4th Pan-American Conference on Unsaturated Soils
Ottawa, Canada, June 22-25, 2025

Shear Strength Behaviour Determination in Unsaturated Soils Using Conventional Laboratory Tests

Aaqib Ali*[1], Umair Ali[1,2], and Mubashir Aziz[1,2]

[1]*Department of Civil and Environmental Engineering, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia*

[2]*Interdisciplinary Research Center for Construction and Building Materials, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia*

**Corresponding author's email:* g202210600@kfupm.edu.sa

Abstract: Traditional techniques with suction control for measuring shear strength in partially saturated soils are often cumbersome, expensive, and time intensive. This study utilizes a simplified approach that integrates the filter paper technique with direct shear tests to evaluate shear strength. The methodology involves deriving the soil water characteristic curve (SWCC) using filter paper method (FPM), followed by direct shear tests to measure shear strength under constant water content (no-drainage) conditions. The experimental results are compared with semi-empirical predictive methods to assess their consistency over a wide suction range. Non-linear regression is applied to fit the FPM-derived SWCC into existing models by adjusting curve-fitting parameters. Results indicate that increasing moisture content reduces suction, while higher matric suction correlates with increased shear strength, following a non-linear trend. Also, apparent cohesion (c) and friction angle (ϕ) show a direct relationship with matric suction. These findings are in qualitative agreement with common unsaturated soil strength behavior and are compared to predictions from semi-empirical models. The comparisons validate the general trends but also highlight deviations at high suctions. Overall, this integrated approach offers a straightforward, cost-effective technique for analyzing the shear strength of partially saturated soils, making it accessible to geotechnical engineering and soil mechanics laboratories.

Introduction

The concept of unsaturated soil strength as introduced by Bishop [1] and further developed by Fredlund et al., [2], present significant challenges in their practical application within engineering practices. Numerous studies have demonstrated that the shear strength of partially saturated soil decreases as its moisture content increases, emphasizing the complex relationship between these two parameters [3], [4], [5]. The shear strength, τ of a partially saturated soil is governed by two independent stress-state variables viz; net normal stress $(\sigma - u_w)$, and the matric suction, $(u_a - u_w)$. The determination of shear strength in unsaturated soils can be achieved using suction controlled direct shear or triaxial instruments [6], [7]. However, these experimental approaches are notably time-consuming and necessitate extensive, costly laboratory setups. Consequently, their use in routine engineering practice is limited.

During recent times, several semi-empirical models have been developed to predict the shear strength of unsaturated soils. These models typically incorporate parameters of saturated shear strength (c and ϕ) along with SWCC [8], [9], [10]. The models relate the soil suction (ψ) and the degree of saturation (S), gravimetric water content (w) and volumetric water content (θ). Because of the strong relationship between water content and shear strength these prediction models use SWCC as a key input. Some computational approaches have also been employed to estimate the unsaturated shear strength and its variation with suction. It is well known that the SWCC for fine-grained unsaturated soils exhibits hysteresis between drying and wetting paths: a soil tends to hold more water during drying than at the same suction during wetting [11]. This hysteresis is generally attributed to factors such as non-uniform pore size distribution, water film adsorption on particle surfaces (capillary condensation), entrapment of air bubbles during wetting, and the volume change (shrink–swell) characteristics of the soil [12]. In the context of partially saturated soils, capillarity and adsorption are the dominant mechanisms, so matric potential is the major component of total suction. For most practical problems, gravitational and pore pressure potentials can be neglected in unsaturated soils [13], so the total suction (Ψ_T) is effectively the sum of matric (ψ_M) and osmotic (ψ_O) components:

$$\Psi_T = \psi_M + \psi_O \tag{1}$$

The current semi-empirical methods for estimating the shear strength of unsaturated soils, as found in existing literature, are based on a limited array of experimental studies. These studies are primarily based on lower suction values typically ranging between 0-50 kPa. Given that traditional suction-controlled shear tests are time-consuming and expensive, there is a need to develop simpler experimental techniques that can quickly determine unsaturated shear strength and also verify the accuracy of existing prediction models over a broader range of conditions. In this study, a simple experimental approach is adopted for measuring the soil suction and subsequently the shear strength of an unsaturated fine-grained soil. The approach integrates an indirect filter paper method for suction measurement with conventional direct shear tests for strength measurement. The experimentally obtained results are then compared with predictions from semi-empirical models using non-linear regression analysis and curve-fitting techniques. By doing so, we evaluate the performance of models not only in their traditional valid range but also at higher suctions encountered in our tests, thereby providing insight into the shear strength behavior of unsaturated soil across a wide spectrum of matric suctions.

Materials and Methods

Soil

The soil used in this study was collected from the northern Himalayan region of India (34°07’18’’ N, 74°50’79’’ E) from three different sites at a depth of 1 m below ground surface (to avoid the influence of organic matter). The soil from each site was air-dried and thoroughly examined in the laboratory. Basic index properties and compaction characteristics for the soils from Site 1 (S-1), Site 2 (S-2), and Site 3 (S-3) were determined according to ASTM standards. Figure 1a shows a typical soil sample (S-1) and Figure 2 illustrates the particle size distribution curves for all three sites. Standard Proctor compaction tests (ASTM D698) were conducted for each soil. The maximum dry density (MDD) was found to be 17.13 kN/m^3, 16.81 kN/m^3, and 16.52 kN/m^3 for S-1, S-2, and S-3 respectively. The corresponding optimum moisture contents (OMC) were 18.06%, 19.52%, and 18.07% for S-1, S-2, and S-3. Figure 3 shows the compaction curves for all three soils, including the zero-air-voids (ZAV) lines based on measured specific gravity (G_s) for each soil (2.62, 2.61, and 2.59, respectively).

Among these soils, the fine-grained S-1 soil (with the highest silt content) was identified as the weakest and most susceptible to shear strength reduction upon wetting. Therefore, S-1 was selected for further detailed testing in this study. The properties of the S-1 soil are summarized in Table 1. S-1 is classified as CL (low-plasticity clay) under the Unified Soil Classification System, with a plasticity index of 16.28%. The in-situ moisture content at the time of sampling was about 28.6% and in-situ dry density was 14.33 kN/m^3 (indicating a fairly loose, wet state in the field).

Table 1 Key properties of soil sample collected from site 1 (S-1)

Natural moisture content (%)	In-situ dry density (kN/m^3)	Specific gravity (G_s)	Plasticity index (%)	USCS	MDD (kN/m^3)	OMC (%)	Strength parameters c (kPa) & ϕ (^{0})
28.6	14.33	2.62	16.28	CL	17.13	18.06	39.84 and 17.07

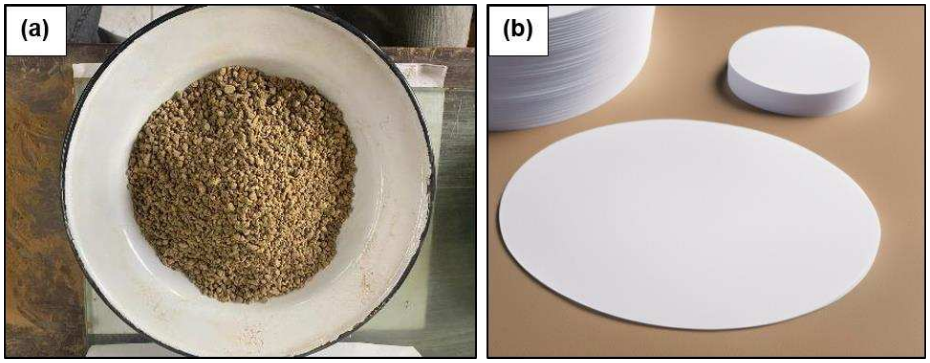

Figure 1 Material samples (a) Soil (b) Whatman filter paper

Grade 42 Whatman Filter paper

The study utilized the Whatman Grade 42 filter paper disks (Figure 1b) for suction equilibration. These are designed to retain particles larger than 2.5 µm, making them suitable for fine particle filtration. These ashless filter papers have a maximum ash content of 0.007%, ensuring minimal residue during use. Their detailed specifications include a grade classification of 42, a nominal thickness of 200 µm, and a typical water flow rate of 2.5 ml/min. Additionally, they exhibit an alpha cellulose content exceeding 98%, further enhancing their purity and performance.

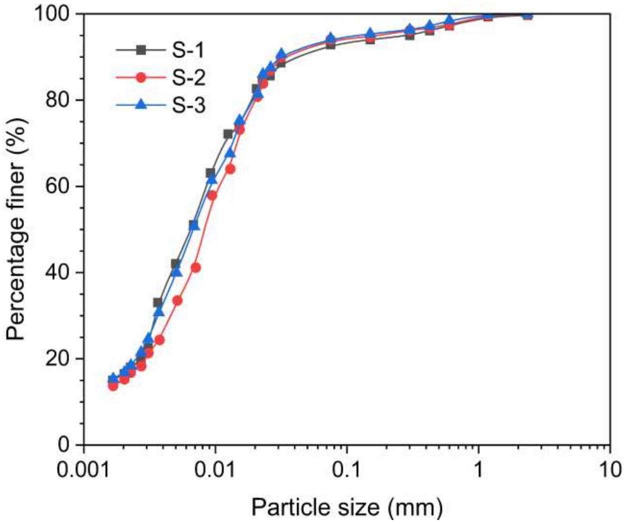

Figure 2 Particle size distribution curves for soil samples

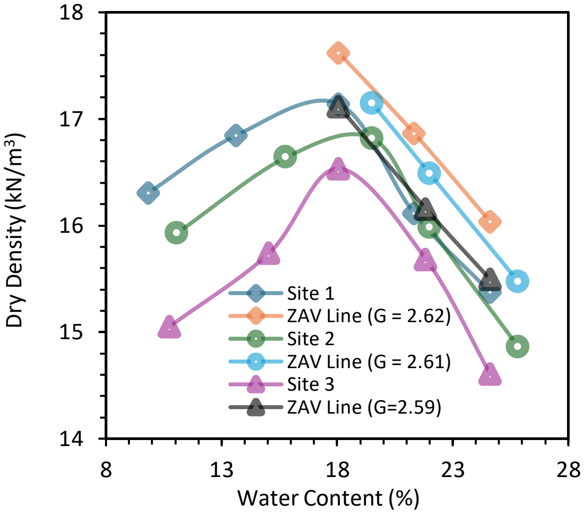

Figure 3 Compaction curves for soil collected from different sites

Filter Paper Method (FPM) for SWCC

To establish the soil-water characteristic curve for S-1 soil, we employed the FPM as an indirect technique to measure matric suction. Whatman Grade 42 filter paper disks were used as the porous medium for suction equilibration. This filter paper has a nominal pore size suitable for measuring a wide range of suctions, and its calibration curves are well documented. In our procedure, soil specimens of S-1 were prepared with varying water contents and allowed to equilibrate with dry filter paper. Specifically, each soil sample (compacted or molded to a target water content and density) was enclosed in an airtight container with a dry filter paper in contact or in close proximity (sandwiched between thin layers of the soil but separated by a thin mesh to avoid direct mixing of soil into the paper). The containers were sealed and kept in a constant-temperature environment. Water started migrating between the soil and the dry filter paper until the equilibrium was reached. At this point the water content of the filter paper corresponds to suction in soil.

After a 7-day equilibration period (sufficient for our sample sizes to reach equilibrium based on preliminary trials), the filter papers were removed, and their gravimetric water content was immediately determined. Using known calibration curves for Whatman No. 42 filter paper (ASTM D5298-94 and other literature sources), the matric suction of the soil corresponding to each filter paper's water content was calculated. In the case of Whatman No. 42 filter paper, the calibration curves proposed are bilinear (Table 2) on a plane of logarithm of suction versus filter paper water content [14]. The general form of calibration equation is as:

$$log\ S = a(wc_{fp}) + b \quad (2)$$

Where S denotes suction in kPa, a is the slope of the line, wc_{fp} is the gravimetric filter paper water content in percentage, and b is the Y-intercept.

For our range of interest (moderate to high suctions), we primarily relied on the calibration by Chandler et al. for matric suction. This indirect method allowed us to obtain multiple points on the SWCC (suction vs. moisture content) relatively quickly and without specialized suction-controlled apparatus.

Table 2 Calibration curves for Whatman Grade 42 filter paper

Reference	Suction	Water (%) Range	Log10(Suction) (kPa)
ASTM D5298 (1992)	Total and Matric Suction	w < 45.3	5.327-0.0779w
		w > 45.3	2.412-0.0135w
Chandler et al. (1992)	Matric	w < 47	4.842-0.0622w
		w > 47	6.050-2.48logw
Oliveira & Marinho (2006)	Total and Matric Suction	w < 33	4.83-0.0839w
		w > 33	2.57-0.0154w
Wang et al. (2003)	Matric	w ≤ 47	5.257-0.070w
		w > 47	2.470-0.0120w

Results and discussions

The research comprised of three phases and in the initial phase the in-situ soil properties of soil from site 1 were determined. The second phase involved evaluating the Atterberg limits, compaction parameters, UCS, and shear strength properties following the relevant ASTM standards for soil from same site. Additionally, the study utilized FPM and direct shear tests for suction measurement and shear strength respectively.

SWCC Data and Modeling

The soil samples were prepared, and filter paper was placed around each sample to measure the moisture content of the wet filter paper. Calibration curves were employed to derive suction values corresponding to various degrees of saturation. Figure 4 presents the SWCC of the tested soil, plotted on a logarithmic scale with estimated suction values against the soil water content. As expected, matric suction increase as water content decreases, a trend clearly observed in Figure 4a. The soil was near saturation at OMC (water content ~18%), had a low initial suction (~5 kPa). As the soil was dried, the suction rose rapidly: for instance, at a water content of about 12%, the equilibrium suction reached on the order of 100 kPa, and at water contents of 6–8%, the suction approached 1000 kPa. The data indicate a typical drying curve for a silt–clay mixture, with a relatively high air-entry value (the transition from near-zero suction to rising suction occurs around 18–20% water content for this soil).

To represent SWCC continuously and to integrate it with shear strength models, the measured SWCC data was fitted using a mathematical model based on the equations proposed by Van Genuchten [15] and Fredlund and Xing [11]. To fit these non-linear models to the observed data, the least-squares regression method was applied. The excel solver function was utilized to minimize the squared differences between the observed and predicted values by adjusting the curve-fitting parameters. This process yielded the best-fit curves, as illustrated in Figures 4(a) and 4(b). The curve fitting parameters for both the models were arranged in a way to get best fit of these models with the experimentally determined values. In these plots θ represents the volumetric water content, θ_s and θ_r are the saturated and residual volumetric water contents, Ψ is matric suction, and a, n, m are fitting parameters. Both models provide a reasonable fit to the experimental SWCC data, with the van Genuchten model capturing the low-suction curvature slightly better and the Fredlund–Xing model capturing the high-suction tail slightly better. The coefficient of determination (R^2) for both fits was above 0.98, indicating that either model can represent our SWCC data well. The mathematical equations obtained for the soil under study are represented as:

$$\Theta = \frac{\theta - 13.3691}{27.9932 - 13.3691} = \left\{\frac{1}{1 + (0.006 * \Psi)^{1.63082}}\right\}^{0.38681} \tag{3}$$

$$\Theta = \frac{28.0822 \times \left\{1 - \dfrac{\ln\left(1 + \Psi/_{1000}\right)}{\ln\left(1 + 10^6/_{1000.38}\right)}\right\}}{\left\{\ln(e + \left(\dfrac{\Psi}{123.41}\right)^{1.57157}\right\}^{0.41356}} \tag{4}$$

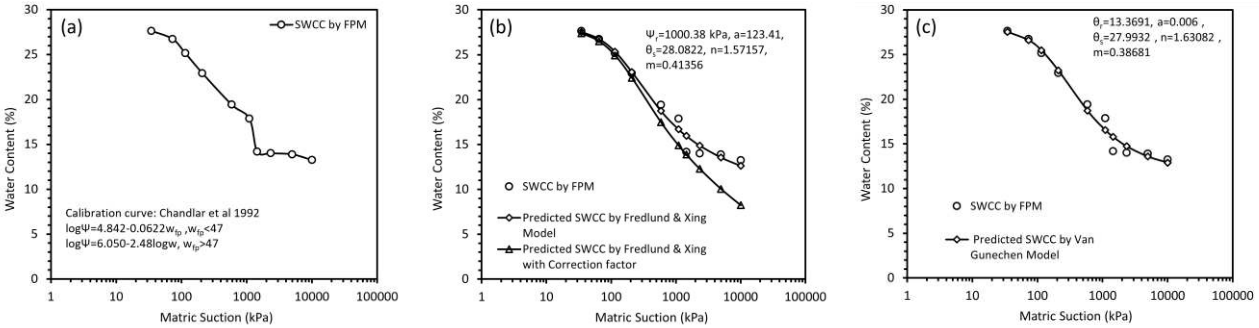

Figure 4 SWCC for fine grained soil dominated by silt content by (a) Filter paper method (b) Van Genutchen (1980) model (c) Fredlund and Xing (1992) model

Direct Shear Tests

To evaluate the shear strength of partially saturated soil from S-1 under different conditions, conventional direct shear tests were conducted. The test specimens prepared in a direct shear box (60 mm × 60 mm x 2 mm) in accordance with ASTM D3080 standards. Soil samples were statically compacted to an MDD of 17.13 kN/m³ and an OMC of 18.06%, with water content adjusted through wet or submerged sand beds separated by filter paper to prevent direct contact. After air drying to achieve varying degrees of unsaturation, the samples were equilibrated in desiccators for 7 days and subjected to shearing in a direct shear box at 1.25 mm/min under normal stresses of 50 kN/m^2, 100 kN/m^2 and 150 kN/m^2(Figure 5).

The direct shear tests were conducted under constant water content conditions. This means the specimen was not allowed to exchange water with its surroundings during the test (no inflow or outflow), although pore-air was free to escape. Under these conditions, the matric suction in the soil is not fixed; it can change as the soil deforms. As the suction was not measured during the shear test, so the interpretation of the shear results will use the initial suction (before shearing) as a reference for each specimen's state. This approach assumes that the shear failure occurs quickly enough and with minimal overall volume change such that the matric suction does not fully equilibrate to a drastically different value by the time of failure. Also, the shear tests were performed at a strain-controlled rate of 1.25 mm/min which was fast enough to approximate undrained loading of the pore fluid phases, given the low permeability of the soil.

The analysis revealed that the shear strength parameters, apparent cohesion *c* and friction angle *ϕ*, varied with water content and matric suction, showing significant non-linear behavior in the shear strength envelopes (Figure 6). For saturated conditions, c= 20.197 kPa and ϕ =7°, with both parameters decreasing as matric suction reduced, indicating the influence of negative pore water pressure and adhesion of fines on shear resistance (Figure 7). Experimental discrepancies due to the filter paper method and laboratory conditions were addressed using reference data from best-fit models, aligning with observations of Fredlund et al. (1996) on non-linear behavior in partially saturated soils.

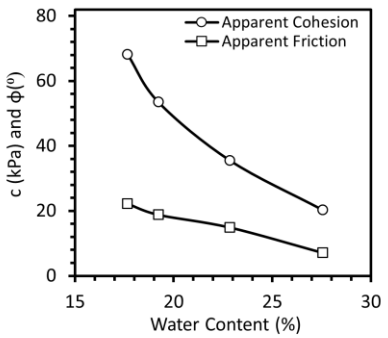

Figure 5 Shear failure envelopes corresponding to different water contents

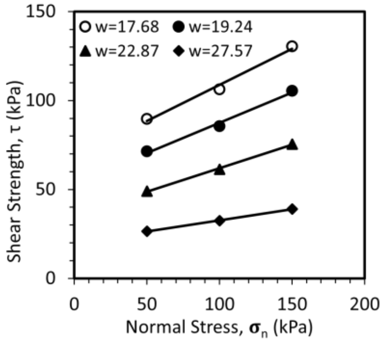

Figure 6 Changes in apparent cohesion and friction with variation in water content

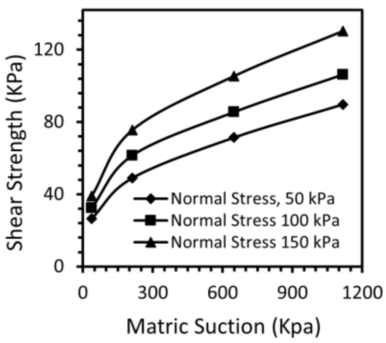

Figure 7 Variation of shear strength with matric suction for different normal stress

Relationship between Experimental Data and Theoretical Procedures

In this study, an attempt was made to predict the unsaturated shear strength of soil using a semi-empirical model and then compare the predictions with experimentally obtained results.

The study used a mathematical model proposed by Vanapalli et al. (1996) to predict the shear strength of partially saturated soil. The model uses SWCC as a reference for forecasting the partially saturated shear strength of soil and is mathematically represented as:

$$\tau = [c + (\sigma_n - u_a)tan\phi + (u_a - u_w)\{(\Theta^k)tan\phi\}] \tag{5}$$

The exponent k is a fitting parameter that accounts for the soil type and is often correlated to the plasticity index or other factors. Essentially, the model linearly interpolates the contribution of suction to shear strength between zero (Sr = 1) and a maximum (Sr = 0), with the nonlinearity controlled by k. From conventional direct shear test c is 20.19 kPa and ϕ is 7° and 'k' has been obtained from empirical relationship shown in eq. 6 and was found to be 2.09.

$$k = -0.0008 * \ (I_p)^2 + 0.0801(I_p) + 1 \tag{6}$$

Figure 8 compares the experimentally observed shear strength envelopes with those predicted by the Vanapalli et al. (1996) model. By applying the model beyond 50 kPa is an extrapolation and it was done to cover the range of our data and evaluate the model's performance. As seen in Figures 8a–c, at lower suctions (0–100 kPa) the model with k=2.09 fits the experimental data quite well. This suggests that the model calibrated with basic soil properties and captured the initial increase in shear strength due to suction. At higher suctions (above 300–400 kPa), however, a gap starts to appear, and the experimental shear strength values are somewhat lower than what the model predicts. For example, at a suction of ∼1000 kPa under 50 kPa normal stress (Figure 8a), the model predicted approx. τ of 150 kPa while the measured τ was 140 kPa. Similarly, under 150 kPa normal stress (Figure 8c), the model overshoots the measured strength by around 10–15 kPa at the highest suction. These differences, while not enormous, indicate that the model with k=2.09 is overestimating the strength contribution of suction at the very dry end for our soil.

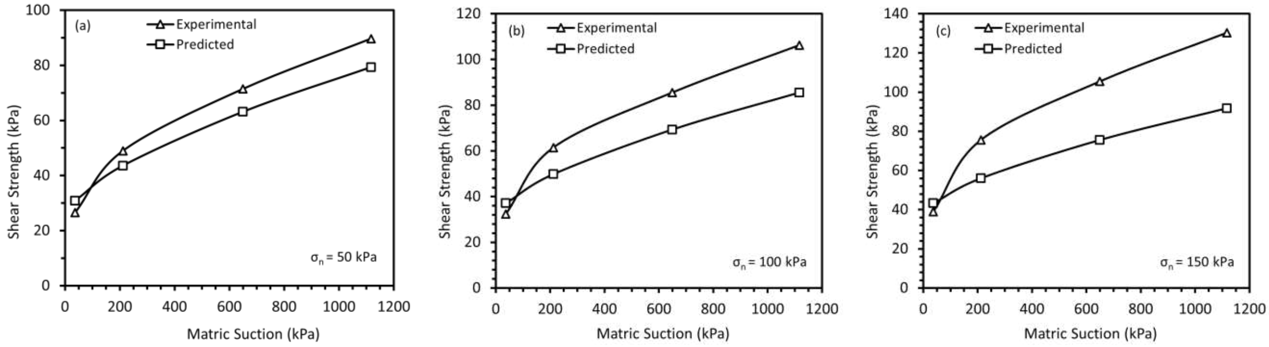

Figure 8 Comparison of experimentally observed and theoretically predicted shear strength envelope for normal stress of (a) 50 kPa, (b) 100 kPa and (c) 150kPa.

To improve the fit, the parameter k was adjusted to 1.7 by trial-and-error and later confirmed by a least-squares fit between model and data. This gave a better overall match with experimental results across the full suction range. A comparison of experimentally observed shear strength with theoretically predicted shear strength was also made for the normal stress of 50 kPa using 'k' as 2.09 and 1.7 in Figure 9. From the figure, the square of difference between experimentally observed values and theoretically predicted values is less when fitting parameter 'k=1.7' is used in the theoretical model. This shows that the data aligns more closely when along equality line when k = 1.7.

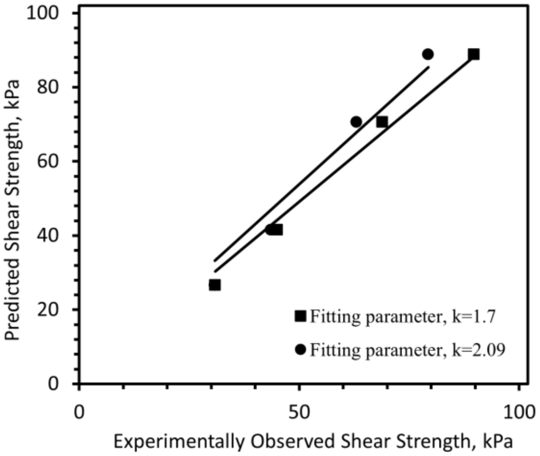

Figure 9 Comparison of experimentally observed shear strength of unsaturated soils with theoretically predicted shear strength of unsaturated soil for the normal stress of 50 kPa

Conclusions

This study demonstrates a simplified and practical methodology that integrates the FPM with direct shear tests for evaluating the shear strength behavior of unsaturated soils. The approach integrates the determination of the SWCC with traditional testing methods, demonstrating strong correlations between shear strength parameters and matric suction. The experimental results showed strong correlations between the shear strength parameters and the initial matric suction of the soil. The findings confirm that both cohesion (c) and the internal friction angle (ϕ) increase with rising matric suction (decreased initial water content), validating the non-linear correlation observed in unsaturated soil behavior. Furthermore, the observed trends in shear strength under constant water content conditions reinforce the critical influence of matric suction on soil strength. The use of non-linear regression to optimize curve-fitting parameters significantly enhances the accuracy of predictions, outperforming standard techniques while maintaining simplicity and efficiency. The experimental data align well with predictions from semi-empirical models especially at lower suctions, after calibrating the model fitting parameter, k. This comparison underscores both the reliability and practicality of this methodology. Additionally, the proposed technique offers a cost-effective alternative to traditional, more time-intensive methods, making it accessible for routine application in soil mechanics and geotechnical engineering laboratories. The research contributes to the understanding of shear strength dynamics in unsaturated soils and addresses some challenges in their evaluation by offering a streamlined experimental method. The insights gained from this can be valuable for practitioners dealing with compacted fills, embankments, or natural slopes in partially saturated conditions. Future work will focus on capturing real-time suction changes during shear and on extending this approach to soils of different plasticity to further generalize the findings.

References

[1] A. W. Bishop, *The principles of effective stress*. Norges Geotekniske Institutt, 1960.

[2] D. G. Fredlund, N. R. Morgenstern, and R. A. Widger, "The shear strength of unsaturated soils," *Canadian geotechnical journal*, vol. 15, no. 3, pp. 313–321, 1978.

[3] C. R. Liu, "The experimental study of the influence of the matric suction on the unsaturated soil strength," *Applied Mechanics and Materials*, vol. 580, pp. 514–517, 2014.

[4] S. K. Vanapalli, D. G. Fredlund, and D. E. Pufahl, "The relationship between the soil-water characteristic curve and the unsaturated shear strength of a compacted glacial till," *Geotechnical Testing Journal*, vol. 19, pp. 259–268, 1996.

[5] G.-F. Chen, C. Deng-Hong, S.-W. Huang, and Y.-F. Lu, "Study on Shear Strength Tests and Uniformed Constitutive Model of Shear Stress-Shear Displacement for Unsaturated Soils," in *Instrumentation, Testing, and Modeling of Soil and Rock Behavior*, 2011, pp. 78–84.

[6] J. K. M. Gan, D. G. Fredlund, and H. Rahardjo, "Determination of the shear strength parameters of an unsaturated soil using the direct shear test," *Canadian Geotechnical Journal*, vol. 25, no. 3, pp. 500–510, 1988.

[7] S. J. Wheeler and V. Sivakumar, "Critical state concepts for unsaturated soil," in *International conference on expansive soils*, 1992, pp. 167–172.

[8] S. K. Vanapalli, D. G. Fredlund, D. E. Pufahl, and A. W. Clifton, "Model for the prediction of shear strength with respect to soil suction," *Canadian geotechnical journal*, vol. 33, no. 3, pp. 379–392, 1996, doi: 10.1139/t96-060.

[9] N. Khalili and M. H. Khabbaz, "A unique relationship for χ for the determination of the shear strength of unsaturated soils," *Geotechnique*, vol. 48, no. 5, pp. 681–687, 1998.

[10] C. G. Bao, B. Gong, and L. Zhan, "Properties of unsaturated soils and slope stability of expansive soils," in *Proceedings of the Second International Conference on Unsaturated Soils (UNSAT 98), Beijing*, 1998, pp. 71–98.

[11] D. G. Fredlund and Anqing Xing, "Equations for the soil-water characteristic curve," *Canadian Geotechnical Journal*, vol. 31, no. 4, pp. 521–532, 1994, doi: 10.1139/T94-061.

[12] R. Chen and C. W. W. Ng, "Impact of wetting–drying cycles on hydro-mechanical behavior of an unsaturated compacted clay," *Appl Clay Sci*, vol. 86, pp. 38–46, 2013.

[13] W. T. Oh, *Simple techniques for the implementation of the mechanics of unsaturated soils into engineering practice*. University of Ottawa (Canada), 2012.

[14] E. C. Leong, L. He, and H. Rahardjo, "Factors affecting the filter paper method for total and matric suction measurements," *Geotechnical Testing Journal*, vol. 25, no. 3, pp. 322–333, 2002.

[15] M. T. van Genuchten and W. A. Jury, "Progress in unsaturated flow and transport modeling," *Reviews of Geophysics*, vol. 25, no. 2, pp. 135–140, 1987.

INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

The paper was published in the proceedings of the 4th Pan-American Conference on Unsaturated Soils (PanAm UNSAT 2025) and was edited by Mehdi Pouragha, Sai Vanapalli and Paul Simms. The conference was held from June 22nd to June 25th 2025 in Ottawa, Canada.