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Influences of degree of saturation and strain rate on strength characteristics of unsaturated granular subbase course material

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ABSTRACT

The aim of this study is to clarify strength characteristics of a subbase course material changed due to the degree of saturation and the strain rate. A series of monotonic triaxial compression tests was carried out under desired unsaturated and strain rate conditions using a medium-size triaxial compression apparatus. The test results indicate that the degree of saturation can significantly affect shear behaviors of the subbase course material in terms of the shear strength and deformability. On the other hand, the triaxial compression tests with the strain rate of 0.5%/min were conducted as well as those with 0.05%/min, which has been usually employed. The experimental results show that the mechanical behavior of the subbase course material is susceptible to the strain rate, and such relations can vary depending on the degree of saturation in shear. Furthermore, change in the strength parameters such as the total internal friction angle and the total cohesion resulting from the degree of saturation and the strain rate effects will be discussed. The calculation results show that the effects of degree of saturation and strain rate on the total internal friction angle appear to be negligible, while the total cohesion can be affected by the degree of saturation and the strain rate. More specifically, the failure envelope for the subbase course material is nonlinear under the low suction ranges. Therefore, the failure surface drawn through the failure envelope with respect to the matric suction is curved surface. The failure surface for unsaturated specimens with higher strain rate is located above that with lower strain rate.

Introduction

Water can penetrate into pavement structures through many methods, such as rainfall and ground water (Dempsey and Elzeftawy, 1976), thereby causing change in degree of saturation inside pavement structures. In a cold snowy region such as Hokkaido, Japan, enormous amounts of thaw water occurring in springtime can infiltrate pavement structures besides the rainfall and ground water. Ishikawa et al. (2012a) pointed out that the increase in degree of saturation triggered by the water inflow led to temporal deterioration in bearing capacity of pavement structures. In addition, Oloo et al. (1997) revealed that the matric suction associated with water content has a significant effect on the bearing capacity of pavement structures. Therefore, to provide rational designs for transportation infrastructures better suited to climatic conditions in cold snowy regions, it is of great importance to understand mechanical behaviors of subbase course materials constituting pavement structures under different unsaturated conditions.

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Unsaturated soil mechanics concerning shear strength, permeability and compaction etc. have been studied and established by many researchers (*e.g.* Bishop and Donald, 1961; Fredlund et al., 1978; Rahardjo et al., 2004; Zhan and Ng, 2006; Vanapalli and Lacasse, 2010; Oka et al., 2010). For example, Rahardjo et al. (2004) conducted consolidated drained and constant water content tests on unsaturated sand to investigate the shear strength characteristics of sand associated with rainfall-induced slope failures. Zhan and Ng (2006) studied the shear strength characteristics of an expansive clay, and discussed the contribution of the matric suction to the shear strength. Oka et al. (2010) found that the initial suction strongly influenced the stress-strain behavior of the unsaturated silt. Thus, previous studies tended to focus on the unsaturated soil mechanics of sand, silt and clay, which have relatively small constituting particles. It is well known that unsaturated soil tests are time-consuming, especially for the specimen with large particles. Therefore, experimental studies on the mechanical behaviors of a gravelly soil such as a subbase course material under unsaturated conditions are very limited. Nishimura et al. (2012) and Ishikawa et al. (2010) performed some laboratory element tests for unsaturated soils by means of the pressure membrane method. In their studies, the validity of the pressure membrane method was confirmed by comparing the test results with those of the pressure plate method, which has been widely adopted for the unsaturated tests in the past. The methodology of the pressure membrane method was proved to successfully shorten the testing time to a significant extent. In addition, Ishikawa et al. (2014) developed a medium-size triaxial apparatus applicable for unsaturated gravelly soils, and the usefulness of the apparatus was confirmed based on the test results of a subbase course material and Toyoura sand.

On the other hand, to evaluate the mechanical stability of pavement structures towards transfer traffic loads, the influence of the strain rate on the shear behaviors of subbase course materials should be considered. According to Yamamuro and Lade (1993), it was revealed that monotonic shear behaviors of a granular soil were susceptible to the strain rate, and the shear strength under drained condition increased with the increase of the strain rate. Moreover, Aqil et al. (2005) performed drained triaxial compression tests at different constant strain rates on a crushed concrete aggregate as a backfill material, and detected that the mechanical behaviors were similar to the above-mentioned results with regard to the strain rate. However, Tatsuoka et al. (2008) performed drained traxial compression tests on Hime gravel material at largely different constant strain rates and found that the strength of the gravel material decreased with an increase in strain rate. Accordingly, it seems to be no uniform tendency regarding the effect of strain rate on the characteristics of granular materials. Especially, there is limited available information in existing literatures about mechanical behaviors of unsaturated subbase course materials with maximum particle size of almost 40 mm subjected to different strain rates.

Keeping in mind the above, in this study, the effects of degree of saturation and strain rate on strength characteristics of a subbase course material were examined. A series of monotonic triaxial compression tests was carried out under desired unsaturated and strain rate conditions using the medium-size triaxial apparatus developed by Ishikawa et al. (2014). Based on the test results, change in strength parameters such as the total internal friction angle and the total cohesion attributed to the matric suction and the strain rate will be discussed in terms of unsaturated soil mechanics (Fredlund and Rahardjo, 1993).

Test material

Physical characteristics

In Hokkaido, Japan, pavement structures contain four layers, i.e., the asphalt-mixture layer, the subbase course layer, the anti-frost layer and the subgrade layer (Ishikawa et al., 2012a). In this study, a subbase course material called "C-40" was employed as the test material, which is a natural crusher-run made from angular, crush, hard andesite stone commonly used in the subbase course layer of pavements in Japan. Though the maximum grain size of C-40 is 40 mm, C-40 material in this study was prepared by screening out particles larger than 38.1 mm from the original material pursuant to method of test for resilient modulus of unbound granular base material and subgrade soils of Japanese Road Association (2007). The finer particle with grain size less than 0.075 mm was about 2%. Physical properties and grain size distribution curve for test specimens are shown in Table 1 and Fig. 1, respectively.

Soil–water characteristics

The soil–water characteristic test was performed on C-40 specimen with degree of compaction (D_c) of 95% based on the test method for water retentivity of soils of the Japanese Geotechnical Society (2009b). The soil-water characteristic curve (SWCC) of C-40 in the drying process is shown in Fig. 2a, which is the desaturation characteristic of C-40 expressed by the relationship between matric suction ($s = u_a - u_w$) and degree of saturation (S_r). Note that the matric suction is equal to suction without regard for the osmotic suction in this study. The SWCC curve in Fig. 2a is a J-shaped curve without clear air entry value (AEV). The residual degree of saturation (S_{r0}) of C-40 is 23.94%, which was estimated by the fitting curve with logistic model A, called LG-A model (Mori et al., 2009) shown in Fig. 2a. The LG-A model can be expressed as Eq. (1). Based on Eq. (1), the suction value under the residual degree of saturation is infinite. The various unsaturated specimens for triaxial compression tests can be obtained by applying corresponding matric suction based on the SWCC curve in Fig. 2a.

$$s_e = \frac{(s_r - s_{r0})}{(s_{r,max} - s_{r0})} = \frac{1}{\{1 + \exp(a_{lg}s + b_{lg})\}^{c_{lg}}} \quad (1)$$

here, s_e and s_r are the effective degree of saturation and the degree of saturation, respectively. s_{r0} and $s_{r,max}$ are the residual degree of saturation and the degree of saturation