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AN ALTERNATIVE METHOD FOR THE MEASUREMENT OF SOIL-WATER CHARACTERISTIC CURVES FOR FINE-GRAINED SOILS

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ABSTRACT The soil-water characteristic curves were measured for three different types of fine-grained soils using a small-scale centrifuge. A specimen holder was specially designed for measuring the soil-water characteristic curves using the centrifuge technique. The three different fine-grained soils used in the study are the Processed silt (w_L = 24 %, 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% and I_p = 21%, and Clay = 70%). The soil-water characteristic curves ranging from 0 to 600 kPa were measured in 12, 24 and 36 hours using the centrifuge technique for Processed silt, Indian Head till and Regina clay respectively. However, a time period of 2, 4 to 6 and 16 weeks were required for measuring the soil-water characteristic curves for the same soils using conventional Pressure plate and Tempe cell apparatus. There is a good comparison between the experimental results obtained by both these methods. The results of this study are encouraging as soil-water characteristic curves can be measured in a considerably short time using small-scale centrifuge.

RÉSUMÉ Les sols de tout type, structure ou minéralogie sont dans une condition d'état limitant saturé à succion zéro et dans une condition sèche à une valeur de succion de 1,000,000 kPa. Comme le sol passe d'une condition saturée à une condition sèche, la distribution de la relation d'interphase sol-eau-air change avec l'état de stresse (i.e succion du sol). Les relations de l'interphase sol-eau-air ont une influence prédominante sur le comportement en ingénierie des sols insaturés. Le contenu en eau résiduelle est une relation importante d'interphase dans la mécanique pour les sols insaturés. Cet article résume et discute la recherche sur le concept du contenu disponible en eau résiduelle dans la littérature. La signification et la pertinence du contenu en eau résiduelle acordées aux sols insaturés sont décrites. Une construction graphique est proposée laquelle utilise une technique informatique pour estimer le contenu en eau résiduelle et la valeur d'entrée de l'air à partir de données d'une courbe caractéristique eau-sol. L'importance d'une condition d'état résiduel en relation avec le comportement de la force de cisaillement des sols insaturés est discutée. L'analyse de ces résultats suggère que la force de cisaillement augmente de façon non-linéaire jusqu'à la valeur de succion résiduelle et commence à perdre de la force à des valeurs plus élevées de succion.

1. INTRODUCTION

From a practical perspective, geotechnical and geo-environmental engineers deal more with unsaturated soils in comparison to saturated soils. In the recent years, there is an increase in interest in the engineering communities towards understanding the engineering behavior of unsaturated soils (Fredlund and Rahardjo 1993). Geotechnical and geo-environmental engineers can propose more rational engineering design procedures based on these studies. The engineering behavior of unsaturated soils can be interpreted in terms of two stress state variables namely; net normal stress, $(\sigma - u_a)$, and soil suction, $(u_a - u_w)$, using experimental test results. However, experimental studies on unsaturated soils are costly and time-consuming. In the last five years, several simple procedures have been proposed in the literature to predict the engineering behavior of unsaturated soils. (Fredlund et al. 1994, Vanapalli et al. 1996a, Oberg and Sallfours 1997, Bao et al. 1998, Khallili and Khabbaz 1998). In many of these procedures, soil-water characteristic curve has been used as an interpretative tool to understand and predict the engineering behavior of unsaturated soils.

The soil-water characteristic curve defines the relationship between the soil suction and soil gravimetric water content, w, or volumetric water content, θ_w, or the degree of saturation, S. Soil-water characteristic curves are commonly measured in the laboratory for a suction range of 0 to 1,000 kPa using conventional testing procedures. Typically, six to eight data points are measured such that the air-entry value and the residual state conditions can be identified from the measured data. The pressure plate, the Tempe cells and the suction table are examples of these procedures. These apparatuses are reliable to measure the soil-water characteristic curve behavior of both the coarse and fine-grained soils.

A saturated soil specimen with known initial volume-mass properties is placed in a pressure plate apparatus and brought to an equilibrium condition under a series of suction values. The mass of the specimen is measured after attaining equilibrium condition under each suction value. In a Tempe cell, the mass of water coming out from the specimen under each applied suction value is measured. In both these procedures, the mass-volume properties of the specimen are measured at the end of the test. The gravimetric water content or volumetric water content or degree of saturation is determined from back calculations for each applied value of suction to obtain the soil-water characteristic curve relationship. More details of the testing procedures are available in Fredlund and Rahardjo (1993).

The time period required for the measurement of soil-water characteristic curve using conventional testing procedures for coarse-grained soil such as sand or silt is between 6 to 8 days (for obtaining 6 to 8 data points). In other words, a time period of approximately one-day is required for the soil specimen to equilibrate under each value of suction. Relatively longer periods of time are required to measure the soil-water characteristic curves for fine-grained soils such as tills and clays in comparison to coarse-grained soils due to the low coefficient of permeability values. A time period of approximately 5 to 6 days is required for the specimen to equilibrate under each value of soil suction. Typically, 4 to 6 weeks of time is required to obtain the soil-water characteristic curve for a fine-grained soil with a suction range of 0 to 1,000 kPa (i.e., for 6 to 8 data points).

A high gravity field is applied to the soil specimen supported on a column of porous ceramic that has a fixed water table at its base, which is equivalent to atmospheric pressure in centrifuge technique. This situation is similar to the field conditions where gravity causes water to drain towards to zero pressure (i.e., natural groundwater table). In the centrifuge, when equilibrium conditions are eventually attained, there is a moisture profile in soil specimen as though the water was draining to a groundwater table in a world where gravity is several times to that on earth.

Pressure plate apparatus and Tempe cells are commonly used for measuring the soil-water characteristic curves. These apparatuses are quite reliable but require considerable time for measuring the soil-water characterstics. Soil-water characteristic curves have been measured for coarse-grained soils and fine-grained soils using the centrifuge technique (Gardner 1937, Russell and Richards 1938, Croney et al. 1952, Skibinsky 1996). However, in most of the above works either air-dry or slurried specimens were used.

From a practical perspective, geotechnical and geo-environmental engineers are interested in the soil-water characteristics of compacted, fine-grained soils. Any methods that would save time and money in measuring the soil-water characteristic curves will be of value. The water content versus suction data can be measured in a shorter period of time using the centrifuge technique in comparison to the conventional Tempe cell or pressure plate.

This paper describes the use of a small-scale medical centrifuge to determine the soil-water characteristic curves for fine-grained soils using statically compacted specimens. Multiple water content versus suction relationship can be obtained in a single test run using this method. A specimen holder has been specially designed and used to hold compacted soil specimens. The proposed centrifuge method can be used for compacted, fine-grained soils to measure the soil-water characteristic curve in a shorter period.

2. PRINCIPLE OF THE CENTRIFUGE METHOD FOR MEASURING SUCTION

Briggs and McLane (1907) were the first investigators to use centrifuge technique for measuring the relationship between suction and the amount of water retained by a soil. Gardner (1937) measured the capillary tension of soil moisture over a wide range of moisture contents by determining the equilibrium moisture content of calibrated filter papers that were in contact with the moist soil. The filter papers were calibrated by determining their moisture 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 moisture retained in soil at different values of applied suctions. The gradient of the capillary potential was found to represent the force that balances the centrifugal force at equilibrium conditions in the centrifuge from these studies. Croney et al. (1952) studied the influence of the material used for the porous cylinder on the time required for the soil specimen to reach moisture equilibrium with the water table in the centrifugal field. Hard chalk cylinders were used in the centrifuge tests. Solid ceramic cylinders reduced the time periods required to attain equilibrium conditions in comparison to hollow cylinders. Figure 1 demonstrates the principle used in the centrifuge method for measuring suction.

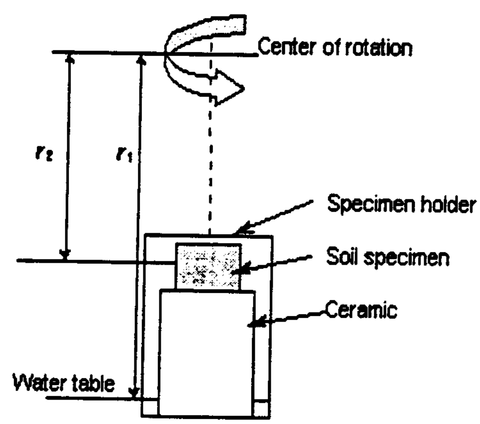

Figure 1. Suction measurement principle of the centrifuge.

The suction in the soil specimen in a centrifuge can be calculated using Eqn. [1].

$$\psi = \frac{\rho\omega^2}{2}\left(r_2^2 - r_1^2\right) \quad [1]$$

where:

ψ = suction in the soil specimen
r_1 = radial distance to the free water surface
r_2 = radial distance to the midpoint of the soil specimen
ω = angular velocity
ρ = density of the pore fluid

3. DESCRIPTION OF THE APPARATUS

A J6-HC small-scale medical centrifuge with JS-4.2 rotor assembly that has an operable radius of 254 mm was used in the study. This centrifuge is capable of a maximum speed of 4200 rpm and can induce a maximum suction of 2800 kPa in the soil specimens. The assembly consists of six swinging type buckets capable of carrying six test specimens in one test run (Figure 2). The swinging type buckets assume horizontal position while the centrifuge is spinning. All the six buckets can be used simultaneously with specimen holders available for testing. However, the mass in all the specimen holders should be the same to avoid rotary imbalance. Thus, six data points of the soil-water characteristic curve can be obtained in one test run using the medical centrifuge. However, in the present study, only two swinging buckets were used with specimen holders for each test run.

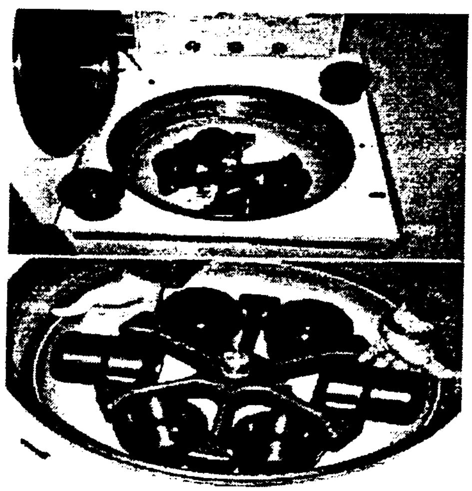

Figure 2. J6-HC centrifuge with six swinging type buckets rotor assembly.

Two aluminum soil specimen holders were specially designed and used for the testing. Soil specimen holders were designed such that they fit exactly into the centrifuge buckets. The specimen holder consisted of a drainage plate, reservoir cup and five rings. The reservoir cup served as a collection area for the water that was extracted out of the soil specimen. The free water surface in the drainage plate is similar to conditions shown in Fig. 1. Similar specimen holder was used earlier for testing slurried specimens of coarse-grained and fine-grained soils (Skibinsky 1996). For the present study, specimen holder was modified such that it can be used to measure soil-water characteristic curves for 10mm thick specimens of compacted fine-grained soils. Figure 3 shows the details of the aluminum soil specimen holder used in the centrifuge testing.

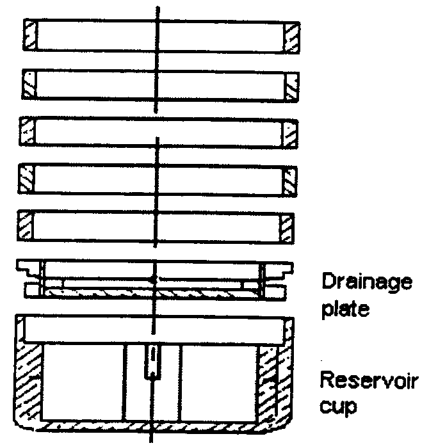

Figure 3. Details of the Aluminum soil specimen Holder. (From Skibinsky 1996)

Special ceramic cylinders of 15 mm, 30 mm, 45 mm and 60 mm heights were prepared such that the soil specimens can be positioned at different distances from the centre of rotation to induce different values of suction at the same speed. The ceramic cylinders were made up of 60% kaolinite and 40% aluminum oxide powder. Ceramic cylinders of two different heights were used in one test run to position the soil specimens at two different distances from the centre of rotation of the centrifuge. The soil specimens were thus subjected to two different centrifugal forces and created two different values of suction in the soil specimens for the same speed. Thus, instead of obtaining readings in duplicate for one test run, two data points of suction versus water content were obtained. Different cylinder heights and test speeds were used in this study to obtain the soil-water characteristic curve ranging from 0kPa to 600 kPa. Table 1 shows the suction in the soil specimens calculated using Eqn. [1].

Table 1. Suction associated with different test speeds and different ceramic cylinders

Test Speed in rpm	Suction in the soil specimen (kPa)			
	15 mm cylinder	30 mm cylinder	45 mm cylinder	60 mm cylinder
300	6.04	8.38	10.51	12.41
500	16.69	23.18	29.06	34.32
1000	67.11	93.26	116.8	138.8
1500	151.1	210.0	263.1	310.8
2000	268.7	373.3	467.7	552.5
2500	420.0	583.6	731.1	863.6

Figure 4 shows the saturated soil specimens on top of the ceramic cylinders of different height in the drainage plate.

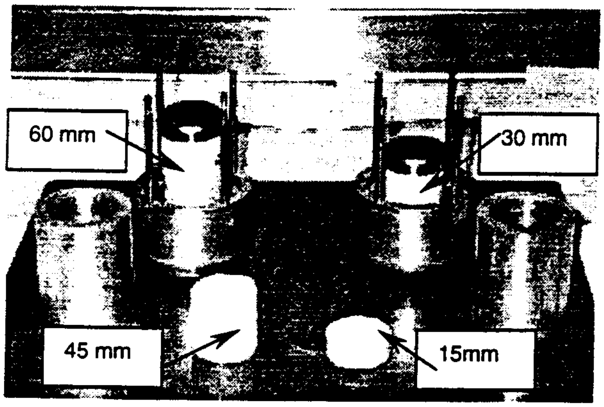

Figure 4. Saturated soil specimens on top of the ceramic cylinders in the drainage plate.

3. SOIL PROPERTIES AND SPECIMEN PREPARATION

Three different fine-grained soils, namely, the Processed 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% and I_p = 21%, and Clay = 70%, G_s = 2.75) were used for testing in the centrifuge. All the three soils were first air-dried and then pulverized. Pre-calculated amounts of water content was added to the soil and stored in polythene bags in a humidity-controlled room for 24 hours to attain uniform water content.

The Processed silt specimens were statically compacted at initial water content, w, of 22% and a dry density, ρ_d, of 1.57 Mg/m^3. For Indian Head till specimens, three initial water contents were selected for preparing the soil specimens representing 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 ρ_d of 1.30 Mg/m^3. All the specimens were compacted in steel rings of 50mm diameter and 10 mm height. More details of soil properties and specimen preparation are available in Khanzode (1999).

TEST PROCEDURE

Ceramic cylinders of two different heights (i.e., 30mm and 60 mm) and the statically compacted soil specimens were saturated by submerging in a water bath for 24 hours. Both the ceramic cylinders were then placed on the drainage plates of the specimen holders (Figure 4). The bottom end of the ceramic cylinder was placed such that it would just dip into the reference free water table in the drainage plate. The mass of the saturated soil specimens were determined and placed on the ceramic cylinders. A filter paper was placed between the soil specimen and the ceramic cylinder to prevent loss of soil particles. The soil specimens were covered on top with an aluminum foil to prevent moisture loss by evaporation. Both the soil specimen holders were then placed in the centrifuge buckets. Figure 5 shows the soil specimen holders in the centrifuge buckets ready for centrifugation.

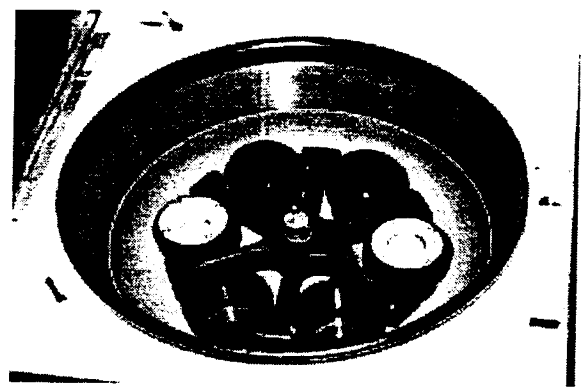

Figure 5. Soil specimen holders in the centrifuge buckets ready for centrifugation.

The centrifuge was initially rotated at 300 rpm until equilibrium conditions were attained. Two hours of rotation time was found to be sufficient to attain equilibrium conditions for soil specimens tested with a thickness less than 10mm for silty soils. Russell and Richards (1938) reported similar observations for the fine-grained soils. However, it was found that 2 hrs of centrifugation time was not sufficient to attain equilibrium conditions for the specimens of Indian Head till and Regina clay. Both these soils had higher percentage of fines in comparison to Processed silt. The time of centrifugation was increased for these specimens to achieve equilibrium conditions. Table 2 summarizes the testing speeds along with the equilibration times used for all the soils tested.

Table 2 Centrifugation time at different testing speeds

S. no	Test speed in rpm	Time of rotation in hrs		
		Silt	Till	Clay
1	300	2	2	4
2	500	2	2	4
3	1000	2	4	6
4	1500	2	4	6
5	2000	2	6	8
6	2500	2	6	8

The centrifuge was stopped after attaining equilbrium conditions at each speed tested and the mass of the soil specimens was determined. After the 2500 rpm run, the soil specimens were kept in an oven for water content determination. The water content values for the earlier test speeds were then back calculated.

5. PRESENTATION AND DISCUSSION OF RESULTS

Figure 6 shows the comparison between the soil-water characteristic curves for the Processed silt measured using Tempe cell and the centrifuge. The soil-water characteristic curves were measured using Tempe cell on the Processed silt specimens compacted at an initial water content of 23% and dry density, ρ_d, of 1.68 Mg/m^3 in two weeks time (Wright 1999). Whereas, the time period required for obtaining the soil-water characteristic curve for Processed silt specimens compacted at an initial water content of 22% and dry density, ρ_d, of 1.57 Mg/m^3 using the centrifuge method was only 12 hours. The small differences in the soil-water characteristic curves behavior may be associated with the differences in the dry densities and initial water contents at which the silt specimens were prepared.

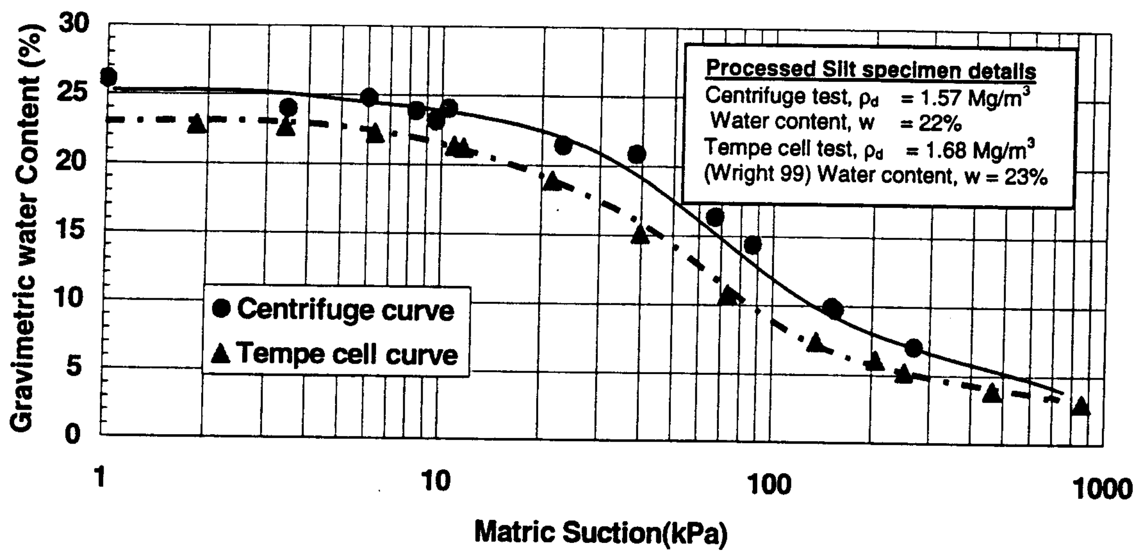

Figure 6. Comparison of measured soil-water characteristic curve using Tempe cell and centrifuge method for Processed silt specimens with initial water content of 22%.

Figures 7, 8 and 9 show the comparison between the soil-water characteristic curves for three types of Indian Head till specimens measured using the Tempe cell and the centrifuge. A time period of only 24 hours was required for all three types of Indian Head till specimens compacted at 19.2% (wet of optimum), 16.3% (optimum) and 13% (dry of optimum) initial water contents to obtain the centrifuge soil-water characteristic curves. However, the time required for similar Indian Head till specimens to obtain the soil-water characteristic curves for the same suction range using the Tempe cell was 6, 5 and 4 weeks respectively. The reason for such variations in time intervals for measuring soil-water characteristic curves using Tempe cell is associated with the structure induced to the soil by initial water content. The initial water content, compaction procedures and the stress history influence the soil-water characteristic curve behavior of compacted, fine-grained soils (Vanapalli, 1999).

For specimens compacted at 19.2% (wet of optimum) the microstructure controls the desaturation behavior. The pore spaces are in a state of occluded condition. Thus, these soils have higher moisture retention capacity. There is a good correlation between the soil-water characteristic curves obtained by both the methods for 19.3% (wet of optimum) specimens as the dry densities and the initial water contents are similar for the specimens (Figure 7).

A fine-grained soil compacted at dry of optimum initial water content conditions has an open structure with relatively large interconnected pores like a granular soil. Macro structure controls the desaturation behavior of the soil-water characteristic curve for the soil specimen tested at this water content. The difference in the soil-water characteristic curves measured by both the methods for the 13% (dry of optimum) specimens is mainly seen in the low suction regions of the curve (Figure 9). This behavior can be attributed to the small differences in the initial water content conditions. The results suggest that initial compacted water content is sensitive to the soil-water characteristic curve behavior in dry of optimum conditions. The soil-water characteristic curves by both the methods for the specimens compacted at 16.3% (at optimum) lie in between these two types of structures (Figure 8).

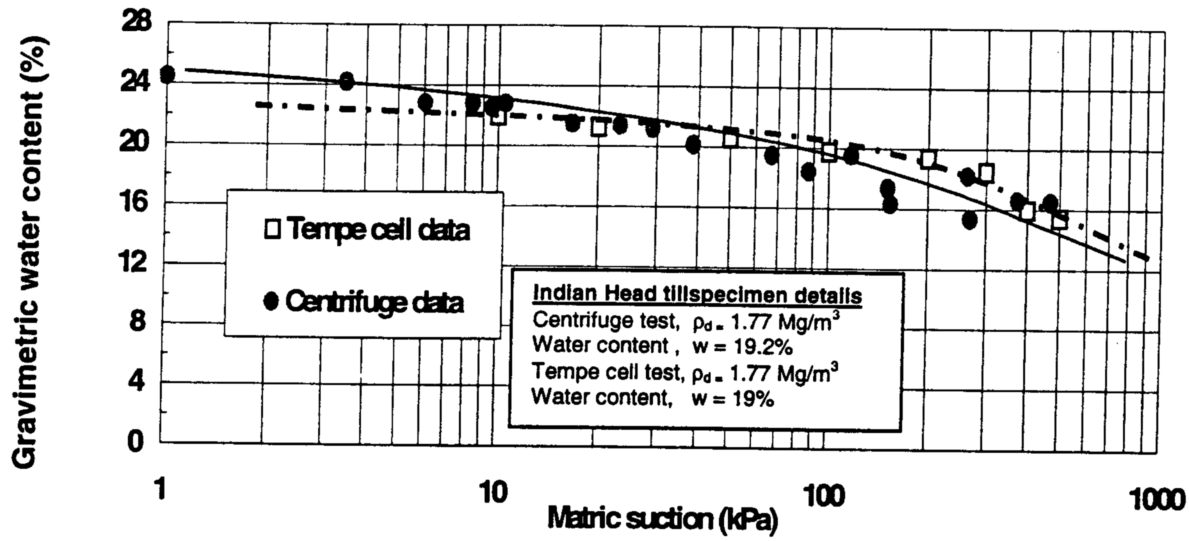

Figure 7. Comparison of measured soil-water characteristic curve using Tempe cell and centrifuge method for Indian Head Till specimens with initial water content of 19.2%.

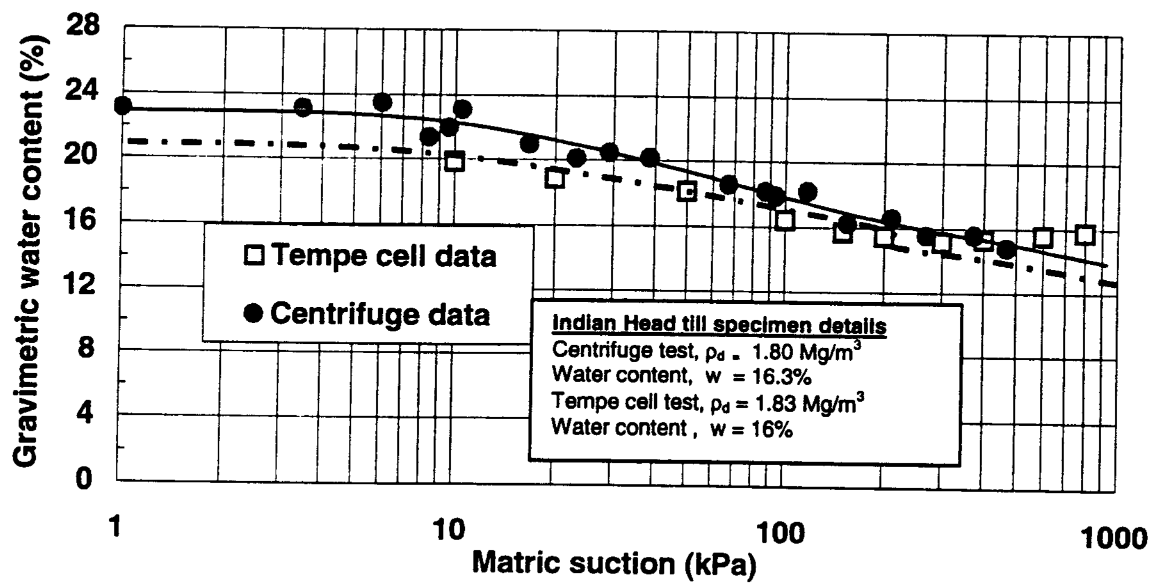

Figure 8. Comparison of measured soil-water characteristic curve using Tempe cell and centrifuge method for Indian Head Till specimens with initial water content of 16.3%.

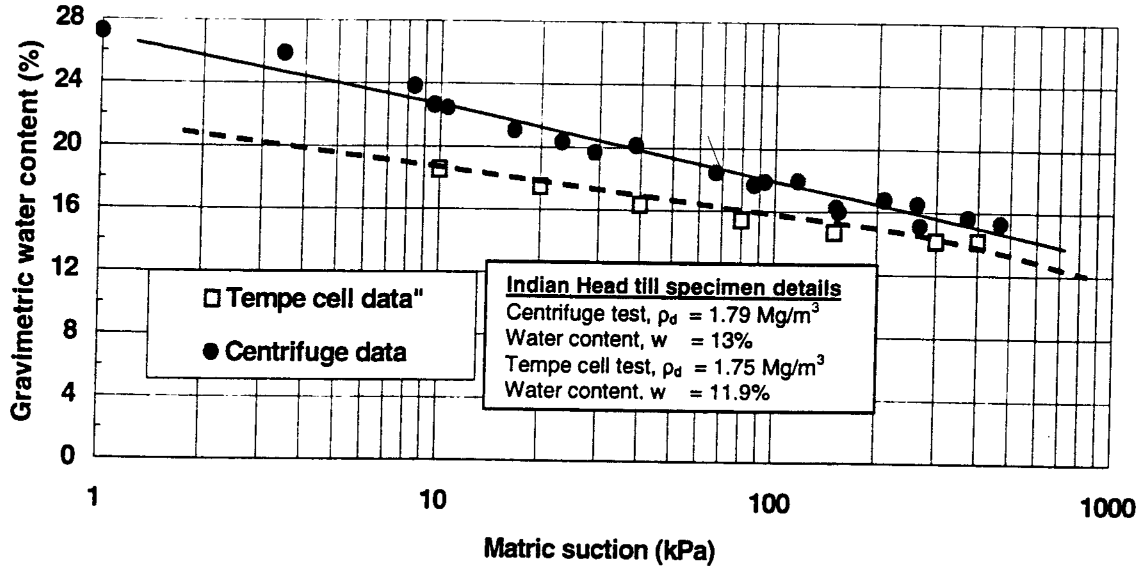

Figure 9. Comparison of measured soil-water characteristic curve using Tempe cell and centrifuge method for Indian Head Till specimens with initial water content of 13%.

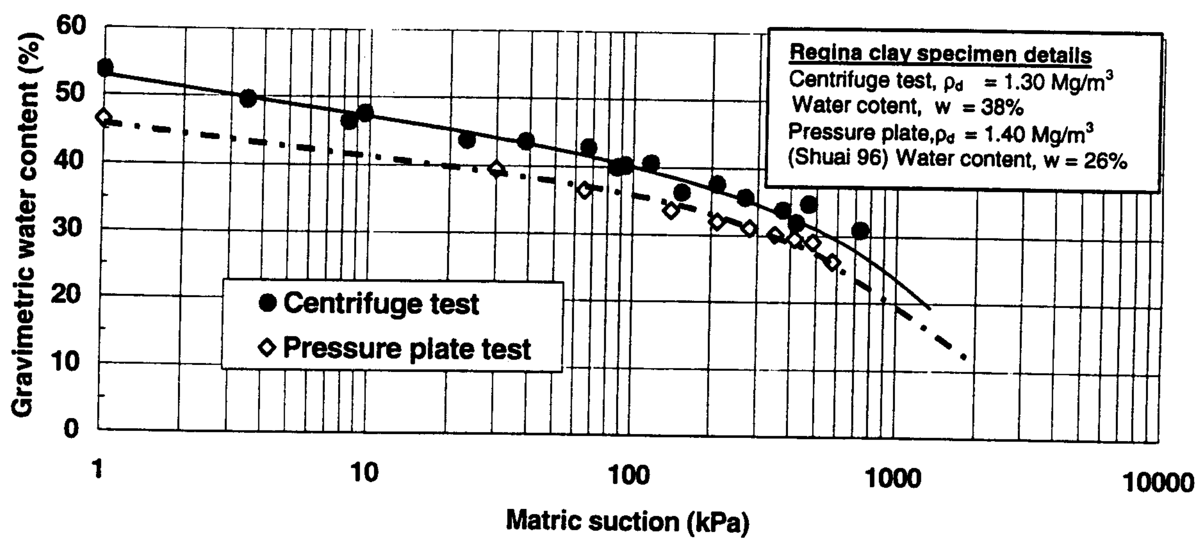

Figure 10. Comparison of measured soil-water characteristic curve using Pressure plate and centrifuge method for Regina Clay specimens with an initial water content of 38%

Figure 10 shows the comparison between the soil-water characteristic curves for the Regina clay measured using pressure plate and the centrifuge method. The Regina clay specimens took 36 hours to obtain the soil-water characteristic curve using the centrifuge. Whereas, a time period of almost 16 weeks was required to obtain the soil-water characteristic curve using pressure plate apparatus (Shuai 1996). The differences in soil-water characteristics are mainly due to the variations in initial water content conditions.

Table 3 shows the time required by all the three types of soils to obtain the centrifuge as well as the Tempe cell and pressure plate soil-water characteristic curves.

Table 3. Time periods to obtain the soil-water characteristic curve using centrifuge and conventional testing methods

Test Method used	Silt	Indian Head till: Dry of Opt.	Opt.	Wet of Opt.	Regina Clay
Centrifuge (time in hrs)	12	24	24	24	36
Tempe cell (time in weeks)	2	4	5	6	16

SUMMARY AND CONCLUSIONS

Multiple water content versus suction data points of the soil-water characteristic curve can be obtained in one test run using the centrifuge method as compared to the conventional apparatuses. The specially designed soil specimen holder can be used to obtain six data points of the soil-water characteristic curve in one test run. Thus, soil water characteristic curve for compacted, fine-grained soils can be obtained in a considerably short period of time using the centrifuge techniques. There is a good comparison between the experimental results obtained by using both the Tempe cell apparatus and the centrifuge. The results of this study are encouraging to use centrifuge testing methods for the determination of the soil-water characteristic curves for fine-grained soils.

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