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Identifying Problematic Soils Using Compressibility and Suction Characteristics

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Abstract: The major problematic soils in semi-arid regions include expansive soils and collapsible soils. These two types of soils cause problems and are hazardous for buildings when moisture is introduced following a dry or semi-dry season. In order to assess the risk and damage likely to occur, a protocol of investigation needs to be considered by geotechnical engineers to quantify and assess the possible heave or collapse that may occur. The characterization and prediction of unsaturated soil behavior in semi-arid areas can now be enabled following the advancement of unsaturated soil mechanics. Heave is associated with the wetting of expansive soils, while excessive settlement or the sudden loss of support may occur when water is introduced to collapsible soils. This work calls for more than one parameter for the assessment of problematic soils to avoid misleading predictions based on a single test. This study presents an investigation of two sets of soil samples obtained from semi-arid areas in Saudi Arabia known for their collapsible or expansive nature. Tests under controlled suction and variable effective stress were conducted. The air entry values, inflection points, and residual points were established and compared for the two problematic soils. A series of oedometer tests was conducted for typical soils, and settlement and collapse were measured and assessed. The swell potential for the tested clays varied from 4% to 22%. It is possible to integrate the data from the soil–water characteristic curve (SWCC) and compressibility tests with any project specification and applied stresses to produce reliable recommendations for the construction and protection of structures in hazardous soils.

Keywords: expansive clay; collapsible soil; structures; cementation; soil suction

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1. Introduction

Volume change, compressibility, and the swelling of soils are the main geotechnical factors that are related to climate conditions and can influence soil behavior. The introduction of moisture to unsaturated soils is normally associated with a range of physico-chemical variations and the entire shake-up of the units composed of clay particles. The interlayer spacing within octahedral and tetrahedral sheets is usually established due to chemistry and the balance of internal force that cause volume changes in the soil. This is clearly visible in agricultural soils known as black cotton soil or expansive clay, in which the volume change cannot be mistaken. Non-agricultural soils composed of cemented sand grains generally with low density can show a tendency to collapse when inundated with water. The collapsible soils can also be made of silt and clays. Calcareous or gypsiferous clay in which voids were created because of weathering or the washing out of fines can also collapse when inundated. Azam [1] investigated the collapse and compressibility behavior of typical soil from an Eastern province in Saudi Arabia. When inundating expansive soils, the water can cause the internal structure to re-arrange, while in collapsible soils, the water tends to dilute the cementation. When water is introduced to clay particles with minerals known for their expansion properties, the interparticle distance between the silica tetrahedron and silica octahedron sheets increases due to van der Waals forces. This force can be defined as the sum of the electrical forces that attract and repel atoms and molecules. These forces are distinct from covalent and ionic chemical bonding because they arise from variations in particle charge densities. This is usually repulsive in expansive soils and pushes adjacent sheets apart. Both types of soils are common in Saudi Arabia (Figure 1). The Kingdom of Saudi Arabia is a typical arid to semi-arid region where weather changes are due to short periods of rainy seasons.

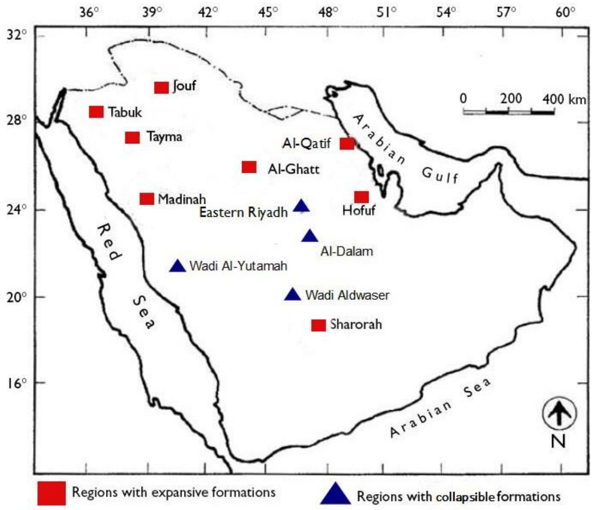


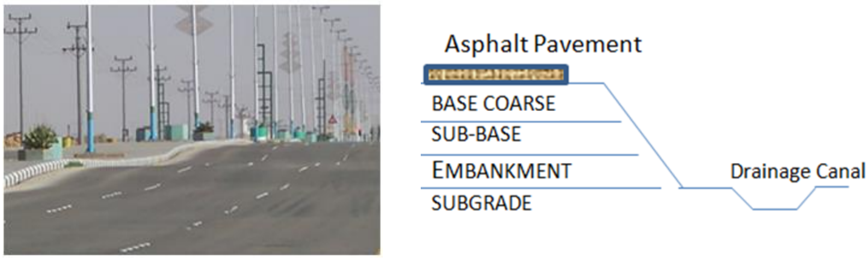
Figure 1. Distribution of expansive and collapsible soil in Saudi Arabia.

The property that defines the relationship between soil suction and corresponding water content is the soil–water characteristic curve (SWCC). The soil suction is known as an indicator of the soil's capability to attract moisture and was found to be very closely related to swelling and expansion. This was not the case when highly expansive clays were stabilized using cement or lime. High suction in this case may not produce high expansion due to particle cementation and the chemistry of the soil particles. Direct measurements of the swelling or collapse potential are usually conducted at a specific stress level. This stress level may be required to increase or decrease. A model based on a measurable parameter can be reliable for predicting or correcting assumed test results.

The use of a soil suction profile, or SWCC, can help in predicting the behavior of the soil at a different stress level. The SWCC can either be determined in the laboratory or established using correlations with soil properties. The expansive soil will result in heave when subjected to inundation and may cause uplift, distortion, and cracks within a utility building or any light structure. The soil–water characteristic curves (SWCC), can be utilized as the main tool to assess and predict the soil's response to wetting and drying when considered with one or more direct compression measurements.

Zheng et al. [2] stated that many provinces and regions in China reported the occurrence of expansive soils. Zheng and Yang [3] stated that 3300 km of highways in China pass over expansive soils. Katti [4] described the expansive soil in India, also known as black cotton soil, as being highly plastic, with a liquid limit in the range of 40 to 100 and a plastic limit of 20 to 60. Methods and approaches for the stabilization of clays in expansive soils were reviewed for lightly loaded structures. The removal of soil or partial soil replacement will significantly affect the cost of pavement or other infrastructure facilities. Houston et al. [5] reported a survey on expansive soils in Arizona (USA).

The Tabuk and Tayma regions are underlain by clayey shale which is known for its expansive and swelling nature. These areas reported problems of heave affecting light structures and pavements. Major highways from Tabuk to Tayma and Medina need to be replaced [6]. These highways were constructed for more than three decades to create links between major cities. The classification and design standards used were much lower than the present existing highways and roads. We can state that the old roads were not designed to accommodate the uplift that occurs due to the wetting of expansive clays. Frequent repairs were not successful, and the authorities suggested replacement highways with higher specifications and good drainage. The cost of reconstruction and maintenance in general was estimated at hundreds of millions of US dollars annually, but in reality, it can amount to several billion US dollars. No surveys were made to determine the extent and size of the damage associated with collapsible soils, but this can be estimated to be millions of dollars annually. Collapsible soils were reported in the central parts of Saudi Arabia where low density, silty, and clayey sands are present. Weakly cemented collapsible soils introduce high settlement and deformation when wetted. The Saudi Building Code (SBC 303) presents measures and procedures to be adopted in local practice for swelling and collapsible soils. The damage to roads and pavements takes different forms, from minor cracking to serious folding and distortion (i.e., Figure 2a). Figure 2b presents a suggested drainage style to reduce the inundation of subgrade soils.



(**a**) (**b**)

Figure 2. (**a**) King Abdul-Aziz access road to Al-Ghatt and (**b**) suggested drainage style to reduce inundation of subgrade soils.

Expansive soils in Saudi Arabia are covered by many studies conducted in the research centers of King Saud University, King Abdul-Aziz University, and King Fahad University of Petroleum and Minerals. The works of Erol and Dhowian [7] highlighted the swelling and shrinking nature of Al-Medinah clay. They subjected the clay to cycles of wetting and drying. They noticed a reduction in swelling when the clay was partially dried, unlike when the clay was fully shrunk, which caused the swelling to increase. They also noticed that after multiple cycles of drying and wetting, the fabric of the clay was destroyed and disoriented. Abduljauwad [8] compared the laboratory swelling potential of the calcareous clay of the eastern province of Saudi Arabia to the swelling potential measured in a field section. The results were in very close agreement.

Al-Mhaidib [9] covered the swelling behavior of expansive soils in the middle region of Saudi Arabia. He found that the testing methodology affects the measured swelling pressure.

Other studies covering expansive soil behavior include the research works of Abduljauwad et al. [10], Al-Muhaidib [11], Al-Muhaidib et al. [12–14], and Al-Shamrani et al. [15,16]. Shamrani et al. [15] conducted a characterization survey of problematic expansive soils from regions including Tabuk, Al-Hafuf, Al-Qatif, and Al-Ghatt and compared the mineralogy and swelling behavior.

Studies conducted by Erol and Dhowian [17], Aiban [18], Dafalla et al. [19], Shaker and Elkady [20], Al-Mahbashi [21], Al-Mahbashi and Elkady [22], and Elkady et al. [23] all addressed the geotechnical parameters and behavior of different types of highly plastic soils encountered in Saudi Arabia. The term "collapsible soil" has been used since 1970, but the existence of this type of soil has been recognized since World War II [24]. Al-Rawas [24] conducted a comprehensive review of collapsible soils and addressed several treatment methods, such as soil replacement, compaction control, and chemical stabilization.

Holtz and Hilf [25] published useful studies describing the effect of saturation on soils showing a collapsed nature. The collapsible soil is present in Riyadh, the capital of Saudi Arabia [26]. Characterization studies were conducted by many geotechnical agencies (e.g., Al Rajhi Hydrosoil). In general, this type of soil is a weakly cemented sand formation. Al-Refeai and Al-Shenawy [27] studied the improvement of collapsible soils in Saudi Arabia.

Al-Harthi and Bankher [28] examined the collapsible loess-like soil in the western part of Saudi Arabia. They investigated material from Alyotama Valley consisting of silt with low plasticity, a high void ratio, and low density. Their study confirmed that the collapse increases with a decrease in soil density.

An irrecoverable collapse strain upon wetting was observed by Alawaji [29] for Al Dalam soils. This study aims to introduce common investigations carried out for these two types of soils and to present test results for selected samples representing each type. It was understood that high suction is associated with high swelling behavior according to many researchers, but this did not prove true for many types of clay materials. The suction can cause water to move into the interlayer particle zones, but this does not mean the clay will expand. Chemistry and cementation have a role in this process. The concept introduced in this research is to assess the clays using double or multiple parameters. This is aimed at viewing suction profiles in light of the compressibility or collapse tests conducted. The suction test can either be conducted in the laboratory or constructed using correlations. It is known that SWCC can be used to predict a range of geotechnical parameters, but these need to be associated with a direct test measurement. A single or multiple direct test measurements can help the geotechnical design engineer to estimate the compression or heave of a problematic material correctly.

The potential settlement (ρ) that may occur in a soil layer under the applied vertical stress is obtained as follows:

$$\rho = (H \times I_c)/100 \tag{1}$$

where

H = Thickness of the soil layer.
I_c = Collapse potential, determined using a predetermined applied vertical stress applied to a soil specimen taken from the soil layer as follows:

$$I_c = 100 \times (d_f - d_i)/h_o \tag{2}$$

where

d_i = Specimen height at the appropriate stress level before wetting.
d_f = Specimen height at the appropriate stress level after wetting.
h_o = Initial specimen height.

Al-Mahabashi and Dafalla [30] can be followed to plot the SWCC curves from the following correlations against the plastic limit, plasticity index, and shrinkage limit, if known.

$$\theta s = 18.212 \ln (w_p) - 19.957 \tag{3}$$

$$AEV(kPa) = 0.7245(PI) + 2.9282 \tag{4}$$

$$\theta r1 = 17.212 \ln (w_p) - 24.297 \tag{5}$$

$$sr1 = 4 \times 106\ (w_{Sh}) - 3.635 \tag{6}$$

where:

θs = Saturated water content;
AEV = Air-entry value;
$\theta r1$ = Residual water content;
$sr1$ = Residual suction;
w_p = Plastic limit;
w_{Sh} = Shrinkage limit;
PI = Plasticity index.

This paper calls for conducting compressibility, swell, and collapse potential tests at predetermined stresses along with soil suction examinations. This approach provides a confirmatory evidence that covers more than one prediction method.

2. Materials and Methods

2.1. Materials

In this study, three types of expansive clay materials, widely present in Saudi Arabia, are investigated: Al-Qatif clay, Al-Gatt clay, and Tabuk clay. Al-Qatif is the highest in plasticity, while Tabuk and Al-Ghatt are considered to have medium plasticity. Typical collapsible soils were obtained from a site in Al Janadriyah district, east of Riyadh. Six samples from two locations with variable depths were studied. These locations are marked as CC and PC followed by numbers, as indicated. To demonstrate that high suction soils can indicate lower swelling behavior, lime-treated clay samples from the Al-Qatif district with a lime addition of 2%, 4%, and 6% were examined.

The use of direct measurement of the strength parameter approach is recommended as a confirmatory protocol to exclude the possible overestimation or underestimation of geotechnical properties.

2.2. Testing Procedures

The routine classification tests were conducted on the selected expansive clay in accordance with the applicable ASTM testing methods used (ASTM D 2487-17 and ASTM D7928, 2017) [31,32]. The liquid limit varied from 43 to 160. The maximum dry density varied from 11.8 to 16.6 kN/m^3 at an optimum moisture content in the range of 17% to 38% (ASTM D698, 2000) [33]. The specific gravity and initial water content for collapsible soils were determined. The typical grain size distribution for expansive and collapsible soils is given in Figure 3.

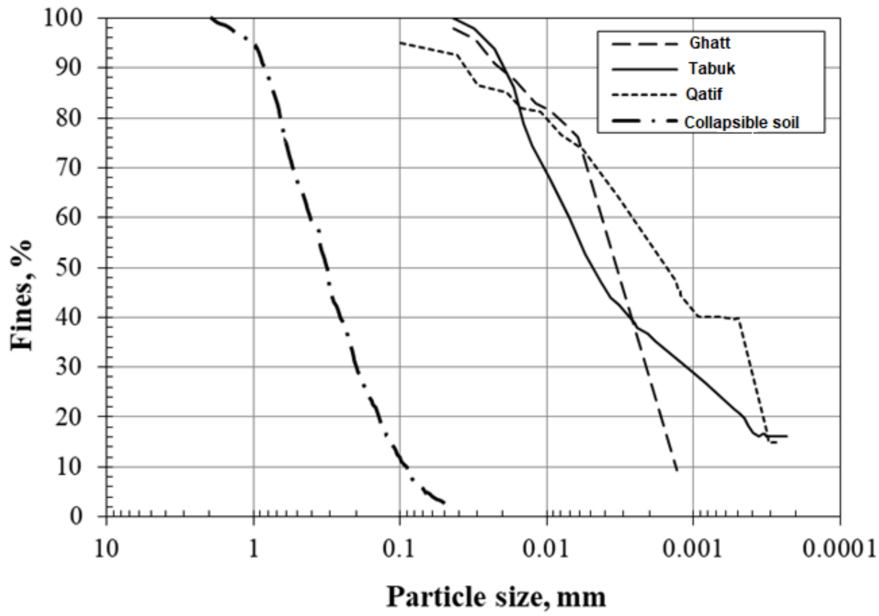


Figure 3. Typical grain size distribution for expansive and collapsible soils.

2.2.1. Swelling, Consolidation, and Collapse Potential Determination

Oedometer swelling and consolidation tests were carried out for the three selected expansive clays: Qatif, Al-Ghatt, and Tabuk. The specimens were prepared for this test by static compaction at the optimum moisture content and maximum dry density. The test procedure was in accordance with ASTM D-2435-11 [34].

The standard test method described by ASTM was used to determine the collapse potential of selected specimens using a one-dimensional consolidation cell. The specimens were loaded at a certain stress level, namely one that is normally comparable to the foundation bearing pressure, and then inundated with distilled water.

2.2.2. Determination of Suction and Soil–Water Content Relationship

The property that describes the relationship between suction and soil–water content is referred to as the soil–water characteristic curve (SWCC). The soil water characteristic curve SWCC test was carried out for three expansive soils and six collapsible soils using the axis translation technique. The pressure plate extractor apparatus was used for this purpose (ASTM D6836-16) [35]. The device was used in several research studies and testing procedures [36–38]. The testing procedure begins with the compacting of the soil specimens to a selected initial molding state, generally at the optimum moisture content and maximum dry density. The saturation procedure was performed under a slight vertical stress equivalent to 7 kPa. The samples were subjected to increasing matric suction in several steps (10, 50, 100, 200, 400, 800, and 1400 kPa). To measure the drying path of SWCC, each step was continued for two to three days until equilibrium was attained and no further flow of water through the soil specimen took place. Figure 4 shows the pressure plate device and a set of specimens used in the test. The laboratory data were fitted to the Fredlund and Xing [39] equation. The collapsible soils were subjected to the collapse test in an oedometer (ASTM D 4546-14) [40] at specific inundation stress levels. Two sets of CC and PC samples were inundated at stress levels of 25 and 100 kN/m^2.

Figure 4. Soil specimen inside pressure plate cell (axis translation technique).

3. Results and Discussion

Table 1 presents the index properties and compaction test results for the selected three types of expansive soils. Table 2 presents the specific gravity and initial water content for the six selected collapsible soils from Al-Janadriyah in Riyadh. Figure 5 presents the suction profile for Al-Qatif clay under different effective stresses [40]. It can be shown that the suction is variable for different effective stresses up to a suction level of 1500 kN/m^2. From the SWCC plot it can be observed that the gravimetric water content is lower for high effective stresses.

Table 1. Index properties and compaction test results of three types of expansive soils.

Soil/Property	Specific Gravity, (Gs)	Liquid Limit, (%)	Plastic Limit, (%)	Shrinkage Limit, (%)	Optimum Moisture Content, (%)	Maximum Dry Density, (kN/m^2)
Al-Qatif	2.7	160.0	60.0	15.0	38.0	11.8
Ghatt	2.9	59.3	33.0	14.0	24.7	16.0
Tabuk	2.8	43.0	27.0	21.0	17.0	16.6

Table 2. Specific gravity and initial water content for collapsible soils from Al-Janadriyah.

Sample Code	Specific Gravity	Initial Water Content (%)
PC-3 (3.0–3.5)	2.703	8.720
PC-6 (3.0–4.0)	2.672	4.010
CC-4 (2.8–3.4)	2.637	2.200
CC-3 (2.0–3.5)	2.666	3.340
PC-3 (4.5–5.0)	2.648	8.720
CC-2 (1.7–2.2) A	2.683	0.840
CC-2 (1.7–2.2) B	2.716	0.840

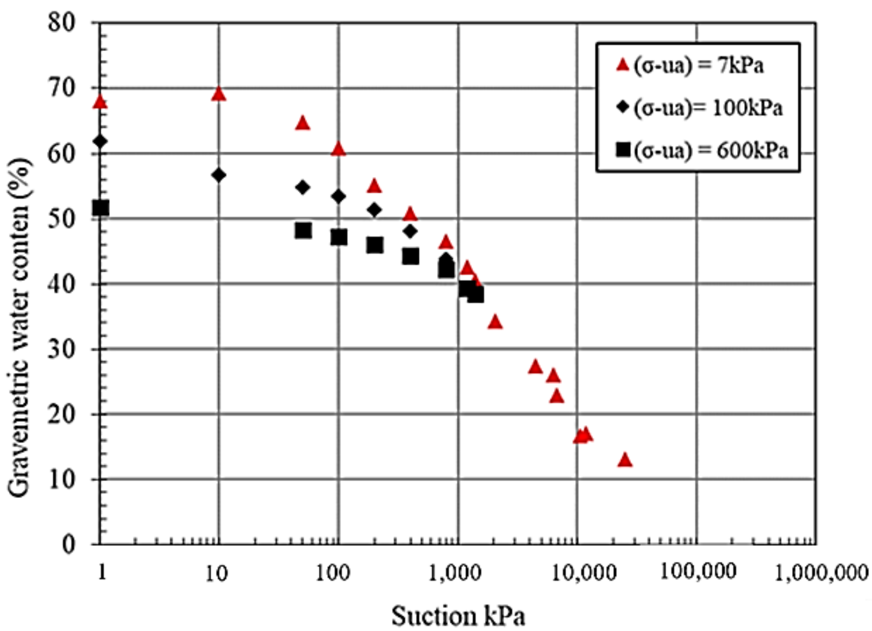
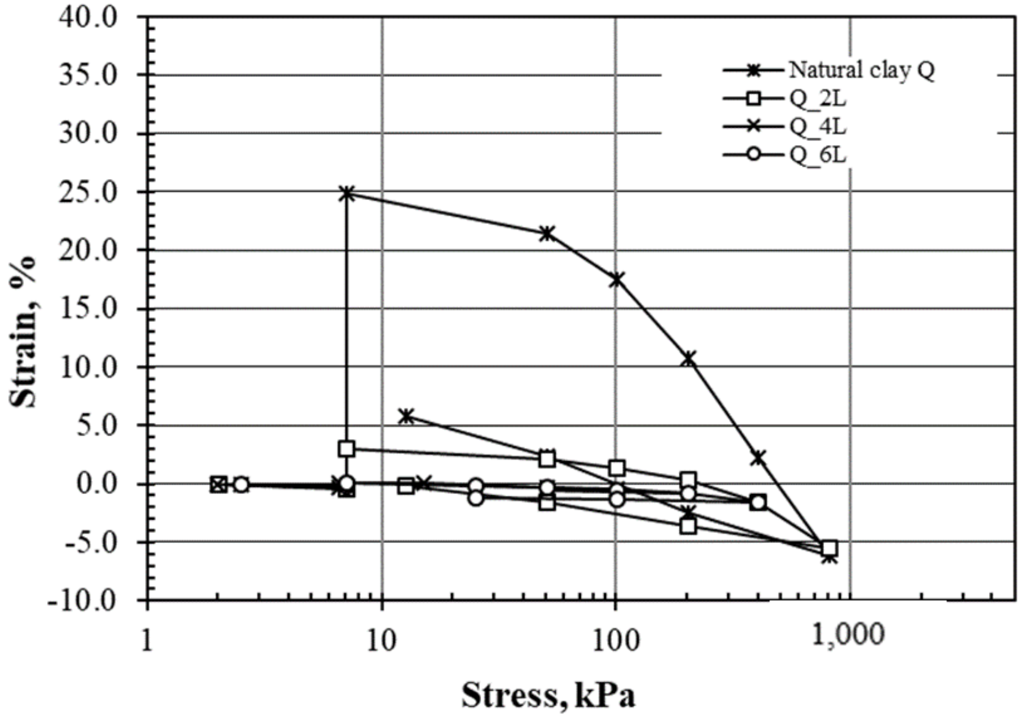
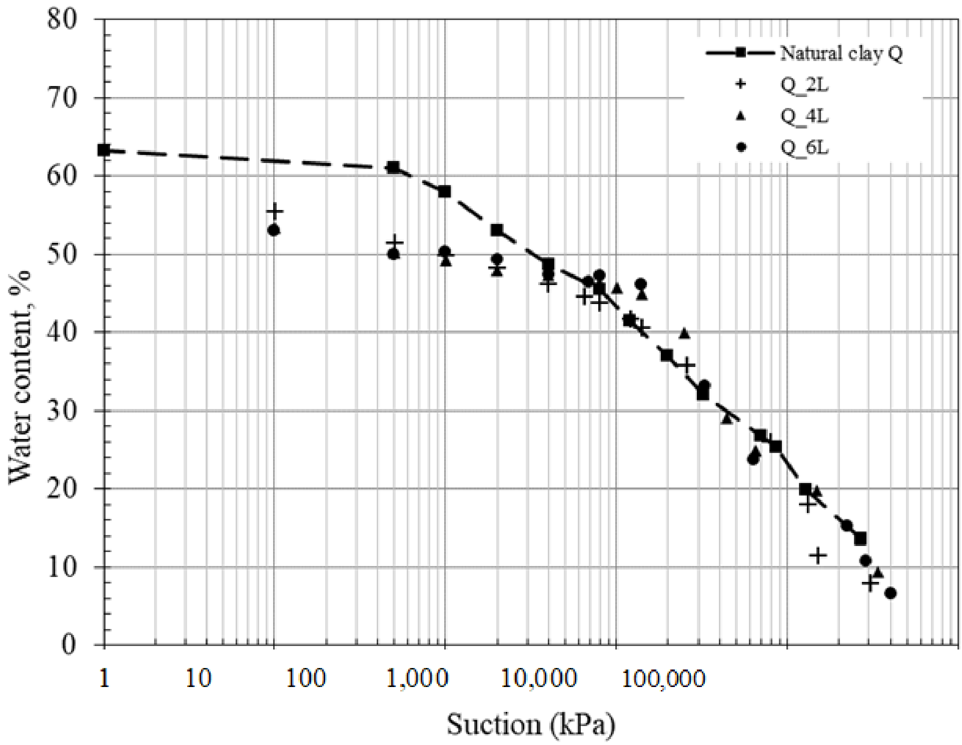


Figure 5. Suction under different effective stresses [21].

Figure 6a presented the swell potential and consolidation of lime-treated Al-Qatif clay with 2%, 4%, and 6% lime content. Figure 6b presents the SWCC of lime-treated Al-Qatif clay with the same lime concentrations.



(**a**)

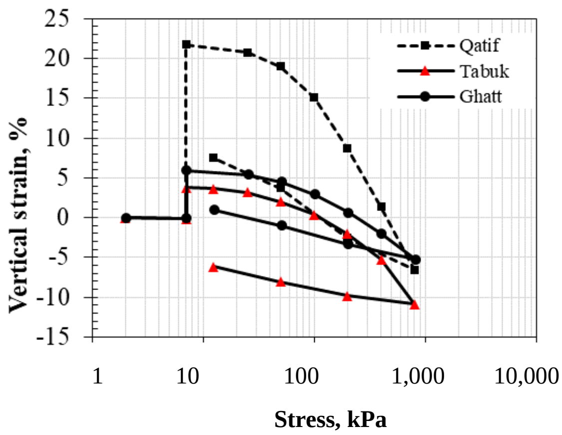


(**b**)

Figure 6. (**a**) Swell potential and consolidation of lime treated Al-Qatif clay. (**b**) SWCC of lime-treated Al-Qatif clay.

From the results of the compressibility of Al-Qatif soils treated with lime, it can be noted that the swell is reduced when the soil has 4% and 6% lime content. The compression index becomes flatter by increasing the lime content. The suction remained high at the tested moisture content. This is attributed to the cementation provided by the pozzolanic reactions that took place; however, cementation can be due to additives, particle chemistry, or mineralogy. The main highlight of this research is that a high suction level measured for soil does not necessarily indicate a high-swell soil.

The oedometer and swelling test results for the three tested types of clay are presented in Figure 7a. The swell potential expressed as vertical strain was found to be 22% for the highly plastic clay of Al-Qatif, while only a 4 to 6% swell potential is recorded for the medium plasticity clays of Al-Ghatt and Tabuk. A steeper slope for the plot of Al-Qatif clay indicates higher compressibility compared to the other two clays. Air entry values (where the largest pores start to desaturate) for all expansive clays were encountered at a matric suction of less than 100 kN/m^2 (Figure 7b).



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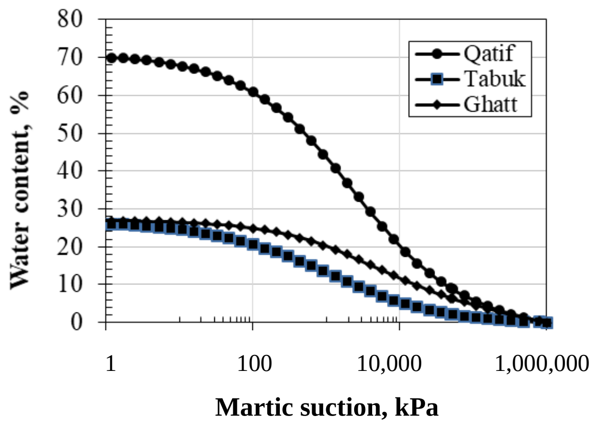
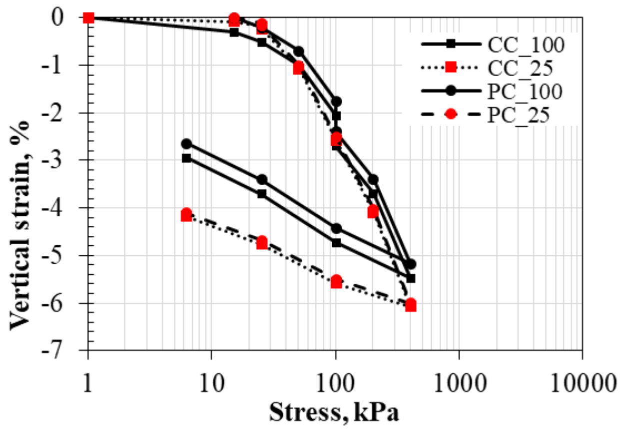


(**b**)

Figure 7. (**a**) Swell potential and consolidation of expansive soils and (**b**) SWCCs of expansive soils.

Figure 8a presents the collapse potential for the two types of collapsible soils measured at 25 and 100 kPa stresses. Figure 8b presents the soil–water characteristic curves for collapsible soils. The retention capacity of these soils is less than the retention capacity of expansive clays, and the air entry values for collapsible soils are within a tenth of those of expansive clays.

The Saudi Building Code (SBC 303), Chapter 9 states that soil investigations shall indicate the value or range of heave that might take place for the structure being studied. Potential soil movement shall be determined based on the estimated depth of the active zone in combination with either ASTM-D 4546 [40] or any other method that can be documented and defended as part of good engineering practice in accordance with the principles of unsaturated soil mechanics. Tables 3 and 4 present classification guides for expansive and collapsible soils. The use of continuous or spread footings on expansive soils is discouraged by the Saudi Building Code unless the subsurface is of low expansion potential. The swelling pressure can be counterbalanced by the weight of the structure if applied pressures do not exceed the bearing capacity of the soil. As recommended by SBC 303, the slab-on-grade (slab-on-ground) foundations on expansive soils shall be designed and constructed in accordance with the WRI/CRSI "Design of Slab-on-Ground Foundations". The Saudi Building Code SBC 303 also states that footings or foundations for buildings and structures founded on collapsible soil areas shall be designed based on the collapse potential determined using the collapse index method, the standard plate load test method, or BREA Building Regulations in Eastern Arriyadh Sensitive Soils Procedures (BPLT).



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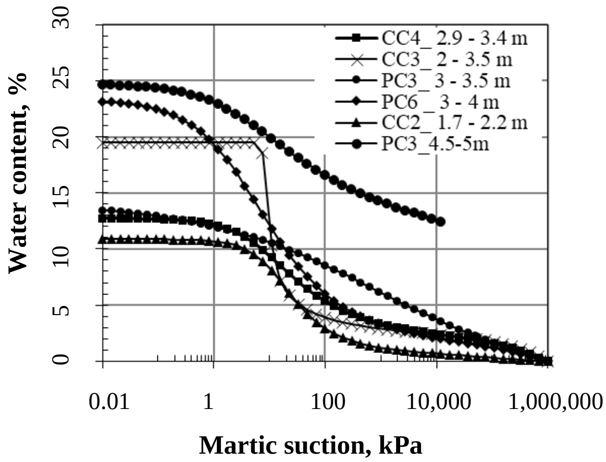

(**b**)

Figure 8. (**a**) Compressibility and collapse potential tests for collapsible soils and (**b**) SWCC of collapsible soils.

Table 3. Classification of expansion potential.

Expansion Index (EI) *	Expansion Potential
0–20	Very low
21–50	Low
51–90	Medium
91–130	High
>130	Very high

* EI = {1000 × (final height of specimen − initial height of specimen)/initial height of specimen}, (SBC 303).

Table 4. Classification of collapse potential.

Collapse Index $(Ie)_a$ %	Degree of Specimen Collapse
0	None
0.1–2.0	Slight
2.1–6.0	Moderate
6.1–10.0	Moderately severe
>10.0	Severe

$(I_e)_a = 100 \times \Delta e/(1 + e_o)$, where Δe = change in void ratio resulting from wetting, and e_o = initial void ratio (after SBC 303).

Dafalla et al. [19] called for the use of protective measures for pavements using clay–sand liners and suggested a drainage system. Pre-wetting approaches are not recommended for expansive soil under pavement, as wetting requires a long time to inundate the clay particles. The increase in pavement thickness and soil replacement can be helpful in reducing the expansion level. It is very common in practice to consider the suction level obtained in an SWCC test as a good predictor of expansion. This is generally valid and acceptable for a wide range of clayey soils, but not true for all soils. High suction does not necessarily imply high swelling. Expansive clays stabilized using cement or lime can show very high suction but low swell potential [21,41,42]. It is common in the literature to find prediction models that estimate the swelling pressure, swell potential, compressive strength, etc. using the SWCC. These are not likely efficient if they do not involve other strength parameters obtained for the subject soil. The call for a dual-parameter assessment is suggested to rule out errors due to clays with variable mineralogy and chemical bonds.

The works of Almahbashi [21] indicate that soil suction for clays under variable effective stress is not the same for suction levels less than 1000 kN/m^2.

Proposed treatments for collapsible soils include pre-wetting and heavy compaction before laying the sub-base and base layers of the pavement; however, the increase in cementation using additives can be considered, but it is likely very expensive. The suction level of the collapsible soil cannot be used as a measure, as the skeleton cementation and fabric of the soil can be lost when water is introduced. For pavement, the collapse potential need to be tested at low stress levels, i.e., 20 to 30 kN/m^2. Heavy structures in a highway inundated under a pressure of 100 kN/m^2 may be a good approach.

The call for constructing the SWCC suction profile along with at least one direct strength measurement test can help in extending the knowledge of soil behavior at different moisture contents, and the curve can be used for various geotechnical predictions.

A single suction measurement cannot be a sufficient guide on the state of the swelling or collapse. If the SWCC profile cannot be conducted using the right apparatus, correlation formulas may be utilized. The works of Al-Mahabashi and Dafalla [30] can be followed to plot the SWCC curves from the following correlations against the plastic limit, plasticity index, and shrinkage limit, if known.

4. Conclusions

This paper presents a study on the geotechnical characteristics of the problematic soils that are known to influence the construction of pavements and different types of structures. The compressibility, swell, and collapse potential were studied at predetermined stresses. Soil suction was examined using pressure plate tests for expansive and collapsible soils selected for this study.

The protection of pavements and substructures using moisture barriers or proper drainage is always recommended for these types of soil. The pre-wetting technique may not work well for expansive soils under pavement due to the low hydraulic conductivity of the clay. The knowledge of soil suction is of great importance when designing structures supported by collapsible or expansive soil. The cementation, mineralogy, and chemistry of the particles are the main factors determining the actual soil strength and the soil–water characteristics themselves. This research recommends constructing SWCCs with at least one strength parameter test for a better evaluation of problematic soils. The prediction of strength properties from SWCCs needs to be counter-checked by a direct measurement test to avoid non-realistic assumptions.

Cementation can be present due to additives, particle chemistry, or mineralogy. The main highlight of this research is that a high suction level measured for soil does not necessarily indicate a high swell soil.

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