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Evaluation of a Centrifuge Consolidation Technique to Determine the Effects of Temperature and Time on Kaolinite Properties

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Project Summary

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Classification: Senior
Grade Point Average: 3.64/4.00
Area of Study: Civil Engineering (Geotechnical Emphasis)
Title of Project: Evaluation of a Centrifuge Consolidation Technique to Determine the Effects of Temperature and Time on Kaolinite Properties

Abstract

The effects of time and temperature on the moisture content and unit weight profiles, as developed during a centrifuge consolidation process, were observed during the research program that is described herein. Specifically, a Beckman-Coulter Model J6-MI centrifuge with a six-place JS-4.2A swinging bucket rotor was utilized to consolidate kaolinite slurry samples. The consolidation procedure utilized specially designed slurry consolidometers, made from acrylic tubes with inside diameters of 2.63 inches (6.67 cm) and heights of 5.13 inches (13.04 cm). The tested kaolinite slurry samples were created by mixing 400 grams of dry kaolinite clay powder with 200 grams of de-aired deionized water (DI water) to reach an initial water content of 50 percent.

Temperatures of -10℃, 0℃ and 20℃ were utilized within the centrifuge with spin times of 12, 18, 24, and 30 hours. After being removed from the centrifuge, each soil specimen was trimmed into multiple slices of approximately 0.25-inch (0.64 cm) thick. The unit weight and moisture content of each individual slice were calculated and reported. The slurry samples were spun at a fixed centrifugal force of 500 revolutions per minute (RPM) that corresponded to an effective stress at the bottom of the samples of 35.57 kPa at the temperature of -10℃, 50.30 kPa at the temperature of 0℃, and 52.47 kPa at the temperature 20℃. The average unit weight values of the spun samples at 30 hours was 15.52 kN/m^3 at the temperature of -10℃, 17.91 kN/m^3 at the temperature of 0℃, and 18.25 kN/m^3 at the temperature of 20℃. Additionally, the average moisture content values of the spun samples at 30 hours samples were 41.90 percent, 31.22 percent, and 30.22 percent for the testing temperatures of -10℃, 0℃ and 20℃, respectively.

Introduction

In nature, water flows through soil due to capillary and gravitational forces. Capillary action is the tendency of liquid to flow against gravity due to the affinity of the liquid to solid surfaces and is typically associated with small pore spaces. For soil, capillary forces cause water to flow through the soil by filling the pore spaces (Terzaghi, 1943). Capillary forces are divided into two categories, adhesion and cohesion. Adhesion is the attraction of water to a solid surface and cohesion is the internal attraction of water to water. Contrarily, gravitational force, caused by the inherent attraction between masses, draws water downward towards the center of the earth. Gravitational forces are more prevalent in saturated soils while capillary forces are more prevalent in partially saturated soils. Soils with larger grain sizes, such as sands, have greater hydraulic conductivity, meaning water can flow at a faster rate through these soils.

Water flow through soil may affect the composition and mechanical properties of the soil. Specifically, index properties like moisture content and unit weight can be affected. The moisture content of soil is affected by the conductivity of water, water storage capacity of the soil, and the external forces applied to the soil. Similarly, the unit weight of soil is dependent on the type of soil, the amount of water in the soil, and the forces exerted on the soil. When similar saturated soils face the same amount of sustained load, the soil with higher moisture content will have a lower unit weight because higher moisture content is associated with less consolidation (McKenzie et al., 2002).

In 2011, researchers at the University of Arkansas determined that centrifuge consolidation techniques were suitable for the preparation of specimens used for direct simple shear strength tests with a reduction in the amount of time required to prepare the specimens (Gilbert et al., 2011). Moreover, in 2018, researchers at the University of Arkansas attempted to develop a hydraulic conductivity placement window to ensure compacted clay liner performance (Thomas, 2018). Even though, the researchers did not succeed in the creation of the placement window, opportunities for other usages of the centrifuge method were discovered.

This research was continuation of a previous investigation conducted at the University of Arkansas and the goal was to use the same equipment, methods, and procedure followed by Gilbert et al. (2011) and Thomas (2018) to quantify changes of the moisture content and unit weight profiles of kaolinite at different temperatures and different intervals of time. The temperatures tested were -10℃, 0℃ , and 20℃, and the intervals of time were 12, 18, 24, and 30 hours.

Furthermore, a comparison between Gilbert et al. (2011) data and this study, for the spin time of 24 hours at the temperature of 20℃ was presented and discussed.

Method and Procedure

A swinging bucket rotor centrifuge was utilized to consolidate the kaolinite slurry samples. Temperatures of -10℃, 0℃, and 20℃ were used with spin times of 12, 18, 24, and 30 hours. The properties of the soil, the testing device and testing procedure are presented and explained in this section.

Soil Properties

The tested soil was the Thiele KaoWhite kaolinite. Kaolinite was selected as the soil to be investigated because many researchers have utilized kaolinite for centrifuge testing (Peric et al., 1988; Ling, 1995; Jeanjean, 2006, Cincioglu, 2005; Cincioglu et al., 2004). Additionally, many researchers at the University of Arkansas have investigated Thiele KaoWhite kaolinite (Gilbert et al., 2011; Thomas, 2018; Mahmood, 2018; Garner, 2017; Zhao, 2016). In natural conditions, Kaolinite is typically classified as clay due to grain size; however, the soil used in the study contained larger grain sizes and classified as a silt.

Testing Device

The soil testing procedure was performed utilizing a Beckman-Coulter Model J6-MI centrifuge with a six-place JS-4.2A swinging bucket rotor. All slurry samples were spun at a fixed centrifugal rate of 500 revolutions per minute (RPM). The centrifuge equipment had a maximum rotor distance of 10 inches (25.40 cm) and a maximum speed of 4,200 RPM. The centrifugal rate and distance from the rotor produced a gravitational force within the samples that was between 40.60 (at the top of the sample, at 5.71 inches from the rotor) and 66.67 (at the bottom of the sample, at 9.38 inches from the rotor) larger than the typical gravitational force on Earth (Equation 1). These centrifugal forces were used to calculate the effective stress at the bottom of the samples. The calculated effective stress at the bottom of the samples was 35.57 kPa at the temperature of -10℃, 50.30 kPa at the temperature of 0℃, and 52.47 kPa at the temperature 20℃. (Equation 2).

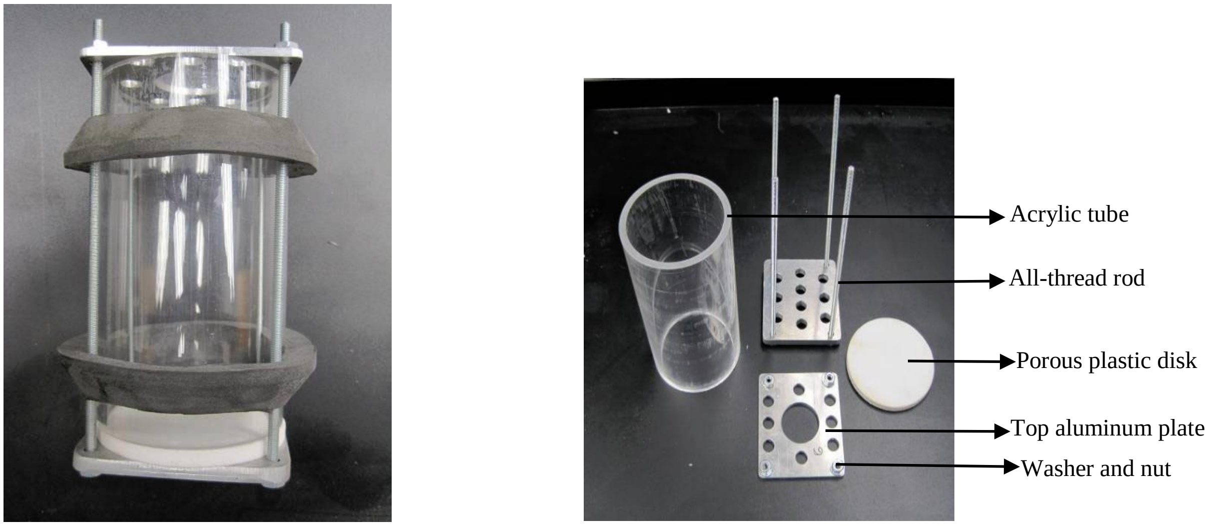
$$\text{RCF or g-force} = 1.12 \cdot r \cdot (M/1000)^2 \qquad \text{Equation 1}$$

$$\sigma'_z = \gamma_{soil} \cdot RCF \cdot H_{soil} - \gamma_{water} \cdot RCF \cdot H_{water} \qquad \text{Equation 2}$$

In Equation 1, RCF is the relative centrifugal force, r is the radius distance (distance from the rotor to the location of interest) in millimeters, and M is the rotational speed in RPM (Beckman Coulter Life Sciences, 2000). In Equation 2, σ'_z is the effective stress in kPa, γ_{soil} is the unit weight of soil in kN/m^3, H_{soil} is the height of soil in meters, γ_{water} is the unit weight of water in kN/m^3, H_{water} is the height of water in meters (Coduto et al., 2011). Slurry samples were placed in the swinging bucket rotor utilizing acrylic tubes that were specially designed for the aforementioned centrifuge machine. The inside diameter of each of the acrylic tubes was 2.63 inches (6.67 cm) and the height of each tube was 5.13 inches (13.04 cm). The acrylic tubes (slurry consolidometers) were assembled with two aluminum plates (one on top and one on bottom), one 0.25-inch thick porous plastic disk just above the bottom plate and one piece of filter paper located between the porous plastic disk and the bottom of the soil sample. Four (4) 1/8 inch (0.32 cm) diameter all-thread rods were utilized to tighten the slurry consolidometer components with washers and nut connections located above the aluminum top and below the bottom plates. A 1-inch (2.54 cm) hole in the top aluminum plate allowed for the slurry to be placed into the acrylic tubes after assembly. Ten (10) holes of 3/8-inch diameter (0.95 cm) on the bottom plate enabled drainage of water from the samples through the bottom plate. For completeness, the centrifuge and slurry consolidometer that were used are presented below in Figures 1 and 2.

(a) (b)

Figure 1. (a) Photograph of Beckman-Coulter Model J6-MI centrifuge. (b) Photograph of Beckman-Coulter six-place JS-4.2A swinging bucket rotor (modified from Gilbert et al., 2011).



(a) (b)

Figure 2. (a) Photograph of assembled slurry consolidometer. (b) Photograph of disassembled slurry consolidometer (modified from Gilbert et al., 2011).

Testing Procedure

Four (4) kaolinite slurry samples with an initial water content of 50 percent were created by hand mixing, for 3.0 minutes, 400 grams of dry kaolinite clay powder with 200 grams of de-aired, deionized water (DI water). The average height of the slurry inside the acrylic tubes was 3.67 inches (9.31 cm). The slurry samples were placed in the slurry consolidometers, and the slurry consolidometers were inserted into the swinging buckets of the rotor. Individual samples were removed from the centrifuge at 12, 18, 24, and 30 hours after the start of centrifugation. After the respective samples were spun at the mentioned intervals of the time, the consolidated samples were cut into slices with an average height of 0.25 inches (0.64 cm). The weight and height of each slice was measured to obtain the unit weight and moisture content profiles for each individual interval of time (Figures 3 and 4).

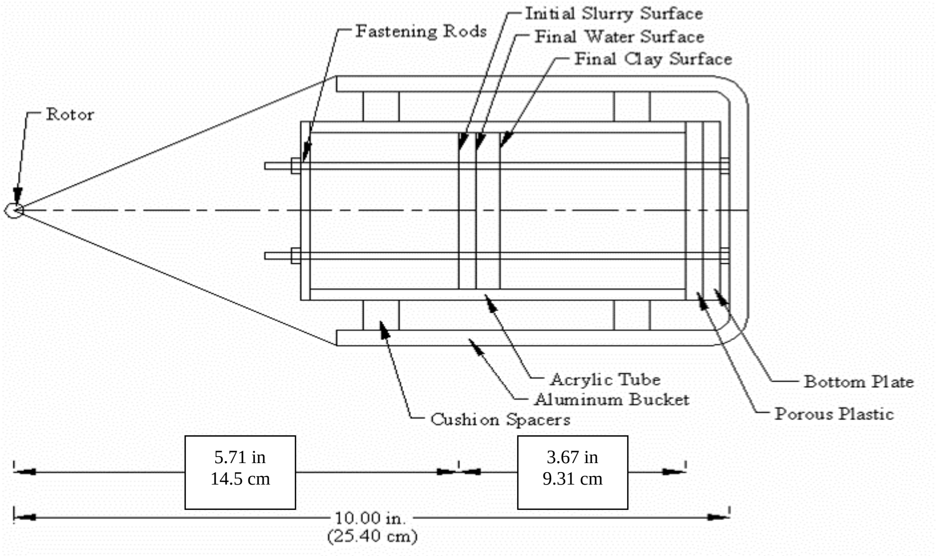


Figure 4. Top view schematic of slurry consolidometer within the centrifuge while the centrifuge is rotating (modified from Gilbert et al., 2011).

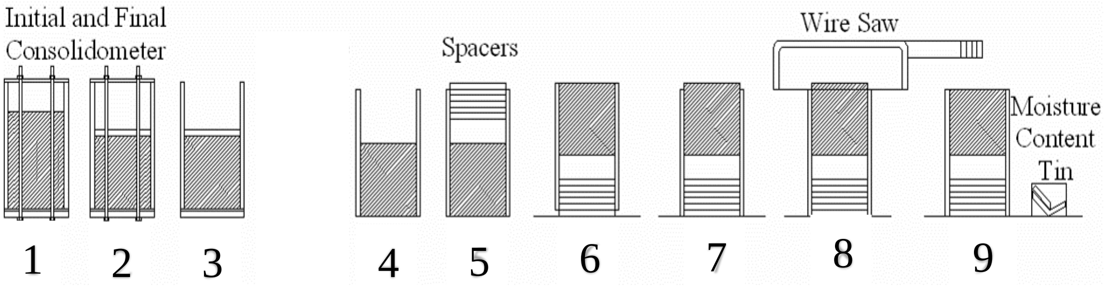


Figure 5. Unit weight and moisture content sample collection schematic (modified from Gilbert et al., 2011).

Results

Unit Weight Profiles

At the temperatures of 0℃ and 20℃, an anomaly was observed when the acquired unit weight profiles were plotted. Unexpected values for the unit weight of the top slices were observed. The errors may be attributed to random errors that were introduced when obtaining the top slices. At the time of trimming the samples, the top of the samples was still in the semi-slurry phase. When the top of the sample reached the top of consolidometer, the sample bled out of the consolidometer. The height of each top slice was not measured properly. The bleeding lead to smaller volumes of soil being acquired for the top slices, which led to larger unit weight values. To correct for the anomaly, the data were altered. The average height of top slices were adjusted until the degree of saturation was equal to one (S=1.0). A square outline on the unit weight profiles encloses the altered data. Similarly, at temperatures of -10℃, an anomaly was observed when the acquired unit weight profiles were plotted. The reason of the anomaly may also be attributed to random errors introduced when obtaining the slices. After the spin times at -10℃, the samples were frozen. A coping saw was the first tool used to cut the samples into slices for the spin times of 12, 18 and 24 hours. Most of the slices broke in two parts using the mentioned tool. As a result, inexact volumes of soil were recorded. At the interval of 30 hours, a dough scraper was used to cut the sample into slices. The dough scraper allowed getting whole single slices. At the temperature of -10℃, the data were not altered. However, only at the interval of 30 hours, the unit weight values were less scatter and followed an expected pattern.

The average unit weight values of the respective samples at the temperatures -10℃, 0℃ and 20℃ are presented in Table 1. Additionally, individual unit weight values at each interval of time are displayed in Figures 5 through 8. Ultimately, at the temperatures of 0℃ and 20℃, the unit weight values did not vary after steady state seepage was reached following the 12-hour interval of spinning. The steady stage seepage occurred when the system has reached equilibrium (Coduto et al., 2011). At 30 hours, the average unit weight was 15.52 at the temperature of -10℃, 17.91 kN/m^3 at the temperature of 0℃ and 18.25 kN/m^3 at the temperature of 20℃. Regardless of temperature, greater average unit weight values may be obtained by applying greater levels of centrifugal force.

Table 1. Average unit weights as a function of time for the testing temperatures.

Cell	Time in the Centrifuge (hours)	Temperature (Celsius)	Average Unit Weight (kN/m^3)	Standard Deviation (SD)
1	12	-10	18.29	4.49
		0	18.40	0.53
		20	18.04	0.68
2	18	-10	17.33	3.66
		0	18.29	0.78
		20	18.58	0.34
3	24	-10	17.78	3.61
		0	18.47	0.38
		20	18.61	0.34
4	30	-10	15.52	3.51
		0	17.91	1.00
		20	18.25	0.57

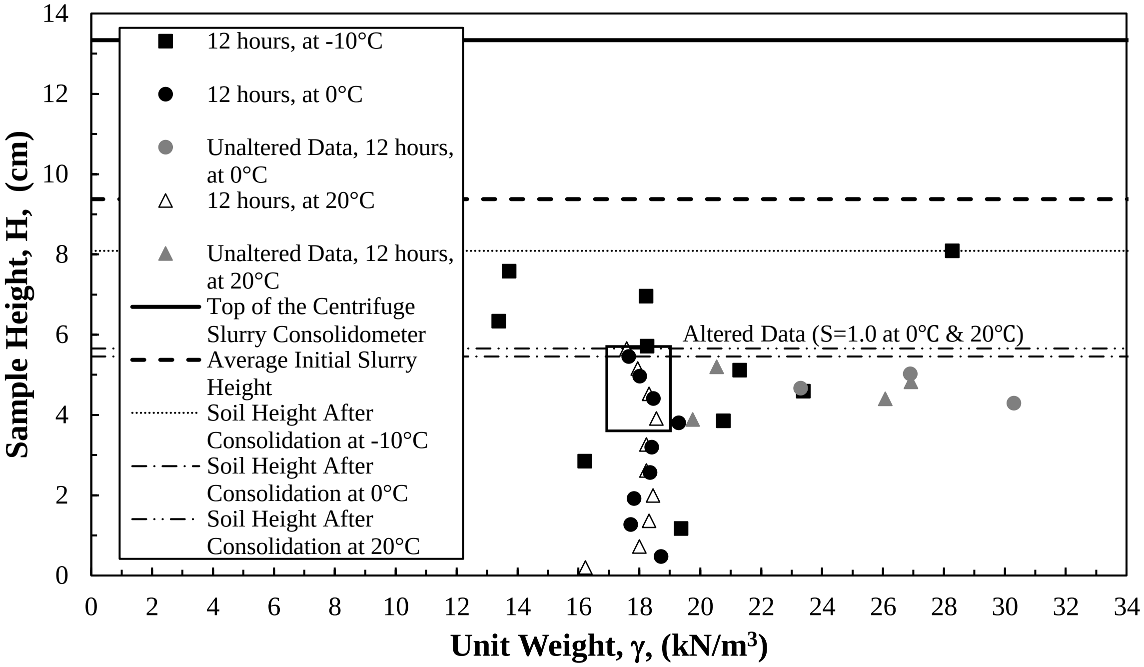


Figure 5. Time dependent unit weight profiles at 12 hours.

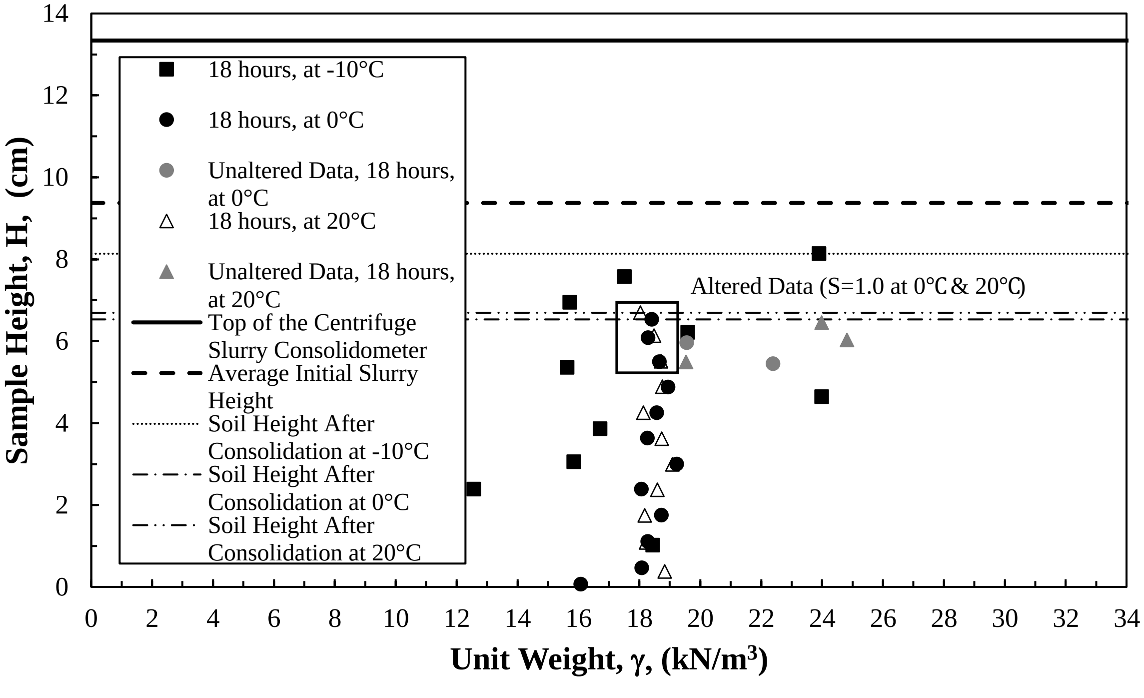


Figure 6. Time dependent unit weight profiles at 18 hours.

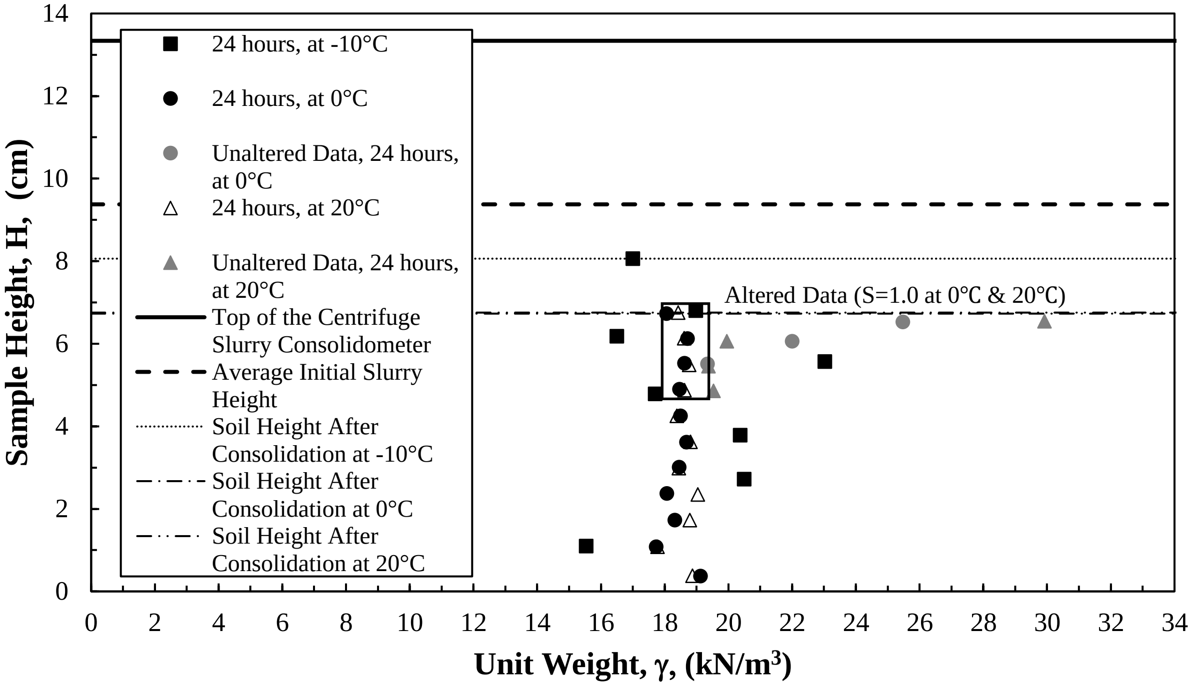


Figure 7. Time dependent unit weight profiles at 24 hours.

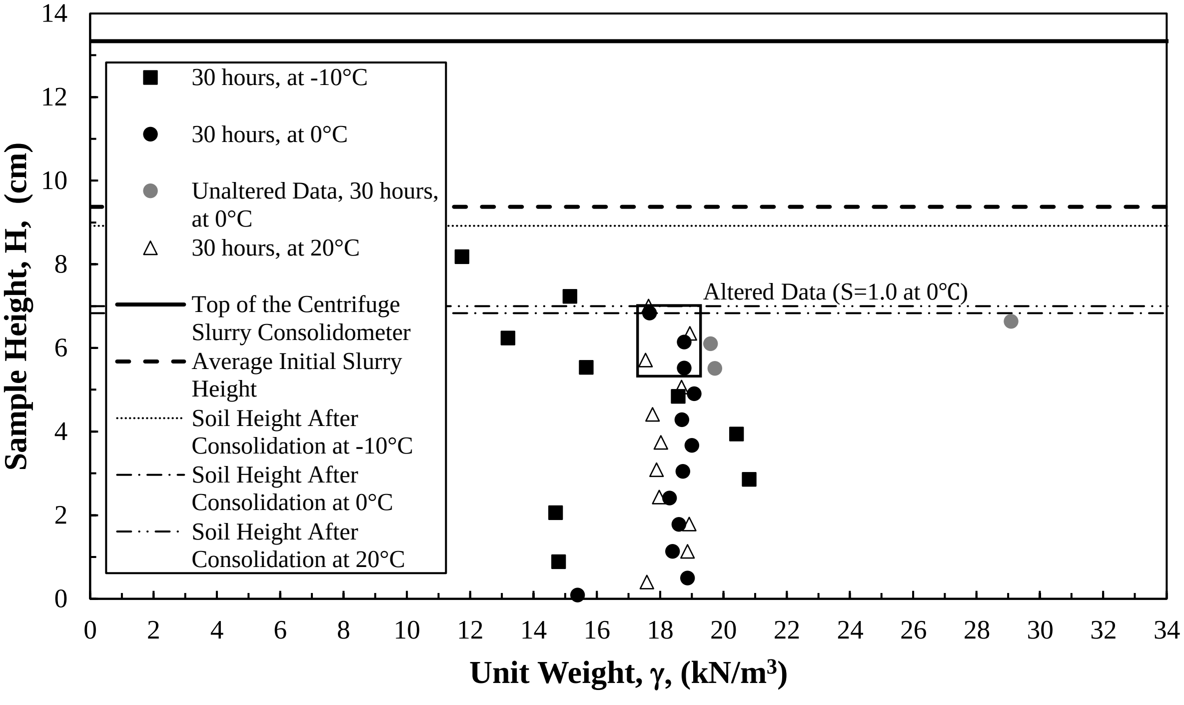


Figure 8. Time dependent unit weight profiles at 30 hours.

Data Comparison of Unit Weight Profiles At 24 Hours

For the 24-hour interval, Gilbert et al. (2011) determined an average unit weight of 18.75 kN/m^3 for a slurry with an initial water content of 44 percent. The average unit weight determined during the current study, at the same interval of time was 18.61 kN/m^3 for a slurry with an initial water content of 50 percent. Although Gilbert et al. (2011) used a lower moisture content, both studies are in relative agreement for 24 hour unit weight profiles (Figure 9). The difference in the initial water content values may explain the slight difference.

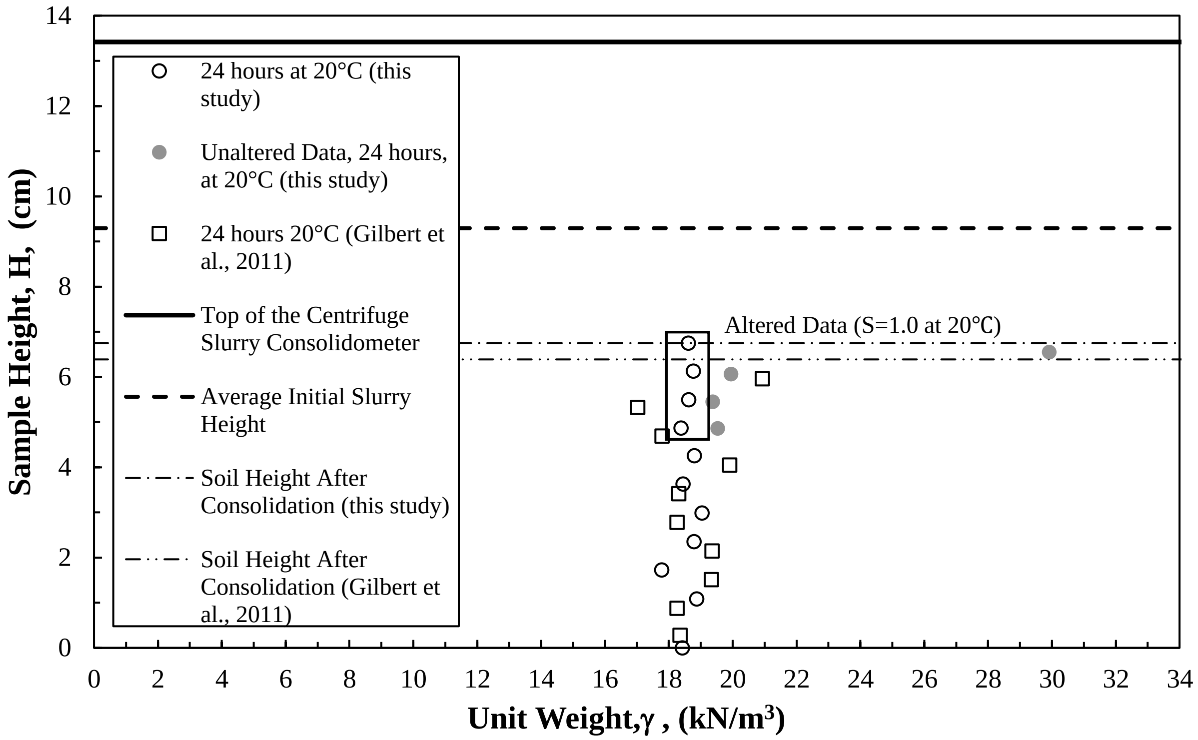


Figure 9. Data comparison of unit weight profiles at 24 hours.

Moisture Content Results

The gravimetric moisture content profiles were calculated for the same slices that were used to calculate the unit weight profiles. As expected, samples tested at -10℃ have higher moisture content values when compared to the sample tested at 0℃and 20℃. Based on the moisture content profile, it appears that steady state seepage developed at the 12-hour time interval. From the 12-hour interval to the 30-hour interval slight differences in water content from the initial slurry water content were observed. At 30 hours, a reduction of 8.10 percent for -10℃, 18.78 percent for

0℃, and 19.78 percent for 20℃ in the water content was observed in the specimens. A summary of the average values is shown in Table 2.

The difference in moisture contents at -10℃, 0℃, and 20℃ at various times was attributed to the viscosity of the pore water at different temperatures. Furthermore, three patterns were observed in the calculated moisture content profiles (Figure 10 to 13). First, the altered data at 0℃ and 20℃, and the broken slices at -10℃ did not affect the moisture content of the samples because gravimetric moisture content (based on weight) was utilized instead of volumetric moisture content (based on volume). Second, at all three testing temperatures, the first and the second slices present higher moisture content than the bottom slices. As the soil consolidates, the solid particles are sent to the bottom of the consolidometer, and the water separates from the soil. The water on the top is then drawn though the samples. Consequently, the top samples are in direct contact with the bleed water and thus present higher water contents. Finally, the bottom slices contain less moisture. The bottom samples face a greater relative centrifugal force because the centrifugal force increases with the distance (radius) from the center. The larger applied force on the soil led to faster extraction of water from the sample at this location (Gilbert et al., 2011).

Table 2. Average moisture contents as a function of time for the testing temperatures.

Cell	Time in the Centrifuge (hours)	Temperature (Celsius)	Average Moisture Content (%)	Standard Deviation (SD)
1	12	-10	43.46	7.59
		0	32.78	3.23
		20	32.12	3.20
2	18	-10	41.99	5.33
		0	31.81	2.92
		20	31.27	2.13
3	24	-10	42.42	6.68
		0	31.65	1.77
		20	30.66	1.03
4	30	-10	41.90	5.44
		0	31.22	2.79
		20	30.22	1.56

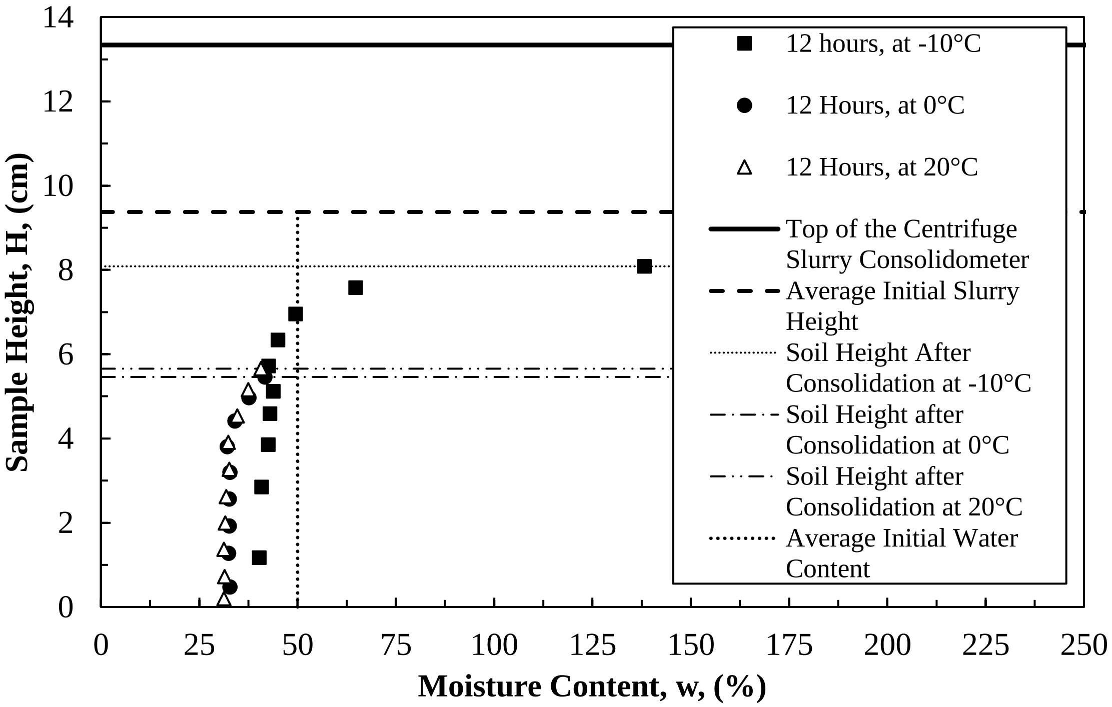


Figure 10. Time dependent moisture content profiles at 12 hours.

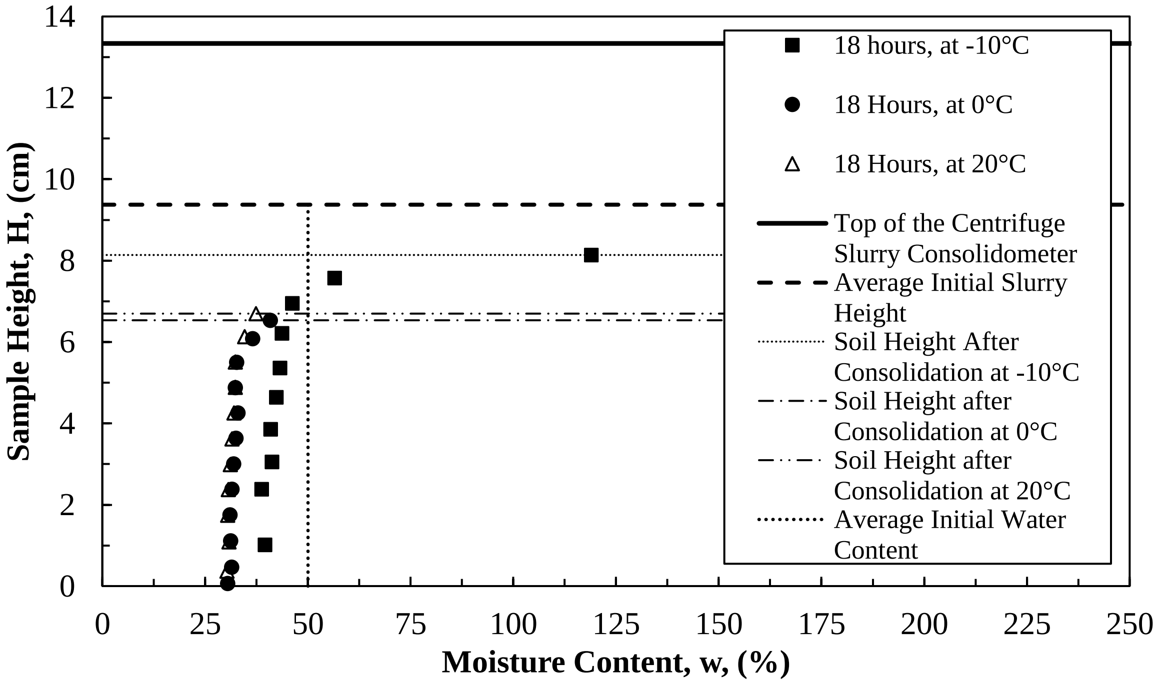


Figure 11. Time dependent moisture content profiles at 18 hours.

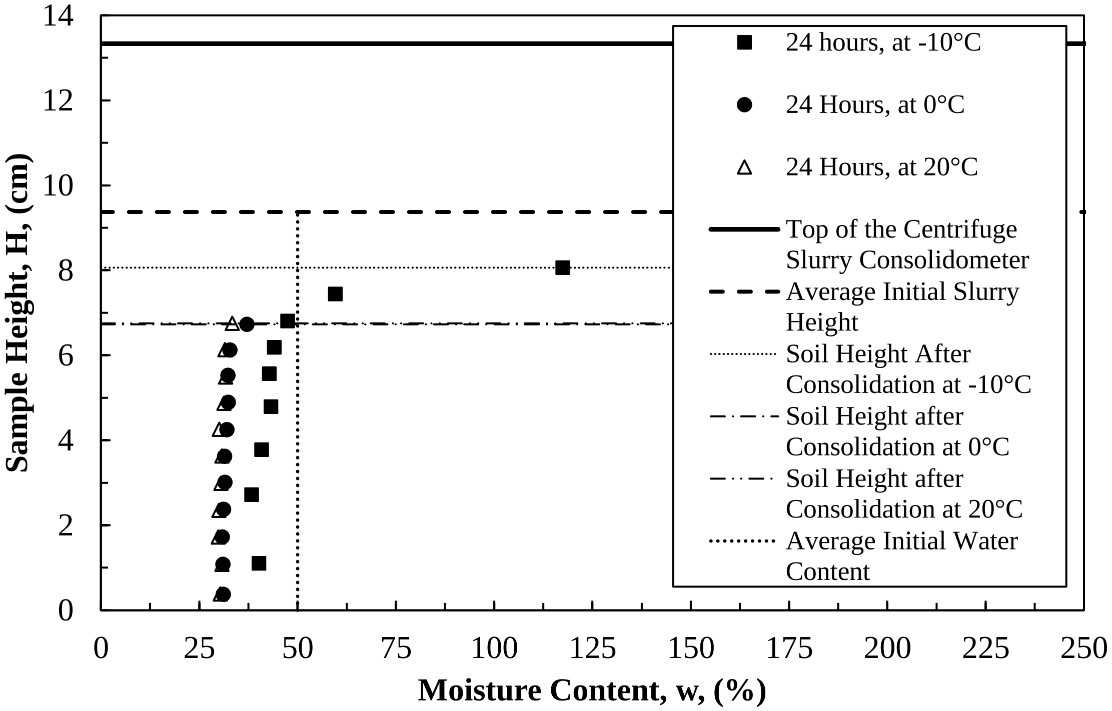


Figure 12. Time dependent moisture content profiles at 24 hours.

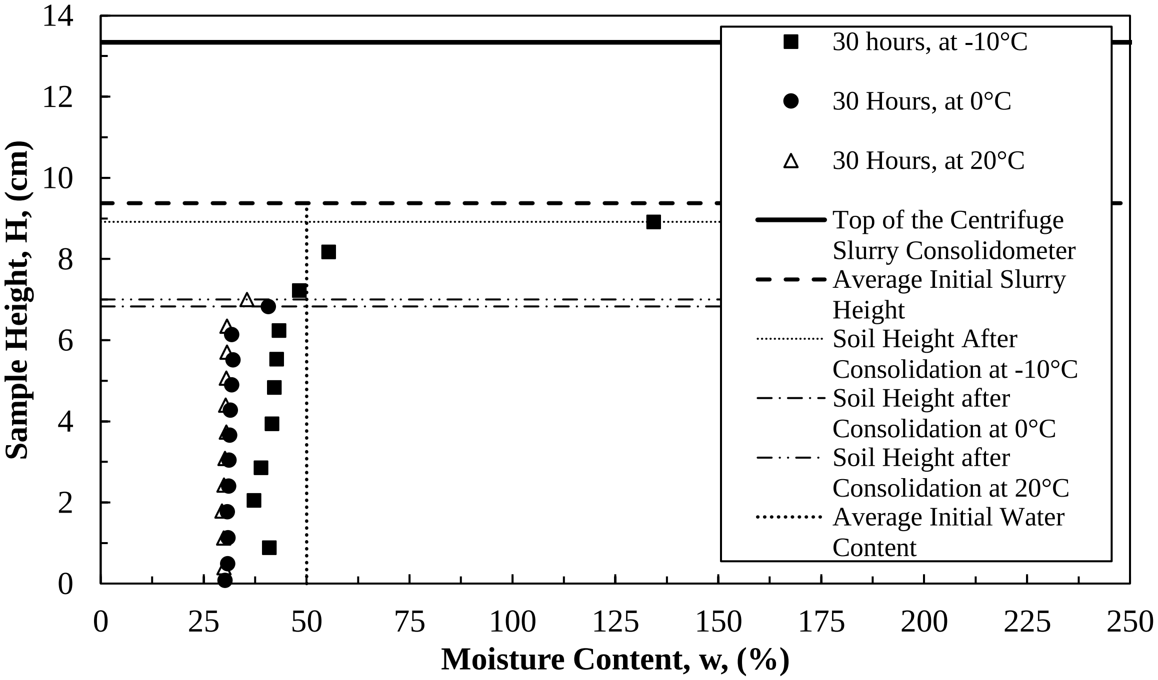


Figure 13. Time dependent moisture content profiles at 30 hours.

Data Comparison of Moisture Content Profiles At 24 Hours

For the 24-hour interval, Gilbert et al. (2011) determined an average moisture content of 30.04 percent. The average moisture content determined in the study described herein was 30.66 percent. As previously mentioned, a difference in the initial moisture content from 44 (Gilbert et al., 2011) to 50 percent (this study) at 20℃, did not significantly affect the post-consolidation moisture content when subjected to a rotation of 500 RPM (Figure 14).

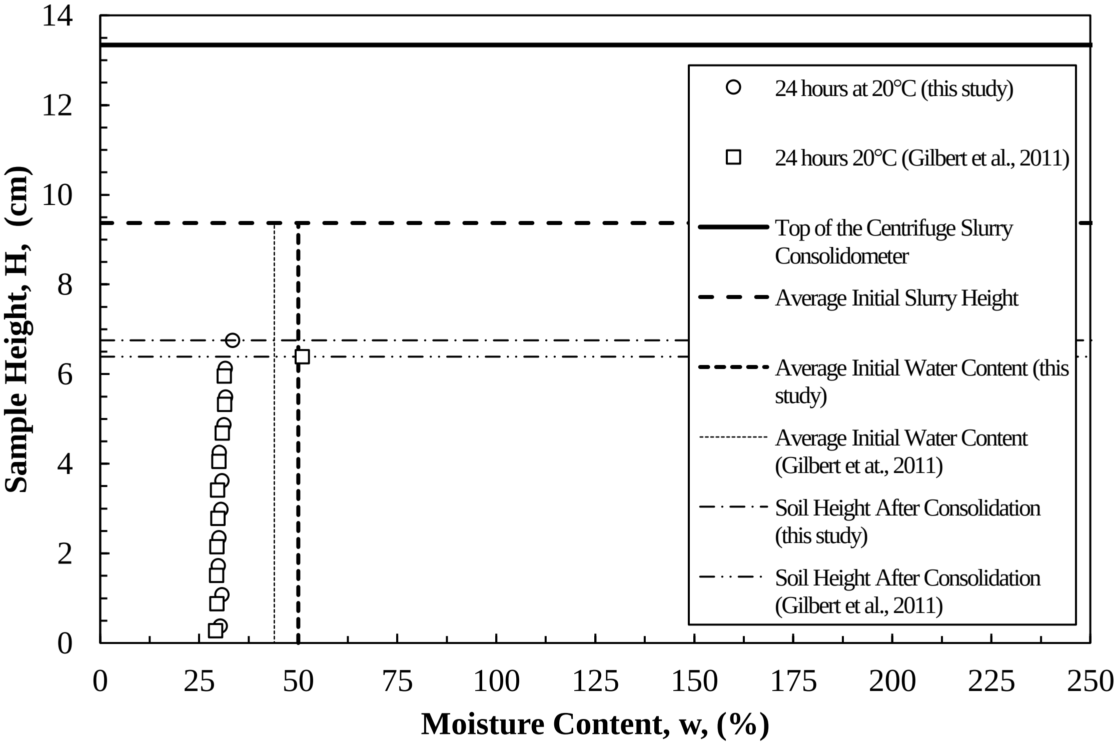


Figure 14. Data comparison of moisture content profiles at 24 hours.

Conclusions

The presented research was a continuation of previous research conducted at the University of Arkansas to quantify changes of the unit weight and moisture content profiles of kaolinite at different temperatures and different intervals of time using a small-scale centrifuge. At 30 hours, the results indicated an average unit weight of 15.52 kN/m^3, 17.91 kN/m^3, and 18.25 kN/m^3 for the kaolinite specimens at -10℃, 0℃, and 20℃ respectively. The average moisture content values at the same interval of time were 41.90 percent for the specimens at -10°C, 31.22 percent for the specimens at 0°C, and 30.22 percent for the specimens 20°C. Furthermore, at the 24-hour interval, the unit weight and moisture content profiles are in relative agreement with specimens obtained from Gilbert et al. (2011) that were performed at 20℃.

Acknowledgements

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