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Research Article

Experimental Study on Thermal Conductivity of Organic-Rich Soils under Thawed and Frozen States

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Thermal properties are important for featuring the water-heat transfer capacity of soil. They are also key to many processes in earth sciences, such as the land surface processes and ecological and geoenvironmental dynamics and their changes in permafrost regions. With loose and porous structures, the organic matter layer in soil strata substantially influences soil thermal conductivity. So far, thermal conductivity of mineral soils has been explored extensively and in depth, but there are only limited studies on that of organic soils. In this study, influences of soil temperature, soil moisture saturation (SMS), and soil organic matter (SOM) content on soil thermal conductivity were analyzed on the basis of laboratory experiments on the silt-organic soil mixtures of varied mixing ratios. Results show that soil thermal conductivity declines slowly with the lowering temperatures from 10 to 0°C; however, it increases and finally stabilizes when temperature further lowers from 0 to -10°C. It is important to note that thermal conductivity peaks in the temperature range of -2~0°C (silty and organic-poor soil) and -5~0°C (organic-rich soil), possibly due to phase changes of ice/water in warm permafrost. Under both thawed and frozen states, soil thermal conductivity is positively related with SMS. However, with rising SOM content, the growth rate of soil thermal conductivity with SMS slows gradually. Given the same SMS, soil thermal conductivity declines exponentially with increasing SOM content. Based on the experimental and theoretical analyses, a new empirical computational formula of soil thermal conductivity is established by taking into account of the SOM content, SMS, and soil temperature. The results may help better parameterize in simulating and predicting land surface processes and for optimizing frozen soil engineering designs and provide theoretical bases for exploring the dynamic mechanisms of environmental changes in cold regions under a changing climate.

1. Introduction

Thermal conductivity is one of the important thermal parameters of soil. Given the same climate changes, thermal conductivity of near-surface soils determines the variability and responsiveness of permafrost temperatures and possible influences on the surrounding environment in response to external thermal disturbances. Thermal conductivity of soils is also the most basic input parameter in many numerical model simulations in earth sciences. Numerous studies have been conducted, such as those on the influencing factors, governing laws, and mechanisms of soil thermal conductivity. They can be summarized into three aspects. (1) Effects of temperature on soil thermal conductivity. At an early stage, Tao and Zhang [1] tested thermal conductivity of carboniferous soil under positive and negative temperatures. Subsequently, some scholars analyzed variations and governing laws for thermal conductivity with soil temperature

[1–4]. (2) Effects of soil water content and dry density on soil thermal conductivity [5–11]. Dry density and water content are basic parameters for assessing soil composition. Dry density determines contents of mineral skeletons in soil, and soil moisture content reflects liquid/unfrozen water and/or ice filling/saturation degree of pores in soils. Xu et al. [12] pointed out that soil thermal conductivity increased with rising soil water and/or ice content or dry density. Wang et al. [13] studied influences of soil moisture content and dry density on thermal conductivity of loess and found that water content affected thermal conductivity more significantly than dry density. (3) Relationships between soil salinity and soil thermal conductivity [14, 15]. Wang [16] concluded that thermal conductivity of frozen soil was negatively correlated to soil salinity given the same dry density and moisture content.

In recent years, scholars began to pay more attention to influences of SOM content on thermal conductivity and to influencing factors and governing laws of the thermal conductivity of organic and other organic soils. They concluded that given the same conditions, thermal conductivity of organic soils was relatively low [5, 17–23]. Some scholars have mixed SOM with sand at different ratios and tested the resultant soil thermal conductivity and concluded a negative correlation between thermal conductivity and SOM content [22]. Some scholars have compared thermal conductivity of organic soils with that of other soil types under the scenarios of different water contents, indicating a smaller thermal conductivity of wetter organic soils in comparison with that of relatively drier sandy or clayey soil [12, 19]. With respect to parameter calculation, concerns are raised for influences of SOM content on soil thermal conductivity, which have been included into the computation. For instance, Letts et al. [24] and Beringer et al. [25] evaluated influences of peat on thermal conductivity in permafrost regions in Canada and Alaska. Lawrence and Slater [26] assumed that values of soil physical parameters are a weighted combination of values for mineral soils and SOM based on the parameterization scheme of Farouki [27]. Taking into account of influences of SOM content on soil porosity and thermal parameters, Chen et al. [28] proposed a thermal parameterization scheme of soils. According to high contents of SOM and gravels in soils on the Qinghai-Tibet Plateau, Ma et al. [29] put forward a parameterization scheme to describe influences of the SOM contents and gravels on thermal conductivity and hydraulic conductivity of soils. Nevertheless, every scheme has limited applications, or it has not yet been strictly validated. This will surely transmit the calculation errors of soil thermal conductivity, a basic input parameter in land surface process models, inevitably lowering the simulation and prediction accuracy.

Over tens of thousands of years, thick layers of SOM have been formed in permafrost regions in Northeast China in an environment of cold climate, moderate precipitation, lush vegetation, abundant litter falls, and water saturation of near-surface soils. There is rich SOM in marshy soils, and the thickness of SOM layers can reach as high as 2 m in some areas [30]. As an extensively distributed surface cover type in permafrost regions, the organic-rich soil layer controls the surface energy exchange and distribution of soil temperature and humidity. As mentioned above, some studies on hydraulic and thermal parameters of SOM have been reported recently, with a series of achievements. Nevertheless, there are still many problems that deserve further explorations. For example, studies on thermophysical properties of SOM mainly focus on thermophysical properties of specific soil types, such as sand, silt, clay, and turfy soil under frozen and/or thawed states. None of them has used SOM content as the criterion for a systematic classification and/or for then valuation of thermophysical properties of organic soils.

Based on the current research status, the effects of SOM content on thermal conductivity are discussed in this study by remolding silt-organic soil mixtures of different ratios. Through a literature review, it has been concluded that thermal conductivity of soils is mainly determined by soil moisture content, soil temperature, freeze and thaw states, porosity, soil texture, and contact state of soil particles [12]. In this study, the silt-organic soil mixtures were used as the samples, which had simple properties. Their porosity and contact state of soil particles were closely related with SOM content. On this basis, influences and governing laws of soil temperature, SMS, and SOM content on thermal conductivity were discussed for the silt-organic soil mixtures. Based on experimental data, the empirical formula of thermal conductivity of organic-rich soil was developed using soil temperature, SMS, and SOM content as the independent variables. This study is expected to provide theoretical references for basic design of engineered foundations and formulation of environmental management and protection policies in cold regions and to provide basic parameters for simulations of land surface processes and frozen soil engineering designs in cold regions.

2. Materials and Methods

2.1. Treatments

2.1.1. Preparation of Soil Samples. In the test, silt and organic soil samples were collected from the Nanwenghe Wetlands Reserve in the Yile'huli mountain knots of the Da and Xiao Xing'anling mountains, Northeast China (Table 1). Organic soil and silt were mixed at ratios of 1/9, 2/8, 3/7, 4/6, 5/5, 6/4, 7/3, 8/2, and 9/1. A total of 11 groups, including the unmixed silt and unmixed organic soil, were prepared. All the soil samples were molded into columns of 70 mm in diameter and 50 mm in height.

The SOM contents in each group were measured by the TOC-L CPH total organic carbon analyzer (Shimadzu Corp., Kyoto, Japan). The total organic carbon analyzer has two heating tanks. One has a temperature up to 900°C for measuring the total carbon (TC) content. The inorganic carbon (IC) content was measured at a temperature of 200°C. After measuring the TC and IC, SOM content was calculated by equation (1) [31]. Clearly, SOM contents present a gradient growth in all 11 groups, covering inorganic soil ($W_u < 5\%$), organic soil ($5\% \le W_u \le 10\%$), and histosols ($W_u > 10\%$) (Table 2). Specifically, samples nos. 1~3 were inorganic soils,

Table 1: Basic material composition of silt (sample no. 1) and organic soil samples (sample no. 11).

Sample no.	1	11
Clay content (%)	10.93	—
Soil organic matter content W_u (%)	0.963	18.78
Natural bulk density ρ_d (g/cm^3)	1.56	0.79

samples nos. 4~6 were organic soils, and samples nos. 7~11 were histosols [32]. The SOM content of 11 groups ranged from 0.963% to 18.78%.

$$W_u = (W_{u\mathrm{TC}} - W_{u\mathrm{IC}}) \times 1.724, \quad (1)$$

where W_u is SOM content (%), $W_{u\mathrm{TC}}$ is total carbon content (%), and $W_{u\mathrm{IC}}$ is inorganic carbon content (%).

2.1.2. Physical Properties of Soil

(1) Bulk Density. The field bulk density was chosen for samples nos. 1 (silt) and 11 (organic soil). The field bulk density was measured by the cutting-ring method and tested in accordance with *Standards for Geotechnical Test Methods* [33]. After the determination of bulk density of samples nos. 2 to 10, it was hypothesized that the particles of silt and organic soil in the mixture were two separated entities, and they were mixed thoroughly. Given the same external conditions, the premise for equation (2) shall be met. The test bulk density (ρ_{di} in g/cm^3) of each soil type was calculated according to the equation (2). The measured bulk density of 11 groups of soil samples ranged between 0.79 g/cm^3 (organic soil) and 1.56 g/cm^3 (silt) (Table 2).

$$\begin{bmatrix} \dfrac{m_1}{m_{11}} = n \longrightarrow \left(\dfrac{9}{1}, \dfrac{8}{2} \cdots \dfrac{1}{9}\right) \\ \dfrac{m_1}{\rho_{d1}} + \dfrac{m_{11}}{\rho_{d11}} = V \end{bmatrix} \longrightarrow \rho_{di} = \frac{m_1 + m_{11}}{V}, \quad (2)$$

where m_1 is the weight of sample no. 1 in the soil with fixed total weight (g), +0.1 g; m_{11} is the weight of sample no. 11 in the soil with fixed total weight (g), ±0.1 g; ρ_{d1} is the field bulk density of sample no. 1 (g cm^{-3}); ρ_{d11} is the field bulk density of sample no. 11 (g cm^{-3}); V is the volume of the samples (cm^3).

(2) Soil Moisture Saturation. SOM content is an important influencing factor for soil moisture content. In the sample preparation, it was found that mass water content of 11 groups of soil samples ranged substantially from dry to saturation. Moreover, the physical state of soil differs significantly at the same moisture content. For example, when the moisture content of soil sample no. 1 is 22%, the state of soil mass is close to the liquid limit, while soil sample no. 11 has not yet reached the plastic limit. Therefore, it is unreasonable to analyze hydraulic-thermal physical properties of the prepared 11 mixtures under a given moisture content. Thus, a concept of SMS is introduced, which refers to the ratio of water volume in a given volume of void in the porous media. In this study, it refers to the ratio of soil moisture content over the water-holding capacity of saturated soil [34]. During the configuration of soil samples, the minimum water-holding capacity of each soil type was used as its maximum moisture content. Four moisture content gradients, 0.25, 0.50, 0.75, and 1.00 times that of the maximum moisture content were set in the test. Finally, all soil moisture contents were converted into the SMS for comparison. Basic physical properties of soil samples are listed in Table 2.

2.2. Measurements. Measurement of soil thermal conductivity includes the methods of steady and transient heat fluxes. The method of steady heat flux usually takes a long time, in which water may migrate under a temperature gradient. Therefore, the method of transient heat flux was used in our study, and thermal conductivity of soil samples was tested by the ISOMET2114 thermophysical property analyzer. It is equipped with two types of measurement probes: needle probes for soft materials, and surface probes for hard materials. The surface probe was used in this study. The analyzer measured the thermal properties at an accuracy of 5%~10%. Precision is 5% of reading +0.001 W m^{-1} K^{-1} in the range of 0.015~0.70 W m^{-1} K^{-1} and 10% of reading in the range of 0.70~6.0 W m^{-1} K^{-1}. The reproducibility of measurement is 3% of reading +0.001 W m^{-1} K^{-1}, utilizing the transient hot-wire method (Figure 1).

The hot-wire method is described as a system involving a vertical and cylindrical symmetry wherein the wire both provides heating and serves as a thermometry. Additionally, the mathematical model is expressed for that of a boundless line source of heat suspended vertically in a boundless medium. For the general thermal equilibrium, considering a sample with boundless size and an initial temperature (T_0), when heat flow starts at $y = 0$ and $t > 0$, the distribution of temperature within the sample will depend only on the distance$y$ between the heat source and the measurement point and the time (t); it can thus be considered a 1D problem [35]. Since the power of thermal systems changes rapidly and the results are measured in a short time, the method can be regarded and expressed as a transient one. The equation of the specified solution of Fourier's law is as follows:

$$T(t) - T_{\mathrm{ref}} = \Delta T = \frac{q}{4\pi\lambda} \ln\left(\frac{4K}{a^2 C} t\right), \quad (3)$$

where $T(t)$ is the temperature of the wire at time t; T_{ref} is the reference temperature; ΔT is the temperature of the cell; q is the applied power; λ is the thermal conductivity, a function of both temperature and density; K is thermal diffusivity; a is the radius of the wire; and $InC = \gamma$, where γ is the Euler constant.

The result of equation (3) is a linear relationship between ΔT and In(t). Deviations in experimental results are seen over short and long time periods. However, for each

Table 2: Basic physical properties of testing silt-organic soil mixture of different ratios samples.

Soil sample nos.		Types organic soils (W_u, volumetric percentage of organic matter, in %)	Soil organic matter content W_u (%)	Bulk density ρ_d (g cm^{-3})	Water content ω (%)	Saturability S_r (%)
1	1-1	Inorganic soils ($W_u < 5\%$)	0.96	1.56	5.18	19.13
	1-2				10.37	38.26
	1-3				15.55	57.40
	1-4				20.74	76.53
2	2-1		2.71	1.42	5.80	17.27
	2-2				11.60	34.54
	2-3				17.40	51.81
	2-4				23.20	69.08
3	3-1		4.91	1.31	6.91	18.14
	3-2				13.83	36.29
	3-3				20.74	54.43
	3-4				27.65	72.58
4	4-1	Organic soils ($5\% < W_u < 10\%$)	5.96	1.21	7.40	16.24
	4-2				14.80	32.49
	4-3				22.20	48.73
	4-4				29.60	64.98
5	5-1		8.12	1.12	9.49	18.71
	5-2				18.99	37.42
	5-3				28.48	56.14
	5-4				37.97	74.85
6	6-1	Histosols ($W_u > 10\%$)	10.17	1.049	10.02	18.21
	6-2				20.04	36.42
	6-3				30.07	54.63
	6-4				40.09	72.84
7	7-1		11.78	0.98	11.01	18.28
	7-2				22.01	36.56
	7-3				33.02	54.83
	7-4				44.02	73.11
8	8-1		13.16	0.93	11.85	18.15
	8-2				23.71	36.29
	8-3				35.56	54.44
	8-4				47.41	72.59
9	9-1		15.40	0.88	11.94	16.98
	9-2				23.88	33.96
	9-3				35.82	50.94
	9-4				47.77	67.92
10	10-1		16.83	0.83	12.86	17.22
	10-2				25.73	34.44
	10-3				38.59	51.66
	10-4				51.46	68.87
11	11-1		18.78	0.79	13.73	17.72
	11-2				27.47	35.44
	11-3				41.20	53.16
	11-4				54.93	70.88

experiment results, a period of time is obtained over which equation (3) is valid, indicating a linear connection between ΔT and $\mathrm{In}(t)$. The slope of the ΔT versus $\mathrm{In}(t)$ relationship is acquired over the valid range between time t_1 and t_2. The thermal conductivity is taken from equation (3) using the applied power. In addition, the temperature assigned to the

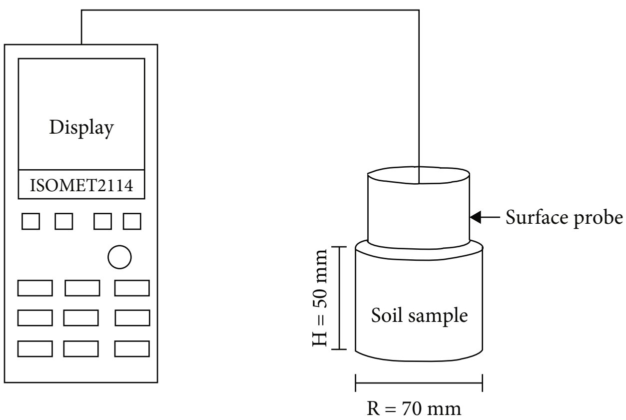


Figure 1: Schematic diagram of the thermal test apparatus (ISOMET 2114 thermophysical property analyzer).

measurement of λ is given by the following:

$$T = T_{\text{ref}} + \frac{1}{2}[\Delta T(t_1) + \Delta T(t_2)], \quad (4)$$

where λ is obtained from an equality of state using an experimentally measured pressure and the temperature described above. ΔT_w is the temperature rise of the wire. Several corrections describe the departure of the actual instrument from the standard model:

$$\Delta T = \Delta T_w - \sum \delta T_i. \quad (5)$$

During the test, each test soil group (Table 2) started cooling from 10°C and thermal conductivities of soil samples at different soil temperatures (10, 5, 2, 0, -2, -5, and -10°C), under different SMS (19.13%~70.88%), and with SOM contents (0.96%~18.78%) were tested by the ISOMET 2114 thermophysical property analyzer. Each piece of data in the Results and Analyses represents an average of three separate tests.

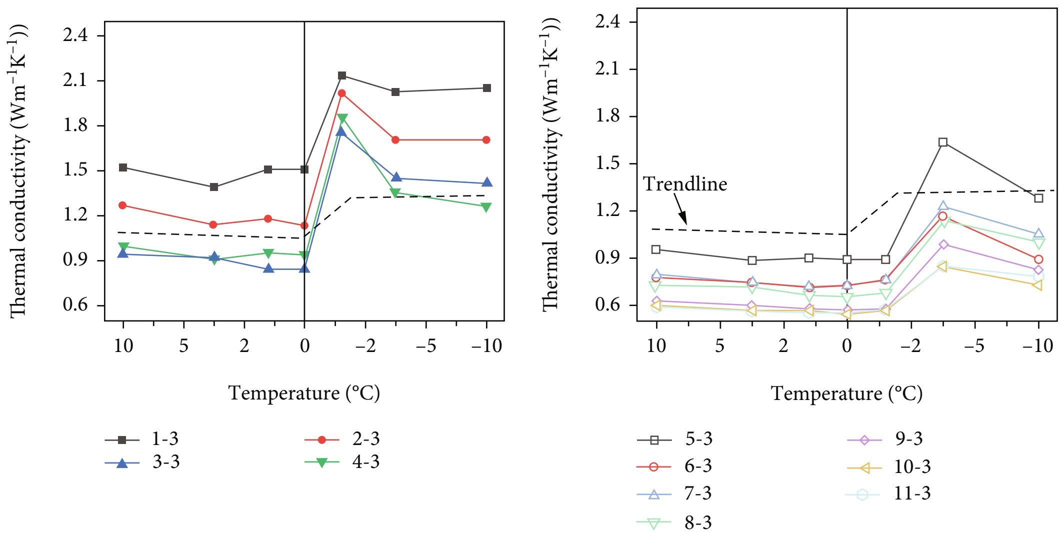
3. Results and Analyses

3.1. Influences of Soil Temperature on Soil Thermal Conductivity. Under the frozen state, temperature mainly influences thermal conductivity of soil by changing the ice-water proportion in soil. In the range of -10~10°C, the variation of soil thermal conductivity with temperature is shown in Figure 2. Obviously, soil thermal conductivity under the frozen state is higher than that under the thawed state because of a much higher thermal conductivity of ice ($2.18\,\mathrm{W\,m^{-1}\,K^{-1}}$) [36] in comparison with that of water ($0.58\,\mathrm{W\,m^{-1}\,K^{-1}}$) [37]. Clearly, upon freezing, soil thermal conductivity increases sharply. Generally, soil thermal conductivity peaks at about -2°C for silt and organic-poor soil samples (Figure 2(a)), but at about -5°C for organic-rich soil samples (Figure 2(b)). According to comparative studies on thermal conductivities of soil samples under the same SOM content and different SMS (Figure 3), the peak of thermal conductivity occurs at about -2°C for soil samples with relatively high SMS, but at about -5°C for soil samples with relatively low SMS. After the peak values, thermal conductivity declines and finally stabilizes with lowering soil temperature (Figures 2 and 3).

3.2. Effects of SMS on Soil Thermal Conductivity. The soil samples were tested across a range of SMS. According to the test results, under the thawed state, thermal conductivity of 11 groups of soil sample ranges between $0.28\,\mathrm{W\,m^{-1}\,K^{-1}}$ (soil sample no. 11 at 20% in SMS) and $1.97\,\mathrm{W\,m^{-1}\,K^{-1}}$ (soil sample no. 1 at 80% in SMS). In contrast, the variation range of thermal conductivity of 11 groups of soil sample under the frozen state is the larger, with a minimum of $0.26\,\mathrm{W\,m^{-1}\,K^{-1}}$ (soil sample no. 11 at 20% in SMS) and a maximum of $2.71\,\mathrm{W\,m^{-1}\,K^{-1}}$ (soil sample no. 1 at 80% in SMS). Figure 4 showed the variation in thermal conductivity of 11 groups of soil samples with varied SMS at -10 and +10°C. Remarkably, thermal conductivity increases with rising SMS. For instance, the thermal conductivity values under the nearly saturated conditions were almost twice those under the dry conditions (Figure 4). This is because when the dry density is held constant, the increase of SMS is realized by the growth of unit volume water (thermal conductivity: $0.59\,\mathrm{W\,m^{-1}\,K^{-1}}$) and reduction of air (thermal conductivity: $0.025\,\mathrm{W\,m^{-1}\,K^{-1}}$). Since the thermal conductivity of ice is nearly 3 times higher than that of water, soil thermal conductivity increases more rapidly with ice saturation, and the growth rate of thermal conductivity at -10°C is higher than that at 10°C (Figure 4).

According to a previous study [12], for the thawed soil, as the soil moisture content increases, the growth rate of thermal conductivity is high first and stable later; but for frozen soil, it is stable at two ends and high in the middle. In other words, soil moisture content significantly influences thermal conductivity of thawed soil when total soil moisture content is lower than the plastic limit, and thermal conductivity increases quickly with rising soil moisture content. In the stage of soil moisture content varying from plastic to liquid limits, influences of soil moisture content on thermal conductivity are weakened and the growth rate of thermal conductivity decreases. Above the liquid limit, the growth rate of thermal conductivity stabilizes gradually. In the first stage (soil moisture content is lower than the plastic limit) of frozen soil, unfrozen water content is relatively low, but the activity of water molecules declines. The growth rate of thermal conductivity decreases. In the second stage (soil moisture content varying from plastic to liquid limits), unfrozen water in soil begin to freeze with rising total soil moisture content and ice crystals increase gradually, thus quickly increasing thermal conductivity. In the third stage (above the liquid limit), influences of ice crystals on growth of thermal conductivity are weakened, thus decreasing the growth rate of thermal conductivity [12]. In this study, soil moisture content is still under the liquid limit. Hence, the third stage is not reached, and the thermal conductivity basically grows linearly with rising SMS.

It is also shown that the change of thermal conductivity with SMS in the silty soils differs from that in the organic-



(a) (b)

Figure 2: Changes in soil thermal conductivity with soil temperatures ((a) silt and organic-poor soil samples; (b) organic-rich soil samples).

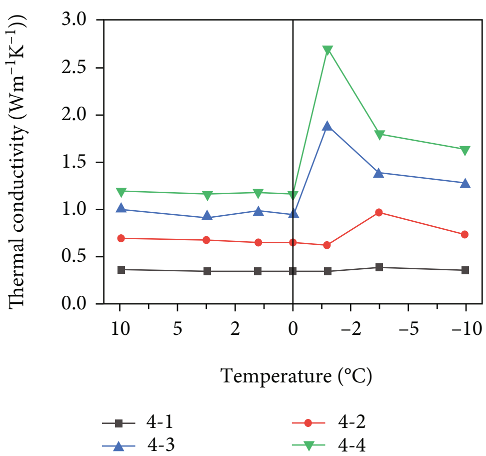


Figure 3: Changes in thermal conductivity of soil sample no. 4 with soil temperature.

rich soils (Figure 4). Thermal conductivity of silty soils increases sharply with rising SMS (Figure 4: linear fitting for thermal conductivity of sample no. 1), while that of organic-rich soils enlarges gradually with increasing SMS (Figure 4: linear fitting for thermal conductivity of sample no. 11). This might be due to the important bridging role of soil water between mineral particles in the relatively dry silty soils. At low soil moisture content ranges, rising soil moisture content has not only increased heat conduction through the more continuous films of liquid water, but it has also greatly improved the heat conduction in the solid fraction due to the bridging effect. However, because of the fibrous structures in organic-rich soils, those effects may be not as significant as those in mineral particles, and thermal conductivity increased linearly with increasing SMS [38, 39]. These results agree with those of Kersten [40] and Zhao and Si [22]. Kersten [40] reported that thermal conductivity of peat exhibited relatively small changes for samples with soil moisture contents ranging between 0.10 and 2.85 g g^{-1}.

3.3. Effects of SOM Content on Soil Thermal Conductivity. Changes in soil thermal conductivity with varying SOM content, SMS, and freeze-thaw state are presented in Figure 5. In the whole range of SMS, thermal conductivity of soil samples declines with increasing SOM content. This is because the average thermal conductivity of minerals (2.13 W m^{-1} K^{-1}) is about 8 times that of organic soils [39]. Meanwhile, with rising SOM content, porosity increases and thermal conductivity decreases [41]. Overall, thermal conductivity is negatively correlated with SOM content. Based on test data, the relations between thermal conductivity and SOM content of samples under different SMS degrees are fitted by linear and exponential functions. Results reveal that the exponential function has a better fitting ($P < 0.05$), and thermal conductivity declines exponentially with increasing SOM content.

3.4. Empirical Formula of Thermal Conductivity with Considerations for SOM Content. Based on laboratory tests and using SPSS, the empirical formula of thermal conductivity was fitted with SMS, soil temperature, and SOM content as independent variables and thermal conductivity as the dependent variable. The empirical formulas of thermal conductivity are expressed as follows:

$$\lambda_f = 0.0303 S_r^{1.0061} T_1^{0.1967} e^{-0.0639 W_u}, \quad (6)$$

where W_u is SOM content (%), S_r is SMS (%), and T_1 is calculated as follows:

$$T_1 = (T+2)^{2/7} - 1.4(T+2)^{1/7} + 1.44, \quad (7)$$

where T is soil temperature (°C).

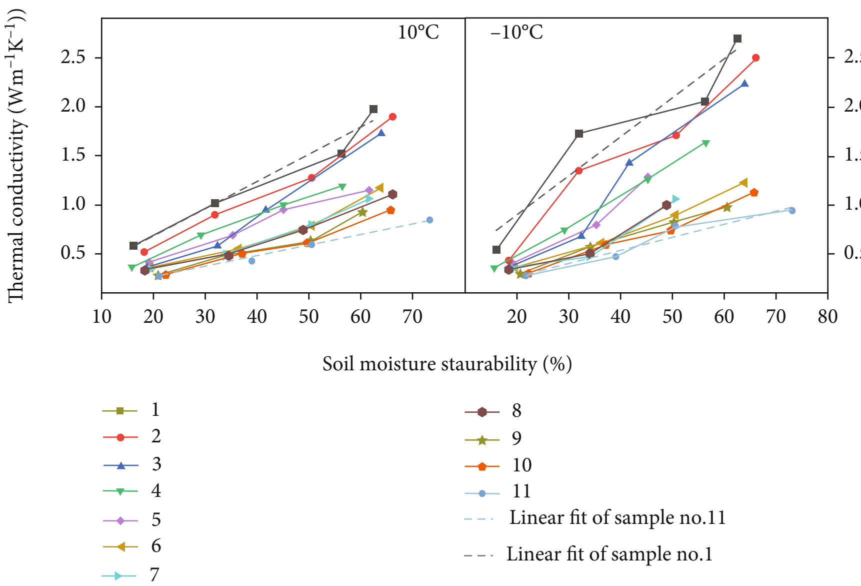


FIGURE 4: Variations of soil thermal conductivity with soil organic matter content under frozen (-10°C) and thawed (+10°C) states.

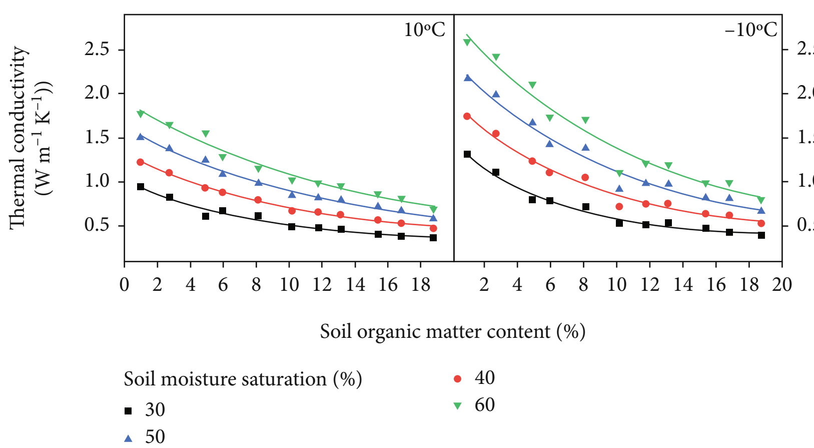


FIGURE 5: Changes in thermal conductivity with varying soil organic matter content and soil moisture saturation degrees at -10 and 10°C.

It is important to note that the fitting of the empirical formula is based on experimental data with a SOM content under 18%, a soil temperature range of −10 ~ +10°C, and SMS under 80%. Additionally, along the curve of thermal conductivity, there are peak points at a soil temperature of -5~0°C due to influences of ice-water phase change (Figures 2 and 3). This agrees well with previous research results [22, 42, 43]. Therefore, the formula for computing soil thermal conductivity is suitable for the negative temperature range below -5°C.

4. Discussion

4.1. Reasons for the Peak Points of Thermal Conductivity Curve under Negative Temperature. In this study, the reason of the peak points of thermal conductivity curve under negative temperature was discussed from two aspects: testing method and soil freezing temperature.

Both transient and steady methods can be used to determine soil thermal conductivity according to temperature change (difference) under a certain heat source. In the tests, soil temperature generally increases because of exogenous heat in the first stage. In the process of temperature rising, (1) in the frozen soil, temperatures of mineral particles, ice, unfrozen water, and vapor rise, and (2), some ice bodies or lenses in the frozen soil melt. Due to different specific heat capacities of mineral particles, ice, unfrozen water, and vapor in frozen soil, there ensues heat conduction upon temperature rises to the same value: (1) heat conduction between external heat source and different phases of frozen soil, and (2) heat conduction among different components of frozen soil. H_2O (water or ice) is a crystal and its temperature remains basically stable after heat fusion in the phase change process. Therefore, the heat applied to soil samples by the external heat source is not completely reflected on the increase in temperature of frozen soil during the thermal

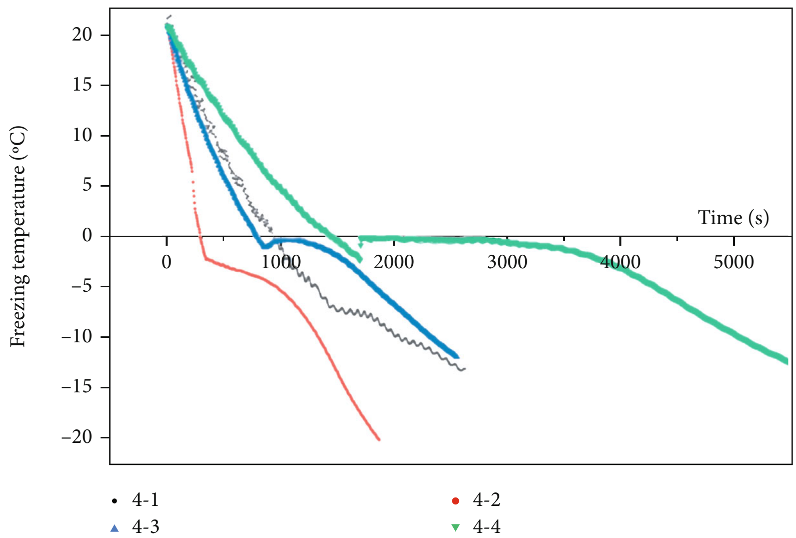


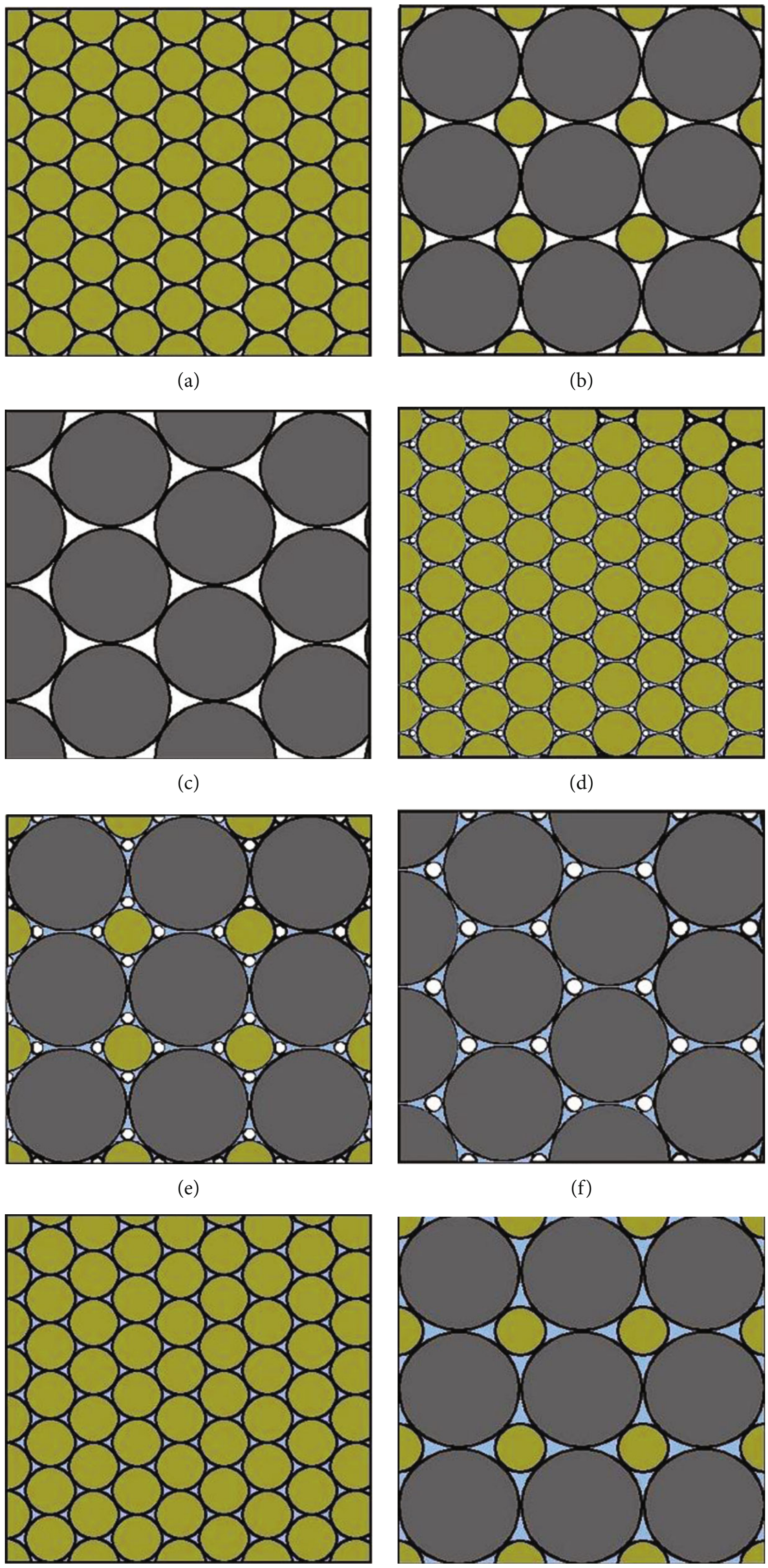
Figure 6: Changes in freezing temperature of soil sample no. 4 with soil moisture saturation (Table 2).

conductivity test. Some are absorbed for melting of ice. In the second stage, the supply of exogenous heat stops and temperature changes of soil samples are measured. In this stage, ice melted in the first stage refreezes and releases great latent heat. Therefore, soil samples undergo intense phase changes within the temperature range of warm frozen soil. Influenced by latent heat absorption at the melting of ice in soils and latent heat at refreezing, temperature difference (ΔT) caused by fusion heat is not reflected in temperature. The phenomenon described above causes the test temperature difference (ΔT) to be smaller than the actual temperature difference, resulting in a larger measured value of thermal conductivity than the real value (equation (3)), resulting in a peak point.

Moreover, in combination with the freezing temperature of a soil sample, the peak point of the thermal conductivity curve is usually observed when the soil temperature is slightly lower than the soil freezing temperature. Take the no. 4 sample group for example (Figure 6), since the freezing temperatures of soil samples nos. 4-1 and 4-2 with a relatively low SMS are lower than -2°C, the peak point of thermal conductivity occurs at -5°C (Figure 3). However, the peak point of thermal conductivity curve occurs at -2°C since the freezing temperatures of soil samples nos. 4-3 and 4-4 are higher than -2°C. The results can be used for reference to select the test temperature point when there is thermal conductivity of the heating-temperature measurement technology. That is, the test temperature point should be much lower than the freezing temperature of the soil under test, so that the phase transition will not occur in the testing process, and more accurate thermal conductivity value can be measured. Moreover, the higher SMS brings the higher latent heat released by phase change of water in soils and the greater difference between the peak and stable values on thermal conductivity curve. Zhao and Si [22] tested thermal conductivity of soil using the dual thermal pulse probe technology and the peak point of thermal conductivity also occurred between -2~0°C for sandy soils and -4~0°C for peat soils. Thus, the difference between measured and theoretical values of thermal conductivity are caused by test methods and latent heat for phase change of soil (Figures 2 and 3). However, the hydrothermal processes and mechanisms of the soil in the phase change zone are quite complex, and the mechanisms await further studies in the future.

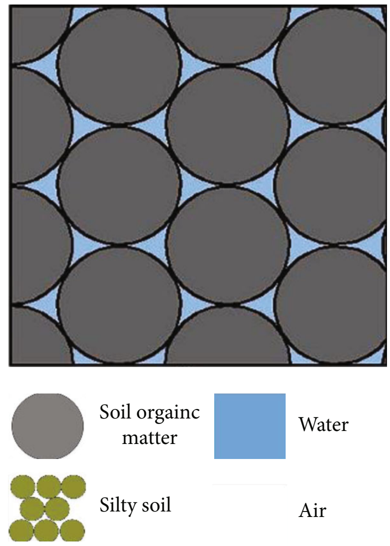
Based on above conditions, attention needs to be paid to the selection of test temperature points when discussing influences of temperature on thermal parameters by the heating-temperature measurement method. For example, the heating-temperature measurement method is not recommended for frozen sand (-2~0°C) and peat soil (-4~0°C) [22, 42, 43] According to test results, the heating-temperature measurement method is not recommended for silt and organic-poor soils at temperatures of -2~0°C and for organic-rich soils at temperatures of -5~0°C. Hence, when measuring the thermal conductivity of soil in the future, the heating-temperature measurement technology should be fully considered, and the measured results of thermal conductivity shall be corrected on the basis of the phase change process.

4.2. Influencing Mechanisms of SOM Content and SMS on Soil Thermal Conductivity. According to comprehensive analyses of experimental data, thermal conductivity lowers exponentially with increasing SOM content. At higher SOM content, the growth rate of thermal conductivity decreases gradually with rising SMS. This is consistent with research result of Zhao and Si [22]. According to analysis, this is mainly because the dependence of heat transmission in soil on the soil skeleton and soil skeleton-water bridge. At an SMS of 0 (dry soil), heat transfers through the contact surface between soil aggregates in the soil skeleton. With increasing SOM content, the volume of soil aggregate increases and soil loosens, thus gradually decreasing the contact area among particles and aggregates (Figures 7(a)→7(b)→7(c), 7(d)→7(e)→7(f), and 7(g)→7(h)→7(i)). For soil particles, the average



(a) (b) (c) (d) (e) (f) (g) (h)

Figure 7: Continued.



(i)

Figure 7: Three-phase diagram of unit volume of soil with different soil organic matter content and varied soil moisture saturation. *Notes*. (1) From (a)→(b)→(c), (d)→(e)→(f), and (g)→(h)→(i): with the increase of soil organic matter content, the contact state changes between soil particles. (2) From (a)→(d)→(g), (b)→(e)→(h), and (c)→(f)→(i): as soil moisture saturation increases, bonded water and water membrane begin to form around soil particles, and soil particle-water bridge is built. (3) From (g–i): when soil moisture saturation further increases, almost all open pores are filled with water.

thermal conductivity of minerals (2.13 $W m^{-1} K^{-1}$) is 7.5 times more than that of peat/organic soil (0.25 $W m^{-1} K^{-1}$) [39]. Heat conduction capacity of SOM is far lower than that of minerals. As a result, thermal conductivity is negatively correlated with SOM content. As SMS increases, bonded water and water membrane begin to form around soil particles and the soil particle-water bridge is built to increase the contact area for heat transfer [44] and increase the heat conduction capacity (Figures 7(a)→7(d)→7(g), 7(b)→7(e)→7(h), and 7(c)→7(f)→7(i)). As SMS further increases, almost all open pores are filled with water (Figures 7(g)–7(i)). A thermal conductivity gap is mainly determined by the difference between the soil skeleton and closed pores (closed pores are not marked out in Figure 7). The increased pore volume of SOM is mainly caused by increasing volume of each pore. Given the same SMS, organic-richer soils have more unfilled residual pores and a weaker soil particle-water bridge for heat transfer (Figures 7(d)–7(f)). Hence, thermal conductivity is negatively correlated with SOM content at the same degrees of SMS. This is attributed to the collaborative effects of basic properties of soil matrix and SOM on pore volume.

In this study, the remolded soil from the mixing of silt and organic soil has simpler properties and the chosen SMS, soil temperature, and SOM content are basically the major influencing factors of thermal conductivity. The influencing mechanisms of SMS and SOM interactions on heat conduction capacity are discussed preliminarily. In fact, there are great structural differences between natural/undisturbed and remolded soils due to complicated influencing factors of thermal conductivity. The structure of frozen soil consisting of porous and multiphase media directly determines thermal conductivity. In addition, porosity and bulk density of soil change due to the presence of SOM. All these factors can influence the heat conductivity of soil. Based on existing work, further studies should consider the complicated influencing factors of thermal conductivity and mutual coupling and influences of different factors using undisturbed soil samples as the research object, in order to provide more accurate parameters for simulating land surface processes and frozen soil engineering.

5. Conclusions

In this study, influences of soil temperature, SMS, and SOM content on thermal conductivity of soils are investigated through laboratory tests and theoretical analysis. The influencing mechanisms are preliminarily analyzed. Some major conclusions could be drawn:

(1) Soil thermal conductivity decreases slowly when soil temperature lowers from 10 to 0°C. Under the frozen state, temperature mainly influences thermal conductivity of soil by changing the ice-water proportion in soil, and the thermal conductivity increases with the soil cooling and stabilizes with the further cooling. Generally, thermal conductivity of soils in the frozen state is higher than that in the thawed state. It should be noted that, in the initial stage of soil freezing (the temperature is higher than the freezing temperature of soil), thermal conductivity of soil increases sharply in response to phase changes of frozen soil and thus the measured values are not real thermal conductivity

(2) At 10 and -10°C, thermal conductivity of soil samples both increases with rising SMS. Such a growth rate is negatively correlated with SOM content

(3) Under different SMS degrees, thermal conductivity of soil declines exponentially with increasing SOM content

(4) Based on experimental data, empirical formulas of thermal conductivity of soil are fitted using SOM content, SMS, and soil temperature as independent variables. These formulas may provide basic parameters for model simulating and predicting of cold-region land surface processes and frozen soil engineering designs

Data Availability

The thermal conductivity of soil data used to support the findings of this study are included within the article and also available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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