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Effect of coarse content on the shear behavior of unsaturated coarse granular soils

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Abstract: The effects of coarse content on the microstructure, soil-water characteristics, shearing behavior and critical state characteristics of three types of unsaturated coarse granular soil with different coarse contents are investigated in an integrated manner through an extensive laboratory test program. The tests were performed on samples with the same void ratio of 0.62. As the coarse content increases, the pore-size distribution of the soil changes from unimodal to bimodal. Accordingly, the soil-water characteristic curve (SWCC) changes from unimodal to bimodal. The whole drainage process of the bimodal SWCC is divided into four stages based on the role of the pore water. The contribution of suction to the peak state parameters and critical state parameters except for the intercept of the critical state line in the stress plane [$\mu(s)$] of a bimodal soil reaches its maximum in the first drainage region. The pore water in the two pore series of a bimodal soil contributes to the shear strength differently during the desaturation process. Hence, the variations of the maximum dilatancy and the shear strength parameters with degree of saturation are highly nonlinear and $\mu(s)$ shows bimodal features. The contributions of suction to the shear strength parameters decrease with increasing coarse content.

Key words: Coarse granular soil, unsaturated soil, dilatancy, critical state, microstructure, SWCC, shear strength

Introduction

Colluvial soils on natural terrains are usually coarse and have been subjected to transportation and particle sorting. One special feature of colluvial soil is that the grading of the material varies with location. Generally, large particles move to the front and to the top surface whilst small particles accumulate at the bottom and in the rear part of the flow deposits (Wang and Hutter 2001; Zhang et al. 2011). A number of research studies have been conducted to investigate the effect of coarse content on one or two aspects of the behavior of silt-clay or sand-clay mixtures: micro-porosities (Li and Zhang 2009; Zhang and Li 2010), void ratio (Lade et al. 1998), collapsibility (Pitman et al. 1994), saturated permeability, shrink-swell potential (Shelley and Daniel 1993), and saturated shear strength (Vallejo and Mawby 2000; Dash and Sitharam 2011; Bergado et al. 2005). Bandini and Coop (2011), and Zhao et al. (2013a) also investigated the effects of coarse content on the critical state characteristics of saturated soils. However, coarse colluvial deposits are often unsaturated; the effects of coarse content on the shearing behavior and critical state characteristics of coarse grained soils under unsaturated conditions have not been well understood.

The soil microstructures change from fines-controlled to coarse-controlled with increasing coarse content. Zhao et al. (2013a) observed that clay aggregates form the skeleton of a fines-controlled soil. Coarse-controlled specimens form a skeleton with grain to grain contacts, with finer particles partially filling the large inter-particle pores. The structure of a transition soil is controlled by clay aggregates and coarse particles together. The pore size distribution of saturated fines-controlled soil shows a unimodal feature while the coarse-controlled soil exhibits a distinct dual-porosity structure. The soil-water characteristic curve (SWCC) is controlled by the soil microporosity structure. A unimodal SWCC was observed for Kaolin clay and clean Ottawa sand (Thu et al. 2007; Likos et al. 2012). The typical shape of a unimodal SWCC is a sigmoid since water drains gradually from a unimodal pore series

(Fig. 1). Bimodal SWCCs with two air-entry suction values were reported by Burger and Shackelford (2001) and Zhang and Chen (2005). These air-entry values are attributed to the presence of two distinct pore series that desaturate at different suction values (Zhao et al. 2013b). The SWCC serves as a controlling parameter function together with the saturated shear strength parameters to predict the unsaturated shear strength of soil (Fredlund et al. 1978; Vanapalli et al. 1996). Equations have been published for estimating the shear strength of soils with a unimodal SWCC. However, the shearing behavior and the critical state characteristics of a coarse soil with a bimodal SWCC have seldom been investigated. The relationships among the microstructure, SWCC, and shear behavior of coarse well graded soils with different coarse contents have not yet been well studied.

The objective of this paper is to investigate (1) the variation of microstructures of coarse granular soils with grading and suction; (2) the effect of coarse content on the SWCCs; and (3) the shearing behavior and critical state characteristics of coarse granular soils with different coarse contents. In this research, the microstructures of three coarse granular soils under the saturated and oven dried conditions were studied through mercury intrusion porosimetry. The SWCCs for three coarse granular soils with different coarse contents were measured. Drained triaxial tests were conducted on these unsaturated coarse granular soils to investigate their shearing behavior. Finally, the effects of coarse content on the microstructure, SWCC and shearing behavior were studied in an integrated manner.

Experimental program

Three series of tests were conducted in this study. The first series of tests (i.e., mercury intrusion porosimetry tests) was performed to quantify the pore-size distributions under saturated and oven-dried conditions. The second series of tests was conducted to study the SWCCs for three types of soil with different coarse contents. The third series of tests (i.e.,

drained triaxial tests) was carried out to investigate the shearing behavior of these unsaturated coarse soils.

A triaxial pressure plate extractor was used to measure the SWCC. The specimen was subject to increasing matric suction in several steps along the drying path. Water was expelled from the soil specimen and the total volume change was continuously monitored as the matric suction was increased. Suction equilibration was considered achieved when the drainage of water in 8 hours was smaller than 0.01% of the total dry soil weight. After reaching the suction equilibrium, the change in the volume of water in the specimen between two successive suctions was measured using a graduated burette with an accuracy of 50 mm³. Two triaxial systems were used to investigate the shearing behavior of saturated and unsaturated specimens. A conventional automatic triaxial apparatus was used to conduct drained tests on saturated specimens. A GDS triaxial apparatus with a 3-bar air-entry disk was used to conduct the drained tests on unsaturated specimens. A water-head control method with an accuracy of ± 0.005 kPa was used to control the matric suction when the suction was lower than 10 kPa (Li et al. 2009). The axis-translation technique was used to control the matric suction when the value was larger than 10 kPa. Matric suction was applied to a specimen through a water pressure controller and an air pressure controller. The pore-air pressure was controlled at the top of the specimen, and the pore-water pressure was applied at the base of the specimen through a ceramic disk. A precision differential pressure transducer with a double-cell was used to measure the total volume change of the unsaturated specimen. The estimated accuracy of the total volume-change measuring system is 31.4 mm³. A flushing system was used to remove the diffused air that might accumulate below the ceramic disk during the test.

Three types of soil with different coarse contents were used in this experimental program. The soils were mixed from a completely decomposed granitic soil at a construction

site in Hong Kong. The natural soil was sieved into 10 different ranges of particle sizes: 10-6.3 mm, 6.3-5 mm, 5-2 mm, 2-1.18 mm, 1.18-0.63 mm, 0.063-0.425 mm, 0.425-0.3 mm, 0.3-0.125 mm, 0.125-0.063 mm, and <0.063 mm. The grain-size distribution of the finest portion with a maximum particle diameter of 0.063 mm was measured using a hydrometer. The particle size ranges from 0.002 mm to 10 mm. Fig. 2(a) shows a photograph of the particle sizes of the soil used in the soil mixtures. The particles are subangular consisting mainly of quartz and feldspar. The grain-size distribution curves of the three mixed soils are shown in Fig. 2(b). The coarse contents, f_c (i.e., particles larger than 0.075 mm following ASTM (2002)), of these soils are 50, 68, and 90%, respectively. The three types of soil are classified as sand lean clay (sandy CL), silty sand with gravel (SM with gravel), and well graded sand with silt and gravel (SW-SM with gravel), respectively according to ASTM D2487 (ASTM 2002). Standard compaction tests using a standard effort of 600 kN-m/m³ (ASTM 2000) were conducted on these soils to obtain their optimal water contents and maximum dry densities, which are 13% and 1845 kg/m³; 12.5% and 1850 kg/m³; 10% and 1945 kg/m³ for sandy CL, SM with gravel and SW-SM with gravel, respectively. The specific gravity of the soil is 2.64. The specimens were prepared using a moist tamping technique, and were statically compacted to the same void ratio of 0.62 at their respective optimum water contents. The specimens for triaxial tests were 70 mm in diameter and 140 mm in height.

In order to apply a consistent matric suction stress path, all the specimens were saturated first. Then the specimens were equilibrated to desired suction values. Suctions were allowed to equilibrate within the whole specimen for several days. The triaxial tests were conducted under low net confining stresses of $\sigma_3' = 5, 15, \text{ and } 25 \text{ kPa}$. These pressures were selected to reflect the stress levels in shallow-seated slope failures. The specimen was first fully saturated and then isotropically consolidated to the desired initial confining pressure (i.e., 5, or 15, or 25 kPa) and the target suction (i.e., 0, 0.5, 10, 80, and 280 kPa). The shearing rates

of the drained tests were 0.002, 0.0036, and 0.005 mm/min (Ho and Fredlund 1982) for the specimens with $f_c = 50\%$, 68%, and 90%, respectively. These strain rates were set to provide a reasonably uniform suction distribution throughout these triaxial specimens. Since the effective confining stresses were very low, the correction of the test data included sample area, membrane strength, membrane penetration and gravity effects, which included the weight of the specimen cap and one half of the weight of the specimen. The methods of correction followed Head (1980).

Variation of microstructure with coarse content

Zhao et al. (2013a) observed that clay developed an aggregated or “packet” fabric in the compacted specimens. The predominant skeleton changes from clay aggregates to coarse particles as the coarse content increases. At a transition state, clay aggregates and coarse particles form the skeleton together. Intra-aggregate pores (with radii smaller than 2 μm) are found mainly within the clay aggregates, whereas inter-aggregate pores (with radii above 2 μm) are located amongst the coarser particles and between the coarser particles and the clay aggregates. Fig. 3(a) shows the pore-size distributions of the specimens with $f_c = 50\%$, 68%, and 90% under the compacted and saturation condition (e.g., samples compacted at their optimum water contents and then saturated). It can be seen that the soil with $f_c = 50\%$ exhibits a unimodal pore size distribution mainly with intra-aggregate pores. The specimens with $f_c = 68\%$ and 90% show two distinct pore series: one is the inter-aggregate pores and the other is the intra-aggregate pores. The soil with $f_c = 68\%$ has the largest volume of inter-aggregate pores ranging from 4 μm to 10 μm . The soil with $f_c = 90\%$ contains large inter-particle pores ranging from 20 μm to 75 μm .

As shown in Fig. 3(b), the pore-size distributions of the soils with $f_c = 50\%$, 68%, and 90% under the oven-dried condition are similar to those of the corresponding compacted and

1 saturated samples. Compared with the saturated specimens (Fig. 3(a)), both the pore radius
 2 and differential pore volume at the peak in the intra-aggregate zone become smaller. The
 3 fines of completely decomposed granite contain approximately 60% of kaolinite and 40% of
 4 lepidokite which are sensitive to water. The fines are anticipated to shrink upon drying. The
 5 decrease in the volume of intra-aggregate pores is due to the contraction of the clay
 6 aggregates. The shrinkage of the clay aggregates leads to some expansion of the inter-
 7 aggregate pores. The soil with $f_c = 50\%$ has a high proportion of clay aggregates which are
 8 easily influenced by desaturation. However, the soils with $f_c = 68\%$ and 90% form structures
 9 supported by a skeleton of coarse particles. Since the coarse particles are more stable than the
 10 clay aggregates upon water actions, the coarse soil structures remain stable and do not show
 11 significant deformation upon drying. The reduction of the volume of the intra-aggregate pores
 12 is much higher in a finer soil. Both in saturated and unsaturated conditions, the volume of
 13 intra-aggregate pores decrease with increasing coarse content, whereas the volume of inter-
 14 aggregate pores increases with coarse content.

16 Variation of SWCC with coarse content

17 Fig. 4(a) shows the drying SWCCs for the specimens with $f_c = 50\%$, 68% , and 90% . The
 18 SWCC for the soil with $f_c = 50\%$ shows unimodal features as the pore water drains from the
 19 unimodal pore structure (intra-aggregate pores). The SWCC for the soil with $f_c = 90\%$ shows
 20 strong bimodal features with two air-entry values. The SWCC for the $f_c = 68\%$ specimen
 21 shows a weak bimodal feature. The differences among the three SWCCs are related to the
 22 grain-size distributions (Fig. 2) and pore-size distributions (Fig. 3). The bimodal SWCC is
 23 better defined for a soil with a greater percentage of coarse content by weight as a result of
 24 the increased inter-aggregate pores. Different from the Burger and Shackelford (2001a, b)
 25 work, the present paper shows that not all coarse grained soils with fines exhibit bimodal

behavior.

The equation proposed by Fredlund and Xing's (1994) is used to fit the SWCC for the $f_c = 50\%$ specimen. As shown in Fig. 4(a), the $f_c = 50\%$ specimen does not reach the residual state in the applied range suction. The residual matric suction is fitted as 1500 kPa using Fredlund and Xing's equation. The degree of saturation at a suction 1500 kPa is taken as the residual degree of saturation of the specimen. An equation proposed by Zhang and Chen (2005) was used to fit the bimodal SWCC. As shown in Fig. 4, the predicted SWCC curves for the soils with $f_c = 68\%$ and 90% are bimodal. The parameters for these SWCCs are presented in Table 1.

The bimodal SWCC is closely related to the dual porosity structure of the soil as water drains from the two major pore series gradually. The water content decreases sharply in the first drainage region from the largest pores and then decreases gradually in the second drainage region. The whole drainage process on the bimodal SWCC is divided into four stages based on the role of the pore water [Fig. 4(b)]. The stage before the first AEV is defined as stage *a*. In stage *a*, all the pores are filled with water. When the suction is larger than the first AEV, the bulk water drains from the inter-aggregate pores in stage *b*, in which the free water forms a continuous phase. As soil suction increases, the drainage of the meniscus water in the inter-aggregate pores follows. A large increase in matric suction only results as slightly change in the water content. This stage is defined as stage *c* and can be referred to as the first residual state. The pore water becomes discontinuous except for the water bounded between the particles and the clay aggregates in the form of water bridges. Further, in the second drainage region, the water stored in the intra-aggregate pores begins to drain (stage *d*). The clay aggregates subsequently become unsaturated. Specifically, the four stages for the two bimodal soils with $f_c = 68\%$ and $f_c = 90\%$ are summarized in Fig. 4(a).

The air-entry value (AEV), ψ_a , decreases with increasing coarse content as shown in

Table 1. When air starts to enter the soil, water first drains from the largest pores. As shown in Fig. 3, as the percentage of the coarse content increases, more inter-aggregate pores develop in the soil. The soil with $f_c = 90\%$ has larger interconnected pores compared with the soils with $f_c = 68\%$ and 50% so less suction is required to desaturate the coarser soil. The rate of drying increases with increasing coarse content, hence the water storage capacity of a soil that corresponds to a particular suction is higher for a soil with a higher percentage of fines. The faster desaturation of the inter-aggregate pores leads to a lower residual matric suction. The residual suction for a unimodal soil or the first residual suction for a bimodal soil decreases with increasing coarse content. The intra-aggregate pores hold more water than the inter-aggregate pores under high suctions. The first residual degree of saturation of the soil decreases with coarse content as fewer intra-aggregate pores are present in a coarser soil (Fig. 4). Since the intra-aggregate pores dominate at large suction levels, the SWCCs for specimens with different coarse contents appear to be similar at very high suctions (>100000 kPa).

Drained shearing behavior of unsaturated soils

A total of 31 suction-controlled drained triaxial shear tests were performed on samples with $f_c = 50\%$, 68% , and 90% . These tests were conducted under very low net confining pressures of 5, 15 and 25 kPa. Five suctions (0, 0.5, 10, 80 and 280 kPa) were selected to cover the four stages of the bimodal SWCC. Figs 5-10 show the variation of the deviator stress, q , and the volumetric strain, ε_v , with the axial strain, ε_a , at different suctions. At the saturated state, the $f_c = 68\%$ specimens show strain-hardening behavior; the $f_c = 90\%$ specimens show distinct strain-softening behavior; and the $f_c = 50\%$ specimens exhibit slightly strain-softening behavior. This is because the saturated clay aggregates in the $f_c = 68\%$ specimens tend to collapse into the large inter-aggregate pores and contract (Zhao et al.

2013a). At the unsaturated state, most of the stress-strain curves exhibit strain-softening behavior. The strain-softening behavior is more pronounced when the specimen is subject to a higher suction. The failure mode changes from ductile failure to brittle failure with increasing suction. Take the soil with $f_c = 50\%$ for example, under the saturated condition, the failure mode is ductile with bulging at large axial strain levels. When the specimen is subject to a high suction of 280 kPa, a shear band is observed (Fig. 11). The ductility of the specimens increases with increasing net confining stress. The lower the net confining stress is, the more distinct the dilatant behavior is, and the smaller the axial strain required for the specimen to reach the maximum deviator stress.

The volumetric change is compressive at first, followed by dilation as the axial strain increases during shearing. It is observed that, for a given net normal stress, the degree of dilation increases with suction. This is likely due to the higher suction resulting in more tightly bound and rigid aggregates of soil particles. The aggregates do not slip easily but rather tend to ride up over each other as the shear stress is increased. The tendency to dilate is most pronounced at low net normal stress values and high suctions. The fabric plays a significant role in the behavior of the unsaturated compacted soil. When the three types of soil are subject to the same net normal stress of 15 kPa and the same suction of 80 kPa, the volumetric strains at the critical state are -5.3, -7.8, and -9.4% for the soils with $f_c = 50\%$, 68%, and 90%, respectively. The volumetric strain at the critical state increases with increasing coarse content. Therefore, the shear-induced volume change is related to the SWCCs for the soils.

Variation of peak shear strength of unsaturated soils with coarse content

Peak shear strength envelopes

Fig. 12 shows the failure envelopes for the three types of unsaturated soil by taking the

shear strength measured at the saturated condition as a reference. Matric suction contributes to the peak shear strength via two mechanisms: the contribution of capillary force to interparticle normal stresses and the effect of suction on soil dilatancy. These effects decrease with increasing coarse content. For example, under a confining pressure of 5 kPa, when the suction increases from 0 kPa to 80 kPa, the increment in the peak shear strengths are 101, 61 and 34 kPa for the soils with $f_c = 50\%$, 68%, and 90%, respectively.

As shown in Fig. 12, the failure envelopes for the three types of soil are almost linear. The strength envelopes at different suctions are not exactly parallel. Let $M_{peak}(s)$ denote the slope of the failure envelope and $\mu_{peak}(s)$ denote the intercept of the failure envelope. The differences in $M_{peak}(0)$ and $\mu_{peak}(0)$ of the corresponding saturated soils are due to the initial fabric. As shown in Fig. 13(a), the soil with $f_c = 90\%$ has the highest value of $M_{peak}(0)$. This is because of the high stiffness skeleton formed by coarse particles. Upon drained shearing, the coarse particles rearrange themselves and gain higher $M_{peak}(0)$ through dilation. The soil with $f_c = 68\%$ exhibits the lowest $M_{peak}(0)$ as strong contractive behavior is observed. The soil with $f_c = 50\%$ gives intermediate $M_{peak}(0)$ values as its skeleton is governed by preconsolidated clay aggregates.

Values of friction slope $M_{peak}(s)$ and cohesion intercept $\mu_{peak}(s)$ are shown in Fig. 13 as functions of suction. Both $M_{peak}(s)$ and $\mu_{peak}(s)$ increase non-linearly with suction until a specific suction is reached, after which they remain nearly constant. The suction to reach the peak decreases with coarse content. These suction values lie in the first residual stage of the bimodal SWCCs, therefore the effect of suction has reached its ultimate in the first drainage region. For the $f_c = 50\%$ specimen, the residual suction has not been reached in the considered suction range, so $M_{peak}(s)$ does not reach a steady value. The increase of the cohesion intercept, $\mu_{peak}(s)$, with suction has been reported by Escario and Juca (1989). But the increase of $M_{peak}(s)$ with suction has not been reported. The increase of $M_{peak}(s)$ of

unsaturated soil is governed by the change in the soil “structure” associated with the inter-particle capillary stress generated by water menisci. In the first drainage region, as the water drains from the inter-aggregate pores, the capillary stress induced by the water meniscus surrounding the contact points of soil particles gradually increases. The capillary stress acts as an internal stress at every contact point and stiffens the soil skeleton. Thus, $M_{peak}(s)$ increases continuously in this region. In the second drainage region, the desaturation rate is much smaller than that in the first region since the intra-aggregate pores are dominant. So the contribution of suction to parameters $M_{peak}(s)$ and $\mu_{peak}(s)$ is limited. The effects of suction on $M_{peak}(s)$ and $\mu_{peak}(s)$ decrease with increasing coarse content.

The maximum dilatancy, D

The maximum rate of dilatancy coincides with the peak state on the stress-strain relationship. The dilatancy of a soil can be examined by studying $d\varepsilon_v^p/d\varepsilon_q^p$, where $d\varepsilon_v^p$ and $d\varepsilon_q^p$ are the plastic volumetric and deviatoric strain increments, respectively. In a triaxial condition with axial and volumetric strain measurements, one has $\varepsilon_q = \varepsilon_a - \varepsilon_v/3$. It is assumed that the elastic components of the volumetric and shear strain increments are relatively small and negligible. The dilatancy of the soil can thus be approximated by $d\varepsilon_v/d\varepsilon_q$.

Fig. 14 shows the variation of the maximum dilatancy, D , with the degree of saturation under different confining pressures. The contribution of suction to the maximum dilatancy depends on the coarse content. The initial fabric dominates the behavior of the saturated soil. The maximum dilatancy is the largest for the soil with $f_c = 90\%$ due to the high stiffness of the skeleton. The soil with $f_c = 68\%$ shows contractive behavior attributed to its highly compressible skeleton. As shown in Fig. 14, the dilatancy increases with a decrease in the degree of saturation for the three types of soil. When the specimens become unsaturated, the suction-induced fabric difference dominates the variation. The effect of degree of saturation

on dilatancy is related to the grading of the soil. As shown in Fig. 3, the pores are expected to shrink as the water meniscus progresses from large pores to smaller pores when the suction is increased. The dilatancy of the soil with $f_c = 50\%$ increases monotonously with the degree of saturation in the considered suction range (Fig. 14) because the fabric change is from the gradual drainage of water from the intra-aggregate pores.

For the soils with a bimodal SWCC ($f_c = 68\%$ and 90%), the pore water in the two pore series contributes to dilatancy differently during the desaturation process. In stage *b*, the bulk water drains from the inter-aggregate pores and the water phase is continuous. During the drying process, the capillary stress increases gradually and the interparticle contacts become more stable, which increases the dilatancy. In stage *c*, the water phase becomes discontinuous except for the water bounded between the particles and the clay aggregates in the form of water bridges. In this stage, the radii of menisci are small and the capillary stresses are high, which increases the resistance to particle slippage and the dilatancy. In the second drainage region, the clay aggregates play a major role as water mainly drains from the intra-aggregate pores. The stiffness of the clay aggregates increases after shrinkage of the clay aggregates [Fig. 3(b)]. The aggregates tend to ride up over each other, making the sample more dilative.

Variation of the critical state strength of unsaturated soils with coarse content

The critical state framework for unsaturated soils has been proposed based on saturated soil mechanics. Wheeler and Sivakumar (1995) suggested critical state relationships for q and specific volume v as

$$\begin{aligned} [1] \quad & q = M(s)p + \mu(s) \\ [2] \quad & v = \Gamma(s) - \psi(s) \ln \frac{p}{p_{at}} \end{aligned}$$

where $M(s)$ is the slope of the projection of the critical state line in the $q : p$ space; $\mu(s)$ is the apparent cohesion intercept cause by suction; $\Gamma(s)$ is the intercept at $p = 1$ kPa; p_{at} is the

atmospheric pressure; and $\psi(s)$ is the slope of the projection of the critical state line in the $v - \log p$ space. All the four parameters are functions of suction.

The stress strain relationships (Figs 5 - 10) of the soils under different suctions show that the true critical state has not been achieved as the volumetric strain continues to change even at very large strains. However, the tests do show that the rate of increase of volumetric strain decreases towards the end of the tests. In order to compare the test results later, the last point of each test at an axial strain of approximately 25% is taken as the critical state.

Critical state lines in the p - q space

Figure 15 summarizes the critical state data in the p : q space from the drained triaxial tests on the soils with $f_c = 50\%$, 68% , and 90% at different suctions. The critical state shear strength is meant to eliminate the contribution of soil dilatancy to the shear strength. The critical state values of q and p at each suction level appear to fall on a straight line. The critical state lines at different suctions are again not parallel. Equation 1 is used to obtain parameters $M(s)$ and $\mu(s)$.

$M(0)$ under the saturated state is an intrinsic material property characterizing the intrinsic friction coefficient of the particle assembly for a given initial soil fabric, but $M(s)$ depends on suction. Fig. 16(a) shows the variation of $M(s)$ with suction, which has the same trend as $M_{peak}(s)$. Values of $M(s)$ of the soils with $f_c = 68\%$ and $f_c = 90\%$ increase with suction until the first residual stage (stage c) of each of the soils has been reached. However, the $M(s)$ of the $f_c = 50\%$ soil increases monotonously since the residual suction has not been reached. It can also be observed from Fig. 15 that the critical state lines lie close to each other for suctions larger than 10 kPa and 80 kPa for the soils with $f_c = 90\%$ and $f_c = 68\%$, respectively. Thus, for the soils with $f_c = 90\%$ and $f_c = 68\%$, the effect of suction has reached its maximum value within the first drainage region.

The variation of $M(s)$ can also be expressed as a function of degree of saturation as shown in Fig. 16(b). The values of degree of saturation are evaluated from the three SWCCs as shown in Fig. 4(a). The change in $M(s)$ with degree of saturation can be related to the different role of the pore water. The value of $M(s)$ for the $f_c = 50\%$ specimen increases almost monotonously as water drains from the intra-aggregate pores gradually. The increases of $M(s)$ for the soils with $f_c = 68\%$ and 90% exhibit highly non-linear features, which is relate to the drainage process of the bimodal SWCC [Fig. 4(b)]. In stage *b*, the pore water drains sharply from the inter-aggregate pores at low suctions. The capillary stress generates a resistance to the slippage at the contacts between the particles (or aggregates) which affect $M(s)$. In stage *c*, the meniscus water is bounded between the particles and the clay aggregates in the form of a bridge. The capillary stress increases as the meniscus radius decreases. The generated capillary force increases the friction between particles. Therefore, $M(s)$ increase with decreasing degree of saturation. In the second drainage region, the stiffness of the clay aggregates increases as the clay aggregates become unsaturated and provide a high friction resistance.

The variation of $M(s)$ with coarse content under different suctions is shown in Fig. 16(c). $M(s)$ increases with coarse content. The increases of $M(0)$ under the saturation state are due to the initial fabric. Under the unsaturated condition, both the soil fabric and suction affect $M(s)$. $M(s)$ can be described as a sum of $M(0)$ and an incremental component due to suction, $\Delta M(s)$. The effect of suction on $\Delta M(s)$ decreases with increasing coarse content. For example, when the suction increases from 0 kPa to 80 kPa, the values of $M(s)$ for the soils with $f_c = 50\%$, 68% , and 90% increase by 0.581 (from 1.419 to 2), 0.381 (from 1.48 to 1.861) and 0.222 (from 1.67 to 1.892), respectively.

$\mu(s)$ quantifies the effect of suction on the shear strength which represents a similar effect of ϕ^b proposed by Fredlund et al (1978) and M_b proposed by Toll (1990). Vanapalli et al.

(1996) pointed out that the area of the pore water in contact with soil particles is responsible for the increase in the shear strength of soils. So the value of $\mu(s)$ is related to the SWCC of the soil. The log scale is used in this plot to reflect the changes in $\mu(s)$ under very low suctions. A value of 0.01 kPa, which is smaller than the smallest AEV (0.07 kPa), is used to represent the saturated state. As shown in Fig. 17, the $\mu(s)$ of the soil with $f_c = 50\%$ increases with suction monotonically. However, the values of $\mu(s)$ for the soils with $f_c = 68\%$ and 90% show bimodal features which are related to their bimodal SWCCs. In the first drainage region (stage *b*), $\mu(s)$ increases with increasing matric suction and decreases near the first residual state (stage *c*). In the second drainage region, $\mu(s)$ increases monotonically with increasing suction. The $\mu(s)$ of the soil with a bimodal SWCC is similar to that of sand in the first drainage region (Donald 1956), but similar to that of clay in the second drainage region. In stage *b*, with increasing suction, the additional bonding force induced by suction increases monotonically and $\mu(s)$ increases accordingly. When the soil enters stage *c* which is the residual stage of the first drainage region, the water menisci vanish and may not transmit suction effectively to the soil particles or aggregate contact points. Thus, $\mu(s)$ decreases with increasing suction. In the second drainage region, the clay aggregates control the unsaturated behavior of the soil. $\mu(s)$ increases as water drains from intra-aggregate pores. Note that this is different from the peak cohesion intercept $\mu_{peak}(s)$, which keeps increasing at high suctions attributed to the suction-induced dilatancy [Fig. 13(b)].

Critical state lines in the v -log p space

Figs 18 (a), (b) and (c) plot the relationships between specific volume v (i.e. $v = 1 + e$) and the logarithm of net mean stress for the soils with $f_c = 50\%$, 68% , and 90% , respectively. The position and the slope of the critical state line at zero suction are very different from those of the critical state lines under unsaturated conditions. This further confirms the

significant influence of suction on the soil fabric. Equation (2) is used to obtain parameters $I(s)$ and $\psi(s)$.

Figs 19 and 20 show the variations of $\psi(s)$ and $I(s)$ with suction or degree of saturation. The saturated soil with $f_c = 68\%$ has the largest value of $\psi(0)$. This is because the $f_c = 68\%$ specimen has the largest volume of inter-aggregate pores (4-10 μm) and the saturated clay aggregates tend to collapse into the large inter-aggregate pores and contract. As shown in Fig. 19(a), the values of $\psi(s)$ increase with suction. Similar results are also observed by other researchers (Wheeler and Sivakumar 1995; Toll and Ong 2003). However, the values of $\psi(s)$ and $I(s)$ of the $f_c = 68\%$ specimen and $f_c = 90\%$ specimen reach a peak at the first residual stages of the soils and maintain the value thereafter. This is because the desaturation rate and the contribution of suction in the second drainage region are very small as the intra-aggregate pores dominate. For the $f_c = 50\%$ specimen, the residual suction has not been reached in the considered suction range, hence, $\psi(s)$ and $I(s)$ do not reach a steady value. The suction values at the peak state decrease with coarse content. Fig. 19(b) and Fig. 20(b) plot the variation of $\psi(s)$ and $I(s)$ with the degree of saturation. Similar to the variation of $M(s)$, $\psi(s)$ and $I(s)$ increase monotonously with the degree of saturation for the $f_c = 50\%$ specimen as the pore water drains from the intra-aggregate pore gradually. The increase of parameters $\psi(s)$ and $I(s)$ for the soils with $f_c = 68\%$ and 90% is related to their bimodal SWCCs. In stage *b*, the capillary stress increases as bulk water drains from the inter-aggregate pores. In stage *c*, the capillary stress also increases as the radius of the meniscus water decreases. The generated capillary stress acts as an internal stress and generates a resistance to the slippage at the contacts between particles (or aggregates), which increase the dilatancy and $I(s)$. In stage *c*, the stiffness of the aggregates increases as the clay aggregates become unsaturated. The coarse particles and aggregates tend to be more dilative, resulting in higher values of $I(s)$.

The aggregate particles significantly influence the shear induced volumetric behavior and the critical state. The shrinkage ability increases with increasing fines content as shown in Fig. 3(b). The role of clay aggregates is more obvious in the finer soil. Fig. 19(c) and Fig. 20(c) show that the contribution of suction on $\psi(s)$ and $I(s)$ decreases with increasing coarse content. The contribution of suction to the critical state parameters of bimodal soils reaches its maximum in the first drainage region. The experimental data on critical state lines for unsaturated soils reported in this paper show a clear pattern of the variations of $\psi(s)$ and $I(s)$ with suction, which may be useful for the development of constitutive models for unsaturated soils, especially bimodal soils.

Conclusions

In this study, the effects of coarse content on the microstructures, soil-water characteristic curves, drained shearing behavior, and critical state characteristics of three types of unsaturated coarse soil were investigated in an integrated manner. The main findings are as follows:

1. As the coarse content increases, the pore size distribution of a coarse soil changes from unimodal to bimodal. After drying, the volume of intra-aggregate pores decreases due to the shrinkage of the clay aggregates, resulting in an enlargement of the inter-aggregate pores.
2. With increasing coarse content, the SWCC also changes from unimodal to bimodal. The unimodal SWCC for the $f_c = 50\%$ specimen is associated with its unimodal pore structure. The SWCCs for the soils with $f_c = 68\%$ and 90% are bimodal due to their distinct dual porosity structure. The drainage of pore water in a bimodal soil can be divided into four stages based on the role of the pore water. The air entry value and the first residual suction decrease with increasing coarse content.

3. The peak shear strength increases with suction due to the contribution of capillary force to interparticle normal stresses and the effect of suction on soil dilatancy. The effect of suction on the friction slope $M_{peak}(s)$ and cohesion intercept $\mu_{peak}(s)$ of a bimodal soil reaches its maximum within the first drainage region. The contribution of suction to the peak shear strength decreases with increasing coarse content.
4. The maximum dilatancy, D , decreases with degree of saturation due to suction-induced fabric changes. For the bimodal soils with $f_c = 68\%$ and 90% , the pore water in the two pore series contributes to dilatancy differently during the desaturation process.
5. Critical state parameters $M(s)$, $\psi(s)$, and $\Gamma(s)$ increase with suction until the residual or first residual stage of the soil has been reached. The contribution of suction to $\mu(s)$ changes from unimodal to bimodal features with increasing coarse content.

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Table 1. SWCC parameters for three types of soil

Description	Symbol	Soil type		
		$f_c = 50\%$	$f_c = 68\%$	$f_c = 90\%$
Air entry value (kPa)	ψ_a	40	1	0.07
Residual/first residual matric suction (kPa)	ψ_r	1500	50	0.7
Residual degree of saturation	s_r	0.432	0.561	0.403
Fitting parameters		$a = 70$	$\theta_l = 24, \theta_s = 13$	$\theta_l = 20, \theta_s = 17$
		$n = 2$	$\psi_l = 1, \psi_s = 3000$	$\psi_l = 0.2, \psi_s = 200$
		$m = 0.4$	$a_l = 0.5, a_s = 200,$	$a_l = 0.15, a_s = 80,$
			$n_l = 1, n_s = 10$	$n_l = 4, n_s = 1$
			$m_l = 0.7, m_s = 0.2$	$m_l = 2, m_s = 0.7$
The stages of SWCC		Stage <i>a</i> : 0-40 kPa	Stage <i>a</i> : 0-1 kPa	Stage <i>a</i> : 0-0.07 kPa
		Stage <i>b</i> : 40-1500 kPa	Stage <i>b</i> : 1-50 kPa	Stage <i>b</i> : 0.07-0.7 kPa
		Stage <i>c</i> : >1500 kPa	Stage <i>c</i> : 50-120 kPa	Stage <i>c</i> : 0.7-30 kPa
			Stage <i>d</i> : >120 kPa	Stage <i>d</i> : >30 kPa

Notes: a , n , and m are three parameters of the SWCC function;

Subscripts l and s represent the inter-aggregate pore component and the intra-aggregate pore component, respectively;

θ_l is the volumetric percentage of the large inter-aggregate pores;

θ_s is the volumetric percentage of the small intra-aggregate pores.

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