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Shrinkage and desaturation properties during desiccation of reconstituted cohesive soil

Takeo Umezaki*, Takashi Kawamura

Department of Civil Engineering, Shinshu University, 4-17-1 Wakasato, Nagano City, Japan

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Abstract

A vacuum evaporation method, proposed by the authors to reduce the water content more quickly than by air drying, was applied to six saturated reconstituted cohesive soil samples to investigate shrinkage and desaturation properties during desiccation. The test conditions were a vacuum pressure of $p_v = -93.9$ to -97.5 kPa, a consolidation pressure of $\sigma_v = 68.6$–392 kPa, an initial water content of $w_0 = 0.59$–$0.92\ w_L$, and an initial surface area of the specimen of $A_{s0} = 20$–205 cm^2, where w_L is the liquid limit. The results obtained for these restricted conditions are as follows. The vacuum evaporation of pore water from the soil occurs at a vacuum pressure higher than about -93 kPa ($|p_v| > 93$ kPa), but the evaporation process is very slow. The minimum void ratio, $e_{\min}$, at the no-shrinkage phase of the soil subjected to the vacuum pressure, becomes a constant value. The relations $e_{\min} \approx 1.15\ e_s$ and $w_s \approx 87(e_{\min}/G_s)$ are obtained, where e_s is the void ratio corresponding to the shrinkage limit, w_s, and G_s is the specific gravity of the soil particles. Using the vacuum evaporation method, the continuous relations for $w-e$, $w-V/V_0$, and $w-S_r$ are more easily and more rapidly obtainable than with the conventional method by air drying. These three relations were formulated using two parameters, namely, an experimental parameter that is simply obtained using vacuum evaporation tests and a parameter that can be assumed and determined easily. The three formulated relations show a good agreement with the experimentally obtained results. Furthermore, if the basic physical parameter, w_s, has already been obtained, then the three relations can be estimated roughly without the performance of any tests.

Keywords: Cohesive soil; Consistency limit; Degree of saturation; Evaporation; Shrinkage; Unsaturated soil; Vacuum pressure; Void ratio; Water content; (IGC: D2)

1. Introduction

The shrinkage limit obtained from shrinkage parameter tests (BS 1377-2: 1990, ASTM D4943-08: 2008, JIS A 1209: 2009) and a shrinkage curve, expressing volumetric shrinkage with a decreasing water content, are important soil shrinkage properties. As shrinkage progresses, the degree of soil saturation decreases. The properties of shrinkage and desaturation, with a decreasing water content, are the fundamental properties of unsaturated soil. Factors influencing the shrinkage properties are the soil structure, the initial water content, the type of clay mineral, the clay content, the organic matter content, the kind and concentration of the cation of the pore water, the drying conditions, etc. (Japanese Geotechnical Society (JGS), 2009). In recent years, the slope failure of unsaturated soil has occurred in many locations due to heavy local rains exacerbated by climate change. Knowledge of

*Corresponding author.
E-mail address: umezaki@shinshu-u.ac.jp (T. Umezaki).
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shrinkage and desaturation properties is necessary for improving evaluations of the strength and the deformation of unsaturated soil and for making advancements in the seepage analyses of unsaturated grounds.

Shrinkage curves are generally portrayed, as shown in Fig. 1(a) and (b), as the relation between w and V/V_0 for two soil conditions. In the figure, V stands for the soil volume, V_0 is the initial volume, V/V_0 denotes the ratio of volume, $(V/V_0)_{\min}$ signifies the minimum ratio, w represents the water content, w_0 is the initial water content, w_L is the liquid limit, w_s denotes the shrinkage limit, and S_r is the degree of saturation. Fig. 1(a) and (b) presents the slurry and the undisturbed conditions of the soil, respectively. In Fig. 1(a), the shrinkage curve for the slurry condition is divided into three phases, namely, normal shrinkage, residual shrinkage, and no shrinkage (Hanes, 1923; Stirk, 1954). In the stage of normal shrinkage, $S_r=100\%$ is maintained and the rate of decrease in volume with the decrease in soil moisture is constant. In the stage of residual shrinkage, the rate gradually becomes smaller. Finally, in the stage of no shrinkage, the volume does not decrease even if the moisture decreases. However, as presented in Fig. 1(b), for the undisturbed condition with a developed soil structure, structural shrinkage is added to the curve. It consists of four phases (Peng and Horn, 2005; Stirk, 1954).

The shrinkage limit, w_s, is defined as the water content at which the soil volume does not decrease even if the soil water content decreases. However, in shrinkage parameter tests, as presented in Fig. 1(a), the intersection of a normal shrinkage line with the saturated condition, $S_r=100\%$, and a no-shrinkage line with minimum volume is determined as the shrinkage limit. The JIS test procedure for soil with particles smaller than 425 μm is shown below. Slurry clay, with an initial water content of $w_0 \approx w_L$, is put into the shrinkage dish. The typical size of a shrinkage dish is 45 mm in internal diameter and 13 mm in depth. The specimen here has an initial volume of $V_0 \approx 20\ \text{cm}^3$ and an initial mass of $m_0 \approx 30$ g. The initial top surface area is $A_{s0} \approx 16\ \text{cm}^2$. After air-drying, oven drying is performed on the sample until the top surface color of the specimen changes to a light color, and the mass and the minimum volume, $V_{\min}$, are determined. The value of $V_{\min}$ is calculated using the wax method by which a specimen is coated with paraffin wax and weighed in air and in water separately. In this test, the drying process might take several days and a shrinkage curve, like that presented in Fig. 1(a), is not usually required. Watahiki (1986, 1987, 1989, 1990, 1991) conducted shrinkage parameter tests by air drying Kaolin clay with the slurry condition. The main results are presented herein. The value of w_s becomes larger for higher w_0. However, conditions such as the shrinkage dish size and shape, the rate of air drying, and the drying temperature are negligible when estimating the value of w_s.

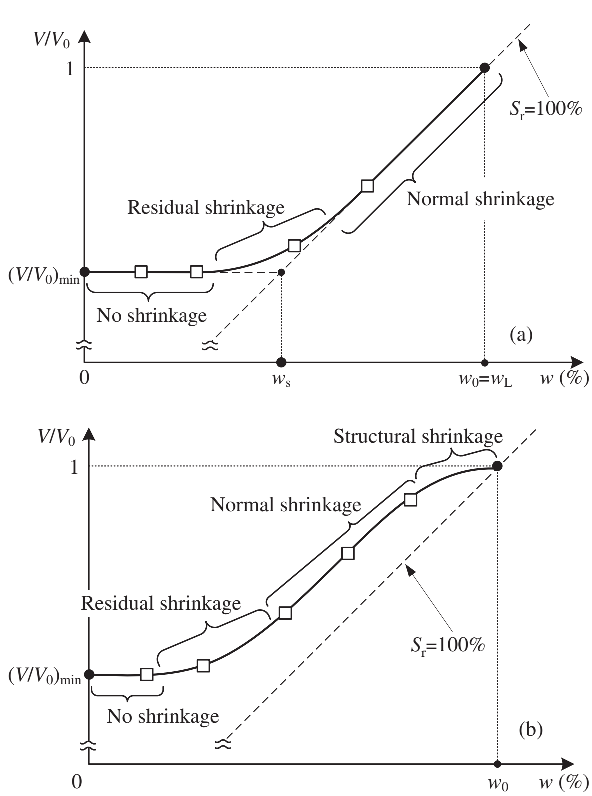

Fig. 1. Shrinkage curves. (a) Slurry condition and (b) undisturbed condition.

Kazama and Takahashi (1998) reported the shrinkage curve obtained using air drying with samples of four slurry clays and reconstituted Kaolin clay. Here, many specimens were used to draw the shrinkage curve. Therefore, the obtained data were scattered slightly. The main results were as follows. In reconstituted clay, residual shrinkage was not recognized clearly in the shrinkage curve. Regarding the relation of the void ratio and the water content, a unique shrinkage curve was obtained that was independent of the initial water content. Several shrinkage curve models have been proposed (e.g., McGarry and Malafant, 1987; Crescimanno and Provenzano, 1999; Peng and Horn, 2005). McGarry and Malafant (1987) divided the shrinkage curve into structural shrinkage, normal shrinkage, and residual shrinkage and proposed a three-straight-line model with 3–5 fitting parameters. Peng and Horn (2005) formulated an equation for the shrinkage curve that was applicable to clay under the conditions of undisturbed clay, reconstituted clay, and paste clay based on the equation for predicting the water retention curve of van Genuchten (1980). Three fitting parameters are necessary for this model. In the above models, a great amount of experimental data must be used to determine the parameters, and they are not easily obtainable.

Air drying, for which the test time is extremely long, is used to obtain the shrinkage curve. However, a vacuum evaporation method was proposed by which the soil water content can be reduced quickly (Umezaki and Kawamura, 2000; Inoue et al. 2005; Umezaki et al. 2008). To avoid confusion with the term vacuum "consolidation", which means drainage and dewatering, as a ground improvement method, the authors have designated the vacuum