Comparison of Air Entry Values from Soil Water Retention and Volumetric Shrinkage Characteristic Curves

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ABSTRACT

The soil water retention curve (SWRC) is the relationship between the volumetric water content and the matric suction of an unsaturated soil. One key parameter of the SWRC is the air-entry value (AEV), which defines the minimum matric suction at which air starts to enter the largest pores in the soil as it desaturates. The volumetric water content at the AEV can also be identified from the evolution of the volumetric shrinkage characteristic curve (VSCC). The VSCC is the relationship between the void ratio and volumetric water content of an unsaturated soil as it dries towards the shrinkage limit. Fine-grained materials, such as dredged materials and mine tailings comprising clay minerals and natural clays, show a marked volume change with variation of the water content. In this study, the AEVs of three fine-grained materials (dredged material, red mud and kaolin) were measured from SWRCs and compared with the shrinkage limit values obtained from the corresponding VSCCs. The SWRC was measured by utilizing full-range polymer tensiometers. The polymer tensiometer is filled with polymer solution instead of water, diminishing the effect of soil salinity, and can measure the matric suction up to -1500 kPa. The SWRC and VSCC results were compared and discussed in terms of their applicability to providing an understanding of unsaturated soils that undergoing large volume change.

Keywords: air entry value, polymer tensiometer, shrinkage limit, soil water retention curve, unsaturated soil, volumetric shrinkage characteristic curve

1 INTRODUCTION

The air entry value (AEV) is an important characteristic of an unsaturated soil defining the point of desaturation from the soil water retention curve (SWRC) as shown in Fig. 1 (Fredlund et al. 1993). However, it is very difficult to exactly locate this point from the water retention curve (Fredlund et al. 2013). Specifically, for high plasticity soils, it requires volume change characteristics for defining the variation in saturation and determining the true air entry value.

The volumetric change of a soil due to swelling and shrinkage is another important phenomenon of the fine-grained soils mainly attributed to the variation of water content and is highly influenced by the clay mineral presence (Marinho 1994). The volumetric change of the fine-grained soil is characterized by the volumetric shrinkage characteristics curve (VSCC) (Fredlund et al. 2013).

Fig. 1. AEV evaluation from SWRC (Fredlund, 1993).

Fig. 2. Shrinkage limit and AEV determination from VSCC (Marinho, 1994).
The VSCC is a continuous measurement of the void ratio and volumetric water content from fully saturated condition until the moisture content reaches the shrinkage limit and beyond to oven dry condition (Fredlund et al. 2013).

One approach for the determination of the shrinkage limit from the VSCC was provided by Marinho (1994). He identifies the point of intersection of the two tangents drawn from the zero-shrinkage portion to the normal shrinkage portion of the VSCC. Two important parameters describing the shrinkage curve are the minimum void ratio (shrinkage limit) and the curvature of the shrinkage curve (general air entry in Fig. 2).

2 MATERIALS

An experimental study was conducted using three different fine-grained materials: dredged mud, red mud and kaolin (as the reference material). Dredged mud was collected from the Moreton Bay that is fed by the Brisbane River in Australia consisting of 40% silt and 50% clay. Red mud is a toxic by-product produced in a slurry form from refining of bauxite to produce alumina which was collected from north-Queensland, Australia (Quintero et al. 2017).

These materials were initially prepared in a slurry condition for the tests and underwent significant volume change as soil suction increased during shrinkage. The summary of material parameters is presented in Table 1.

| Properties           | Kaolin (%) | Red mud (%) | Dredged mud (%) |
|----------------------|------------|-------------|-----------------|
| Liquid limit (%)     | 89.9       | 51.1        | 54.1            |
| Plastic limit (%)    | 35.6       | 31.9        | 35.8            |
| Shrinkage limit (%)  | 34.7       | 14.9        | 18.3            |
| Specific gravity     | 2.6        | 2.9         | 2.5             |

3 MEASUREMENT METHOD FOR THE VSCC

One of the important soil properties in soil classification is the shrinkage limit that can be determined by conducting a shrinkage test according to ASTM D427. In this study, shrinkage limit of kaolin, dredged mud and red mud were recorded based on the diameter and height of samples. Cylindrical acrylic rings were designed and fabricated with 15 mm height and 76 mm diameter. The usage of a transparent ring allows the identification of air bubbles (heterogeneous material) inside the material which cannot be seen when a metal ring is used. Also, the effect of denting can be seen on the surface of the dried material in the metal ring from caliper (slurry height measurement) which is prevented by using a transparent graduated ring and improve the accuracy of measurement (Fig. 3).

Homogeneous soil samples were poured into the testing rings. Under the assumption that there is no crack during the soil drying process.

The height and diameter of soil samples (with their distance from the ring) were measured by using 16 measurement points using rulers with a rotating angle of 45°. Prior to the test, the initial water content and dry density were determined and calculated based on the ring volume. The soil mass was continuously recorded in 60 seconds intervals by a digital balance with a precision of 0.01g and automated recording during the test.

The averaged soil volume, $V_{ave}$, for each day reading was calculated by taking the average sample area (from measuring the radius in 8 directions) and the average height of the sample (measured at 8 positions) $H_{ave}$, according to the following equation:

$$V_{ave} = A_{ave} \times H_{ave}$$

The dry density for each reading can be expressed with the following equation by knowing the dry soil mass, which is constant throughout the test, the initial water content, $w_i$, and initial bulk soil mass, $M_b$, as follows:

$$\rho_d = \frac{\rho_b}{(1 + w)}$$

$$\rho_b = \frac{M_b}{V_{ave}}$$

where $M_b$ and $V_{ave}$ are the measured bulk mass and the calculated average soil volume at each reading. The Figures 4 and 5 show the shrinkage limit test setup for kaolin, red mud and dredged mud at the beginning of the test and the end, respectively.
4 MEASUREMENT METHOD FOR THE SWRC

Acrylic columns with 20 cm height and 10 cm diameters (Fig. 6), precision balances, and full range tensiometers (Fig. 7) were used to measure the SWRC of kaolin, dredged mud and red mud. A tensiometer is a device that consists of a porous cup, water reservoir and a pressure gauge. The ceramic cup is filled with de-aired water and can be buried in soil. Depending on the soil moisture condition, a small volume of water moves from the cup into the soil and develops a negative pressure or suction, which is measured by the pressure gauge (de Rooij et al. 2009). Conventional tensiometers filled with water are sensitive to salinity and prone to cavitation. But polymer tensiometers, which were used in this study, are not affected by salinity and allow high accuracy of suction measurements up to -1500kPa.

In this experiment, samples were poured into the columns and the polymer tensiometers were inserted into the soils. The columns were placed on the digital balance of 0.1 g precision to continuously record sample weight at 60 seconds intervals until no significant mass changes were observed. The tensiometers were connected to a data logger to record data every 60 seconds to develop the SWRC curves.

5 RESULTS AND DISCUSSIONS

The shrinkage tests with continuous readings were continued beyond the shrinkage limit until no significant mass changes were observed. Once the shrinkage test was finished, the entire set of readings was analyzed and the shrinkage curves of the tested soils were plotted as shown in Fig. 8 to 10 in terms of void ratio versus gravimetric water content.

As shown in Fig. 8 Kaolin was prepared with 124.5% gravimetric water content at the beginning of the test which is approximately 1.4 times higher than the Liquid Limit, and the Shrinkage Limit was measured at 34.7% gravimetric water content.

According to Fig. 9 Red mud was prepared in a slurry form with nearly 2 times Liquid Limit, and the Shrinkage Limit was measured at 14.9% gravimetric water content.
As illustrated in Fig. 10, the initial condition of the dredged mud was a slurry with 121% gravimetric water content, and the Shrinkage Limit was measured at 18.3% gravimetric water content. The Shrinkage Limit was determined from the VSCC using the double tangent method. The tangent was drawn from the zero shrinkage portions and from the normal shrinkage portion. The point of intersection of the two tangents was taken as the Shrinkage Limit. Table 2 summarizes the details of water content at air entry value from SWRC together with the Shrinkage Limit obtained from VSCC.

Table 2. Determined AEV and Shrinkage Limit

|          | Kaolin | Red mud | Dredged mud |
|----------|--------|---------|-------------|
| AEV      | 34.5   | 28.3    | 31.2        |
| Shrinkage limit (%) | 34.7   | 14.9    | 18.3        |

The results from Table 2 show that the gravimetric water content corresponding to the AEV is higher than Shrinkage Limit at which desaturation starts. Huge differences between AEV and Shrinkage Limit can be recognized specially for red mud and dredged mud. Also, it can be seen that the gravimetric water content at the AEV derived from the SWRC plotted for the gravimetric water content is close to the plastic limit (see also Table 1).

6 CONCLUSIONS

In this study, it was demonstrated that the ring method can be used to quantify the volumetric shrinkage characteristics curve (VSCC) of high plasticity soil from initially high-water content to completely dry condition. The shrinkage curve can be used to determine the true air-entry value when for the first time the initial saturation significantly changes. Polymer tensiometer was shown to be effective to measure the suction up to -1500 kPa in a soil with high salinity and substantial organic content. The water content at air entry value (AEV) was determined from the SWRC and it was found that it is more than the shrinkage limit value determined from the VSCC. In addition, it was observed that gravimetric water content corresponding to AEV from SWRC is higher than shrinkage limit and approximately close to the plastic limit. From this study, it can be concluded that the ring method is ideal to measure shrinkage limit of soft soils based on the VSCC from slurry state to oven-dry condition with simple and low-cost equipment.

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