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Effect of Soluble Salt on Thermal Conductivity of Saline Soil

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Abstract: ***Soil thermal conductivity (λ), as one of the key thermal properties of soil, has become a research focus in fields such as energy, engineering, earth sciences, and geology in recent years. This paper primarily analyzes the influence and mechanisms of different types of soluble salts on the thermal conductivity of saline soil, based on experimental studies conducted by domestic and international scholars. The results indicate that different types of salts have varying effects on the thermal conductivity coefficient of saline soil. The combined effect of salt and temperature influences the thermal conductivity of soil, mainly manifested in certain soluble salts lowering the freezing point of water. This leads to an increase in the unfrozen water content during the freezing process of saline soil at low temperatures, thereby reducing its thermal conductivity. Furthermore, the flocculation effect of salt ions on soil particles in certain saline soils changes thermal conduction pathways, thereby affecting the thermal conductivity of the soil. Some researchers have refined existing thermal conductivity theories and semi - empirical parameterized models, enhancing their applicability to saline soils.***

Keywords: Thermal conductivity, Saline soil, Parametric model.

1. Introduction

Thermal conductivity (λ) is one of the key thermal properties of soil, holding significant importance in applications such as geological exploration, engineering construction, permafrost studies, and geothermal development [1, 2].

Saline - alkaline soils encompass saline soils, alkaline soils, and various other types of salinized and alkalinized soils [3, 4]. The accumulation of salts in saline soils results from geochemical processes occurring in the Earth's crustal surface layer, with their salt composition primarily consisting of carbonates, sulfates, and chlorides.

To comprehensively understand the research hotspots and influencing factors of soil thermal conductivity, a search was carried out in the Web of Science database using the keywords "soil & thermal conductivity" to retrieve relevant papers from the past decade. The results of the bibliometric visualization analysis are presented in Figure 1. Analysis reveals that research on soil thermal conductivity has mainly concentrated on non - saline soils, and the thermal conductivity shows a close correlation with soil type.

This paper synthesizes experimental studies conducted by domestic and international scholars on the thermal conductivity of saline soils, summarizing the effects of several major soluble salts on this property. It aims to provide valuable references for future geothermal energy development and engineering projects in cold regions.

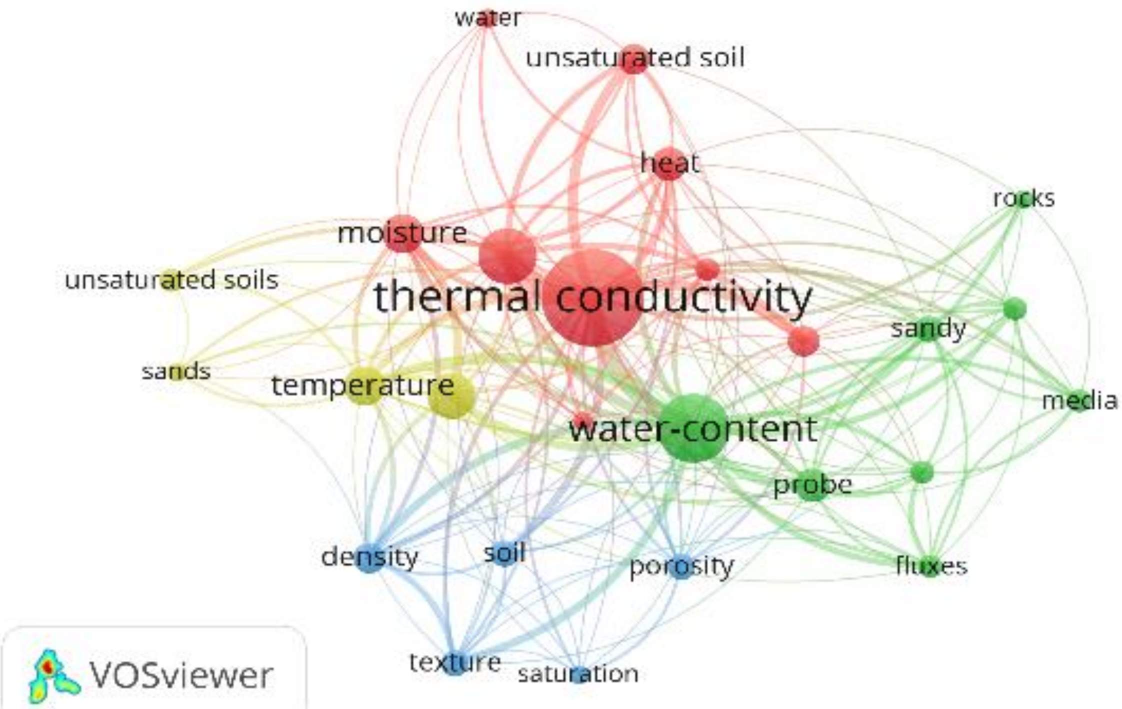

Figure 1: Visualisation and analysis of literature related to soil thermal conductivity

2. Principles and Methods for Testing Soil Thermal Conductivity

Soil consists of solid, liquid, and gaseous phases. Molecules in each phase undergo random motion and possess their own thermal conductivity. The distribution and combination of these three phases collectively influence the soil's thermal conductivity. The coefficient measured experimentally represents the soil's equivalent thermal conductivity.

According to theory, the heat flux density represents the amount of heat passing through a unit area per unit time, denoted by q (W/m²). The magnitude of heat flux density in thermal conduction follows Fourier's Law.

$$q = -\lambda \frac{dT}{dx} \tag{1}$$

Figure 2 depicts a soil sample of thickness L and lateral area A, with temperatures T_1 and T_2 ($T_1 > T_2$) on either side. The temperature difference between the two sides can be expressed as

$$\frac{dT}{dx} = \frac{T_2 - T_1}{L} = \frac{\triangle T}{L} \tag{2}$$

According to Fourier's law, the heat flux density q is given by

$$q = -\lambda \frac{dT}{dx} = \lambda \frac{\triangle T}{L} \tag{3}$$

Thus, the heat transfer rate Q through both sides of the soil sample is the product of the area A through which the heat flux passes and the heat flux density q.

$$Q = Aq = A\lambda \frac{\triangle T}{L} \tag{4}$$

Thermal conductivity coefficient λ is

$$\lambda = \frac{Q}{A \cdot \triangle T / L} \tag{1}$$

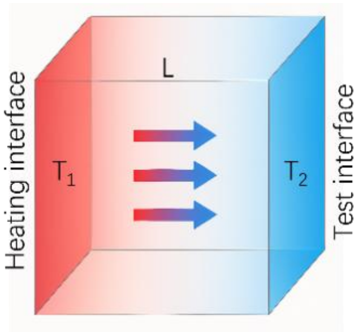

Figure 2: Schematic diagram of thermal conductivity test principle

Laboratory techniques for measuring thermal conductivity can be classified into two primary categories according to their principles: steady - state methods and transient methods [5-7].

The principle of the steady - state method entails calculating the thermal conductivity of a specimen by measuring the temperature difference across its cross - section, its thickness, and the heat flux density when the heat transfer rate into the specimen reaches equilibrium with its heat dissipation rate [7]. This method is founded on the steady - state heat conduction differential equation, characterized by a well - defined theoretical foundation, simple computation, and high measurement precision. Nevertheless, it demands a substantial amount of time to attain steady - state conditions, making the measurement procedure rather arduous.

The transient approach is a high - speed technique for the measurement of thermal conductivity. This approach entails the application of a transient thermal pulse to the material surface and the measurement of the internal temperature variation with respect to time, thus enabling the calculation of the thermal conductivity [7]. It is mainly classified into the hot probe method and the plane transient method. The transient approach presents advantages including rapid measurement and minimal damage to the material, which leads to its extensive utilization in determining the thermal conductivity of soils.

3. Effect of Soluble Salt Content and Type at Ambient Temperature on Soil Thermal Conductivity

Diverse types of salts impose distinct impacts on the thermal conductivity of various types of saline soil [8]. Mochizuki [9] utilized the probe method to measure the thermal conductivity of sandy soils with different concentrations of NaCl, $CaCl_2$, and Na_2SO_4 at room temperature. The findings indicated that, in comparison to salt - free sandy soils, the thermal conductivity declined as the concentration of all three salts augmented. Among soils with the same salt concentration, those containing Na_2SO_4 showed the most substantial reduction in thermal conductivity. Mochizuki [10] explored the effects of sodium chloride and moisture content on the thermal conductivity coefficients of expansive and non - expansive clays. The thermal conductivity coefficient of expansive clay increased marginally with the increase in NaCl content, whereas that of non - expansive clay remained stable or presented a linear decrease as the NaCl content rose.

Ju et al. [11] prepared test specimens by blending diverse chloride salts, sulphate salts, and bicarbonate salts with quartz sand at a room temperature of 25°C. The findings suggest that under the condition of the same volumetric moisture content, the thermal conductivity of quartz sand diminishes as the concentrations of all three soluble salts increase. When the salt content and volumetric moisture content remain constant, chloride salts have the most significant impact on the thermal conductivity of quartz sand, whereas bicarbonate salts have the least.

4. Impact of Temperature on the Thermal Conductivity of Saline Soil

Temperature constitutes a crucial factor exerting an influence on the thermal characteristics of soil [1, 12, 13]. Zhang Lixin et al. [14] utilized the steady - state approach to ascertain the thermal conductivity of frozen Lanzhou sandy soil and Lanzhou loess under diverse moisture contents and sodium chloride concentrations. At the same sub - zero temperature, the thermal conductivity of Lanzhou sandy soil exhibited a decreasing trend with the increasing NaCl content, while that of Lanzhou loess initially increased and subsequently decreased as the NaCl concentration rose.

Wang Chengwei [12] utilized a transient approach to measure the thermal conductivity of shallow alkaline saline soil in Lanzhou roadbeds. The results demonstrated that, under the condition of the same moisture content, at positive temperatures, the thermal conductivity of Lanzhou saline - alkali soil samples exhibited an upward trend with the increase in $CaCl_2$ content, while it showed a downward trend with the increase in $MgSO_4$ content. At 0°C and sub - zero temperatures, the thermal conductivity of Lanzhou saline soil decreased as the contents of $MgSO_4$ and $CaCl_2$ increased. Deng Yousheng et al. [15] measured the thermal conductivity of three soil types, namely Qinghai - Tibetan sandy soil, Lanzhou loess, and Qinghai - Tibetan clay, under different concentrations of Na_2SO_4 and NaCl. The results are shown in Figure 3. The findings suggest that at the same sub - zero temperature, the thermal conductivity of Qinghai - Tibetan sandy soil, Lanzhou loess, and Qinghai - Tibetan clay all declined as the concentrations of Na_2SO_4 and NaCl increased. Figure 4 presents the results of Chao Lyu et al.'s [16] investigation on the influence of 0%, 2%, and 5% NaCl content on the thermal conductivity of Xuzhou clay (ω = 22%). The results indicate that, regardless of whether the temperature is positive or negative, the thermal conductivity of the clay initially increases and then decreases as the NaCl content rises.

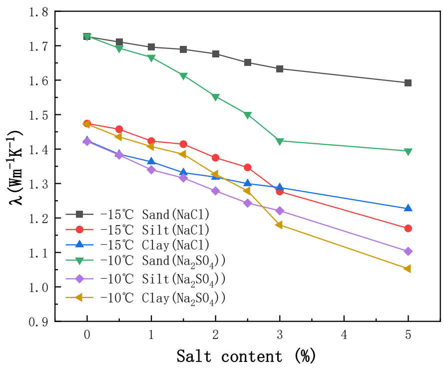

Figure 3: Relationship curve between soil thermal conductivity and salt content (Deng 2004)

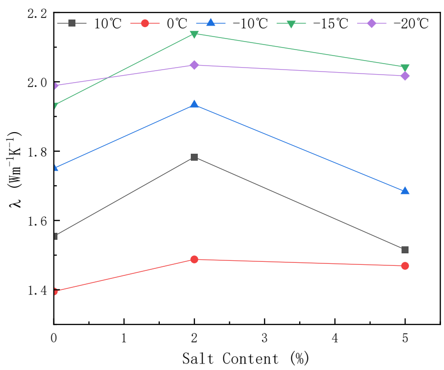

Figure 4: Variations in thermal conductivity with salt concentration (Chao Lyu 2019)

The thermal conductivity of ice is fourfold that of water. At low temperatures, the types and concentrations of soluble salts can exert an influence on the water - to - ice phase transition during the freezing process of saline soil, thereby significantly impacting the soil's thermal conductivity. Chao Lyu et al. [16] utilized ultrasonic testing to analyze variations in the volume of unfrozen water within soil samples. The results indicated a notable decline in the freezing temperature as the sodium chloride content gradually increased. Zhou Yan [17] ascertained that, under conditions of identical dry density, moisture content, and sulphate concentration, the thermal conductivity of frozen Lanzhou saline soil was significantly higher than that of unfrozen soil. Figures 5 and 6 respectively present the findings of Wang Chengwei [12] and Deng Yousheng [15] regarding the temperature dependence of λ in sulphate - affected soils. Their research disclosed that as the temperature rose (while remaining below the freezing point), the unfrozen water content increased and the ice content decreased during the freezing process of different types of sulphate - affected soils, leading to a reduction in the thermal conductivity of saline soil.

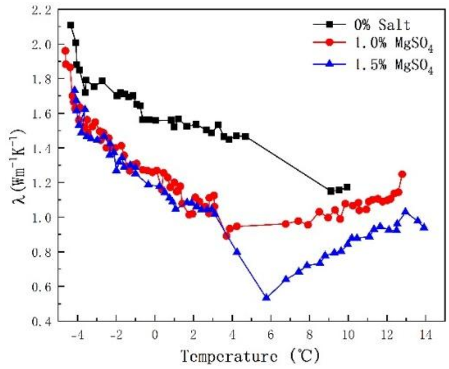

Figure 5: Relationship of saline soil coefficient of thermal conductivity with temperature change by a sine wave (Wang 2014)

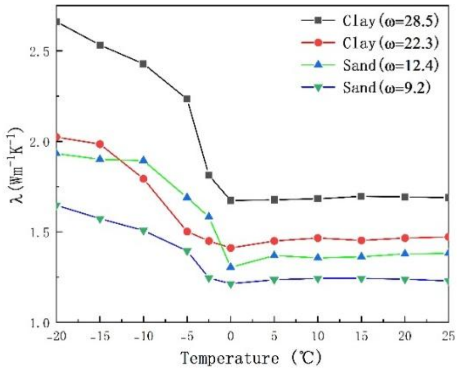

Figure 6: Curves of thermal conductivity coefficient vs. sodium sulphate content (Deng 2004)

5. The Influence of Soluble Salt Ions on Soil Thermal Conductivity

Farouki [18] posited that the chemical bonds furnished by exchangeable cations could contribute to the strength of clay, and these bonds exert an influence on the heat transfer processes within the soil [19]. The experiments conducted by Van Olphen H indicated that, under the condition of identical moisture contents, an increase in salt concentrations leads to the adsorption of Na^+ onto the surfaces of clay particles, thereby neutralizing the negative charge of soil particles. As a result, the electrolyte concentration within the pore water of saline soils rises, giving rise to the phenomenon of compressed double layers (Figure 7). Noborio [20] and Nidal [21] demonstrated that an increase in the chloride salt content in clay significantly reduces the soil's thermal conductivity. This is because the clay employed for thermal conductivity testing contains a high proportion of clay particles. The interaction between clay particles and salt ions induces flocculation and aggregation, which hinders the heat transfer processes [20], The interstitial spaces between soil particles expand, soil particles are separated by free water, and the cohesive forces between soil particles decrease. Consequently, the heat conduction pathway shifts from solid - solid conduction to solid - liquid conduction [22].

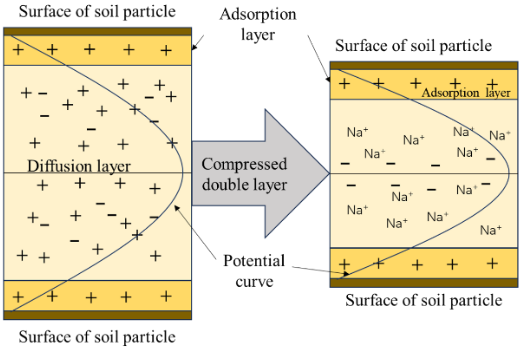

Figure 7: Compressed double layer on the surface of soil particles with NaCl

Duan Zhao et al. [23] utilized the transient equilibrium heat source method to examine the variation patterns of thermal conductivity in wind - deposited loess from Jingyang, Shanxi, under the influence of moisture content and salt content (NaCl). The results suggest that at low salt concentrations, the "liquid bridge" and "compressed double - electric layer" phenomena are the dominant mechanisms in the soil. In this case, the heat transfer pathways are mainly solid - liquid conduction accompanied by a certain amount of solid - solid conduction, and the thermal conductivity increases with the increase of salt content. Once the salt concentration exceeds a certain threshold, the "flocculation" phenomenon becomes the dominant mechanism. As a result, the heat transfer pathways shift towards solid - liquid conduction, solid - solid conduction weakens, liquid - liquid conduction strengthens, and the thermal conductivity decreases.

Zhao Xia et al. [24] carried out laboratory investigations on clay from Hengyang County. They found that as the concentrations of NaCl and $CaCl_2$ increase, saline soil undergoes flocculation and aggregation at the microscopic level. This process creates interconnected air - filled pores within the soil structure, namely intra - aggregate pores and inter - aggregate pores, which have low thermal conductivity. Consequently, the thermal transmission efficiency of the saline - alkali soil reduces, leading to a decline in its thermal conductivity.

6. Investigation into Thermal Conductivity Calculation Models of Saline soil

Presently, scholars from both domestic and international arenas have constructed empirical models, theoretical models, and semi - theoretical models for the thermal conductivity of saline soil on the basis of fundamental parameters including soil salinity, moisture content, bulk density, particle size distribution, and mineral composition.

Qiu Enxi et al. [25] put forward a novel thermal conductivity model for sodium sulphate - salinised soils by integrating the theory of generalised geotechnical material thermal conductivity with the variation characteristics of sulphate ice content in saline soils. This novel model utilises shape parameters α, β, and τ to define the volume proportions of needle - shaped, spherical, and disc - shaped soil particles respectively, and makes a comparison with arithmetic mean and geometric mean models. At positive temperatures, the arithmetic mean model can accurately predict the thermal conductivity of sulphate - affected silty clay. As the soil temperature drops to sub - zero conditions, the new model generates λ values that are closer to the measured values.

Yan et al. [26] utilized the transient plane heat source method to measure the thermal conductivity of loess in the Guanzhong region of China, characterizing its thermal conductivity coefficients under different moisture contents and salt concentrations (NaCl). Based on the test outcomes, the applicability of five representative thermal conductivity models, namely Kersten (1949), Campbell (1985), Gangadhara Rao and Singh (1999), Usowicz et al. (2006), and Ren et al. (2019), was evaluated, and the results are presented in Figure 8. Among the five models evaluated, the Usowicz et al. (2006) model exhibited the most precise predictions at salt contents of 0%, 2%, 4%, and 6%.

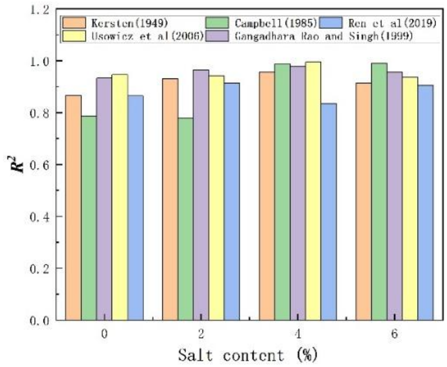

Figure 8: Histogram of the R2 values of models of soil with different salt contents (Yan 2019)

Ju et al. [27] tested the thermal conductivity of six different types and concentrations of soluble salts in saline-alkali soils across China's saline-alkali regions. They re-evaluated the applicability of the Johansen 1975 model, Cote and Konrad 2005 model, and Lu 2007 model. Considering the influence of soil salinity, they proposed an improved λ model based on Lu 2007. Figure 9 compares the modified model λ predictions with measured values, demonstrating good agreement between the two.

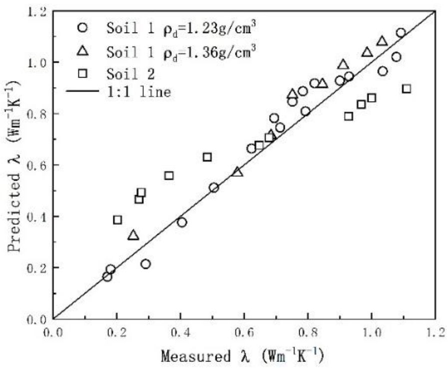

Figure 9: The comparison of the λ estimated using the modified model and the measured λ for the independent salt-affected soils (Ju 2023)

7. Conclusion

Through a comprehensive review of relevant literature, this paper predominantly collates and analyzes the impacts of diverse types of soluble salts on the thermal conductivity of saline soil. The main conclusions are presented as follows:

(1) Diverse types of soluble salts impose distinct effects on the thermal conductivity of saline soil.

(2) Temperature acts as a crucial factor affecting the thermal conductivity of saline soil. At low temperatures, a higher salt content depresses the freezing point of water, elevating the unfrozen water content in frozen soil and diminishing the thermal conductivity. Moreover, certain soluble salt ions cause the flocculation of clay particles, improving the pore connectivity in saline soil, which reduces the thermal conductivity.

(3) Some scholars have refined the existing thermal conductivity theories and semi - theoretical parametric models, thereby enhancing the predictive precision of these models for the thermal conductivity of saline soil.

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