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Effect of freezing on mechanical behaviour of peaty soils: a case study on ecological fragile zone of Qinghai Tibet Plateau, China

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Abstract. Considerable engineering infrastructure has been constructed in cold regions with widespread peaty soil deposits, particularly in Western Sichuan Plateau, China. However, the mechanical properties of frozen peaty soils remain poorly documented in the literature. In this paper, a series of unconfined compression tests were carried out on frozen peaty soil at varying freezing temperatures and time. The experimental results indicated that the mechanical behaviours of frozen peaty soil are characteristic of elastic-plastic deformation, greatly affected by freezing temperature. The measured UCS varies from 40 kPa to 1062 kPa when the freezing temperature is between 0 °C and -25 °C, and the freezing time is between 6 h and 30 h. The UCS increases sharply when the freezing temperature decreases to -15 °C from 0 °C, and the rate of increase of UCS slows down, when the freezing temperature is lower than -15 °C. The results of environmental scanning electron microscope demonstrated that the connection strength between ice and soil structure was improved owing to complete freezing, resulting in a significant increase in the cohesion of the ice-soil skeleton and playing a key role in improving the macroscopic mechanical strength.

Keywords: *organic matter; frozen soil; unconfined compression strength; microstructure*

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INTRODUCTION

Peat and other highly organic soils are widely distributed across global geographical regions and are occupying significant portions of the world's land surface. These problematic soils present substantial challenges in geotechnical engineering applications (O'Kelly 2017; O'Kelly, Pichau 2013; ElMouchi *et al.* 2021). The Ruoergai Plateau in China contains the country's largest peat deposits, with a total peat swamp area of approximately 5×10^5 hectares and peat reserves of 1.0×10^9 m³ (Chai 1990). Located in the north-eastern Tibetan Plateau, the region has an average annual precipitation of 650–750 mm and minimum temperatures reaching -20°C. These humid climatic conditions promote peaty soil formation (Zhao, Si 2019).

Peaty soil is characterized by extremely high-water content, high organic content, low particle density, low bulk density, low shear strength, and exceptionally high compressibility and creep rates (Huat *et al.* 2011, 2014; Ibrahim *et al.* 2014). Considerable engineering infrastructure has been constructed in cold regions, particularly in China's permafrost zones, including highways, railways, underground pipelines, airports, and transmission towers (Lai *et al.* 2009, 2013; Wen *et al.* 2012). In recent decades, engineering challenges related to peat deposits have drawn considerable attention to peat's mechanical properties. These challenges include embankment failures (Den Haan, Feddema 2013), dike breaches (Bezuijen *et al.* 2005; O'Kelly 2008), large-scale slope instabilities (Long, Jennings 2006; Boylan *et al*. 2008; Long *et al.* 2011), and wind turbine foundation failures.

Compared to unfrozen soil, frozen soil exhibits more complex mechanical behaviour due to its heterogeneous composition and temperature sensitivity (Arenson, Springman 2005; Yang *et al.* 2016; Zhou *et al*. 2018). A series of experimental studies on the strength and mechanical behaviour of frozen soil has been conducted (Chamberlain *et al.* 1972; Cui 1998; Li *et al.* 2004; Wang *et al.* 2005; Torrance *et al.* 2007; Qi, Ma 2007; Zhang *et al*. 2007; Lai *et al.* 2008).

However, the mechanical behaviour and microstructural features of frozen peaty soil have rarely been reported. Understanding the strength and mechanical behaviour of frozen peaty soils is of great importance for foundation treatment in frozen peat regions and controlling the engineering diseases problems. In this paper, the unconfined compression tests of frozen peaty soil have been conducted at varying freezing temperatures ranging from -5 °C to -25 °C and varying freezing time ranging from 6 h to 30 h. The experimental results verify that the unconfined compressive strength of frozen peaty soil increases with the decrease of freezing temperature, and increases with the increase of freezing time. To analyze the influence of freezing time and temperature on the unconfined compressive strength of frozen peaty soil, the relation of the unconfined compressive strength with changing freezing temperature and freezing time was established by multiple nonlinear regression analysis based on test data. Furthermore, the environmental scanning electron microscope (ESEM) was used to observe the microstructure of frozen peaty soil; it revealed that the improvement of the connection strength between ice and soil structure was attributed to the complete freezing effect, resulting in a significant increase in the cohesion of the ice-soil skeleton, and playing a key role in improving the macroscopic mechanical strength.

EXPERIMENTS

Sample preparation

The sampling site is located in Ruoerge County, Western Sichuan Plateau, China. The broad valleys distributed in the Ruoerge region provide favourable conditions for the formation of marshes and peat deposition. Extreme temperatures can reach -20°C, and cold, humid climate slows the decomposition rate of organic matter, promoting plant growth and its accumulation. The flat valley floor, high groundwater level, and poor drainage collectively create ideal waterlogged conditions for peat bog development. The abundant alpine meadows and wetland vegetation contribute a large amount of organic material to peat formation. The peat layers deposited during the Holocene cover the entire valley floor, with thicknesses ranging between 0.5 m and 10 m (Chai 1990).

To ensure taking completely frozen peaty soils, the sampling time was chosen in January when the average daily temperature was lower than 0 °C. In order to collect undisturbed samples, a cylindrical sampler, with a diameter in 10 cm and height in 20 cm, was used to take the soil by penetrating into the soil layer in vertical direction for soil sampling (Fig. 1). And then, the soil samples were sealed with cling film and placed in an incubator to keep the moisture content of soil in a natural state.

Description of soil sample properties

Peaty soils are multi-component organic and inorganic composites with a high water content. Its physical and chemical properties are depended on organic matter and mineral composition (O'Kelly 2017); the

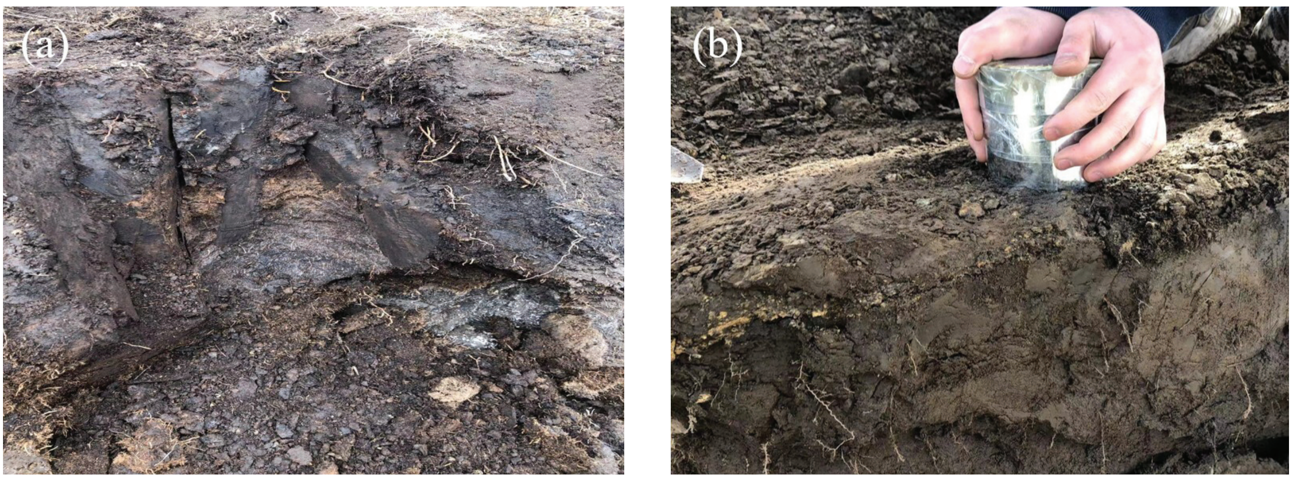

Fig. 1 Sampling site (a) and sampling method with a cylindrical sampler (b)

organic matter is derived from incompletely decomposed plant residues and humus (Paul *et al.* 2021). Latifi *et al.* (2016) indicated that the non-clay minerals, such as quartzes, were the primary components of peaty soil, and iIlite and kaolinite were the main components of clay minerals.

In accordance with the *Standard for Soil Test Methods* (GB/T 50123-2019), four representative peaty soil samples were selected, dried, and ground. The particle size distribution of the soils was then determined through sieving and hydrometer methods. A grain-size distribution curve showed that the fine-grained fraction (silt + clay) made up 94.35%–96.51% of the material, sand comprised 3.88%–4.56%, and gravels generally comprised > 50% (Fig. 2). Four groups of samples of the peaty soils were tested to determine the physical and chemical properties of soils, with the results summarized in Table 1.

The total organic matter content in peaty soil was determined by the loss-on-ignition method: organic content (%) = $[m_1-(m_3-m_2)]/m_1 \times 100\%$, where: m_1 = mass of oven-dried soil sample (g) m_2 = mass of crucible (g) m_3 = mass of soil sample and crucible after combustion in muffle furnace (g). In accordance with the Standard Test Method for Laboratory Determination of the Fiber Content of Peat Samples by Dry Mass (ASTM D1997-2020), the fiber content in peaty soil was determined by the wet sieving method: fiber content (%) = m/M × 100%, where: m = mass of fiber after low-temperature drying (g); and M = mass of oven-dried soil sample (g).

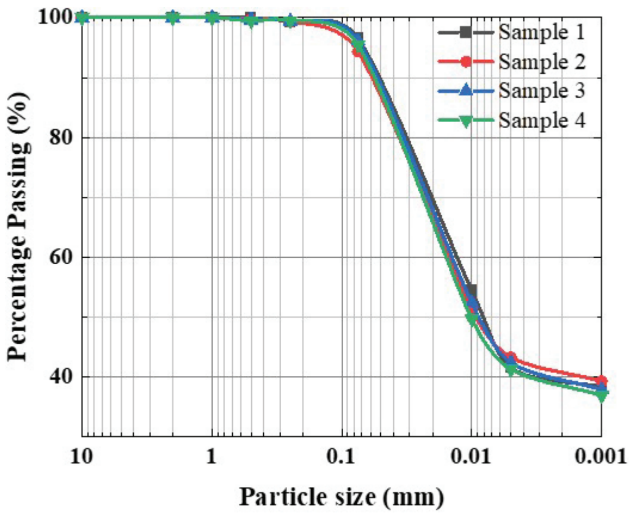

Fig. 2 Particle size distribution curve of peaty soils in Ruoerge region

It can be seen from Table 1 that the water content of the peaty soils is approximately 112.45%, void ratio of 1.36, Fc < 33%, 5.5 < PH < 7. According to the Standard Test Methods for Moisture, Ash, and Organic Matter of Peat and Other Organic Soils (ASTM D2974-2014), Standard Test Method for Laboratory Determination of the Fiber Content of Peat and Organic Soils by Dry Mass (ASTM D 1997–2020), and Standard Test Method for pH of Peat Materials (ASTM D2976-2015), the peaty soil is classified as fully decomposed and high-ash peaty soil and as slightly acidic peaty soil with a pH between 5.5 and 7. Full decomposition leads to a less residual fiber content and a higher mineral content. Compared with semi-fibrous and fibrous peats, fully decomposed peat has a lower water-holding capacity, less macropores and a greater content of fine particles. The deposits of organic matter and decompositions of humus cause the peaty soils to be slightly acidic (Kolay *et al.* 2011).

Experimental method

Freezing

The freezing of samples was conducted using an automated freeze-thaw testing chamber (Fig. 3). This device has rapid cooling, low-temperature preservation, heating, and high-temperature preservation modes. For example, during the cooling phase, the chamber temperature was reduced to -5°C within 0.1 hours, followed by a 6-hour preservation period. This procedure was repeated for all designated test temperatures and freezing durations.

Unconfined compression testing

The MTS-810 testing machine was used to determine the unconfined compression strength parameters of 42 samples with six varying freezing temperatures ranging from -5 °C to -25 °C, and four varying freezing times ranging from 6 h to 30 h, with the freezing scheme of samples detailed in Table 2. The MTS-810 strain-controlled unconfined compression test device of the is shown in Fig. 4a, and the hydraulic pressure-controlled apparatus is used for sample preparation (Fig. 4b), which can ensure the dry density of the standard cylindrical sample of 0.74 g/cm^{-3}, the diameter of 39.1 mm, and the height of 80 mm (Fig. 4c).

Table 1 Physical and chemical properties of peaty soils in Ruoerge region (mean value)

Parameters									
Water content ω (%)	Void ratio (e)	Density ρ (g/cm^{-3})	Specific gravity G_s (g/cm^{-3})	Plastic limit ω_p (%)	Liquid limit ω_L (%)	Plasticity index I_p (%)	Organic content O_c (%)	Fiber content F_c (%)	Acidity (pH)
112.45	1.36	1.56	1.73	73.9	129.5	55.6	26.04	10.8	6.0

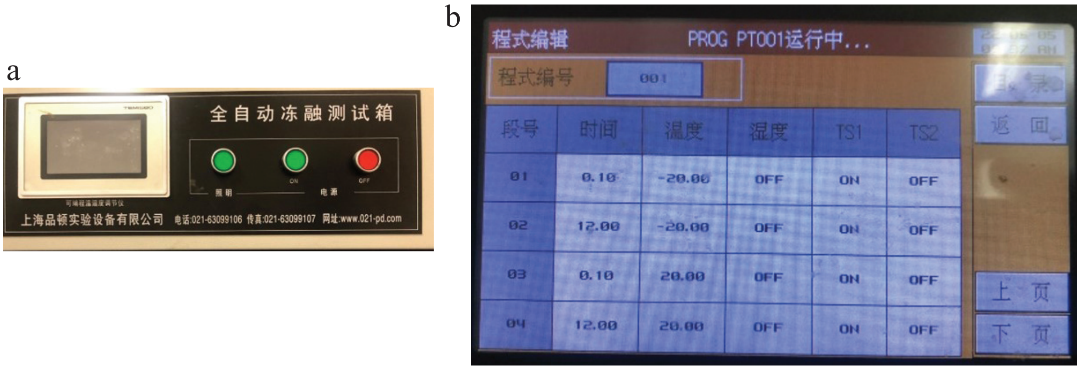

Fig. 3 Freeze-thaw testing equipment: automatic freeze-thaw testing chamber (a) and program setup (b)

Table 2 Freezing and testing scheme of samples

Freezing temperature (°C)	Freezing time (h)	Number of unconfined compression test
0	0	2
-5	6, 18, 24, and 30	8
-10	6, 18, 24, and 30	8
-15	6, 18, 24, and 30	8
-20	6, 18, 24, and 30	8
-25	6, 18, 24, and 30	8

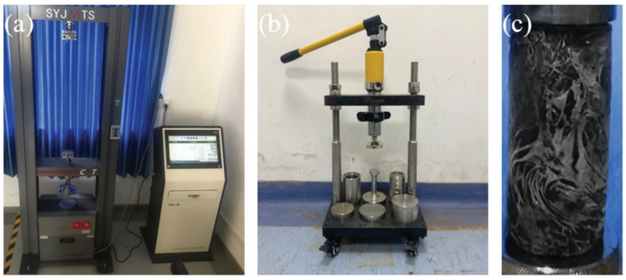

Fig. 4 MTS-810 unconsolidated compression test device (a) hydraulic pressure-controlled apparatus for sample preparation (b) and a testing sample of frozen peaty soil (c)

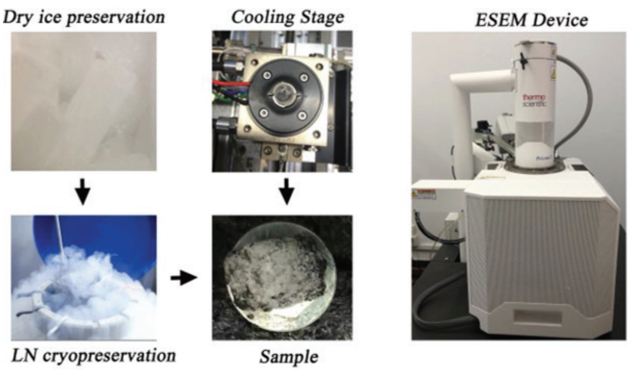

Fig. 5 Sample preparation process and test devices before scanning

According to the Chinese standard for soil test methods (GB/T 50123-2019), the samples were loaded at a constant rate of 1 mm/min; when the stress reached the peak stress or the axial strain reached 15%, the test was terminated. Five data of axial displacement and axial stress were recorded per second.

To avoid the error of test results due to melting, the unconfined compression test was completed within one to two minutes. Two samples were prepared for testing at each assumed freezing condition, the average value of two tests was taken as the test result. A total of 42 samples were tested for unconfined compression strength.

Environmental scanning electron microscope (ESEM)

The environmental scanning electron microscope (ESEM) was used to observe the microstructure of frozen peaty soil (Negre *et al.* 2004; Zhang *et al.* 2020), with sample preparation process and device shown as Fig. 5. A sample with a cross-sectional area of 1 cm × 1 cm was prepared and then stored in a freezer for 30 hours with temperatures of -25 °C to ensure the sample was fully frozen. In order to eliminate the error caused by melting, dry ice and liquid nitrogen were used to keep the ice-soil structure stable before scanning. In addition, the use of the cooling device can also effectively avoid errors caused by sample melting during scanning.

EXPERIMENTAL RESULTS AND ANALYSIS

Freezing temperature effect

Stress-strain curves

Based on large amounts of test data of uniaxial compression, Zhu *et al.* (1992) pointed out the mechanical behaviours for frozen soil in uniaxial compression could be classified as viscoelastic-plastic and elastic-plastic types, with the stress-strain curve shown as Fig. 6.

Figure 7 shows the stress-strain curves of peaty soils for various assumed freezing temperatures in unconfined compression. It can be seen that the stress-strain curves of frozen peaty soils are greatly affected by the freezing temperature characteristic of elastic-plastic deformation behaviours. The deformation and failure

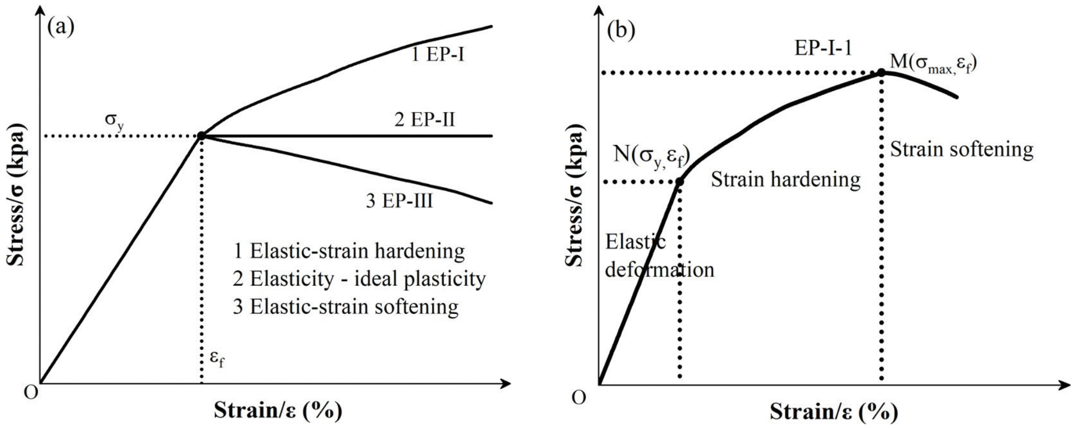

Fig. 6 The stress-strain behaviours for frozen soil in uniaxial compression (Zhu *et al.* 1992): elastic-plastic stress-strain curve (a) and elastic strain hardened type (b)

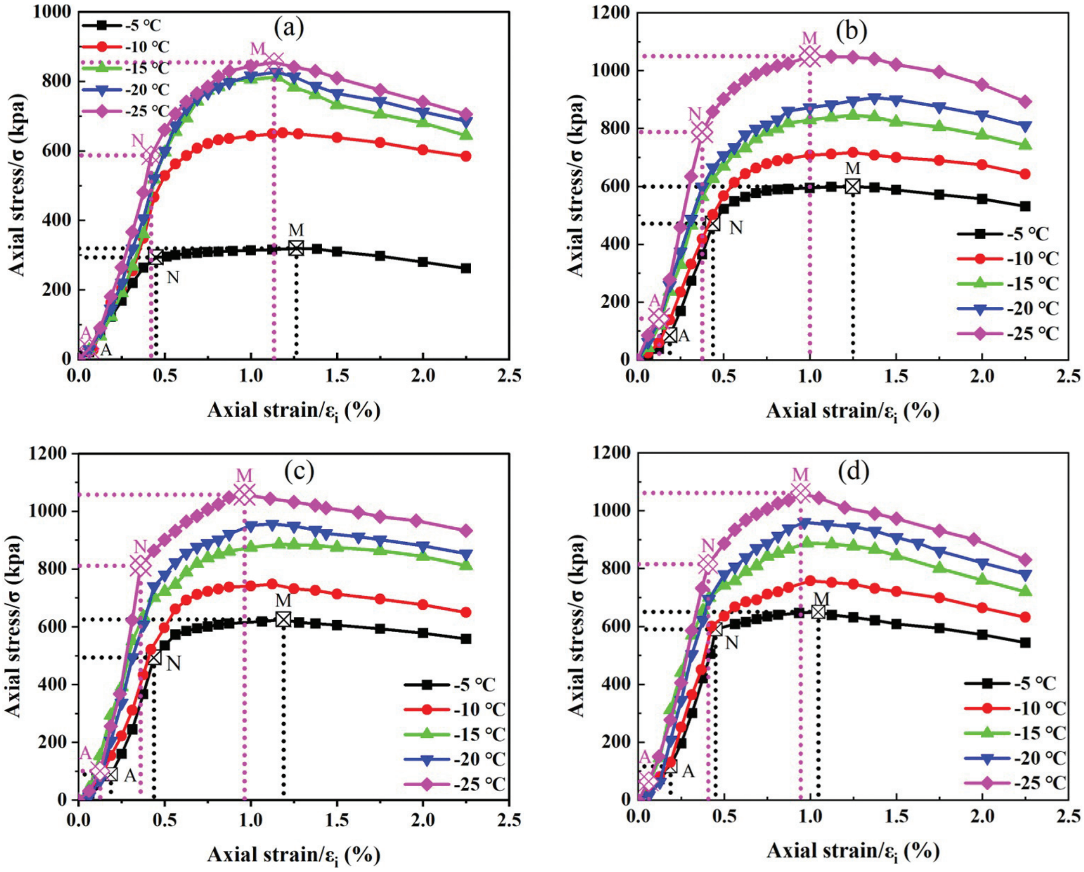

Fig. 7 The stress-strain curves for various assumed freezing temperature with the freezing time of 6 h (a), 18 h (b), 24 h (c) and 30 h (d)

progressed through the following four stages: compaction stage (OA), elastic deformation stage (AN), strain hardening stage (NM), and strain-softening stage (post peak phase). The deformation behaviors of frozen peaty soils in unconfined compression affected by freezing temperature are summarized as follows: (1) The axial strains are less than 0.25% in the compacting stage (OA) for various assumed freezing temperatures, which indicates that the specimen has undergone a short-term compaction process; (2) With the gradual increase of loading stress, deformation develops to the elastic deformation stage (AN), and the axial strains are less than 0.5%. The lower the assumed freezing temperature, the greater the slope of the curve, which manifests that the brittleness of the frozen soils increases as the decreases of the freezing temperature (3). In the strain hardening stage (NM), the stress-strain curve is an upward convex, with the slope decreasing gradually. The lower the assumed freezing temperature, the less the axial strains at peak stress. Moreover, the slope of the stress-strain curve is the maximum for the freezing temperature of -25 °C and is the minimum for the freezing temperature of -5 °C especially when the freezing time is 30 hours; this phenomenon is most significant (Fig. 7d). (4) After peak point M, the stress-strain curves are characterised by strain softening behaviour. The applied load remains constant, the axial strain increases continuously, and the axial stress drops continuously; the lower the freezing temperature, the greater the stress drop. Namely, the measured stresses drop most when the freezing temperature is -25 °C, indicating that a lower freezing temperature can improve the ability of frozen soil to resist plastic deformation.

Unconfined compression strength

Figures 8 and 9 show the unconfined compressive strength (UCS) and the rate of increase of UCS when the assumed freezing temperature varies from -5 °C to -25 °C. It can be concluded that the UCS increases with the decrease of freezing temperature for various assumed freezing time. The UCS increases sharply with the decrease of freezing temperature when the freezing temperature decreases from 0 °C to -15 °C. However, the rate of increase of UCS slows down with the decrease of freezing temperature, when the freezing temperature is lower than -15 °C. For instance, the measured UCS of frozen peaty soils is 7.03, 15.38, 19.45, 19.78 and 20.47 times that of unfrozen peaty soils, when the freezing temperature is -5 °C, -10 °C, -15 °C, -20 °C and -25 °C, respectively, and the freezing time is assumed to be 6 hours.

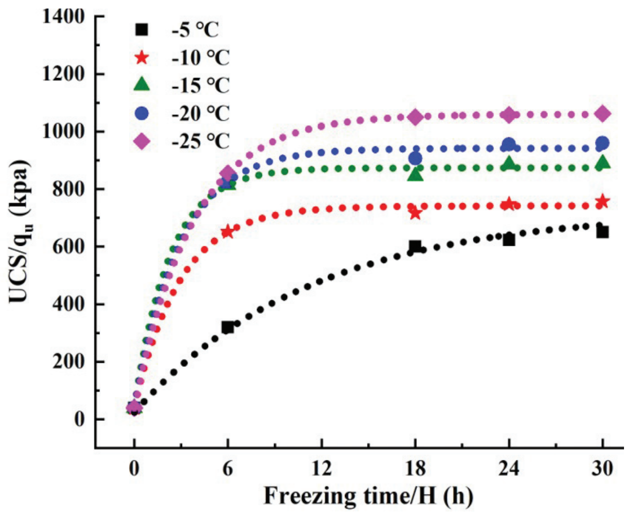

Fig. 8 The relations between UCS and freezing temperatures while for various assumed freezing times

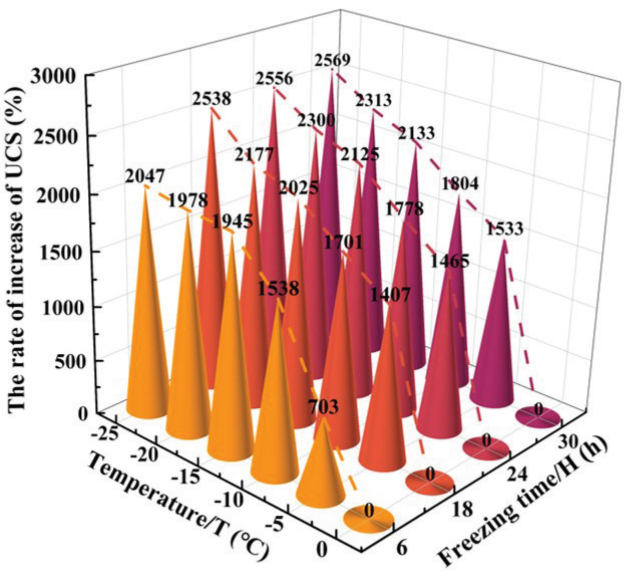

Fig. 9 The rate of increase of UCS when the freezing temperature is -5 °C, -10 °C, -15 °C, -20 °C, and -25 °C for various assumed freezing times

Freezing time effect

It can be seen that the UCS of frozen soil increases with the increase of freezing time for various assumed freezing temperatures. The UCS varies from 319.8 kPa to 854.6 kPa when the freezing time is assumed to be 6 h and when various assumed freezing temperatures are 7.03 to 20.47 times that of unfrozen peaty soils. The UCS increases sharply with the increase of freezing times. When the freezing time is between 24 h and 30 h, the increase of UCS tends to be stable basically.

FREEZING TEMPERATURE AND TIME EFFECT ON UNCONFINED COMPRESSION STRENGTH

Numerous research conclusions showed that the strength of pore ice, soil strength and the bonding of ice can increase the effective stress of soil, enhancing the shear strength (Li *et al.* 2012; Pouragha *et al.* 2023). Freezing temperature and freezing time are primary factors that increase ice strength and cohesion between ice and soil and finally improve the strength of the ice-soil skeleton.

Based on unconfined compression test results, a predictive model for the unconfined compressive strength (UCS) of frozen peaty soil was developed through multivariate nonlinear regression analysis (Eq. 3). This model quantifies the coupled effects of freezing temperature and duration on UCS. The corresponding regression coefficients and goodness-of-fit statistics (R^2) are presented in Table 3.

$$q_u = aT^2 + bT + cH^2 + dh + k \tag{1}$$

where q_u is the unconfined compressive strength (kPa), T is the freezing temperature (°C), H is the freezing time (h), a and b are the regression coefficient related to freezing temperature, c and $d$are the regression coefficients related to freezing time, and k is the constant value.

To analyze the influence of freezing time and temperature on UCS of frozen peaty soil, the three-dimensional relation curved surface between freezing temperature, freezing time and UCS has been obtained by interpolation based on test data, as shown in Fig. 10.

Table 3 Regression coefficients and correlation coefficients in relation of UCS with freezing temperature and freezing time

Regression coefficient	Values	R^2	k
a	-0.6848	0.9458	142.6755
b	-42.732		
c	-0.3096		
d	18.2273		

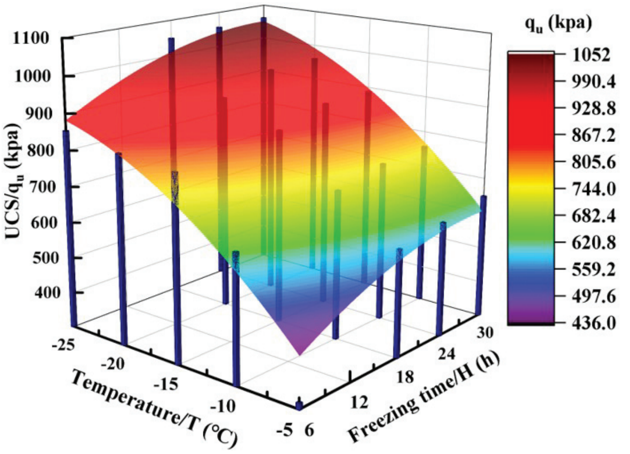

Fig. 10 The three-dimensional relation curved surface between freezing temperature, freezing time and unconfined compressive strength

It can be seen that the measured UCS of peaty soil varies from 40 to 1062 kPa when the freezing temperature is between 0 °C and -25 °C and the freezing time is between 6 h and 30 h and increases with the decrease of freezing temperature and the increase of freezing time. The maximum UCS of frozen peaty soils increased 26.55 times compared with the strength of unfrozen soil. The UCS is more affected by freezing temperature compared with freezing time. Specifically, when the freezing temperatures vary from -5 °C to -25 °C and the freezing time is assumed to be 6 h, the measured UCS varies from 320 kPa to 855 kPa with the average increase rate of UCS of 26.7 kPa for decrease in temperature of one degree. When the freezing times vary from 6 h to 30 h and the freezing temperature is assumed to be -5 °C, the measured UCS varies from 320 kPa to 650 kPa with the average increase rate of UCS of 13.8 kPa for increase in freezing time of one hour.

DISCUSSION

Causes of mechanical behaviour and strength change based on microstructure

Tsytovich *et al.* (1975) pointed out that the mechanical strength of frozen soil tremendously depends on the strength of ice and on connection between ice and soil structure. With the decrease of freezing temperature and increase of freezing time, the pore wa-

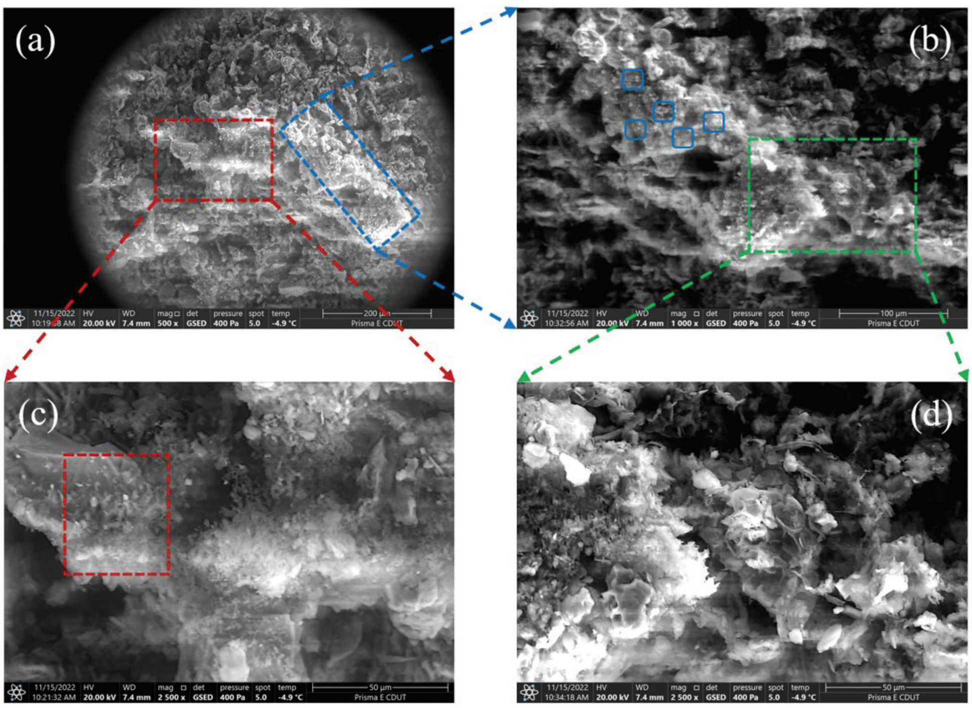

Fig. 11 ESEM results of frozen peaty soil sample: the ice-soil composite mixtures with porphyritic and banded structures (a), the ice crystal filled in the tiny pores between clay aggregate (b), the irregular floccule ice crystals connect the clay aggregates with the silt particles (c), and a small amount of plant fiber lead to a weak connection between ice and soil structure (d)

ter within the soil was gradually transformed into ice crystals; correspondingly, the soil particles and components were cemented into firm and stable ice-soil skeletons by ice crystals. When the soil was completely frozen, the ice-soil composite mixtures with porphyritic and banded structures were produced, which presented a structural form dominated by organic colloids, mineral particles and ice aggregates, as shown in Fig. 11a. Figure 11b shows a local enlarged drawing of ice-soil composite mixture, which reveals the organic colloid in the ice-soil composite mixtures led to the formation of micropores between clay aggregates; and the ice crystal was evenly filled in the tiny pores between clay aggregate (blue area in Fig. 11b). Figure 11c shows a local enlarged drawing of ice-soil composite mixture, which indicates that the irregular floccule ice crystals connect the clay aggregates with the silt particles (red area in Fig. 11c), resulting in a stronger connection strength between ice-soil structures. Meanwhile, a small amount of plant fiber in a highly decomposed peaty soil remains in the ice-soil composite mixture (Fig. 11d), which leads to a weaker connection between ice and soil structure.

To sum up, the connection strength between ice and soil structure was improved owing to complete freezing, resulting in a significant increase in the cohesion of the ice-soil skeleton and playing a key role in improving the macroscopic mechanical strength. Furthermore, the brittleness of completely frozen soil samples is more obvious, and its properties of resistance to plastic deformation were enhanced (Schulson 2001; Liu *et al.* 2018; Yamamoto, Springman 2014). On the other hand, the ice-soil composite mixtures, comprised of organic colloid, mineral particle, plant residue, and ice, etc., frozen cracks and pores between aggregates can result in an uneven composition of peaty soil; this property can be demonstrated through a short compaction in the stress-strain curve under unconfined compressive test.

CONCLUSIONS

This study investigates the mechanical behaviour and strength of frozen peaty soils at varying freezing temperatures and varying freezing time in Western Sichuan Plateau of China. Based on the testing results, the following conclusions can be drawn:

1) The stress-strain curves of frozen peaty soils in unconfined compression are greatly affected by freezing temperature, characteristic of elastic-plastic deformation behaviours. The established relations of the unconfined compressive strength of frozen peaty soil with freezing temperature and freezing time indicate that the measured UCS varies from 40 kPa to 1062 kPa when the freezing temperature is between 0 °C and -25 °C and the freezing time is between 6 h and 30 h and increases with the decrease of freezing temperature and the increase of freezing time.

2) The UCS is more affected by freezing temperature compared with freezing time. It increases sharply when the freezing temperature decreases from 0 °C to -15 °C and the rate of increase of UCS slows down when the freezing temperature is lower than -15 °C.

3) The results of environmental scanning electron microscopy demonstrated that the connection strength between ice and soil structure was improved owing to complete freezing, resulting in a significant increase in the cohesion of the ice-soil skeleton and playing a key role in improving the macroscopic mechanical strength. Furthermore, the brittleness of completely frozen soil samples is more obvious, and its properties of resistance to plastic deformation were enhanced.

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