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Application of the punch shear test to evaluate adfreezing strength of frozen soil-structure interface

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ABSTRACT

The direct shear test is commonly used to evaluate shear behavior of frozen soil-structure interface under normal stress. However, failure criteria including the Coulomb failure criterion should be needed to obtain unconfined shear strength. Hence, the punch shear test, which is usually used for estimating shear strength of rock without confinement, was examined in this study to directly determine the adfreezing strength measured as shear strength of frozen soil-structure interface under unconfined condition. Different soils of silica sand, field sand, and field clay were prepared inside the steel and concrete ring structure. Soil and ring structure were frozen together at the target temperature for more than 24 hours. Then, the punch shear test was conducted. The test result shows that the punch shear test is applicable to measure the adfreezing strength of the frozen soil-structure interface.

1. INTRODUCTION

Artificial ground freezing method for ground improvement and waterproofing has been widely applied in tunneling constructions (Afshani and Akagi 2015, Russo et al. 2015, Tounsi et al. 2019, Zheng et al. 2021). The frozen soil could adhere to the surface of structures such as shield machine and tunnel segment via ice formed by frozen pore water at those sites. This process is called adfreezing, and adfreezing strength is defined as maximum shear stress making the interface between the frozen soil and the surface of structures slipped. Adfreezing is able to damage the tunnel segment or give additional load to the shield machine (Quanbin et al. 2018). Furthermore, adfreezing strength is affected by diverse influence factors: temperature, soil properties, water contents,

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[1), 2)] Graduate Student, [3)] Professor, [4)] General Manager, [5)] Assistant Professor material of structure, rate of load application, confining stress, etc. Therefore, estimating adfreezing strength under various conditions is necessary for ground freezing works.

Terashima (1997) summarized four conceptual experiments to evaluate adfreezing strength: push-out test, pull-out test, twist test and shear test, and concluded that the four tests showed the same results. Many researchers have explored the adfreezing strength through direct shear test with different normal stress (Ko and Choi 2011, Choi 2011, Lee et al. 2013, Liu et al. 2014, Wang et al. 2019, Pengfei et al. 2020, Pengfei et al. 2021). While the direct shear test can consider the effect of normal stress and is easy, it should use failure models such as Coulomb criterion to gain unconfined shear strength. Hence, a new experimental method is demanded to directly assess the unconfined adfreezing strength as a critical state from a design perspective.

The purpose of this study is to examine the applicability of the punch shear test for evaluating adfreezing strength depending on soil type, materials of structure, temperature, water contents. In the rock mechanics, the results of the punch shear test are received as the shear strength of rock with zero confinement (Jaeger 1979, Li et al. 2017, Wu et al. 2017, Xu et al. 2019). Based on this knowledge, the punch shear was introduced to determine maximum shear stress, which has the frozen soil detached from structure by developing an appropriate specimen preparation method with ring structure.

2. EXPERIMENTAL METHODOLOGY

2.1 Punch shear test

Punch shear test is the common test method to measure the shear strength of thin disc rock specimens. Shear stress is delivered by compressive force through a cylindrical punch head and parallel to the shear surface (Zhu and Li 2021). In order to apply the punch shear test for adfreezing estimation, a suitable specimen preparation method was developed with ring structure. The punch test illustrated in Fig. 1 consists of punch head, a soil-ring structure, and bottom ring support. The punch head whose diameter is equal to the inner diameter of ring structure carries normal load to soil-ring structure. Soil-ring structure bears the compressive force on its shear surface where soil specimen meets ring structure, then is separated into soil specimen and ring structure if the shear stress exceeds adfreezing strength. Bottom ring support props up only ring structure so that the soil specimen can be slipped alone.

The adfreezing strength σ_{adf} could be calculated by Eq. (1) as a maximum value of the compressive force divided by the shear surface area.

$$\sigma_{adf} = \frac{F_{max}}{\pi D H} \tag{1}$$

where F_{max} is a maximum value of compressive force, D is an inner diameter of ring structure, and H is a height of ring structure.

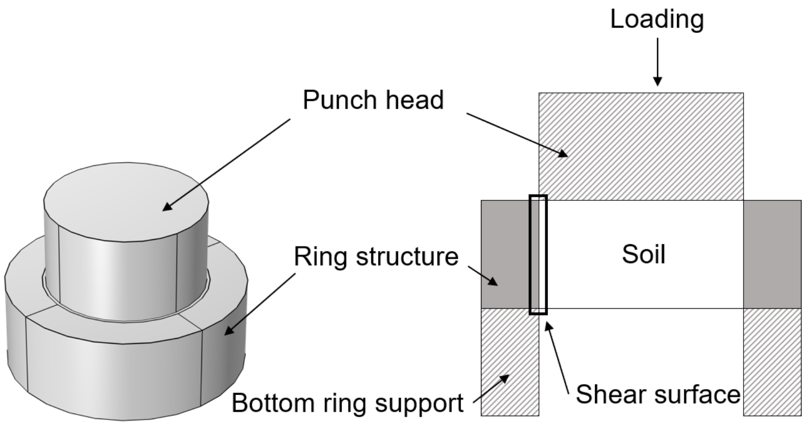

Fig. 1 Schematics of punch shear test setup and shear surface

2.2 Experimental work

Silica sand, field sand, and field clay were prepared as soil specimens. The basic physical properties of the soil are shown in Table 1. The materials of ring structures were stainless steel and concrete consisting of ordinary Portland cement and water by a mixing ratio of 100:14, and the inner diameter of the ring structure is 76 mm and the height of the ring structure is 40 mm. The punch head and the bottom ring support were made of stainless steel. The diameter of the punch head and the inner diameter of the bottom ring support were equal to the inner diameter of the ring structure as 76 mm. Also, the heights of the punch head and the bottom ring support were 40 mm.

Soil-ring structures were fabricated by compacting soil specimens inside the ring structures, and then frozen together at the target temperature. The target temperature was designed as -5, -10, -15, and -20 °C. In the case of sands, when the soil specimens were compacted, dry density was 1.5 g/cm^3, and water contents had four cases as 10, 13, 16, and 19%. However, in field clay, the clay specimens were remolded with four relative water contents ranging from 52 to 65% at each comparison group. After the soil-ring structure was frozen at the target temperature for more than 24 hours, the punch head and bottom ring support were assembled with soil-ring structures, and then the punch shear test was conducted. A compression test system was utilized to employ compressive force on the punch head, and the velocity of the punch shear test is 1 mm/min.

Through the above experimental work, the adfreezing strength according to the type of soil, ring structure material, temperature, and water contents was evaluated via the punch shear test.

Table 1. The basic physical properties of soils

	Specific gravity (Gs)	Coefficient of uniformity (Cu)	Coefficient of curvature (Cc)	Liquid limit (LL)	Plastic limit (PL)	Classification (USCS)
Silica sand	2.65	0.02	0.87	NP	NP	SP
Field sand	2.66	2.27	1.18	NP	NP	SP
Field clay	2.72	-	-	61.98	30.93	CH

3. RESULTS AND DISCUSSION

The shear stress in shear stress-displacement curves from the punch shear test had a sharp decrease after reaching the maximum shear stress, which means the normal force divided by the shear surface area went beyond the adfreezing strength of the frozen soil-structure interface.

Experiment results illustrate that the adfreezing strength between soil and concrete ring structure increases along with water contents increment at -15 °C. Because if the soil has more water contents, the amount of ice usually raises at the same temperature, and then cementation action of ice, i.e. adfreezing, becomes more substantial. Fig. 2 represents the effect of water contents on adfreezing strength. The relative water contents of field clay were represented as 1 to 4. Also, the absolute water contents of sands were expressed as 10 to 19%.

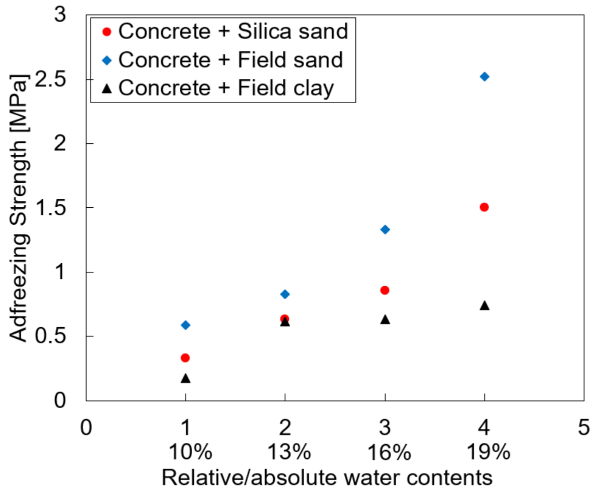

Fig. 2 Relationship between adfreezing strength and water contents with concrete ring structure at -15 °C

Fig. 3 depicts the variation of adfreezing strength for frozen soil and steel ring structure with the temperature at 16% and 3 of water contents. It can be seen from Fig. 3 that adfreezing strength tends to increase with the decrease of temperature. Since the decrease of temperature leads to the amount of unfrozen water decrease and makes the ice more formed in the voids of soil, the adfreezing strength is intensified.

The effect of the ring material on adfreezing strength is not noticeable in our experiment, which is different from Ladanyi (1995), however, there is a significant difference according to the soil types. Although the field clay has the highest water contents compared with the other sands, the field sand shows the largest adfreezing strength, followed by the silica sand and the field clay under the same temperature and ring structure. This difference appears due to the soil properties.

These results indicate that the adfreezing strength is not affected predominantly by one influencing factor but affected in a complex way by various influencing factors. For this reason, a proper estimation method for adfreezing strength under the specific condition is necessary, and the punch shear test introducing the proposed method was examined as a suitable way, because the test results are consistent with the theoretical trends on the temperature and water contents.

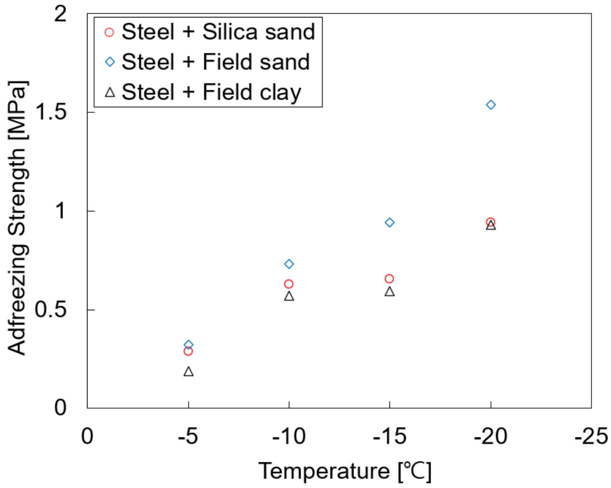

Fig. 3 Relationship between adfreezing strength and temperatures with steel ring structure at 16% and 3 of water contents

4. CONCLUSIONS

Multiple laboratory experiments have been carried out to find the adfreezing strength using a direct shear test that is simple and can reflect a confined condition. In practice, however, there are times when it is necessary to get unconfined adfreezing strength assuming a critical situation and the direct shear test needs certain models to predict that strength.

The punch shear test which can directly measure the shear strength of rock with zero confinement is suggested to evaluate adfreezing strength between frozen soil and structure with a suitable specimen preparation method. The punch shear test system consists of the punch head, soil-ring structure, and bottom ring support, and the adfreezing strength was calculated under different conditions: soil types, materials of the ring structure, water contents, and temperature.

Experimental results show that the adfreezing strength increases with increments of water contents and decrease of temperature and is affected by soil properties. Since all the results are reasonable in accordance with theoretical knowledge, applying the punch shear test is possible to estimate adfreezing strength.

Nevertheless, there are some limitations of this research. The punch shear test results should be identified by comparing the direct shear test results in order that which stage of normal stress, i.e. confining pressure, in the direct shear test can be valid for the punch shear test. Also, the dimension problem needs to be considered because soil and ring structure sizes could influence the results (Terashima 1997). Therefore, further research will be conducted to overcome these limitations by additional experiments and numerical analysis.

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