Fracture behavior of frozen soil

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ABSTRACT

Previous research shows that the mechanical behavior of frozen soil is different from the unfrozen one in that the frozen soil has different composition from the unfrozen one consisting of soil particle, air, ice and unfrozen water. Especially the frozen soil is sensitive to creep behavior due to the influence of the ice and unfrozen water. Previous research shows that the creep behavior can be governed by fracture in some specific conditions. The cracks in the frozen soil also can lead to unexpected destruction in soil structure. Therefore, it is necessary to investigate the fracture behavior of frozen soil and how it affect the long-term behavior of the frozen soil. However, the research to investigate the fracture behavior of frozen soil was rarely performed and some researches have been performed under limited conditions. Therefore, in this research, three-point bending test was performed using frozen uniform sand with fine contents of 0, 5, 10 and 15% under various temperature to investigate the influence of the fine contents and temperature on the fracture behavior of the frozen soil.

Keywords: frozen soil; fracture; three-point bending test; fine contents

1 INTRODUCTION

Many countries are interested in development of the permafrost area because of the abundant resources such as oil and natural gas. Frozen soil has different composition from the unfrozen one consisting of soil particle, air, ice and unfrozen water. Especially frozen soils are sensitive to creep behavior due to the influence of the ice and unfrozen water (Ladanyi 1972). Since 2012, coping with the social needs on the development of a permafrost area, the geotechnical research group at Dankook University has been performing research on the mechanical behavior of frozen soil. A number of papers on the mechanical behavior of frozen soil have been published and these researches showed that the tertiary creep response, the last stage of the creep of the frozen soil, can be governed by the fracture behavior in some specific conditions (Chae et al. 2015; Cho et al. 2015). The cracks developed during compression and creep process in the frozen soil also can lead to unexpected destruction in soil structure. Therefore, it is necessary to investigate the fracture behavior of the frozen soil and how it affects the long-term behavior of the frozen soil.

However, few researches have been performed to investigate the fracture behavior of frozen soil and some researches have been performed under limited conditions. Therefore, in this research, three-point bending test was performed using frozen uniform sand with fine contents of 0, 5, 10 and 15% under various sub-zero temperature to investigate the influence of the fine contents and temperature on the fracture behavior of frozen soil. The test results were analyzed based on the linear elastic fracture mechanics.

2 LITERATURE REVIEW

2.1 Composition of the frozen soil

Fig. 1 shows two dimensional schematic of the proposed structure of the frozen sand system.

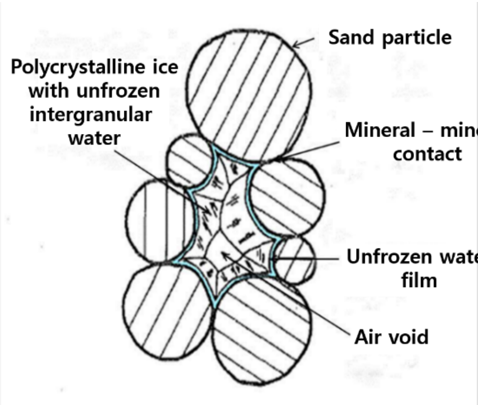

Fig. 1. Two dimensional schematic of the proposed structure of the frozen sand system (Ting 1981)

Frozen soils have different composition from the unfrozen one consisting of soil particle, ice, unfrozen water and air unlike typical unfrozen soils. Especially, the mechanical behavior of the frozen soil greatly depends on pore ice and unfrozen water. The unfrozen water exists in two states, strongly bound water and weakly bound water. The strongly bound water surrounding mineral particles exists in a form of film and holds them by high intermolecular forces that suppress freezing, even at very low temperature. The rest of the pore water except the strongly bound water is weakly bound water and can be frozen easily. The ice in the pore of the frozen soil is a polycrystalline type with a random crystal orientation (Anderson and Morgenstern 1973).

2.2 Linear Elastic Fracture Mechanics (LEFM)

Linear Elastic Fracture Mechanics (LEFM) is the basic theory of the fracture mechanics. After early works of Inglis (1920) and Griffth (1913), the fracture mechanics theory has been developed to account for various types of nonlinear material behavior such as plasticity and viscoplasticity. However, all of these works are the extensions of the LEFM and many researches on the fracture have applied LEFM for the purpose of simplify the problem (Guan et al. 2018; Li and Yang 2000).

In order to apply LEFM theory, some assumptions need to be made. One of these assumptions is that material is elastic except a vicinity of the crack tip with a sharp development of crack. Generally, some kinds of inelasticity must take place in the vicinity of the crack tip because the stress near the crack tip can be very intensive. However, if the size of the linear elastic body is large relative to the inelastic zone, then the disturbance induced by the inelastic region would be small. Therefore, using these assumptions, LEFM can be used as a basic theory for the explanation of the behavior of any material cracks such as asphalt and concrete even though precise calculation may not be made.

2.3 Stress intensity factor

The theory of LEFM has been developed using a stress intensity factor (K) determined by the stress analysis. Many researches had been performed to find a solution for the stresses in the isotropic linear elastic material behavior (Westergaard 1939; Irwin 1956). The stress intensity factor is one of the key coefficients for determining the stress around the crack tip depending on the modes of loading.

There are three types of loading mode that can advance a crack (Fig. 2). Mode I loading, where the principal load is applied normal to the crack plane, tends to open the crack. Mode II corresponds to in-plane shear loading and tends to slide one crack face with respect to the other. Mode III corresponds to out-of-plane shear loading. Generally, the mode of loading is indicated by lower subscript of the stress intensity factor (K_I, K_{II} or K_{III}). If a material fails at some critical combination of stress or strain, fracture must be taken at a critical value of the stress intensity, K_{Ic} called fracture toughness. Fracture toughness is a material property to describe the ability of a material to resist fracture and becomes one of the most important properties for many design applications related to the fractures or cracks.

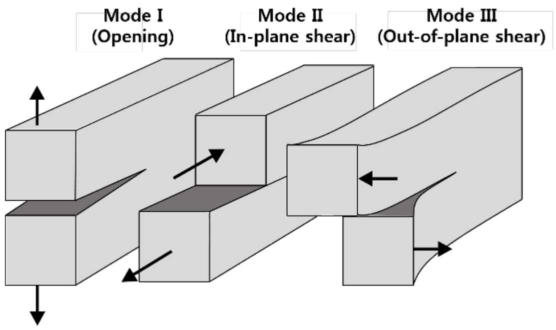

Fig. 2. The three modes of loading that can be applied to a crack.

Tada et al. (1985) proposed several solutions of the stress intensity factor for various geometry of the body and Eq. (1) is the stress intensity factor for a single-edge notched bend specimen.

$$K_I = \frac{P}{B\sqrt{W}} f\left(\frac{a}{W}\right) \qquad (1)$$

$$f\left(\frac{a}{W}\right) = \frac{3\left(\frac{S}{W}\right)\sqrt{\frac{a}{W}}}{2\left(1+2\left(\frac{a}{W}\right)\right)\left(1-\left(\frac{a}{W}\right)\right)^{3/2}} \left[1.99 - \frac{a}{W}\left(1-\frac{a}{W}\right)\left\{2.15 - 3.93\left(\frac{a}{W}\right) + 2.7\left(\frac{a}{W}\right)\right\}^2\right]$$

Where P is the applied force, B is specimen thickness, W is specimen width, a is the crack length and S is specimen length.

3 THREE-POINT BENDING TEST

In this research, three-point bending tests were performed using the frozen sand with fine contents 0, 5, 10 and 15% at -5 and -10°C to investigate the effects of fine contents and temperature on the fracture behavior of frozen soil. Unfortunately, the standard method for three-point bending test of frozen soil has not been established yet. Therefore, a testing program for the three-point bending test of frozen soil was set up herein by referring to the preceding research (Li and Yang 2000; Yamamoto and Springman 2016) and standard methods for other material such as metal and concrete (ASTM E399-17 2017; ASTM C78/C78M-18 2018).

3.1 Tested soil and specimen preparation

Jumunjun sand and kaolinite used in this test are classified into poorly graded sand (SP) and silt with low plasticity (ML) respectively according to the Unified Soil Classification System. After kaolinite was added to oven-dried Jumunjin sand with specified contents (0, 5, 10 and 15%), distilled water was added to them with initial water content of about 21% by weight. The mixed soils were placed in the mold and compacted by rammer to reach the specified density. Fig. 3 shows the mold for frozen notched specimen and produced test specimen. The dimension of the specimen is 250mm × 70mm ×

70mm. In order to make the notched specimen homogeneously, a metal plate with 35mm depth and 2mm width was placed in the middle of the specimen before freezing. The plate was extruded by the double nut bolt with uniform rate after the specimen was frozen completely.

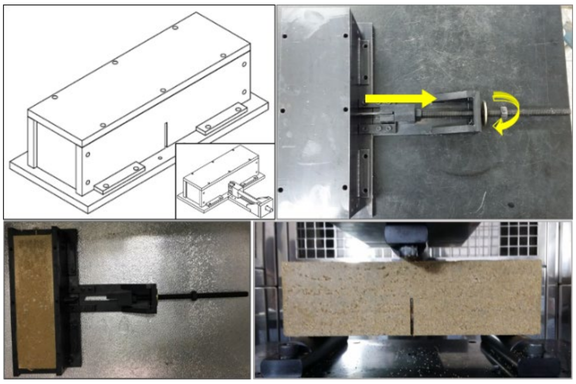

Fig. 3. Mold for frozen notched specimen and manufactured test specimen.

3.2 Test procedure

Fig. 4 shows the testing machine and schematic diagram of three-point bending test. All the tests were performed in the freezing chamber that is kept the temperature constant. The tests were conducted using an Instron FastTrack 8800 Materials Test Control System and the test results were collected in the computer memory automatically. A 100kN capacity load cell was used to measure the applied load and the accuracy was ±0.3 %. In order to measure the crack mouth opening displacement (CMOD), a clip gauge attached to the lower part of the specimen. The gauge has a capacity and accuracy of 4 mm and ±0.1 %, respectively. The test was performed by controlling load point displacement rate with 0.1mm/min until the CMOD reached 4mm.

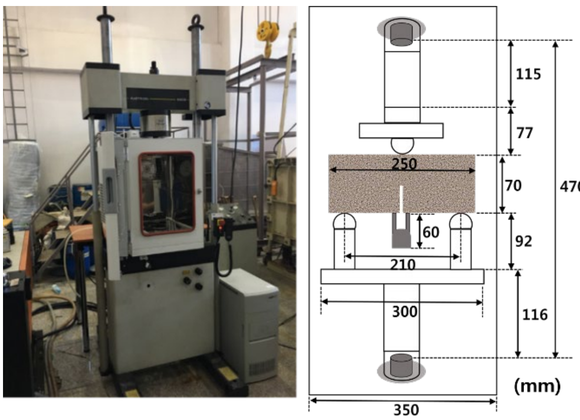

Fig. 4. Testing machine and schematic diagram of three-point bending test.

4 TEST RESULTS

In this research, three-point bending tests were performed using frozen uniform sand with fine contents 0, 5, 10 and 15% at -5 and -10℃ to investigate the effect of fine contents and temperature on the fracture behavior of frozen soil. Fig. 5 shows load-CMOD curve of the test specimens and Table 1 summarizes the test results. Based on the comparison of the load-CMOD curves of tested specimen with different fine contents, the peak load increases with the fine contents increase under both tested temperatures except 15% fine contents. The peak load of the frozen specimen with 15% fine contents decreases unlike previously mentioned trend. In addition, the peak load of the frozen sand increases with the temperature decrease at a given fine contents.

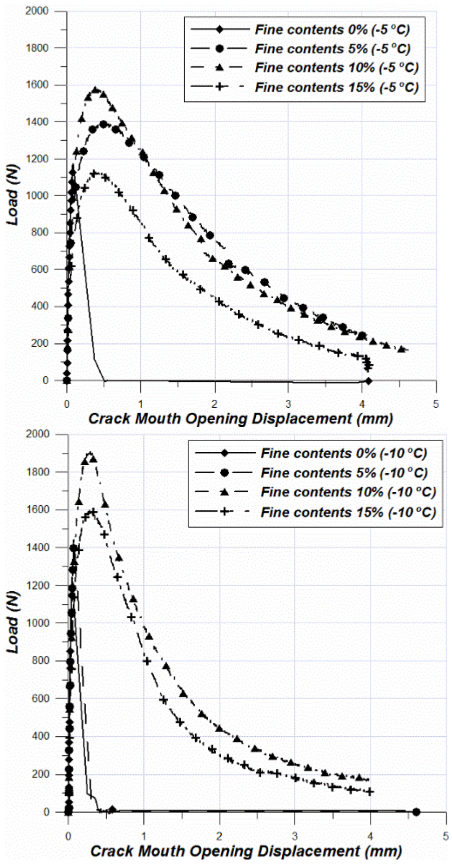

Fig. 5. Load-CMOD curve of the frozen sands with 0, 5, 10 and 15% fine contents at -5℃ (upper) and -10℃ (lower)

Table 2. summary of the test results

Temperature (℃)	fine contents (%)	P_{max} (kN)	K_{IC} (Mpa·m$^{1/2}$)
-5	0	1.176	0.507
	5	1.408	0.607
	10	1.589	0.685
	15	1.140	0.492
-10	0	1.240	0.535
	5	1.448	0.625
	10	1.919	0.828
	15	1.601	0.691

Fig. 6 shows fracture toughness of the frozen sand, calculated by Eq. (1) with regard to the various fine contents. Fracture toughness also shows the same tendency with peak load as illustrated in Fig. 6.

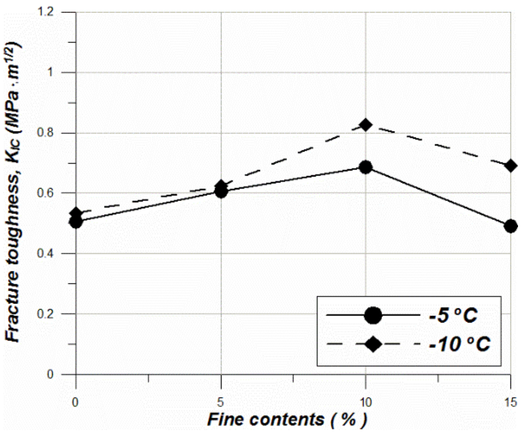

Fig. 6. The fracture toughness of the tested specimen with 0, 5, 10 and 15% fine contents at -5 and -10°C

Based on the test results, the fine contents and temperature affect the fracture behavior of the frozen sand specimen. This can be explained by unfrozen water and ice strength. The amount of unfrozen water in frozen soil at a given temperature can be related to the specific surface area of the soil particles (Anderson and Tice 1972) and the strength of the ice increase with decreasing temperature (Andersland and Ladanyi 2004). As fine contents of frozen soil increase, the unfrozen water in the frozen soil increases and it can reduce the soil-ice interaction such as ice bonding and friction resistance. Since the loss of the fracture toughness due to the unfrozen water is greater than the increase due to fine contents increasing surface area and friction, it reduces the fracture toughness of frozen sand of 15% fine contents. However, further research is needed to investigate the effect of fine contents on the fracture behavior of the frozen soil more clearly.

5 CONCLUSIONS

In this research, the three-point bending test was performed on the frozen uniform sand with fines at various temperatures to investigate the effect of fine contents and temperature on the fracture behavior of the frozen soil. Based on the test results, fracture toughness was calculated by LEFM theory and following conclusions can be drawn for the fracture behavior of the frozen sand with fine.

The fine contents and temperature affect fracture toughness of the frozen sand because of the unfrozen water and ice strength. As the fine contents increase, the peak load and fracture toughness increase less than 15% fine contents at all tested temperature. The fracture toughness is also increase with the temperature decreases. Further research is needed to investigate the effect of fine contents on the fracture behavior of frozen soil and how it affects the long-term behavior of the frozen soil.

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