NOTE

Measurement of soil-water characteristic curves for fine-grained soils using a small-scale centrifuge

R.M. Khanzode, S.K. Vanapalli, and D.G. Fredlund

Abstract: Considerably long periods of time are required to measure soil-water characteristic curves using conventional equipment such as pressure plate apparatus or a Tempe cell. A commercially available, small-scale medical centrifuge with a swinging type rotor assembly was used to measure the soil-water characteristic curves on statically compacted, fine-grained soil specimens. A specimen holder was specially designed to obtain multiple sets of water content versus suction data for measuring the soil-water characteristic curve at a single speed of rotation of the centrifuge. The soil-water characteristic curves were measured for three different types of fine-grained soils. The three soils used in the study were processed silt (liquid limit, w_L = 24%; plasticity index, I_p = 0; and clay = 7%), Indian Head till (w_L = 35.5%, I_p = 17%, and clay = 30%), and Regina clay (w_L = 75.5%, I_p = 21%, and clay = 70%). The soil-water characteristic curves for the above soils were measured in 0.5, 1, and 2 days, respectively, using the centrifuge technique for suction ranges from 0 to 600 kPa. Time periods of 2, 4–6, and 16 weeks were required for measuring the soil-water characteristic curves for the same soils using a conventional pressure plate apparatus. There is reasonably good agreement between the experimental results obtained by the centrifuge and the pressure plate methods. The results of this study are encouraging as soil-water characteristic curves can be measured in a reduced time period when using a small-scale centrifuge.

Key words: unsaturated soils, soil-water characteristic curve, centrifuge technique, soil suction, matric suction, water content.

Résumé : L'utilisation d'équipements conventionnels (e.g., cellule Tempe) pour mesurer les courbes caractéristiques sol-eau requiert des durées considérables. Une petite centrifugeuse médicale disponible commercialement a été utilisée pour mesurer la courbe caractéristique sol-eau de spécimens de sols à grains fins compactés de façon statique. Un support pour les spécimens a été conçu spécialement à cet effet. Les mesures ont été effectuées sur trois types de sols : silt (w_L = 24 %, I_p = 0, et argile = 7 %), till Indian Head (w_L = 35,5 %, I_p = 17 %, et argile = 30 %), et argile de Regina (w_L = 75,5 %, I_p = 21 %, et argile = 70 %). Les courbes caractéristiques sol-eau couvrant de 0 à 600 kPa ont été mesurées en un demi jour, un jour, et un jour et demi avec la centrifugeuse sur ces trois sols, respectivement. Cependant, des périodes de 2, 4 à 6, et 16 semaines étaient requises avec une méthode conventionnelle. L'accord entre les résultats obtenus par les deux méthodes est satisfaisant. Les résultats de cette étude sont encourageants puisque les courbes caractéristiques sol-eau peuvent être mesurées durant une période de temps réduite lorsque la petite centrifugeuse est utilisée.

Mots clés : sols non saturés, courbe caractéristique sol-eau, centrifugeuse, suction, contenu en eau.

Introduction

Geotechnical and geo-environmental engineers are often required to analyze problems involving unsaturated soils. The engineering behavior of unsaturated soils can be interpreted in terms of net normal stress, $(\sigma - u_a)$, and matric suction, $(u_a - u_w)$, using experimental test results (Fredlund and Rahardjo 1993). When soil behavior is related to the stress

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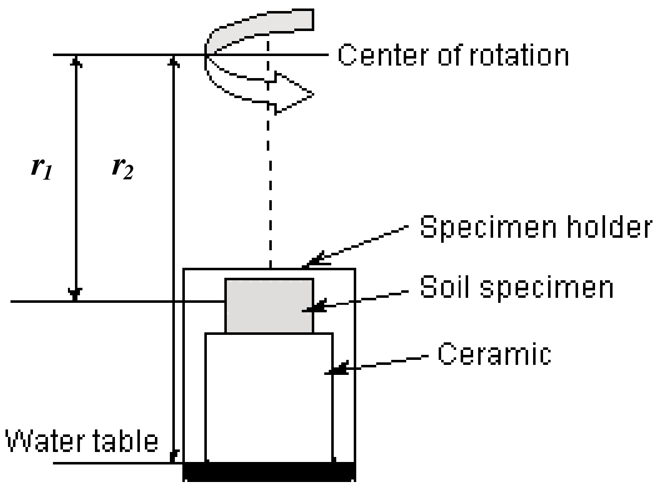
Fig. 1. Soil suction measurement principle of the centrifuge.



state, it is possible to propose more rational engineering design procedures. Experimental studies on unsaturated soils are costly and time-consuming and as a result several semi-empirical prediction procedures have been proposed in the literature to estimate unsaturated soil properties using the soil-water characteristic curve and the saturated soil properties (van Genuchten 1980; Fredlund et al. 1994; Vanapalli et al. 1996; Barbour 1998).

The soil-water characteristic curve defines the relationship between soil suction and gravimetric water content, *w*, volumetric water content, θ_w, or degree of saturation, *S*. Soil-water characteristic curves are commonly measured in the laboratory for a suction range of 0–1500 kPa using conventional pressure plate equipment. Typically, six to eight data points are measured such that the important features of the soil-water characteristic curve (i.e., air-entry value and the residual state conditions) can be determined from the measured data. Pressure plate or the Tempe cells are reliable apparatuses for both coarse- and fine-grained soils, but considerable testing time is required.

In this paper, a Beckman J6-HC small-scale medical centrifuge with a swinging type JS – 4.2 rotor assembly (six buckets) was used to measure the soil-water characteristic curves. The design details of a specially designed soil specimen holder are described. Multiple water contents versus suction data points can be obtained at one single speed of rotation using the described specimen holder. Comparisons are made between the measured soil-water characteristic curve data obtained using conventional equipment and the data from the small-scale centrifuge. Data is shown for three different, fine-grained soils with varying percentages of clay.

Background

Briggs and McLane (1907) appear to be the first investigators to use the centrifuge technique for measuring the relationship between soil suction and the water content retained by a soil. Gardner (1937) measured the capillary tension in a soil over a wide range of water contents by determining the equilibrium water content of calibrated filter papers that were in contact with the moist soil. The filter papers were calibrated by determining their water content when brought to equilibrium with a free water surface in a centrifugal field. Russell and Richards (1938) improved the technique introduced by Briggs and McLane (1907) for measuring the amount of water retained in a soil at different values of applied suction. Hassler and Brunner (1945) used a centrifuge method to obtain the relationship between capillary pressure and saturation for small, consolidated core specimens. Croney et al. (1952) studies showed that the use of a solid ceramic cylinder in a centrifuge, in comparison to a hollow cylinder, considerably reduced the time required to attain equilibrium conditions.

Typically, in a conventional water-retention centrifuge technique, soil-water characteristic curves are measured by draining a saturated soil specimen. Different values of equilibrium water content conditions (i.e., lower than the saturated water content condition) can be rapidly achieved by varying the distance of the soil specimen from the center of rotation of the centrifuge and the speed of rotation of the centrifuge. An increase in the applied soil suction results in a decrease in the water content of the soil specimens. In other words, data required for the soil-water characteristic curve (i.e., water content versus suction relationship) can be obtained using the centrifuge technique. The Gardner (1937) equation can be used to estimate the suction in the soil specimen and the water content can be determined using conventional procedures. In the described centrifuge testing procedure, there is a water content variation along the length of the soil specimen. However, the relative changes in water content and suction values over the thickness of the soil specimen are relatively small if thin specimens are used (i.e., 10–15 mm).

Principle of the centrifuge technique

A high gravity field is applied to an initially saturated soil specimen in the centrifuge. The soil specimen is supported on a saturated, porous ceramic column. The base of the ceramic stone rests in a water reservoir that is at atmospheric pressure conditions. The water content profile in the soil specimen after attaining equilibrium is similar to water draining under in situ conditions to a groundwater table where gravity is increased several times.

Figure 1 demonstrates the principle used in the centrifuge method for measuring soil suction. The suction in the soil specimen in a centrifuge can be calculated using eq. [1] as proposed by Gardner (1937)

$$[1] \qquad \psi = \frac{\rho\omega^2}{2g}(r_1^2 - r_2^2)$$

where

- ψ is the suction in the soil specimen,
- r_1 is the radial distance to the midpoint of the soil specimen,
- r_2 is the radial distance to the free water surface,
- ω is the angular velocity,
- ρ is the density of the pore fluid, and
- g is the acceleration due to gravity.

Equation [1] defines a nonlinear relationship between soil suction and centrifugal radius. The soil suction, ψ, becomes a function of the difference of the squares of the centrifugal radii, r_1 and r_2, while the density, ρ, and angular velocity, ω,

Fig. 2. Small scale medical centrifuge rotor assembly with six swinging type buckets.

are constant. The distance from the centre of the rotation to the free water surface, r_2, is a constant.

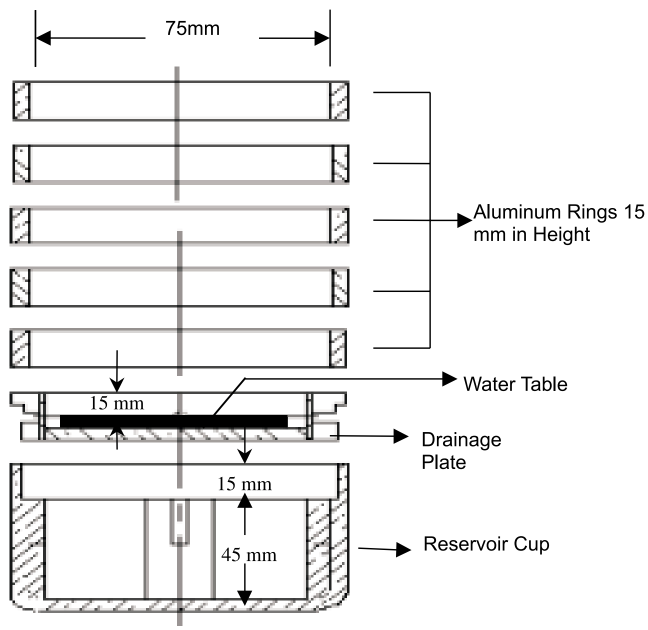
Different values of suction can be induced in a soil specimen by varying the radial distance to the midpoint of the soil specimen, r_1. In other words, ceramic cylinders of different heights can be used to achieve different suction applied to the soil specimen at a single speed of rotation. Higher values of soil suction can be subsequently induced into soil specimens by increasing the test speed (i.e., angular velocity, ω).

Description of the apparatus

A commercially available Beckman J6-HC small-scale medical centrifuge with an operable radius of 254 mm was used in the research program. The JS – 4.2 rotor assembly of the centrifuge consists of six swinging type buckets capable of carrying six test specimens in one test run (Fig. 2). The buckets in the centrifuge can be subjected to angular velocities varying from 50 to 4200 rpm. The maximum suction that can be applied to the specimen at 4200 rpm is 2800 kPa.

The swinging buckets of the centrifuge assume horizontal positions when the centrifuge is spinning. All of the six buckets can be used simultaneously with six specimen holders available for testing. Six data points of water content versus soil suction can be obtained from a single test run of the centrifuge at a constant angular velocity, ω. The mass in all of the specimen holders, however, should be essentially the same to avoid rotary imbalance. Identical soil specimens must be placed at different heights in the six specimen holders to obtain six data points of water contents for different suction values. Specially designed soil specimen holders were constructed to accommodate the soil specimens in the two centrifuge buckets (see two soil specimen holders in two opposite buckets in Fig. 2). The water content in the specimen can be measured after attaining equilibrium conditions and the soil suction in the specimen is computed using eq. [1].

Fig. 3. Details of the aluminum soil specimen holder.



Higher values of soil suction can be induced in the same soil specimen by increasing the speed of rotation and centrifuging the specimens until new equilibrium conditions are attained.

Soil specimen holders

Two aluminum soil specimen holders were specially designed for the centrifuge to hold 12 mm thick soil specimens at different heights. Figure 3 shows the typical aluminum soil specimen holders used in the study. The soil specimen holder consists of outer rings and a drainage plate with a free water surface reservoir to accommodate a ceramic cylinder. The outer rings have an inner diameter of 75 mm and

Fig. 4. A schematic to demonstrate the effects of centrifugation on the shift of the centre of gravity of solid cylindrical specimens.

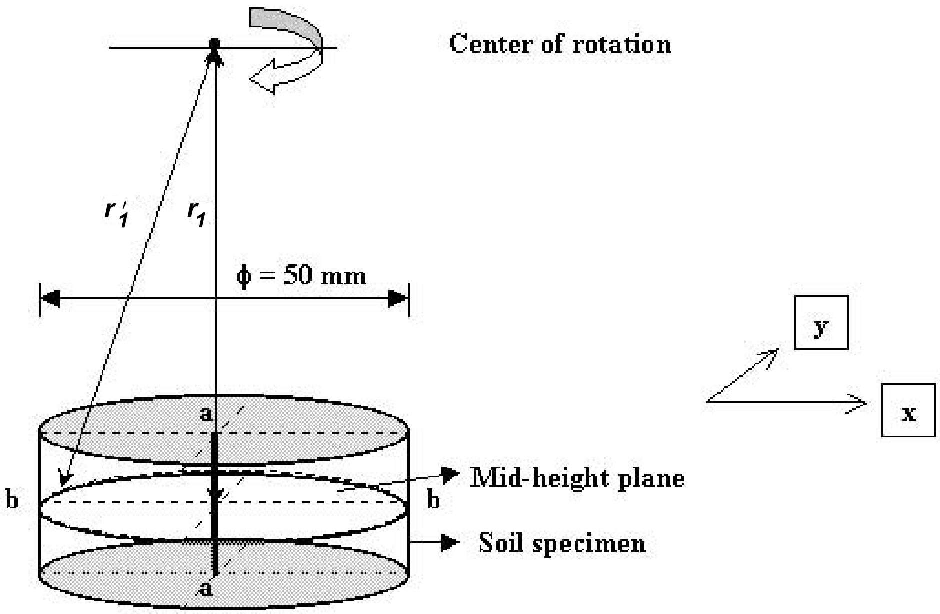


Table 1. Soil suctions associated with different test speeds and different ceramic cylinders.

	Suction in the soil specimen (kPa)			
Test speed (rpm)	15 mm cylinder	30 mm cylinder	45 mm cylinder	60 mm cylinder
300	3.28	5.91	8.33	10.53
500	9.08	16.43	23.15	29.24
1000	36.34	65.74	92.52	116.99
1500	81.78	147.94	208.43	263.27
2000	145.35	262.9	370.43	467.89
2500	227.0	410.74	578.68	730.94

are 15 mm thick. A reservoir cup serves as a collection area for water extracted from the soil specimens at the base of the holder.

A porous ceramic cylinder was designed to act as a filter while allowing the movement of water from the specimen to the drainage plate. This plate facilitates drainage into the reservoir cup through eight evenly spaced drainage ports drilled horizontally through the sides of the plate. The horizontal overflow ports are connected to vertically drilled drainage holes to allow for the removal of water. The water then flows down from the drainage plate into the reservoir cup.

Ceramic cylinders

The ceramic cylinders used in the drainage plate were made of 60% kaolinite and 40% aluminum oxide. The porosity of the ceramic cylinders was approximately 45%. Four ceramic cylinders with heights of 15, 30, 45, and 60 mm were made to keep the soil specimens at four different distances from the centre of rotation to induce four different suction values in the specimens at one speed of rotation. Table 1 summarizes the soil suctions associated with varying test speeds using different ceramic cylinders. Equation [1] was used to calculate the soils suction values.

In the present study, two ceramic cylinders of different heights were used in one test run to position the soil specimens at two different distances from the centre of rotation in the two opposite buckets of the centrifuge (see Fig. 2). The soil specimens were subjected to two different centrifugal forces and different values of soil suction were induced in two identical soil specimens placed in the soil specimen holders, subjected to the same angular velocity, ω.

Equation [1], used for calculating the equilibrium suction values in the soil specimen, does not take into account the shift in the centre of gravity of the soil specimen due to radial effects. The centre of gravity of a solid cylinder (similar to the test specimens used in this research program for measuring the soil-water characteristic curves) with parallel bases lies along centre line (*a*–*a*) connecting the centres of the top and bottom circular bases of the cylinder (Fig. 4). In other words, the centre of gravity of a soil specimen will be along the plane (*b*–*b*), which lies at mid-height of the soil specimen. In spite of centrifugation, the centre of gravity will be along the mid-height plane and may shift towards the boundary of the soil specimen (i.e., away from the axis *a*–*a*). In such situations, r_1' should be used in eq. [1] instead of r_1 (Fig. 4). Table 2 summarizes the suction values in soil specimens using r_1 and r_1' for a 15 mm height ceramic cylinder. The errors associated due to radial effects are less than 6% for a 50 mm diameter specimen used in the study for a test speed range of 0 to 2500 rpm. The errors associated with the use of 30, 45, and 60 mm height ceramic cylinders are 5.2, 3.7, and 2.9%, respectively. These errors from a practical perspective are not significant. Hence, the suctions calculated using eq. [1] at the mid-height of the specimen approximately represent the suction at the centre of gravity of the specimen.

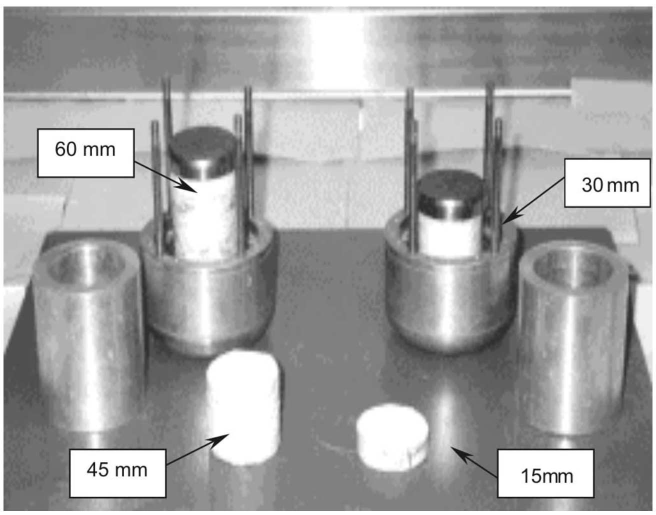
Test program

Three different fine-grained soils; namely, the processed

Table 2. Calculation of suction values in specimens using r_1 and r_1' for the 15 mm height ceramic cylinder.

Test speed (rpm)	Suction at the midpoint of the specimen using r_1 for 15 mm cylinder (kPa)	Suction at the boundary of the specimen using r_1' for 15 mm cylinder (kPa)	Maximum possible error in %
300	3.28	3.08	6.0
500	9.08	8.57	5.6
1000	36.34	34.30	5.61
1500	81.78	77.18	5.62
2000	145.35	137.17	5.60
2500	227.0	214.29	5.60

Fig. 5. Saturated soil specimens on top of the ceramic cylinders in the drainage plate.



silt (w_L = 24%, I_p = 0, and clay = 7%, G_s = 2.7), Indian Head till (w_L = 35.5%, I_p = 17%, and clay = 30%, G_s = 2.73) and Regina clay (w_L = 75.5%, I_p = 21%, and clay = 70%, G_s = 2.75) were used in the testing program. The three soils were first air-dried and then pulverized. Predetermined amounts of water content were added to the soil that was stored in polythene bags in a humidity-controlled room to cure for 24 h.

The processed silt specimens were statically compacted at an initial water content of 22% and a dry density, ρ_d of 1.57 Mg/m^3. For the Indian Head till specimens, three initial water contents were selected for preparing the soil specimens. The water contents represented wet of optimum (initial water content of 19.2% and ρ_d of 1.77 Mg/m^3), optimum (initial water content of 16.3% and ρ_d of 1.80 Mg/m^3), and dry of optimum (initial water content of 13% and ρ_d of 1.79 Mg/m^3). The Regina clay specimens were statically compacted at an initial water content of 38% and a ρ_d of 1.30 Mg/m^3. All of the specimens were compacted in steel rings of 50 mm in diameter and 12 mm in height. More details regarding the soil properties and specimen preparation are available in Khanzode (1999).

Test procedure

Ceramic cylinders of two different heights (i.e., 30 and 60 mm) and the statically compacted soil specimens, were saturated at the start of the test by submergence in a water bath and the application of a small vacuum pressure for 24 h. The centrifuge was started and allowed to run at 300 rpm for 0.5 h to obtain an equilibrium temperature of 20°C in the rotating chamber. All tests were conducted at a controlled temperature of 20°C.

Table 3. Centrifugation time at different testing speeds.

	Time of rotation (h)		
Test speed (rpm)	Processed silt	Indian Head till	Regina clay
300	2	2	4
500	2	2	4
1000	2	4	6
1500	2	4	6
2000	2	6	10
2500	2	6	12

Figure 5 shows the soil specimens along with the ceramic cylinders placed in the drainage plates of the specimen holders. The wet soil specimens were covered with an aluminum foil to prevent drying due to evaporation. A saturated filter paper was placed between the soil specimen and the ceramic cylinder to prevent loss of soil particles. A direct hydraulic connection was provided between the pore water in the soil specimens and the water surface at the base of the ceramic cylinder. Water from the saturated soil specimen escapes into the bottom reservoir through the ceramic cylinder. The mass of the saturated soil specimens was measured prior to placement on the ceramic cylinders. Water was also added to the top of the ceramic cylinders before placing the specimens. Hollow spacer cylinders were then placed around the ceramic cylinders and the soil specimens.

The spacer cylinders were required as the soil specimens and the ceramic cylinders had a diameter of 50 mm and the outer aluminum spacer rings of the holder had an inner diameter of 75 mm. The aluminum spacer rings were pushed down along the side bolts around the hollow aluminum spacer cylinders and tightened with nuts on top.

The mass of the specimen holder was weighed before being subjected to spinning. The difference in the masses between both the specimen holders was controlled to less than 0.5*g*. The soil specimen holders were then placed in opposite centrifuge buckets before centrifugation (see Fig. 2).

Fig. 6. Comparison of measured soil-water characteristic curves using a Tempe cell and the centrifuge method for processed silt specimens with an initial water content of 22%.

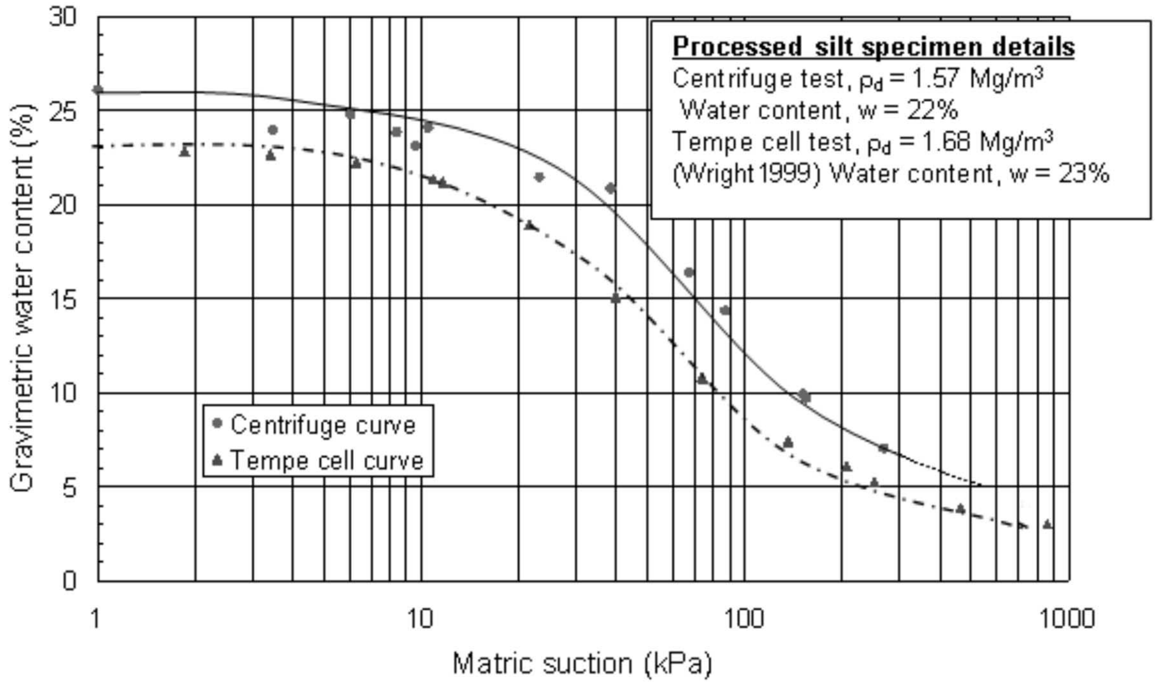
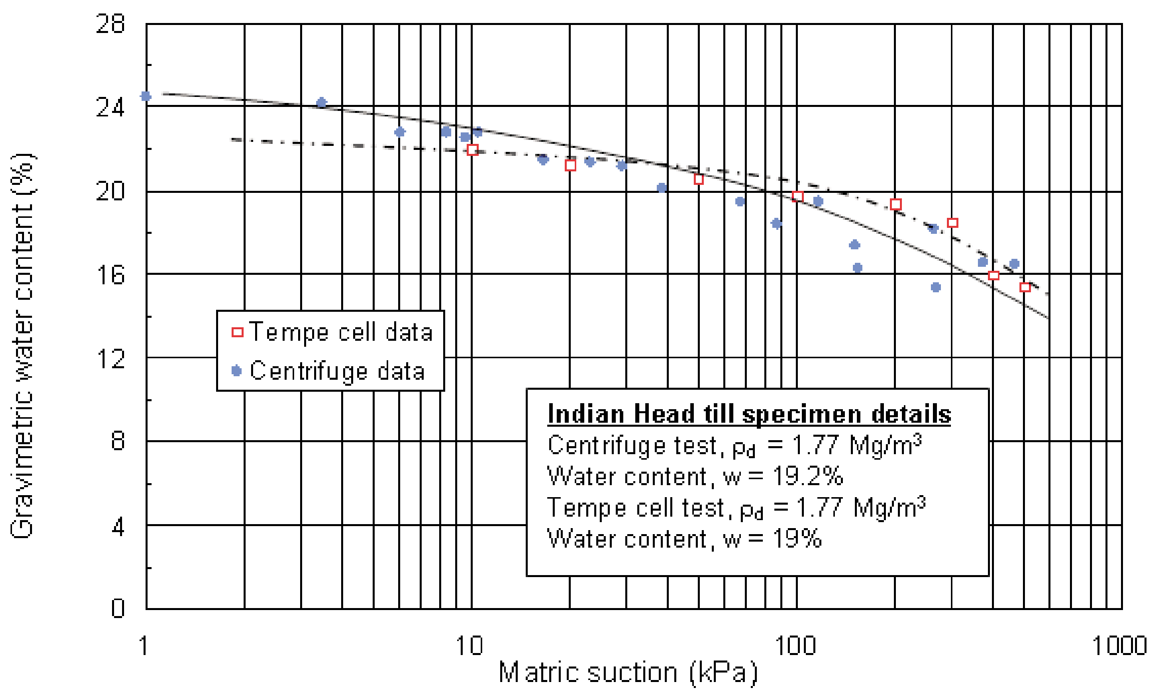


Fig. 7. Comparison of measured soil-water characteristic curves using a Tempe cell and the centrifuge method for Indian Head till specimens with an initial water content of 19.2%.



Two hours of rotation time was found to be sufficient to attain equilibrium conditions for silty soil specimens with a thickness of 12 mm. However, 2 h of centrifugation time was not sufficient to attain equilibrium conditions for the specimens of Indian Head till and Regina clay. Table 3 summarizes the testing speeds along with the equilibration times used for all of the soils tested.

The centrifuge was stopped after attaining equilibrium conditions at each speed tested, and the mass of each soil specimen was measured. After the 2500 rpm run, the soil specimens

Fig. 8. Comparison of measured soil-water characteristic curves using a Tempe cell and the centrifuge method for Indian Head till specimens with an initial water content of 16.3%.

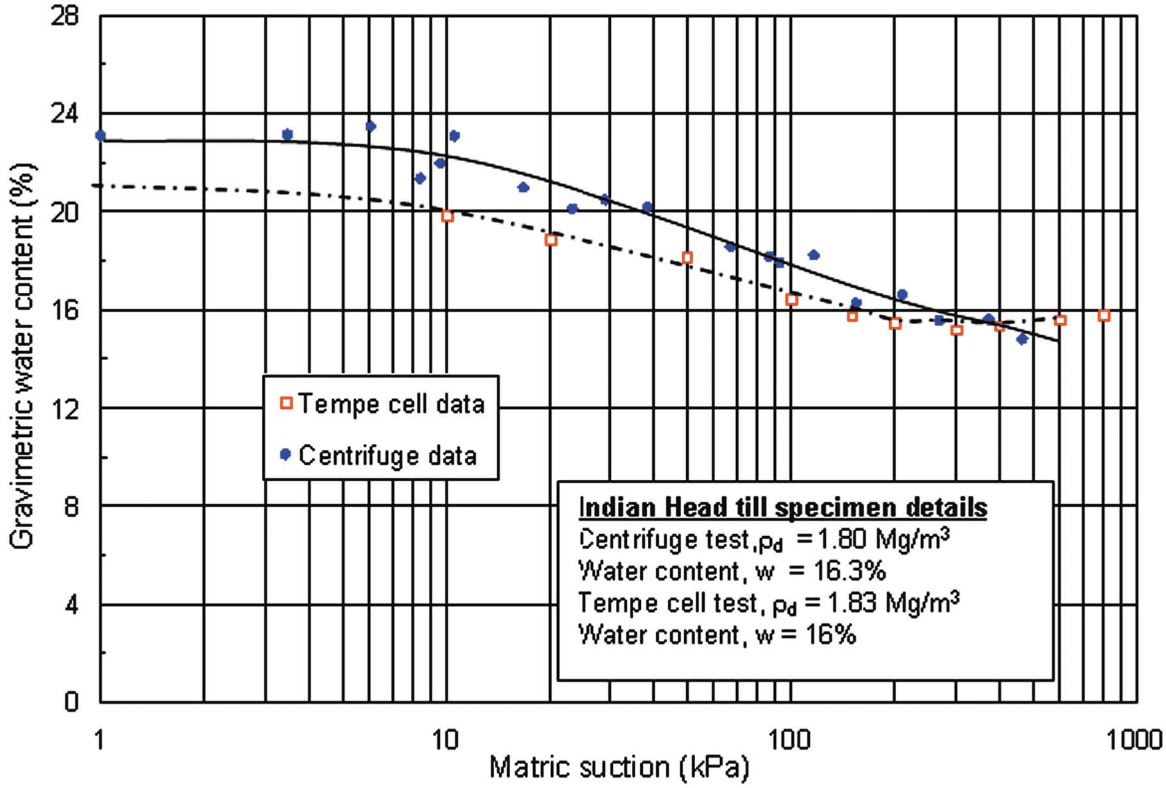


Fig. 9. Comparison of measured soil-water characteristic curves using a Tempe cell and the centrifuge method for Indian Head till specimens with an initial water content of 13%.

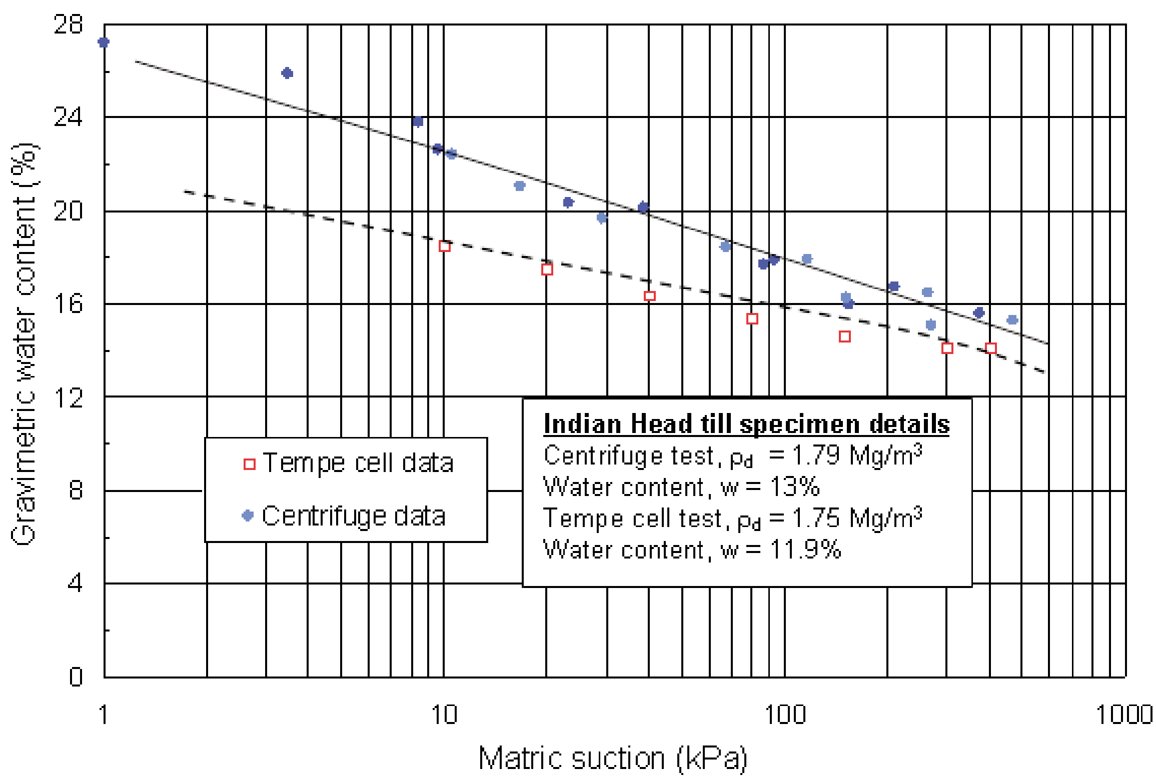


Fig. 10. Comparison of measured soil-water characteristic curves using the pressure plate and the centrifuge methods for Regina Clay specimens with an initial water content of 38%.

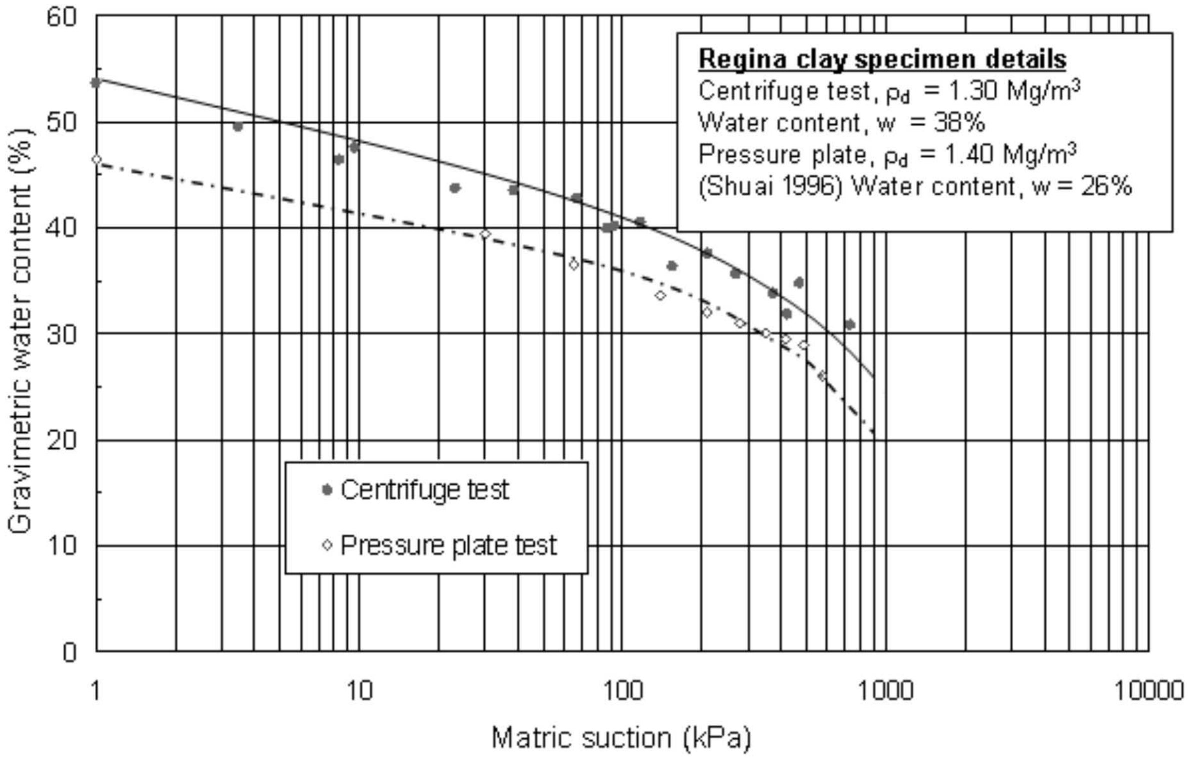


Table 4. Time periods to obtain the soil-water characteristic curve using centrifuge and conventional testing methods.

Test method	Processed silt	Indian Head till: Dry of optimum	Optimum	Wet of optimum	Regina clay
Centrifuge (time in days)	0.5	1	1	1	2
Tempe cell (time in days)	14	28	35	42	112

were dried for the final water content determination. The water content values for the earlier test speeds were then back-calculated.

Presentation and discussion of results

Figure 6 shows the comparison of the matric suction versus water content data for the processed silt, measured using the Tempe cell and the centrifuge. The specimen used for measuring the soil-water characteristic curve in the Tempe cell was statically compacted at an initial water content of 23% and ρ_d of 1.68 Mg/m^3 (Wright 1999). The specimen for measuring the soil-water characteristic curve using centrifuge had an initial water content and ρ_d equal to 22% and 1.57 Mg/m^3, respectively. While the time period required for determining the soil-water characteristic curve using the centrifuge was only 12 h, a time period of 14 days was required using the Tempe cell. The small differences in the soil-water characteristic curve behavior for the processed silt specimens using the two different apparatuses may be associated with the differences in the dry densities and initial water contents at which the statically compacted silt specimens were prepared. There may also be an influence from the increased gravitational forces applied to the soil structure.

The soil-water characteristic curve data were determined for Indian Head till specimens using the Tempe cell and the centrifuge. Indian Head till specimens were prepared using three different initial water content conditions reflecting wet of optimum (19.2%), optimum (16.3%), and dry of optimum (13%) initial water contents. Figures 7 and 8 show the comparison between the measured soil-water characteristic curve using the Tempe cell and the centrifuge for specimens compacted at an initial water content reflecting wet of optimum and optimum conditions, respectively. There is a reasonably good comparison between the data measured using both methods. Variations in the test results, particularly in the low matric suction region, may be associated with the differences in dry density and initial water content conditions.

Figure 9 shows the comparison between the measured soil-water characteristic curve using the Tempe cell and the centrifuge for specimens compacted at an initial water content reflecting dry of optimum condition. The data points in Fig. 9 for the suction range between 400 and 800 kPa suggest that there is a loss of contact between the ceramic disk of the Tempe cell apparatus and the soil specimen. Typically, a fine-grained soil compacted at an initial water content dry of optimum has an open structure with relatively large interconnected pores. The resulting soil structure is a function of the initial compaction water content. The difference in the soil-water characteristic curve data measured by both methods can be attributed to differences in the initial compaction water content conditions of the specimens used in the Tempe cell and the centrifuge. The results of the present study suggest that the soil-water characteristic curve behavior for fine-grained soils, such as Indian Head till, are sensitive for specimens compacted with initial water contents reflecting dry of optimum conditions. Vanapalli et al. (1999) reported similar observations from their studies. The increased gravitational forces associated with centrifugation may also be an influencing factor.

The time required for determining the soil-water characteristic curves using the Tempe cell for a suction range between 0 and 600 kPa (i.e., three different initial water contents representing wet of optimum, optimum, and dry of optimum conditions), was 6, 5, and 4 weeks, respectively. A time period of 1 day was sufficient for determining the soil-water characteristic curve using the centrifuge.

Figure 10 shows the comparison between the soil-water characteristic curves for Regina clay measured using the pressure plate method and the centrifuge method. The centrifuge soil-water characteristic curve was measured in 48 h. A time period of 16 weeks was required to obtain the soil-water characteristic curve using the pressure plate apparatus (Shuai 1996). The differences in soil-water characteristics are mainly due to the variations in the initial water content conditions.

Table 4 shows the comparison between the times required for determining the soil-water characteristic curves using the centrifuge and the Tempe cell or pressure plate apparatus for the three different types of soils used in the present research study.

Conclusions

Commercially available small-scale centrifuges can be used to obtain multiple water contents versus suction data points for the soil-water characteristic curve at a single speed of rotation. Additional data for the soil-water characteristic curve for the suction range of interest (i.e., between 0 and 2800 kPa) can be generated using different speeds of rotation.

The time period for measuring the soil-water characteristic curves for fine-grained soils reduces considerably using the centrifuge method in comparison to conventional testing procedures such as the pressure plate apparatus or a Tempe cell. There is reasonably good agreement between the experimental results obtained using conventional procedures and the centrifuge procedure for the three fine-grained compacted soils used in this research. The results of this study are encouraging for geotechnical and geo-environmental engineers who use soil-water characteristic curves for interpreting or predicting the engineering behavior of unsaturated soils.

Further study needs to be undertaken to determine the influence of the increased gravity forces on the soil specimens. As well, increased care needs to be exercised to ensure that the initial density and water content conditions are the same for specimens tested using the centrifuge and the pressure plate apparatus.

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