Cold Regions Science and Technology 136 (2017) 44–51

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

Effect of temperature and strain rate on mechanical characteristics and constitutive model of frozen Helin loess

Xiangtian Xu [a], Yubing Wang [b,*], Zhenhua Yin [a], Hongwei Zhang [c]

[a] Institute of Transportation, Inner Mongolia University, Hohhot 010070, China
[b] Fugro Consultants, Inc., 8613 Cross Park Drive, Austin, TX 78754, United States
[c] Inner Mongolia Communications Constructions Engineering Quality Supervision Bureau, Hohhot 010020, China

ARTICLE INFO

Article history:
Received 23 June 2016
Received in revised form 14 January 2017
Accepted 31 January 2017
Available online 02 February 2017

Keywords:
Frozen Helin loess
Uniaxial compressive
Stress-strain
Strength
Elastic modulus

ABSTRACT

To investigate the effect of temperature and strain rate on the mechanical properties of frozen loess, a series of uniaxial compressive tests were conducted on saturated frozen Helin loess under five different strain rates (1×10^{-2}/s, 1×10^{-3}/s, 1×10^{-4}/s, 5×10^{-5}/s, and 1×10^{-5}/s) and at four different temperatures (−2 °C, −4 °C, −5 °C, and −7 °C). From the stress-strain curves under different testing condition, the stain-softening behavior is observed and the yield point can be obviously seen. The yield stress and strength increase linearly with the decrease of temperature and increase exponentially with the increase of strain rate. The initial tangent modulus and the secant modulus corresponding to half the strength are taken to describe the stiffness of frozen loess. And the effects of temperature and strain rate on the tangent and secant modulus are analyzed. Furthermore, an elasto-plastic constitutive model considering the effects of temperature and strain rate has been proposed to describe the strength and deformation behavior of frozen Helin loess.

1. Introduction

The mechanical properties of frozen soil have gained importance on engineering design process, construction and maintenance phase after construction in cold regions (Qi and Ma, 2010; Li et al., 2016). Therefore, various experiments have been performed to explore the mechanical properties of frozen soil (Yang et al., 2010; Xu et al., 2011; Lai et al., 2014; Yang et al., 2016a, 2016b; Zhou et al., 2016). Presently, to study the mechanical characteristics of frozen soil under different testing conditions involving temperature, strain rate, and confining pressure (Bragg and Andersland, 1981; Lai et al., 2013), the majority of laboratory tests are uniaxial compressive test and triaxial compressive tests (Baker et al., 1982; Andersen et al., 1995; Arenson and Springman, 2005). Since triaxial compression test is capable to simulate the effect of earth pressure on the mechanical performance of frozen soil, so it is applicable to investigate the mechanical properties of frozen soil with deep embedment (Sayles, 1973; Jones and Parameswaran, 1983; Zhang et al., 2007; Lai et al., 2010; Zhao et al., 2011). In contrast, for the frozen soil with ice-rich and ice-saturated frozen soil, confining pressure has little impact on its strength and deformation characteristics. Thus, it is time-saving and cost-effective to explore the mechanical properties of the ice-rich and ice-saturated frozen soil by uniaxial compressive test. The uniaxial compressive test is generally capable to characterize the mechanical properties of frozen soil except the examination of the effect by confining pressure. Especially, for the layer frozen soil at shallow embedment depth, the stiffness and strength characteristics determined by uniaxial compressive tests can be easily applied to engineering practice. Furthermore, the unixial compressive test is usually used to investigate other geomaterials under lower temperature condition (Martin and Jun, 2010; Yang et al., 2015; Yang et al., 2016a, 2016b).

The characterizations in the strength and deformation of frozen soil were firstly started by performing uniaxial compressive tests at the early stage. For example, in 1930s, Tsytovich pioneered to study mechanical properties of frozen sand under different temperatures and strain rates by carrying out series of uniaxial compressive tests. He found that, with the decrease of temperature and the increase in strain rate, the strength of frozen sand increased nonlinearly, but the increasing rate of strength gradually mitigated (Tsytovich, 1972). Tsytovich, Vialov, Ladanyi and Haynes et al. (Tsytovich, 1975; Vialov, 1959; Ladanyi, 1981; Haynes et al., 1975; Haynes and Karalius, 1977) conducted a series of unconfined compressive tests on frozen soil under different temperatures, strain rates and unit weight and arrived at similar conclusion by Tsytovich (1972), Wu et al. (1994) also attained that the strength of frozen sand was related to temperature and strain rate, and he accomplished an empirical relationship that strength is a function of temperature based on series of unconfined compressive tests on frozen sand. Chen et al. (1988) found that there exist changes in both physical and chemical properties of frozen soil with the decrease of temperature, which resulted in an increase in soil strength. Zhu and

* Corresponding author.
E-mail address: wangyubing@utexas.edu (Y. Wang).

http://dx.doi.org/10.1016/j.coldregions.2017.01.010
0165-232X/

Nomenclature

σ_y	yield stress
σ_{y0}	reference yield stress
σ_f	strength
σ_{f0}	reference strength
σ_{ij}	stress tensor
$\dot{\varepsilon}_a$	strain rate
$\dot{\varepsilon}_{a0}$	reference strain rate
ε_{ij}	strain tensor
ε_{ij}^e	elastic strain tensor
ε_{ij}^p	plastic strain tensor
T	temperature
T_0	reference temperature
K	elastic volumetric modulus
G	elastic shear modulus
E	elastic modulus
υ	poisson's ratio
Y	yield function
k	hardening parameter
D_{ijkl}^e	elastic flexibility tensor
D_{ijkl}^p	plastic flexibility tensor

Carbee (1984) completed a series of uniaxial compressive tests on frozen sand under different temperatures and different strain rates, and proposed a prediction model for strength which is a function of different temperature. Yang et al. (2006) discovered three characteristics of saturated saline frozen silty clay from a series of uniaxial compressive tests: (1) the negative temperature had a great effect on the strength of frozen soil; (2) the uniaxial compressive strength increased linearly with the decrease of temperature; (3) at a certain strain rate, the uniaxial strength was twice higher than the yield stress. Li et al. (2004) conduct a series of uniaxial compressive tests on saturated frozen clay to investigate the effects of temperature, strain rate and dry density on its strength. Zhao et al. (2013) applied the uniaxial compressive test to study the deformation and strength of frozen clay under thermal gradient condition. All of the conclusions from these existing research results point out the temperature and strain rate are the primary external factors affecting the mechanical properties of frozen soil. However, the mechanical response of frozen soil under various thermal-mechanical conditions is not only determined by those external factors, the internal factors, such as water content, dry unit weight, salt content, and degree of saturation, are also critical to the mechanical properties of frozen soil. These internal factors result in the measured mechanical characteristics of the same type of frozen soil are different from each other even under the same experimental conditions. These disagreements made it difficult when applying those experimental results to solving practical engineering problems and referencing those researchers' work for future study. The purpose of this paper is to report mechanical properties of frozen loess collected for a road project in Helin County, Hohhot City, Inner Mongolia Autonomous region. A series of uniaxial compressive tests were conducted on the frozen loess under different strain rates (1×10^{-2}/s, 1×10^{-3}/s, 1×10^{-4}/s, 5×10^{-5}/s, and 1×10^{-5}/s) at different temperatures (−2 °C, −4 °C, −5 °C, and −7 °C). Based on the tests results, attention has focused in particular on the stress-strain curves, yield strength, elastic modulus and constitutive model with the variation of temperature and strain rate, which provides reference for the construction projects in cold regions.

2. Test program

2.1. Test material

The soil material was collected from Helin County, Hohhot City, Inner Mongolia Province, China. The grain size distribution determined by a laser particle size analyzer was shown in Table 1. From the distribution, the soil is classified as silty sand. The specific gravity is 2.526 by specific gravity test.

2.2. Sample preparation

In this paper, the preparation of frozen loess sample was followed by the sample preparation method by Chang et al. (1995). Firstly, the impurities such as small pebbles in the natural loess collected from field were screened out by the sieve with 2 mm mesh size. Then, the loess was reconstituted by mixing thoroughly with distilled water (appropriate 10% by weight of soil), and sealed for 12 h to ensure that water content was uniform in the mixed soil. Next, the mixture was compacted into a cylinder with the diameter of 6.18 cm and the height of 12.5 cm and filled into a three-piece split mold. We placed one porous stone at the top and one at the bottom of specimen. Afterwards, the specimens were evacuated and saturated with water for 24 h and then placed into refrigerator for 48 h. The three-piece split mold was removed from the specimen and epoxy resin platens were place on top and bottom of specimen while a rubber membrane being wrapped around. The specimens are divided into two groups for different testing scopes: the specimens in the first group were used to test in different temperature (−2 °C, −4 °C, −5 °C, and −7 °C) under the same strain rate (1.67×10^{-4}/s); the specimens in the second group were used to test at different strain rate (1×10^{-2}/s, 1×10^{-3}/s, 1×10^{-4}/s, 5×10^{-5}/s, and 1×10^{-5}/s) but at a constant temperature at −4 °C. All of the specimens were kept at the target temperature at least for 12 h so that temperature inside each specimen is homogenous. The water content of saturated specimen is 24.58%, and dry density is 1.97 g/cm^3.

2.3. Test apparatus and test procedure

A frozen soil creep apparatus used in this study is capable of applying axial force ranging from 0kN up to 100kN, and controlling temperature from −25 °C to room temperature with resolution of 0.1 °C. The apparatus can be either strain-controlled or stress-controlled. In this study, the strain-controlled mode was used.

The testing procedure was summarized as following. First, we tested the specimens in the first group. We placed the specimen into the loading chamber where the temperature was set up to the same one as in the specimen preparation stage. Then we waited for a couple minutes for the temperature reached equilibrium state, and we slowly lowered down the loading piston until the platen of piton was perfectly in contact with the top of specimen. Last, we started loading the sample at strain rate of 1.67×10^{-4}/s, and stopped loading at 20% strain limit.

We followed same procedure to test the second group, except that the loading rate was set up to 1×10^{-2}/s, 1×10^{-3}/s, 1×10^{-4}/s,

Table 1
Particle fraction of Helin loess.

<0.005 mm	0.005–0.05 mm	0.05–0.075 mm	0.075–0.10 mm	0.10–0.25 mm	>0.25 mm
1.91%	12.59%	20.76%	20.71%	40.56%	3.43%