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Research Article

Shear Behavior of Frozen Rock-Soil Mixture

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Mechanical behavior of frozen rock-soil mixture was investigated through direct shear test based on remolded specimens. The peak shear strength of rock-soil mixture increases greatly when it is fully frozen. The shear process goes through four stages including compaction, elastic deformation, plastic yield, and failure. The specimen has slight compaction in vertical direction at the beginning of shear test; then it changes to dilatancy. The temperature and ice content have vital important effect on the shear behavior of frozen rock-soil mixture. Results indicated that the peak shear strength of rock-soil mixture increases with temperature decreasing when temperature ranges from −1°C to −16°C. But the curve has clear inflexion at −5°C. When temperature is higher than this degree, the peak shear strength increases sharply with temperature decreasing. Otherwise, the rise of the peak shear strength with the decrease of temperature becomes gentle. The shear strength of rock-soil mixture goes up first and then down with ice content increasing at −5°C for samples with initial water contents varying from 9% to 14%. The shear strength reaches its peak value at initial water content ranging between 10% and 12% by weight.

1. Introduction

Frozen soil is a natural particulate geological composite comprising solid particles, ice, unfrozen water, and air, forming a discontinuous four-component system. The existence of ice is the main factor by which the frozen soil differs from the unfrozen soil. The ice bond binds the solid particles together and changes the interaction of soil components, posing great influence on the mechanical behavior of soil. The solid particles can be in various sizes and shapes. When solid particles include rock blocks, the determination of soil mechanical properties becomes more complicated. The strong gravel sized and/or rock blocks encased in soft soil matrix, also called bimrocks (block-in-matrix rocks) [1], cause great spatial and geomechanical variability on such materials. The presence of competent rock blocks also gives rise to heterogeneous distribution of unfrozen water and ice during freezing. Furthermore, the difference between the absorption of fine grains and the absorption of coarse grains leads to a large phase change range. Andersland and Ladanyi [2] indicated that the freezing temperature of gravel sized blocks, which have small specific surface area, is close to 0°C, and for fine-grained soils, the temperature will be as low as −5°C.

Ice content is considered to be one of the principal factors that have marked effect on mechanical behavior of frozen soils. The mechanical behavior of frozen soil depends greatly on the proportion of pore ice. Many researchers have studied the mechanical behavior of frozen sand with different sand and ice proportions [3–10]. Sayles and Garbee [11] analyzed the relationship of particles' concentration and the mechanical behavior of ice-silt mixtures. Nickling and Bennett [12] revealed that the ice content has huge impact on the mechanical behavior of frozen coarse granular debris. Wijeweera and Joshi [13] evaluated the sensitivity of strength of fine-grained frozen soil to ice content with initial water contents which varies from 15% to 105%. Hivon and Sego [14] illustrated that the proportion of ice and unfrozen water has an essential impact on the strength of frozen soil. The ice bond is the main control factor when most of the soil pores are filled with ice. Gertsch et al. [15] indicated that the strength of Lunar Regolith increases with ice content. It was noted that the Regolith containing 0.3% ice acts like weak coal and like sandstone when ice content increases to 10.6%. Yang et al.

[16] concluded that the peak compressive strength of ice-rich organic silt increases with water or ice contents. But, till now, the influence of ice content on mechanical behavior of frozen soil was often inconsistent for different soil types [17].

Temperature is another acknowledged factor that has a direct influence on the mechanical behavior of frozen soil. Temperature of frozen soils, on one hand, determines the amount of ice and unfrozen water and, on the other hand, influences the strength of intergranular ice. Haynes and Karalius [18] suggested that the strength of frozen soil increases with the decrease of temperature in a certain temperature range by means of direct shear test. Bragg and Andersland [19] provided the relationship between temperature and compressive strength of frozen sand. It was found that the compressive peak strength and the initial tangent modulus increase with decrease of temperatures. Zhu and Carbee [20] conducted a series of uniaxial tests on Fairbanks' frozen silt and found that the peak strength is susceptible to temperature at a certain strain rate. Wijeweera and Joshi [13] showed that the compressive strength of saturated fine-grained frozen soil increases exponentially with decrease of temperature. Li et al. [21] also presented that the compressive strength of saturated Lanzhou's silt is very vulnerable to temperature and increases exponentially with decrease of temperature. Yang et al. [22] recognized that warm and ice-rich permafrost collected from Qinghai-Tibet Plateau is very sensitive to change of temperature. Ma et al. [10] studied the variability of mechanical properties of frozen sand by means of triaxial compressive test and demonstrated that the variability of mechanical properties increases with decrease of temperature. The mechanical properties of seasonal and permafrost ice-rich organic silt were also investigated recently. It was illustrated that the ultimate compressive strength, Young's modulus, and shear wave velocity of both seasonally frozen and permafrost soils all decrease with increase of temperature [16].

Despite the fact that numerous researches have been done in the field of mechanics of frozen soil, there is little effort which focused on the mechanical behavior of frozen rock-soil mixtures. The rock-soil mixture has a wild distribution throughout the permafrost or periglacial region and has a comprehensive application in engineering [23]. The mechanical behavior of this material is necessary to be studied. Direct shear test is one of the commonly used laboratory test methods for mechanical behavior research of frozen soil. A series of direct shear tests were carried out in this paper to investigate the mechanical behavior of rock-soil mixture and its response to different influencing factors.

2. Samples Preparation and Test Method

The rock-soil mixtures tested in this investigation are naturally frozen talus sampled near Kunlun Mountain Pass in Qinghai, China, at a depth of 20 to 70 cm. The collected samples were wrapped using clean plastic bags and stored in insulated polystyrene boxes. Then the samples were sent to laboratory for physical and mechanical tests. The representative density of the samples is 1839 kg/m^3. The typical grain

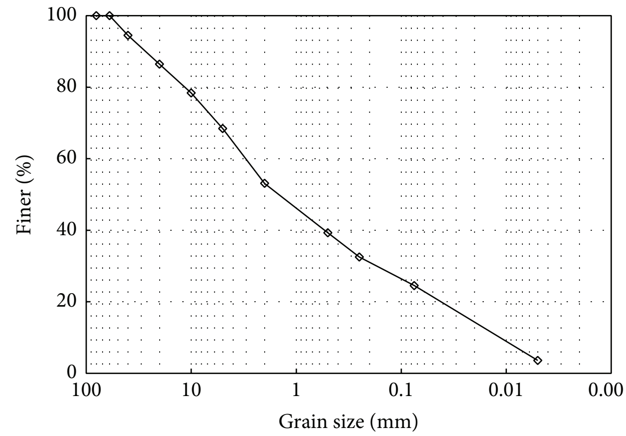

Figure 1: Grain size distribution of collected sample.

Figure 2: Initial remolded specimen.

size distribution was given in Figure 1. The soil was classified as silty sand according to Unified Soil Classification System (ASTM D2487) [24]. The rock blocks are angular and the content is 31.6% by weight. The water content of the sample after melting is 10.3%.

The shear test was on remolded specimens. The shear box of the experimental devices is a metal box with a size of 150 mm × 150 mm × 150 mm, which is split horizontally in halves. The samples were first dried and sieved. A known amount of rock blocks was mixed uniformly with fine grains. The composition of rock blocks and fine grains was according to the field collected samples. But, for avoiding the influence of the size effect, the blocks larger than 2 cm were replaced by the same weight gravels with size of 0.5~2.0 cm. Then a well calculated amount of water was added to the dry mixtures to obtain the required water content. The mixtures were poured into cube molds with sides' length of 150 mm and compacted in layers to obtain the required specimens. The preparation of the specimen was seriously controlled according to the requirements of Chinese Standard for Soil Test Method (GB/T 50123-1999) [25]. Two PT100 temperature probes were located at the center of each specimen to monitor the internal temperature. A typical artificial specimen ready to freeze was presented in Figure 2. The

Figure 3: Representative shear plane of tested specimen.

specimens were then placed in a low temperature thermostat chamber to cool. After the temperature of the specimen reached the required degree, the specimens were still cooled for another 48 hours for full frost. After that, the mold was dismantled, the temperature probes were pulled out, and the specimens were subsequently coated by a plastic film to avoid moisture evaporation. Then the specimens were placed in shear apparatus for testing. The shear apparatus was settled in a walk-in test chamber at a required test temperature within accuracy of ±5°C.

3. Shear Test on Frozen Rock-Soil Mixture

Artificial rock-soil mixture specimens were prepared according to the proportion of the natural sample. The water content is 10.3% by weight as natural samples. The initial density of the specimen is 1838 kg/m^3. After being frozen to a stable temperature of −5°C, the specimens were sent to shear test. The normal stresses are set to be 39 kPa, 56 kPa, 73 kPa, and 90 kPa. The shear rate is 0.5 mm/min. The representative shear plane of tested specimens was shown in Figure 3. The shear plane is rough and undulate.

Figure 4 shows the relationship of shear stress and shear displacement under different normal stresses. It can be observed that the stress-displacement curves clearly include four stages: the compaction stage, the linear elastic deformation stage, plastic yield stage, and failure stage. Compaction process occurs at the beginning of the test. The displacement during this process is about 2 mm. Then a long linear elastic deformation process follows. When the shear stress reaches the elastic yield point, the curves show elastoplastic deformation characteristics. The displacement increases fast with shear stress until it reaches the peak strength point; then the specimen fails and the curve clearly drops.

It can also be concluded from Figure 4 that the peak shear stress increases with normal stress. The slopes of the shear stress-displacement curves also are elevated and the displacements corresponding to specimen failure decrease with increase of normal stress. The failure displacements under normal stress of 39 kPa, 56 kPa, 73 kPa, and 90 kPa are 11.23 mm, 10.43 mm, 9.65 mm, and 9.21 mm, respectively.

The vertical displacement versus shear displacement curves were given in Figure 5. The specimen first illustrates

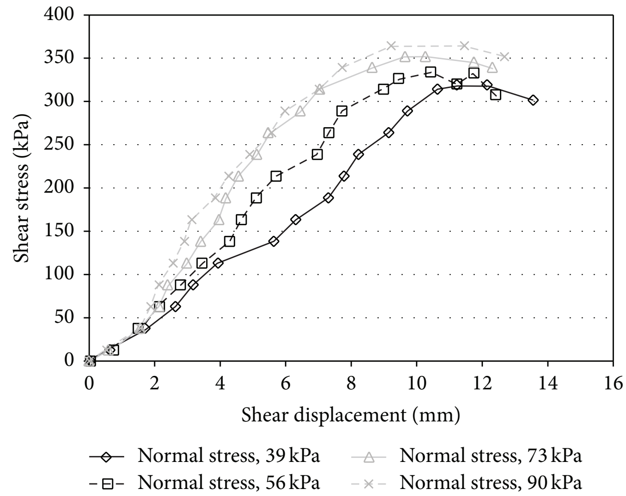

Figure 4: Relationship of shear stress and shear displacement for remolded rock-soil mixture with initial water content of 10.3% at −5°C.

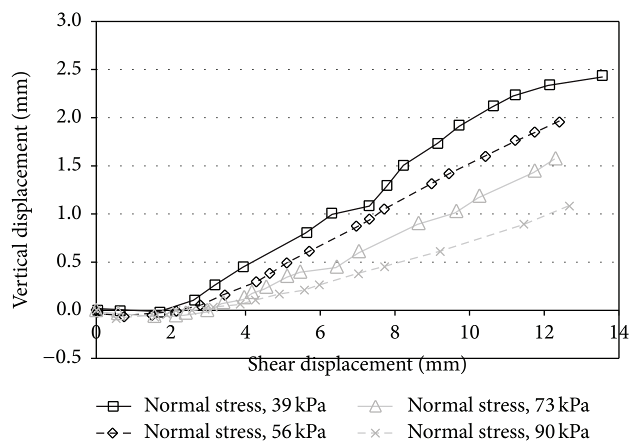

Figure 5: Relationship of vertical displacement and shear displacement for remolded rock-soil mixture with initial water content of 10.3% at −5°C.

a slight contraction and then dilatancy. At the beginning of the test, compaction occurs between the particles with weak bonds under normal stress. So the specimen shows contraction in the vertical direction. After contraction, the specimen is to dilate during shear. Under the action of shear stress, a lever motion may occur between the interlocking neighboring grains in the shear band, resulting in a bulk expansion of the specimen. It can also be observed that the dilatancy increases with shear displacement under a constant normal stress. For different normal stresses, the dilatancy decreases with increase of normal stress.

In order to thoroughly understand the difference between shear behavior of frozen rock-soil mixture and shear behavior of unfrozen rock-soil mixture, the shear curves of specimens before and after freezing were illustrated in Figure 6. It illuminates that the peak shear strength of the frozen specimen is far greater than that of the unfrozen one. The peak shear strength of unfrozen specimen is 81.6 kPa, while the frozen specimen at −5°C reaches 364.2 kPa. Unlike frozen sample, the shear

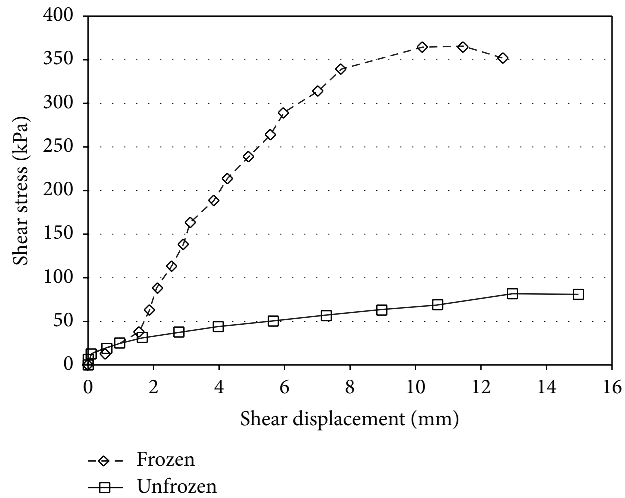

Figure 6: Shear stress-shear displacement curves of frozen and unfrozen rock-soil specimens.

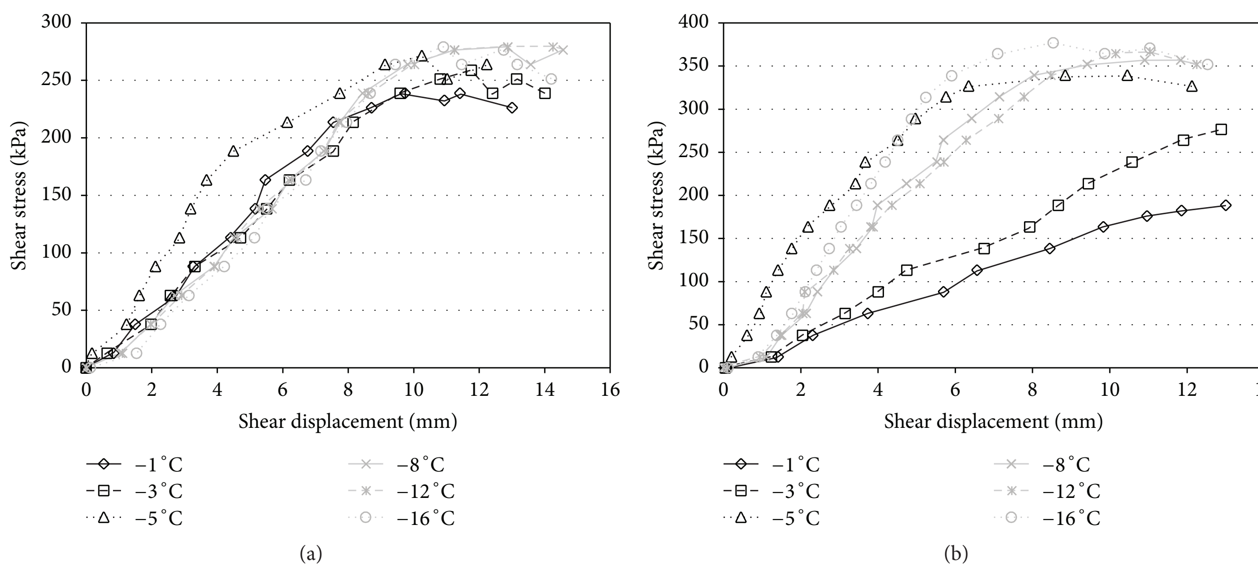

Figure 7: Relationship between shear stress and shear displacement for rock-soil mixtures with initial water content of (a) 9% and (b) 14% at different temperatures.

curve of unfrozen rock-soil mixture has no obvious linear period. Unfrozen specimen yields instantly after loading and demonstrates strain hardening characteristics. The difference between shear behavior of frozen soil and shear behavior of unfrozen soil is determined by ice. Ice bond is the most important bond of frozen soil, which controls the deformation and shear strength of the soil. After thawing, the ice bond disappeared and strength of soil decreases sharply.

4. Effect of Temperature on Behavior of Frozen Rock-Soil Mixture

The temperature, on one hand, determines the proportion of ice and unfrozen water and, on the other hand, affects the structure and the strength of the polycrystalline ice. Thus, it has an essential influence on shear behavior of rock-soil mixture. For the purpose of understanding the influence of temperature on shear behavior of rock-soil mixture, the specimens with initial water contents of 9% and 14% were tested at temperatures of −1°C, −3°C, −5°C, −8°C, −12°C, and −16°C. The normal stress is 90 kPa. The shear stress-displacement curves for the three specimens under different temperature were displayed in Figure 7.

Figure 7 indicates that the peak strength of stress-displacement curve increases significantly with decrease of temperature for specimen with same initial water content. For specimens with high initial water content, the increment is more obvious. It can also be observed that the specimens demonstrate plastic deformation characteristics at relatively high temperature (temperature higher than −3°C) like remolded soil. A decrease in temperature results in a significant drop of strength after the peak. This phenomenon is more obvious for specimen with high initial water content. For specimen with initial water content of 14%, the

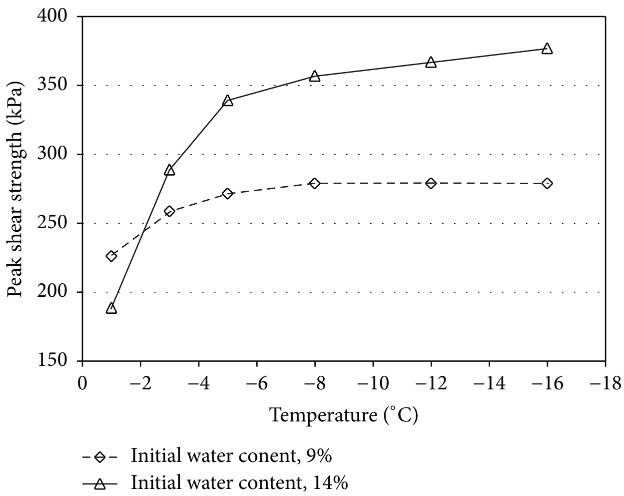

Figure 8: Influence of temperature on peak shear strength of frozen rock-soil mixture.

shear stress-strain curve has no obvious yield point when temperature is higher than −3°C (Figure 7(b)). But when temperature is lower than −5°C, the strength has a large drop after peak point. It can also be observed from Figure 7(a) that the shear compaction is high for specimens with low initial water content in which most of the pores were not occupied by ice.

Figure 8 illustrates the variation of the peak strengths of the specimens with decrease of temperature. The peak strength of each specimen increases first rapidly and then gently. When the temperature is below −5°C, the influence of temperature on the strength of rock-soil mixture reduces. The strength only increases slightly when temperature changes from −5°C to −16°C. When the temperature is near the thawing point of ice, the peak strength of specimen with initial water content of 9% is higher than the peak strength of specimen with initial water content of 14%. At a temperature of −1°C, the peak shear strength is 226.0 kPa for the former and 188.4 kPa for the latter. But the peak strength of specimen with initial water content of 14% increases more rapidly with decrease of temperature. When temperature decreases to lower than −3°C, the peak strength of specimen with initial water content of 14% reaches 288.8 kPa, which is larger than that of specimen with initial water content of 9%, 258.7 kPa. When the temperature drops to −16°C, the peak strength of specimen with initial water content of 14% is 376.8 kPa, corresponding to 278.8 kPa for specimen with initial water content of 9%. The results indicate that strength is more sensitive to temperature variation for rock-soil mixture with high initial water content.

5. Effect of Ice Content on Behavior of Rock-Soil Mixture

Due to the fact that the vast majority of free water transforms to ice at −5°C, the test temperature was set as −5°C to study the influence of ice content on shear behavior of rock-soil mixture. The initial water contents are set to be 9%, 10.3%, 11%, 12%, 13%, and 14% by mass. In the analysis, we assumed that all free water transformed to ice at −5°C. For every water content, three sets of specimens were tested under normal stresses of 56 kPa, 73 kPa, and 90 kPa, respectively. The stress-displacement curves under different normal stresses were shown in Figure 9.

Figure 9 reveals that the stress-displacement curves with different normal stress have similar variation tendency. The peak strength of the specimen increases clearly with the increase of ice content and then decreases. The slope at the ascent stage of the curve increases and the drop after peak strength becomes more obvious. When the specimen has low initial water content, the ice was mainly on the surface and at the connection of soil grains. It has a minor contribution to the strength of rock-soil mixture. With the increase of initial water content, the pores were filled with ice after freezing. The ice binds the soil particles together, leading to high peak strength. It can also be observed from Figure 9 that the peak strength increases with normal stress. The drops after peak strength also enhance with normal stress.

The peak strength does not increase with ice content linearly. When the ice content reaches a certain value, the peak strength achieves its maximum value and then goes down. Figure 10 gives the relationship of peak strength versus ice content at −5°C. When ice content increases from 9% to 10.3%, the peak strength increases nearly linearly. The maximum peak strength is 349.2 kPa, 361.7 kPa, and 376.8 kPa at normal stresses of 56 kPa, 73 kPa, and 90 kPa. When the ice content is larger than 12%, the peak strength declines with increase of ice content. Thus, there is a crucial value for the effect of ice content on peak strength of rock-soil mixture. In this study, the optimal ice content ranges from 10% to 12%.

6. Summary and Conclusion

A series of direct shear tests were performed on rock-soil mixtures to investigate the shear behavior and the effect of temperature and ice content on shear strength of such mixtures. The temperature ranges from −1°C to −16°C and the initial water content of specimen is between 9% and 14%. The main conclusions can be summarized as follows:

(1) The shear strength of rock-soil mixture increases obviously after freezing. The peak shear strength increases from 81.6 kPa to 364.2 kPa when the temperature of rock-soil mixture decreases from 1.0°C to −5°C. The shear stress-shear displacement curves of frozen rock-soil mixture include four stages: compaction stage, linear elastic stage, yield stage, and failure stage.

(2) The vertical deformation during shearing is first contraction then dilatancy. The dilatancy under constant normal stress increases with shear deformation and does not level off at the end of this test. The dilatancy decreases with the increase of normal stress.

(3) Temperature has a marked effect on the mechanical behavior of frozen rock-soil mixture. The peak shear strength increases obviously with decrease of temperature when temperature is relatively high. The shear

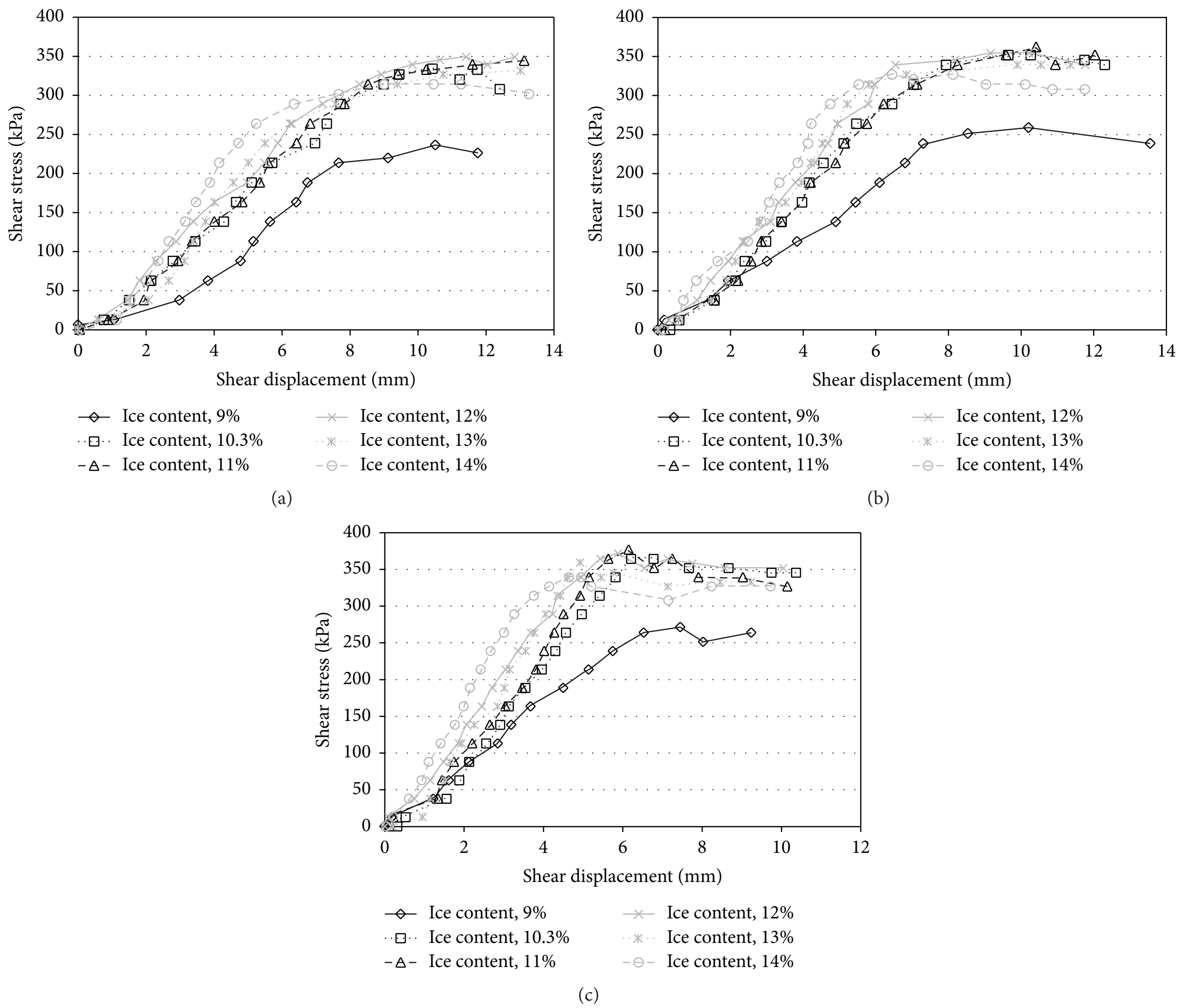

Figure 9: Relationship between shear stress and shear displacement for frozen rock-soil mixture at a normal stress of (a) 56 kPa, (b) 73 kPa, and (c) 90 kPa.

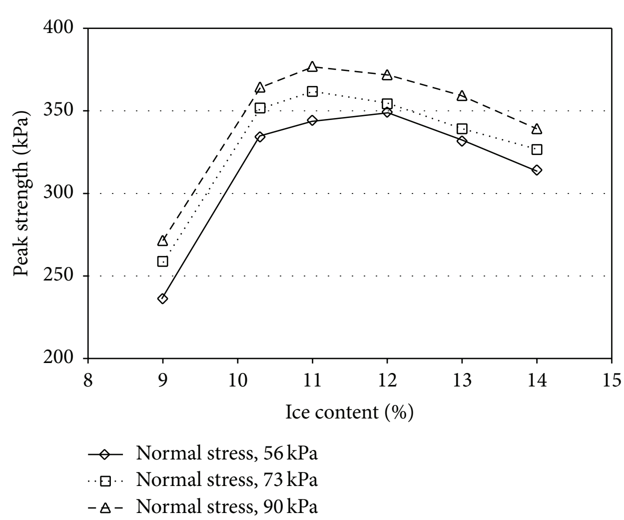

Figure 10: Effect of initial water content on peak shear strength of frozen rock-soil mixture at −5°C.

strength increments of rock-soil mixtures are 45.2 kPa and 150.7 kPa when temperature decreases from −1°C to −5°C for specimens with initial water content of 9% and 14%, respectively. After that point, the increase rate reduces. The shear strength increment is only 7.5 kPa for specimen with initial water content of 9% and 37.7 kPa for specimen with initial water content of 14% when temperature decreases from −5°C to −16°C.

(4) The shear strength of frozen rock-soil mixture depends greatly on the amount of ice. The peak strength first increases nearly linearly and then decreases. For rock-soil mixture with low ice content, the strength of rock-soil mixture depends mainly on the cohesion and interparticle friction of blocks and soil particles. With the increase of ice content, most of the pores of the mixtures were filled with ice. The ice binds the solid particles together, rendering rapid increase of the strength of rock-soil mixture. With the continuous increase of ice content, the 9% expansion of water-ice phase change destroys the initial bonded and interlocked structure of solid particles. The contribution of the interparticle friction and interference weakens. Thus, the shear strength starts to decline. There is a crucial value for the effect of ice content on peak strength of rock-soil mixture. The optimum ice content of the rock-soil mixture in this research is about 10%–12% at −5°C.

Competing Interests

The authors declare that there are no competing interests regarding the publication of this paper.

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