Review on the Influence of Environmental Negative Temperature on Tensile Strength of Frozen Soil

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Abstract. The tensile strength of frozen soil is affected by many factors such as temperature, particle size distribution, and moisture content, among which temperature is the primary influencing factor. Temperature affects it mainly by affecting the ice and unfrozen water in the frozen soil. By summarizing the research on tensile strength and temperature of frozen soil, the rules between them are systematically summarized. The results show that the relationship between tensile strength and temperature of frozen soil can be described by linear and nonlinear models. The tensile strength of warm frozen soil increases with the decrease of temperature. However, the tensile strength of cryogenic frozen soil may increase first and then decrease with decreasing temperature. This temperature at which the tensile strength decreases is called the "brittle temperature".

Keywords: Tensile strength; Temperature; Cryogenic frozen soil; Warm frozen soil.

1 Introduction

Frozen soil is a type of soil which contains ice at temperatures below 0°C, and it's widely distributed around the world. In soil mechanics, the tensile strength is ignored due to its loose nature. However, frozen soil tensile strength is determined by the soil skeleton, pore ice, and "pore water-pore ice-soil particles" and the tensile strength of it is often much greater than that of unfrozen soil [1]. As the number of permafrost engineering projects increases globally, the study of frozen soil tensile strength becomes increasingly important.

Temperature affects frozen soil tensile strength mainly by affecting the ice and unfrozen water in frozen soil [2]. Depending on soil temperature, frozen soil can be categorized into warm and cryogenic frozen soil. They have different forms of failure

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under external loads. Cryogenic frozen soil is generally brittle, while the warm is plastic.

The tensile strength is closely related to the stability of slopes in permafrost region, frozen wall design and other cold region projects. Previous researches have shown the tensile strength of frozen soil is affected by many factors, such as particle size distribution, temperature, moisture content, etc., among which temperature is the primary influencing factor [3]. However, there is limited research on temperature and the tensile strength of frozen soil, and there is a lack of regular summary. Therefore, summarized the research on frozen soil tensile strength affected by temperature, systematically analyze the characteristics of them, to provide references for the construction of permafrost engineering and disaster prevention.

2 Tensile Strength of Warm Frozen Soil

2.1 Tensile Strength-Temperature Linear Model of Warm Frozen Soil

Warm frozen soil is also called plastic frozen soil, and its temperature is usually between the 0°C and -2°C. Since the temperature range is in the strong phase transition zone, this results in its engineering properties being very fragile and sensitive to temperature, with small temperature changes leading to changes in its strength.

Some studies believe the tensile strength of warm frozen soil is linearly related to temperature. They proposed a linear mode. Lu [4] found that the tensile strength of powdery clay increased linearly with the decrease of temperature in -0.57~-2.02°C and gave a linear equation between them (Fig. 1; Table 1). Hu et al. [5] showed that the tensile strength of saturated frozen chalky clay in -0.4~-2.0°C also increases linearly (Fig. 1; Table 1).

Their relationship equation is as follows:

Table 1. Linear equation of tensile strength-temperature of warm frozen soil

Temperature/°C	Soil texture	Moisture content/%	loading rate mm/min	Regression equation	references
-0.57~-2.02	Silty clay	30	1.0 1.25 4.0	$\sigma_t = -0.0056 - 0.0167\theta$	Lu [4]
-0.4~-2.0	Silty clay	100	1.0 2.0 4.0	$\sigma_t = 0.1058 - 0.0683\theta$	Hu et al. [5]

where σt is the tensile strength (MPa), and θ is temperature (°C). The same below.

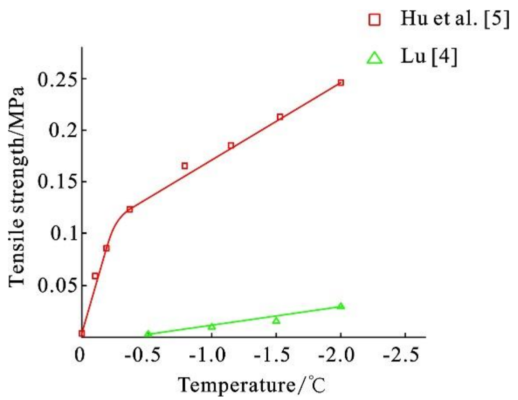

Fig. 1. Linear curve of tensile strength-temperature of warm frozen soil

2.2 Tensile Strength-Temperature Nonlinear Model of Warm Frozen Soil

Some studies believe the model of warm frozen soil tensile strength as a function of temperature is nonlinear. Akagawa et al. [1] showed that in 0~-1.31°C, the tensile strength increased nonlinearly. Azmatch et al. [3] found the tensile strength increased with decreasing temperature in range of -0.3~-1.4°C (Fig. 2), and the two showed a power function (Table 2). Zhou et al. [6] showed that in 0~-2°C, the relationship between them is also a power function (Fig. 2), and its functional equation is shown in Table 2. Similar findings have been made by Hu et al. [5] and Wang et al. [7] (Fig. 2; Table 2).

Table 2. Nonlinear equation of tensile strength-temperature of warm frozen soil

Temperature/°C	Soil texture	Moisture content/%	loading rate mm/min	Regression equation	references
-0.3~-1.4	Muck	55	0.8	$\sigma_t = 1.020(\theta/\theta_0)^{0.339}$	Azmatch et al. [3]
0~-0.4	Silty clay	100	1.0 2.0 4.0	$\sigma_t = -0.6586\theta^2 - 0.5663\theta + 0.00069$	Hu et al. [5]
0~-2	Clay Silty clay	20	2.0	$\sigma_t = 0.2(\theta/\theta_0)^{0.422} + 0.00098$ $\sigma_t = 0.175(\theta/\theta_0)^{0.430} + 0.00036$	Zhou et al. [6]
0~-2	Silty clay	23	2.0	$\sigma_t = 0.223\lvert\theta\rvert^{0.5068}$	Wang et al. [7]

where θ_0 is the dimensionless reference temperature (-1°C), and the same below.

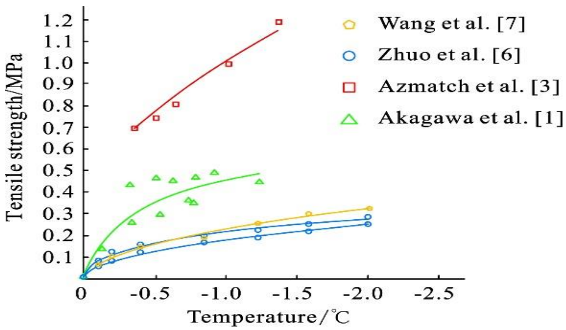

Fig. 2. Nonlinear curve of tensile strength-temperature of warm frozen soil

The above studies have shown that in the warm temperature range, the tensile strength increases with decreasing temperature. There are linear and nonlinear models for them. This is because in the warm temperature range, as the temperature decreases, the pore ice gradually increases, and the cementation due to pore ice gradually increases, which improves the tensile strength. From the nonlinear model, the tendency of the enhancement of tensile strength gradually decreases as the temperature decreases. The reasons for this phenomenon need further study.

3 Tensile Strength of Cryogenic Frozen Soil

3.1 Tensile Strength-Temperature Linear Model of Cryogenic Frozen Soil

Cryogenic frozen soil, also known as hard permafrost, has a higher pore ice content compared to warm frozen soil. Some studies have shown cryogenic frozen soil tensile strength increases linearly with decreasing temperature in a temperature range. Shen et al. [8] found a linear model of the tensile strength with temperature in -2~-15°C (Fig. 3). Ma [9] discovered linear equations for the temperature-dependent uniaxial tensile strength in -7~-17°C (Fig. 3; Table 3). Peng [10], Huang et al. [11], and Shen et al. [12] all proposed linear models for them (Fig. 3; Table 3).

Table 3. Linear equation of tensile strength-temperature of cryogenic frozen soil

Temperature/°C	Soil texture	Moisture content/%	loading rate mm/min	Regression equation	references
-7~-17	Clay Sand	30 16	/	$\sigma_t = 0.648 - 0.05\theta$ $\sigma_t = 0.371 - 0.03\theta$	Ma [9]
-2~-10	Loess	21.1	/	$\sigma_t = 0.207 - 0.2\theta$	Peng [10]

-1~-20	Silty clay Loess Sand	16.03 15.3 12.5	8.25	$\sigma_t = 0.3046 - 0.1054\theta$ $\sigma_t = 0.0106 - 0.0468\theta$ $\sigma_t = 0.1437 - 0.0918\theta$	Huang et al. [11]
-1~-15	Sand	16	1.0	$\sigma_t = 0.427 - 0.11\theta$	Shen et al. [12]

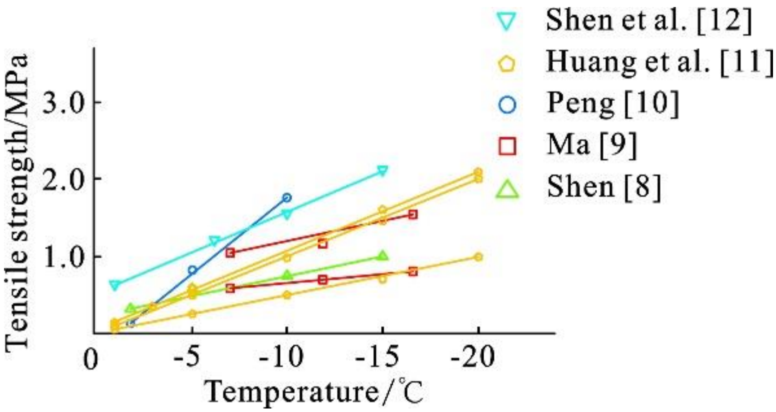

Fig. 3. Linear curve of tensile strength-temperature of cryogenic frozen soil

3.2 Tensile Strength-Temperature Nonlinear Model of Cryogenic Frozen Soil

Some studies have shown the model of cryogenic frozen soil tensile strength with temperature is a nonlinear model. Christ et al. [13] conducted tensile tests on Siberian silt in -2 to -20°C and found the tensile strength increases with decreasing temperature, and the increasing trend is getting larger and larger (Fig. 4; Table 4). Li et al. [14] showed that in -0 to -15°C, the tensile strength increases with decreasing temperature. Its curve is a power function (Fig. 4; Table 4).

However, some studies have shown that when the temperature is lower than a certain temperature, the tensile strength decreases with decreasing temperature. Zhu et al. [15] found the ultimate tensile strength increased with decreasing temperature at temperatures greater than -10°C, and when the temperature was less than -10°C, the ultimate tensile strength decreased with decreasing temperature (Fig. 4; Table 4). Zhao [16] showed the tensile strength in -1 to -24°C increases and then decreases with decreasing temperature, and the changing curve is a power function (Fig. 4; Table 4).

Table 4. Nonlinear equation of tensile strength-temperature of cryogenic frozen soil

Temperature/℃	Soil texture	Moisture content/%	loading rate mm/min	Regression equation	references
-0~-15	Silty clay	59	9	$\sigma_t = 0.1303(\theta/\theta_0)^{0.57} + 65.45$	Li et al. [14]
-1~-24	Silty clay	14	1.0	$\sigma_t = -0.0008\theta^2 + 0.0353\theta + 0.0688$	Zhao [16]

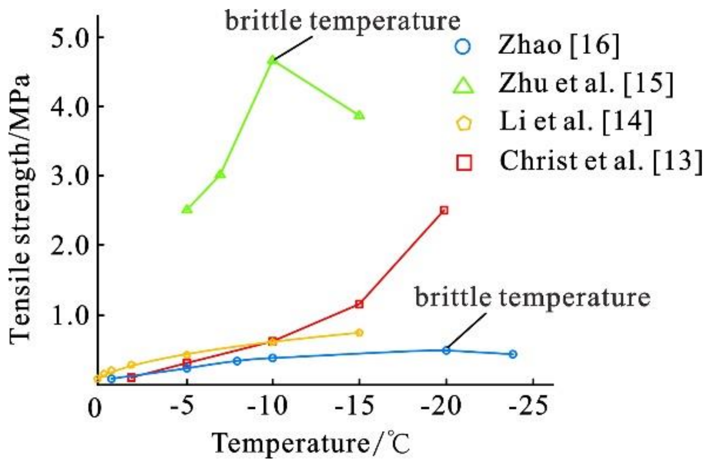

Fig. 4. Nonlinear curve of tensile strength-temperature of cryogenic frozen soil

These studies show cryogenic frozen soil tensile strength is relatively complex with the decrease of temperature. (1) The tensile strength of cryogenic frozen soil increases linearly with the decrease of temperature. (2) The tensile strength of cryogenic frozen soil increases nonlinearly with decreasing temperature. (3) The tensile strength of cryogenic frozen soil increases first and then decreases with decreasing temperature. The first two cases are because decreasing temperature leads to the enhancement of the pore ice cementation, which in turn increases the tensile strength of cryogenic frozen soil. For the third case, some scholars proposed the temperature at which the tensile strength decreases is "brittle temperature" and cryogenic frozen soils with different properties have different "brittle temperature". In the range where the temperature is higher than "brittle temperature", the decrease of temperature enhances the pore ice cementation inside cryogenic frozen soil, which leads to the increase of the tensile strength. When the temperature is lower than "brittle temperature", cryogenic frozen soil changes from semi-plastic soil to brittle soil, which leads to a decrease in its tensile strength.

4 Conclusions

Based on previous studies, this paper summarizes the studies on the influence of temperature on the tensile strength of frozen soil, and draws the following conclusions: (1) For warm frozen soil, its tensile strength increases with decreasing temperature, and the relationship between them can be described by linear and nonlinear models. (2) For cryogenic frozen soil, its tensile strength increases with decreasing temperature. However, once the temperature range is exceeded, the tensile strength of cryogenic frozen soil may decrease with decreasing temperature. (3) The temperature at which the tensile strength of cryogenic frozen soil begins to decrease is "brittle temperature", and the "brittle temperature" is different with different properties of cryogenic frozen soil.

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