.873	0.879	0.355	0.468	13.4	2849

The variation in initial conditions is noteworthy, with the non-moisture adjusted specimen being drier and more densely compacted than the moisture adjusted field specimen. Despite this difference, which typically would have led to an increased magnitude of swelling based on previous research, the moisture adjusted field specimen underwent a greater amount of change in its void ratio and swelling over a longer duration of primary swelling than the non-moisture adjusted specimen. The differences in the amount of volumetric change were again attributed to differences in the composition of the clay trimmings, which consisted of all soil in the top five feet mixed together. The results from the field specimens were consistent with the effect of fabric on the time characteristics of swelling previously seen in the first section of this testing program, although there was some effect on the magnitude of swelling that may come from heterogeneity and the method of preparing the non-moisture adjusted specimens.

CONCLUSION

The effect of fabric on swelling characteristics was evaluated using a newly developed centrifuge-based swelling methodology. Soil specimens from laboratory-reconstituted and field-sampled specimens were moisture adjusted and tested to evaluate the swelling characteristics of dispersed and field clay structures. Comparative tests using non-moisture adjusted samples were also performed to evaluate the swelling characteristics of more flocculated structures.

Two soils with differing grain size distributions were used for testing of the reconstituted specimens, and a field-sampled soil and air-dried, rehydrated portions of its trimmings were used for testing of the field-sampled specimens. The samples were examined for changes in void ratio during testing, duration of primary swelling, and changes in volumetric moisture content at the beginning and end of testing.

The main effect of fabric was found to be on the time response of swelling, specifically the duration of primary swelling. During the moisture conditioning process, the assumed reduction in macro-voids of the dispersed structure reduced the pathways for the soil to become rapidly saturated. When compared to the flocculated specimens, this dispersed structure is also assumed to have a lower hydraulic conductivity that increased the amount of time for moisture to migrate through a specimen.

The effect of fabric on the magnitude of swelling differed between the two testing programs. For the testing program on laboratory reconstituted specimens, the magnitude of swelling was not significantly affected by the moisture conditioning process. However, for the testing program on field-sampled specimens, the magnitude of swelling was higher for the field specimens as compared to the reconstituted specimens. This difference can be attributed to spatial heterogeneity in the soil deposit.

Results from this paper indicate that laboratory reconstituted specimens remolded at the same initial dry density and gravimetric moisture using a similar compaction technique will see a similar magnitude of swelling. However, laboratory reconstituted specimens may not capture the effect of the structure in field deposits.

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