Testing of unsaturated soil-steel interface shear strength

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ABSTRACT: There is limited information in the literature about the unsaturated shear strength of soil-steel interface. Information of interface shear strength is useful in the rational design of geotechnical infrastructure that are placed or in contact with unsaturated soils. For this reason, in this study, a commercial direct shear apparatus is used to determine the shear strength of soil-steel interface when the soil is in a state of unsaturated condition. The peak and residual shear strength results are interpreted using the information of soil suction and water content. Analysis of the direct shear test results suggests that suction contributes to both peak and residual interface shear strength. The contribution of suction towards the shear strength at soil interface under unsaturated conditions has been explained from two aspects: first, suction enhances soil aggregation and contribute to the shear strength. Furthermore, matric suction that generates at the air-water menisci along the shear plane significantly contributes to the peak strength. However, after reaching peak shear strength, the area of water-air menisci greatly reduces due to the rearrangement and sliding of soil particles due to extended displacement. Due to this reason, there is limited contribution from suction towards the residual interface shear strength. The results of the present study undertaken on an expansive soil are useful for practicing engineers.

1 INTRODUCTION AND BACKGROUND

The groundwater table is typically at a greater depth from natural ground surface in semi-arid and arid regions. Due to this reason, soil above the groundwater table is in a state unsaturated condition. Geotechnical infrastructure such as the pile foundations performance placed in unsaturated soils is significantly different in in comparison to saturated soils. This is because there is transfer of stress between the two materials through a contact zone in structural elements of the geotechnical infrastructure which are in contact with unsaturated soil are significantly different from conventional saturated soil, due to the influence of soil suction. There are limited studies reported in the literature that highlight the importance of role of the suction played in the mobilization of the interface shear strength (Sharma et al. 2007; Hamid & Miller 2009; Hossain & Yin 2013). Due to this reason, there is a need to undertake more research studies such that they can be extended in the rational design of geotechnical infrastructure placed in unsaturated soils.

Three different types of apparatus were used in the literature to determine the soil-interface shear strength under unsaturated conditions. The first two types of apparatus involved modifications of traditional direct shear apparatus and the third apparatus involved modifications to the triaxial apparatus. The first apparatus involved modification to the direct shear test which enables the interface shear test to be performed under a constant matric suction value. In this type of tests, axis translation technique was used to control and (or) apply the matric suction in the soil (Hamid & Miller, 2009). The modifications to the traditional direct shear apparatus includes the addition of an air-pressure chamber, new testing cells, high air-entry porous disc (HAEPD), and a pore-water pressure control system [as shown in Figure 1(A)]. Hamid and Miller (2009) conducted a series of interface shear tests between unsaturated Minco silt and stainless steel plates. Three matric suction values used in this test are chosen as 20, 50 and 100 kPa. Khoury et al. (2010) also have used the same apparatus to study the effect of soil matric suction (25, 50 and 100 kPa) on the mechanical behavior of unsaturated manufactured silty soil-geotextile interface. Hossain and Yin (2013) performed a series of interface direct shear box tests between a compacted decomposed granite soil and cement grout under different matric suctions (50, 100, 200 and 300 kPa) and net normal stresses. Borana et al. (2015 and 2016) also used similar apparatus to conduct a series of soil-steel interface tests at different shearing planes in the soil. These tests were conducted under a constant net normal stress of 50 kPa and different matric suctions of 0, 50 and 200 kPa.

The second type of modification includes installation of a miniature pore pressure transducer (PPT) into the direct shear apparatus (Fleming et al. 2006), which is shown as Figure 1(B). This technique facilitates the measurement pore-water pressure changes within the vicinity of structural element–soil interface during shearing stage of the test specimen. Fleming et al. (2006) and Sharma et al. (2007) monitored changes in the pore water pressure (i.e. matric suction) in the range of 0 to 30 kPa at geomembrane-soil interface during shearing stage using the PPT.

Hanson et al. (2001) used a modified triaxial apparatus to measure interface shear strength for interfaces with unsaturated geotextiles [as shown in Figure 1(C)], which forms the third apparatus. This device which is mounted inside a triaxial cell is useful to pressurize and shear the specimen. Similar to the first type of modification, axis translation technique was used to apply matric suction (4.8 kPa matric suction was used for this test).

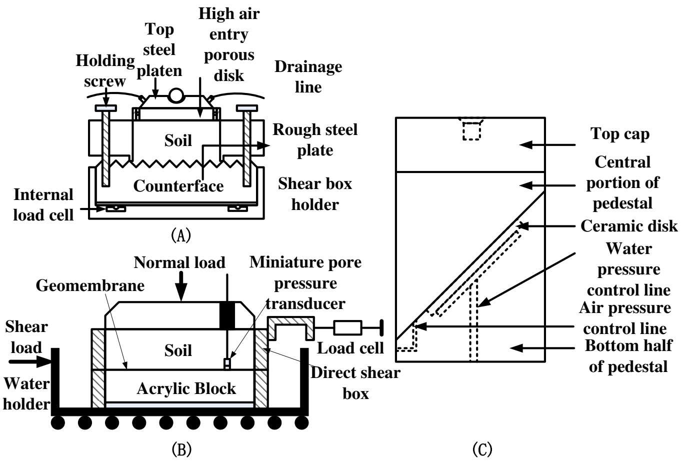

Figure 1. Apparatus for the unsaturated interface shear test [(A) is modified after Hamid and Miller 2009; (B) is modified after Fleming et al. 2006; (C) is modified after Hanson et al. 2001].

Vaunat et al. (2006), Vaunat et al. (2007) and Merchán et al. (2008) studied the effect of suction on the residual shear strength at high suctions (i.e., higher than 10 MPa). In their tests, vapour equilibrium method was employed to apply suction to the soil sample and determine the shear strength of unsaturated interface. As shown in Figure 2, the ring box assembly is put inside a chamber isolated from the relative humidity of the room atmosphere by a vapour-tight rubber membrane. Two small tubes connect the chamber to the atmosphere above a saline solution in a closed environment. Different saturated saline solutions in the closed environment contribute to different relative humidity values which help induce different suction values to the soil specimen. A pump connected to one of the tube allows for establishing a forced convection of vapour in the circuit. Eventually, the test specimen reaches equilibrium condition with the vapour pressure associated with the relative humidity induced by the saline environment. However, it typically takes several weeks for reaching equilibrium conditions. A hygrometer equipped with an internal thermometer registers the values of relative humidity and temperature inside the chamber during the test.

Apart from controlling or measuring the matric suction during shearing, some researchers measured the matric suction of the soil after completion of the interface shear strength test. For example, Hatami and Esmaili (2015) presented the results of small-scale pullout and interface tests on a woven geotextile reinforcement material in different marginal soils in order to quantify the difference in the soil–geotextile interface shear strength as a function of gravimetric water content. In their tests, the suction of the soil after shearing is determined through measured water content and the soil water characteristic curve (SWCC). The dew point potentiometer (WP4-T) can also be used for the suction measurement on the failed specimens. Chowdhury (2013) used this technique and performed a series of direct shear tests to determine influence of suction on the shear strength of unsaturated Regina clay. In comparison with the axis translation technique, this is a relatively simple technique to measure the water content or matric suction of soil specimen after the shear strength test is performed. This technique alleviates the long equilibrium time required for the axis translation technique and can be applied to the test specimen over the entire suction range (0 to 10^6 kPa). However, this testing can have some limitations with respect to obtaining reliable measurements of water content at failure conditions. This is due to collection of the soil sample required for determination of the water content after the removal of net normal stress which results in volume rebound of the soil.

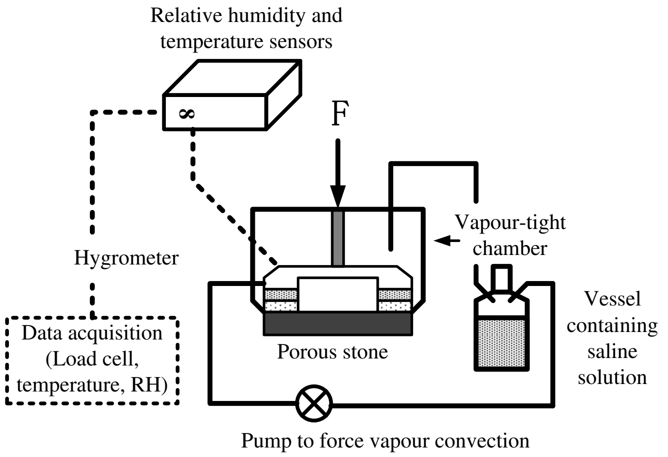

Figure 2. Apparatus used by Vaunat et al. (2006) to apply high suction.

From experimental studies reported in the literature, some general conclusions can be summarized with respect to the influence of suction on the unsaturated interface shear strength; they are:

(i) Suction contribution towards an increase in the peak interface shear strength is more significant for a rough interface in comparison to smooth interface (Hamid & Miller 2009; Khoury et al. 2010; Hossain & Yin 2013; Borana et al. 2015).

(ii) The post-peak (i.e., residual) interface shear strength at a given net normal stress is not significantly influenced by matric suction (Hamid & Miller 2009; Khoury et al. 2010). Such a behavior was attributed to the air–water menisci that are completely disrupted during shearing beyond the peak interface shear stress resulting in a negligible strength contribution due to matric suction (Hamid & Miller, 2009).

(iii) The applied net normal stress not only contributes to the mobilization of interface shear strength but also towards changes in the interface shear failure mechanism. Based on interface shear tests results on non-textured geomembrane–soil interfaces, Fleming et al. (2006) suggested that a higher net normal stress could change the interface shear failure mechanism from a sliding mechanism to a combination of sliding and plowing due to embedment of soil particles into the structure interface. Similar trends of results were also reported by Fan (2007) from interface shear tests on expansive soil-concrete. If a relatively high net normal stress value is applied, it helps in the development of a thin layer of soil that strongly adheres to the concrete surface. Due to this reason, shearing occurs only between the thin layer of soil adhered to the concrete and the remainder of the soil instead of the soil and actual concrete surface.

In this study, in order to study the influence of suction on the interface shear strength between unsaturated expansive soil and steel plate, a series of unsaturated soil and unsaturated soil-steel interface direct shear tests were conducted. The conclusions from this study regarding influence of suction on the interface shear strength are useful for practicing engineers to better understand the influence of suction on the interface shear strength behavior for typical expansive clays.

2 TESTING PROGRAM

The expansive clay used in the present study was collected from Regina, Saskatchewan. The natural soil collected from the field was air-dried and grinded. The optimum water content and maximum dry unit weight determined from the compaction curve correspond to 29% and 13.82 kN/m^3, respectively. Table 1 provides summary of various other soil properties. In the present study, soil specimens prepared at three different water contents of 24%, 27% and 30% at different dry densities which corresponds to16.95, 17.36 and 17.77 g/cm^3, respectively were used for determination of the peak and residual shear strength. The peak and residual shear strength were also determined at the soil-steel interface using the same water content and dry density conditions. The target water content was added to soil particles passing No.10 sieve (2 mm) and statically compacted test specimens were prepared for determining the shear strength from direct shear tests.

The specimens were statically compacted in the shear box assembly and quickly placed in of the direct shear apparatus and sheared under different net normal stress values of 50, 100 and 150 kPa. The soil specimens were sheared at a rate of 1mm/min (relatively quick rate of shear) to failure conditions, which completed in a time period of approximately 15 minutes. During the shearing process, infiltration holes and all the gaps in the shear chamber were blocked or covered using wet cotton to avoid any possible water loss. After shearing of the test specimen, soil sample at the shear plane was collected for the measurement of water content and suction. Suction measurement was conducted using filter paper method and dew point potentiometer (WP4-T). A test specimen with a smooth and flat surface is required for establishing an intimate contact with the filter paper for reliable matric suction measurements (ASTM D5298 - 16). Such a specimen is difficult to obtain from the direct shear test after the failure of the test specimen. For this reason, the sample in the present was used only to measure total suction using non-contact method.

Table 1. Basic properties of Regina clay

Standard compaction tests	
Maximum dry unit weight (kN/m^3)	13.82
Optimum moisture content (%)	29
Grain size distribution	
Specific gravity	2.85
Atterberg limits	
Liquid limit (%)	89
Plastic limit (%)	32
Plasticity index (%)	57

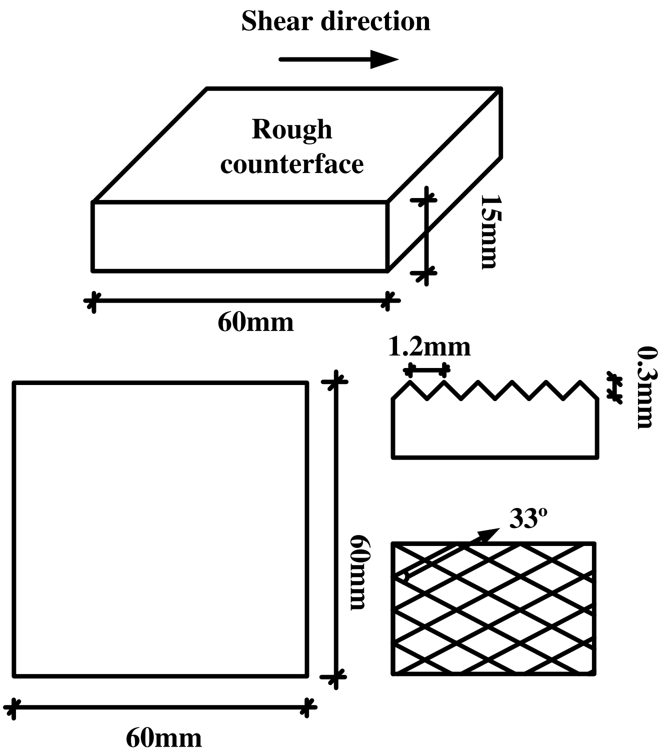

Figure 3. Steel block with rough counterface.

The interface shear tests were performed placing prefabricated steel block in the bottom half of the shear box with the rough surface facing up as shown (see Figure 3). The expansive soil of different wet densities was statically compacted in the upper half of the shear box. Care was taken such that the position of the shear plane was at the top of these teeth to alleviate any damage during shearing (as shown in Figure 4). The direct shear tests were performed at different normal stresses using the rate of shear as discussed earlier. After shearing of the specimen, some soil sample that was adhered to the steel block was collected and the water content was measured. Suction measurements were not obtained for interface shear tests because of difficulties associated with the collection of soil sample from the steel block. For this reason, suction was estimated from the SWCC using the information of water content.

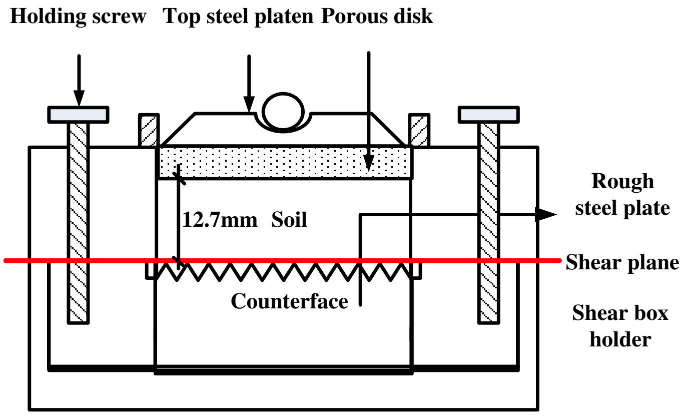

Figure 4. Setting of direct shear apparatus and model block.

3 TEST RESULTS AND ANALYSIS

Figure 5 and 6 summarize the results of direct shear tests on unsaturated expansive clay and interface shear test between unsaturated expansive clay and steel bock with rough surface, respectively. Two relationships are presented for each test: the first one is between the shear displacement and vertical deformation ratio. The vertical deformation ratio is defined as the ratio between vertical displacement to the initial height of the soil sample (for soil test it is 27.7 mm and for interface test it is 12.7 mm). The second one reveals the development of shear stress with shear displacement increment. Figure 7 summarizes the results of water content and suction measurement. Some observations from these testing results are summarized below.

(i) The shear stress initially increases with increasing shear displacement for all the three different specimens prepared at different initial water contents tests during the shearing process. However, after reaching the peak value, the shear stress tends to reduce to a residual value. The soil specimen prepared at an initial compaction water content of 24% reaches the residual shear strength under all the three different normal stresses at a shear displacement of 15mm. While for soil of water content of 27% and 30%, more shear displacement was required to reach residual shear strength conditions. For interface shear tests, for all the specimens compacted at three different initial water contents and net normal stresses, the interface shear strength reaches peak values with limited shear displacement and then reduces to residual values. For both soil and interface tests, the shear displacement required to achieve the peak shear strength increases with suction increment. Compared to soil, less shear displacement is needed for interface shear strength to reach the peak value.

(ii) For both soil and interface tests, peak shear strength increases with decreasing water content (increasing suction) for the same normal stresses. Measured total suction values for water content of 24%, 27% and 30% are approximately around 1500, 1020 and 950 kPa, respectively. Although the water content differences among three soil compacted are all the same (i.e. 3%), suction difference is much more significant for specimens with water content 24% and 27% in comparison to specimens with 27% and 30%. There is a strong relationship between the peak shear strength and suction in comparison to peak shear strength and gravimetric water content. The reason can be summarized as following: matric suction contributes to the peak shear strength through menisci between soil grains. As a part of total suction, matric suction increases with decreasing water content as well. However, due to limitations of the experimental technique used in the present study, it is difficult to separate the contribution arising from matric suction and osmotic suction during the test, especially for high suction (higher than 1500 kPa). Also, the interface peak shear strength of soil is higher in comparison to all other cases. This is due to the difference in the soil fabric and evolution of soil menisci in the shear plane between soil and interface test (Hamid & Miller 2009).

(iii) According to Figure 6, the residual interface shear strength is also affected by suction; however, the influence is less significant. Such a behavior may be attributed to the rearrangement and sliding of soil particles which greatly reduce the area of menisci in the shear plane. Furthermore, Vaunat et al. (2007) proposed a hypothesis that suction develops aggregation of particles, which makes the sample behave like a more frictional material during shearing. This hypothesis could explain both the increase in residual interface shear strength and the dilation of soil during shearing.

(iv) For both soil and interface tests, dilation are observed during the shearing process until the peak shear strength is reached. However, as the normal stress increases, compression is observed prior to dilation. Typically, with an increase in the normal stress, the amount of compression increases and dilation decreases. In addition, as suction increases, for most cases the dilation decreases. This can be attributed to the increment of stiffness of soil with increasing suction (Adem & Vanapalli 2014) and the suction induced development of soil aggregations (Vaunat et al. 2007).

(v) Figure 7 summarizes water content measurements before and after the direct shear test. These results suggest that there is approximately water content loss of around 1% from the tests conducted on the soil specimens. These results suggest some water loss due to drainage or due to evaporation losses. Hamid and Miller (2009) offered an alternate explanation for such a behavior; they concluded this may be due to the rearrangement and sliding of soil particles which results in the disruption and possibly the rupture of menisci between soil grains. The disruption of menisci contributes to an increase in pore water pressure or decrease suction. As a consequence, the water flows out from the soil specimen. This conclusion was also verified from the interface shear tests; the soil sample that adhered to the steel block had a little higher water content than the soil sample collected from the upper part of the shear chamber.

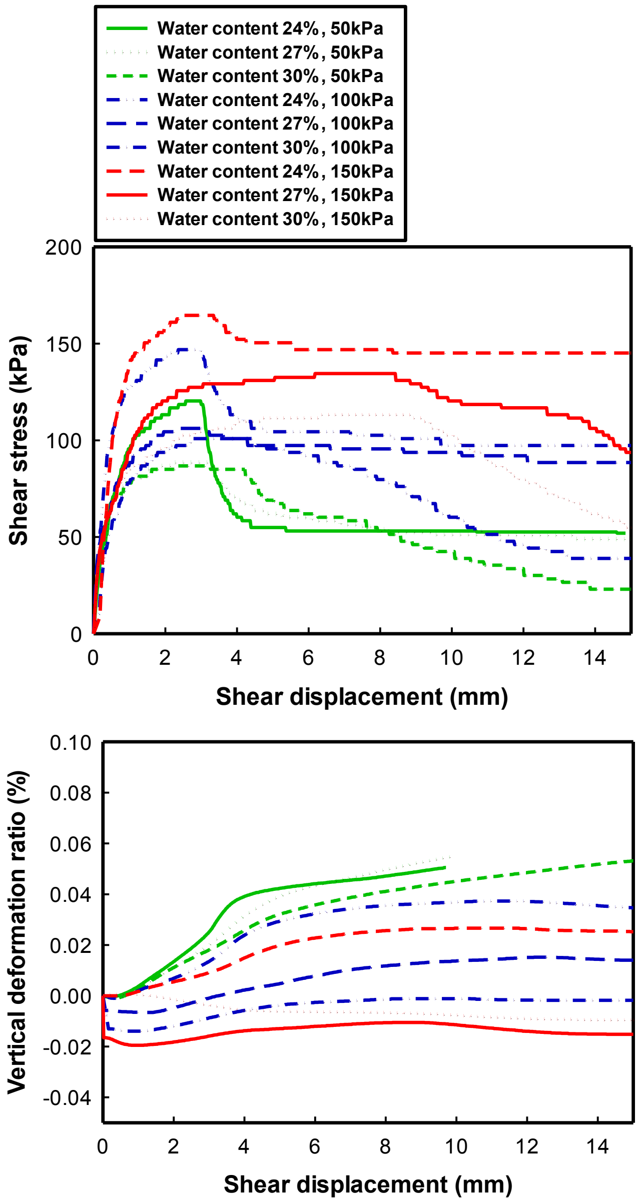

Figure 5. Direct shear tests on unsaturated expansive clay.

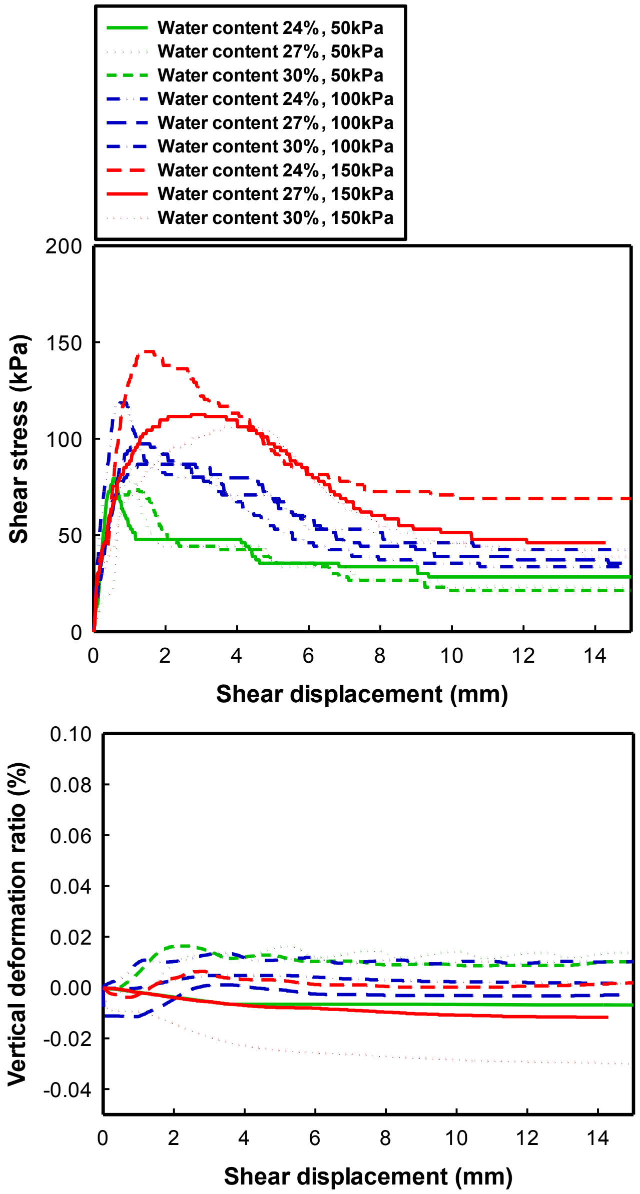

Figure 6. Interface direct shear tests between unsaturated expansive clay and steel block.

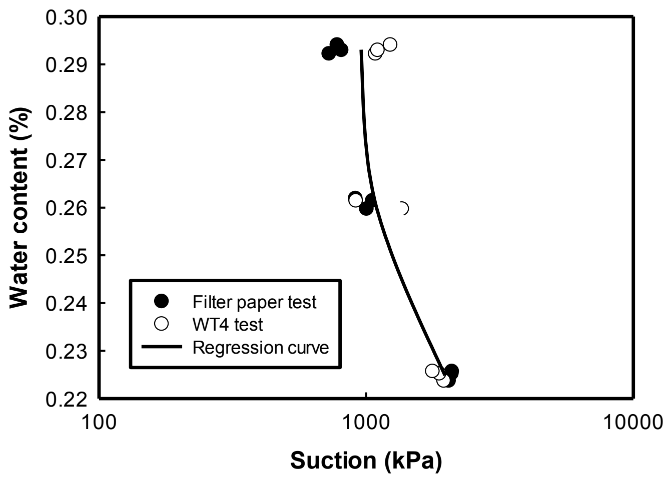

Figure 7. Measurement of suction on soil samples collected after soil direct shear test.

4 CONCLUSIONS

Research studies related to unsaturated interface shear strength are valuable for the rational design of infrastructure such as the pile foundations that are placed in unsaturated soils. Based on direct shear tests on expansive soil and expansive soil- rough steel interface shear strength results, the following conclusions can be derived:

(1) Both peak and residual interface shear strength increase with increasing suction. The contribution of suction can be explained from two aspects: firstly suction enhances soil aggregation, which makes the soil behave as a coarse-grained soil with high shear strength. Secondly matric suction generates air-water menisci in the shear plane. The contribution of suction to peak shear strength is more significant than residual shear strength. This is because the area of water-air menisci greatly reduced during the shearing process upon rearrangement and sliding of soil particles.

(2) During the shearing stage, soil specimen compression increases and dilation decreases with an increase the normal stress. For most cases, the dilation decreases as suction increases. This can be attributed to the increment of stiffness of soil with increasing suction and the suction induced development of soil aggregations.

(3) The disruption of menisci during shearing can cause a tendency for increasing pore water pressure and decreasing suction. As a consequence, water from can flows out from the test specimen.

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