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Effects of Sesquioxide Content on Stress-Dependent Water Retention Behaviour of Weathered Soils

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Abstract

Lateritic soils generally have high content of iron and aluminium oxides (i.e., content of sesquioxides), which is found able to enhance soil aggregation and therefore to alter pore size distributions. So far, however, there is no study on the influence of sesquioxides on its stress-dependent soil water retention curve (SDSWRC). In this study, SDSWRCs of compacted lateritic clay (LAT) were measured at various stress levels using a modified stress-controllable pressure plate apparatus. The results were then compared with SDSWRCs of two other weathered soils, including sandy silt (i.e., CDV) and a gravely sand (i.e., CDG). These three soils have different sesquioxide contents (i.e., 38% for LAT, 27% for CDV and 19% for CDG). Moreover, scanning electron microscopy (SEM) tests were carried out to analyse the microstructure associated with these soils. At a given stress, it was found that LAT had the lowest water retention ability among the three soils, even though it had the most clayed particles. This is mainly because clay particles in the LAT formed aggregates due to its high sesquioxide content, altering the pore size distribution. Consequently, the LAT specimen had many large-size inter-aggregate pores, as revealed by the SEM images. Furthermore, the influence of stress on the water retention ability of LAT seems negligible in the stress range considered (0-120 kPa). On the contrary, the water retention ability of CDV and CDG increases with an increase in net stress, likely attributed to a reduction in average pore size with an increase in stress.

Keywords: lateritic soil; water retention curve; unsaturated soil; sesquioxides content

Introduction

Lateritic soil is a type of soils formed by chemical weathering that occurs extensively in the humid tropical and sub-tropical zones of the world (Otálvaro *et al.*, 2016; Sun *et al.*, 2016). According to FAO (1989), lateritic soil covers about 8% of the Earth surface. They are widely used as construction materials in slopes and geotechnical structures such as pavements, embankments, and building foundations. On the other hand, the process of laterization induces high content of iron and aluminium oxides (sesquioxides). The iron and aluminium oxides are found able to enhance the formation of soil aggregates and therefore to change the pore size distribution (PSD) (Otálvaro *et al.*, 2016). It is therefore expected that the sesquioxide content significantly affects the SDSWRC, which is an important parameter in transient seepage analysis (Ng et al., 2015), because soil behaviour is greatly affected b its microstructure (Ng et al., 2009). To the best of the authors' knowledge, this susceptibility of SDSWRC in the presence of sesquioxides content has not purposely been investigated in the literature.

Miguel & Vilar (2009) measured the SWRCs of intact clayey lateritic soil sampled at different depths in Brazil. They focused on the effects of soil structure on SWRC, emphasizing on micro-aggregation and pore distribution at different depths. The study concluded that the lateritic soil studied, which is clayey in nature, shows many features of granular material. Recently, Sun *et al*. (2016) investigated the effects of microstructure and pore size distribution on SWRC of intact and compacted samples of Guilin lateritic clay, with consideration of volume change due to suction increase. The study focused on the primary drying curve. It was concluded that compacted samples exhibit distinct bimodal PSDs, while intact samples exhibit unimodal PSDs. During compression, the initial void ratio of a compacted unsaturated sample only affects the inter-aggregate pore volume, and the volume of intra-aggregate pores remains almost constant. A change in the moisture leads to a change in the inter-aggregate pores and the intra-aggregate pores remain almost unchanged. In the above two studies, the authors did not consider the influence of stress state on the SWRC and did not measure the soil volume change during drying and wetting. According to the experimental study, the SWRC is significantly affected by stress condition (Vanapalli et al., 1999; Ng & Pang, 2000). Moreover, the previous studies did not analyse the influence of sesquioxide content on water retention behaviour.

The key objective of this study is to investigate the influence of sesquioxide content on the SDSWRC of recompacted sandy clay (LAT). To meet this objective, the SDSWRC of a lateritic soil was measured and then compared to that of two other weathered soils, including the completely decomposed volcanic (CDV) (Ng & Pang, 2000) and granite (CDG) (Tse, 2007). These three soils have different sesquioxide contents. To help explain the measured SDSWRCs of these three soils, the microstructures of these three soils were determined in this study through SEM tests. It should be pointed out that apart from sesquioxide content, LAT, CDV and CDG are different in many aspects such as soil type and clay content. The current study mainly focuses on the influence of sesquioxide content on the aggregation (obtained from SEM images) and hence on the water retention behaviour of unsaturated soils.

Test program

SDSWRCs of LAT were measured using a modified pressure plate apparatus in a suction range of 0.1 kPa to 400 kPa. In total, four specimens were tested under different net stress of 0, 40, 80 and 120 kPa). The SDSWRCs of LAT were then compared to those of CDV and CDG, reported in the literature. To provide insights into the measured SWRC, SEM tests, as well as XRD and XRF analysis, were carried out to determine the microstructure, mineralogical and chemical composition of the three soils.

Test soil and specimen preparation

The LAT used in this study was taken from Ibadan in Oyo-state, Nigeria. The in-situ moisture content and dry density were measured to be 9 % and 1.67 Mg/m^3 respectively. The CDV and the CDG used for comparisons are from Hong Kong. A summary of the properties of the soil is shown in Table 1. To ensure that all specimens have the same initial water content and void ratio, they were prepared using the same method as Ng and Pang (2000). Firstly, oven-dried soil was mixed with water to obtain the desired water content. Then, soil specimens were statically compacted inside an oedometer ring (70 mm in diameter and 19 mm in height) using the same method. Compaction was done by three layers (i.e. 6.33 mm height of each layer), with scarification between each layer to ensure the homogeneity of the specimen. In order to achieve the target void ratio, the height of each layer was controlled carefully through a ruler attached to the loading rod. After compaction, the height of each specimen was determined, confirming that the initial void ratios of all specimens are the same.

Figure 1 shows the particle size distribution of the three soils, determined according to BS1377, 1990 for both dry and wet sieving. It is clear that the sieving method (wet or dry sieving) greatly affects the particle size distribution of LAT and CDV. This is mainly due to the obvious aggregation in these two soils during the wet sieving. For CDG, however, the wet and dry sieving curves are almost the same.

The amount of sesquioxide content of these three soils was determined based on XRF analysis: LAT (Fe_2O_3: 10%, Al_2O_3: 28%), CDV (Fe_2O_3: 4%, Al_2O_3: 23%), CDG (Fe_2O_3: 2%, Al_2O_3: 17%) (see Table 2). Hence, LAT contains more sesquioxides than CDV and CDG by 30% and 50%, respectively. The silica content of LAT, CDV and CDG are 60%, 63%, and 71%, respectively. On the other hand, the common minerals in all three soils samples are quartz, hematite, and kaolinite as determined by XRD analysis. A significant amount of goethite mineral, which is present in LAT, was not found in CDV and CDG. The presence of goethite in some lateritic soils has been reported (Miguel & Vilar, 2009; Otálvaro *et al.*, 2016). It is discussed later how the presence of goethite mineral may affect the SDSWRC.

All specimens (70 mm in diameter and 19 mm in height) were prepared using the method described by Ng *et al.* (2016). LAT specimens were compacted to relative compaction of

95% at a water content of 18.5%. CDV and CDG specimens were compacted to relative compaction of 92 % and 86 % at water contents of 30 % and 16.1 %, respectively. More details of these specimens are summarized in Table 3.

Test apparatus and procedures

The stress-controllable volumetric pressure plate designed by Ng & Pang (2000) (see Figure 2) was improved and utilised in this study. This apparatus was selected because it could be used to study the effects of stress state on the SWRC. During some trial tests with the apparatus used, the problem of eccentric loading was encountered. This was due to the difference in the internal diameter of the base plate and the external diameter of the cylindrical chamber (Ng & Pang, 2000). This problem was solved by developing a guard cell, as shown in Figure 3(a). The guard cell is made of a stainless steel plate of 115 mm in diameter and 20 mm in height. A circular hollow cavity, which is 71 mm in diameter at the top and enlarges to 74 mm at the bottom, was created at the middle of the steel plate. The smaller diameter at the top allows for a perfect union between the porous stone attached to the loading rod and the soil specimen. The larger diameter at the bottom (i.e. 74 mm) allows the guard cell to house the top part of the oedometer ring (Figure 3(b)). Without the presence of the guard cell, the configuration of a specimen inside the apparatus is like as shown in Figure 3(c). The guard cell thus makes the specimen configuration similar to the configuration in the oedometer setup (Figure 3(d)). This configuration ensures that the problem of eccentric loading is prevented. It is worth noting that the guard cell is not in direct contact with the ceramic disk (Fig. 3(b)), and the grove (Fig. 3(a)) allows for a distance of 10 mm between the ceramic disk and the guard cell. Hence, there is no water remaining at bottom of the guard cell. The ceramic disk was fully saturated before testing and the range of suction tested is below the AEV of the disk, hence it still remained saturated during the wetting process. Therefore, any water absorbed during the wetting process is by the specimen which is in direct contact with the ceramic disk.

Figure 4 illustrates the stress paths followed in this study. Firstly, it was ensured that the ceramic disk fully saturated by filling the setup with a column of water and applying air pressure to flash the water through the disk. Accumulated air bubbles under the ceramic disk were periodically removed by flashing de-aired water through the connected tubes. This procedure was repeated until a continuous flow of water without any air bubble was observed for 24 hrs before each test. The specimens were saturated using the method proposed by Vanapalli et al. (1996). During the saturation process, water level in the pressure plate was maintained at about two-thirds of the specimen height. Soil specimen was allowed to adsorb water freely for 24 hours. Compared to other saturation methods such as submersing soil specimen in the water, rising water from the bottom can better displace air bubbles trapped within the sample. Moreover, the weight and dimension of each specimen were measured after the saturation process. The obtained results showed that all samples achieved degree of saturation of almost 100%, as summarized in Table 3, confirming that the saturation method is effective. The specimens were then compressed to a targeted net stress (O to B) as shown in Table 3. This was done by applying required dead loads on top of the loading rod (Figure 2) and waited until the vertical displacement was less than 0.001mm over 24 hours. This step was then followed by a suction increase (B to C') and then decrease (C' to B) to obtain the dying and wetting curves of a SDSWCC. Suction was assumed to be equalized when the inflow/outflow rate of water was below 8×10^{-13} m^3/s (Ng et al., 2016). The criterion assumes that when the change of water content is less than 0.05%, suction equalisation is considered to be achieved. The criterion is independent of soil property and would work for the soil tested in this study. By using this criterion, it took 3-10 days for suction equalisation. Details of the experimental procedures for measuring SDSWCC were given in Ng et al. (2016).

SEM test was used to determine the microstructures of the three soils at their compaction conditions. Their specific surface area and total pore volume per unit dry mass were determined by the Brunauer-Emmett-Teller (BET) method (Maček et al. 2013). In the BET tests, an oven-dried specimen of each soil was outgassed for about 150mins at temperature of 120^{o}C. Then, the outgassed specimens were subjected to liquid nitrogen for both adsorption and desorption processes. The surface area and total pore volume were calculated using the method described in Zielinski & Kettle, (2013). Furthermore, the SEM image of as-compacted specimens were determined. Specimens were compared to the same state as the sample used for the SDSWRCs. After compaction, the samples were extruded from the compaction mould and specimen of about 10 mm^3 was cut out and quickly frozen at -56 ºC by immersing in liquid nitrogen. The frozen sampled were then dried at vacuum of 0.3 Pa for a period of about 72 hours (Delage et al., 1982; Zhang et al., 2018). After 72 hours the sample were removed for the SEM tests. The results are summarized in Table 2.

Interpretations of experimental results

SDSWRC of LAT

Figure 5(a) shows the relationship between volumetric water content and suction for LAT. Table 4 presents the estimated AEVs from the SDSWRCs based on the approach proposed by Vanapalli et al. (1999) and other parameters such as desorption and absorption rate and size of the hysteresis loop. The rate of desorption and absorption were estimated by taking the slope of the point of inflection for the drying and wetting curves respectively.

During the drying process, the data shows that the specimen at zero stress retains the highest volumetric water content in several suction ranges: 0.1 to 1 kPa; 3 to 400 kPa. When the net stress was increased to 40 kPa, the SDSWRC shifted to lower volumetric water content. The rate of desorption increased with an increase in net stress, probably because the pore size distribution of soil specimen became more uniform. During the drying process, AEV is defined as the suction value at which there is a marked changed in the volumetric water content with an increase in suction. The figure shows that LAT-0 has a slightly larger AEV than LAT-40, while both LAT-80 and LAT-120 has the same AEV which is higher than that of LAT-0 (see Table 4). An increase in AEV caused by an increase in net stress was often reported in the literature (Chiu & Ng, 2012; Salager *et al*., 2013; Ng *et al*., 2016). Compared with the existing results in the literature, the influence of stress on the AEV of LAT is almost negligible.

During the wetting process, the rate of absorption is estimated and summarized in Table 4. A consistent decrease in the rate of absorption with an increase in net stress was observed, except for specimen at 80 kPa net stress. The highest rate of absorption was estimated for zero net stress condition, followed by 40, 120 and 80 kPa respectively. It is worth noting that the rate of adsorption is governed by the size and connectivity of inter-aggregate pores (Wheeler *et al*. 2003; Koliji et al., 2010; Ng & Menzies, 2014).

Fig. 6(a) shows the changes during the SDSWRC measurement. For the LAT-0, the insignificant change in void ratio suggests that the compaction-induced state was maintained during the drying process. Hence, inter-aggregate pore with relatively higher connectivity existed in the LAT-0 than specimens under higher stress level. This, therefore, leads to a higher capillary rise to develop in the LAT-0 during the wetting process resulting in the highest rate of absorption. For the specimens under higher stresses, LAT-80 shows the lowest rate of adsorption. The lowest rate of absorption associated with LAT-80 is consistent with the change in void ratio with an increase in suction. The compression and drying process, therefore, might have resulted in pore sizes with a smaller diameter or an increase in tortuosity. Accordingly, it is more difficult for water to be absorbed quickly into the specimen LAT-80. In other words, a longer time is required for a similar amount of water to be absorbed by the LAT-80. It can be concluded that the absorption phenomenon of LAT under these stress conditions is governed by the compaction-induced state and void ratio after compression ($\boldsymbol{e}_c$) (Table 3) respectively.

Comparisons between SDSWRCs of LAT and CDV

Figure 5(b) demonstrates the plots of SDSWRC in terms of volumetric water content against suction for CDV. The figure shows that SWRCs for specimen under higher stress lies below specimens under zero stress between the suction value of 0.1 kPa and 15kPa. Nevertheless, it is evident that the curves for specimens at higher stress levels shift upwards when suction was increased beyond 15 kPa. Comparing Figure 5(a) and 5(b), the results show that the CDV retained high volumetric water content at any given suction for both drying and wetting for all the stress conditions within the suction range considered than the LAT. There are two possible reasons that may account for the observed behaviour.

Firstly, as will be seen and discussed later, there are larger aggregates and inter-aggregates voids in the LAT than in CDV. This is mainly because the fine content in the LAT form aggregation into larger-size aggregates, although it contains high clay content (about 42%, see Table 1). This is as a result of the state (as defined by the degree of petrification) and higher content of sesquioxides in LAT than in CDV. Hence, it causes the LAT specimen at zero stress to lose water quickly than CDV at any given suction. For those specimens that were compressed before drying, on the other hand, more pores of large size might have resulted from the rearrangement of the aggregates. This thus leads to a higher rate of desorption and more water is easily removed from the LAT than CDV at an equivalent suction. The influence of the state of sesquioxides on the level of aggregation is later discussed.

Secondly, the CDV specimens were compacted to a higher initial void ratio, which corresponds to higher initial volumetric water content at after saturation. Moreover, in the stress path followed in this study, specimens were fully saturated after initial suction measurements and were then followed by compression before suction was applied. In other words, the CDV had higher water ratio ($e_w = e \times S_r$; *where* e_w *is water ratio*) (Tombolato & Tarantino, 2005; Monroy *et al.*, 2010) than LAT due to higher initial void ratios.

Figure 1 shows that the particle size distribution changes significantly between dry and wet sieve analysis for both LAT and CDV studied. The extreme change in particle size distribution is mainly because of the aggregation caused by sesquioxides found in these soils. The aggregation thus imposes on these soils apparent particle size distribution in the dry state (solid triangle and solid circle), which as a matter of fact are finer when soaked in water (opened triangle and open circle). In comparison, it seems that the aggregation observed in CDV from the particle size distribution (see Figure 1) does not affect the SWRC. This is probably due to the fragile nature of the aggregated particles (Chiu, 2001), coupled with the side of OMC that the specimens were compacted. Therefore, the aggregates could be broken down completely by compaction and loading, causing much finer material to result. Hence, the soil sample behaves more like a fine material rather than aggregated fabric. Applying stress thus could only cause a reduction in average pore size and hence a decrease in the rate of desaturation (Vanapalli *et al.*, 1999) and permeability with net stress levels (Ng & Pang, 2000). This could explain the increase in AEV with an increase in net stress for the CDV. This is also justified when the parameters estimated for LAT and CDV in Table 4 are compared.

The data in Table 4, (row 2 and 3, column 5) indicates that the rate of desorption for LAT-0 is less than CDV-0. For the specimens under higher stresses, the rate of desorption is more than twenty and thirty times for LAT-40 and LAT-80 than CDV-40 and CDV-80 respectively. Besides, the higher rate of desorption for CDV under zero net stress in comparison with LAT under equivalent stress underscores the effects of lager pores on the rate of desorption.

Comparisons between SDSWRCs of LAT and CDG

Figure 5(c) illustrates the plot of SWRC in terms of volumetric water content as the ordinate and suction as the abscissa for CDG at different net stresses. The data shows that the CDG demonstrates a similar trend for water retention behaviour with increasing net stress as was observed for the CDV. The water retention behaviour demonstrated by the CDG as reported by Tse (2007), also contradicts that of the LAT studied. Comparing Figure 5(a) and 5(c) and considering the zero net stress condition, the LAT retained high volumetric water content at any given suction for both drying and wetting than CDG for the range of suction considered. Except for between 0.1 and 1.0 kPa where the specimen CDG-0 retained slight high water content than LAT-0. For the intermediate (i.e. 40 and 53 kPa for LAT and CDG respectively) and the highest stress levels considered in these studies, however, the CDG retains higher volumetric water content than LAT.

The CDG used by Tse (2007) in measuring the water retention curve is coarser than the LAT and CDV (see Figure 1). It was therefore expected for the CDG to show higher desorption rate and probably to retain less water content with an increase in suction due to the larger inter-aggregate pore associated with granular materials (Ng & Menzies, 2014). On the contrary, the LAT retained less water than CDG at any given suction. The larger-size inter-aggregate voids due to the presence of larger aggregates, which exit in the LAT causing water to be lost very easily with an increase in suction, could be one possible reason. It is evident that the LAT-0 which showed a lower rate of desorption (see Table 4) retained higher water than CDG-0. This highlights the influence of compression on the PSD and hence the rate of desorption. The second reason is the difference in water ratio ($e_w = e \text{ x } S_r$) caused by the difference in the initial void ratio. Romero *et al*. (2011) have reported similar findings a study in which the SWRC data is expressed in terms of water ratio against suction.

Unlike the CDV in which a distinct increase in AEV with an increase in stress is observed, CDG and LAT show different behaviour. CDG demonstrated similar water retention behaviour with an increase in stress but in terms of AEV, it shows a lesser value for a specific stress state than for LAT. Moreover, the CDG shows only a slight increase in the AEV (i.e. 0.1 kPa) even at 80 kPa net stress. For the LAT, an increase in net stress from 0 to 40 kPa resulted in a decrease in AEV (i.e. from 1.9 to 1.1 kPa). For net stresses higher than 40 kPa on the contrary, AEV increases from 1.1 to 2.5 kPa and remains constant even at 120 kPa. The measured AEV of the LAT is only 2-3 kPa, which is much lower than that of other clays. The unique property of LAT is mainly because its clay particles form large-size aggregations due to its high sesquioxide contents. The size of inter-aggregate pores is very large, resulting in low AEV."

It is found that the CDG has a higher number of non-aggregated granular particles as compared to the LAT (see later in Figure 9(c) and 9(f)). These observations from the SEM images are consistent with the insignificant change in the particles size distribution of the CDG even after wet sieve analysis (see Figure 1). It is interesting, however, to note the extremely large differences between the estimated parameters in Table 4 for the LAT and the CDG in comparison with the CDV. This observation also supports the claim that the LAT truly possesses "apparent" granular soil behaviour due to particle aggregation caused by higher content and the state of sesquioxides.

Volume changes of LAT, CDV and CDG during drying and wetting

Figure 6 illustrates the variation in void ratio with suction during the SWSWRC measure for the soils studied. Figure 6(a) shows the variation of the void ratio against suction for LAT. Along the drying path, the void ratio is almost constant up to suction of 400, 50, 5 and 20 kPa for specimens LAT-0, LAT-40, LAT-80, and LAT-120, respectively. The specimen LAT-0, which was not subjected to mechanical loading, experienced the least decrease in the e_c (i.e.

about 0.9%) with an increase in suction. The largest reduction of the void ratio is observed for specimen LAT-80 (Δe = 6% when suction was increased from 5 kPa to 400 kPa). This is probably because LAT-80 had some large inter-aggregate pores, which were induced by the particle rearrangement during compression. These large pores collapsed when suction was increased. It can be seen from Figure 6(b) that the void ratio of CDV specimens is almost constant during the drying and wetting process. This is likely because CDV has high AEV and low desorption rate owing to its higher fine content. As a result, the degree of saturation remains very high (above 85%) within the suction range considered. Consequently, the volume change due to the shrinkage of inter-aggregate pores is negligible as compared with LAT and CDG. The behaviour of change in void ratio with suction increase for the CDG is consistent with that of the LAT with the suction range lying between 50 kPa and 200 kPa (Figure 6(c)). From Fig. 5(b) the estimated AEV based on the method proposed by Vanapalli et al., 1999 is below 10 kPa and the corresponding rate of desorption is very low (see Table 4). The changes observed in the current void ratio with an increase in suction (Figure 6(a) and (c)) for the LAT and CDG are consistent with the rate of adsorption (Table 4 column 6, row 2 & 4). Thus the samples that experienced the highest shrinkage collapsed during drying shows the least rate of adsorption.

Along the wetting path, specimens LAT-0 and LAT-120 maintained almost constant void ratio. Specimens LAT-40 and LAT-80 showed an increase in the void ratio with a decrease in suction level. For the CDV, the void ratio remains unchanged for all specimens during the entire wetting process (see Figure 6(b)). An increase in the void ratio as suction decreases can be observed for all three samples (see Figure 6(c)) for the CDG. This indicates that both the LAT and the CDG have a tendency to swell when suction was reduced from 400 to 200 and 200 to 50 respectively. This is because the stability provided to the aggregates by water meniscus (Gallipoli et al., 2003a) is thus lost with a decrease in suction. Moreover, as the volumetric water content increases due to suction decrease, bulk water increases at the expense of meniscus water. In other words, aggregates undergo distortion upon wetting, filling the available pore space (Sivakumar et al., 2006). The swelling gradient thus decreases with a decrease in suction leading to a decrease in swelling towards lower suction as observed for LAT40 and LAT-80. This behaviour is observed also for all three specimens of CDG. The volumetric behaviour of the LAT used in this study during drying-wetting process contradicts what was reported for lateritic soils from Brazil by Miguel & Vilar (2009). The conclusion, therefore, is that the shrinkage collapse is only significant when suction is higher than the past suction experienced by the soil for both LAT and CDG compacted at dry of OMC and at OMC respectively. The suction increase, however, has no effects on CDV compacted on the wet side of OMC for the suction range considered. This implies that volumetric behaviour and hence SWRCs is highly dependent on the compaction-induced state, void ratio after compression and the associated PSD.

Hysteresis of drying and wetting SDSWRCs

Based on the SWRCs shown in Figure 5, the degree of hysteresis (D_h) is determined using the method proposed by Lu and Khorshidi (2015). The (D_h) at a specific suction is defined as the difference between wetting and drying water content over the mean water content. The relationship between D_h and suction is summarized in Figure 7. It can be seen from Figure 7(a) that generally all the stress state considered assumes a similar shape for the D_h against suction. However, maximum D_h shifts upward with an increase in net stress and then decreases subsequently except for LAT-40. The D_h for the LAT-40 shows a tendency to increase between suction values of 10 kPa and 100 kPa. The peak values of the D_h are within 1.0 kPa to 2.5kPa suctions for LAT, indicating hysteresis behaviour is probably only related to macrostructural pores (Miguel & Vilar, 2009). Thus, the D_h increases from a minimum value (for LAT-0) to a maximum value at the net stress of 120 kPa. This is attributed to the rearrangement and subsequent compression of the aggregated particles caused by stress or possible shrinkage caused by an increase in suction. Further explanation is provided in the later section under the discussion on the effects of compression on SWRC.

The D_h against suction for CDV is presented in Figure 7(b). In terms of magnitude, the CDV shows an insignificant D_h in comparison to the LAT. The peak values correspond to 10 kPa and 100kPa for the CDV-0 and CDV-40 suction respectively, indicating that hysteresis may only be related to microstructural pores. Furthermore, a horizontal shift from a lower suction towards a higher of the peak values as the net was stress increased could be observed (Figure 7(a) and (b)). This implies that although a soil sample compacted at the wet of OMC may initially possess a unimodal pore size; increasing net stress may not only cause a reduction in average pore size (Ng & Pang, 2000) but could also modify the PSD. A study by Monroy *et al*., 2010 and Tarantino, 2011 showed that the PSD could be modified significantly by mechanical and hydraulic loadings, and may even evolve from unimodal to bimodal, or vice versa.

Figure 7(c) illustrates the D_h against suction for the CDG. Comparing Figure 7(a) and (c) provides more insight into how the rearrangement and (or) compression of the aggregates associated with the LAT and the CDG affect their PSD and consequently SWRCs. This is because a horizontal shift in the peak of D_h from a lower suction towards a higher suction physically means an increase in the difficulty for water to be removed or taken into the soil sample during the drying and the wetting process. It is evident from Figure 7(c) that the magnitude of D_h decreases with an increase in net stress. The data from Figure 7(a) and (c) shows that the specimen LAT-0 shows a lower D_h than CDG under the same net stress for any given suction. The lowest D_h associated with LAT-0 is due to the compaction-induced state maintained by the specimen. On the other hand, the higher D_h and the observed trend for samples at higher stresses are because of their respective soil structure after rearrangement of aggregates caused by mechanical loading.

Considering CDG, the soil particles were probably not crash under the stress level considered but compressed significantly. This is because the stress level considered is smaller than the P_c value estimated for CDG in Table 3. Applying these stresses could thus only cause particle rearrangement and consequently reduces the average pore size between particles (Mesri & Vardhanabhuti, 2009). The particles rearrangement and compression of the inter-aggregate pores could thus be the most likely mechanisms controlling the features of the water retention behaviour of the CDG under the stress range considered. Further discussion on the response of aggregates to compression is provided in a later session.

The LAT and CDG show a low degree of hysteresis in higher suction range and this difference can be explained by the relative contribution of capillary and absorption phenomenon. In a capillary fringe regime in which suction is below the AEV, the soil is saturated, and water is under tension by capillary forces (Lu & Likos, 2006). In a funicular regime between the AEV and residual suction, the water phase is continuous and negative water pressure is induced by capillary tension (Romero *et al.*, 2011). Although higher rearrangement and compression of inter-aggregate pores occurred, the relatively rigid soil particles help higher capillarity to be maintained in both LAT and CDG as compared with CDV. Accordingly, higher adsorption is observed for both soils than CDV, since capillary tension (rise) increases with decreasing average pore size.

One interesting observation to note is the peaks of the degree of hysteresis. The peak values seem to correspond to the AEV of each specimen for both LAT and CDG except LAT-0 and LAT-40. Although this may be a coincidence, a similar observation can be made for an intact loess specimen tested under 0 kPa net stress by Ng *et al.* (2016). However, more data on other soils are required to be able to make any conclusion about this observation.

At the end of the tests, the wetting curves for all three soils return only to positions lower than their original positions. The relative positions of the wetting and drying curves at the end of the test defines the occluded (entrapped) air bubbles. The air-occluded bubbles were taken as the difference between the volumetric water content at 0.1 kPa suction at the beginning drying and at the end of wetting. In Figure 5(a), it is interesting to observe that unlike CDV (Figure 5(b)) and CDG (Figure 5(c)), the air-occluded bubbles is independent of an increase in net stress for the LAT.

Stress effects on the degree of hysteresis

To investigate the effects of stress on hysteresis associated with the SWRC in a systematic manner, the size of the hysteresis loop was calculated from the area enclosed by the drying and wetting curves. This was achieved by using the 8.5 version of the "*Origin Pro software*", and considering the enclosed area as a polygon. Figure 8 illustrates the size of the hysteresis loop against stress for the three soil studied. For the LAT, firstly, the size of hysteresis increases sharply when net stress was increased to 40 kPa. The sharp increase is then followed by a gradual decrease, as net stress is increased to 80 kPa, and then begins to increase again at higher stress levels. The observed trend of the size of the hysteresis loop is consistent with the rate of absorption estimated (see Table 4). It can thus be concluded that the SWRC of LAT is dependent on the compaction-induced state, void ratio after compression and the associated PSD. To better explain and compare the effects of stress on the size hysteresis loop for the LAT and the CDV, the size of the hysteresis loop against net stress is illustrated in Figure 8. Figure 8 shows that the size of the hysteresis loop for the CDV (solid diamond) continuously decreases with an increase in net stress. However, no unique relationship is observed between the level of net stress and the size of the hysteresis loop for the LAT (Figure 6 (a)). One possible reason could be the significant change in soil structure due to rearrangement and subsequent shrinkage in the LAT than in the CVD. Thus, as stress is increased, the average pore size decreases and the size of the loop closes. The extent of the rearrangement is also affected by the side of proctor OMC at which the specimens were compacted. The simple conclusion is that hydraulic hysteresis is more pronounced in the LAT and CDG than the CDV, except for zero net stress condition where the size of the loop is larger for the CDV than both the LAT and the CDG. These observations also support the claim of larger pore size effects on the rate of desorption. In Fig 8, it is also interesting to see that the size of the loop converges as net stress increased to 80 kPa for the LAT and CDV.

Comparing to the LAT, the decrease in the size of the hysteresis loop begins when net stress is increased from 0 to 53 kPa for the CDG (Figure 8). For the LAT, however, this phenomenon happened when the net stress was increased above 40 kPa. Thus, the hysteresis loop of both LAT and CDG show a tendency to increase with an increase in stress. This implies that the high content and the state of the sesquioxides in the LAT cause high aggregation of the fine particles. As a result, the LAT shows many features of a granular soil (i.e. low AEV, high desorption rate, large hysteresis loop). A similar observation was made by (Miguel & Vilar, 2009). This unique feature associated with the granular and fine material is discussed extensively elsewhere (Ng & Menzies, 2014).

To sum up, the decrease in the size of the hysteresis loop with net stress for LAT and CDG shows a trend that is contrary to that of the CDV. Moreover, the size of the hysteresis loop does not necessarily reduce with an increase in net stress as commonly reported in the literature (Ng & Menzies, 2014). The simple conclusion is that particle size distribution cannot be used to predict the SWRC of weathered soils.

Microstructural Analysis for LAT, CDV and CDG

Understanding the pore structure is essential to relate the water retention behaviour to soil deformation (Zhou & Ng, 2014). Samples of the three soils prepared at the same water contents corresponding to their WRC specimens were examined at different levels of magnification as shown in Figure 9. From Figure 9(a), at a magnification of 1000 times, a highly aggregated soil mass can be seen in the LAT. For the CDV, aggregates with dimensions of 39 x 29 µm (Figure 9(b)) are observed. Regarding the CDG, some granular particles can be identified (Figure 9(c)). However, on further magnification to 5, 000 times, aggregates with dimensions of 26 x 10µm with large-size inter-aggregate voids are seen in LAT (Figure 9(d)). A clear plate-like clay matrix with relatively uniform inter-aggregate voids is seen in the CDV (Figure 9(e)). In the case of the CDG, a close look reveals a higher number of non-aggregated granular particles (Fig. 9(f)) as compared to both LAT and CDV. The insignificant difference between the particles size distribution for dry and wet sieve analysis for the CDG (see Figure 1) justifies this observation. CDG, therefore, does not show any particle aggregation. A similar conclusion was reached by Lee & Coop (1995).

For fine grains soils such as CDV, the particles are essentially plate-like in shape, for example, see Figure 9(e), therefore, contacts may be edge-edge (EE), edge-face (EF), or face-face (FF) (Zhang *et al.*, 2014) in the natural state. A flocculated or dispersed particles rearrangement with a preferred orientation will thus result when the soil is compacted on either dry or wet of OMC respectively (Lambe, 1958). The flocculated and dispersed particle arrangements essentially refer to an open (i.e. EE and EF on the dry side) and close-packed (i.e. FF on the wet side) structure (Sides & Barden, 1970) respectively. This implies that the aggregates observed for CDV from the SEM image (Figure 9(e)) are primarily associated with the dispersed structure since the specimens were compacted at the wet of OMC.

It can be seen that different forms of aggregation exist in LAT and CDV though both showed a drastic change in particle size distribution on wet sieve. This is mainly because of the different contents and the state of sesquioxides found in these soils. The XRF results showed a lower sesquioxides content with corresponding higher silica content for CDV and CDG. The factors controlling the content and state are majorly climatic conditions and topographic relief under which these soils were formed (Sunil & Krishnappa, 2012). This is mainly because of the inadequate leaching in Hong Kong due to highly undulating topography, as a result, the sesquioxides exist in the combined state (e.g. aluminosilicate) (see

XRD results). Moreover, a lower degree of petrification was measured for the CDV. Further discussion on the state of sesquioxides, which is defined by the degree of petrification (Nascimento *et al*., 1964), is provided in a later section. Consequently, the influence of aggregation on water retention behaviour is less noticeable for the CDV and CDG. Rahardjo *et al*. (2004), pointed out that the variations in climatic and environmental conditions influencing the formation and constituent mineralogy of its locality, the characteristics of residual soils vary from region to region even in the compacted state.

To assess the influence of leaching on porosity, the total pore volume per a given dry mass of soil sample measured using the BET method for LAT, CDV and CDG are indicated in Table 2. The data shows that LAT contains higher total pore volume for the same mass of soil sieved through a 63μm sieve than CDV and CDG. As mentioned, the XRD result showed significant content of goethite mineral in the LAT. Studies by Airey *et al*. (2012), showed that lateritic soils, which contains a significant proportion of the mineral goethite (nano in size), form aggregations (size of 10s to 100s of microns). Hence, contains large-structure-supported voids. In addition, studies on the de-aggregation of aggregated goethite have also shown that these aggregates are stable at neutral pH conditions. As a result, the aggregates can only be de-aggregated to the macro-scale and very high-energy input is required to reach the Nano-scale (Blakey & James, 2003; Ding & Pacek, 2008). This implies that the goethite mineral is able to provide some additional strength to the aggregated particles in the LAT.

Therefore, although the LAT was compacted to a very dense state, the higher initial suction during compaction and the additional strength from the goethite mineral preserved the relatively large aggregate particles. Toll, (1999) observed that higher initial suction is able to provide support to the aggregated particles and thus prevents them from being remoulded.

The data for the specific surface area per given dry mass measured using the BET surface area analyser is indicated in Table 2. The specific surface area for the LAT is about 1.4 and 19 times larger than the CDV and CDG respectively. Khorshidi *et al*., (2002), has reported a direct relationship between SWRC and specific surface area at suction values greater than the residual suction. This implies that although the range of suction considered in this study is lower than residual suction (1500 kPa) (Vanapalli *et al*., 1999) if all three soils are prepared to an identical state, the LAT may probably demonstrate higher water retention ability at suction levels above the residual suction.

Effects of the state of sesquioxides on particles aggregation for the soils studied.

The role of sesquioxides in the formation of micro-aggregates in weathered (e.g. laterites/lateritic) soils are generally ascribed to one or all of the followings: (a) Cementation due to precipitation of hydrated iron or aluminium gels and subsequent irreversible dehydration of these materials (Townsend *et al*., 1971). (b) The presence of iron in solution, inhibiting de flocculation (Nanda & Krishnamachari, 1958). (c) The formation of organic mineral compounds of humic acids with free sesquioxides (McIntyre, 1956). Therefore, the state in which these sesquioxides exist in a soil sample during their testing is very important. Grant & Aitchison, (1970) have emphasised the need to recognise the difference between materials in which all the iron had been dehydrated to the ferric state and those in which some of the iron is still in the hydrated condition. The material in the former is inert, whereas in the latter the material has the potential of self-stabilisation and thus need to be treated as such.

In this study, a method proposed by Nascimento et al. (1964) that can determine the degree of potential self-stabilisation (aggregation) was adopted and utilised. In this method, a part of soil pre-dried at 60°C is placed on saturated porous plates immersed in water with the upper surface at the level with the water. After 24hrs, the water content of the soil sample is determined and is identified as the absorption limit. The so-called degree of petrification (Dp) is determined as a ratio of shrinkage limit to the absorption limit. As this value increases so does the self-stabilisation, especially in the surface layers of a soil profile where drying is more marked. In addition, improved behaviour is to be expected with successive drying period (Nascimento et al., 1964). The Dp values are summarised in Table 2. The values determined for the LAT and CDV are 414% and 370% respectively. The shrinkage limits of the soils were estimated from chat proposed by Sridharan et al. (1988). These values indicate that LAT has a higher aggregation potential than CDV and thus justifies the microstructure shown by the SEM images. This parameter, however, could not be determined for CDG as it is non-plastic material even though it has the same parent rock as the LAT used in this study. This again emphasises the effects of the factors stated above on content and state of sesquioxides and its influence on the geotechnical properties of these soils under study. CDG, therefore, does not show any potential of self-stabilization and as such, any form of particles bonding is because of electrostatic force as suggested by Lee & Coop (1995). This statement is buttressed by the insignificant difference between the dry and wet particle size distribution of CDG (Figure 1). From Table 2, it can be seen that there is a direct relationship between, sesquioxides content, Dp, Specific Surface Area, and total pore volume.

Effects of aggregates response to compression on SDSWRCs

The evolution of AEV under different loading conditions can be related directly to the changes in average pore size and pore geometry due to an increase in net stress. Generally, all the specimens for all three soils at net stresses higher than zero experienced a significant change in the void ratio due to compression (see Figure 6). Hence, changes in PSD and AEV with an increase in net stress was thus expected as commonly reported (Ng & Pang, 2000; Ng et al., 2016). On the contrary, specimen LAT-0 shows a higher AEV than specimen LAT-40 while that of CDG-0 and CDG-53 are similar. In addition, LAT-80 and LAT-120 show similar AEV. The following is an attempt to provide a better explanation for the inconsistencies in the water retention behaviour observed.

The Pre-consolidation pressure (Pc) estimated for each soil from the isotropic compression test on compacted specimens is indicated in Table 3. The Pc values estimated for each soil is 80 kPa, 20 kPa and 100 kPa for LAT, CDV and CDG respectively. The value of the Pc may be taken as yield stress that acts as a boundary between the elastic and plastic zone of the yield surface (Chiu & Ng, 2003). Using this approach, the initial state of the specimens that were compressed before the SWRC measurement can be identified. Additionally, the coefficient of compressibility (λ) of the soils is also presented in Table 3. The Pc and λ values used herein are the same as those published in recent work by Ng et al. (2019).

For the LAT specimen, the specimen at net stresses of 40, 80 and 120 kPa lies inside the elastic zone, on the yield surface, and inside plastic zone respectively. In the case of the CDV, the initial state of the specimens at the net stresses of 40 and 80 kPa lies inside the plastic zone, while the 53 and 80 kPa place the initial state of the CDG samples in the elastic zone. This suggests that the aggregates in LAT-40 specimen experienced elastic response which is primarily particle rearrangement rather than plastic deformation.

This implies that for the LAT-40 the compaction-induced state experienced less distortion in comparison with specimens at 80 and 120 stresses. Hence, the specimen possessed relatively large inter-aggregate voids with the compaction-induced PSD still maintained. For the LAT-80 and LAT-120, the positions of their initial states suggest that the compaction-induced state experienced higher distortion. This thus led to a significant smaller contact and causes more pore of larger size to result.

In a coupled hydromechanical study on the behaviour of unsaturated compacted clay, Tombolato & Tarantino, 2005, showed that the water retention ability expressed in terms of water ratio of soil increases with decreasing the void ratio. Contrary to Tombolato & Tarantino, 2005, an increase in net stress even up to 120 kPa still resulted in water retention curve lying below that of the specimen under zero net stress for the LAT (Figure 5(a)) as suction was increased. The fact that specimens of LAT at higher stress level retained less water implies that the connecting passageways between voids were rather more connected, though void ratio reduced (Figure 6(a)). The higher connectivity of the resulted large pores thus caused a higher desorption rate with an increase in suction, which is contrary to Wheeler et al. (2003).

The LAT studied contains about 42% clay (see Table 1); however, due to aggregation caused by the sesquioxides, the specimen shows an “apparent” granular behaviour in the unsaturated state. Despite this apparent granular behaviour, the SWRC of the LAT is still different from that of CDG, which is actually a granular material. The difference is possibly as a result of distortion (change in shape) of the saturated aggregates after rearrangement during compression at stress levels greater than the Pc value for the LAT. This is because for deformable soils the remoulding of the aggregates marks Pc (Chandler, 1985). It should be noted that the increase in suction (during the drying process) could enable the “apparent” granular behaviour to be maintained by LAT (Nascimento et al., 1964). However, for the 1D condition, there seems to be a limited rearrangement caused by loading. This is mainly because of the lateral restraint by the oedometer ring imposing a limit to the extent of rearrangement (Mesri & Vardhanabhuti, 2009). Hence, the similar SWRCs for specimens LAT-80 and LAT-120 on the drying path. Nevertheless, the LAT-80 retains more water than LAT-120 on the wetting path. This is because of the higher shrinkage experience by the LAT-80 than LAT-120 during the drying process (see Figure 6(a)). This shrinkage caused by an increase in suction further reduced the inter-aggregate pores and thus increased the capillary rise in ALT-80 than LAT-120 during the wetting process. This implies that suction-induced shrinkage is dependent on the void ratio prior to the drying-wetting process and extent to which the compaction-induced state is distorted.

Similarly, CDV also contains about 37% clay (see Table. 1), however, unlike LAT, the aggregates caused by the sesquioxides are very delicate even in the unsaturated state (Chiu, 2001). To avoid the breakdown of the delicate aggregates in CDV before testing, Chiu (2001), in determining the NCL, prepared the soil by the falling method and compacted the sample used to 70% of Proctor maximum. Compacting at such relatively low density helped reduce the extent of aggregates remoulding. By using this approach, a P_c of 20 kPa was measured for CDV (Chiu, 2001). The state of the sesquioxides in CDV has resulted in clay particles that are plate-like in shape as observed in the SEM images. Wang & Siu, (2006) observed that when the EF (open structure) association dominates, the samples possess larger void ratios and shows higher compressibility, which is associated with the inter-aggregate pores. On the other hand, denser specimens with lower compressibility due to stronger double-layer repulsion were observed when the FF alignment prevails. The strain response never becomes isotropic, even when it is subjected to higher confinements.

It should be noted that the CDV specimens used by Ng & Pang (2000) in measuring the SWRCs were compacted to 92% of *R.C.* at wet of OMC and this seems to have caused particles anisotropy (i.e. dispersed structure due to FF orientation). Sivakumar & Wheeler, (2000) suggested that one-dimensional compaction inevitably generates a degree of anisotropy in a soil sample in fine soils (stress-induced anisotropy). This implies that compaction could have dragged the NCL line of the CDV to a higher stress level with a corresponding increase in P_c value. Hence, the stress range (0, 40 & 80 kPa) considered in the study was smaller than of the newly created P_c. Therefore, the application of stress could only cause a reduction in average pore size with a resulting consequence on SWRCs as reported (Ng & Pang, 2000). The reduction in average pore size, due to an increase in net stress, thus causes an increase in AEV and reduces permeability (Ng & Pang, 2000). The effects of particle anisotropy on the permeability of soils have been reported (Stewart *et al*., 2006). This accounts for why the smallest degree of hysteresis (Figure 7(b)) is associated with the drying-wetting process (Figure 5(b)) for the CDV. It also explains the negligible variation in void ratio with suction (Figure 6(b)).

CDG is known to be granular material, and the intrinsic property of the soil to maintain the property of parent rock thus confers on it a higher P_c yield stress (Lee & Coop, 1995). The stress levels (0, 53 and 80) considered by Tse (2007) were, therefore, lower than the P_c and hence could not cause grains crushing. Mesri & Vardhanabhuti (2009b) studied the compression (i.e. both 1D and iso-comp) data for over 100 sands and explained that the particle crushing is clearly marked when net stress exceeds the P_c. This implies that unlike the LAT in which the aggregates could be distorted, the granular particles in CDG were preserved even at 80 kPa net stress since the stress level considered is lower than the P_c of the soil (see Tables 2). However, the coefficient of compressibility suggested that the soil is more compressible than LAT and CDV. Hence, rearrangement and compression of pores between particles is the most likely mechanism controlling the water retention behaviour of the CDG. This explains the AEV values measured for CDG (Table 4) and thus the increase in SDSWRCs is due to the reduction of average pore size.

Conclusions

The SDSWRCs of recompacted LAT at different stress levels were measured and compared them with published SDSWRCs of two other weathered soils (i.e., CDV and CDG). The three soils studied contain varying contents of sesquioxides. The contents of sesquioxides were found to be 38%, 27% and 19% in LAT, CDV and CDG, respectively. Based on the stress conditions and the range of suctions considered, the following conclusions may be drawn:

1. At a given suction, the compacted LAT was observed to show lower water retention ability than CDV and CDG, although the latter two soils had a higher initial void ratio than that of LAT. This is mainly because the LAT samples contained larger aggregated particles. The larger inter-aggregate voids for the LAT samples were revealed by SEM images. As a result, the samples exhibited a higher rate of desorption with an increase in suction and thus loses water easily.

2. The LAT specimen at zero net stress had a slightly higher AEV than specimen at 40 kPa net stress, while it remains constant at stress levels higher than 40 kPa. In contrast, CDV and CDG showed an increase in SWR ability with an increase in stress. For the CDV, a monotonic increase in AEV with an increase in net stress was observed. For the CDG, the AEV only increases slightly to a constant value with an increase in stress.
3. There is a marked hysteresis within the range of suctions considered between the drying and wetting curves for all soil specimens tested. In addition, the degree of hysteresis is more significant around suction of 2.5 kPa for both LAT and CDG and between 10 to 100 kPa for the CDV. Generally, the size of the loop increase with an increase in net stress for the LAT and CDG. However, some differences between them can be found. The size of the loop of CDG first decreases, and then increase with net stress. For the LAT, a decrease in the size of the loop was observed when net stress was increased to 80 kPa, but it increased at higher net stress than 80 kPa. This is probably because of the significant rearrangement and higher compression of inter-aggregate (or inter-grains) pores as the higher net stress is applied. For the CDV, the hysteresis loop size decreased with an increase in net stress, which is probably due to a reduction in the average pore size.
4. Due to aggregation caused by the high content of sesquioxides in LAT, the “apparent” particle size distribution of it cannot be used to predict SWRC. Hence, it is recommended that SDSWRCs with a consideration of pore size distribution should more appropriate for investigating unsaturated lateritic soils.

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References

Agus, S. S., Leong, E. C., & Rahardjo, H. (2001). Soil-water characteristic curves of Singapore residual soils. In Unsaturated soil, concepts and their application in geotechnical practice (pp. 285-309). Springer, Dordrecht.

Airey, D., Suchowerska, A., & Williams, D. (2012). Limonite–a weathered residual soil heterogeneous at all scales. Géotechnique Letters, 2, (7-9), 119-122.

ASTM, D. (2011). 2487 (2006) Standard practice for classification of soils for engineering purposes (Unified Soil Classification System). Book of Standards, 4(08).

Blakey, B. C., & James, D. F. (2003). Characterizing the rheology of laterite slurries.

International journal of mineral processing, 70, (1-4), 23-39.

Burton, G. J., Sheng, D., & Campbell, C. (2014). Bimodal pore size distribution of a high plasticity compacted clay. Géotechnique Letters, 4, 2, 88-93.

Chiu, C. F. (2001). Behaviour of unsaturated loosely compacted weathered materials. PhD thesis, Hong Kong University of Science and Technology, Hong Kong.

Delage, P., Tessier, D., & Marcel-Audiguier, M. (1982). Use of the Cryoscan apparatus for observation of freeze-fractured planes of a sensitive Quebec clay in scanning electron microscopy. Canadian Geotechnical Journal, 19(1), 111-114.

Ding, P., & Pacek, A. W. (2008). De-agglomeration of goethite nano-particles using ultrasonic comminution device. Powder Technology, 187, 1, 1-10.

FAO (1989) Soil map of the world. ISRIC, Wageningem. 138 p. (FAO.UNESCO Technical

Paper, 20)

Futai, M. M., & Almeida, M. S. S. (2005). An experimental investigation of the mechanical behaviour of an unsaturated gneiss residual soil. Géotechnique, 55(3), 201-214.

Gallipoli, D., Wheeler, S. J., & Karstunen, M. (2003). Modelling the variation of degree of saturation in a deformable unsaturated soil. Géotechnique, 53, 1, 105-112.

Gidigasu, M. D. (1974). Degree of weathering in the identification of laterite materials for engineering purposes—a review. Engineering Geology, 8, 3, 213-266.

Grant, K., & Aitchison, G. D. (1970). The engineering significance of silcretes and ferricretes in Australia. Engineering Geology, 4, 2, 93–120.

Khorshidi, M., ASCE, S. M., Lu, N., ASCE, F., Akin, I. D., ASCE, S. M., ASCE, M. (2002).

Intrinsic Relationship between Specific Surface Area and Soil Water Retention, 143, 1, 1–10.

Koliji, A., Vulliet, L., & Laloui, L. (2010). Structural characterization of unsaturated

aggregated soil. Canadian Geotechnical Journal, 47, (3), 297–311.

Lambe, T. W. (1958). The structure of compacted clay. Journal of the Soil Mechanics and Foundations Division, 84, 2, 1-34.

Lee, I. K., & Coop, M. R. (1995). The intrinsic behaviour of a decomposed granite soil. Géotechnique, 45, 1, 117-130.

Lu, N., & Khorshidi, M. (2015). Mechanisms for Soil-Water Retention and Hysteresis at High

Suction Range. Journal of Geotechnical and Geoenvironmental Engineering, 141, (8), 04015032.

Lu, N., & Likos, W. J. (2006). Suction Stress Characteristic Curve for Unsaturated Soil. Journal of Geotechnical and Geoenvironmental Engineering, 132, 2, 131–142.

Mesri, G., & Vardhanabhuti, B. (2009). Compression of granular materials. Canadian

Geotechnical Journal, 46, 4, 369-392.

McIntyre, D. S. (1956). The effect of free ferric oxide on the structure of some Terra Rossa and

Rendzina soils. European Journal of Soil Science, 7, 2, 302–306.

Merchán, V., Romero, E., & Vaunat, J. (2011). An adapted ring shear apparatus for testing partly saturated soils in the high suction range. Geotechnical Testing Journal, 34, 5, 433–444.

Monroy, R., Zdravkovic, L., & Ridley, A. (2010). Evolution of microstructure in compacted London Clay during wetting and loading. Géotechnique, 60, 2, 105–119.

Muñoz-Castelblanco, J. A., Pereira, J. M., Delage, P., & Cui, Y. J. (2012). The water retention properties of a natural unsaturated loess from northern France. Géotechnique, 62, 2, 95– 106.

Miguel, M. G., & Vilar, O. M. (2009). Study of the water retention properties of a tropical soil. Canadian Geotechnical Journal, 46, 9, 1084-1092.

Nanda, R. L., & Krishnamachari, R. (1958). Study of soft aggregates from different parts of India with a view to their use in road construction, II. Laterites. Central Road Res. Inst., Road Res. Pap., 15, (32).

Nascimento, U. (1964). Swelling and petrifaction of lateritic soils.

Ng, C. W. W., Chen, Z. K., Coo, J. L., Chen, R., & Zhou, C. (2015). Gas breakthrough and emission through unsaturated compacted clay in landfill final cover. Waste management, 44, 155-163.

Ng, C. W., & Chiu, A. C. (2003). Laboratory study of loose saturated and unsaturated decomposed granitic soil. Journal of Geotechnical and Geoenvironmental Engineering, 129, 6, 550-559.

Ng, C. W. W., & Menzies, B. (2014). Advanced unsaturated soil mechanics and engineering. CRC Press.

Ng, C. W. W., Mu, Q. Y., & Zhou, C. (2018). Effects of specimen preparation method on the volume change of clay under cyclic thermal loads. Géotechnique, 69(2), 146-150.

Ng, C. W. W., & Pang, Y. W. (2000). Influence of stress state on soil-water characteristics and slope stability. Journal of geotechnical and geoenvironmental engineering, 126, 2, 157166.

Ng, C. W. W., Sadeghi, H., Hossen, S. B., Chiu, C. F., Alonso, E. E., & Baghbanrezvan, S. (2016). Water retention and volumetric characteristics of intact and re-compacted loess. Canadian Geotechnical Journal, 53, 8, 1258-1269.

Oh, S., & Lu, N. (2014). Uniqueness of the suction stress characteristic curve under different confining stress conditions. Vadose Zone Journal, 13(5).

Otálvaro, I. F., Neto, M. P. C., Delage, P., & Caicedo, B. (2016). Relationship between soil structure and water retention properties in a residual compacted soil. Engineering Geology, 205, 73-80.

Rahardjo, H., Aung, K. K., Leong, E. C., & Rezaur, R. B. (2004). Characteristics of residual soils in Singapore as formed by weathering. Engineering Geology, 73(1-2), 157-169.

Romero, E., Della Vecchia, G., & Jommi, C. (2011). An insight into the water retention properties of compacted clayey soils. Géotechnique, 61, 4, 313–328.

Salager, S., Nuth, M., Ferrari, A., & Laloui, L. (2013). Investigation into water retention behaviour of deformable soils. Canadian Geotechnical Journal, 50, 2, 200-208.

Sivakumar, V., Tan, W. C., Murray, E. J., & McKinley, J. D. (2006). Wetting, drying and compression characteristics of compacted clay. Géotechnique, 56, 1.

Sides, G., & Barden, L. (1971). The microstructure of dispersed and flocculated samples of kaolinite, illite, and montmorillonite. Canadian Geotechnical Journal, 8, 3, 391-399.

Sunil, B. M., & Krishnappa, H. (2012). Effect of drying on the index properties of lateritic soils. Geotechnical and Geological Engineering, 30, 4, 869-879.

Stewart, M. L., Ward, A. L., & Rector, D. R. (2006). A study of pore geometry effects on anisotropy in hydraulic permeability using the lattice-Boltzmann method. Advances in water resources, 29, 9, 1328-1340.

Tarantino, A. (2011). Unsaturated soils: Compacted versus reconstituted states. Edited by EE Alonso and A. Gens. CRC Press, Barcelona, Spain, 113-136.

Toll, D. G. (1990). A framework for unsaturated soil behaviour. Géotechnique, 40, 1, 31–44.

Tombolato, S., & Tarantino, A. (2005). Coupling of hydraulic and mechanical behaviour in unsaturated compacted clay. Géotechnique, 55, 4, 307–317.

Townsend, F. C., Manke, P. G., & Parcher, J. V. (1971). The influence of sesquioxides on lateritic soil properties. Highway Research Record, (374).

Tse, M. K. (2007). Influence of stress states on soil-water characteristics, conjunctive surface subsurface flow modelling and stability analysis. MPhil thesis, Hong Kong University of Science and Technology, Hong Kong.

Vanapalli, S. K., Fredlund, D. G., & Pufahl, D. E. (1996). The relationship between the soil-water characteristic curve and the unsaturated shear strength of a compacted glacial till. Geotechnical Testing Journal, 19, 3, 259-268.

Vanapalli, S. K., Fredlund, D. G., & D. E. Pufahl. (1999). The influence of soil structure and stress history on the soil-water characteristic of a compacted till. Geotechnique, 49, 2, 143– 159.

Wang, Y., & Siu, W. (2006). Structure characteristics and mechanical properties of kaolinite soils. II. Effects of structure on mechanical properties, 617, 601–617.

Webb, P. A., & Orr, C. (1997). Analytical methods in fine particle technology. Micromeritics Instrument Corp.

Wheeler, S. J., Sharma, R. S., & Buisson, M. S. R. (2003). Coupling of hydraulic hysteresis and stress-strain behaviour in unsaturated soils. Géotechnique, 53, 1, 41-54.

Zhang, X. W., Kong, L. W., & Li, J. (2014). An investigation of alterations in Zhanjiang clay properties due to atmospheric oxidation. Géotechnique, 64, 12, 1003–1009.

Zielinski, J. M., & Kettle, L. (2013). Physical characterization: surface area and porosity. London: Intertek.

Zhou, C., & Ng, C. W. W. (2014). A new and simple stress-dependent water retention model for unsaturated soil. Computers and Geotechnics, 62, 216–222.

Table 1: Basic properties of the soils studied

Index Properties	Soil type		
	LAT (this study)	CDV (Ng & Pang, 2000)	CDG (Tse, 2007)
Standard compaction Test			
Maximum dry density: Mg/m^3	1,696	1,603	1770
Optimum water content: %	20	22	16.1
Grains size distribution			
Gravel content: %	-	4.9	9
Sand content: %	42	36.6	90
Silt content: %	16	36.6	1
Clay content: %	42	37.1	0
Specific gravity	2.67	2.62	2.6
Atterberg limits			
Liquid limit: %	44	55.4	N.A.
Plastic limit: %	24	33.4	N.A.
Plasticity index: %	20	22	N.A
Soil classification based on USCS (ASTM, 2011)	Sandy lean clay (CL)	Sandy silt/clay (ML)	Poorly-graded sand (SP)

NB: LAT = Lateritic soil; CDV = Completely Decomposed Volcanic; CDG: Completely Decomposed Granite

Table 2: Secondary properties of the soils studied

Soil type	Sesquioxides content (%)	Degree of petrifaction (D_p) (%)	Specific surface area (m^2/g)	Total pore volume (mil/g)
LAT	38	414	35	0.13
CDV	27	370	20	0.09
CDG	19	N.A	2	0.01

NB: D_p could not be determine for CDG, because it is none-plastic.

Table 3: Test Program

Soil Type	Test ID	Net stress (kPa)	Target void ratio after compaction (e_i)	Void ratio prior to drying and wetting (e_c)	Degree of saturation (S_r)	Pre-consolidation pressure (kPa)	Coefficient of compressibility (λ) (Ng *at al.*, 2019)
LAT	LAT-0	0	0.670	0.670	1.00	80	0.07
	LAT-40	40		0.647	1.00		
	LAT-80	80		0.636	1.00		
	LAT-120	120		0.626	1.00		
CDV	CDV-0	0	0.782	0.782	--	20	0.09
	CDV-40	40		0.748	--		
	CDV-80	80		0.709	--		
CDG	CDG-0	0	0.718	0.718	--	100	0.11
	CDG-53	53		0.689	--		
	CDG-80	80		0.689	--		

Table 4: Estimated parameters from SDSWRC

Soil Type	Test ID	Net stress (kPa)	AEV (kPa)	Desorption rate (x 10^{-4}) (kPa^{-1})	Adsorption rate (x 10^{-4}) (kPa^{-1})	Estimated hysteresis loop size (kPa)
LAT	LAT-0	0	1.9	10	77	1.9
	LAT-40	40	1.0	155	50	4.6
	LAT-80	80	2.5	233	43	4.3
	LAT-120	120	2.5	319	47	5.1
CDV	CDV-0	0	1.2	14	9	6.0
	CDV-40	40	4.0	7	9	4.7
	CDV-80	80	5.0	7	5	4.4
CDG	CDG-0	0	1.2	433	70	2.3
	CDG-53	53	1.3	393	65	2.1
	CDG-80	80	1.3	186	22	3.5

NB: AEV = air-entry value

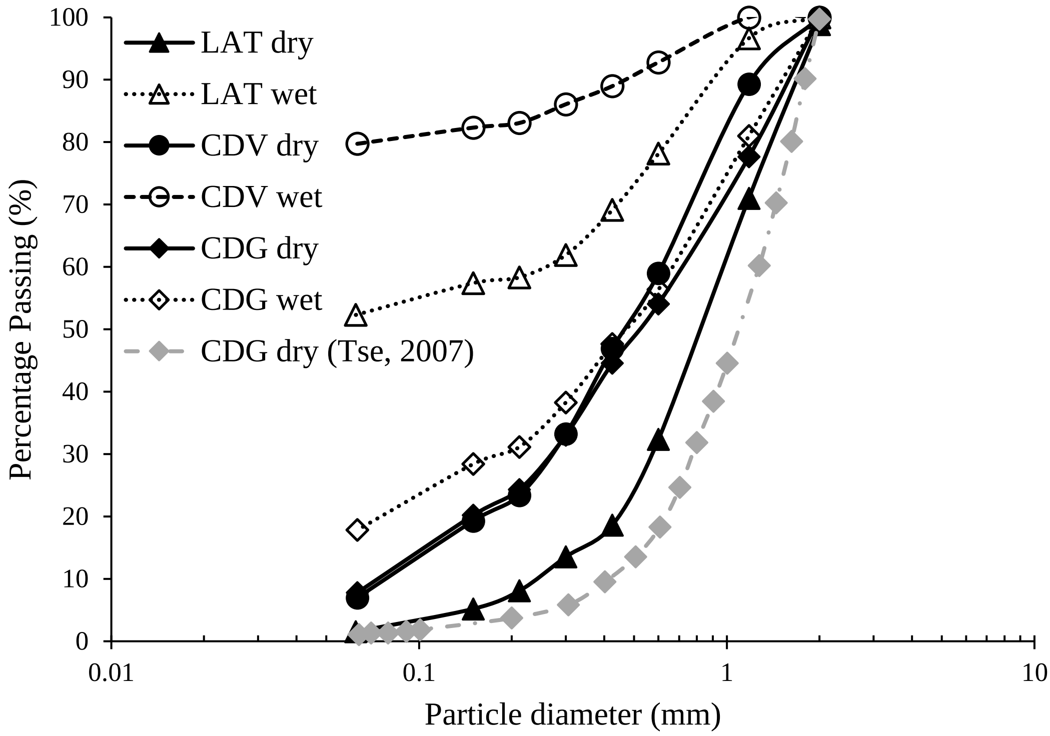

Figure 1: Particle size distribution of the soils studied.

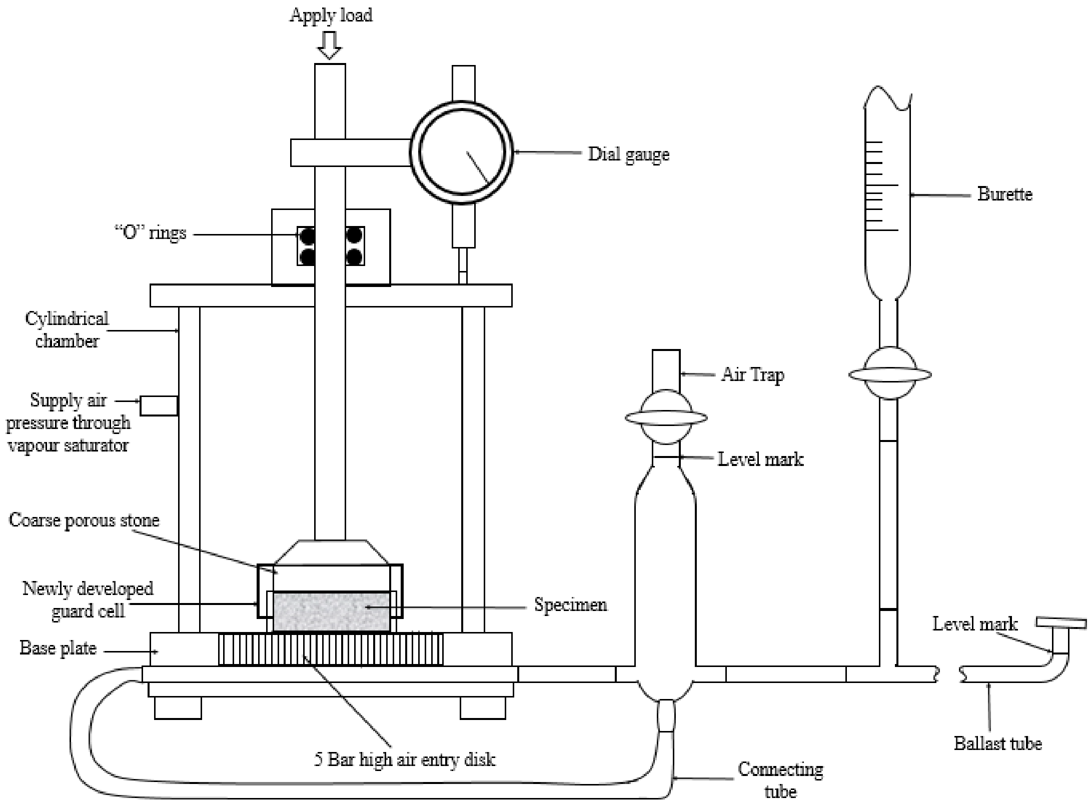

Figure 2: Schematic diagram of improved stress-controlled pressure plate apparatus (after Ng & Pang, 2000)

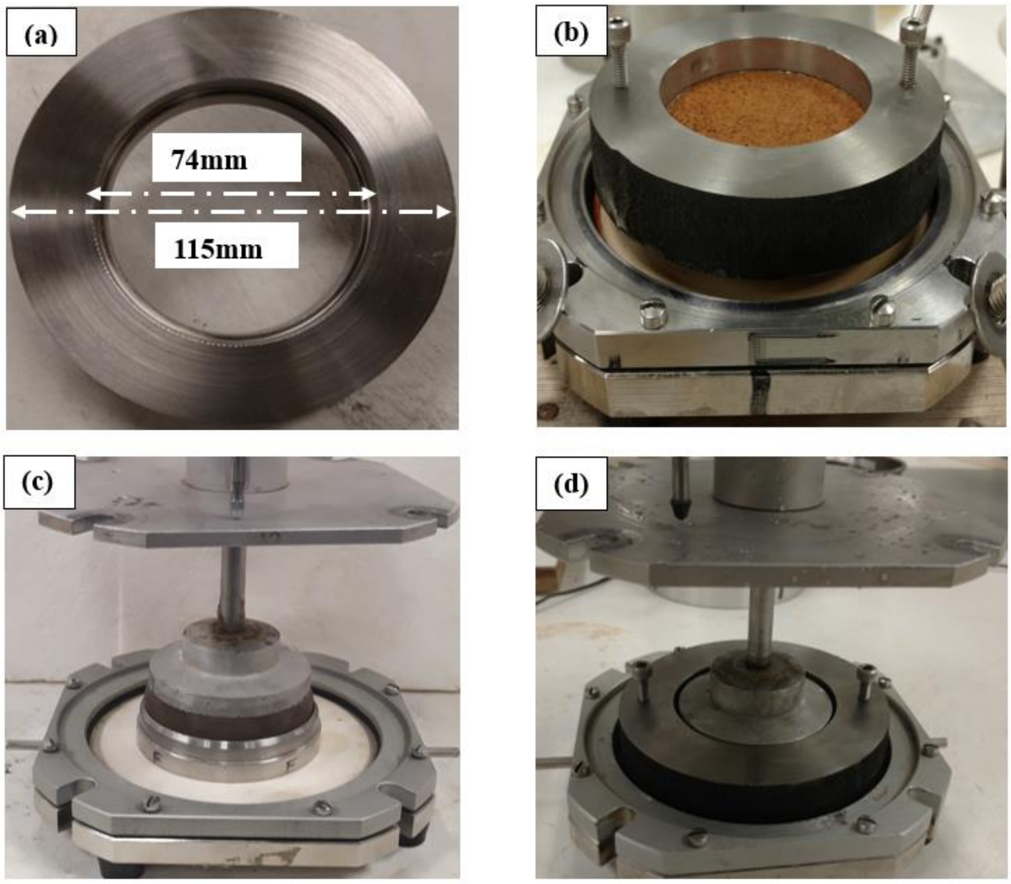

Figure 3: Guard cell developed to eliminate eccentric loading of specimen. (a) Newly fabricated guard cell; (b) Lateral view of mounted guard cell; (c) Configuration of specimen inside the setup without the guard cell; (d) Configuration of specimen inside the setup with the guard cell.

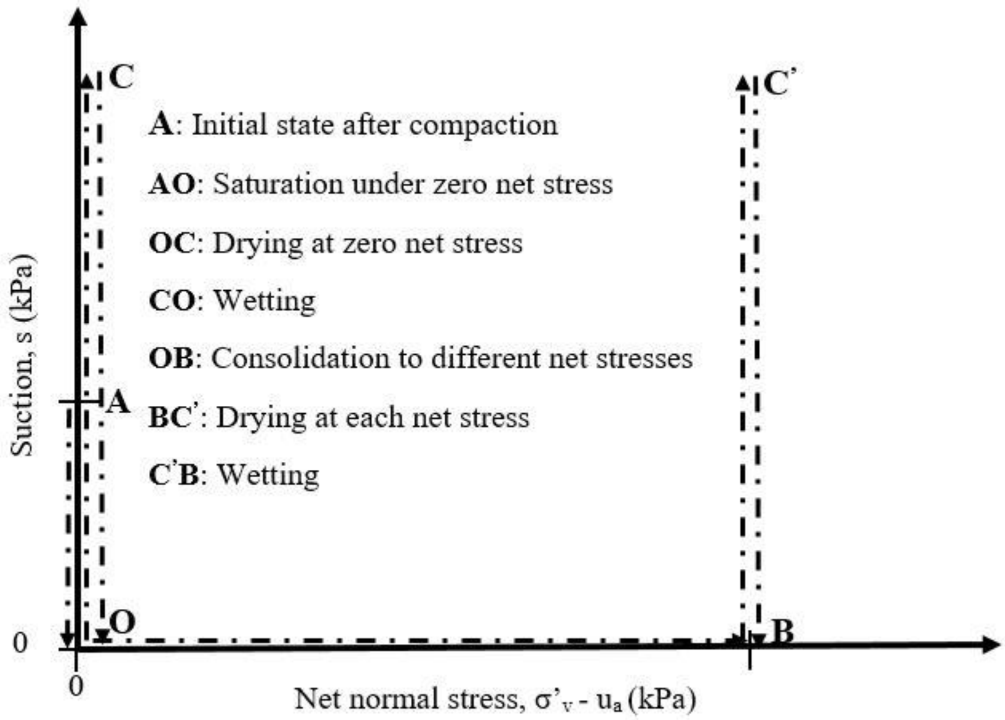

Figure 4: Stress paths for measuring drying - wetting water retention behaviour.

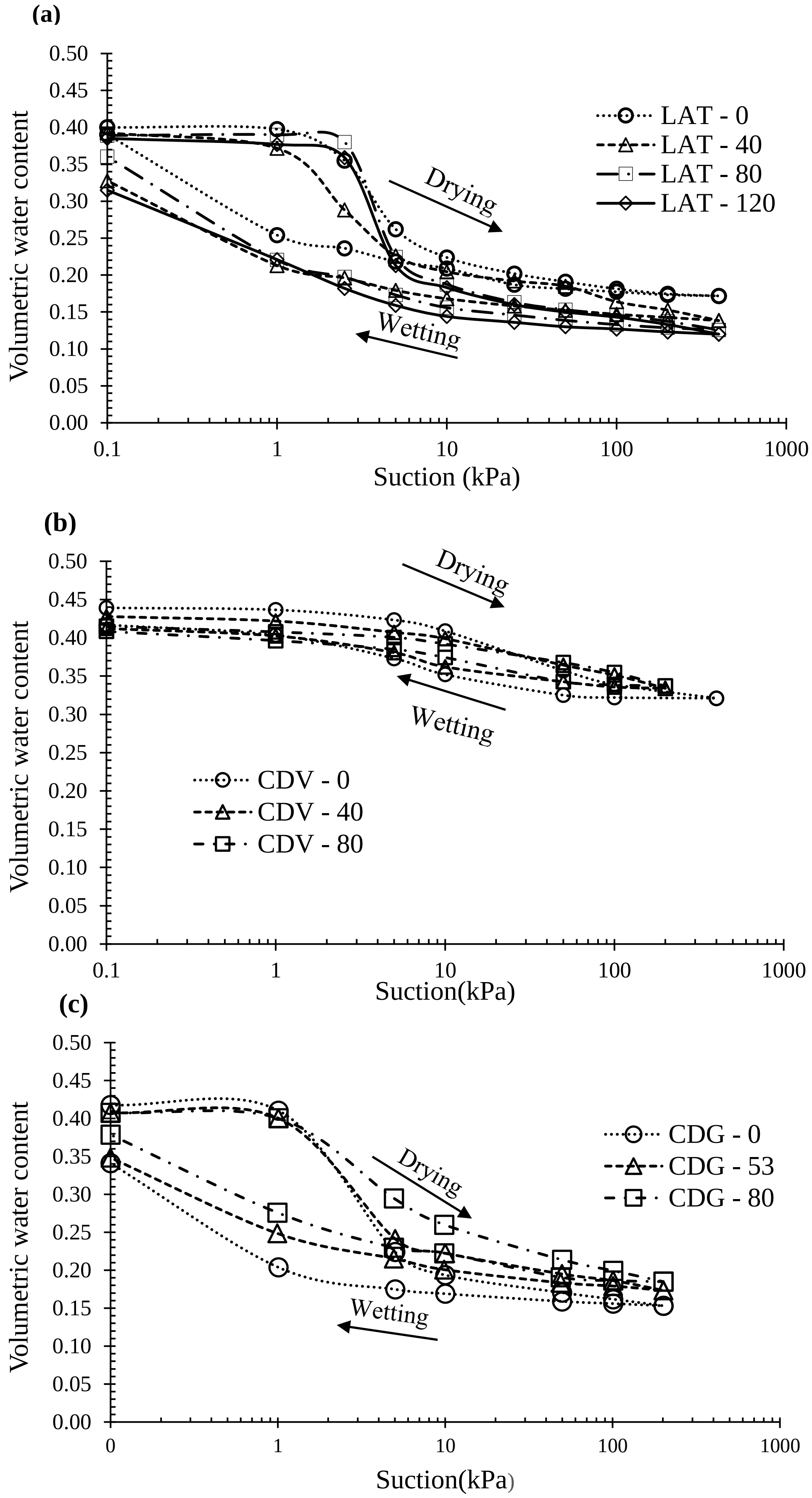

Figure 5: SDSWRC in terms of volumetric water content against suction under different net stresses; (a) for LAT; (b) for CDV; (c) for CDG.

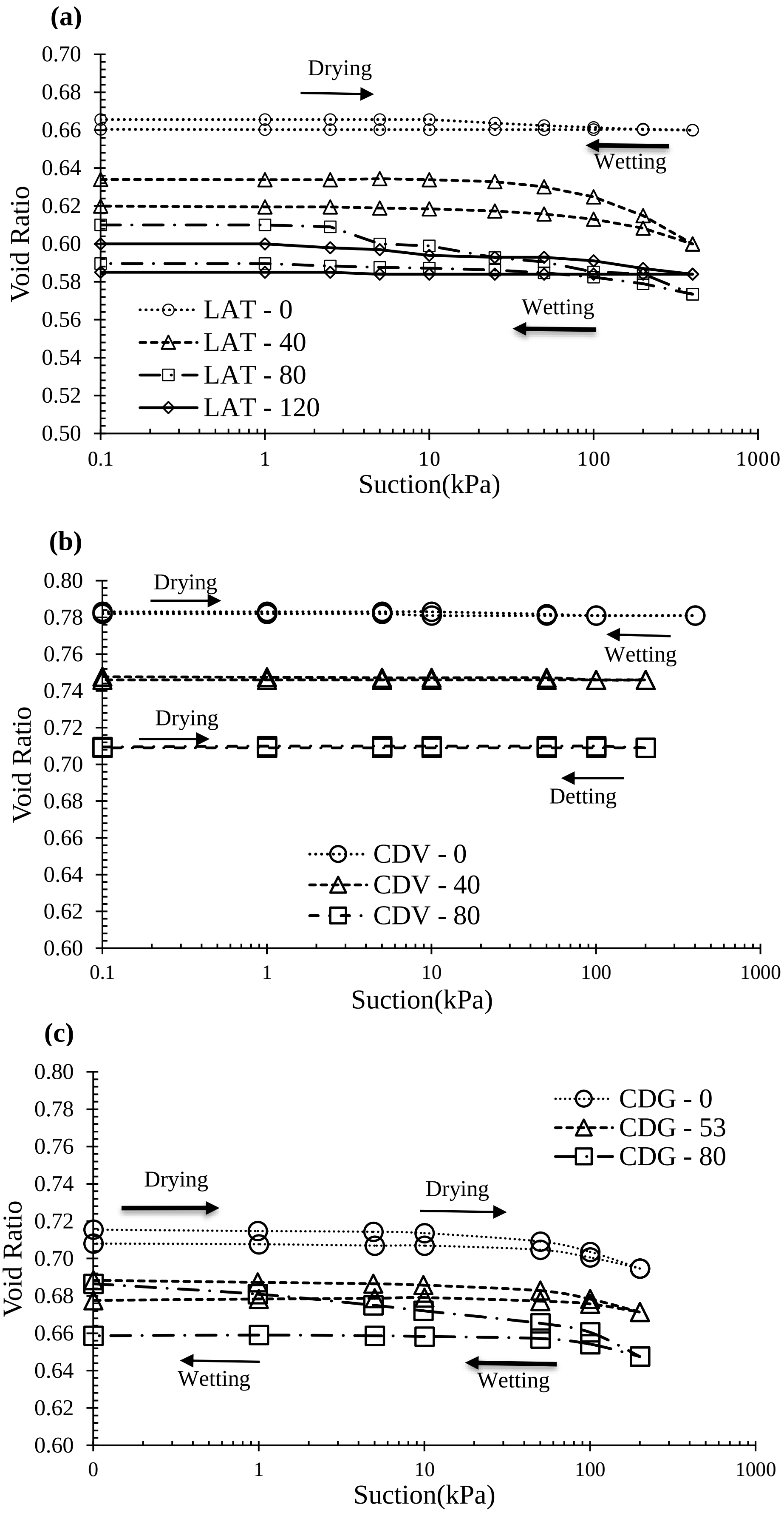

Figure 6: Variation of void ratio against suction; (a) for LAT; (b) for CDV; (c) for CDG.

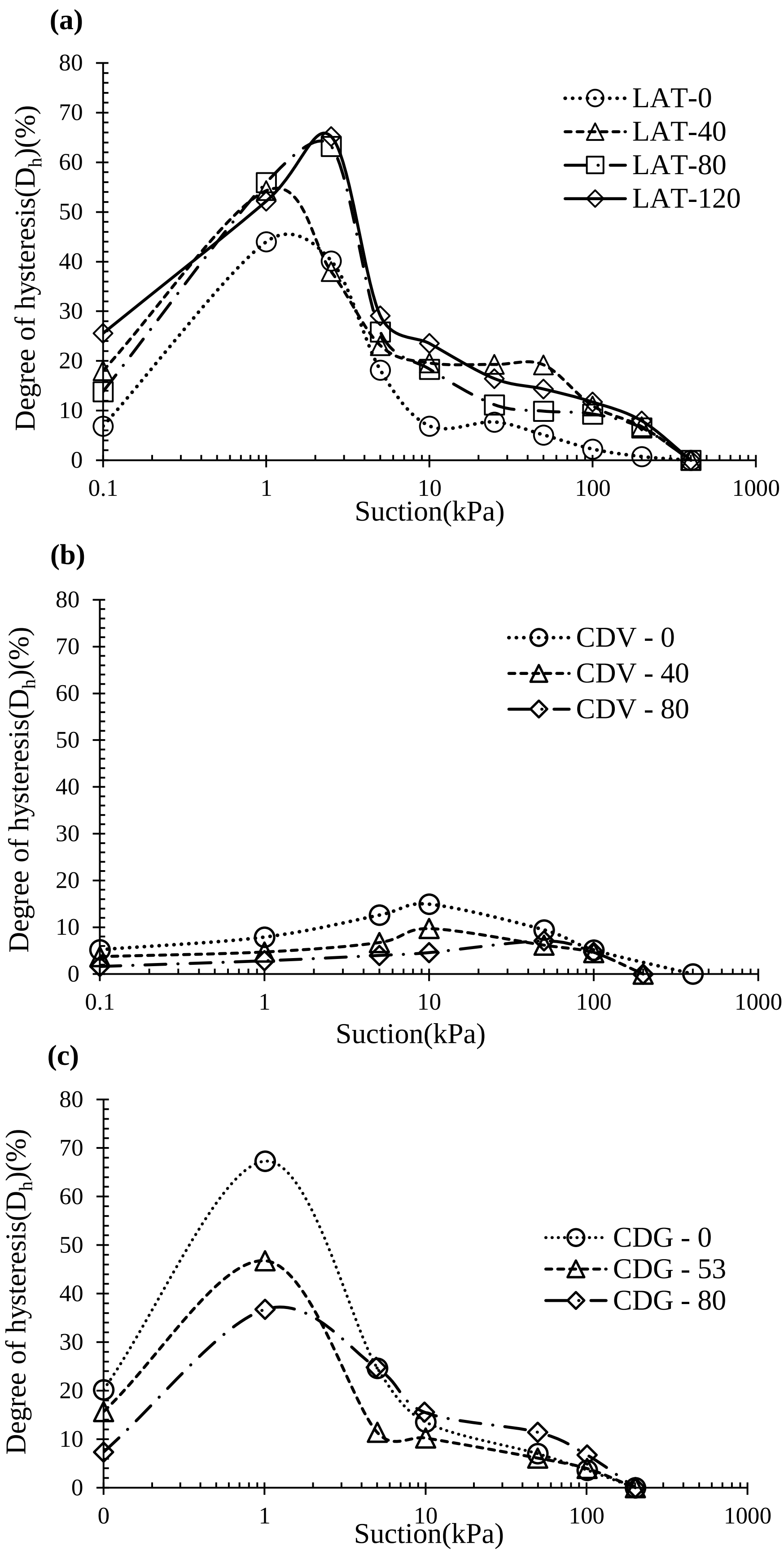

Figure 7: Degree of hysteresis against suction (a) for LAT; (b) for CDV; (c) for CDG, under different net stress.

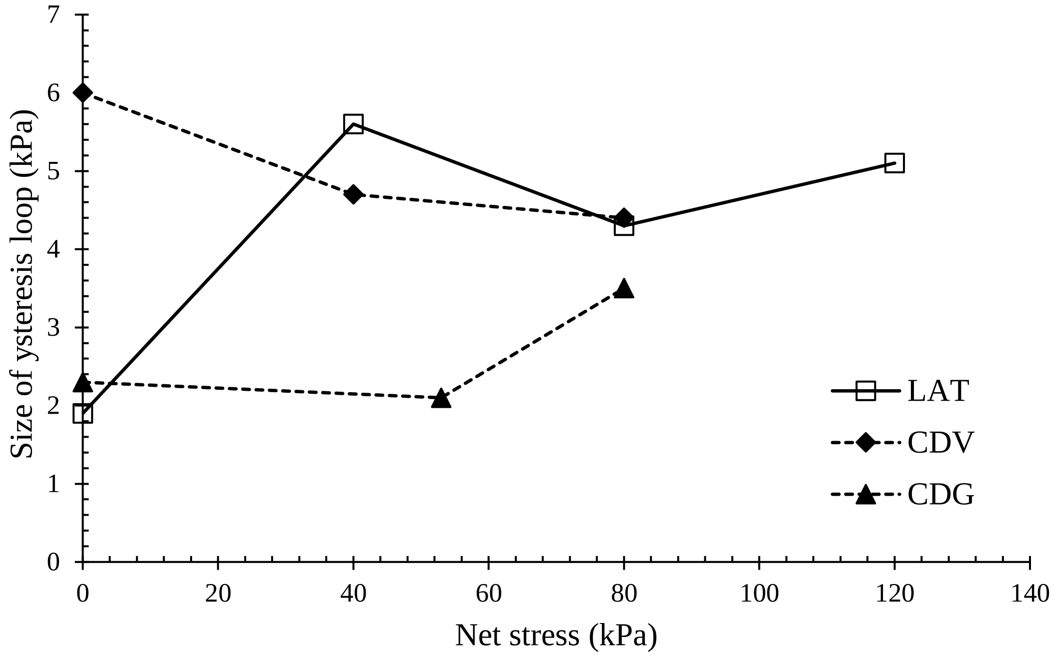

Figure 8: Estimated hysteresis loop size

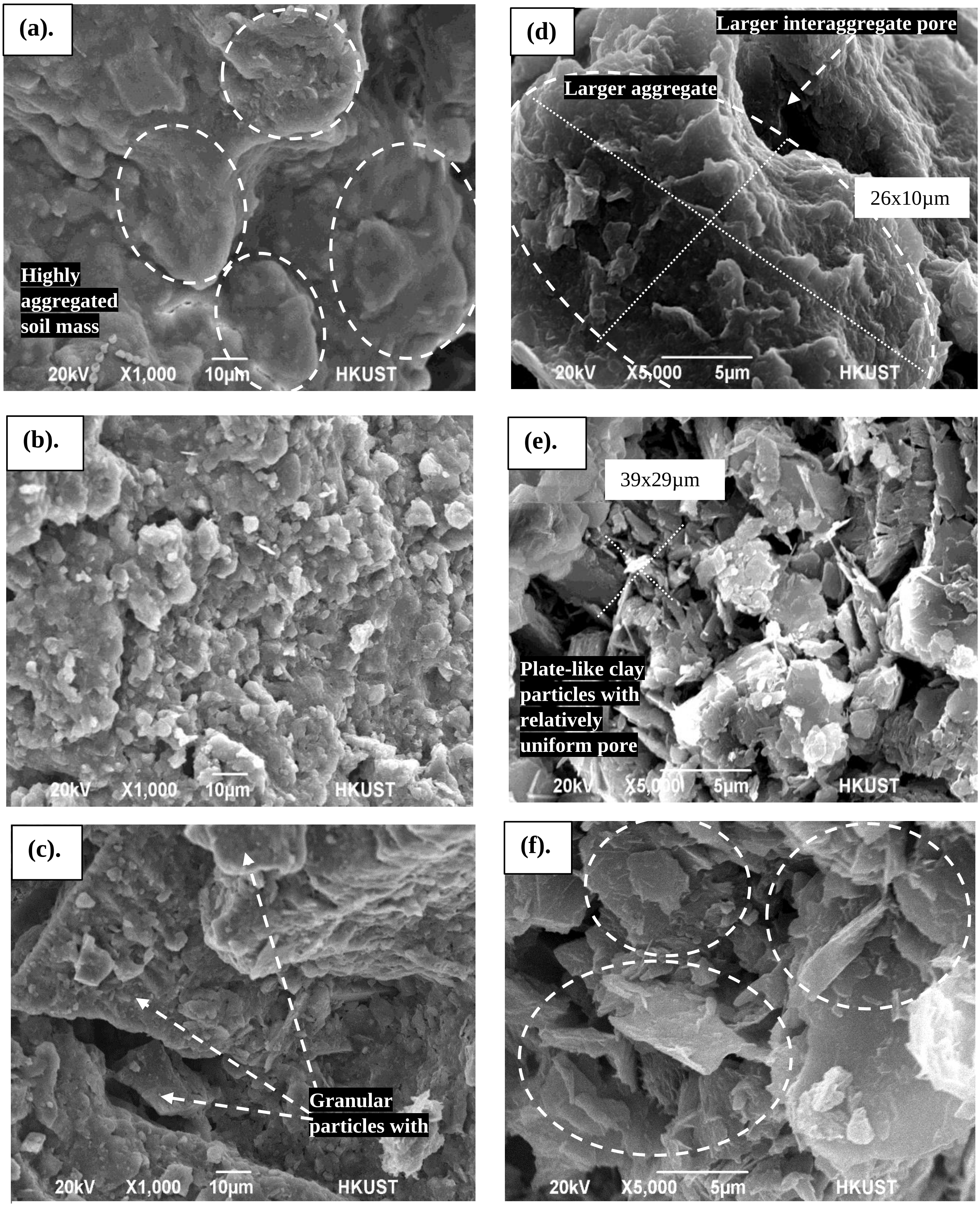

Figure 9: SEM images of the three soils at different magnifications; (a) LAT under X 1,000; (b) CDV under X 1,000; (c) CDG under X 1,000; (d) LAT under X 5,000; (e) CDV under X 5,000; (f) CDG under X 5,000.