Verification of ASTM Centrifugation Equations for Soil Suction Determination

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Verification of ASTM Centrifugation Equations for Soil Suction Determination

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering

by

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ABSTRACT

The unit correction constant ($\beta$) in the ASTM D6836 standard needs to be evaluated. The $\beta$-value was proposed to be 0.00548 instead of 0.00553. This apparent discrepancy led to an investigation comparing the predicted and measured suction values for high air entry (HAE) ceramic disks. A Beckman-Coulter Model J6-MI six-bay centrifuge and a WP4C Dewpoint Potentiometer were used in the testing program. HAE ceramic disks rated with bubbling pressures of 3-bar and 5-bar were used as analogue soil specimens. The HAE ceramic disks were spun in the small-scale centrifuge to apply prescribed suction amounts and then placed in the WP4C Dewpoint Potentiometer to obtain corresponding suction readings. In addition, the weight of the pore water within the HAE ceramic disks was investigated to determine the pressure equilibrium for each ceramic disk. Based on the obtained results, the measured suction values were approximately an order of magnitude greater than the predicted suction values. Three recommendations for the laboratory testing procedure are provided for future research to improve the testing system. Thus, the unit correction constant ($\beta$) of the ASTM D6836 standard may be further evaluated to refine the suction measurements.
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Everything started as a dream. I dreamt that I could be the first in my family to earn a master's degree in civil engineering one day. This thesis is the last step to achieving that dream. First, I would like to acknowledge my teaching assistantship supervisor and committee member, Dr. Rodney Williams, for allowing me to serve as one of his teaching assistants in the Surveying System Class. As a teaching assistant, I developed public speaking, organizational, and leadership skills to ensure success in my future professional career. Next, I would like to thank my thesis advisor, Dr. Richard Coffman, for his patience and dedication. Thank you for answering my questions and clearing up my doubts. You are a detail-oriented professional, and your attire is always on point. I feel honored to be one of your advisees, a title that I hold proudly everywhere I go. Third, I would like to thank Dr. Michelle L. Bernhardt-Barry for serving on my research committee and for her practical advice on living a balanced life during and after college. Finally, I would like to thank my best friend, Brayan. With no blood relatives in the United States of America, you are my family and support in this country. Thank you for your sincere friendship, and the fantastic memories created together since day one of our friendship.
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1.0. INTRODUCTION

The soil water characteristic curve (SWCC) is a relationship between volumetric soil water content and soil suction within unsaturated soils. The ability of unsaturated soils to hold and store water at various soil suction levels is depicted by the SWCC. The amount of water and water storage capacity of soils influences the engineering properties of unsaturated soil, such as shear strength, hydraulic conductivity, and volume changes. Leong (2019) described that the aforementioned engineering properties may be directly or indirectly calculated using information from SWCCs. Many laboratory techniques have been developed to obtain the SWCCs of unsaturated soils. Five of the laboratory techniques are described in the ASTM D6836 (2016) standard. The laboratory techniques include:

- Hanging column,
- Pressure plate with volumetric water content,
- Pressure plate with gravimetric water content,
- Chilled mirror hygrometer, and,
- Centrifuge

The earliest studies on water storage in soils and soil suction were carried out in soil physics. Lyman Briggs, a soil physicist of the U. S. Department of Agriculture, tested soil specimens to obtain the moisture equivalent in an attempt to classify soils (Briggs, 1897). Later, Briggs and McLane (1907) studied and graphically displayed the soil and water relationship using centrifugation. Gardner (1937) studied the amount of water storage in a soil specimen when subjecting soil specimens to different centrifugal forces and proposed the centrifugation equation for soil suction. The centrifugation equation proposed by Gardner (1937) was slightly
modified throughout the years and is included as Equation 11 of the ASTM D6836 (2016) standard.

An apparent discrepancy in the unit correction constant ($\beta$) of Equation 11 of the ASTM D6836 (2016) standard was the primary focus of the research described herein. This thesis is divided into eight chapters. The introduction is presented in Chapter One. The definition of an SWCC, early studies on SWCCs, and the laboratory techniques to obtain the SWCCs for unsaturated soils are provided in Chapter Two. The explanation of the issue related to Equation 11 of ASTM D6836 (2016) standard, the equipment description, and the testing program are covered in Chapter Three. The experimental results obtained from the performed research are contained in Chapter Four. The analysis and discussion of the results are stated in Chapter Five. Conclusions, recommendations, and references are covered in Chapter Six, Chapter Seven, and Chapter Eight, respectively.
2.0. BACKGROUND

The scope of construction projects advanced tremendously due to the industrial revolution, especially in the last half of the nineteenth century (Coduto, 1999). With iron and steel being commonly used engineering materials, urban areas grew continually with larger and larger buildings being constructed. Civil engineers still relied on empirical methods and previous experience to assess soil conditions during this time. The ever-increasing size of engineering projects also increased the concerns about foundation failures and the consequence of structural collapses. With the leadership of professionals, such as Karl Terzaghi, Ralph Peck, Harry Seed, and Arthur Casagrande, Geotechnical Engineering emerged as a recognized discipline. The professionals above established theories and techniques to assess soil conditions.

Saturated soil conditions have been, and continue to be, the focus of deep foundations and earth structures. Currently, Geotechnical Engineering is in a period of change to develop theories and practices for site assessment and construction practices for unsaturated soils. Unsaturated soils are of interest because one-third of the Earth’s surface is composed of arid or semiarid soils (Dregne, 1976). The soil water characteristic curve (SWCC) is an engineering tool used in soil mechanics to measure unsaturated soil property functions. The definition and engineering applications of the SWCCs are presented in the following sections.

2.1. Definition of Soil Water Characteristic Curves (SWCCs)

As defined in Lee (1998), Khanzode et al. (2000), McCartney and Zornberg (2010), Alsherif et al. (2015), ASTM D6836 (2016), and Fredlund (2017), SWCCs are plots or numerical equations that provide information about the amount of water within the soil (either presented as gravimetric water content, volumetric water content or degree of saturation) and the corresponding soil suction. The SWCCs are also referred to as soil moisture curves, soil
water retention curves, soil moisture retention curves, soil water release curves, or capillary pressure curves.

According to Lee (1998) and Vanapalli et al. (2002), the SWCCs are characteristic for each soil type due to the unique pore-size distribution of the different soils. As shown in the SWCC from Vanapalli et al. (2002) in Figure 2.1, three distinctive phases in an SWWC are commonly observed. The phases include the boundary effect stage or capillary saturation zone, the transition stage or desaturation zone, and the residual stage of unsaturation.

In the boundary effect stage, the soil specimen is fully saturated, and the pore water is in tension due to the capillary forces. The break in the curve between the boundary effect and transition stages is called the air-entry value. The air-entry value is when air enters the largest pores of the soil. The transition stage occurs when the water content decreases considerably with increased suction values. The break between the transition zone and the residual stage is known as the residual water content. Within the residual stage, considerable changes in suction values cause relatively small variations in moisture content. The movement of water in the residual stage is associated with changes in water vapor.

As shown in Figure 2.2, when SWCCs of different soil types, from uniform sand to clay, are plotted on the same graph, the following conclusions can be drawn. As cited in Lee (1998) and McCartney and Zornberg (2010), the decrease in particle size and the increase in moisture content result in a flattened slope for the SWCCs. Moreover, high soil suction values are associated with low soil moisture contents, and low soil suction values are related to high soil moisture contents.
Figure 2.1. Phases of the soil water characteristic curve (Figure 3 from Vanapalli et al., 2002).

Figure 2.2. Series of soil water characteristic curves (Figure 14a from Lee, 1998).
2.2. Early Studies on Soil Water Characteristic Curves (SWCCs)

The water storage capacity of soils concerning soil suction was first studied in soil Physics. Briggs (1897), a physicist at the U.S. Department of Agriculture (USDA), studied the role of surface tension (capillarity) and gravity in determining the state of static soil moisture. As illustrated in Figure 2.3, Briggs (1897) stated that water travels from low-tension, large-curvature regions to high-tension, small-curvature regions in a porous media. In Figure 2.3, the circles represent spherical soil particles. The straight arrows point out the direction and relative magnitude of the capillary force on the air-water interface between particles, and the curved arrows show the direction of water flow.

![Diagram of soil water characteristic curves](image)

Figure 2.3. Idealized diagram of an unsaturated porous medium presented by Lyman Briggs. (Figure 6 from Briggs, 1897).

Another researcher from the USDA, Buckingham (1907), reported on capillary conductivity and capillary potential of the soil. As shown in Figure 2.4, the research of Buckingham (1907) consisted of imbibition experiments of six types of soils that varied from sand to clay. In the end, Buckingham (1907) defined capillary potential as the attraction of soil for water and identified that energy to be dependent on the water content within the soil sample.
Figure 2.4. The moisture retention curves were obtained from 48-inch columns after 53 to 68 days. As displayed on the vertical axis (y-axis), capillary potential $\psi$ equals elevation $x$ times a constant $A$. (Figure 7 from Buckingham, 1907).

Briggs and McLane (1907) were the first researchers to utilize centrifugation to study the relationship between soil water content and soil suction. Briggs and McLane (1907) tested soil specimens within a centrifuge at 3000g to obtain the moisture equivalent for soil classification purposes. Briggs and McLane (1907) defined the moisture equivalent as the amount of water that a soil can retain when in equilibrium with a constant measured centrifugal force. This concept is similar to that of field capacity used today, except that field capacity is developed when subjected to only the Earth’s gravitational force. A photograph of the device developed by Briggs and McLane (1907) is also presented in Figure 2.5.
Gardner (1937) built upon the work of Briggs and McLane (1907) and reported the response of soil specimens over a range of centrifugal forces. Soil specimens were subjected to centrifugal forces until each soil sample reached equilibrium (as determined by no additional changes in the mass of the specimen). Gardner (1937) proposed a centrifugation equation that was derived through several steps. The derivations of the centrifugation equation are shown below (Equation 2.1 and Equation 2.2). The capillary tension of each soil sample was calculated using Equation 2.3. The gravimetric water content was calculated by weighing the two filter paper disks in contact with each soil sample.

As in Buckingham (1907), Gardner (1937) defined capillary tension (capillary potential) as the attraction of soil particles for water and reasoned that this energy was dependent on the
amount of water content, structure, and composition of the soil sample. The experimental results of the four soils tested by Gardner (1937) were presented in Figure 2.6. Capillary tension is related to centrifugal force by the following relationship:

\[ \frac{d\psi}{dr} = r \omega^2 \]

Gardner (1937), Equation 2.1

Where:

\( \psi \) = capillary tension = capillary potential (numerically),
\( r \) = the radius of the centrifuge to any point under consideration, and,
\( \omega \) = the angular velocity.

The following relationship is determined by taking two values of \( r \) and integrating Equation 2.1:

\[ \psi_1 - \psi_2 = \frac{(r_2^2 - r_1^2) \omega^2}{2} \]

Gardner (1937), Equation 2.2

Where:

\( \psi_1 \) = capillary tension at the midpoint of the soil specimen,
\( \psi_2 \) = capillary tension at the free water surface,
\( r_2 \) = the radial distance to the free water surface, and,
\( r_1 \) = the radial distance to the midpoint of the soil specimen.

Because the capillary tension is 0 at the water surface, \( \psi_2 \) will be 0, if \( r_2 \) is at a water surface. The proposed centrifugation equation was the following mathematical statement:

\[ \psi = \frac{(r_2^2 - r_1^2) \omega^2}{2} \]

Gardner (1937), Equation 2.3
Figure 2.6. Curves 1 and 2 are for sandy soils, curve 3 is for a loam, and curve 4 is for a clay loam. The vertical axis is the percentage of moisture, and the horizontal axis is the logarithm of capillary tension (Figure 2 from Gardner 1937).

Following the centrifugation procedures used by Briggs and McLane (1907), and Gardner (1937), Russell and Richards (1938) expanded the knowledge of centrifuge testing on soil specimens. Russell and Richards (1938) centrifuged four different soil types (fine sand, sandy loam, silty loam, and silty clay) under similar conditions to those used in the research of Briggs and McLane (1907). The test results of Russell and Richards (1938) were shown in Figure 2.7.
Figure 2.7. The points lying between pF 3.0 and 4.0 were determined by centrifugation. Points obtained from other methods were also included to emphasize the continuity of the curves. The moisture desorption curves did not depart widely from linearity in the pF range from 2.0 to 4.2 for the tested soil. (Figure 3 from Russell and Richards, 1938).

Since 2000, there has been a push to utilize temperature-controlled centrifuges as a less time-consuming technique to reach equilibrium and obtain soil properties of unsaturated soils. Floor-standing centrifuges are currently being used to develop Soil Water Characteristic Curves (SWCCs) and determine the hydraulic conductivity functions for different soil types. As described in Khanzode et al. (2000), McCartney and Zornberg (2010), Reis et al. (2011), and Rahardjo et al. (2018), soils in unsaturated conditions, such as clean sand, processed silt, low plasticity clay, and high plasticity clay have been investigated.

Khanzode et al. (2000) reported on the use of a Beckman J6-HC small-scale medical centrifuge to measure the SWCC for three different fine-grained soils (processed silt, Indian head till, and Regina clay). The obtained results from the centrifuge tests were compared to two conventional laboratory techniques (i.e., pressure plate and Tempe cell). A photograph of the
device used by Khanzode et al. (2000) is provided in Figure 2.8. The obtained results were encouraging. Centrifugation provided remarkably similar results to traditional techniques in the range from 0 to 600 kPa in less time, as shown in Figure 2.9.

Figure 2.8. J6-HC centrifuge with six swinging-type buckets of the JS-4.2 rotor assembly. Two centrifuge canisters holding the samples and four empty canisters. (Figure 2 from Khanzode et al., 2000).

Figure 2.9. Comparison between the soil-water characteristic curves measured using the conventional and the proposed new procedure using the small-scale medical centrifuge (Figure 6 from Khanzode et al., 2000).
McCartney and Zornberg (2010), researchers at the University of Texas at Austin, used a small radius (0.7 m) centrifuge to study the hydraulic characteristics of an unsaturated compacted clay and then compared the results to the outcomes from 1-g column infiltration tests. The results from centrifugation contained less scatter than the traditional laboratory technique and were obtained in considerably less time, as shown in Figure 2.10. It took 1,200 hours to obtain two points using the 1-g column infiltration test in contrast to only 200 hours to obtain 20 points using the centrifuge.

![Figure 2.10. Comparison of hydraulic characteristics of the remolded and compacted clay specimens obtained using steady-state infiltration in a centrifuge permeameter to those obtained with 1-g steady-state infiltration (Figure 12b from McCartney and Zornberg, 2010).](image)

Reis et al. (2011) also reported the similarity of results of different testing methods for a residual gneissic soil profile using undisturbed and remolded soil specimens. Good agreement was observed between centrifugation and conventional laboratory techniques, such as filter paper and pressure plate techniques, in the soil suction up to 900 kPa. The comparison between centrifugation
and traditional laboratory techniques of the undisturbed clayey silt sand specimens was reported in Figure 2.11.

![Figure 2.11](image)

Figure 2.11. Comparison between soil water retention curves from conventional methods fitted by the Mualem-van Genuchten model and the small-scale centrifuge method data for undisturbed clayey silt sand specimens (Figure 8 from Reis et al., 2011).

Rahardjo et al. (2018) reported results obtained from testing three different types of soils (clean sand, clayey sand, and clay obtained from residual soils in Singapore). Rahardjo et al. (2018) utilized an Eppendorf model 5804R centrifuge to obtain the soil suction values up to 250 kPa and a WP4C Dewpoint Potentialmeter to measure the suction for values higher than 250 kPa. As shown in Figure 2.12, the obtained SWCC results of the clay soil showed good agreement from 0.01 to 250 kPa between centrifugation and the Tempe cell. The testing procedure to obtain the SWWC for the clay took two months using the Tempe cell compared to only two days in the small-scale centrifuge.
2.3. Laboratories Techniques to Measure Soil Water Characteristic Curves (SWCCs)

The chilled mirror hygrometer and centrifugation are two of the five laboratory techniques described in the ASTM D6836 (2016) standard. These two laboratory techniques are the focus of this research. These testing procedures determine SWCCs during desorption (drying). The history, the laboratory procedure, the recommended soil types to be tested in each laboratory technique, and the most suitable suction range for each method are described in this section.

2.3.1. History of Chilled Mirror Hygrometer

As stated in Decagon Devices (1999), the first hygrometers were built as potable tools to measure the moisture content in the air (humidity). With an increasing scientific interest in unsaturated soil mechanics, researchers required an automatic, accurate, and user-friendly laboratory device to speed up the testing process of measuring the amount of suction in unsaturated soils. As a result, the chilled mirror hygrometer was developed as a reliable and
easy-to-use apparatus to measure soil suction for the mid-to-high-range of suction from 3000 kPa to 300,000 kPa (Gee et al., 1992).

2.3.2. The Laboratory Procedure for the Chilled Mirror Hygrometer

According to Lu and Likos (2004), the chilled mirror hygrometer (Figure 2.13) is a sealed device that measures the dew point temperature by evenly circulating cold air above the soil sample to create condensation of water vapor on a metal plate (mirror). Using this device, total suction is calculated from relative humidity values that are correlated with the dew point temperature. As listed in Equation 2.4, total suction is the combination of matric and osmotic suction. As reported by Krahn and Fredlung (1972), osmotic suction is the suction that arises from the presence of dissolved solutes (salt and ionic concentrations), and matric suction is defined as the pressure of the dry soil exerted on the surrounding soil to equalize the moisture content in the soil matrix.

\[
\psi_t = \psi_o + \psi_m
\]

ASTM D6836 (2016), Equation 2.4

Where:

\(\psi_t\) = total of the soil specimen (kPa),

\(\psi_o\) = osmotic suction (kPa), and,

\(\psi_m\) = matric suction (kPa).

The procedure to obtain the soil suction of a soil specimen using a chilled mirror hygrometer is very simple. A soil specimen is placed in a dish (made of non-porous and non-corroding materials like stainless steel or plastic) with a diameter of at least 20 mm and a height of at least 5 mm. When the soil specimen is placed inside the chilled mirror hygrometer, the device measures the water activity of the soil sample (dew point temperature). The Kelvin equation (Equation 2.5) is then used to calculate the total suction of the soil sample.
\[ \psi_t = - \left( \frac{RT}{V_{w0}\omega_v} \right) \times \ln \left( \frac{u_v}{u_{v0}} \right) = - \left( \frac{RT}{V_{w0}\omega_v} \right) \times \ln (RH) \]

Lu and Likos (2004), Equation 2.5

Where:

\( \psi_t \) = total suction of the soil specimen (kPa),

\( R \) = universal gas constant (8.31432 J mol\(^{-1}\) K\(^{-1}\)),

\( T \) = absolute temperature (K),

\( V_{w0} \) = specific volume of water (i.e., reciprocal of density, m\(^3\)/kg),

\( \omega_v \) = the molecular mass of water vapor (18.016 kg/kmol),

\( u_v \) = partial pressure of soil water vapor (kPa), and,

\( u_{v0} \) = saturation pressure of pure water vapor (kPa).

Figure 2.13. Photograph of a chilled mirror hygrometer with an open sample drawer and specimen to be inserted for testing (Figure 7 from ASTM D6836, 2016).
2.3.3. Soil Type and Suitable Range for the Chilled Mirror Hygrometer

According to the ASTM D6836 (2016) standard, the hygrometer is suitable for defining the soil water characteristic curves for both coarse- and fine-grained soils, especially at higher suctions (typically >1000 kPa or >10 bar) and lower water contents. Under these conditions, the osmotic suction is small for soils within the lower water content range. Thus, the total and matric suction are comparable within this range.

2.3.4. History of Centrifugation

Stephenson (2016) defined centrifugation as separating components with different densities by spinning the elements around a fixed axis at high speeds. Cash (2017) stated that the first centrifuge-type machine was utilized in the dairy industry in 1864 by the German Antonin Prandtl to separate the milk and the cream. Later in 1869, the centrifugation technique moved into the field of medicine. Friedrich Miescher, a Swiss biologist, built the first crude centrifuge to separate blood components (Cash, 2017). Since then, centrifuges have become readily available and are commonly used in all medical laboratories and the dairy industry.

The centrifugation technique also helped the development of the field of engineering. As previously mentioned, physicists at the U.S. Department of Agriculture (USDA), Lyman Briggs and J. McLane developed a centrifuge technique to study the moisture equivalent of soils. Later, Gardner (1937) established the centrifugation equation based on radial distance and angular velocity. Since 1937, investigators have employed the device to obtain the soil water characteristic curves for different soil types in less time than other techniques.

2.3.5. The Laboratory Procedure of Centrifugation

The last laboratory technique covered in the ASTM D6836 (2016) standard is Centrifugation (Figure 2.14). This method is used to obtain SWCCs by desorption of soil
samples. Soil specimens in a support chamber were subjected to centrifugal forces. The suction of the soil is directly related to the density of the pore fluid, the maximum radius of the centrifuge, and the angular speed. Therefore, different soil suctions can be induced by changing the pore fluid density, the radial distance, or angular velocity.

The height and diameter of the soil specimens depend on the type of centrifuge being used to test the soil. As per ASTM D6836 (2016) standard, soil specimens trimmed from undisturbed samples with a diameter of 38 mm and a height of 51 mm are recommended. Soil specimens are typically placed in the centrifuge buckets and spun for at least 120 minutes or until no additional liquid is displaced from the sample (pore liquid equilibrium). The magnitude of the matric suction is calculated using Equation 2.6, and the water content is calculated as established per ASTM D2216.

$$\psi_i = \beta (\rho_w - \rho_g) \omega^2 (r_b^2 - r_t^2)$$  \hspace{1cm} \text{ASTM D6836 (2016), Equation 2.6}

Where:

$\psi_i$ = the $i$th matric suction (kPa),

$\beta$ = unit conversion constant = 0.00553,

$\rho_w$ = density of the pore liquid (typically water, 1.0 kg/L),

$\rho_g$ = density of the pore gas (typically assumed to be zero),

$\omega$ = angular velocity (rpm),

$r_b$ = outer radius of rotation (m), and,

$r_t$ = inner radius of rotation (m).
2.3.6. Soil Type and Suitable Range for the Centrifuge

According to Mirshekari et al. (2018), the centrifuge technique is ideal for fine-grained soils due to greater drainage rates during centrifuge modeling and for coarse-grained soils where an appreciable amount of water can be extracted. Centrifugation is suitable to define the soil water characteristic curve at lower suctions (0 to 120 kPa or 0 to 1.2 bar) near saturation and to identify the air entry suction, as reported in the ASTM D6836 (2016) standard.

2.4. Applications of Soil Water Characteristic Curves (SWWCs)

As cited in Vanapalli et al. (1996), Lee (1998), McCartney and Zornberg (2010), Gilbert et al. (2011), Coccia et al. (2013), and Leong (2019), shear strength, hydraulic conductivity, and volume changes of unsaturated soils are engineering properties that are directly influenced by the amount of water within the soil and the water storage capacity of the soil. These engineering
properties can be calculated indirectly from SWCCs. However, only shear strength and hydraulic conductivity are discussed below.

### 2.4.1. Shear Strength

According to Vanapalli et al. (1996), the relationship between shear strength and matric suction was determined to be nonlinear. Vanapalli et al. (1996) performed a comprehensive experimental program using statically compacted specimens of glacial till classified as sandy lean clay, under saturated and unsaturated conditions. The unsaturated shear strength of the samples was determined using multi-stage direct shear testing with a device designed by Gan and Fredlund (1988). Predetermined normal stress and the desired matric suction were applied to soil specimens by maintaining constant air pressure and by maintaining a saturated high air entry disk. Finally, the unsaturated shear strength was calculated using Equation 2.7 (Fredlund et al., 1988).

\[
\tau_f = c' + (\sigma_n - u_a) \tan \phi' + (u_a - u_w) \tan \phi^b
\]

Fredlund et al. (1988), Equation 2.7

Where:

- \( \tau_f \) = shear strength of unsaturated soil,
- \( c' \) = effective cohesion of the soil,
- \( \phi' \) = effective angle of shearing resistance for saturated soil,
- \( \phi^b \) = angle of shearing resistance relative to an increase in matric suction,
- \( \sigma_n \) = normal stress,
- \( u_a \) = pore-air pressure,
- \( u_w \) = pore-water pressure,
- \( (\sigma_n - u_a) \) = net normal stress on the failure plane at failure, and,
- \( (u_a - u_w) \) = matric suction at the point of failure.
Vanapalli et al. (1996) concluded that the shear-strength envelopes were linear up to the air-entry value of the soil. After the air-entry value, the soil specimens began to desaturate. The area of water available for transmitting shear strength decreased. As a result, shear strength decreased with an increase in matric suctions, as shown in Figure 2.15.

Figure 2.15. Shear strength as a function of matric suction under different net normal stresses with initial water content at dry of optimum conditions (Figure 2 from Vanapalli et al., 1996).

2.4.2. Hydraulic Conductivity

Hydraulic conductivity is directly measured in soil laboratories using a rigid wall permeameter, a flexible wall permeameter, or a centrifuge permeameter. However, these laboratory techniques are costly and time-consuming. The hydraulic conductivity of soils can also be determined indirectly. For example, Rahardjo and Zai (2015) conducted research to determine the hydraulic conductivity of four soil types (volcanic sand, glass beads, fine sand, and
Rahardjo and Zai (2015) proposed a new equation to calculate the hydraulic conductivity of unsaturated soils using matric suction (Equation 2.8).

\[
\begin{align*}
    k_r &= \frac{\sum_{i=m}^{n} [(i-m)^2-(i-m-1)^2] \psi_i^{-2}}{\sum_{i=1}^{n} [(i)^2-(i-1)^2] \psi_i^{-2}} \\
    \text{Rahardjo and Zai (2015), Equation 2.8}
\end{align*}
\]

Where:

- \( k_r \) = relative hydraulic conductivity, (i.e., \( k_r = k(\theta_w) / k_s \)),
- \( i \) = interval number that increases as the volumetric water content decreases,
- \( m \) = total number of intervals between the saturated volumetric water content, \( \theta_s \), and the lowest volumetric water content, \( \theta_L \), and,
- \( \psi_i \) = the \( i \)th matric suction (kPa).

The general form of the equation was initially used by Marshall (1958) to determine the unsaturated hydraulic conductivity. The general equation was later refined by Kunze et al. (1968). In Equation 2.8, suction was considered a variable, and the SWCC, in the form of degree of saturation, was adopted as a probability function. The soil volume change was also incorporated into the equation. The hydraulic conductivity values obtained in the conducted research were compared with the data collected by Brooks and Corey (1964) as shown in Figure 2.16. Rahardjo and Zai (2015) concluded that using a maximum suction of \( \psi_r \) (as shown in Table 2.1) the hydraulic conductivity values of the four tested soils aligned with the measured data in the range of 0.1 to 30 kPa. The investigators also observed that the unsaturated hydraulic conductivity for sandy soils decreased faster than the hydraulic conductivity for clayey soils, as associated with an increase in matric suction.
Table 2.1. Fitting parameters and SWCC variables (Table 1 from Rahardjo and Zai, 2015).

<table>
<thead>
<tr>
<th>Type of Soil</th>
<th>Fitting Parameters</th>
<th>SWWC Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a (kpa)</td>
<td>n</td>
</tr>
<tr>
<td>Volcanic Sand</td>
<td>1.88</td>
<td>9.44</td>
</tr>
<tr>
<td>Glass Beads</td>
<td>3.03</td>
<td>28.97</td>
</tr>
<tr>
<td>Fine Sand</td>
<td>4.23</td>
<td>8.34</td>
</tr>
<tr>
<td>Touchet Silt Loam</td>
<td>8.30</td>
<td>9.64</td>
</tr>
</tbody>
</table>

*Note: a, n, m are the fitting parameters for Fredlund and Xing's (1994) equation, AEV is the air entry value, and \( \psi_r \) is the residual suction value.

Figure 2.16. Calculated results using the proposed equation and a maximum suction of \( \psi_r \) (Figure 12 from Rahardjo and Zai, 2015).

2.5. Summary

This Chapter consisted of four sections. The definition of a soil water characteristic curve (SWCC) was covered in Section 2.1. The early studies on SWCCs with laboratory data and
figures are mentioned in Section 2.2. Two laboratory techniques to measure the SWCCs are discussed in Section 2.3. The parameters to indirectly obtain engineering properties, such as shear strength and hydraulic conductivity of soils from SWCCs, are detailed in Section 2.4.
3.0. METHODS AND MATERIALS

A comprehensive testing program was performed to evaluate Equation 11 of the ASTM D6836 (2016) standard. A Beckman-Coulter Model J6-MI six-bay centrifuge and a WP4C Dewpoint Potentiometer were used to test analogue specimens. High Air Entry (HAE) ceramic disks were selected as the analogue specimens for the testing program to compare the predicted suction values (using the Equation 11 of the ASTM D6836 standard) with the measured suction values (using the WP4C Dewpoint Potentiometer) of the analogue samples. The initially saturated HAE ceramic disks were subjected to different angular velocities and different time intervals in the centrifuge. A description of the equipment and the testing program are covered herein.

3.1. ASTM D6836 (2016) Standard Discrepancy

The unit correction constant (β) in Equation 11 of the D6836 (2016) standard needs to be further evaluated (Equation 3.1). The β-value was mathematically calculated to be 0.00548 instead of the current 0.00553. This apparent discrepancy led to an investigation comparing centrifuge-predicted suction and centrifuge-measured suction. The hand calculations below indicate the approach that was used to obtain the proposed new β-value.

\[ \psi_i = \beta (\rho_w - \rho_g) \omega^2 (r_b^2 - r_t^2) \]  
ASTM D6836 (2016), Equation 3.1

The \( \psi_i \) in units of kPa of the left side of Equation 11 of the ASTM D6836 (2016) standard was simplified below.

\[ \psi_i \text{ in units of kPa} = \left[ \frac{km^2}{m^2} \right] = \left[ \frac{km}{m^2} \right] \times \left[ \frac{1000 N}{kN} \right] = \left[ \frac{1000 \times kg \times m}{s^2} \right] = 1000 \times \left[ \frac{kg}{s^2} \times m \right] \]

The units on the right side of Equation 11 of ASTM D6836 (2016) standard are listed next.

\[ = [\beta \text{ dimensionless}] \times \left[ \frac{kg}{L} \right] \times \left[ \left( \frac{rev}{min} \right)^2 \right] \times \left[ m^2 \right] \]
= \left[ \beta \text{ dimensionless} \right] \times \left[ \frac{kg}{L} \times \frac{1000 L}{m^3} \right] \times \left[ \frac{rev}{min} \times \frac{min}{60 \text{ sec}} \times \frac{2\pi \text{ rad}}{rev} \right]^2 \times [m]^2

= 1000 \times \left[ \beta \text{ dimensionless} \right] \times \left[ \frac{kg}{m^2} \right] \times \left[ \frac{2\pi \text{ rad}}{60 \text{ sec}} \right]^2 \times [m]^2

= 1000 \times \left[ \beta \text{ dimensionless} \right] \times \left[ \frac{2\pi \text{ rad}}{60 \text{ sec}} \right]^2 \times \left[ \frac{kg}{s^2 \cdot m} \right]

By setting the right and the left side of Equation 11 of ASTM D6836 (2016) standard equal to each other, the \( \beta \)-value is obtained.

1000 \times \left[ \frac{kg}{s^2 \cdot m} \right] = 1000 \times \left[ \beta \text{ dimensionless} \right] \times \left[ \frac{2\pi \text{ rad}}{60 \text{ sec}} \right]^2 \times \left[ \frac{kg}{s^2 \cdot m} \right]

\( \beta = 0.01097 \) [dimensionless]

The equation proposed by Gardner (1937), shown previously as Equation 2.3, requires the \( \beta \)-value to be divided by two due to the integration. Therefore, the \( \beta \)-value needs to be divided by two.

\( \beta \)-proposed = 0.00548 [dimensionless]

3.2. Equipment Description

The equipment used in the testing program was located within the soil mechanics laboratories of the University of Arkansas. Two laboratory devices were used in the testing program: a temperature-controlled centrifuge and a chilled mirror hygrometer (WP4C Dewpoint Potentiometer). Both pieces of equipment tested the High Air Entry (HAE) ceramic disks. The HAE ceramic disks were used as analogue soil specimens, and special centrifuge consolidometers were constructed to contain the HAE ceramic disks during spinning within the centrifuge. The testing equipment is described in-depth in the following sections.

3.2.1. High Air Entry Ceramic Disks

Padilla et al. (2006) stated that High Air Entry (HAE) ceramic disks are porous stones that provide a medium for water in a soil specimen to migrate into without losing solid particles
from the soil specimen. As shown in Figure 3.1, HAE ceramic disks are rated in terms of bubbling pressure. The bubbling pressure is the maximum allowed air pressure that the ceramic disk can withstand without allowing air to freely pass through the ceramic disk. HAE ceramic disks are commonly used as a restricting medium and axis translation material in laboratory devices, such as pressure plates, Tempe cells, and centrifuges. The physical properties of the HAE ceramic disks that were used in this study are listed in Table 3.1.

![Figure 3.1. High Air Entry (HAE) ceramic disks (photograph taken by the author).](image)

### Table 3.1. Physical properties of HAE ceramic disks used as the analogue specimens.

<table>
<thead>
<tr>
<th>HAE Ceramic</th>
<th>Diameter</th>
<th>Thickness</th>
<th>Bubbling Pressure</th>
<th>Bubbling Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disk</td>
<td>[mm]</td>
<td>[mm]</td>
<td>[kPa]</td>
<td>[bar]</td>
</tr>
<tr>
<td>1-bar</td>
<td>28.74</td>
<td>7.28</td>
<td>100</td>
<td>1</td>
</tr>
<tr>
<td>2-bar</td>
<td>28.74</td>
<td>7.28</td>
<td>200</td>
<td>2</td>
</tr>
<tr>
<td>3-bar</td>
<td>28.74</td>
<td>7.28</td>
<td>300</td>
<td>3</td>
</tr>
<tr>
<td>5-bar</td>
<td>28.74</td>
<td>7.28</td>
<td>500</td>
<td>5</td>
</tr>
<tr>
<td>15-bar</td>
<td>28.74</td>
<td>7.28</td>
<td>1500</td>
<td>15</td>
</tr>
</tbody>
</table>

3.2.2. Centrifuge Consolidometers

As shown in Figure 3.2, the centrifuge consolidometers were constructed from multiple individual parts assembled into an apparatus. At the University of Arkansas, similar types of centrifuge consolidometers have been used in past centrifugation research, such as Gilbert et al. (2011), Miranda (2018), and Thomas (2018). In this research, each centrifuge consolidometer consisted of the following items:

- One 1.58-inch (4.01 cm) diameter by 5.19-inch (13.19 cm) long PVC tube,
- One 0.23-inch (0.58 cm) thick aluminum oxide porous stone,
• Four 0.16-inch (0.40 cm) diameter by 6.46-inch (16.41 cm) long all-threaded rods,
• Eight circular-shaped threaded nuts,
• Four round flat washers,
• One 0.12-inch (0.31 cm) thick aluminum top plate,
• One 0.24-inch (0.62 cm) thick aluminum bottom plate, and,
• Two rubber gaskets.

As displayed in Figure 3.3, the centrifuge consolidometers, on average, were 5.82 inches (14.79 cm) tall when assembled (distance from the bottom of the bottom plate to the top of the top plate). 10 holes of 3/8-inch (0.95 cm) diameter were drilled in the bottom plate to enable drainage of the pore liquid from the analogue specimens through the bottom plate. When assembled, the slurry consolidometers were slid into a 3.98-inch (10.12 cm) diameter by 5.53-inch (14.05 cm) tall centrifuge aluminum swinging buckets as shown in Figure 3.4.

Figure 3.2. Parts of a centrifuge slurry consolidometers (photograph taken by the author).
Figure 3.3. The centrifuge consolidometers, on average, were 5.82 inches (14.79 cm) tall when assembled (photograph taken by the author).

Figure 3.4. The centrifuge consolidometer was placed inside the centrifuge aluminum bucket (photograph taken by the author).
3.2.3. Centrifuge

A Beckman-Coulter Model J6-MI centrifuge with a six-place JS-4.2A swinging bucket rotor was used for the testing program (Figure 3.5). According to Gilbert et al. (2011), the floor-standing device had a maximum angular velocity of 4,200 revolutions per minute (5,020 g) at a maximum rotor distance of 10 inches (25.40 cm). The dimensions of the centrifuge were 28 inches wide (71.1 cm) by 33 inches (83.8 cm) deep and 35.5 inches (90.1 cm) tall, and the centrifuge weighed about 555 pounds (252 kg). The panel display board of the centrifuge was digital and easy to operate.

The J6-MI high-capacity centrifuge was acquired by Dr. Richard Coffman in 2010 and was located within the soil mechanics laboratory of the University of Arkansas (Bell Engineering 1140). The centrifuge has been used to conduct other investigations in recent years, such as the following list:

1. To prepare samples for direct simple shear tests (Gilbert et al., 2011),
2. To study the hydraulic conductivity of clayey soils (Thomas, 2018), and,
3. To evaluate the engineering properties of prepared soils at different temperatures and angular velocities (Miranda, 2018).
According to Meter (2018), the WP4C Dewpoint Potentiometer is a fast and reliable instrument for measuring the total suction of soil samples using the chilled-mirror dew point technique. METER Group, Inc. designed and distributed this apparatus that was acquired by Dr. Coffman in 2019. As stated in the WP4C Dewpoint Potentiometer operating manual (Meter, 2018), this device is suitable for 0 to 300 MPa (0 to 300,000 kPa or 0 to 3000 bar) and has a reading time of approximately 20 minutes in the precise mode. The WP4C Dewpoint Potentiometer had a length of 9.5 inches (24.1 cm), a height of 9.0 inches (22.9 cm), a width of 3.5 inches (8.9 cm), and weighed about 7.1 pounds (3.2 kg). As shown in Figure 3.6 and Figure 3.7, the panel display board of this device was an alphanumeric LCD with backlighting.
3.3. Testing Program

The testing procedure was divided into two phases: the calibration phase and the testing phase. Five sets of HAE ceramic disks rated with different bubbling pressures (1, 2, 3, 5, and 15 bar) were tested at different angular velocities (100, 200, 500, 1000, and 2000 RPM) and removed from the centrifuge at different time intervals (1, 2, 4, 8, 12, 16 and 24 hours). The selected angular velocities and the fixed radial distance of the analogue samples in the testing
phase were chosen to have predicted suction values below the bubbling pressures of the HAE ceramic disks. As presented in the results section, the predicted suction values that were calculated using Equation 11 of the D6836 (2016) standard and the measured suction values obtained using the WP4C Dewpoint Potentiometer are presented in units of kilopascals (kPa), and the pore water weights are shown in the unit of grams (g). The parameters for the testing phase were selected after the calibration phase.

3.3.1. The Calibration Phase

The calibration testing was aimed at determining the appropriate centrifugal velocities and the appropriate time intervals for the testing phase. The calibration phase was initiated by saturating the High Air Entry (HAE) ceramic disks with boiling de-aired deionized water (DI water). The DI water was brought to a boil by means of a hot plate at a temperature of 500 degrees Celsius for 15 minutes. Next, the ceramic disks were submerged in the boiling DI water for an additional 15 minutes. While immersed in the DI water, the HAE ceramic disks were then allowed to cool down to room temperature for 30 minutes.

After being cooled, the HAE ceramic disks were placed inside the centrifuge consolidometers as displayed in Figure 3.8. The aluminum oxide porous stones placed at the bottom of the slurry consolidometers were also saturated by submerging the stone in DI water before the assembly. As shown in Figure 3.9, a set of four slurry consolidometers with the same pressure-rated HAE ceramic disks were placed in the centrifuge during each spin cycle.
Figure 3.8. Assembly of an individual centrifuge consolidometer with an HAE ceramic disk. The centrifuge consolidometer was then inserted into the centrifuge aluminum swinging bucket (Photograph taken by the author).

Figure 3.9. Set of four slurry consolidometers, with HAE ceramic disks, placed in the centrifuge aluminum swinging buckets (Photograph taken by the author).
The HAE ceramic disks were spun for 1, 2, 4, and 8 hours at an angular velocity of 100 RPM. When the four slurry consolidometers have spun in the centrifuge for one hour, one of the centrifuges consolidometers was removed from the centrifuge device. The HAE ceramic disk was taken out from the removed centrifuge consolidometer and then weighed with an analytical balance (Model A-200DS). After the mass of the HAE ceramic disk was obtained, the removed disk was placed in a WP4C Dewpoint Potentiometer to obtain the corresponding suction reading. A dummy weight was put into the empty centrifuge canister, and the canister was placed back into the centrifuge to balance the centrifuge with the remaining three centrifuge consolidometers.

The second centrifuge consolidometer was removed at the two-hour mark, and the previously mentioned procedure was repeated. The third and fourth centrifuge consolidometers were rotated in the centrifuge for four and eight hours, respectively. The process was repeated at each angular velocity of 100, 200, 500, 1000, and 2000 RPM for the set of the different pressured-rated HAE ceramic disks (1, 2, 3, 5, and 15 bar). The centrifuge temperature during the calibration phase was set to 15 degrees Celsius, and the testing temperature of the WP4C Dewpoint Potentiometer was set to 20 degrees Celsius.

3.3.2. Testing Phase

The main differences between the calibration phase and the testing phase were that only the 3-bar and 5-bar HAE ceramic disks were tested during the testing phase and that these HAE ceramic disks were spun in the centrifuge for longer time intervals. The preparation method for the HAE ceramic disks and centrifuge consolidometers was the same in the testing phase as in the calibration phase. Likewise, obtaining the pore water weights and the measured suction values was the same as those used during the calibration phase. The testing time intervals were 1, 2, 4, 8, 12, 16, and 24 hours at angular velocities of 100, 200, 500, 1000, and 2000 revolutions.
per minute. Similarly, the testing temperature of the centrifuge and WP4C Dewpoint Potentiometer were kept the same as the temperatures used during the calibration phase.

A second round and the third round of tests were also performed with minor changes in the testing procedure during the testing phase. The second round of tests was performed using the 3-bar and 5-bar HAE ceramic disks. The first difference of the second round, when compared to the first round of tests, was that the 3-bar and 5-bar HAE ceramic disks were tested only at angular velocities of 1000 and 2000 RPM for the time intervals of 1, 2, 4, 8, 12, 16, and 24 hours. Secondly, the underlying aluminum oxide porous stones were not saturated with DI water before placing the stones into the centrifuge consolidometers. Thirdly, after the first specimen had spun in the centrifuge, the pore liquid at the bottom of each aluminum bucket was drained, and the bucket was dried. The drying of the pore liquid from the bottom of the aluminum buckets was repeated after every time interval. The second round of testing was performed to compare how much the measured suction values and pore water weights changed by not saturating the underlying aluminum oxide porous stones and by drying the bottom of the aluminum buckets after every time interval.

The third round of tests was performed only using the 3-bar HAE ceramic disks. The preparation procedures were the same as previously mentioned in the first rounds of tests with minor modifications. First, the 3-bar HAE ceramic disks were tested only at 1000 and 2000 RPM for time intervals of 1, 2, 4, and 8 hours. Next, the aluminum oxide porous stones were not saturated before placing the stones into the centrifuge. Third, the radial distances were reduced to half values when compared to the first round of tests. At last, after the first specimen had completed the required time in the centrifuge, the pore liquid at the bottom of each aluminum bucket was drained, and the bucket was dried. This drying procedure was repeated after every
time interval. The objective of the third round of testing was to compare the changes in the measured suction when changing the radial distances of the specimens within the centrifuge and when drying the bottom of the aluminum swinging buckets after every time interval.

3.3.3. Calibration of WP4C Dewpoint Potentiometer

As stated in the WP4C Dewpoint Potentiometer operating manual (Meter, 2018), the device must be calibrated before testing, using a standard solution of Potassium Chloride (KCl) provided by the manufacturer. The calibration of the WP4C Dewpoint Potentiometer was achieved by entering the system configuration menu and selecting the calibration options. Secondly, the standard solution was placed into a plastic container and put into the sample drawer. Suction readings for the KCl sample were then obtained. Care was taken to not to spill or splash the standard solution within the chamber. The calibration reading should be within ± 0.05 MPa of the correct reading of the KCl standard solution at the testing temperature. As reported in the WP4C Dewpoint Potentiometer operating manual (Meter, 2018), at 20 degrees Celsius, the reading should be -2.19 MPa, and at 25 degrees Celsius should be -2.22 MPa.

If the reading was not within ± 0.05 MPa, the cleaning instructions were followed to clean the device. The provided cleaning kit supplied by the manufacturer was used to complete the cleaning task. The device was unplugged, and the case lid was removed to expose the chamber cavity. Any debris and dust that may have collected within and around the sample chamber was removed. Specifically, the provided wipes were moistened with the cleaning solution and all surface edges of the sample chamber were cleaned. The edges of the sample chamber were then rinsed with the provided deionized water. Finally, the case lid was secured back in place and the instrument performance was again checked with the provided standard solution of KCl.
3.4. Summary

This Chapter contained three sections. The issue of the ASTM D6836 (2016) standard was defined in Section 3.1. The descriptions of the HAE ceramic disk, the centrifuge consolidometers, the centrifuge, and the WP4C Dewpoint Potentiometer were included in Section 3.2. The testing program was covered in Section 3.3. The testing program was divided into three parts, the calibration phase, the testing phase, and the calibration of the WP4C Dewpoint Potentiometer.
4.0. RESULTS

The results obtained by following the methods and procedures that were described in the previous chapter were divided into three sections and are discussed herein. The lessons learned from the calibration phase are presented in Section 4.1. The three rounds of tests of the 3-bar HAE ceramic disks, including the predicted suction values, measured suction values, and pore water weights, are presented in Section 4.2. The two rounds of tests of the 5-bar HAE ceramic disks, including the predicted suction values, the measured suction values, and the pore water weights, are summarized in Section 4.3.

4.1. Lessons Learned from the Calibration Phase

The first lesson learned from the calibration phase of the testing program was that all testing equipment must be in the same room. The centrifuge and the WP4C Dewpoint Potentiometer were found in the same room (Bell Engineering 1140). However, the analytical balance Model A-200DS was in a different laboratory at the University of Arkansas (Bell Engineering 1145). During transit between laboratories, the temperature of the HAE ceramic disks increased enough to be too hot to be read by the WP4C Dewpoint Potentiometer. Because the sample was too hot to be read, the tested HAE ceramic disk was placed in the environmental chamber, which was kept at five degrees Celsius, for two minutes. After being placed in the environmental room, the HAE ceramic disk was inserted into the WP4C Dewpoint Potentiometer, and the suction reading was obtained. Adding water in the form of water vapor due to temperature changes may have affected the final suction readings. These adverse chances cannot be quantified.

The second lesson learned was that laboratory devices must be calibrated before testing and when readings become erroneous. The WP4C Dewpoint Potentiometer was recently acquired
by Dr. Coffman at the University of Arkansas, and this is the first investigation in which the mentioned laboratory device has been used. Thus, the calibration phase was required. High suction readings were obtained during the calibration stage. These high readings were not noticed until most of the calibration stage was performed due to a delay in analyzing the data. Although high suction readings were initially obtained, multiple readings were obtained. The measured suction readings, obtained during the calibration phase, followed a pattern that assisted with the selection of the testing phase parameters.

4.2. 3-Bar High Air Entry (HAE) Ceramic Disks

4.2.1. Predicted Suction Values of 3-bar HAE Ceramic Disks

The predicted suction values were calculated using Equation 11 of the ASTM D6836 (2016) standard. The inputs used in Equation 11 are displayed in Tables 4.1 and 4.2. Using the parameters reported in Tables 4.1 and 4.2, the predicted suctions of the 3-bar HAE ceramic disks were calculated and tabulated in Table 4.3.

Table 4.1. Inputs of Equation 11 of ASTM D6836 (2016) standard of the 3-bar HAE ceramic disks.

<table>
<thead>
<tr>
<th></th>
<th>(\beta)</th>
<th>[-]</th>
<th>(\rho_w)</th>
<th>[kg/L]</th>
<th>(\rho_g)</th>
<th>[kg/L]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.00553</td>
<td>1.0</td>
<td>0.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2. Inputs into ASTM D6836 (2016) Equation 11 of the 3-bar HAE ceramic disks.

<table>
<thead>
<tr>
<th>3-bar</th>
<th>Max radius</th>
<th>Space between the bottom plate and canister</th>
<th>Aluminum oxide porous stone thickness</th>
<th>HAE disks</th>
<th>(\Gamma_0)</th>
<th>(\Gamma_1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[m]</td>
<td>[m]</td>
<td>[m]</td>
<td>[m]</td>
<td>[m]</td>
<td>[m]</td>
</tr>
<tr>
<td>1 hr</td>
<td>2 hrs</td>
<td>4 hrs</td>
<td>8 hrs</td>
<td>12 hrs</td>
<td>16 hrs</td>
<td>24 hrs</td>
</tr>
<tr>
<td>0.2540</td>
<td>0.0130</td>
<td>0.0063</td>
<td>0.0073</td>
<td>0.2277</td>
<td>0.2274</td>
<td>0.2281</td>
</tr>
</tbody>
</table>
Table 4.3. Predicted suction values of the first round of tests of the 3-bar HAE ceramic disks using Equation 11 of ASTM D6836 (2016) standard.

<table>
<thead>
<tr>
<th>Angular velocity [rev/min]</th>
<th>$\Psi_{predicted}$ [kPa]</th>
<th>$\Psi_{predicted}$ [kPa]</th>
<th>$\Psi_{predicted}$ [kPa]</th>
<th>$\Psi_{predicted}$ [kPa]</th>
<th>$\Psi_{predicted}$ [kPa]</th>
<th>$\Psi_{predicted}$ [kPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
</tr>
<tr>
<td>200</td>
<td>0.73</td>
<td>0.73</td>
<td>0.73</td>
<td>0.73</td>
<td>0.73</td>
<td>0.73</td>
</tr>
<tr>
<td>500</td>
<td>4.54</td>
<td>4.54</td>
<td>4.55</td>
<td>4.54</td>
<td>4.54</td>
<td>4.55</td>
</tr>
<tr>
<td>1000</td>
<td>18.17</td>
<td>18.17</td>
<td>18.20</td>
<td>18.17</td>
<td>18.17</td>
<td>18.20</td>
</tr>
<tr>
<td>2000</td>
<td>72.69</td>
<td>72.56</td>
<td>72.80</td>
<td>72.69</td>
<td>72.56</td>
<td>72.80</td>
</tr>
</tbody>
</table>

The centrifuge consolidometers, when assembled, were targeted to be the same height. The top and bottom radii of the centrifuge consolidometers at the different time intervals were similar values, as reported in Table 4.2. The pore liquid density and the bottom and top radii were held constant throughout the investigation. Therefore, the predicted suctions using Equation 11 of ASTM D6836 (2016) standard became a function of the angular velocity. As reported in Table 4.3, the predicted suction values were similar in magnitude throughout the different time intervals at each angular velocity.

### 4.2.2. Measured Suction Values and Pore Water Weights of 3-Bar HAE Ceramic Disks

The measured suction values of the first round of tests are presented in Table 4.4. The obtained pore water weights within each of the 3-bar HAE ceramic disks are shown in Table 4.5. Additionally, the pore water weights of the 3-bar HAE ceramic disks at different time intervals are displayed graphically in Figure 4.1.

Table 4.4. Tabulated results from the first round of tests of the measured suction values for 3-bar HAE ceramic disks.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>110</td>
<td>90</td>
<td>130</td>
<td>270</td>
<td>110</td>
<td>230</td>
<td>120</td>
</tr>
<tr>
<td>200</td>
<td>70</td>
<td>60</td>
<td>160</td>
<td>200</td>
<td>100</td>
<td>60</td>
<td>200</td>
</tr>
<tr>
<td>500</td>
<td>140</td>
<td>140</td>
<td>120</td>
<td>90</td>
<td>210</td>
<td>190</td>
<td>410</td>
</tr>
<tr>
<td>1000</td>
<td>310</td>
<td>260</td>
<td>150</td>
<td>320</td>
<td>240</td>
<td>320</td>
<td>440</td>
</tr>
<tr>
<td>2000</td>
<td>320</td>
<td>310</td>
<td>220</td>
<td>790</td>
<td>450</td>
<td>430</td>
<td>1020</td>
</tr>
</tbody>
</table>
Table 4.5. Tabulated results from the first round of tests of the pore water weights for 3-bar HAE ceramic disks.

<table>
<thead>
<tr>
<th>RPM</th>
<th>1 hr</th>
<th>2 hrs</th>
<th>4 hrs</th>
<th>8 hrs</th>
<th>12 hrs</th>
<th>16 hrs</th>
<th>24 hrs</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1.2347</td>
<td>0.1853</td>
<td>1.3012</td>
<td>1.4137</td>
<td>1.2913</td>
<td>1.2611</td>
<td>1.5493</td>
</tr>
<tr>
<td>200</td>
<td>1.2667</td>
<td>0.2674</td>
<td>1.3959</td>
<td>1.5101</td>
<td>1.2336</td>
<td>1.2787</td>
<td>1.5472</td>
</tr>
<tr>
<td>500</td>
<td>1.1979</td>
<td>0.2268</td>
<td>1.2713</td>
<td>1.5180</td>
<td>1.2415</td>
<td>1.2561</td>
<td>1.3636</td>
</tr>
<tr>
<td>1000</td>
<td>1.2695</td>
<td>0.2966</td>
<td>1.3954</td>
<td>1.5163</td>
<td>1.2375</td>
<td>1.2691</td>
<td>1.4228</td>
</tr>
<tr>
<td>2000</td>
<td>1.1943</td>
<td>0.2464</td>
<td>1.1903</td>
<td>1.4055</td>
<td>1.1325</td>
<td>1.0809</td>
<td>1.2429</td>
</tr>
</tbody>
</table>

Figure 4.1. Pore water weights of the 3-bar HAE ceramic disks during the first round of tests.

The following outcomes were obtained from the first round of 3-bar HAE ceramic disk tests. At the 1-hour time interval, the pore water weight fluctuated with no clear downward pattern until the angular velocity of 1000 RPM was reached. A small decrease in the pore water weight was observed after pore water equilibrium was reached at the angular velocity of 1000 RPM. Pore water equilibrium was defined as the angular velocity from which the pore water weight started the downward pattern.
The pore water equilibrium was reached at an angular velocity of 1000 RPM for the 2-hour time interval. When the ceramic disk used for the 2-hour interval was compared with other values in Table 4.5, the pore water weights were one order of magnitude lower than the others. The 2-hour interval ceramic disk was believed to have higher porosity and therefore was assumed not to be a 3-bar HAE ceramic disk. In terms of measured suction, the measured suction value at 1000 RPM was 260 kPa for the 2-hour time interval. Likewise, at the 4-hour time interval, pore water equilibrium appeared to occur at an angular velocity of 1000 RPM with a corresponding measured suction value of 150 kPa.

At the 8-hour time interval, pore water equilibrium was reached at the angular velocity of 500 RPM. The measured suction values for 500 RPM, 1000 RPM, and 2000 RPM were measured to be 90 kPa, 320 kPa, and 790 kPa, respectively. Similarly, the pore water equilibrium was found at the angular velocity of 500 RPM for the 12-hour interval with a corresponding measured suction value of 210 kPa.

At the 16-hour interval, the pore water equilibrium was shown at an angular velocity of 1000 RPM, and the measured suction value for the 1000 RPM loading was 320 kPa. Finally, at the 24-hour interval, the pore water equilibrium was reached at the first tested angular velocity of 100 RPM. From 100 RPM to 2000 RPM, the measured suction values were 120, 200, 410, 440, and 1020 kPa, respectively.

The measured suction values and the pore water weights obtained during the second round of tests for the 3-bar HAE ceramic disks are summarized in Table 4.6. The pore water weights are graphically displayed in Figure 4.2. In addition, the measured suction values as a function of the pore water weights for the 3-bar HAE ceramic disks are shown in Figure 4.3.
Only the time intervals of 1, 8, and 12 hours of both tested angular velocities were included in the graph.

Table 4.6. The measured suction values and the pore water weights of 3-bar HAE ceramic disks that were obtained during the second round of tests.

<table>
<thead>
<tr>
<th>Angular velocity, $\omega$, [rev/min]</th>
<th>1 hr</th>
<th>2 hrs</th>
<th>4 hrs</th>
<th>8 hrs</th>
<th>12 hrs</th>
<th>16 hrs</th>
<th>24 hrs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pore Water Weights [g]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.1399</td>
<td>0.1774</td>
<td>1.2502</td>
<td>1.1602</td>
<td>1.0234</td>
<td>0.0264</td>
<td>0.0777</td>
<td></td>
</tr>
<tr>
<td>Measured Suction, $\psi_{\text{measured}}$, [kPa]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>320</td>
<td>210</td>
<td>290</td>
<td>1080</td>
<td>860</td>
<td>2840</td>
<td>28750</td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pore Water Weights [g]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0830</td>
<td>0.2316</td>
<td>1.2935</td>
<td>0.8738</td>
<td>0.8321</td>
<td>0.4962</td>
<td>0.2162</td>
<td></td>
</tr>
<tr>
<td>Measured Suction, $\psi_{\text{measured}}$, [kPa]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>360</td>
<td>440</td>
<td>350</td>
<td>1860</td>
<td>1390</td>
<td>890</td>
<td>10040</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.2. Pore water weights of the 3-bar HAE ceramic disks were obtained during the second round of tests.
The following outcomes were measured during the second round of tests using the 3-bar HAE ceramic disks. At 1000 RPM, the measured suction values went from 320 kPa at the 1-hour interval to 28750 kPa at the 24-hour mark. Similarly, at the 2000 RPM rate, the measured suction value was 360 kPa at the 1-hour interval and 10040 kPa at the 24-hour interval.

At the time intervals of 1, 8, and 12 hours, the pore water weights of the HAE ceramic disks decreased in values as the angular velocity increased from 1000 to 2000 RPM. Consequently, the measured suction values of these time intervals at the angular velocity of 2000 RPM were greater than the values of the angular velocity of 1000 RPM for the 3-bar HAE ceramic disks. At the time intervals of 2, 4, 16, and 24 hours, the pore water weights of the HAE ceramic disks increased in values when increasing the angular velocity from 1000 to 2000 RPM.
When the 2-hour time interval was compared with other values displayed in Table 4.6, the pore water weights were one order of magnitude lower than the others. Like in the 2-hour time interval of the first-round tests for the 3-bar HAE ceramic disk, the 2-hour interval ceramic disk of the second-round test was believed to have higher porosity. Hence, it was assumed not to be a 3-bar HAE ceramic disk.

During the third round of tests, the radial distances of the centrifuge consolidometers were reduced to half values when compared to the first round of tests. The radial distances of 3-bar HAE ceramic disks were presented in Table 4.7. The predicted and measured suction values were shown in Table 4.8. Pore water weights obtained during the third round of tests for the 3-bar HAE ceramic disks were presented in Table 4.9 and graphically displayed in Figure 4.4.

Table 4.7. Inputs into ASTM D6836 (2016) Equation 11 of the 3-bar HAE ceramic disks for the third round of tests.

<table>
<thead>
<tr>
<th>3-bar</th>
<th>Max radius</th>
<th>Aluminum oxide porous stone</th>
<th>HAE stone</th>
<th>Space between the canister and bottom plate</th>
<th>( \Gamma_0 )</th>
<th>( \Gamma_t )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[m]</td>
<td>[m]</td>
<td>[m]</td>
<td>1 hr</td>
<td>2 hrs</td>
<td>4 hrs</td>
</tr>
<tr>
<td>0.254</td>
<td>0.0063</td>
<td>0.0073</td>
<td>0.0675</td>
<td>0.0665</td>
<td>0.0675</td>
<td>0.0674</td>
</tr>
</tbody>
</table>

Table 4.8. Predicted and measured suction values of the 3-bar HAE ceramic disks that were obtained during the third round of tests.

<table>
<thead>
<tr>
<th>3-bar, diameter = 28.74 mm, Third Round of Tests</th>
<th>( \omega ) RPM</th>
<th>Suction</th>
<th>Suction</th>
<th>Suction</th>
<th>Suction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted Suction Values</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>14.32</td>
<td>14.23</td>
<td>14.31</td>
<td>14.33</td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>57.28</td>
<td>56.93</td>
<td>57.25</td>
<td>57.31</td>
<td></td>
</tr>
<tr>
<td>Measured Suction Values</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>460</td>
<td>470</td>
<td>310</td>
<td>1200</td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>370</td>
<td>870</td>
<td>440</td>
<td>3390</td>
<td></td>
</tr>
</tbody>
</table>
Table 4.9. Pore water weights of the 3-bar HAE ceramic disks were obtained during the third round of tests.

<table>
<thead>
<tr>
<th>Pore water weights [g]</th>
<th>Saturated</th>
<th>1 hr</th>
<th>2 hrs</th>
<th>4 hrs</th>
<th>8 hrs</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-bar, diameter = 28.74 mm, Third Round of Tests</td>
<td></td>
<td>9.8656</td>
<td>9.3007</td>
<td>10.3500</td>
<td>10.0123</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>1.0712</td>
<td>0.2191</td>
<td>1.2413</td>
<td>1.1270</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>1.0905</td>
<td>0.1489</td>
<td>1.1813</td>
<td>0.5304</td>
</tr>
</tbody>
</table>

Figure 4.4. Pore water weights of the 3-bar HAE ceramic disks were obtained during the third round of tests.

Only the angular velocities of 1000 and 2000 RPM were tested for the third round of tests at time intervals of 1, 2, 3, and 8 hours. The measured suction values and the pore water weights followed similar patterns to those patterns seen in the first and second rounds of tests. In general, the measured suction values increased with an increase in angular velocities, and the pore water weights decreased with an increase in angular rates. Like in the first and second rounds of tests for the 3-bar HAE ceramic disks, the pore water weights of the 2-hour time interval were one
order of magnitude smaller than the other time intervals, as stated in Table 4.9. Therefore, the 2-hour HAE ceramic disk was believed to have higher porosity and it was assumed not to be a 3-bar HAE ceramic disk.

4.2.3. Predicted and Measured Suction Values of the 3-Bar HAE ceramic disks Comparison.

A summary of the first, second, and third rounds of tests of the predicted and the measured suction values of the 3-bar HAE ceramic disks were tabulated in Table 4.10, Table 4.11, and 4.12, respectively. The summary of all three rounds of tests was graphically displayed in Figure 4.5. A discussion of the results for the three rounds of tests was reported below.

Table 4.10. Summary of the first round of tests of the predicted and the measured suction values of the 3-bar HAE ceramic disks.

| 3-bar, diameter = 28.74 mm, First Round of Tests | \(\omega\) \begin{tabular}{c|c|c|c|c|c|c|c|c|c} \hline RPM & 1 hr & 2 hrs & 4 hrs & 8 hrs & 12 hrs & 16 hrs & 24 hrs \\ \hline [rev/min] & [kPa] & [kPa] & [kPa] & [kPa] & [kPa] & [kPa] & [kPa] \\ \hline Predicted Suction Values & & & & & & & & \\ 100 & 0.18 & 0.18 & 0.18 & 0.18 & 0.18 & 0.18 & 0.18 \\ 200 & 0.73 & 0.73 & 0.73 & 0.73 & 0.73 & 0.73 & 0.73 \\ 500 & 4.54 & 4.54 & 4.55 & 4.54 & 4.54 & 4.54 & 4.55 \\ 1000 & 18.17 & 18.14 & 18.20 & 18.18 & 18.17 & 18.14 & 18.20 \\ 2000 & 72.69 & 72.56 & 72.80 & 72.71 & 72.69 & 72.56 & 72.80 \\ \hline Measured Suction Values & & & & & & & & \\ 100 & 110 & 90 & 130 & 270 & 110 & 230 & 120 \\ 200 & 70 & 60 & 160 & 200 & 100 & 60 & 200 \\ 500 & 140 & 140 & 120 & 90 & 210 & 190 & 410 \\ 1000 & 310 & 260 & 150 & 320 & 240 & 320 & 440 \\ 2000 & 320 & 310 & 220 & 790 & 450 & 430 & 1020 \\ \hline |
Table 4.11. Summary of the second round of tests of the predicted and the measured suction values of the 3-bar HAE ceramic disks.

<table>
<thead>
<tr>
<th>3-bar, diameter = 28.74 mm, Second Round of Tests</th>
<th>( \omega )</th>
<th>1 hr</th>
<th>2 hrs</th>
<th>4 hrs</th>
<th>8 hrs</th>
<th>12 hrs</th>
<th>16 hrs</th>
<th>24 hrs</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPM [rev/min] Suction [kPa]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Predicted Suction Values</td>
<td>1000</td>
<td>18.17</td>
<td>18.14</td>
<td>18.20</td>
<td>18.18</td>
<td>18.17</td>
<td>18.14</td>
<td>18.20</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>72.69</td>
<td>72.56</td>
<td>72.80</td>
<td>72.71</td>
<td>72.69</td>
<td>72.56</td>
<td>72.80</td>
</tr>
<tr>
<td>Measured Suction Values</td>
<td>1000</td>
<td>320</td>
<td>210</td>
<td>290</td>
<td>1080</td>
<td>860</td>
<td>2840</td>
<td>28750</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>360</td>
<td>440</td>
<td>350</td>
<td>1860</td>
<td>1390</td>
<td>890</td>
<td>10040</td>
</tr>
</tbody>
</table>

Table 4.12. Summary of the third round of tests of the predicted and the measured suction values of the 3-bar HAE ceramic disks.

<table>
<thead>
<tr>
<th>3-bar, dia=28.74 mm, Third Round of Tests</th>
<th>( \omega )</th>
<th>1 hr</th>
<th>2 hrs</th>
<th>4 hrs</th>
<th>8 hrs</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPM [rev/min] Suction [kPa]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Predicted Suction Values</td>
<td>1000</td>
<td>14.32</td>
<td>14.23</td>
<td>14.31</td>
<td>14.33</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>57.28</td>
<td>56.93</td>
<td>57.25</td>
<td>57.31</td>
</tr>
<tr>
<td>Measured Suction Values</td>
<td>1000</td>
<td>460</td>
<td>470</td>
<td>310</td>
<td>1200</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>370</td>
<td>870</td>
<td>440</td>
<td>3390</td>
</tr>
</tbody>
</table>

As previously mentioned in Section 3.3.2, the predicted suction values were calculated using Equation 11 from the ASTM D6836 (2016) standard. The measured suction values were calculated by first placing 3-bar HAE ceramic disks into the centrifuge to apply selected suction magnitudes and then determining the suction in the HAE ceramic disks using the WP4C Dewpoint Potentiometer. As observed in Figure 4.5, only the values up to 1500 kPa are displayed on the x-axis (the measured suction values) for aesthetic purposes. Only the linear equations and linear regression values of the tested time intervals of the first round of tests were presented in Figure 4.5. The 12-hour interval of the first round of tests showed the best agreement based on
the slope of the line and linear regression value \((R^2)\). At the 12-hour interval, the slope of the line was 0.2155, and the linear regression value was 0.9277. Both, the linear equation, and the linear regression value of the 12-hour time interval were squared in Figure 4.5 for easy identification.

Figure 4.5. Predicted suction values as a function of the measured suction values with linear trend line equations and regression values for three rounds of tests of 3-bar HAE ceramic disks.

4.3. 5-Bar High Air Entry (HAE) Ceramic Disks

4.3.1. Predicted Suction Values of 5-Bar HAE Ceramic Disks

Similar to the predicted suction values of the 3-bar HAE ceramic disks, the predicted suction values of 5-bar HAE ceramic disks were calculated using Equation 11 of ASTM D6836 (2016) standard. The inputs used in Equation 11 are displayed in Tables 4.13 and 4.14. The calculated predicted suction values of the 5-bar HAE ceramic disks are shown in Table 4.15.
Table 4.1. Inputs of Equation 11 of ASTM D6836 (2016) standard of the 5-bar HAE ceramic disks.

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta$</td>
<td>[-]</td>
<td>0.00553</td>
</tr>
<tr>
<td>$\rho_w$</td>
<td>kg/L</td>
<td>1.0</td>
</tr>
<tr>
<td>$\rho_g$</td>
<td>kg/L</td>
<td>0.0</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>5-bar</th>
<th>Max. radius</th>
<th>Space between the bottom plate and canister</th>
<th>Aluminum oxide porous stone thickness</th>
<th>HAE disks</th>
<th>$\Gamma_b$</th>
<th>$\Gamma_l$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[m]</td>
<td>[m]</td>
<td>[m]</td>
<td>[m]</td>
<td>[m]</td>
<td>[kPa]</td>
<td>[kPa]</td>
</tr>
<tr>
<td>0.254</td>
<td>0.013</td>
<td>0.0063</td>
<td>0.0073</td>
<td>0.2277</td>
<td>0.2274</td>
<td>0.2281</td>
</tr>
</tbody>
</table>

Table 4.15. Predicted suction values of the first round of tests of the 5-bar HAE ceramic disks using Equation 11 of ASTM D6836 (2016) standard.

<table>
<thead>
<tr>
<th>Angular velocity</th>
<th>$\psi_{predicted}$</th>
<th>$\psi_{predicted}$</th>
<th>$\psi_{predicted}$</th>
<th>$\psi_{predicted}$</th>
<th>$\psi_{predicted}$</th>
<th>$\psi_{predicted}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[rev/min]</td>
<td>[kPa]</td>
<td>[kPa]</td>
<td>[kPa]</td>
<td>[kPa]</td>
<td>[kPa]</td>
<td>[kPa]</td>
</tr>
<tr>
<td>$\omega$</td>
<td>1 hr</td>
<td>2 hrs</td>
<td>4 hrs</td>
<td>8 hrs</td>
<td>12 hrs</td>
<td>16 hrs</td>
</tr>
<tr>
<td>100</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
</tr>
<tr>
<td>200</td>
<td>0.72</td>
<td>0.72</td>
<td>0.72</td>
<td>0.72</td>
<td>0.72</td>
<td>0.72</td>
</tr>
<tr>
<td>500</td>
<td>4.51</td>
<td>4.50</td>
<td>4.51</td>
<td>4.51</td>
<td>4.50</td>
<td>4.50</td>
</tr>
<tr>
<td>1000</td>
<td>18.03</td>
<td>18.00</td>
<td>18.06</td>
<td>18.03</td>
<td>18.03</td>
<td>18.00</td>
</tr>
<tr>
<td>2000</td>
<td>72.12</td>
<td>71.99</td>
<td>72.22</td>
<td>72.13</td>
<td>72.12</td>
<td>71.99</td>
</tr>
</tbody>
</table>

Like with the testing procedure of the 3-bar HAE ceramic disks, the heights of the centrifuge consolidometers (when assembled) were the same for the different testing time intervals. As a result, the predicted suction values using Equation 11 of ASTM D6836 (2016) standard became a function of the angular velocity. The predicted suction values were similar in magnitude at each angular velocity all through the different time intervals, as tabulated in Table 4.15.

### 4.3.2. Measured Suction Values and Pore Water Weights of 5-bar HAE Ceramic Disks

The measured suction values of the first round of tests of the 5-bar HAE ceramic disks are tabulated in Table 4.16. The pore water weights of the 5-bar HAE ceramic disks at different
time intervals are summarized in Table 4.17. Furthermore, the pore water weights of the 5-bar HAE ceramic disks at different time intervals are graphically displayed in Figure 4.6.

Table 4.16. Tabulated results from the first round of tests of the measured suction values for 5-bar HAE ceramic disks.

<table>
<thead>
<tr>
<th>Angular velocity [rev/min]</th>
<th>1 hr</th>
<th>2 hrs</th>
<th>4 hrs</th>
<th>8 hrs</th>
<th>12 hrs</th>
<th>16 hrs</th>
<th>24 hrs</th>
</tr>
</thead>
<tbody>
<tr>
<td>ω [kPa]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>100</td>
<td>160</td>
<td>100</td>
<td>70</td>
<td>150</td>
<td>150</td>
<td>260</td>
</tr>
<tr>
<td>200</td>
<td>160</td>
<td>50</td>
<td>60</td>
<td>180</td>
<td>110</td>
<td>110</td>
<td>130</td>
</tr>
<tr>
<td>500</td>
<td>50</td>
<td>130</td>
<td>330</td>
<td>200</td>
<td>270</td>
<td>250</td>
<td>360</td>
</tr>
<tr>
<td>1000</td>
<td>310</td>
<td>120</td>
<td>510</td>
<td>720</td>
<td>490</td>
<td>350</td>
<td>490</td>
</tr>
<tr>
<td>2000</td>
<td>360</td>
<td>260</td>
<td>630</td>
<td>990</td>
<td>850</td>
<td>900</td>
<td>1240</td>
</tr>
</tbody>
</table>

Table 4.17. Tabulated results from the first round of tests of the pore water weights for 5-bar HAE ceramic disks.

<table>
<thead>
<tr>
<th>Water weight in HAE ceramic disks [g]</th>
<th>RPM</th>
<th>1 hr</th>
<th>2 hrs</th>
<th>4 hrs</th>
<th>8 hrs</th>
<th>12 hrs</th>
<th>16 hrs</th>
<th>24 hrs</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1.3380</td>
<td>1.4232</td>
<td>1.4045</td>
<td>1.3974</td>
<td>1.4088</td>
<td>1.5038</td>
<td>1.5073</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>1.3945</td>
<td>1.4465</td>
<td>1.4733</td>
<td>1.4446</td>
<td>1.4184</td>
<td>1.4890</td>
<td>1.4965</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>1.4616</td>
<td>1.5138</td>
<td>1.4873</td>
<td>1.4893</td>
<td>1.3687</td>
<td>1.4472</td>
<td>1.3614</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>1.4058</td>
<td>1.4626</td>
<td>1.4781</td>
<td>1.4709</td>
<td>1.3630</td>
<td>1.3957</td>
<td>1.4444</td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>1.2737</td>
<td>1.3160</td>
<td>1.2607</td>
<td>1.4305</td>
<td>1.2191</td>
<td>1.2258</td>
<td>1.2966</td>
<td></td>
</tr>
</tbody>
</table>
As previously mentioned in the results of 3-bar HAE ceramic disks, the pore water equilibrium was defined as the angular velocity at which the pore water weight started the downward behavior. Pore water equilibrium was reached at 500 RPM for the 1-hour time interval. The measured suction values obtained by spinning at 500 RPM, 1000 RPM, and 2000 RPM were 50, 310, and 360 kPa, respectively.

Likewise, the pore water equilibrium was reached at the angular velocity of 500 RPM for the 2-hour interval with a measured suction of 130 kPa at 500 RPM. Similarly, at the 4-hour break, pore water equilibrium was reached at an angular velocity of 500 RPM. The measured suction at 500 RPM was 330 kPa. At the 8-hour interval, pore water equilibrium was reached at the angular velocity of 500 RPM. For the 8-hour interval, the measured suction values of 500 RPM, 1000 RPM, and 2000 RPM were 200, 720, and 990 kPa.

Figure 4.6. Pore water weights of the 5-bar HAE ceramic disks during the first round of tests.
At the 12-hour interval, equilibrium was reached at the angular velocity of 200 RPM. For the 12-hour interval, the measured suction values were 110 kPa for 200 RPM, 270 kPa for 500 RPM, 490 kPa for 1000 RPM, and 850 kPa for 2000 RPM. Pore water equilibrium was reached at an angular velocity of 100 RPM for the 16-hour interval. The measured suction values from 100 to 2000 RPM rates were 150, 110, 250, 350, and 900 kPa. Similarly, at the 24-hour interval, pore water equilibrium was found at 100 RPM. From 100 to 2000 RPM, the measured suction values were 260, 130, 360, 490, and 1240 kPa, respectively.

The outcomes of the measured suction values and the pore water weights of the 5-bar HAE ceramic disks obtained during the second round of tests are tabulated in Table 4.18. The pore water weights are shown in Figure 4.7. Additionally, the graph of the measured suction values as a function of the pore water weights is displayed in Figure 4.8.

Table 4.18. The measured suction values and the pore water weights of 5-bar HAE ceramic disks that were obtained during the second round of tests.

<table>
<thead>
<tr>
<th>Angular velocity, $\omega$, [rev/min]</th>
<th>1hr</th>
<th>2 hrs</th>
<th>4 hrs</th>
<th>8 hrs</th>
<th>12 hrs</th>
<th>16 hrs</th>
<th>24 hrs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>1.3032</td>
<td>1.3522</td>
<td>1.2578</td>
<td>1.1540</td>
<td>0.9526</td>
<td>0.7627</td>
<td>0.5322</td>
</tr>
<tr>
<td>Measured Suction, $\psi_{measured}$, [kPa]</td>
<td>170</td>
<td>240</td>
<td>530</td>
<td>1280</td>
<td>1930</td>
<td>2810</td>
<td>4750</td>
</tr>
<tr>
<td>2000</td>
<td>1.3042</td>
<td>1.4157</td>
<td>1.1770</td>
<td>0.8660</td>
<td>1.0664</td>
<td>1.0058</td>
<td>0.0702</td>
</tr>
<tr>
<td>Measured Suction, $\psi_{measured}$, [kPa]</td>
<td>320</td>
<td>740</td>
<td>1100</td>
<td>1310</td>
<td>1800</td>
<td>2390</td>
<td>15110</td>
</tr>
</tbody>
</table>
Figure 4.7. Pore water weights of the 5-bar HAE ceramic disks were obtained during the second round of tests.

Figure 4.8. Measured suction values as a function of Pore water weights of the 5-bar HAE ceramic disks during the second round of tests.
At 1000 RPM, the measured suction values went from 170 kPa at a 1-hour time interval to 4750 kPa at a 24-hour time interval. Likewise, at the 2000 RPM rate, the measured suction outcomes were a value of 320 kPa at the 1-hour interval and a value of 15110 kPa at the 24-hour interval. At 4, 8, and 24 hours, the pore water weights decreased from 1000 RPM to 2000 RPM. The measured suction values increased from 1000 to 2000 RPM at the time intervals of 1, 2, 4, 8, and 24 hours at the angular velocities.

4.3.3. Predicted and Measured Suction Values of the 5-bar HAE Ceramic Disk Comparison.

The results of the first round of tests of the predicted and measured suction values of the 5-bar HAE ceramic disks were summarized in Table 4.19. The outcomes of the second round of tests of the 5-bar HAE ceramic disks were presented in Table 4.20. Moreover, both rounds of the predicted and measured suction values were graphically displayed in Figure 4.9.

Table 4.19. Summary of the first round of tests of the predicted and the measured suction values of the 5-bar HAE ceramic disks.

<table>
<thead>
<tr>
<th>RPM [rev/min]</th>
<th>1 hr</th>
<th>2 hrs</th>
<th>4 hrs</th>
<th>8 hrs</th>
<th>12 hrs</th>
<th>16 hrs</th>
<th>24 hrs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted Suction Values</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
</tr>
<tr>
<td>200</td>
<td>0.72</td>
<td>0.72</td>
<td>0.72</td>
<td>0.72</td>
<td>0.72</td>
<td>0.72</td>
<td>0.72</td>
</tr>
<tr>
<td>500</td>
<td>4.51</td>
<td>4.50</td>
<td>4.51</td>
<td>4.51</td>
<td>4.51</td>
<td>4.50</td>
<td>4.51</td>
</tr>
<tr>
<td>1000</td>
<td>18.03</td>
<td>18.00</td>
<td>18.06</td>
<td>18.03</td>
<td>18.03</td>
<td>18.00</td>
<td>18.06</td>
</tr>
<tr>
<td>2000</td>
<td>72.12</td>
<td>71.99</td>
<td>72.22</td>
<td>72.13</td>
<td>72.12</td>
<td>71.99</td>
<td>72.22</td>
</tr>
<tr>
<td>Measured Suction Values</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>100</td>
<td>160</td>
<td>100</td>
<td>70</td>
<td>150</td>
<td>150</td>
<td>260</td>
</tr>
<tr>
<td>200</td>
<td>160</td>
<td>50</td>
<td>60</td>
<td>180</td>
<td>110</td>
<td>110</td>
<td>130</td>
</tr>
<tr>
<td>500</td>
<td>50</td>
<td>130</td>
<td>330</td>
<td>200</td>
<td>270</td>
<td>250</td>
<td>360</td>
</tr>
<tr>
<td>1000</td>
<td>310</td>
<td>120</td>
<td>510</td>
<td>720</td>
<td>490</td>
<td>350</td>
<td>490</td>
</tr>
<tr>
<td>2000</td>
<td>360</td>
<td>260</td>
<td>630</td>
<td>990</td>
<td>850</td>
<td>900</td>
<td>1240</td>
</tr>
</tbody>
</table>
Table 4.20. Summary of the second round of tests of the predicted and the measured suction values of the 5-bar HAE ceramic disks.

<table>
<thead>
<tr>
<th>5-bar, diameter = 28.74 mm, Second Round of Tests</th>
<th>Predicted Suction Values</th>
<th>Measured Suction Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>18.03</td>
<td>18.00</td>
</tr>
<tr>
<td>2000</td>
<td>72.12</td>
<td>71.99</td>
</tr>
</tbody>
</table>

Among all tested time intervals in the first round of tests, the 16-hour time interval presented the best agreement based on the trend line slope and the linear regression coefficient (R²). At the 16-hour time interval, the slope of the linear trend line was 0.0945 and the linear regression value was 0.9874. The linear equation and the linear regression value of the 16-hour time interval were squared in Figure 4.9 for easy recognition. The maximum measured suction value in the second round of tests was 15110 kPa at the 24-hour interval when subjected to 2000 RPM. For aesthetic reasons, only values less than 1500 kPa of the measured suction values were included in Figure 4.9.
4.4. Comparison Between Literature Reported Predicted and Measured Suction Values

An investigation into the predicted and measured suction values was needed because of the discrepancy that was observed between the centrifuge-predicted suction values (based on angular velocity and radial distance) and the measured suction values (from the WP4C Dewpoint Potentiometer). Two literature datasets were used to evaluate if there were similar differences in the reported values in the literature. The dataset was obtained from Khanzode et al. (2000) and Rahardjo et al. (2018). As mentioned in Section 2.2, Khanzode et al. (2000) reported data for Regina Clay, Indian Head Till, and Silt; Rahardjo et al. (2018) reported data for Clay, Clayey Sand, and Sand. The data from Khanzode et al. (2000) and Rahardjo et al. (2018) were digitalized using the Plot Digitizer program (Source Forge, 2023). Soil water characteristic curves (SWCCs) were fit through the data using the Van Genuchten (1980) fitting parameters in
the RETC (USDA, 1991) program. The Van Genuchten (1980) fit SWCCs for the Khanzode et al. (2000) data and the Rahardjo et al. (2018) data are presented in Figures 4.10 and 4.11, respectively.

Figure 4.10. Van Genuchten (1980) fit SWCCs for the Khanzode et al. (2000) SWCC. a) Regina Clay, b) Indian Head Till, c) Silt.
Figure 4.11. Van Genuchten (1980) fit SWCCs for the Rahardjo et al. (2018) SWCC. a) Clay, b) Clayey Sand, c) Sand.

The fitting parameters were used to determine given levels of suction at specified water contents for the centrifuge curves, Tempe cell curves, and/or pressure plate curves. The values of measured suction (as obtained from the pressure plate or Tempe cell) were divided by the values of predicted suction (as determined from the angular velocity and radial distance that were used during testing). Plots of predicted and measured suction values for the Khanzode et al. (2000) and the Rahardjo et al. (2018) data sets were included in Figures 4.12 and 4.13, respectively. Based on the results shown, the measured and predicted values are not found on the line of unity. Several of the curves are plotted above the line of unity (predicted suction was greater than measured suction). Several of the curves also are plotted below the line of unity (measured suction was greater than predicted suction). Lines with up to one order of magnitude difference (1:10 or 10:1) between the measured and predicted values are provided for comparison. The measured Khanzode et al. (2000) values tended to underpredict the measured value by a half-order of magnitude. The measured Rahardjo et al. (2018) values tended to underpredict the measured value by up to one order of magnitude. The results obtained from this research were more in line with the findings of Rahardjo et al. (2018).
Figure 4.12. Comparison of predicted and measured suction values from Khanzode et al. (2000).

Figure 4.13. Comparison of predicted and measured suction values from Rahardjo et al. (2018).
5.0. DISCUSSION OF RESULTS

After performing the comprehensive testing program, the following lessons were learned from the results. Two trends were noticed when the predicted suction values were calculated using Equation 11 of the ASTM D6836 (2016) standard. The predicted suction values increased with the angular velocities, and the predicted suction values did not change with an increase in time. Angular velocity ($\omega$) is a variable in Equation 11 of ASTM D6836 (2016) standard, but time is not. Similar predicted suction values were obtained for all testing time intervals for each angular velocity of the 3-bar and 5-bar High Air Entry (HAE) ceramics disks.

During the three rounds of tests of the 3-bar ceramic disks and the two rounds of tests of the 5-bar HAE ceramic disks, the pore liquid density, and the radial distances were kept constant. Therefore, the measured suction values became functions of angular velocity. In other words, the measured suction values increased with an increase in angular velocity.

The difference between the first and the second round of tests for the 3-bar and 5-bar HAE ceramics disks was the magnitudes of the measured suction values. For instance, during the first round of tests for the 3-bar HAE ceramics disks, the measured suction value at the 24-hour time interval was 1020 kPa when subjected to 2000 RPM. During the second round of tests, the measured suction value at the 24-hour time interval was 10040 kPa when rotated at a rate of 2000 RPM. Similarly, during the first round of tests of 5-bar HAE ceramics disks, the measured suction value at the 24-hour time interval was 1240 kPa when rotate at a rate of 2000 RPM and 15110 kPa at the 24-hour time interval when subjected to 2000 RPM in the second round of tests. This difference in magnitude was associated with two events.

The difference in magnitudes between the first and the second round of tests for the 3-bar and 5-bar HAE ceramics disks was associated with capillary action. By not saturating the
aluminum oxide porous stones before placing the stones in the centrifuge consolidometers and by drying the bottom of the centrifuge aluminum canisters after each time interval, capillary action was believed to become stronger between the analogue soil samples and the aluminum oxide stones. Second, during the first and the second rounds of tests of the 3-bar and 5-bar HAE ceramics disks, the analogue soil specimens were not covered when rotated inside the centrifuge consolidometers. Evaporation may have occurred when applying the centrifugal force, especially at high angular velocities.

During the third round of tests of the 3-bar HAE ceramics disks, the radial distance was decreased to half the value of the radial distance of the second round of tests. Also, the aluminum oxide porous stones were not saturated before placing the stones in the centrifuge consolidometers, and the bottom of the centrifuge aluminum canisters was dried after each time interval. However, the measured suction values were similar in magnitudes to the second round of tests of the 3-bar HAE ceramics and not decreased values. Like in the second round of tests, capillary action was believed to become stronger between the HAE ceramics disks and the aluminum oxide stones and may have affected the results.

The measured pore water weights displayed similar behaviors in the first rounds of tests of the 3-bar and 5-bar HAE ceramics disks. The pore water weights decreased with an increase in angular velocity. Small changes in pore water weights were observed after reaching pore water equilibrium at each time interval. For the second round of tests of the 3-bar and 5-bar HAE ceramics disks, the pore water weights dropped significantly when compared to the first rounds of tests, especially in the longer time intervals. The significant drop in the second round of tests was associated with capillary action and evaporation.
Based on the linear equations and the linear regression values of the first rounds of tests, the 12-hour time interval of the 3-bar HAE ceramic disks and the 16-hour time interval of the 5-bar HAE ceramic disks presented the best agreement based on the slope of the linear trend line and the regression value ($R^2$). The slope of the linear trend line was 0.2155 and the linear regression value was 0.9277 for the 3-bar HAE ceramic disks at the 12-hour time interval. Moreover, the slope of the linear trend line was 0.0945 and the linear regression value ($R^2$) was 0.9874 for the 5-bar HAE ceramic disks at the 16-hour time interval.

As covered in Section 3.1, the unit correction constant ($\beta$) in the ASTM D6836 standard needs to be further evaluated. However, based on the obtained results, the measured suction values were approximately an order of magnitude greater than the predicted suction values. The difference between the predicted and measured suction values was associated with the testing procedure. A further discussion of specific recommendations for future research is discussed in Chapter 8.0.
6.0. CONCLUSIONS

The apparent discrepancy found in the unit correction constant (β) of Equation 11 of the ASTM D6836 (2016) standard led to an investigation in which predicted and measured soil suctions were compared to further evaluate the unit correction constant (β). The predicted suction values were calculated using Equation 11 of the D6836 (2016) standard. The measured suction values were obtained by first spinning the High Air Entry (HAE) ceramic disks in the centrifuge and then placing the HAE ceramic disks in the WP4C Dewpoint Potentiometer to obtain the corresponding suction readings.

Based on the obtained results, the measured suction values were larger in magnitudes than the predicted suction values. When the first rounds of tests of the predicted and the measured suction values were plotted for comparison, the 12-hour time interval of the 3-bar HAE ceramic disks and the 16-hour time interval of the 5-bar HAE ceramic disks presented the best agreement based on the slope of the linear trend line and the linear regression value (R²).

The differences in magnitudes between the predicted and measured suction values were associated with the laboratory testing procedure. For future research, each possible reason that might have affected the measured suction values must be investigated for further evaluation of the correction constant (β) of Equation 11 of the ASTM D6836 (2016) standard. Three specific recommendations for future research are provided in Chapter 7.0.
7.0. RECOMMENDATIONS

Three specific recommendations are provided herein:

1. Reduce the issue of evaporation,
2. Use saturated High Air Entry (HAE) ceramic disks for the testing procedure, and,
3. Compare the measured soil water characteristic curve (SWCC) of the HAE ceramic disks using centrifugation with the measured SWCC of the HAE ceramic disks using other typical laboratory techniques.

Khanzode et al. (2000) and Rahardjo et al. (2018) discussed that the issue of evaporation might affect the mass equilibrium of soil specimens, especially at higher angular velocities. Khanzode et al. (2000) placed aluminum foil on the soil specimens to reduce moisture loss by evaporation. Similarly, Rahardjo et al. (2018) put a plastic film on the top of each soil sample to minimize the influence of evaporation. Two procedures are recommended to reduce the issue of evaporation. First, cover the analogue specimen (HAE ceramic disks) with a plastic film or aluminum foil at all spinning cycles. Second, separate the laboratory testing into two parts. Determine the pore liquid equilibrium at each predetermined angular velocity during the first phase. Measure the suction of the HAE ceramic disks with the WP4C Dewpoint Potentiometer as soon as the spinning cycle is completed during the second phase.

As discussed in Section 3.3.1, the HAE ceramic disks were rotated in the centrifuge to apply prescribed amounts of suction and then placed in the WP4C Dewpoint Potentiometer to measure corresponding suction readings. Two of the differences between the first round of tests and the second and third rounds of tests were that the aluminum oxide porous stones were not saturated before placing the stones in the centrifuge and that the bottom of the centrifuge aluminum canisters was dried after each time interval. Capillary action was believed to become
stronger between HAE ceramic disks and aluminum oxide porous stones in the second and third rounds of tests. As a result, this movement of pore water may have affected the results in a way that cannot be quantified.

Khanzode et al. (2000) used saturated ceramic cylinders composed of 60% kaolinite and 40% aluminum oxide between the soil samples and the drainage plate. Similarly, Rahardjo et al. (2018) used a saturated filter paper between the soil specimen and the bottom part of the specimen holder. The results of the research of Khanzode et al. (2000) and Rahardjo et al. (2018) showed good agreement between centrifugation and typical laboratory procedures (Tempe cell and pressure plate). Therefore, the usage of saturated HAE ceramic disks is recommended because it has been shown to work in the past.

Another approach that should be taken to further correct the unit conversion constant ($\beta$) in Equation 11 of the ASTM D6836 (2016) is to compare the measured SWCC of the HAE ceramic disks using centrifugation with the measured SWCC using other typical laboratory techniques. In other words, obtain the SWCC for each rate of the HAE ceramic disks using centrifugation and the SWCC of the HAE ceramic disks using typical axis-translation methods, such as the pressure plate or Tempe cell, and compare both curves. The SWCCs of soil specimens obtained from centrifugation techniques are comparable to typical axis-translation methods as described in Section 2.2. After the comparison of the obtained SWCCs, conclusions can be reached as to whether HAE ceramic disks are a suitable option to be used as analogue soil samples. By applying the three recommendations presented herein, the unit correction constant ($\beta$) in Equation 11 of the ASTM D6836 (2016) standard could be properly evaluated as attempted in this investigation.
8.0. REFERENCES


Conference on Unsaturated soils (UNSAT-ASI 2000) From Theory to Practice, May. 10 Pages.


