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A New Model for the Characterization of Frozen Soil and Related Latent Heat Effects for the Improvement of Ground Freezing Techniques and Its Experimental Verification

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Abstract: The correct determination of thermal parameters, such as thermal conductivity and specific heat of soil during freezing, is the most important and basic problem for the construction of an appropriate freezing method. In this study, a calculation model of three stages of soil temperature was established. At the unfrozen and frozen stages, the specific temperatures of dry soil, water, and ice are known. According to the principle of superposition, a calculation model of unfrozen and frozen soils can be established. Informed by a laboratory experiment, the latent heat of the adjacent zone was calculated for the freezing stage based on different water contents in the temperature section. Both the latent and specific heat of water, ice, and particles were calculated via superposition of the weight percentage content. A calculation model of the specific heat of the freezing stage was built, which provides both guidance and theoretical basis for the calculation of the specific heat of frozen soil.

Keywords: Freezing construction, latent heat, frozen soil, specific heat.

1 Introduction

With the rapid economic and social development in China, the construction of artificial freezing methods is increasingly required for various civil engineering projects. In underground construction projects such as tunnel excavation, pit excavation and mine excavation in flood-prone areas, freezing construction has often become the first choice due to its wide adaptability.

Because of the complexity of problem and the limitations of existing technology, the construction of freezing methods faces many unsolved problems. Examples are the soil thermal parameters, freezing time and power configuration, the effect of groundwater on the freezing process, the mechanism of freeze-thaw and coalescence, the development laws of stress and strain in the process of freeze-thaw and subsidence. Among them, the determination of thermal parameters, such as thermal conductivity and specific heat in the freezing process, is the primary and basic problem to be solved. Thermal parameters are also the basis for studying other topics of the freezing method.

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Compared to the mineral composition, dry density, saturation, porosity and other factors, water content is a centrally important factor affecting the specific heat of soil and thermal conductivity. The mineral composition of soil differs, and the moisture content of different types of soil is not identical or constant; however, the specific heat and thermal conductivity of each component are basically similar. In addition, the specific heat and the thermal conductivity of water differ greatly from that of ice. Therefore, the thermal parameters of the soil before and after being frozen will change significantly. Due to the action of the electric double layer, the freezing of water in the soil happens at a temperature below 0°C instead of the conventional 0°C, indicating that water freezing is a process rather than a temperature point. During this process, the latent heat of water is gradually released, thus complicating the determination of soil thermal parameters.

Soil specific heat at the freezing stage has been extensively investigated. Abu-Hamdeh et al. showed that the specific heat of soil is related to the water content and soil density and determines the relationship among soil thermal conductivity, density and water content [Abu-Hamdeh (2003)]. By comparing the theoretical and experimental values of the specific heat capacity of sand and clay, an empirical formula concerning the specific heat capacity and thermal conductivity of the soil, voidage, dry density and water content was derived [Bristow (1998)]. In an analysis of road freezing, Cames-Pintaux used GEL1D software to quantitatively analyze the effect of thermal parameters and the interactions between the parameters, indicating that both the convection exchange coefficient and initial temperature play an important role in the hydrothermal properties of subgrade [Cames, Nguyen and Aguirre-Puente (1986)]. Their study suggests that the specific heat of soil is not constant [Comini, Guidice, Lewis et al. (1974); De Vries (1963); Bristow (1998); Bristow, Kluitmberg, Godong et al. (2001)] and is not only affected by the unfrozen water content in the frozen soil, but also related to factors such as dry density, saturation, water content and temperature [Kozlowski (2012); Kozlowski and Nartowska (2013)], among which, moisture content significantly affects latent heat. In China's freezing method construction before the 1970 s, the values of thermophysical parameters were mostly based on foreign data [Wang, Hu, Long et al. (2007); Liu (2009); Wang, Liu and Lu (2007); Wen, Wu, Jiang et al. (2013)]. In 2001, China promulgated the *frozen soil Engineering Geological Survey Specification* (GB50324-2001) that reflects the latest research achievements in the field of frozen soil due to the founding of the People's Republic of China. Basically, indoor and outdoor experiments have been carried out. In this study, thawing results were studied in a complex composition of soil particles, pore water and pore gas. The freezing process of soil is essentially a combination of physical processes such as the freezing and cooling processes of pore water, the cooling process of pore ice and soil particles, and the migration process of pore water. Regardless of water migration, the heat loss of soil in the freeze-thaw process includes a temperature change of particles, a temperature change of water (ice), and the latent heat of ice-water phase change. The freezing stage is a dynamic equilibrium process, in which ice and water contents constantly change.

The study of the specific heat of frozen soil often ignores the latent heat release from the conversion of pore water into pore ice, by either assuming that the specific heat of the soil is constant from normal temperature to complete freezing, or by only focusing on changes in the specific heat with water content and density, without considering the continuity of the phase change. Rubinsky indicated that specific heat constants of soil before and after freezing differ [Rubinsky (1982)]. Judging from the definition of latent heat, these literature methods for determining the specific heat of frozen soil are insufficient. Only by following the fact that the icing of pore water in soil is a continuous process at a relatively large negative temperature range, the latent heat released during this interval must be considered (not only at 0°C) for a reasonable calculation of the specific heat of soil in the freezing process. The specific heat of soil freezing phase must be related to the phase transition process of pore water and the corresponding latent heat. Therefore, the latent heat change is calculated based on the unfrozen water content, and the latent heat energy and the energies of water and granular body are combined into the total energy. The calculation model of the thermal parameters in the freezing stage was deduced. Based on laboratory experiments, the relationship among soil density, moisture content, temperature, and thermal conductivity was investigated. A theoretical model of the thermal conductivity during the freezing phase was established based on temperature changes. Thus, a thermal conductivity calculation model for the three temperature stages of the soil for the melting and freezing stages was established.

2 Model for computing theory of frozen soil specific heat by sensible heat method

2.1 Frozen soil classification based on pore water phase

Geotechnical material is a type of natural geological material with complex and varied chemical and mineral composition. Moreover, in addition to soil particles, saturated soil contains pore water. Unsaturated soil has pore gas in addition to soil particles and pore water. In addition to conventional solid, liquid and gas phases, frozen soils also have ice masses that are extremely sensitive to temperature changes compared to ordinary soils.

Water exists in three forms, namely liquid, solid and gaseous. According to the definition of temperature, the temperature of ice water mixture of pure water is defined as 0°C at standard atmospheric pressure conditions, i.e., water above 0°C exists in the form of liquid and the form of ice below 0°C. Due to varying chemical composition, mineral composition and double electric layer, the physical properties of water in soil during the freezing process are obviously different from those of the normal state. The main difference is that in the relatively long negative temperature range below 0°C, the water in the soil exists as both liquid water and solid ice. Even if the temperature is significantly lowered, a certain amount of unfrozen water still remains in the soil, as shown in Fig. 1.

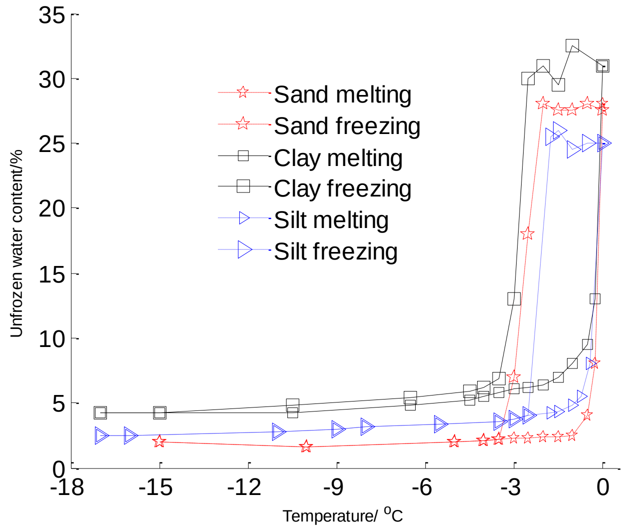

Figure 1: Relationship between the content of unfrozen water and temperature

The pore water at a distance from the soil particles is less affected by the electric double layer and Van der Waals force. Therefore, the freezing temperature of this part of the pore water is close to 0°C. The pore water close to the soil particles has a relatively low freezing temperature, because of varying chemical composition, mineral composition and double electric layer and Van der Waals force. Therefore, unfrozen water in the soil often exists near the soil particles. In case of water supplementation, this part of the pore water often becomes a pathway for moisture migration.

The phase transition process of water in soil with decreasing temperature can be divided into three stages, namely, drastic phase transition zone, transition zone, and frozen zone. In the drastic phase transition zone, when the temperature changes by 1°C, the amount of unfrozen water changes by more than 1%, and free water and weakly bound water change from liquid water to solid ice. In the transition zone, when the temperature changes by 1°C, the unfrozen water content varies from 0.1% to 1%, at which time, the weakly bound water with variable phase components will condense to ice. In the freezing temperature zone, for every 1°C decrease in temperature, the amount of ice in the aqueous phase becomes less than 0.1%. It has also been suggested that there is only strong bound water in liquid water in the frozen stage of soil. In essence, strong bound water is part of the solid particles of the soil. Therefore, with further decreasing temperature, the proportion of phase components in the frozen soil in the freezing stage will stabilize.

The frozen soils in the drastic phase transition zone and the transition zone have a common feature, i.e., they contain pore water with variable phase components. The total amount of heat exchange at this time includes two parts, one part to change the temperature of each component, and the other part to change the phase state of pore water. Therefore, depending on whether there is variable water in the phase composition, the drastic phase transition zone and the transition zone can be merged into one type and named “freezing stage.”

According to the characteristics of the phase change in water in the soil, clay will go through three stages with decreasing temperature, i.e., i) liquid water does not exist in the thawing phase where the phase state changes; ii) part of the liquid water turns into the freezing phase of the solid water; and iii) there is no frozen phase in which liquid water is converted into solid ice.

Corresponding to these three stages, frozen soil can be reclassified from a thermal perspective. i.e., with decreasing temperature, the water-containing clay can be divided into three types, i.e., thawing soil, freezing clay, and frozen clay.

2.2 Specific heat of soil particles, water and ice

The specific heat of the soil is equal to the sum of heat absorbed or released by all components at a temperature increase or decrease of 1°C. The specific heat of soil at a certain temperature T should include the amount of heat required for the phase change of pore water (pore ice), during a slight change in ΔT near that temperature.

For clay, silty clay and silt, the specific heat C_p of soil particles is 0.845, 0.826, and 0.824 kJ/(kg.K), respectively, indicating that the specific heat of soil particles varies with the area and particle thickness, but the variation range remains within 3%, showing limited variation in the specific heat of soil particles.

The specific heat of any substance is not constant, but varies with temperature, and the specific heat of purified water and pure ice is no exception. At standard atmospheric pressure, the specific heat of pure water and pure ice at different temperatures is shown in Fig. 3.2. Under natural conditions, the temperature of the thawing soil is generally <30°C. In frozen construction, the temperature of artificial frozen soil is generally within -30°C, indicating that the specific heat of water and ice can be considered constant in the range from -30°C to 30°C. This assumption fully complies with engineering requirements and is a common simplification.

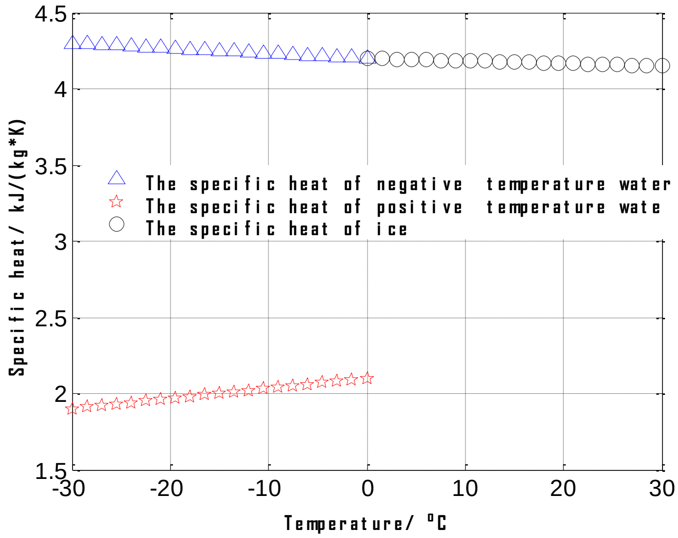

Figure 2: Specific heat of water and ice at different temperatures

2.3 Specific heat of soil particles, water and ice

Unfrozen soil is a three-phase system consisting of soil particles, pore water and pore gas. Freezing soil is a four-phase system consisting of soil particles, pore ice (a small amount of stable pore water) and pore gas. The liquid content of unfrozen soil and frozen soil is constant, and there is no phase change and corresponding latent heat change with temperature change. In the freezing phase, the liquid water in the soil continuously condenses into ice with changing temperature, the liquid water content continuously decreases and the ice content gradually increases. Therefore, the specific heat of frozen soil should include the latent heat of phase change. Because the phase state of water in soil is very different before and during freezing, studying the specific heat of soil in all stages is necessary.

2.3.1 Heat composition when temperature changes

According to the heat exchange principle of the mixture, when the soil temperature changes, the total energy change is equal to the sum of the energy exchanges of all components, i.e.,

$$N = N_1 + N_2 + N_3 + N_4 \tag{1}$$

where

N=Total energy change in soil;

N_1=Energy required for temperature change in water in soil;

N_2=Energy absorbed or released during the phase change of water in soil;

N_3=Energy required to change the ice temperature in the soil;

N_4=Energy required to change the temperature of the soil particles.

2.3.2 The specific heat of thawing soil

Specific heat is defined as the amount of heat required per unit mass of a substance to increase or decrease the temperature by 1 °C. Thawing soil is a mixture of soil particles, pore water and pore gas. The specific heat is determined by the specific heat of soil particles, pore water and pore gas. Because the quality of the pore gas is negligible, the specific heat of the fused soil *C* depends on the soil particles and pore water, i.e.,

$$C_1 = \left(C_p + wC_w\right)/\left(1 + w\right) \tag{2}$$

where C_p and C_w represent the specific heats of soil particles and water, respectively, and w represents the water content of the soil.

2.3.3 Specific heat of frozen soil

In frozen soils, phase transitions no longer occur with a further decrease in temperature. Therefore, the specific heat of frozen soil is determined by the specific heat of soil particles, pore ice and pore gas. Similarly, the specific heat, *C*, of frozen soil depends on soil particles and pore ice, irrespective of the specific heat of the pore gas, i.e.,

$$C_2 = \left(C_p + wC_i\right)/\left(1 + w\right) \tag{3}$$

where C_i represents the specific heat of ice, and *w* represents the amount of ice and is equal to the water content of the corresponding thawing soil. Since the specific heat of ice is much smaller than that of water, the specific heat of frozen soil is less than that of thawing soil.

2.3.4 Specific heat of freezing soil

In the unfrozen and frozen phases, since the specific heat levels of dry soil, water and ice are known, the specific heat calculation model for unfrozen and frozen soil can be established by the superposition method. During the freezing stage, the corresponding temperature zone can be equally divided into n equal parts, and the latent heat of the adjacent zone can be calculated according to the difference in the unfrozen water content in each temperature zone. The latent heat and the specific heat of water, ice and particles were added according to the content weight, and a calculation model for specific heat in the freezing stage was established. The theoretical relationship between specific heat and water content, dry density, temperature and other factors was further investigated.

Freezing soil is a multi-phase mixed system composed of solid particles, pore ice, pore water and pore gas. The specific heat of frozen soil depends on the specific heat of each component in the frozen soil and its corresponding content [Cames, Nguyen and Aguirre (1986); Bristow (1998)]. Based on the theory of the mixture, the specific heat of the frozen soil should include a weighted average of specific heat of soil particles, pore ice, pore water and pore gas. If the gas phase composition in frozen soil is neglected, the specific heat of frozen soil is often expressed as

$$C_2 = \left[C_p + \left(w - w_u\right)C_i + w_u C_w\right]/\left(1 + w\right) \tag{4}$$

where w_u represents the unfrozen water content at a certain negative temperature and can be obtained by nuclear magnetic resonance and other methods. The specific heat of frozen soil is calculated by Eq. (4). Eq. (4) only covers the sensible heat in soil when temperature changes, but does not include the corresponding latent heat. When the temperature of the freezing soil changes slightly, the corresponding sensible heat is expressed as follows.

$$\Delta Q_1 = C_0 \times \Delta T \tag{5}$$

From the definition of specific heat, the specific heat of frozen soil is the amount of heat required per unit mass of substance for its temperature to increase or decrease by 1°C. For freezing soils, when the temperature changes, even if the total water content does not change, the solid and liquid water content will change due to freezing or melting. Due to the phase transition of water, freezing or melting must be accompanied by the absorption or release of latent heat. Compared to the specific heat of liquid water and solid ice, the latent heat of the phase change of water is large. Under normal conditions, the latent heat of water is 335 kJ/kg, which is approximately 80 times the specific heat of water and 160 times the specific heat of ice. Therefore, the latent heat of water should play an important role in the calculation of the specific heat of frozen soil. Eq. (4), which is normally used for the calculation of specific heat of frozen soil, does not cover the latent heat of water. Therefore, this type of calculation method is unreasonable.

3 The specific heat calculation model considering the latent heat of phase change

Assume that at a negative temperature T_1, the unfrozen water content in the soil is w_{u1}; when the temperature drops to T_2, the unfrozen water content in the soil is w_{u2}. The corresponding reduction in the amount of unfrozen water with temperature changes is

$$\Delta w_u = w_{u1} - w_{u2} \tag{6}$$

Let the specific heat of T_1, without consideration of latent heat, be C_0; when the temperature is lowered to T_2, the specific heat without consideration of latent heat is

$$C_0' = \frac{C_p + (w - w_u + \Delta w_u)C_i + (w_u - \Delta w_u)C_w}{1+w} \tag{7}$$

Therefore, in the range T_1-T_2, the average specific heat without consideration of latent heat is as follows.

$$C_\alpha = \frac{C_p + \left(w - w_u + \dfrac{\Delta w_u}{2}\right)C_i + \left(w_u - \dfrac{\Delta w_u}{2}\right)C_w}{1+w} \tag{8}$$

The latent heat corresponding to the change in the unfrozen water content is expressed by the following equation.

$$\Delta Q_2 = L\Delta w_u \tag{9}$$

Therefore, when the temperature of the freezing soil changes, the heat consists of two parts, namely the sensible heat required for the temperature change and the latent heat required for the phase change.

$$\Delta Q = \Delta Q_1 + \Delta Q_2 \tag{10}$$

According to the definition, the specific heat C_β of the freezing soil should be

$$C_\beta = {\Delta Q}/{\Delta T} \tag{11}$$

Namely, $C_\beta = C_\alpha + {L \times \Delta w_u}/{\Delta T}$ (12)

Eq. (12) used for the calculation of specific heat of freezing soil considers latent heat of phase change. Therefore, compared to the original calculation method (formula (4), this method is obviously more reasonable.

According to Eq. (4) and Eq. (12), the specific heat of a type of clay in Xinxiang City, Henan Province, was calculated (as listed in Tab. 1), indicating a significant difference between the specific heat obtained by the two methods in a temperature range from 0°C to -5°C.

Table 1: Comparison of calculation results based on Eq. (4) and Eq. (12)

Temperature (°C)	6	3	0	-05	-1	-2	-3	-5	-8	-10	-15
C_2	2.25	2.22	2.01	2.58	2.74	2.49	2.38	2.0	1.81	1.72	1.68
C_β	2.25	2.24	2.02	1.92	1.84	1.78	1.75	1.73	1.71	1.68	1.67

4 Determination of specific heat of frozen soil

Specific heat is mainly determined by the calorimeter method, heating-cooling method and adiabatic method. Recently, several self-developed test methods have been developed, but they need to be gradually improved. The hybrid calorimetry method uses the principle of heat balance and is the method used to measure specific heat in common physical experiments.

The specific calculation process can be simply described as follows. First, a soil sample with a mass of M g and a temperature of T was loaded into a calorimeter with m g of water and an initial temperature of t. It is known that the heat capacity of the calorimeter is w. When the heat exchange equilibrium is reached, the temperature of the entire system will be stabilized at the same value t'. Assuming that the specific heat of the soil sample to be measured is an unknown C_z, and the specific heat of water is known as $C_0 = 1K/(g.^0C)$, it is not difficult to obtain the heat balance equation as

$$C_z M(T - t') = (C_0 m + w)(t' - t) \tag{13}$$

From this, the specific heat of the soil sample is calculated as

$$C_z = \frac{w + C_0 m}{M} \cdot \frac{t' - t}{T - t'} \tag{14}$$

The test instruments used include a calorimeter, a temperature recorder and a computer terminal that has communication lines. Before the test begins, the platinum resistance probe must be calibrated. However, the temperature used in the above calculation formula is ultimately the temperature difference. Therefore, the calculation process eliminates the effect of the temperature test error in the final calculation result and no calibration was performed during this test.

This test method uses the heat capacity w of the calorimeter, which can be obtained by the following method. First, the empty temperature T_1 in the calorimeter is measured, and then, water with mass m and initial temperature T_0 is poured into the calorimeter. After the temperature reaches equilibrium, it can be read to obtain a stable temperature T. From the principle of conservation of energy, the amount of water heat reduction will be equal to the calorimeter's increased heat. Therefore, the heat capacity of the calorimeter is as follows.

$$w = mC_0 \frac{T_0 - T}{T - T_1} \tag{15}$$

The test is repeated three times and the average value is used as the final value. The measured values for the three measurements were 43.77 cal/(g·°C), 40.75 cal/(g·°C) and 42.13 cal/(g·°C), and the average value was 42.21 cal/(g·°C). Therefore, the heat capacity of the calorimeter was 42.21 cal/(g·°C). Three parallel samples of soil sample 1 were taken and weighed to obtain masses M_1, M_2 and M_3, respectively. The initial temperatures measured by the temperature sensors were T_1, T_2 and T_3, respectively. The three parallel samples were successively placed in a calorimeter filled with water. The masses of water were m_1, m_2 and m_3, and the initial temperatures of the water were t_1, t_2 and t_3, respectively. After equilibration, the mixing temperatures after stabilization are t_1', t_2' and t_3', respectively. Using Eq. (14), the specific heats of three parallel samples were calculated, and the average value is the specific heat of the soil sample. Using the same method, the specific heat of soil samples 2-7 were obtained, as shown in Fig. 3. Among them, Series 1, 2, 3, 4, 5, 6, 7 and 8 indicate the relationship of the specific heat value and temperature of each sample when the water content is 23.7, 19.2, 17.5, 17.2, 15.2, 14.7 and 12.03%, respectively.

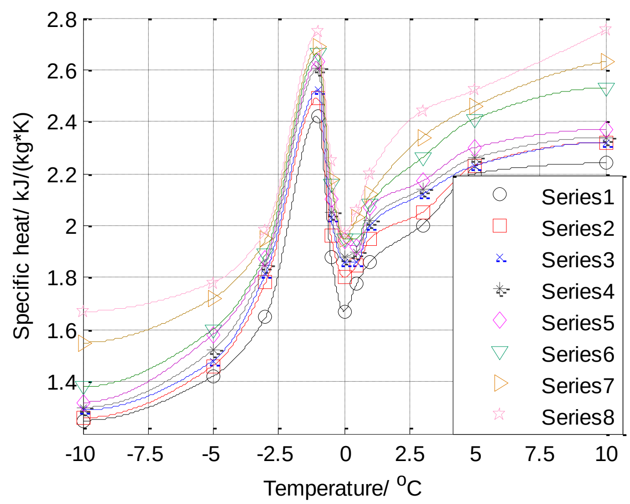

Figure 3: Variation in the specific heat of soil with temperature

As shown in Fig. 3, the specific heat of the test soil varies with temperature and is basically positively correlated. However, near the freezing point, the specific heat of the soil will change, due to the latent heat released when the pore water phase became ice.

5 Model validity analysis

Clay from Xiaodian District, Xinxiang was used as the test soil, with physical indexes of 41 for the liquid limit, 19 for the plastic limit, 22 for the plasticity index, 1.71 g/cm^3 for the dry density and 40% for the moisture content.

5.1 Unfrozen water content

To verify the validity and accuracy of Eq. (12), determination of the unfrozen water content at different temperatures is necessary. There are many laboratory methods for measuring the unfrozen water content, among which the pulsed nuclear magnetic resonance (NMR) method is simple and quick and yields an accurate result. Therefore, the NMR method was used to determine the unfrozen water content in reconstituted soil samples at different negative temperatures. The main experimental instruments include a DR-2A freeze-thaw test box, a Praxis-PR-103 pulsed nuclear magnetic resonance instrument, a K-type thermocouple and a glass test tube. The experimental procedures are briefly described as follows.

The original soil was dried, stirred with distilled water, and prepared to a water content of 40%. The soil was loaded in a test tube at a loading height of 5 cm. The thermocouple was buried in the center of the tube containing the soil, and the tube was then placed in the freeze-thaw chamber.

The content of unfrozen water in soil at 6, 3, 0, -0.2, -0.3, -0.7, -1, -2.0, -3.0, -5.0, -8.0, -10 and -15°C was measured. First, the freeze-thaw chamber was set at 6 °C, and the data on the temperature collector were read at 0.5, 1, 1.5, 2, 2.5, 3, 3.5 and 4 h. When the data were consistent with the temperature of the test chamber and tended to be stable, the test tube was quickly removed from the freeze-thaw chamber, and the probe was inserted to record the signal intensity. The test tube was then placed in a freeze-thaw chamber, and the temperature of the freeze-thaw chamber was set to 3°C. The above process was repeated until the last temperature test point, i.e., the test at -15°C.

After the end of the experiment, the unfrozen water content at different negative temperatures was calculated with Eqs. (16) and (17).

$$w_u = {}^{w_0 y}\!\diagup_{y_1} \tag{16}$$

$$y_1 = a + b \cdot T \tag{17}$$

where

w_0=The initial water content of the soil sample;

y=Signal intensity;

y_1=The calculated signal intensity;

a and b are empirical coefficients

The test results for the unfrozen water content of the sample at different temperatures are shown in Fig. 4, indicating 0°C to -10°C as the phase change phase.

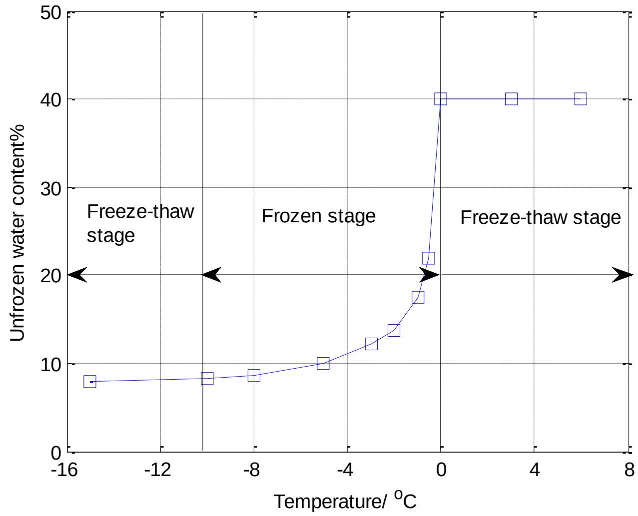

Figure 4: Content of unfrozen water at different temperatures during phase transition

5.2 Specific heat calculated value

The test data of the frozen water content indicate that the drastic phase transition zone of this type of reshaped clay is from 0 to -5°C, the transition zone is from -5 to -10°C and the frozen zone is below -10°C. In addition, according to whether there is latent heat, this type of clay thaws above 0°C, freezes in the range from 0° to -10°C and is frozen below -10°C.

According to the unfrozen water content at different temperatures expressed in Fig. 3, the specific heat of the freezing soil can be obtained by combining Eqs. (8) and (12). Among them, the specific heats of soil particles (C_p), water (C_w) and ice (C_i) are 0.845, 4.18 and 2.09 kJ/(kg.K), respectively. The latent heat of phase change L=335 kJ/kg. Using the method of center point difference, the specific heat at different temperature points was calculated, and the calculated results are shown in Fig. 4. In addition, the specific heat levels of the thawing soil and the frozen soil were calculated according to Eqs. (2) and (3), respectively. The results are shown in Fig. 5.

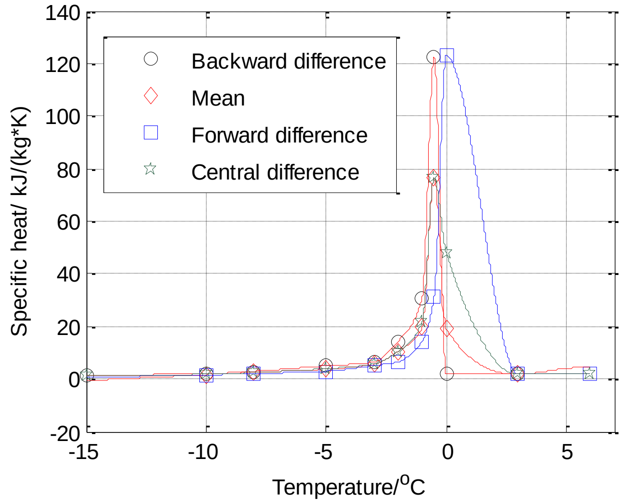

Figure 5: Specific heat at different temperatures during the phase change

6 Conclusions

According to the state of pore water and its changing trend, frozen soil is further divided into freezing soil and frozen soil. The specific heat of soil with temperature changes should be calculated for all stages, namely, the thawing stage, the freezing stage and the frozen stage. In the thawing stage, the pore water is liquid, in the freezing stage, this liquid water can be further frozen into ice, while in the frozen stage, there is no liquid water to be further frozen as ice. Due to the existence of liquid water further condensing into ice, further cooling of the freezing soil is accompanied by sensible heat and latent heat energy exchange. During the thawing and the freezing stages, the temperature change is only accompanied by sensible heat. Based on the weighted superposition law of the specific heat capacity of the mixture, a calculation method for the specific heat of frozen soil covering latent heat and sensible heat was established. The specific heat test of the clay shows that the calculation method is reasonable.

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