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Impact of Salinity on Thermal Properties of Frozen Sand in Artificial Ground Freezing Systems

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ABSTRACT

Artificial ground freezing (AGF) is a supplementary technique used to enhance ground stability and control groundwater movement by circulating a coolant through a network of closely positioned freezing pipes. In environments where the ground is influenced by seawater, the salinity of the pore water can significantly affect the soil's thermal properties, which are crucial for the effective and safe design of AGF systems. This study investigates the impact of salinity on the thermal properties of frozen sand by measuring the unfrozen water content and thermal conductivity at various freezing temperatures and salt concentrations. Additionally, the thermal conductivity of frozen sand is predicted using the parallel, series, and geometric mean heat transfer models. Comparison with experimental results indicates that the geometric mean model provides the most accurate predictions.

1. INTRODUCTION

Artificial ground freezing (AGF) is used to enhance ground stability and control groundwater movement in challenging ground conditions. This system involves positioning a network of freezing pipes through which a coolant circulates (Andersland and Ladanyi, 2004). This method is widely employed in geotechnical engineering to stabilize soils for tunneling, mining, and other underground constructions. Given that AGF involves freezing the ground through heat absorption, analyzing the thermal behavior of the frozen soil is crucial for improving energy efficiency. Reliable data on the thermal conductivity of frozen ground are particularly important for understanding the heat transfer mechanisms within the ground (Li et al., 2019).

In environments influenced by seawater, the salinity of the pore water can significantly affect the thermal conductivity of the frozen soil, which is critical for the effective and safe design of AGF systems (Kim and Go, 2023). The presence of salts in

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pore water lowers the freezing point, leading to the formation of unfrozen water films around soil particles even at subzero temperatures. These films impact the thermal conductivity of the soil, a key parameter in AGF design.

This study investigates the impact of salinity on the thermal properties of frozen sand by measuring the unfrozen water content and thermal conductivity at various freezing temperatures and salt concentrations. Specifically, the study aims to understand how different salinity levels affect the thermal conductivity of frozen sand and to evaluate the predictive accuracy of various heat transfer models.

2. LABORATORY EXPERIMENTS AND RESULTS

2.1 Unfrozen water content

The experiment was conducted to measure the unfrozen water content in frozen sand, influenced by temperature and the salinity of pore water, using the Time Domain Reflectometry (TDR) method. Since the thermal conductivity of ice (2.18 W/m·K) is much higher than that of water (0.58 W/m·K), the ice and unfrozen water content in frozen soil significantly influence its thermal conductivity. To measure the unfrozen water content, the silica sand specimens were prepared with a dry density of 1.41 g/cm^3 in plastic molds, and a TDR probe was embedded at the center of each specimen as shown in Fig. 1. The specimens were saturated with either fresh water or brine, with sodium chloride used to adjust the brine's salinity. The measurements were conducted at temperatures of -5, -10, -15, -20, and -25°C under salinity conditions of 0, 3.5, 5, 10, and 15%, with the 3.5% salinity chosen to reflect the salt concentration typical of seawater. The specimens were stored in a refrigerator at the target temperature for more than 24 hours to ensure complete freezing before measuring the unfrozen water content.

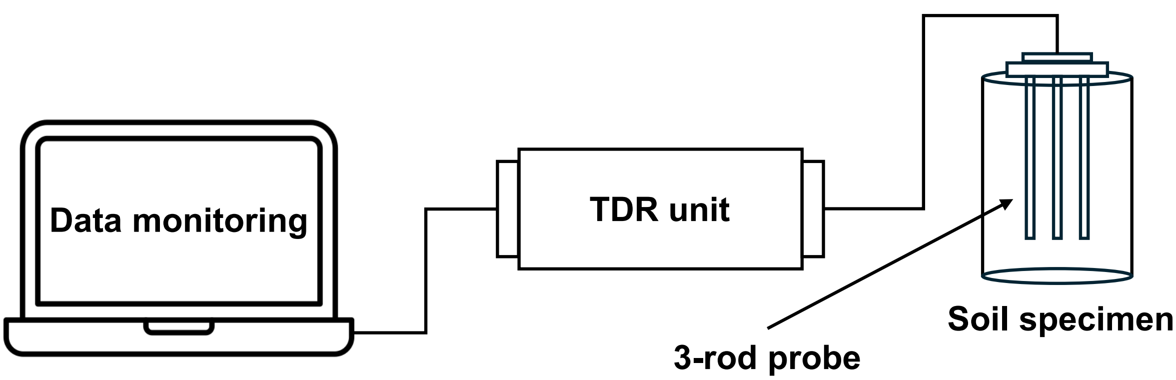


Fig. 1 TDR measuring system

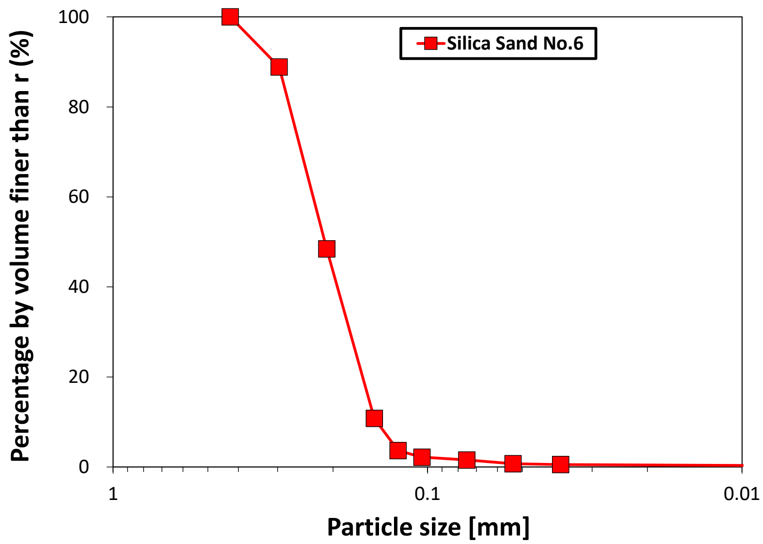


Fig. 2 Particle size distribution

The sieve analysis and basic physical property tests were performed to obtain the grain-size distribution and fundamental properties of the silica sand. The particle size gradation of the silica sand was found to be relatively uniform. Fig. 2 and Table 1 present the particle size distribution and fundamental physical properties of the silica sand, respectively.

Table 1 Physical properties of silica sand

Specific gravity	Void ratio		Grain size analysis (%)				C_u	C_c
	e_{max}	e_{min}	No.10	No.30	No.100	No.200		
2.64	1.069	0.655	100	88.4	1.02	0.45	1.57	2.05

The results demonstrated a clear trend of decreasing unfrozen water content with decreasing temperatures across all salinity levels, highlighting the significant influence of temperature on water freezing in sand. Furthermore, higher salinity consistently resulted in higher unfrozen water content at each temperature due to the freezing point depression effect, where higher salinity lowers the freezing point of pore water, thus maintaining a larger amount of unfrozen water at lower temperatures. At -5°C, the unfrozen water content ranged widely from 5 to 45% depending on salinity, but at -25°C, it converged to approximately 0 to 10% across all salinity conditions. Nevertheless, even within this range, higher salinity levels corresponded to higher unfrozen water content. The experimental results are shown in Fig. 3.

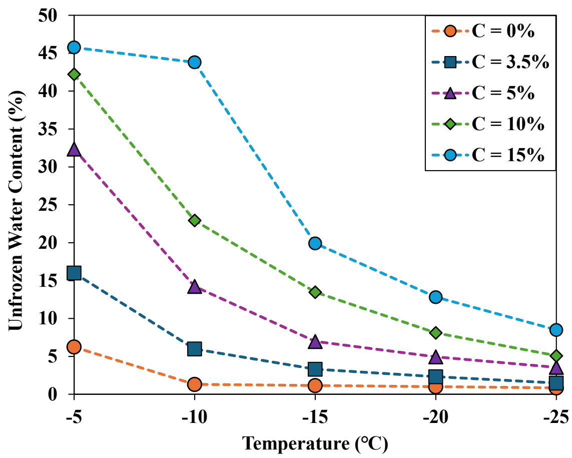


Fig. 3 Unfrozen water content

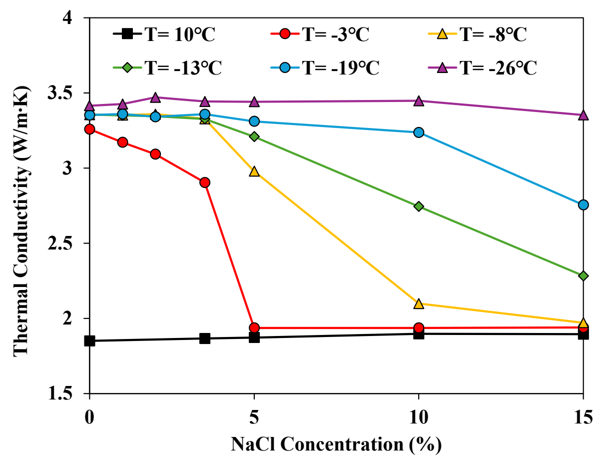


Fig. 4 Thermal conductivity

2.2 Thermal conductivity

The thermal conductivity of frozen soil is significantly influenced by the ice and unfrozen water content due to the distinct difference in their thermal conductivities. To investigate this effect, an experiment was conducted using the same specimens and methods as those used for measuring the unfrozen water content, focusing on the thermal conductivity of frozen sand. Thermal conductivity measurements were taken at temperatures of 10, -3, -8, -13, -19, and -26°C under salinity conditions of 0, 1, 2, 3.5, 5, 10, and 15%. The thermal conductivity values were measured at least five times for each specimen using the transient hot wire method, according to the standard procedure (ASTM 5334).

The measurements revealed significant characteristics related to the influence of salinity and temperature, and the results are presented in Fig. 4. A general trend was observed where thermal conductivity decreases with increasing salinity at each temperature. This decrease can be attributed to the impact of salinity on the unfrozen water content in the frozen sand. As salinity increases, the freezing point of the pore water is depressed, resulting in a higher amount of unfrozen water at any given subzero temperature. Since the thermal conductivity of water (0.58 W/m·K) is much lower than that of ice (2.18 W/m·K), a higher unfrozen water content leads to a lower overall thermal conductivity.

However, it is noteworthy that the thermal conductivity remained constant regardless of salinity at the highest temperature (10°C) and the lowest temperature (-26°C). At 10°C, where the sand was unfrozen, the presence of salt did not significantly alter the thermal conductivity of the saturated sand. In this case, the salt was dissolved in water and hardly contributed to the change in the thermal conductivity of pore water. On the other hand, at the lowest temperature, nearly all the pore water was frozen regardless of the salinity. The thermal conductivity of the frozen sand was primarily influenced by the sand particles and ice content, which have relatively high and stable thermal conductivities. Here, the salt in the specimen caused only minor variations in thermal conductivity, resulting in the observed constant values. Consequently, once the soil was mostly frozen, the impact of salinity on thermal conductivity was considered insignificant.

3. PREDICTION OF THERMAL CONDUCTIVITY

3.1 Volume *fraction of components*

To obtain a continuous function of unfrozen water content with respect to temperature, the soil freezing characteristic curve (SFCC) fitting models were adopted from previous research (Michalowski, 1993; Xin et al., 2023; Bi et al., 2023). The freezing point depression due to salinity can be expressed by Eq. (1), where T_{sf} (K) is the freezing point of saline soil, K_F (=1.86 K·L/mol) is the coefficient of freezing point depression, and c_e (mol/L) is the effective ion molarity in the equilibrium solution of soil (Zhou et al., 2023).

$$T_f - T_{sf} = K_F c_e \tag{1}$$

As the brine freezes, the dissolved salts are excluded from the water, causing ice and salt to exist separately in the pores. This segregation occurs because salts do not integrate into the crystal structure of the ice (Panday and Corapcioglu, 1991). Cohen-Adad and Lorimer (2013) found that the solubility of sodium chloride remained relatively constant at approximately 25% within the scope of this study. By combining the continuous unfrozen water content function with the solubility of sodium chloride, the volume of precipitated solid salts within the specimen can be estimated, as shown in Fig. 5. Finally, by subtracting the volumes of unfrozen water, solid salts, and soil particles from the total specimen volume, the volume of the remaining component, ice, can be determined.

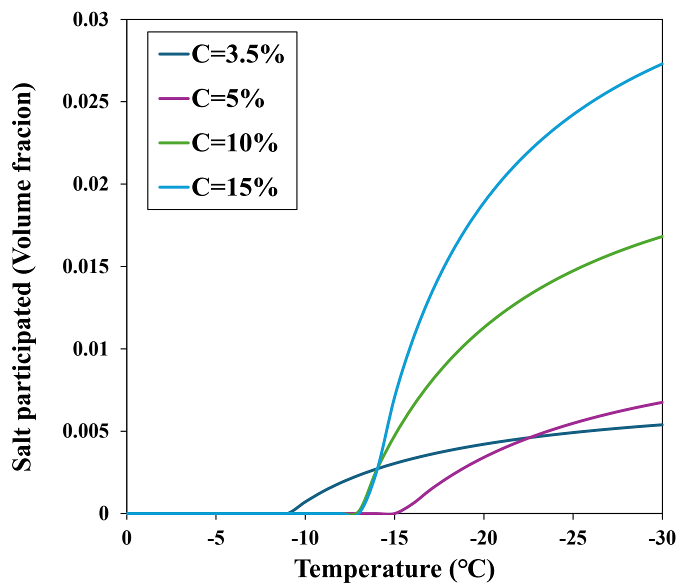


Fig. 5 Volume fraction of precipitated solid salt

3.2 Estimation *of thermal conductivity*

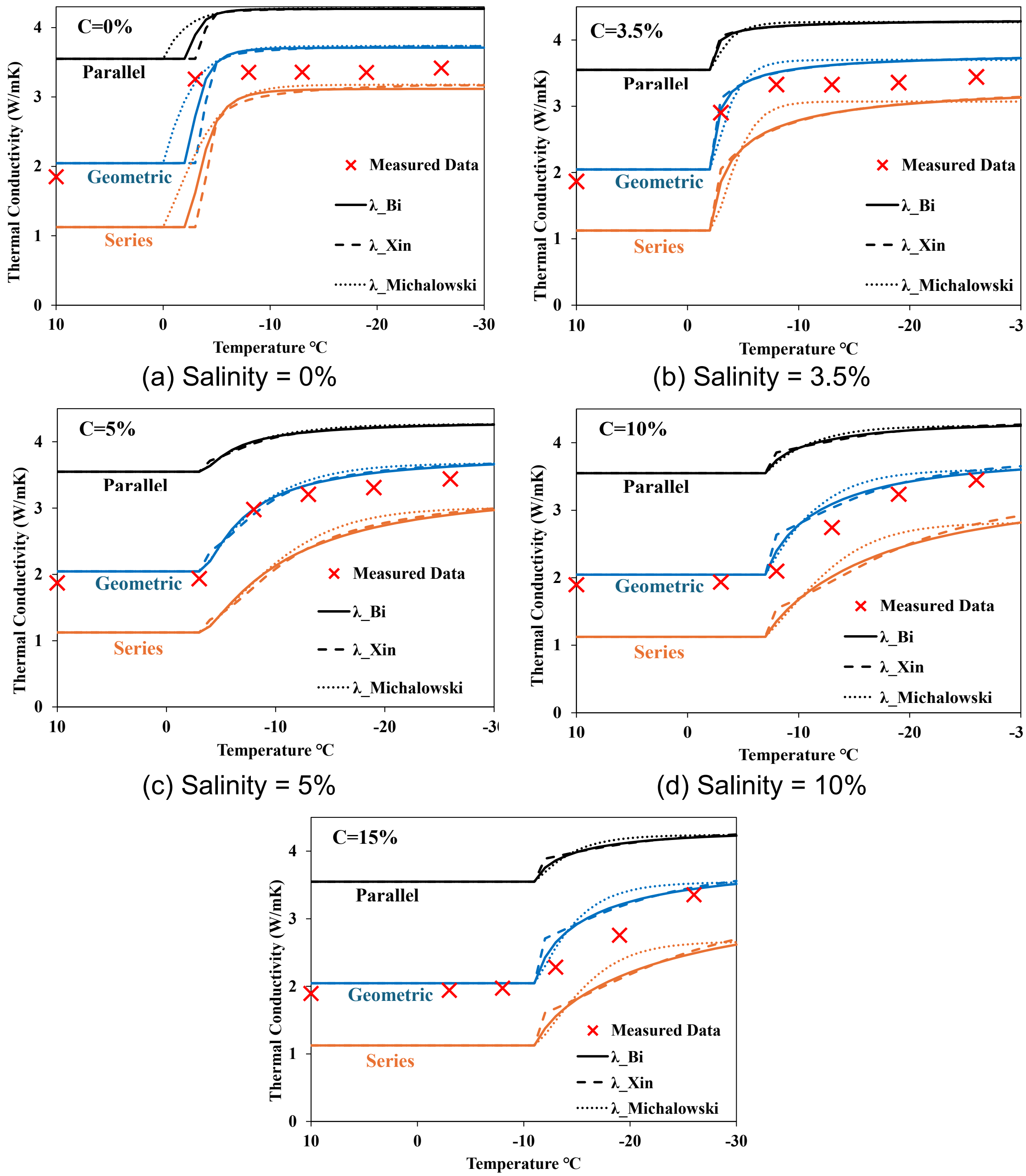
In this study, the volume fractions of each component were used to determine the thermal conductivity, assuming that saturated frozen soil consists of a four-phase structure: unfrozen water, ice, soil particles, and precipitated solid salts. According to Zhang et al. (2018), there are three general models based on the contributions of these four-phase substances: the weighted arithmetic mean model (parallel model), the weighted harmonic mean model (series model), and the weighted geometric mean model. The equations for each model are presented in Eq. (2), (3), and (4), where φ represents the volume fraction, and λ_{eff} denotes the effective thermal conductivity. The subscripts s, i, w, and c refer to soil particles, ice, unfrozen water, and solid salt, respectively. When the heat flow direction is parallel to the orientation of each component, the effective thermal conductivity of the soil is calculated using the weighted arithmetic mean method. In contrast, the weighted harmonic mean method is used when the heat flow direction is perpendicular to the orientation of each component.

$$\lambda_{eff} = \varphi_s \lambda_s + \varphi_i \lambda_i + \varphi_w \lambda_w + \varphi_c \lambda_c \quad (2)$$

$$\frac{1}{\lambda_{eff}} = \frac{\varphi_s}{\lambda_s} + \frac{\varphi_i}{\lambda_i} + \frac{\varphi_w}{\lambda_w} + \frac{\varphi_c}{\lambda_c} \quad (3)$$

$$\lambda_{eff} = \lambda_s^{\varphi_s} + \lambda_w^{\varphi_w} + \lambda_i^{\varphi_i} + \lambda_c^{\varphi_c} \quad (4)$$

The thermal conductivity measurements and model predictions for different salinity levels at various temperatures are shown in Fig. 6. The three models (parallel, geometric and series model) were compared with the measured data to evaluate their accuracy. The results indicate that the parallel model forms the upper bound and the series model forms the lower bound for thermal conductivity. The geometric mean model, which lay between these two, demonstrates the highest accuracy. This suggests that the thermal conductivity within frozen soil is influenced by a combination of both perpendicular and parallel heat flow orientations of the components. In addition, it is noteworthy that as salinity increases, the changes in thermal conductivity due to enhanced freezing point depression become more pronounced. However, when the frozen soil is completely frozen, the thermal conductivity eventually converges to a consistent value regardless of the salinity level, indicating that precipitated solid salts have a negligible impact on the effective thermal conductivity of frozen soil.



(a) Salinity = 0%

(b) Salinity = 3.5%

(c) Salinity = 5%

(d) Salinity = 10%

(e) Salinity = 15%

Fig. 6 Prediction of thermal conductivity

4. CONCLUSIONS

In this study, laboratory tests were conducted to investigate the influence of salinity on the thermal characteristics of sand by measuring the thermal conductivity and unfrozen water content of frozen sand at various salt concentrations. The experimental results demonstrated that higher salt concentrations led to more unfrozen water at given subzero temperatures, resulting in lower thermal conductivity of the frozen sand. However, as the freezing temperature decreased below a certain threshold, the thermal conductivity eventually converged to a consistent value regardless of the salinity level. This indicates that the precipitated solid salts do not significantly impact the effective thermal conductivity of the frozen soil.

Additionally, thermal conductivity was predicted using the weighted arithmetic mean model (parallel model), the weighted harmonic mean model (series model), and the weighted geometric mean model. Among these three models, the weighted geometric mean model consistently provided the most accurate predictions across all salinity levels and temperatures. This result suggests that the thermal conductivity within frozen sand is influenced by a combination of both perpendicular and parallel heat flow directions of the components.

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