One-dimensional compressibility and shrinkage behavior of an initially saturated clay

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Abstract

This paper presents the experimental study on one-dimensional compressibility behavior, soil water characteristic and soil shrinkage behavior of slurry Amberger kaolin. Soil water characteristic curve (SWCC) (Sr-ψ) was determined using conjunction between SWCC (w-ψ) and soil shrinkage curve (w-e). The oedometer test was performed with a maximum applied vertical stress of 6.4 MPa. The volume change behavior of sample due to the suction and that due to applied vertical stress demonstrated a similarity within the saturation domain.

Key words: *Oedometer test, unsaturated soil, suction, shrinkage*

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1. Introduction

Consolidation process concerns the mechanical process in which volume of the soil changes due to a change in applied pressure. Tezaghi (1943) was the first to introduce a theory to describe the consolidation process. At first, when the soil is subjected to an increase in applied pressure, the liquid phase which is considered as an incompressible phase absorbs almost entirely the external pressure, this results in excess pore water pressure. With time, as the seepage occurs, the soil skeleton which is virtually compressible starts to carry the applied pressure gradually. The effective stress is mathematical expressed as (Tezaghi 1936):

$$\sigma' = \sigma - u_w \qquad (1)$$

Oedometer tests are used widely commonly to determine one-dimensional compressibility of the clays. A number of studies have been carried out in an attempt to understand various aspect of compressibility behavior of clays (Sridharan et al. 1986, Burland 1990, Fleureau et al. 1993, Mitchell 1993, Nagaraj et al. 1994, Bo et al. 2002, Marcial et al. 2002, Hong et al. 2010, Baille et al. 2014, Baille et al. 2016).

However, soils under partially saturated conditions comprise of three phases. The volume changes of unsaturated soil due to the change of applied pressure is a complex mechanism of interaction between solid, air and water phase (Yidong and Lu 2020). The volume change of the soil is virtually dominated by the effective stress. Bishop (1959) and Bishop (1960) were the first who tried to extend the effective stress concept of Tezaghi to unsaturated soil which has been considered as single stress variable approach.

$$\sigma' = (\sigma - u_a)+\chi\cdot\psi \qquad (2)$$

where σ' is the effective stress, σ is the total normal stress, ψ is the matric suction and equal to the difference between ua (pore air pressure) and uw (pore water pressure). χ is the effective stress parameter which has been considered as the upscaling function capturing the contribution of suction to the effective stress.

On the other hand, Fredlund and Morgenstern (1977) suggested an approach of two stress state variables when dealing with volume change and shear strength behavior of unsaturated soil. From a micromechanical point of view, Lu and Likos (2006) introduced the term of suction stress which could be defined as the sum of interparticle forces per unit area intersecting a representative elementary volume of the soil. Fleureau et al. (1993) investigated the drying and wetting path behavior of clayey soils and compared the result with the void ratio – applied pressure relationship obtained from oedometer tests in saturated condition. They concluded that the volume change behavior of the soil from drying path and oedometric compression path are equivalent. Baille (2014) performed water retention and oedometer compression tests at high pressure regime on three types of clays. The author pointed out the validity of Tezaghi's effective stress concept within the saturated regime. To establish the relationship between void ratio and suction following the drying path, the precise volume measurement plays a crucial role.

The primary objective of this paper is to establish soil water characteristic curve (SWCC) and soil shrinkage curve (SSC) of slurry clay. The secondary objective is to perform the oedometer compression tests on the slurry clay with the applied pressure up to 6,4 MPa. Afterward, the validity of effective stress concept within the saturated domain was examined based on the volume change behavior of the studied clay obtained from drying path of SWCC and the one achieved from oedometric compression path.

2. Material

Amberger kaolin was used in this study. The kaolin was exploited from the mines located in Germany by Amberger Kaolinwerke Eduard Kick company. The main component of kaolin is about 80% of mineral kaolinite. The basic properties of the soil are summarized in Table 1. The soil was mixed with the predetermined amount of water corresponding to 1.1wL (slurry mixture). Afterward, the mixture was stored in some sealed bags and a closed bucket for 4 days to achieve homogeneous condition in water content distribution. Eventually, using the mixture, the sample preparation was performed for the soil shrinkage test, SWCC and the oedometer compression test.

Table 1: Material properties of Amberger kaolin

Properties	Amberger kaolin (AK)
Specific gravity, G_s	2.639
Liquid limit, w_L [%]	56.6
Plastic limit, w_P [%]	40.1
Plasticity index, I_P [%]	16.5
$1.1{\cdot}w_L$ [%]	62.26
USCS	MH

3. Apparatus used and test procedure

The apparatus used for establishment the SWCC was the chilled mirror hygrometer (Aqualab) which is based on the dew point technique to measure the total suction of a soil sample. Leong EC et al. (2003) described the detail of this technique as a precise manner to measure the water potential of a soil sample. A desiccator with Natri Hydroxide (NaOH) corresponding to 330MPa suction was used in this study.

First of all, the dry Amberger kaolin was mixed with predetermined amount of 1,1wL. After storing phase in 4 days as mentioned in the manuscript, the cups with known dimension and weight were filled with the mixture. The criterion used to assess the identical condition of the samples was based on the known dimension of the cups (3 cm in diameter and 0.5 cm in height), the initial water content, the weight of samples after pasting and therefore the initial void ratio of the sample. The samples were weighted to determine the initial condition and immediately transferred to the desiccator. Afterward, the sample was measured the weight using a precise digital balance and the relative humidity using the Aqualab regularly. Adopting the Kelvin's equation (see eq. 3), the total suction can be calculated from the measured relative humidity.

$$\psi_{tot} = -\frac{RT}{M_w(1/\rho_w)}\ln\left(\frac{RH}{100}\right) \quad (3)$$

Where ψ_{tot} is the total suction (kPa), R is the universial gas constant (8.314 J/mol K), T is the absolute temperature (K), Mw is the molecular weight of water (18.016 kg/kmol), ρ_w is the unit weight of water (kg/cm^3) as the function of temperature and RH is the measured relative humidity in percent. The total suction is significantly sensitive to temparature changes. Therefore, the desiccator with the samples and the Aqualab were placed in the relative humidity and temperature-controlled room. Figure 1 shows the device used for SWCC determination.

In order to determine soil shrinkage curve, the immersion weighing method was adopted. A series of samples which were identical to the samples of SWCC were prepared. The samples were placed in some large ceramic trays and were allowed to air dry slowly using plastic membrane covering on top of the tray. To maintain the constant condition, the test was conducted in the controlled relative humidity and temperature room. At predetermined certain values of water content, a sample was submerged into paraffin oil to measure the volume of sample and therefore the void ratio. The experimental setup for soil shrinkage curve is shown in Figure 2.

The ELE oedometer device was adopted to investigate the one-dimensional compressibility behavior of the

Figure 1: (a) Chilled mirror hygrometer and (b) Samples in the desiccator

Figure 2:

(a) Samples under drying process and

(b) A precise balance and paraffin oil

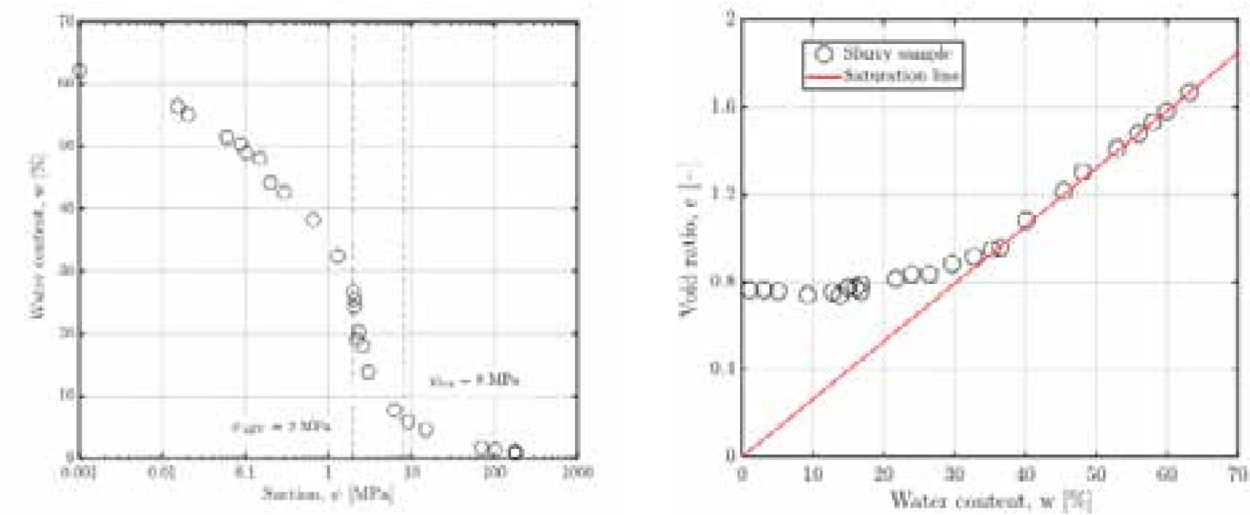

Figure 3: (a) SWCC of the slurry sample and (b) SSC of the slurry sample

slurry sample. The slurries were carefully pasted into the oedometer ring which has dimension of 5cm in diameter and 2cm in height. The initial condition of sample was calculated from the initial volume and water content. After placing the oedometer ring containing the sample in the oedometer cell, the loading frame was assembled. The vertical displacement of sample was monitored using a high precise displacement sensor. A series of successive loads equal to 6.25, 12.5, 25, 50, 100, 200, 400, 800, 1600, 3200 and 6400 kPa were applied.

4. Results and Discussion

The effect of applied suctions on the water content are shown in Figure 3a. Using the conjunction between water content, void ratio and degree of saturation, the degree of saturation was determined and are shown in Figure 4a with respect to suction. Generally, three zones were observed in the SWCC. The saturated zone was the zone between soil suction ψ = 0kPa and the air-entry value (ψ_{AEV} = 2.0MPa) which was determined based on the best-fit of the Sr-ψ data using the model of Fredlund and Xing (1994). The relationship between the degree of saturation and the suction was virtually linear in the saturation domain. In the transition zone (>(ψ_{AEV}), a pronounced increase in the rate of reduction in the water content and also the degree of saturation of sample could be seen. In the residual zone (ψ>10MPa), the increase in applied suction resulted in inconsiderable decrease in the degree of saturation.

Figure 3b depicts the soil shrinkage curve of the slurry sample. When the soil was in saturation condition, the decrease in void ratio due to the reduction of water content was a linear relationship. After passing a value about 40% in water content, the shrinkage curve started deviating from the saturation line followed by a mostly constant value in the void ratio which is related to the shrinkage limit of sample. This phenomenon has been explained by Sridharan and Prakash (1998). The surface tension which increase as the radius of meniscus increase is the main component of capillary stresses. During drying process, the sample is in desaturation range, the suction stress which contributes to effective stress and therefore shear strength of the soil is mainly dominant by the capillary stresses. As a result of reduction water in the pore system, the process of equalization between the shear strength and the shear stresses induced by the capillary stresses occurs and the void ratio reachs a constant value when the stress equilibrium achieves.

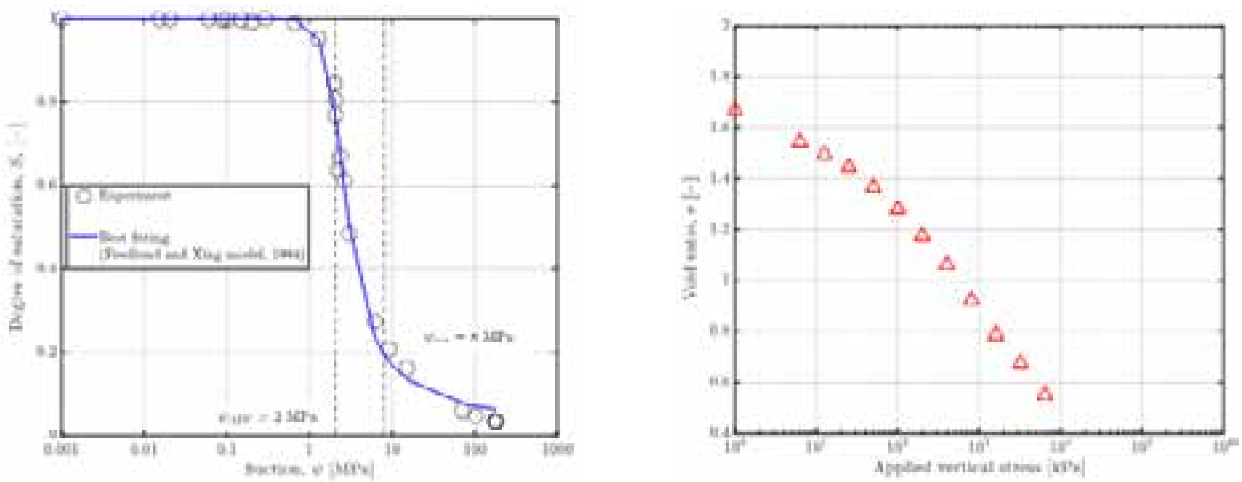

Figure 4: (a) SWCC (Sr-ψ) and (b) Oedometer test result

The oedometer test result of the slurry sample is shown in Figure 4b. The void ratio of slurry sample decreased significantly as the applied vertical stress increased. The compression path of the sample exhibited a slight curve at streses smaller than 300kPa, while a linear behavior was found at stresses greater than 300kPa.

Figure 5 shows a comparison between one-dimensional compressibility path and the suction versus void ratio relationship. For the suction or applied vertical stress below 800kPa, there was an equivalent correlation between two curves which indicated that both applied vertical stress and suction had similar effect on the volume change of the sample. For the suction from 800kPa to 2000kPa, the volume change of the sample due to the external loading (i.e. applied vertical stress in oedometer test) was found to be slightly smaller than that due to the internal loading (i.e. suction stress). Such behavior may be due to the oriented fabric or the rearrangement of pore system of sample which is more sensitive to the high applied vertical load (above 800kPa).In general, this indicated the validity of Tezaghi's effective stress concept within saturation regime. The results coincide with the test results published by some researchers for different types of clay (Baille 2014, Tripathy et al. 2010).

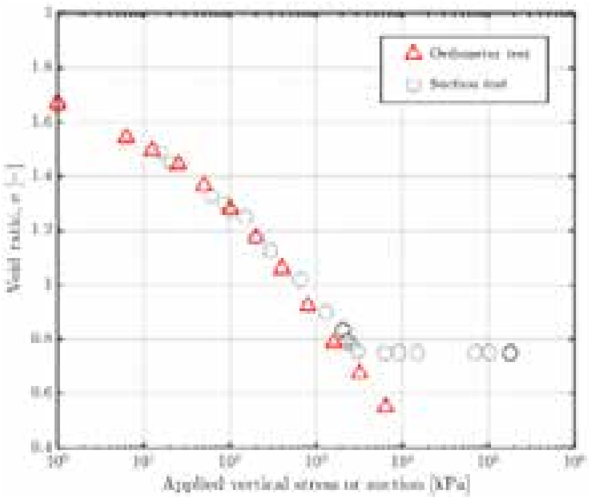

Figure 5: Influence of applied vertical stress and suction on volume change behavior of slurry Amberger kaolin

5. Conclusions

The one-dimensional compressibility, soil water characteristic and soil shrinkage behavior of slurry Amberger kaolin was studied. Using the conjunction between SWCC (w-ψ) and soil shrinkage curve (w-e), the SWCC (Sr-ψ) was established. The oedometer test was performed with a maximum applied vertical stress of 6.4 MPa. For the slurry Amberger kaolin, the volume change behavior of sample due to the suction and that due to applied vertical stress was found to be very similar within the a range of suction smaller than air entry value./.

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