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Research Article

Comparative Study on the Field- and Lab-Based Soil-Water Characteristic Curves for Expansive Soils

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Expansive soils are problematic and viewed as a potential hazard for buildings and structures due to swell and shrink phenomena. The damaging effect of these soils is strongly correlated with the soil-water characteristics of expansive soils present in the shallow depth. The seasonal wetting-drying cycle is vital in fluctuating moisture content in the surficial soils. As such, soils remain unsaturated most of the time due to high absorption capacity. Therefore, it is crucial to assess them as unsaturated soil, and the soil-water characteristic curve (SWCC) is an essential tool for measuring unsaturated soils' mechanical and hydraulic properties. The main objective of this study was to establish both field- and lab-based SWCCs for the expansive soils and compare them for determining the possible difference between them. For this purpose, eight sites of expansive soils were selected for sampling and in situ testing. These sites include three locations of Karak, three locations of Kohat, and two locations of D.I areas. Based on the experimental results, Karak's expansive soil indicated a high suction value of 705 kPa, while D. I Khan's soil showed the least suction equal to 595 kPa. The comparison of field and lab SWCCs for the potential sites presented a close agreement in the matric suction values beyond the air entry values (AEVs), particularly in the residual suction zones. It was also concluded that for expansive soils, the field- and lab-based SWCCs are comparable beyond the AEVs. The established curves can be successfully utilized to assess local expansive soils in the framework of unsaturated soils.

1. Introduction

Expansive soils are typical soils, which swell and shrink more than ordinary soils, due to which these soils are considered a potential hazard for engineering buildings and structures [1]. Expansive soils can cause severe damage and distortion if not adequately treated [2]. Buildings and structures, which are more susceptible to deformations, include single-story buildings, pavements, canal linings, slab-on-grade members, water channels, and underground pipelines [3]. Thus, numerous techniques and materials have been introduced recently for stabilizing problematic soils including the work of [4, 5] to restore the buildings and stabilize the soil beneath after being deformed due to various natural soil aspects including the swelling-shrinkage behavior [6, 7].

The main cause of the undesirable behavior of expansive soil is the current limited state of knowledge and practice, as soil mineralogical changes and unsaturated parameters of expansive soils are not frequently taken into consideration in the analysis [8, 9]. As problematic soils are near the natural surface level (NSL), the swell and shrink phenomena are more critical in the surficial depth, approximately 3 meters.

The detrimental effect of expansive soils is closely related to the soil-water characteristic of the surficial soil layer exposed to the seasonal wetting-drying cycles. Furthermore, the moisture content in the shallow depth is more critical due to more exposure to environmental agencies and is not very common in the deep layers. The field assessment presents that the soil-moisture interaction altered by the wetting-drying cycle is a highly complex process and comprised the cumulative effects between the matric potential (negative pore water pressure), water fluctuation, distortion, stress condition, and shear strength parameters variations [10].

As expansive clays are known as challenging soils for geotechnical engineers, however, the presence of suction in these soils reduces the impact of potential problems. Recent investigation recommends incorporating matric suction in the analysis to better approximate expansive behavior. Matric suction depends on moisture content, chemical composition, surface area, structure, voids ratio, and pore distribution. The pore size distribution plays a vital role in the estimation of permeability and other related hydraulic properties. The latest studies also focused on the development of the model for estimating unsaturated properties. The "valve model" as proposed in [11] has recently been utilized for estimating the relative coefficient of permeability.

Moisture content has more impact than other factors while assessing the swell–shrink behavior. Recent research presented that soil mineralogy does not affect the matric suction; however, pore water has a significant impact [12]. As mentioned early by Fredlund and Rahardjo, and Rao and Singh, for recognizing the unsaturated behavior of expansive soil, it is crucial to incorporate SWCCs in the investigation [13, 14]. The unsaturated parameter (matric suction) is generally estimated from the SWCCs. The variation of pore water pressure and volumetric water content during dry and rainy periods has been assessed by [15] using the principles of unsaturated soil mechanics. The SWCC can be established by incorporating both field and lab approaches. However, due to certain limitations and stress conditions in a specific site, field-based SWCC is quite different from the curves plotted from lab testing [16].

Expansive soils can be assessed better in the framework of unsaturated soil mechanics. However, geotechnical engineers ignore this aspect of expansive soils while dealing with complex engineering problems due to the involvement of highly sophisticated equipment and prolonging the test duration. For simplicity, such issues are tackled by assuming fully saturated or dry conditions. This approach increases the overall cost and threatens the structure's safety at the same time. As such, constraints and the complexity of this domain require further investigation concerning the unsaturated characteristic of expansive soils.

The current investigation aims to promote the principles of unsaturated soil mechanics in geotechnical engineering practice and establish the SWCCs for some expansive soils based on lab testing and field instrumentations.

2. Importance and Background of SWCC

The SWCC graphically represents the variation of soil suction concerning moisture content. Soil suction may be matric or total suction for low and high suction ranges, while for the moisture content, volumetric and gravimetric moisture or degree of saturation can be utilized for establishing SWCC. Many properties, including volumetric strain, shear strength, hydraulic conductivity, and distribution of pores, can determine from SWCC for a wide range of soils. Additionally, the water retained in the pores can be estimated for any saturation level [17–19]. Fredlund and Rahardjo indicated that the typical shape of SWCC is sigmoidal as presented in Figure 1 and is hysteretic [13]. For instance, at any moisture content, higher matric suction exists in the drying curve (desorption) than in the wetting curve (sorption) [20]. The accuracy and precision in the unsaturated soil properties mainly depend on the precise establishment of SWCC. The shape of SWCC is also affected by initial moisture content, voids ratio, stress history, soil structure, and compaction methods [18]. In these parameters, the initial moisture and stress history have a significant effect and are responsible for a specific shape of SWCC [17]. As there are many challenges involved in estimating the sorption curve, only the desorption portion is commonly estimated [20, 21]. Similarly, the SWCCs are also hysteretic due to the entrapped air volume and this behavior has been well depicted in the past investigations. A statistical equation was also developed for quantifying the hysteresis of SWCC due to the "ink bottle" effect in the latest investigation [22].

The key points of the SWCC are initial moisture, air-entry value (AEV), residual moisture, and residual suction values. The AEV represents the stage of matric suction at which moisture is extracted from the largest voids present in the soils and desaturation starts. Due to initial saturation and sample disturbance, the AEV and desaturation positions significantly change [23]. Similarly, the depth and hydraulic conductivity can also change SWCC, depending on the soil's suction and stress history [19]. The values of air entry and residual moisture increase with the increase in fine materials in a soil which ultimately increases the water-retaining capacity [24]. As in the field, the density of soil increases with depth, due to which different SWCCs will be plotted for different depths [25]. Numerous studies have been conducted for investigating SWCCs for different types of expansive soils. For instance, the shear strength and water retention properties were investigated by Ye et al. for low expansive soil utilizing modified triaxial apparatus [26].

The SWCCs plotted from the in situ suction measurement, and water content is quite different from those plotted from lab results. Lab tests produce a uniform SWCC with a unique curvature due to the least effect on the environment. Field measurements can have more reliable SWCC for different wetting or drying environments at various geostatic stresses, and soil's response is captured in its natural environment. The development of both field- and lab-based SWCC are crucial for reliable engineering protocol regarding expansive soils. Numerous investigations have been carried out for suction and moisture correlations in the last two decades. For instance, Bujang et al. compared the field- and lab-based SWCCs utilizing tensiometers (quick draw) and Rowe Cell (modified) for residual soils. The study concluded that the field-based SWCC consists of intermediate curves before joining sorption and desorption curves.

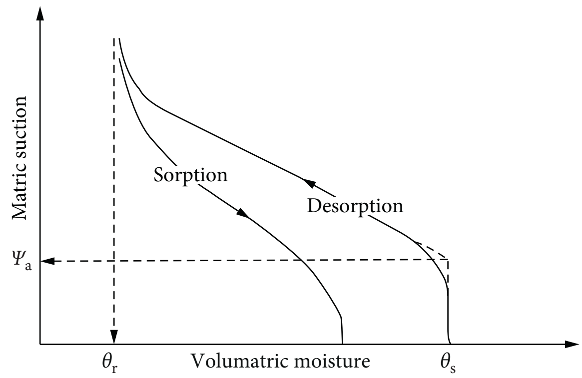

Figure 1: Description of drying (sorption) and wetting (desorption) SWCC [13].

The field data is spread between the wetting and drying curves [27].

Similarly, Chen et al. investigated the fluctuation of water content and matric suction at different depths of red clay (slope) in various weather conditions. The study reported that the field SWCC lies between the wetting and drying curves [28]. A comparative study was also carried out by Bordoni et al. regarding the hydrological application of SWCC and noticed that the field SWCCs could be described well by hysteresis, which affects the moisture content in the soil [17]. The capability of field-based SWCC for high gravely soils was investigated by Al Yahyai [29]. Additionally, matric potential in the low range was measured by Jabro et al., in 2009 for developing a rural area [30].

Furthermore, field and lab SWCCs were compared by Iiyama, in 2016 and noticed that both these curves are not the same [31]. Recently, Campbell et al., reported that field SWCC for a shallow depth is comparable with the lab-based SWCC for sandy soil [32]. A full-scale field study was conducted by Li et al., for investigating an instrumented slope in Hong Kong utilizing tensiometers and moisture probes [33]. The changes in matric suction and water content at the different depths of the residual soil were examined during the infiltration. Their relation was observed by Mohamad Ismail et al. [34].

In situ measurement techniques have been utilized and validated to assess the inherent mechanism of soil in the field subjected to different environments. The retention characteristics were examined by Rocchi et al. for a deep layer of soils incorporating a novel technique for sensors insertion [35]. The most recent study in this domain was conducted by Hedayatia et al. The volumetric water content and matric suction were measured with the help of moisture sensors and potentiometers, respectively, at different locations of highway embankments for establishing SWCC [36]. The previously conducted investigation offers a productive beginning for the utilization of SWCCs in various geotechnical projects, including river training work and road pavements utilizing unsaturated parameters of soils. Field-based SWCCs were also developed by Zamin et al. for the expansive soil deposits [28]. The most recent investigation regarding the field and lab SWCCs was carried out by [37]. The study concluded that the field measurements are located along the scanning curve which is reasonable as the soil on-site has already been subjected to a cycle of drying and wetting. While field measurement will not go into a very high suction range, the measured field data can be used to pinpoint the location of the scanning curve [37].

The previously conducted investigation offers a productive beginning for the utilization of SWCCs in different geotechnical projects, including river training work and road pavements utilizing unsaturated parameters of soils.

3. Materials and Methods

The material used in this research was the different types of expansive soils acquired from eight locations in Khyber Pakhtunkhwa (KPK), Pakistan. These locations include three sites in Karak, two sites in D.I Khan, and three sites in the Kohat regions. Samples were collected from open trenches excavated in the mentioned sites. These trenches were also instrumented for measuring field-based SWCCs. The collected specimens were assessed for their basic engineering and unsaturated properties while for in situ testing, moisture sensors (pre-calibrated), gypsum blocks (G-block) sensors, and tensiometers were installed at various depths. For plotting the lab-based SWCCs, the Fredlund SWC-150 apparatus was utilized at the National Center of Excellence in Geology (NCEG), Peshawar, Pakistan. The details for the testing procedure and site instrumentation are presented in Figure 2.

4. Results and Discussions

The collected samples from the mentioned sites were assessed for their basic engineering properties. The basic testing includes liquid limit (LL), plastic limit PL, plasticity index, and specific gravity G_s. All the samples were tested following the latest available ASTM standard methodology. The experimental findings are listed in Table 1, and a comprehensive discussion of the results is presented in the following section.

4.1. Fundamental Engineering Properties. The collected samples of expansive soils were assessed for consistency limits and specific gravity. The consequences of the different specimens of soils are recorded in Table 1. Based on the experimental outcomes, sample S_1 showed the highest plasticity value while sample S_5 showed the minimum plasticity. Karak's expansive soil is comparatively more plastic than Kohat and D.I Khan's expansive soils based on the consistency limits values while sample S_8 of Kohat soil showed the highest specific gravity among all the samples.

4.2. Field-Based SWCCs. The instrumented trenches were monitored for thirty days (one month), and the collected data of different sensors were processed for plotting the field-based SWCCs. The experimental results are presented in the following sections.

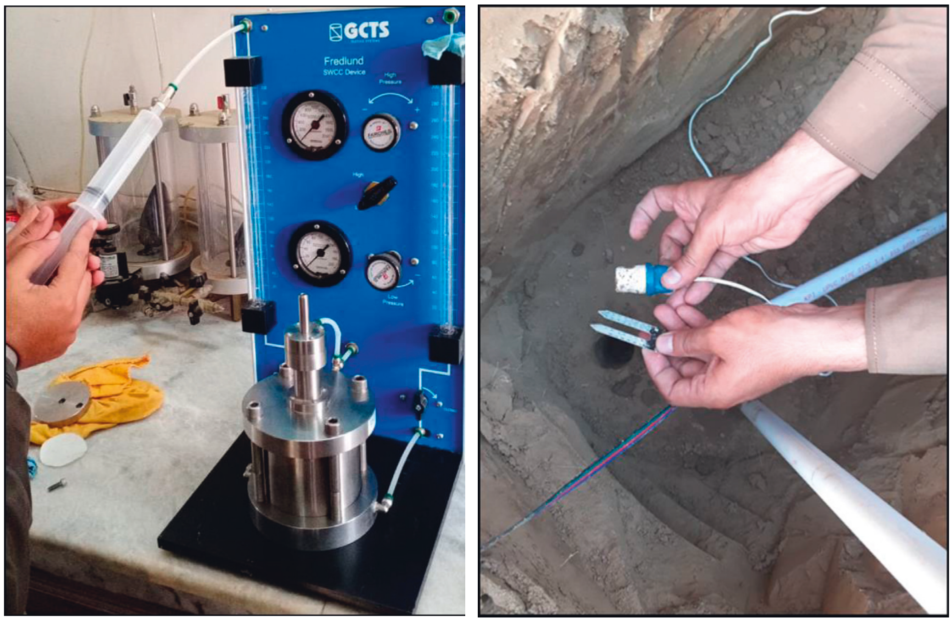

Figure 2: Demonstration of the lab- and field-testing for developing SWCCs of expansive soils.

Table 1: The summary of the selected parameters for the investigated soils [31].

Locations	Symbols	LL (%)	PL (%)	PI (%)	G_s
Karak	S_1	60	23	37	2.68
	S_2	55	21	34	2.6
	S_3	52	18	34	2.62
D.I Khan	S_4	34	11	23	2.60
	S_5	33	11	22	2.66
Kohat	S_6	48	19	27	2.64
	S_7	46	21	25	2.63
	S_8	50.5	20	30.5	2.70

4.2.1. SWCCs for Karak Soils. The field-based SWCCs for Karak soils (S_1, S_2, and S_3) are demonstrated in Figure 3. The S_1 site showed a maximum suction of 705 kPa at a depth of 2 feet from NSL with a 14.5% gravimetric moisture content. The S_2 site showed the suction value of 645 kPa at 14% of gravimetric moisture content while for the S_3 site, matric suction was 670 kPa at 15% of moisture content. The difference between these sites' initial and final suction values was not very significant since all these sites pertain to a similar geological formation (strata).

The extreme suction values' percent contrast was 3.7%–4.9% for sites S_1, S_2, and S_3. This difference accrued because of the slight change in soil density at each site. Additionally, field-based SWCCs for S_1, and S_2 were closer to one another and placed in the upper loop. However, the SWCC for the S_3 site was placed in the lower loop, as appeared in Figure 3, showing less moisture retaining capacity.

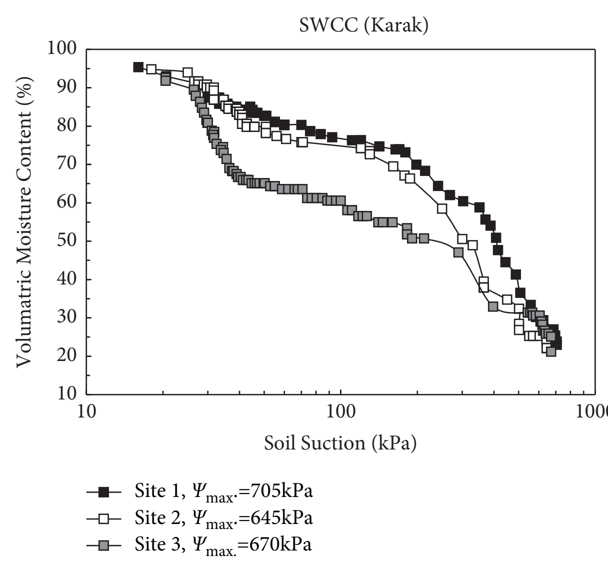

Figure 3: Demonstration of field-based SWCCs for sites S_1, S_2, and S_3 in Karak Expansive soil.

4.2.2. SWCCs for D.I Khan Soil. The field-based SWCCs for S_3 and S_4 sites are demonstrated in Figure 4. The highest suction was 610 kPa for site S_3 measured at a depth of two feet from NSL with a 10.5% moisture content.

However, the S_4 site presented comparatively low matric suction and equal to 595 kPa with gravimetric moisture of 10.0%. The difference between initial and final suction values for these sites was not very significant since these sites pertain to similar geological strata that were located about 1 Km away from each other. The percent change between the matric suction (maximum) values for S_3 and S_4 sites was only 2.4%. Additionally, both curves showed a close agreement and were placed in the lower loop presenting these expansive soils' low moisture retaining capacity.

4.2.3. SWCCs of Kohat Expansive Soil. The field-based SWCCs for S_6, S_7, and S_8 sites are demonstrated in Figure 5.

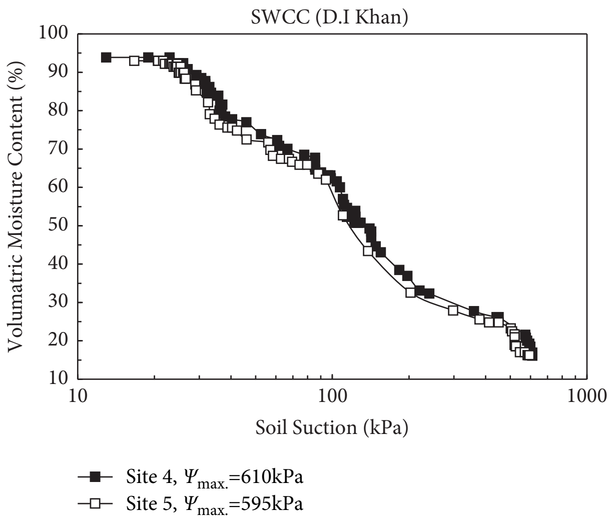

Figure 4: Demonstration of field-based SWCCs for sites S_4 and S_5 in D.I Khan Expansive soil.

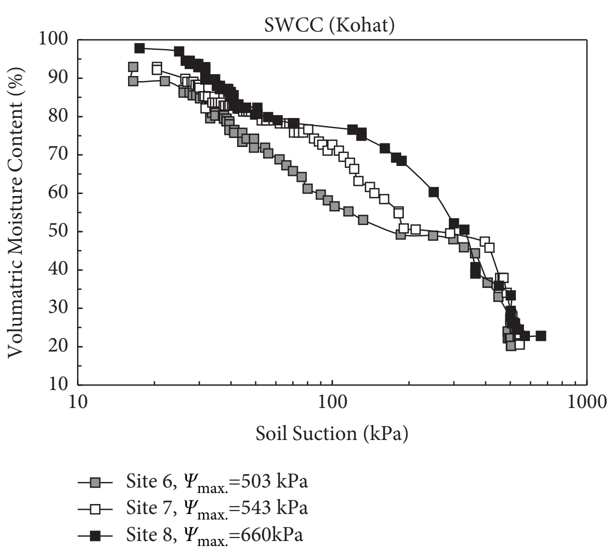

Figure 5: Field-based SWCCs for sites S_6, S_7, and S_8 in Kohat's expansive soil.

The S_8 site showed a maximum suction of 660 kPa with a moisture content of 13.0% and a depth of 2.0 feet measured from NSL. For the S_7 site, the measured suction was 543 kPa with gravimetric moisture of 13.2% while the S_6 site presented the minimum matric suction of 504 kPa concerning 14% of water content. It was also noticed that the residual zones of all the three areas were merging, having a minute change in the suction and gravimetric water.

However, the difference in the inflation zone was much more significant because of the change in the geological stratification. The percent difference for sites S_6, S_7, and S_8 between maximum suction lies between 7.30% and 23.78%, which is more than the percent change as measured for D.I Khan and Karak expansive soils. The SWCCs for sites S_8 and S_6 occurred in the upper loop and merged beyond the AEVs while the S_7 site occupied an intermediate position between S_6 and S_7 sites.

5. Comparison of Field and Lab SWCCs

The field- and lab-based SWCCs curves have been compared in this section for determining their difference. Due to time restraints, only the SWCCs of the potential expansive soils in each region have been compared. These sites include S_1, S_4, and S_8 from Karak, D.I Khan, and Kohat regions, respectively, which are more critical than S_2, S_3, S_5, S_6, and S_7 sites in the mentioned locations. For developing lab-based SWCCs, the Fredlund SWC-150 apparatus was incorporated. For this purpose, specimens were prepared following the provided manual and subjected to standard incremental suction. The minimum suction was kept at zero and gradually the initial suction was raised by doubling the previous values, for instance, 0, 20, 40, 80, 100, 200, etc.

The field and lab testing results are demonstrated in the following section.

5.1. Comparison of Karak Soil. The lab- and field-based SWCCs have been compared in Figure 6 for Karak expansive soil. As measured in the lab and field environment, the maximum suction was 860 kPa and 705 kPa, respectively, while the matric suction was 245 kPa at the air entry value (AEV) at 54.5% of volumetric moisture content. Similarly, the residual suction was 600 kPa with a moisture content of 24.0%.

The variation in volumetric moisture was more significant at the low suction range and AEVs. It was also noticed that field- and lab-based SWCCs are more compatible in inflection points close to the residual zone. The descriptive statistics and details of the various parameters are mentioned in Table 2.

5.2. Comparison of D.I Khan SWCC. The lab- and field-based SWCCs have been compared in Figure 7 for D.I Khan's expansive soil. As measured in the lab and field, the maximum suction values were 840 kPa and 610 kPa, respectively. The suction at the AEV was 68 kPa at volumetric moisture of 60%, while at the residual point, the suction and volumetric moistures were 220 kPa and 22.0%, respectively.

The initial degree of saturation was kept constant, due to which these curves merged in the low suction range while the curves divert at a high suction range due to the difference in the volumetric moisture and suction in the high suction range, as appeared in Figure 7. At the high suction range, the curves divert, showing different suction and moisture content values as mentioned in Figure 3. The descriptive statistics and details are listed in Table 3.

5.3. Comparison of Kohat Soil. The lab- and field-based SWCCs have been compared in Figure 8 for D.I Khan's expansive soil. The maximum matric suction values were 840 kPa and 660 kPa as measured in the lab and field, respectively, while at residual condition, the suction was 510 kPa with volumetric moisture of 22.5%. It was also noticed that the moisture fluctuations were comparatively more at the AEVs.

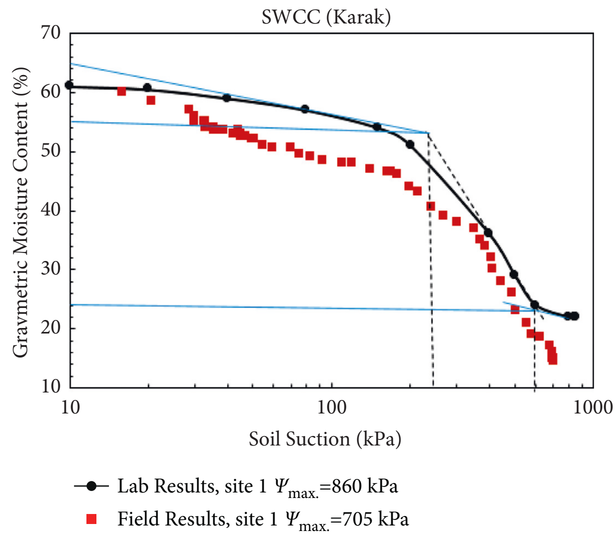

FIGURE 6: Demonstration of field- and lab-based SWCCs for Karak expansive soil.

TABLE 2: Descriptive statistics for the measured parameters of Karak expansive soils.

Descriptive statistics					
Parameters	No.	Minimum	Maximum	Mean	Std. Deviation
Moisture (L)	12	22.00	61.00	41.4583	16.96984
Suction (L)	12	10.00	860.00	375.8333	336.84251
Moisture (F)	82	14.50	60.00	45.4024	12.48442
Suction (F)	82	16.00	705.79	172.2838	210.54223

TABLE 3: Descriptive statistics for the measured parameters of D.I Khan expansive soils.

Descriptive statistics					
Parameters	No.	Minimum	Maximum	Mean	Std. deviation
Moisture (L)	11	17.00	62.00	36.2727	19.93535
Suction (L)	11	10.00	850.00	327.2727	318.24805
Moisture (F)	82	10.50	61.00	38.2195	15.00928
Suction (F)	82	12.92	610.00	161.6578	180.84027

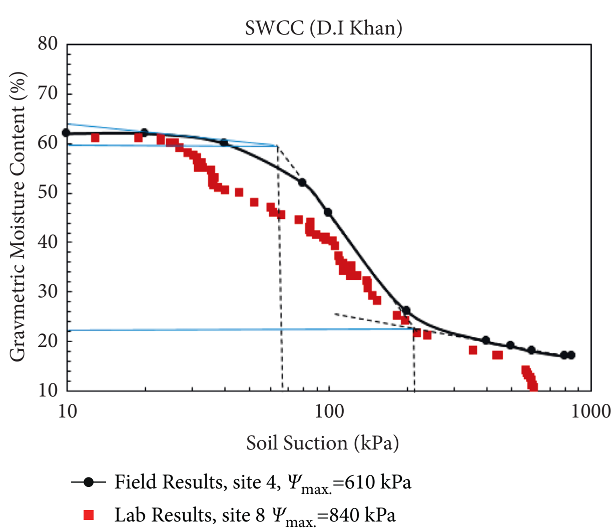

FIGURE 7: Demonstration of field- and lab-based SWCCs for Karak expansive soil.

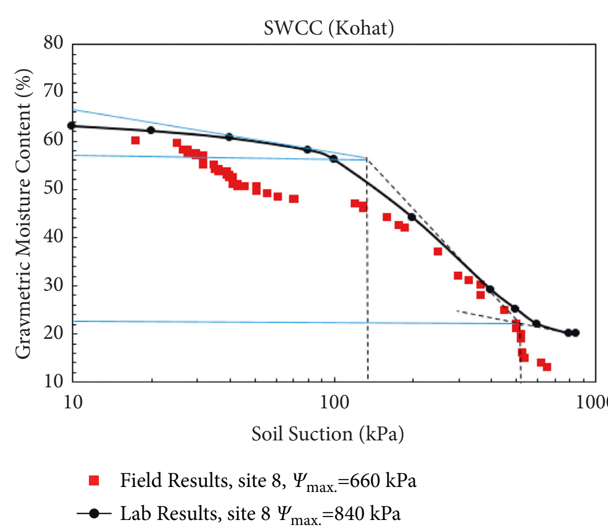

FIGURE 8: Comparison of field and lab results of the SWCC of Kohat's expansive soil.

Table 4: Descriptive statistics for the measured parameters of Kohat expansive soils.

Descriptive statistics					
Parameters	No.	Minimum	Maximum	Mean	Std. Deviation
Moisture (L)	11	10.00	850.00	327.2727	318.24805
Suction (L)	11	20.00	63.00	41.7727	18.61366
Moisture (f)	82	13.00	60.00	45.2927	13.49279
Suction (f)	82	17.50	660.00	149.3233	187.74162

Table 5: Summary of the key parameters for the selected sites of expansive soils.

Locations	AEVs (kPa)	Residual suction (kPa)	Residual moisture (%)	Field suction (kPa)	Field moisture (%)
Karak	245	600	24	705	14.5
D.I Khan	68	220	22	610	10.5
Kohat	140	510	22.5	660	13

The details of the measured parameters for SWCCs and the descriptive statistics are presented in Table 4.

5.4. Summary of Field and Lab SWCCs. The key parameters for SWCCs as measured in the lab condition and field environment are summarized and mentioned in Table 5.

6. Conclusions

The experimental-based study "Comparative Study on The Field- and Lab-Based Soil-Water Characteristic Curves (SWCCs) for Expansive Soils" was conducted to investigate field and lab SWCCs and determine their possible differences. For this purpose, eight different sites of expansive soils in the Karak, Kohat, and D.I Khan areas were selected. The study comprised both lab testing and field investigation. The major conclusions are drawn as follows:

(1) The field- and lab-based SWCCs for the potential sites showed the same trend of moisture and suction fluctuation; for instance, as matric suction increased, moisture content decreased.

(2) The lab-based SWCCs occupied the upper bond of the graph, with well-defined AEVs and residual suction values as the soil is surrounded by confining soil in the field where suction is applied from all around, while in the lab testing, the specimen is subjected to air suction at the base only.

(3) The field curves are plotted below the lab sorption curve and comprise a few separate curves with varying curvatures. For specified amounts of suction and moisture content, field and lab curves for expansive soils are compatible beyond the AEVs.

(4) The field curve has a general form that is comparable to the lab-drying curve and diverts in the high suction range.

(5) According to the lab curves, as a soil's expansivity increases, the AEV point (desaturation) and residual zone shift further to the right of the curve, indicating a high suction value at a fixed moisture content.

(6) The current study's findings can assist practicing engineers looking for strategies to take advantage of foundations positioned at shallow depths on unsaturated soils to reduce the settlement in such soils.

7. Recommendations

(1) The shape of field-based SWCCs is influenced by various parameters, including the soil texture, structure, hydraulic conductivity, and field ambient temperature. It is recommended that the minimum number of tests be performed on each type of soil considering the mentioned factors to study the effect of the above factors in future research.

(2) Expansive soils are characterized by both swelling and shrinking. The Fredlund SWC-150 device limits the measurement of volumetric shrinkage of the specimen during the test. As a result, more research is needed in this area, with linear or volumetric shrinkage being the primary focus of the investigation.

(3) It is also suggested that more research be done on the hysteretic nature of SWCCs to refine them further, especially for high expansive soil.

(4) Furthermore, in the future, some new approaches will need to be investigated to shorten the testing time, as present procedures have taken a long time to reach the high suction range.

(5) In the field, a considerable period of testing is required to measure the suction in completely dry conditions using a G-block or other similar sensor. The G-block sensors are brittle and can easily be damaged, especially during the dismantling step; hence, a more compact device is required for field suction measurement in the future.

(6) In addition, undisturbed specimens (block samples) must be tested in the lab for SWCCs, and the results

must be compared to the current investigation's findings.

Data Availability

The data used to support the findings of this study are available and can be demanded from the corresponding author.

Conflicts of Interest

The corresponding author states that there are no conflicts of interest on behalf of all authors.

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