Interpretation of Desiccation Soil Cracking in the Framework of Unsaturated Soil Mechanics

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ABSTRACT: Cracks evolve in expansive soils when subjected to drying and shrinkage processes. The underlining driving mechanism is the development of the tensile stress in perpendicular direction to the crack length. The tensile stresses are generated from the restrictions applied on the soil from shrinking freely. When the tensile stress exceeds the soil tensile strength, cracks initiate and propagate. The soil shrinkage, generated tensile stress, and tensile strength are governed by the effective stress regime existing in the soil microspores. All these mechanisms require the tracking of the soil cracking phenomenon from the internal stresses developed in the microspores system. Understanding the stresses that are developed in the soil microspores system is a challenging task. It is mainly due to the complexity of the physicochemical interactions taking place in the soil pores. This paper presents understanding and modelling the soil cracking by relying on unsaturated soil mechanics. Based on the laboratory results from desiccating expansive soils subjected to restricted shrinkage, this paper demonstrates that the crack growth in soils occurs mostly in the unsaturated condition for initially saturated soils. Restricted shrinkage tests are carried out using restrained ring testing method to induce cracks in the soil specimens. The results demonstrate that a crack for initially saturated soils first initiates at suction close to the air-entry value. Free shrinkage tests are also conducted to predict the soil shrinkage curve. The results from restrained ring tests are explained in terms of the soil-water characteristic curve and soil shrinkage curve.

KEYWORDS: Desiccation cracks, Unsaturated soil mechanics, Restrained ring testing method, Shrinkage curve

1. INTRODUCTION

Drying shrinkage can lead to cracking in the soil layers. Cracks can substantially decrease the strength and increase the compressibility and permeability (Morris et al. 1992). The existence of cracks in the soil layers utilized for the environmental purposes can result in losing their functions (Peron et al. 2009). The presence of cracks in pavement shoulders can extend the seasonal moisture variation and hence subject the subgrades to more movements. In extreme conditions, cracks can initiate in the subgrade and may propagate to cause longitudinal cracks in the pavement layers. Such cases have widely been reported (Lytton et al. 2005, Luo and Prozzi, 2009; Bulut et al. 2014; Wanyan et al. 2015).

Typically, soil in the field undergoes one dimensional vertical shrinkage before cracking (Abu-Hedjleh and Znidarcic 1995). It cracks when the horizontal tensile stress exceeds the soil tensile strength (Morris et al. 1992). During desiccation, the soil relieves the internal stresses caused by the increase of suction by changing its volume (i.e. reduction of void ratio). Since soil has some tensile strength that may arise from the apparent cohesion between the soil particles, it will restrict the displacement in the horizontal direction which, in turn, will develop the horizontal tensile stress. As the crack initiates at the soil surface, it can propagate downward depending on the changes in the soil suction profile.

It has been widely accepted that desiccation cracking takes place in Mode I fracture (Harison et al. 1994). The last two-three decades have witnessed considerable attention to the studies of the soil cracking. Some studies analyze the crack formations and crack intensity factors for soils subjected to desiccation (Yesiller et al. 2000; Atique and Sanchez 2011; Tang et al. 2011; Peron et al. 2013; Safari et al. 2014). Other studies investigate the fracture parameters governing the soil cracking such as the tensile strength, fracture toughness, critical J integral (Harison et al. 1994; Wang et al. 2007; Prat et al. 2008; Amarasiri et al. 2011; Costa and Kodikara 2012; Lakshmikantha et al. 2012). Other studies track the stress that leads to crack initiation (Thusyanthan et al. 2007; Abou Najm et al. 2009). Analytical studies have also been undertaken to characterize the desiccation cracking in a fracture mechanics framework (Morris et al. 1992; Konrad and Ayad 1997; Amarasiri and Kodikara 2011).

Morris et al. (1992) presented three different solution techniques of the cracking problem based on the elasticity theory, transition between tensile and shear failure, and linear elastic fracture mechanics (LEFM). For the first two solutions, they solved the problem by formulating the horizontal tensile stress or horizontal principal stress for zero lateral strain before cracking. This stress will be equal to the tensile strength at the time of crack initiation. Morris et al. (1992), therefore, assumed that the crack depth is where the tensile stress equalizes the soil tensile strength. They predicted the crack depth based on the three solutions. Morris et al. (1992) pointed out that the LEFM based solution predicts higher crack depth than that predicted by the other two solutions.

Abu-Hedjleh and Znidarcic (1995) proposed that the shrinkage of soft fine-grained soils can be modeled by four stages: consolidation under one-dimensional compression, desiccation under one-dimensional shrinkage, propagation of vertical cracks, and desiccation under three-dimensional shrinkage. A crack is initiated in the second stage when the total lateral stress at the crack tip is equal to the tensile strength. The crack can propagate to the depth at which the void ratio reaches the critical void ratio. Abu-Hedjleh and Znidarcic (1995) suggested that soil shrinkage has only two stages. The first stage is that the soil remains saturated and decreases in volume until it reaches the shrinkage limit which is also the air-entry value. The second stage takes place beyond the shrinkage limit. It is referred to as “zero shrinkage”, at which the soil does not undergo any shrinkage. They claimed that this is the case of for soft fine-grained soils in slurry conditions.

Konrad and Ayad (1997) presented a framework to predict the crack depth and crack space based on linear elastic fracture mechanics (LEFM). The crack initiates at the surface when the lateral total stress reaches the soil tensile strength at the critical suction which can be estimated from the soil friction angle and tensile strength. Then, the crack propagation is predicted by the LEFM when the stress intensity factor is equal to the fracture toughness while the space between the primary cracks is determined from the horizontal stress relief distribution around the crack.

In spite of the notable efforts in the above approaches, implementing them into the engineering practice is highly challenging. That is because quantifying the soil fracture parameters (e.g. tensile strength, stress intensity factor, fracture toughness, and critical J integral) and the inter-particle developed stresses during desiccation is very difficult. Fracture parameters vary with the reduction of water content (i.e. increase of suction). Measuring the fracture parameters of engineering materials is conventionally carried out by applying external mechanical loads. It is uncertain how to use these measurements to explain the desiccation cracking in the soils.

Likewise, the prediction of the internal stresses that developed from water-soil particles interactions is still under debate.

Soil suction is one of the stress state variables that govern the soil behavior (Fredlund and Morgenstern 1977). The advances in the measurement of suction in the laboratory and field provide a practical mean of predicting the soil crack initiation and propagation based on soil suction. Therefore, it appears possible to predict and model desiccation cracks using soil suction. This can be undertaken by detecting the critical suction of crack initiation. The crack growth is then predicted as a consequence of the soil shrinkage from the increase of suction beyond the critical value.

Despite the high complexity involved in the soil cracking phenomenon, numerous researches have indicated that crack first initiates when the suction of saturated soils subjected to desiccation attains the air entry value (AEV), where at soils commence to desaturate even though these studies employ different testing methods (e.g. Lloret et al. 1998; Nahlawi and Kodikara 2006; Rodríguez et al. 2007; Peron et al. 2009; Shin and Santamarina 2011; Shannon et al. 2015; Saleh-Mbemba et al. 2016). Similar observations have also been reported for other materials (Brinker and Scherer (1990) for gels; Slowik et al. (2009, 2010) for concrete). Peron et al. (2009) stated that the growth of air bubbles forms flaws in the soil. These flaws then act as crack inceptors. Further, the water content of the AEV is very close (or equal) to the plastic limit (e.g. see Fredlund et al. 2012) so that the soil often does not show a fracture behavior before that water content. This can be confirmed from the description of the ductility level demonstrated by Hanson et al. (1994). They classified the soil based on the water content into three categories: region I-the water content is greater than the plastic limit (i.e. the soil is saturated) and the soil shows no fracture behavior, region II-the water content is between the plastic limit and shrinkage limit (i.e. the soil is unsaturated) and the soil transitions from the plastic to brittle behavior, and region III-the water content is less than the shrinkage limit and the soil shows brittle fracture. From the soil shrinkage curve, the air entry stage falls at the end of the normal shrinkage (Figure 1).

This paper presents experimental results for soils under desiccation conditions. Free shrinkage tests were conducted to predict the soil shrinkage curve. The soil suction was measured using WP4 chilled-mirror psychrometer and UMS-T5 tensiometer sensors to construct the soil water characteristic curve. Restricted shrinkage tests were carried out using restrained ring testing method to induce cracks in the soil specimens. The results confirm that a crack for initially saturated soils first initiates at suction close to the air-entry value. The crack growth takes place mainly during the residual shrinkage zone in the unsaturated state of the soil.

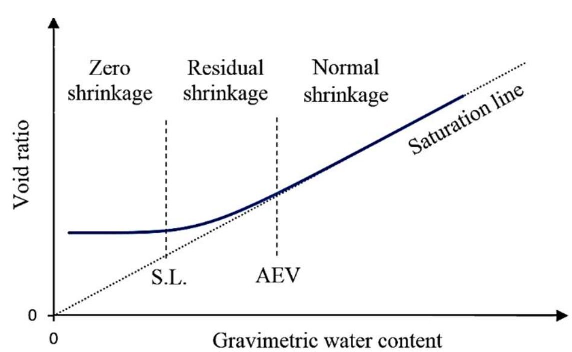


Figure 1 Typical shape of the soil shrinkage curve for slurried soils

2. SOIL MATERIAL AND ITS PROPERTIES

The soils tested in this study were obtained from Ardmore and Lake Hefner in Oklahoma using the push-tube sampling. They were broken into pieces, air-dried, and further broken into much smaller sizes. The soil at the Ardmore is considered medium to high expansive, while the soil at the Lake Hefner site is considered low to medium expansive. The basic geotechnical properties of the soil were obtained by following the relevant ASTM standards. The optimum water content and maximum dry density were determined following the standard Proctor test in ASTM D698 and the results are given in Table 1.

Table 1 Basic properties of tested soils

Soil property	Ardmore	Lake Hefner
Clay content (%)	40	30
Silt content (%)	47	54
Fine sand content (%)	13	16
Plastic limit (%)	24	15
Liquid limit (%)	55	29
Optimum water content (%)	26.5	15
Maximum dry density (g/cm^3)	1.45	1.82

3. LABORATORY TESTS

3.1 Suction Measurement and Free Shrinkage Test

Identical cylindrical soil specimens were prepared for both the suction measurements and the free shrinkage test (FST). The specimens were prepared by molding the wet soil inside a steel ring with inside dimensions of 6.4 cm in diameter and 1.9 cm in height. Since the specimens were highly wet, no compaction was applied because the soil was close to a slurry state. The soil suction was measured by the WP4 device for high suction (i.e. greater than 200 kPa) and the UMS-T5 tensiometer for low suction (i.e. less than 100 kPa). The WP4 device utilizes the chilled mirror dew point method as described in detail in Bulut and Leong (2008). In this study, it was assumed that the osmotic suction component is negligible.

The free shrinkage test (FST) was undertaken by subjecting the specimen to air drying in the laboratory at approximately 40% relative humidity. While the soil was drying and shrinking, the specimen weight was measured continuously by a balance. In addition, the shrinkage process was captured by two high resolution cameras at 15 minutes time intervals. One camera was utilized for the top view to capture the radial shrinkage and the other one for the side view to capture the shrinkage in the thickness of the specimen (Figure 2). The digital images from both cameras were considered for evaluating the soil shrinkage during the desiccation process. The volume change was estimated by incorporating the results of the radial shrinkage with those of the thickness of the specimen. The digital image analysis was carried out in MATLAB using *GeoPIV-RG* subroutines. Information about the background and the theory involved in these software subroutines can be found in White et al. (2003) and Stanier et al. (2016).

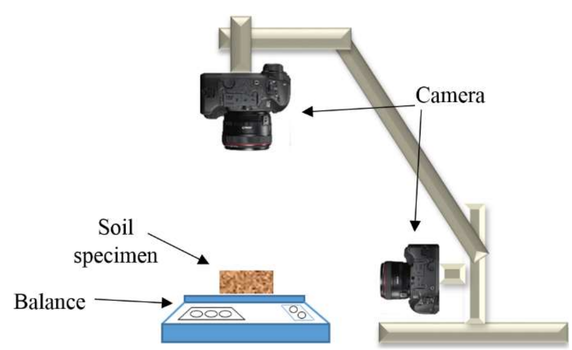


Figure 2 Schematic drawing for the free shrinkage test

3.2 Restrained Ring Test

The RRT is a testing technique in which the soil is restrained from shrinking freely as it is subjected to desiccation conditions. It has been used to study drying cracking in soils by Abou Najm et al. (2009), Chen (2015), and Shannon et al. (2015). In this test, the soil shrinks radially and applies a pressure on the core PVC ring. This pressure is evaluated as a current transferred by strain gauges to a data acquisition to collect the outcomes. The test is stopped when a crack initiates and grows from the inner to the external face of specimen. Additional information of this test can be found in Abou Najm et al. (2009).

The restrained ring test (RRT) was conducted on a donut-shaped specimen with 5.5 cm in internal diameter, 15.24 cm in external diameter, and 1.65 cm in thickness (Figure 3). The specimen was prepared by molding the wet soil inside a PVC ring with the same external diameter. The high water content, slurry, soils were molded inside the PVC without a need for compaction. Compacted specimens from Ardmore soil were also tested. The compacted specimens were prepared by compacting the soil inside the PVC ring in two layers with each layer receiving 36 blows using a wooden rod with rubber cab (diameter = 2.54 cm). With the help of a sharp edge steel cylinder, 5.5 cm in diameter, a hole in the sample core was made by pushing the sharp edge steel cylinder through the core of the specimens. The obtained soil specimen was sealed and stored in an ice-chest for curing and suction equilibrium for one week. Before starting the test, a PVC ring with 5.5 cm in outer diameter was gently pushed inside the hole in the core of the specimen. Three strain gauges were attached to the inner face of the ring as shown in Figure 3. Before starting the test, the soil specimen was sealed by plastic wrap from the bottom and a rubber membrane from the circumference to maintain the sealing for uniform shrinkage as the soil sample shrinks radially. Attention was given to prevent the rubber membrane from applying any pressure on the soil by keeping it loose and for sealing purpose only. Small white sand particles are spread randomly on the specimen surface (Figure 3) to help capture the displacement of the surface specimen computed by *GeoPIV-RG.*

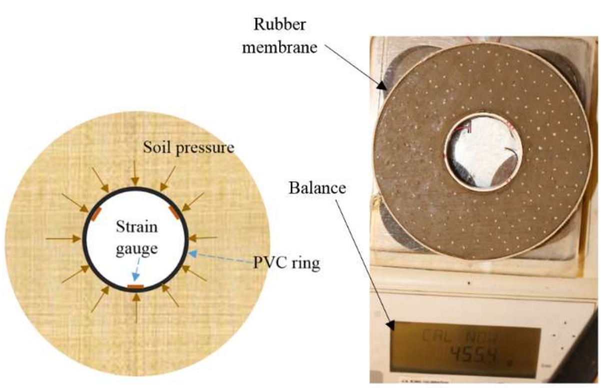


Figure 3 Soil specimen in the Restrained Ring Test

4. RESULTS AND DISCUSSIONS

4.1 Suction Measurement and Free Shrinkage Test

The soil shrinkage curve (SSC) for the Ardmore and Lake Hefner soil was constructed using the test results obtained from the continuous volume change measurements in the free shrinkage test and the gravimetric water content measurements. As mentioned, the free shrinkage volume change measurements were made utilizing the digital image analysis. The continuous gravimetric water content values of the soil specimen were determined through a back-calculation analysis using the changes of the total mass of the soil in the desiccation test performed on a balance. The test results are fitted by Fredlund et al. (2002) model and depicted in Figure 4.

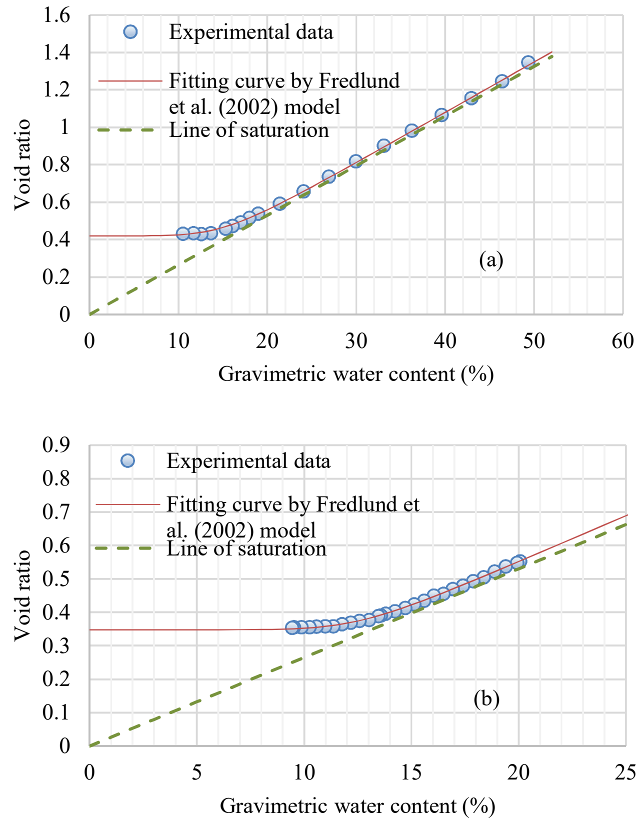


Figure 4 Soil shrinkage curve derived from Free Shrinkage Test on initially slurried specimens for: (a) Ardmore Soil, and (b) Lake Hefner Soil

The soil-water characteristic curve in terms of the gravimetric water content (SWCC-w) was fitted with the Fredlund and Xing (1994) equation. The generated SWCC is illustrated in Figure 5.

4.2 Restrained Ring Test Results

The soil-water characteristic curve in terms of the degree of saturation (SWCC-S) is determined by incorporating the SWCC-w with the SSC (Figure 6). The SWCC-S takes into account the volume change such that the AEV can be correctly located (Krisdani et al. 2008; Fredlund and Houston 2013; Wijaya et al. 2015; Bani Hashem and Houston 2015; Krisnanto et al. 2016). The SWCC-S is used to track the crack initiation in the restrained ring test (RRT). The restrained ring test results for both soils have shown that the crack initiates in the specimens at suction very close to the AEV (Figure 6).

All the specimens from both soil types encountered the same situation with regard to the crack formation; a single crack initiates at the inner face of the specimens and grows toward the outer face. All the slurried soil specimens were tested at high initial water contents with degree of saturations close to 100% in the drying shrinkage tests. Specimens of Ardmore soil with initial gravimetric water content (w) equal to 35% and 36.1% crack at w equal to 17.6% and 17.8%, respectively. Specimens of Lake Hefner soil with initial w equal to 20.2% and 17.8% crack at w equal to 13.2% and 12.8%, respectively, as in Table 2.

After the crack initiates at suction close to the AEV, the crack width increases. This crack growth happens in the unsaturated state. An example is illustrated in Figure 7.

The compacted specimens of the Ardmore soil were prepared at water contents close to the optimum for the drying shrinkage tests. The compacted specimens crack at a slightly higher water content than the high water content, or slurry, specimens. Compacted specimens with initial w equal to 25.6% and 27.7% crack at w equal to 18.6% and 19.1%, respectively. This may be attributed to the existence of the macropores in the compacted soils. These macropores act as flaws in the soil forming the cracks later during shrinkage.

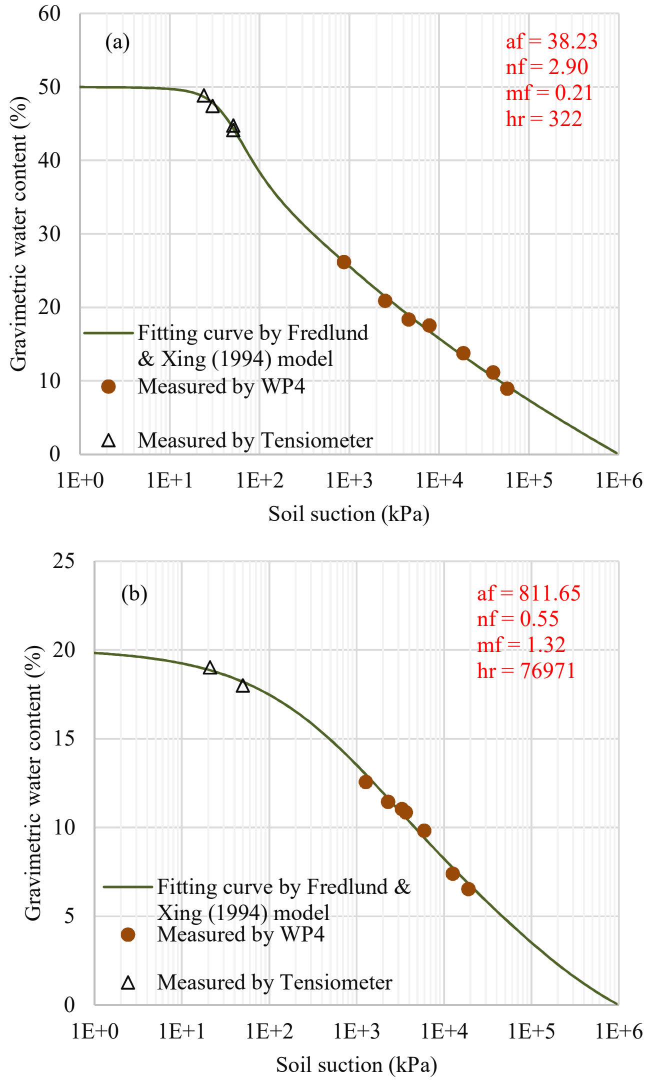


Figure 5 Soil-water characteristic curves of (a) Ardmore soil and (b) Lake Hefner soil obtained from initially slurried specimens. The af, nf, mf, and hr given on both figures are fitting parameters of Fredlund and Xing (1994) equation

Table 2 Summary of the results of semi-slurry specimens in the Restrained Ring Test

Soil	Initial water content (%)	Cracking water content (%)	Cracking suction (*log* kPa)
Ardmore	35	17.6	3.69
	36.1	17.8	3.67
Lake Hefner	20.2	13.2	3.06
	17.8	12.8	3.15

4.2.1 Tensile Stress Results

The tensile stresses in the soil specimen are obtained using the elastic solution of a cylinder under compressive forces as originally proposed by Timoshenko and Goodier (1987). This elastic solution was later adopted by Weiss and Ferguson (2001) for predicting the development of the tensile stresses in fresh concrete and by Abou Najm et al. (2009) for estimating the development of the tensile stresses in a desiccated soil. These approaches adopt the solution for the tensile stress in the pressurized cylinder by considering the sample as an elastic and isotropic material before cracking.

In this study, the tensile stress of the desiccated soil in the restrained ring test (RRT) is predicted using the approach provided in Abou Najm et al. (2009). The elastic solution for the maximum tensile stress (σ_t) is given as follows:

$$\sigma_t = -\epsilon(t)E\left(\frac{R_{Osoil}^2+R_{Oring}^2}{R_{Osoil}^2-R_{Oring}^2}\right)\left(\frac{R_{Oring}^2-R_{Iring}^2}{2R_{Oring}^2}\right) \qquad (1)$$

where $\epsilon(t)$ is the average micro-strain values captured by the three strain gauges with time t, E is the modulus of elasticity of the PVC ring (2.9 GPa), R_{Osoil} is the radius of the soil specimen, R_{Oring} is the radius of the ring to the outer face, and R_{Iring} is the internal radius of the ring.

The computed tensile stress versus soil suction for non-compacted high water content and compacted specimens of Ardmore soil is shown in Figure 8. The results reveal that tensile stress increases in a quasi-linear relation with the soil suction until the soil cracks. The soil cracks when the tensile stress attains the tensile strength of the soil. Therefore, the tensile stress at the time of cracking is also the tensile strength of the soil. The restrained ring test is perhaps the only method to estimate the tensile strength of the soil due to the desiccation without applying an external mechanical load. The compacted specimens show slightly smaller values of tensile strength. This may also be attributed to the existence of the macropores in the compacted specimens. These macropores form defects in the soil, which may lower the apparent cohesion between the soil particles and thus the overall tensile strength.

5. CONCLUSIONS

This paper presents experimental results for soils that shrink and crack under desiccation in the restrained ring test (RRT). The soil-water characteristic curve is constructed to track the crack initiation. The drying soil-water characteristic curve in terms of the gravimetric water content (SWCC-w) is predicted using the suction measurements from WP4 and tensiometer sensors. The free shrinkage test is conducted to establish the soil shrinkage curve (SSC). The soil-water characteristic curve in terms of the degree of saturation (SWCC-S) is assessed by incorporating the SWCC-w with the SSC. The crack initiation stage is located on the SWCC-S. The results for initially highly saturated soils in the RRT show that the crack first initiates at suction very close to the air-entry value (AEV). These results come with good agreement with the findings of previous studies. Initially compacted specimens with water content close to the optimum are also tested. The crack initiates in these specimens at a little higher water content (i.e. less suction). This may be attributed to the existence of the macropores in the compacted soil which play an important role in the crack initiation. For initially highly saturated specimens, the crack growth occurs in the residual shrinkage zone (i.e. unsaturation state) from the air entry stage until the shrinkage limit stage. At the shrinkage limit, the crack reaches a stable width, which is rational since the shrinkage ceases. The tensile stress results indicate a semi-linear relationship with the soil suction from the beginning of the test until the crack initiation stage. It is recommended for future studies to investigate whether the crack initiation for unsaturated compacted soils occurs at the end of the normal shrinkage from soil shrinkage curve.

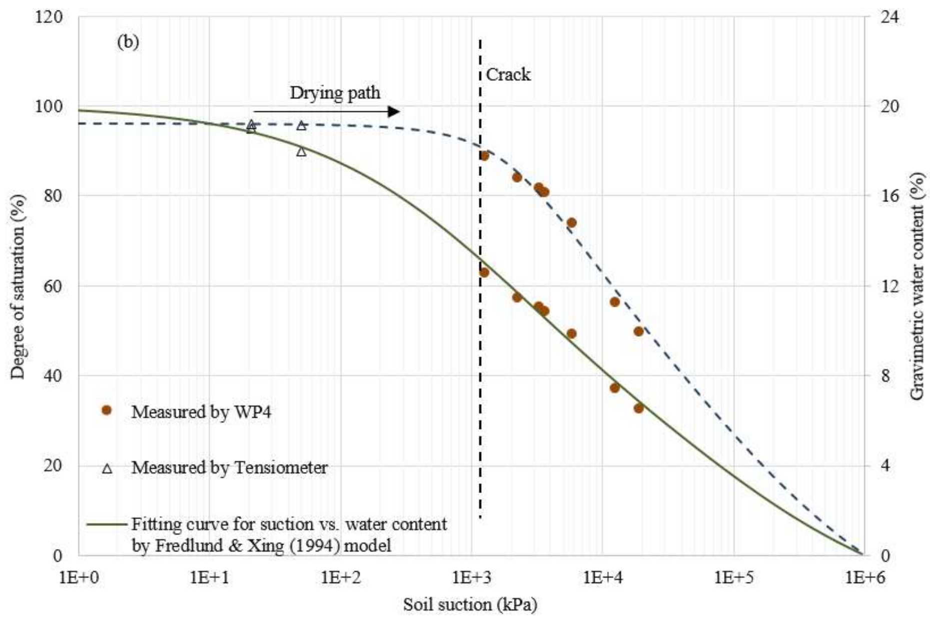


Figure 6 Soil water characteristic curves showing the crack initiation stage for (a) Ardmore soil and (b) Lake Hefner soil obtained from initially slurried specimens. The af, nf, mf, and hr given on both figures are fitting parameters of Fredlund and Xing (1994) equation

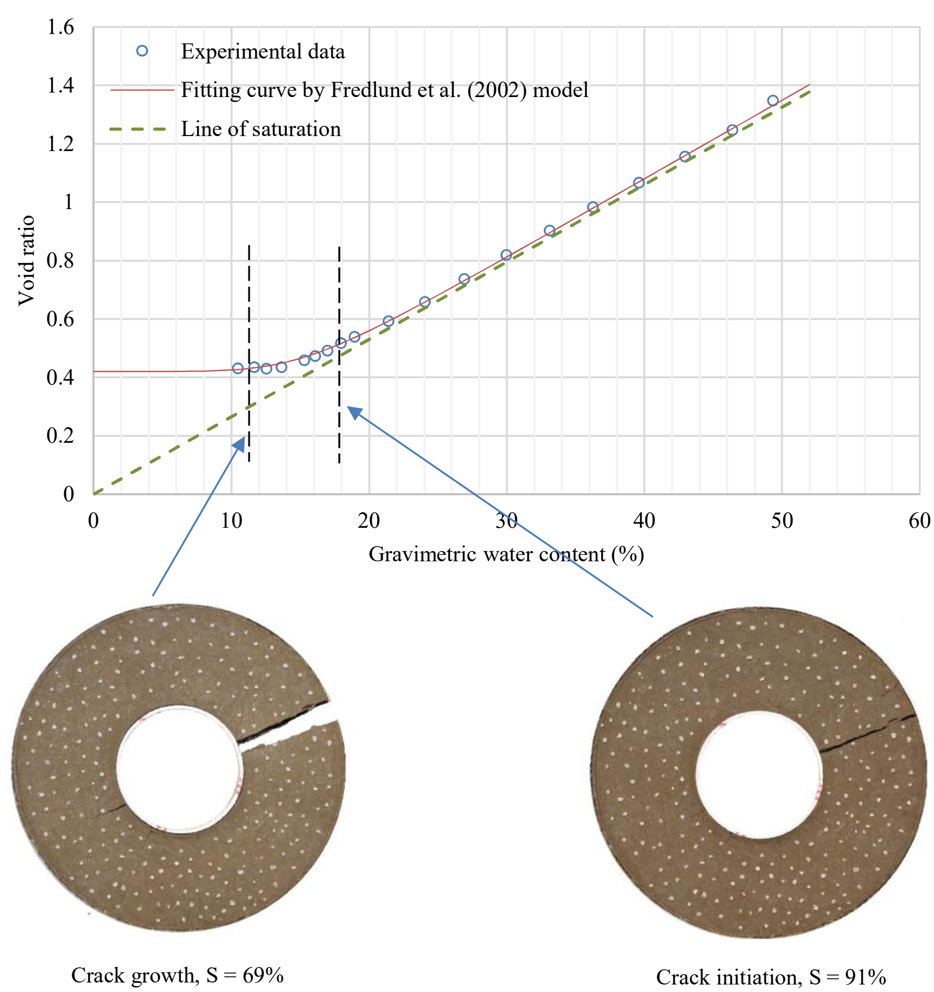
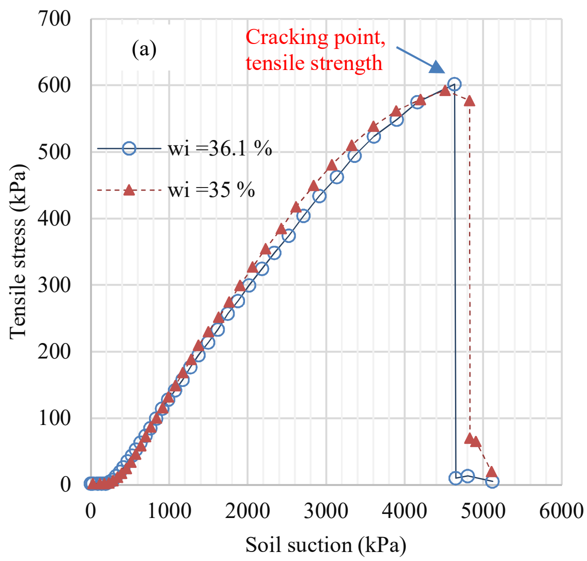


Figure 7 Image for crack initiation and crack growth showing their stage from the soil shrinkage curve



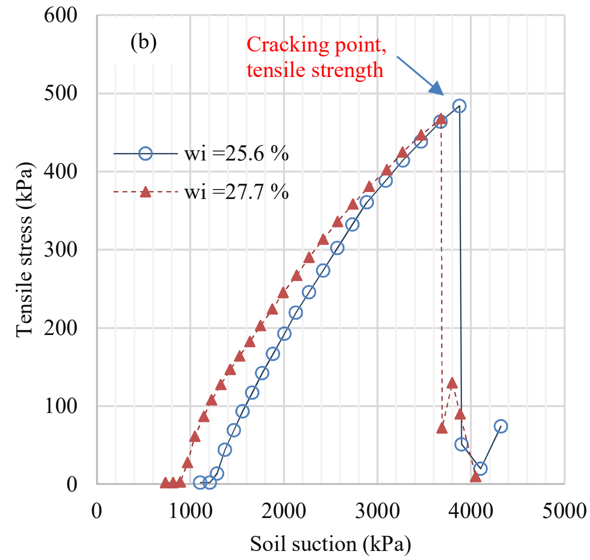


Figure 8 Tensile stress vs. suction for specimens in the Restrained Ring Test of Ardmore Soil, (a) High initial water content specimens molded without compaction, and (b) Compacted specimens with initial water content close to the optimum water content (i.e. 26.5 %)

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