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Research Paper

Experimental and modeling investigation of the thermal conductivity of fiber-reinforced soil subjected to freeze-thaw cycles

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HIGHLIGHTS

- The thermal conductivity of soil decreased with the addition of fibers.
- Thermal conductivity of reinforced soil reduced when freeze-thaw cycles increased.
- The statistical-physical model provided good correlation with experimental data.

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ABSTRACT

The thermal conductivity of fine-grained soil, both unreinforced and reinforced with randomly oriented basalt, glass, and steel fibers, was tested by means of the transient hot-wire method with a Quickline-30 Thermal Properties Analyzer. The thermal conductivities of specimens were determined as a function of fiber volume fractions, freeze-thaw cycles, and temperature through laboratory studies. Thermal conductivity of the fiber-reinforced soil decreased for all freeze-thaw cycles and temperature values. The most remarkable reduction of thermal conductivity was measured on all ratios of the steel fiber-reinforced soil and 1% basalt fiber-reinforced soil. Moreover, the statistical-physical model proposed by Usowicz was applied to evaluate the thermal conductivity of fiber-reinforced soil by considering soil-fiber composites and environmental factors. The results showed a close match between the values estimated by the statistical-physical model and the experimental values for various fiber-reinforced soils in a wide range of fiber ratios, temperatures, water contents, and freeze-thaw cycles.

1. Introduction

Soil thermal conductivity is a significant parameter of the thermal balance of ground surfaces, which is a prime factor in the damage to engineered structures caused by thaw settlement and frost heave. Also, the soil thermal conductivity helps to investigate the depths of freeze-thaw cycles and the heat transfer rates during thermal stability predictions in cold regions [1].

Changes in soil temperature have drastic effects on water migration conditions. In soil with a large content of unfrozen water, the penetration of the freezing process into the soil requires more time, because a larger amount of heat transfer must occur. Knowing the water content of the soil is essential for determining the thermo-physical properties of permafrost. Volumetric fractions of soil constituents affect the effective thermal conductivity [2–4].

In cold regions, soil particles are formed in various shapes and sizes with a thin layer of unfrozen water binding them. The water, or ice, in the voids affects the permeability, the porosity and the soil density. A decrease in grain size causes a change in specific surface area and a significant decrease in the permeability [5,6]. In the freezing process, the curvature of the water/ice interfaces increases sharply, resulting in smaller capillaries. Hence, there is a correlation between the radius of the water/ice interface and the particle size distribution [7,8].

When the water inside the pores is converted into ice, the volume of soil increases by about 9%, and the soil mass forms unequal frost heaves. Thus the entire increase in soil volume is due to the increase in pore volume when saturated soil freezes. However, freezing soils are usually unsaturated, so the airless freezing limitations seriously restrict what could be inferred by experimentally relating the water-holding properties for soils from soil water

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curves in the moist range to soil freezing curves in the dry range [9–11].

Crucially, soil aggregation controls water conditions and heat distribution between soil particles. Freezing of cohesive soils results in increased agglomeration of smaller particles [5,6,12]. The inter-particle contact area is where water absorption occurs, different materials are connected, and chemical reactions take place. The mineralogical differences in sand, silt, and clayey fractions and the fact that sandy soils include more quartz could be the main reasons why sandy soils usually have greater thermal conductivity and diffusivity than do clayey soils [13–16].

In seasonally frozen regions, natural soils are blended with different materials to reduce frost heave damage and to improve thermal conductivity. For instance, fibers, geotextile materials, Portland cement, or asphalt are added to alter thermal conductivity and to prevent frost heave in road pavements [17,18]. Various materials may be used to mitigate the effects of frost damage; they include shredded rubber tire waste, fibers, straw, and various solid wastes. The voids in frozen soils are thus filled by non-aqueous solid materials that, are known to be good insulators due to improved (reduced) thermal conductivity [19–21].

Anderson and Hoekstra [22] determined the effects of the freeze-thaw cycle on sodium-bentonite composites. Test results showed that, unfrozen water was removed from the composite mixture while the temperature decreased but was later restored when the temperature increased.

Newman [23] used clay/ore mixes, sandstones, and basement quartzite at the McArthur River uranium mine in Canada to study artificial ground freezing. The mechanical freezing system consisted of a brine-based cooling and distribution network plus a series of brine freeze pipes installed in the ground.

Generally, frozen soil is described as a composite material because it includes soil particles, unfrozen water, ice, and gas. Bovesecchi and Coppa [24] measured the thermal conductivity of pozzolanic soils and blue marlstone rocks using the thermal probe technique over a wide range of temperatures (from −20 °C to 20 °C). Test results demonstrated that the thermal conductivity of unfrozen pozzolanic soil was about three to four times lower than that of water, and that the thermal conductivity of frozen soil was higher than that of the unfrozen soil.

Kim et al. [25] investigated the comparison of soil water content, thermal conductivity, and matric suction of pure bentonite and mixtures of bentonite and sand at different blending ratios. Their results indicated that there is a bilinear relationship between matric suction and thermal conductivity of unreinforced and reinforced soil specimens. When matric suction increased slightly, the thermal conductivity increased. Then, as the air-water ratio decreased quickly, the thermal conductivity of the specimens decreased.

According to previous studies, the use of various fibers in soil reinforcement has had significant effects on static, dynamic, and thermal properties of subgrade soil. Glass fiber, with differing blended ratios has often been used to investigate the engineering properties of soil. The literature reports little research with this fiber under freeze-thaw cycles, however. Also, the glass fiber has taken a place among the most adaptable in civil and highway engineering construction. In those applications, glass fiber provides effective bulk density, hardness, stability, and flexibility/stiffness. While basalt fibers are generally utilized as an alternative to metal reinforcements in building materials, such as steel and aluminum, those fibers have not been studied enough in blended soil for their effects on soil engineering properties. Moreover, basalt fiber is used in reinforcement technology for stabilization of roads and highways to maintain the pavement life by decreasing the effects of cracks caused by excessive traffic loading, age hardening, and temperature changes [26]. Because of the useful and advantageous properties of basalt and glass fibers, both were chosen for the investigation of the thermal behavior of blended soil with those fibers exposed to freeze-thaw cycles.

An understanding of heat flow in a fiber-reinforced soil structure is essential to foundation technology, road construction and earthwork applications in cold regions, but it has not been adequately studied. The goal of this paper is to evaluate the thermal characteristics of the fiber-reinforced soil specimens exposed to freeze-thaw cycles and to summarize the behavior of fiber-reinforced soil structures as a function of freeze-thaw cycles, fiber volume fraction and temperature. Also, to validate the experimental results, a statistical-physical model was applied that utilized the thermal conductivity values measured during the experiments.

2. Materials and methods

2.1. Materials

Clay soil from the Qinghai-Tibet Plateau in China was tested to determine its thermal properties. The particle size distribution and the engineering properties of the clayey soil are shown in Table 1.

All the soil specimens were formed into columns 61.8 mm in diameter and 60 mm in height. The basalt, glass, and steel fiber contents were varied through 0%, 0.5%, and 1% by weight of dry soil. For every mixture, the exact weight of each additive material was determined on the basis of the maximum dry density and the optimum moisture content obtained from the standard Proctor test. The clayey soil and fibers were mixed in dry conditions, then water was added slowly, and the mixture forced through a 4.75 mm sieve to flocculate. The mixtures of soil-fiber-water were compacted into three layers. Table 2 and Fig. 1 depict a plan of the thermal properties and the freeze-thaw tests in detail, along with the preparation of soil specimens for testing.

2.2. Experimental method

A Quickline-30 Thermal Properties Analyzer (Anter Corporation) was used to determine the thermal properties of all specimens. The analyzer measured the thermal properties at an accuracy of 0.1 W/(m·K), utilizing transient hot-wire the method (Fig. 2).

The methodology of the hot-wire method is described as a system involving a vertical and cylindrical symmetry wherein the wire provides both heating and thermometry. Also, the mathematical model expressed is that of a boundless line source of heat suspended vertically in a boundless medium.

Temperature change has a great influence on the thermal properties of soils. That is seen especially on the freezing point in a soil medium when there is an extreme difference in the heat transfer coefficients across the freezing front. That is an essential part of

Table 1
Engineering properties and the particle size distribution of the clayey soil.

Grain composition[a] (%)				Dry density (g/cm^3)	Optimum water content (%)	Plasticity index
d > 0.01	0.01 ⩾ d ⩾ 0.005	0.005 ⩾ d > 0.005	d ⩽ 0.001	1.80	18.03	8.05
67.29	11.16	15.95	5.59			

[a] Determined by a laser particle size analyzer Mastersize 2000. Classified as CL according to the Unified Soil Classification System (USCS).

Table 2
The experimental plan for the measurement of thermal conductivity.

Specimen	Freeze-thaw (F-T) cycles	Freeze-thaw temperature	Measured temperatures for thermal properties
Soil	0, 2, 5, 10, 15	Freezing temperature (−15 °C)	20 °C, 0 °C, −5 °C, −15 °C
Soil-0.5%Glass F	0, 2, 5, 10, 15	Thawing temperature (20 °C)	20 °C, 0 °C, −5 °C, −15 °C
Soil-1%Glass F	0, 2, 5, 10, 15		20 °C, 0 °C, −5 °C, −15 °C
Soil-0.5%Basalt F	0, 2, 5, 10, 15		20 °C, 0 °C, −5 °C, −15 °C
Soil-1%Basalt F	0, 2, 5, 10, 15		20 °C, 0 °C, −5 °C, −15 °C
Soil-0.5%Steel F	0, 2, 5, 10, 15		20 °C, 0 °C, −5 °C, −15 °C
Soil-1%Steel F	0, 2, 5, 10, 15		20 °C, 0 °C, −5 °C, −15 °C

(a) Preparation of soil specimens

(b) Specimens covered membrane before tests

(c) Thermal conductivity test system

(d) Freeze-thaw cabinet

Fig. 1. Preparation of soil specimens for testing.

the freezing system, and thus one can consider invariable values for the heat transfer coefficients for each zone with a small error rate. In the transient hot-wire method, variation in temperature indicates any changes in the thermal properties [27].

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 as a 1-D problem [28].

Since the power of thermal systems changes rapidly and the results are measured in a short time, the method can be expressed as transient. The equation of the specified solution of Fourier's law is:

$$T(t) - T_{ref} = \Delta T = \frac{q}{4\pi\lambda} \ln\left(\frac{4K}{a^2C}t\right) \quad (1)$$

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

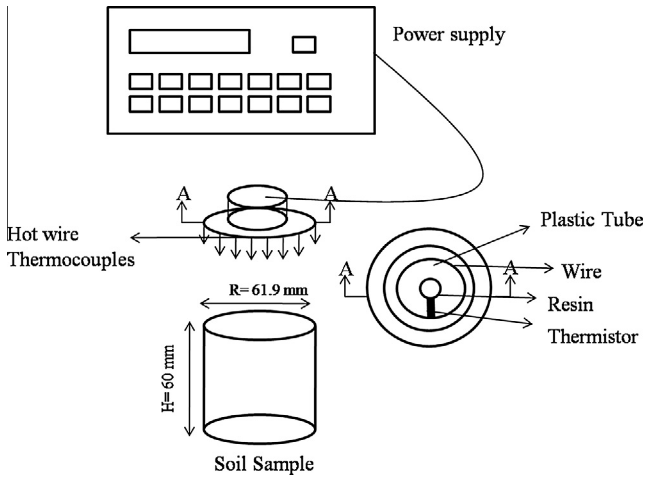

Fig. 2. Schematic diagram of the thermal test apparatus.

temperature and density; K is thermal diffusivity; a is the radius of wire; and $\ln C = \gamma$, where γ is Euler's constant.

The result of Eq. (1) is a linear relationship between ΔT and ln (t). Deviations in experimental results are seen over short and long time periods. However, for each experimental result a period of time is obtained over which Eq. (1) is valid, showing that the connection between ΔT and $\ln(t)$ is linear. The slope of the ΔT versus $\ln(t)$ relationship is acquired over the valid range between times t_1 and t_2. The thermal conductivity is taken from Eq. (1) by using the applied power. Also, the temperature assigned to the measurement of λ is given by:

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

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:

$$\Delta T = \Delta T_W - \sum \delta T_i \quad (3)$$

3. Results and discussion

3.1. Thermal conductivity of specimens as a function of fiber volume fractions and temperature

The measurements of thermal properties on unreinforced and reinforced soil specimens were carried out by a Quickline-30 Thermal Properties Analyzer at temperatures shown in Fig. 3a–e. Each piece of data represents an average of four separate tests, carried out with two "down" surfaces and two "up" surfaces. These figures show that an increase in the fiber volume fraction decreases the thermal conductivity of soil specimens, because a decrease in soil porosity leads to better heat transfer due to stronger connections between the soil particles [5,29–31]. Also, a decrease in dry soil density increases the porosity and leads to a reduction in the thermal conductivity. Moreover, there is a substantial interaction between soil particles during heat transfer. For soils with a low degree of saturation, that interaction causes the particles to form as ice during the freezing process. Thus, reduced heat flow leads to lower thermal conductivity in frozen soils as compared with unfrozen soils [32–35].

The effects of freeze-thaw cycles (N) on the thermal conductivity (λ) for unreinforced and fiber-reinforced soil were presented for different temperature changes in Fig. 3a–e. The results showed that the λ of the unreinforced soil increased with the number of freeze-thaw cycles. Moreover, the increment of the λ decreased with the addition of the basalt, glass, and steel fibers.

Significant results were observed on fiber-reinforced soil in achieving the lowest thermal conductivity after freeze-thaw cycles. Comparison of the results on fiber-reinforced soil for before freeze-thaw cycles showed that addition of 1% basalt fiber in clayey soil resulted in the lowest λ for $T = 20$ °C and $T = 0$ °C and decreased the λ value to 12.0% and 23.1%, respectively. The reductions obtained in λ were 52.5% on 0.5% steel fiber-reinforced soil at $T = -5$ °C and 50.0% on 1% steel fiber-reinforced soil at $T = -15$ °C. Comparison of the results on fiber-reinforced soil after two freeze-thaw cycles indicated that the addition of 1% glass fiber in clayey soil exhibited the lowest λ for $T = 20$ °C and $T = -5$ °C and reduced λ value by 13.3% and 32.0%, respectively. Moreover, the presence of 1% steel fiber in soil reduced the λ at the rate of 17.0% and 48.5% at $T = 0$ °C and $T = -15$ °C, respectively. After five freeze-thaw cycles, the minimum values of λ for all temperatures were observed for the mixtures of steel fibers. The λ decreased 13.7% with the addition of 0.5% steel fiber at $T = 20$ °C. When the steel fiber content was increased from 0.5% to 1%, a decrease in λ was obtained at the rate of 28.8% at $T = 0$ °C, 29.0% at $T = -5$ °C and 49.2% at $T = -15$ °C. Moreover, the minimum reductions in λ were observed as 12.0% at $T = 0$ °C on 1% basalt fiber-reinforced soil and 22.9%, 48.2% and 39.8% at the temperatures of 0 °C, −5 °C, and −15 °C, respectively on 1% steel fiber-reinforced soil after ten freeze-thaw cycles. Comparison of the results on fiber-reinforced soil after fifteen freeze-thaw cycles showed that addition of 1% steel fiber in clayey soil resulted in the lowest λ for all temperature values and decreased the λ value by 12.6% at $T = 20$ °C, 15.3% at $T = 0$ °C, 39.5% at $T = -5$ °C, and 13.5% at $T = -15$ °C.

As presented in the previous paragraph, the λ with temperature differences gradually changed during freeze-thaw cycles. Namely, λ was reduced with a decrease in temperature to 0 °C, and then it increased with a decrease in temperature to −15 °C for unreinforced and fiber-reinforced soil. The explanation is that the thermal conductivity of frozen soils is noticeably higher than that of unfrozen soils because the thermal conductivity value of ice is higher than that of water [36]. Furthermore, the addition of fibers into clay soil can reduce problems resulting from temperature differences on earthwork application.

3.2. Thermal conductivity of specimens as a function of freeze-thaw cycles

In a soil medium, the process of freezing and thawing leads to considerable heat transfer in the phase transition zone. Martynov [37] noted that the effective heat capacity was generally higher than the actual capacity. As ice content in the soil medium increases with decreasing temperature in a cold region, a change occurs in the density of the ions in the phase boundary, and there is an aggregation of exchange reactions involving the cations [38]. Moreover, during the thawing process, exchange cations exhibit the behavior of rehydration of the mineral particles and aggregates.

Heat transfer mechanisms in the soil particles depend greatly on the distribution of the soil water and the type of soil [39]. The thermal conductivity of the soil structure changes with small changes in the amount of water. That is principally due to the amount of water at the contact spots, according to other literature. Dimo [40] referred to the relationship of increasing water content to the replacement of poorly conducting air by water, as well as the relationships between water, soil, and the characteristics of water interfaces.

In cold regions, soil particles are of various shapes and sizes are bound with a thin film of unfrozen water. The water or ice in the

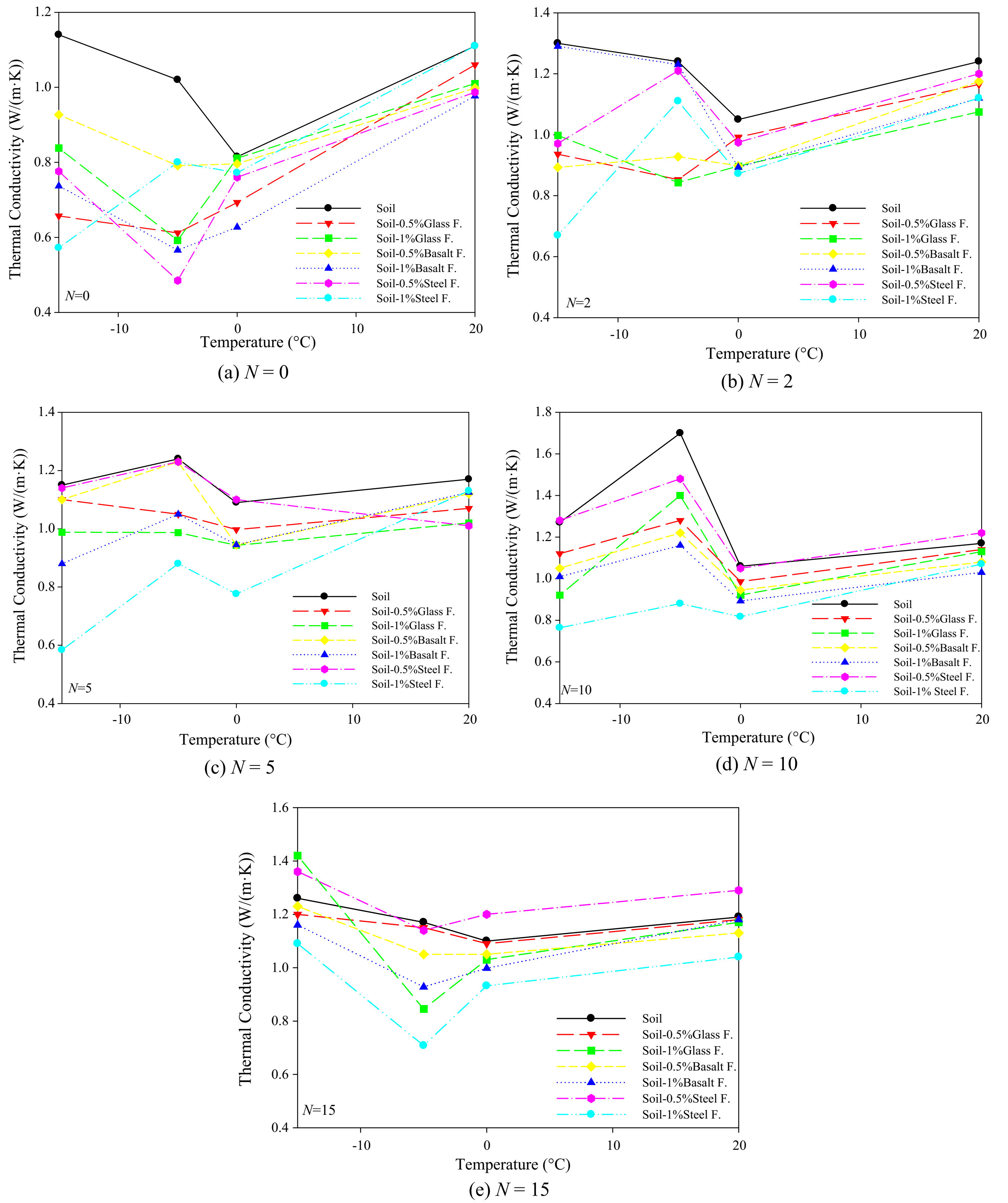

Fig. 3. Thermal conductivity of unreinforced and fiber-reinforced specimens versus temperature for different freeze-thaw cycles.

voids affects the permeability, the porosity, and the soil density. A dimensionless parameter, D, for the soil specimens after freeze-thaw cycles has been determined to represent the effect of the freezing-thawing cycle on the soil specimen's water content as follows:

$$D = \frac{\Delta w}{w_0} \tag{4}$$

where Δw is the increasing amount of water content after N cycles in the thawed phase and w_o is the initial water content in the

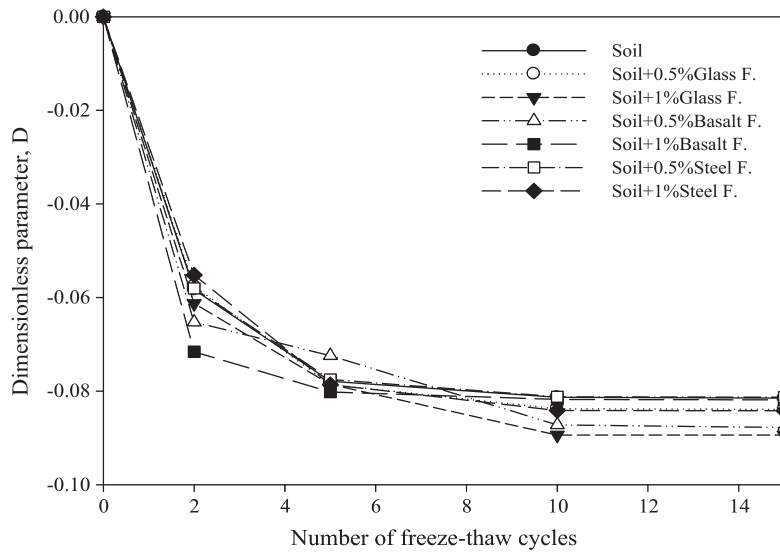

Fig. 4. D versus the number of freeze- thaw cycles.

unfrozen soil. Fig. 4 shows D and the number of freeze-thaw cycles for tested unreinforced and reinforced specimens. At the beginning, the water content of the specimens decreased with an increasing number of freeze-thaw cycles, then slowly steadied after the tenth freezing-thawing cycle. Moreover, it was observed that the inclusion of fiber, especially basalt and glass fibers, decreases the water content little more than unreinforced soil specimens and steel fiber-reinforced soil specimens do. Layers of woven fibers like basalt and glass fibers can drain water from the soil volume, but the reduction is negligible.

The freeze-thaw increment coefficient, η_f, is introduced in Fig. 5a–e to show the effects of the freezing and thawing on the unreinforced and fiber-reinforced soil specimens to better serve developments in earthwork applications. The freeze-thaw increment coefficient is described as the function of the thermal conductivity before and after freezing and thawing on the unreinforced and reinforced specimens. The freeze-thaw increment coefficient equation is as follows:

$$\eta_f = 1 - \left(\frac{\lambda_0 - \lambda_{aN}}{\lambda_0}\right) \quad (5)$$

where λ_0 is the thermal conductivity value of the related specimen before the freeze-thaw cycles and λ_{aN} is the thermal conductivity value of the related specimen after N freeze-thaw cycles.

Fig. 5a–d shows the freeze-thaw increment coefficient, η_f, versus fiber content at various temperatures. The freeze-thaw cycles and the temperature changes have the same effects on unreinforced and fiber-reinforced soil. The λ of the specimens under different freeze-thaw cycles has also shown gradual changes with different temperatures. The bar charts of the freeze-thaw increment coefficients at above-freezing temperatures exhibit a decreasing trend, so there is no significant difference between the ranges of the coefficients at temperatures above freezing. However, when the temperature approached the freezing point or went below freezing, the ranges of those coefficients increased. After fifteen freezing and thawing cycles, the maximum freeze-thaw increment coefficient of clay soil was observed o be 17.0% with the addition of 0.5% steel fiber at $T = 20$ °C. Moreover, the addition of 1% basalt fiber at $T = 0$ °C increased the freeze-thaw increment coefficient by 23.6%. When the temperature fell below zero, the maximum freeze-thaw increment coefficients were observed to increase by 93.4% with the addition of 0.5% steel fiber at $T = -5$ °C and 88.9% with the addition of 0.5% glass fiber at $T = -15$ °C. Also, it was observed that the ranges of the increments after fifteen freeze-thaw cycles were greater, because the rate of increase of the freeze-thaw cycles disturbs the natural soil structure, and thermal resistance increases.

3.3. The statistical-physical model

The model can be described by many laws, in terms of heat transfer, such as a polynomial distribution, Fourier's law, Ohm's law, and two of Kirchhoff's laws [41]. It is assumed that the volumetric unit of soil includes solid particles, water, and air and that they behave as a cubic system occurring as layers in the volumetric unit. Also, it is accepted that in a cubic system, the connected spots between layers and the layers between neighboring cubic systems will be expressed by serial and parallel connections of thermal resistance.

The sum of the parallel and serial connections of thermal resistances is determined by the bulk density and the water content in the soil medium. When the amount of water between the solid particles and contact spots increases, the bulk density and the water content in the unit of soil medium increases. The results of the thermal system, taking into consideration all potential forms of particle relations, together with a mean thermal resistance of given unit soil volume, allows the thermal conductivity of soil λ_0 (W/(m·K)) to be predicted according to the equation:

$$\lambda_0 = \frac{4\pi}{u\sum_{j=1}^{L}\frac{P(x_{1j},\ldots x_{kj})}{x_{1j}\lambda_1(T)r_1+\ldots x_{1k}\lambda_k(T)r_k}} \quad (6)$$

where $\lambda_1, \lambda_2, \ldots, \lambda_k$ is the thermal conductivity, u is the number of parallel connections of soil particles, L is the number of all potential combinations of particles, $x_1, x_2, \ldots, x_k$ is the number of individual particles, and $r_1, r_2, \ldots, r_k$ is particle radius, and where:

$$\sum_{i=1}^{k} x_{ij} = u \quad (7)$$

$j = 1, 2, \ldots, L$ is the probability of the existence of a described soil particle determined from the polynomial distribution, $P(x_{ij})$.

$$P(x_{1j},\ldots,x_{kj}) = \frac{u!}{x_{1j}^{!}\ldots x_{kj}^{!}} f_1^{x_{1j}} \ldots f_k^{x_{kj}} \quad (8)$$

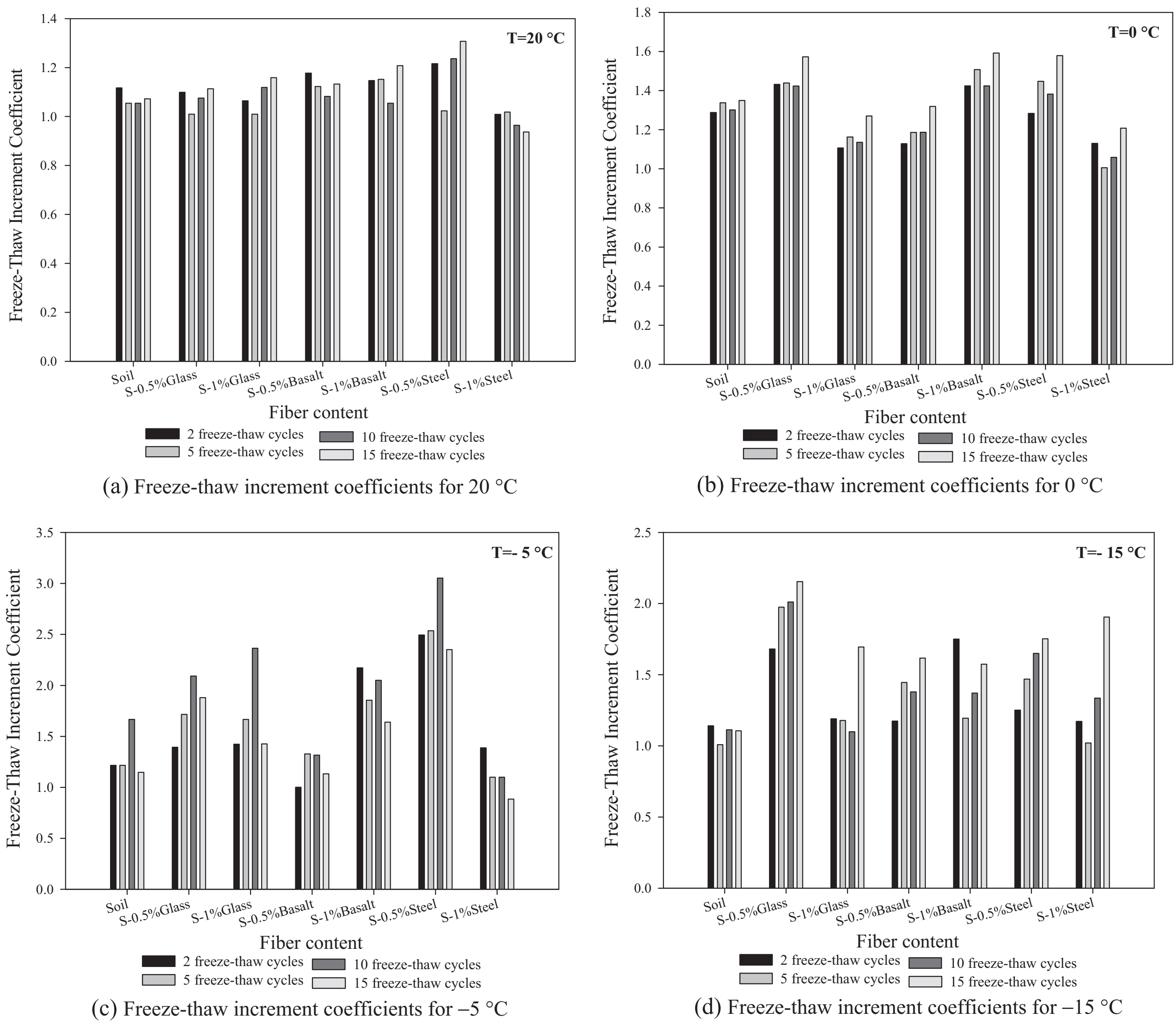

Fig. 5. Freeze-thaw increment coefficients versus fiber content at various temperatures.

The conduction equation, $\sum_{j=1}^{L} P(X = x_j) = 1$, must also be met. The probability of selecting a described soil component f_i, $i = s, w, g$ in a single trial was stated on the basis of physical soil properties. Thus, f_s, f_w, and f_g are the amount of individual minerals and organic matter ($f_s = 1 - \varphi$), water ($f_w = \theta$) and air ($f_g = \varphi - \theta$) in a unit of volume, where φ is the soil porosity.

3.4. Identification and verification of the model

The model is explained by a statistical determination coefficient of probability occurrence for a soil complex and its volumetric compounds. The concept formation of individual particles, which are assumed to be spherical in structure, is the main factor to determine porosity ratio, radii of the spheres, and probability.

The statistical-physical model was employed as proposed by Usowicz [42] to determine the thermal conductivity of unreinforced and fiber-reinforced soils under various temperatures and various number of freeze-thaw cycles. The volumetric weight fraction of soil particles and fibers, water content, air content, and external conditions such as freeze-thaw cycles and temperatures constitute the inputs of the model.

The thermal conductivity model can be written as:

$$\lambda = [\lambda_n, w, T, \beta, N] \tag{9}$$

where λ_n is the thermal conductivity of each of the individual particles in the model, w is water content, T is temperature, β is fiber content, and N is the number of freeze-thaw cycles.

Usowicz [42] showed that the number of parallel connections of thermal resistors u depended on the macroscopic factor of soil, given by the ratio of the water content in volumetric unit, (θ_v)/porosity (ϕ). The value u is greatest for $\theta_v = \phi$, and smallest when $\theta_v = 0$.

In this paper, some assumptions were made to simulate the thermal conductivity of the unreinforced and fiber-reinforced soil specimens as a function of temperature, freeze-thaw cycles and volume fraction of fibers. The assumptions made to set up the statistical-physical model were as follows:

- For the best fit, we assumed that all particles were spherical, and the radii for unreinforced and fiber-reinforced specimens above freezing were the same, and $u = 3$.
- When the temperature (T_f) approached the freezing point (T_0), the radius of all specimens above freezing temperature (r_f) was greater than the radius at freezing (r_0). But, when the temperatures decreased to below freezing (T_{-f}), the radius was not same below freezing (r_{-f}). Thus, the radius of spheres enlarges (Table 3).

$$T_{+f} \rightarrow T_0,\ r_{+f} > r_0 \tag{10}$$

$$T_0 \rightarrow T_{-f},\ r_0 < r_{-f} \tag{11}$$

- When the temperature of all soil specimens dropped to the freezing point, the radius of the spheres decreased in the unfrozen condition. But, after freeze-thaw cycles, due to decreased water content, the radius of the spheres decreased. We assumed that the rate of increase of the radius of all specimens arising from increased temperature equaled the rate of decrease of the radius arising from the changed water content.

Fig. 6 shows a comparison of predicted and experimental data of thermal conductivity for unreinforced and fiber-reinforced soil exposed to freeze-thaw cycles. The proposed statistical-physical model, for all specimens exposed to freeze-thaw cycles with the boundary conditions assumed by the authors, allows those values to be determined with a coefficient of determination (R^2) of 0.7673.

Table 3
Assumptions made to establish the model.

Freeze-thaw cycles	Temperature (°C)	r_{ij} (m)	Freeze-thaw cycles	Temperature (°C)	r_{ij} (m)
0 F-T cycle	20	0.64	10 F-T cycle	20	0.64
0 F-T cycle	0	0.47	10 F-T cycle	0	0.47
0 F-T cycle	−5	0.51	10 F-T cycle	−5	0.51
0 F-T cycle	−15	0.55	10 F-T cycle	−15	0.55
2 F-T cycle	20	0.64	15 F-T cycle	20	0.64
2 F-T cycle	0	0.47	15 F-T cycle	0	0.47
2 F-T cycle	−5	0.51	15 F-T cycle	−5	0.51
2 F-T cycle	−15	0.55	15 F-T cycle	−15	0.55
5 F-T cycle	20	0.64			
5 F-T cycle	0	0.47			
5 F-T cycle	−5	0.51			
5 F-T cycle	−15	0.55			

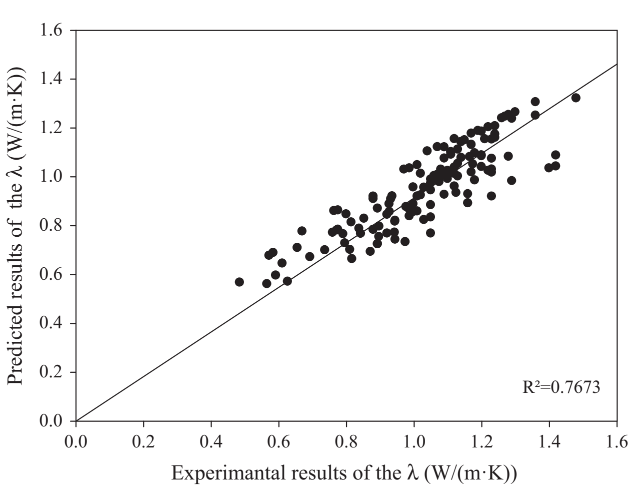

Fig. 6. Comparison of predicted and experimental data of the thermal conductivity for unreinforced and fiber-reinforced soil specimens subjected to freeze-thaw cycles.

The results in this paper showed that the model realized a high sensitivity with various volume fractions of fibers and various freeze-thaw cycles and temperatures. Thus, the model indicates to have the potential for simulating thermal conductivities of fiber-reinforced soil structures with known values of fiber ratios, temperatures, and freeze-thaw cycles.

The root mean square error (RMSE), the maximum relative error (MRE), determination coefficients (R^2), and linear regression coefficients were calculated to determine the validity of the statistical-physical model on fiber-reinforced soil exposed to freeze-thaw cycles. RMSE was calculated by means of the following equation:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(f_{mi} - f_{ci})^2}{k}} \tag{12}$$

where f_{mi} is the experimental dynamic parameter, f_{ci} is the predicted value $k = n - 1$ if $n < 30$ and $k = n$ if $n > 30$, and n is the number of data. The MRE was computed from the following equation:

$$MRE = \max_{i=1,2\ldots n}\left\{\left|\frac{(f_{mi} - f_{ci})}{f_{mi}}\right| 100\%\right\} \tag{13}$$

The relationship between the predicted and measured values for small values of RMSE and MRE is good, with minor deviations.

Evaluation of the thermal conductivity (λ) for all soil specimens, using a high R^2 value of 0.7623, shows a close match between the values predicted by the statistical-physical model and the experimental values (Fig.6). The RMSE of λ ranged from 0.0319 to 8.45×10^{-5} W/(m·K) and the MRE ranged from 0.086% to 26.924%.

4. Conclusion

In this study, the thermal conductivity of unreinforced and fiber-reinforced soil with randomly oriented basalt, glass, and steel fibers was investigated as a function of freeze-thaw cycles, fiber volume fractions, and temperature. The thermal conductivity of the specimens was measured by means of the transient hot-wire method at various temperatures with a Quickline-30 Thermal Properties Analyzer. The experimental results of thermal conductivities were then compared with the predicted values with a statistical-physical model. The following conclusions can be drawn:

- The experimental results showed that thermal conductivity of fiber-reinforced soil is significantly affected by fiber content, water content, and freeze-thaw cycles. Thermal conductivity of fiber-reinforced soils decreased with an increased fiber content and increased with an increase in freeze-thaw cycles. However, the lowest thermal conductivity results were observed on fiber-reinforced soil after freeze-thaw cycles.
- The water content of all specimens decreased slightly with increased freeze-thaw cycles at the beginning but gradually steadied after ten cycles. Moreover, it was observed that the inclusion of fiber, especially basalt and glass fibers, decreased the water content little more than in unreinforced soil specimens and steel fiber reinforced soil specimens.
- When the temperature of all specimens decreased, the thermal conductivity increased. The tests results showed that, as porosity approaches 100%, the thermal conductivity of frozen soils can be assumed to be near the conductivity of ice, while unfrozen soils approach the conductivity value of water. However, an increase in fiber content at freezing temperatures showed lower thermal conductivity than in unreinforced soils.
- At the maximum volume fraction of fiber, the thermal conductivity of the specimens varied from 0.566 to 1.11 W/(m·K) at zero freeze-thaw cycles in the temperature range of 20 °C to −15 °C, 0.67 to 1.29 W/(m·K) at two freeze-thaw cycles, 0.584

to 1.13 W/(m·K) at five freeze-thaw cycles, 0.817 to 1.40 W/(m·K) at ten freeze-thaw cycles and 0.764 to 1.42 W/(m·K) at fifteen freeze-thaw cycles.
- The statistical-physical model for the unreinforced and fiber-reinforced soils at different temperatures and after different numbers of freeze-thaw cycles was used to predict thermal conductivity values. The volumetric weight fraction of soil particles and fibers, water content, air content, and external conditions such as freeze-thaw cycles and temperatures constitute the inputs of the model. The results show that the model has a good agreement with the experimental data. Evaluation of the thermal conductivity (λ) for all specimens, using a high R^2 value of 0.7623, shows a close match between the values predicted by the statistical-physical model and experimental values. The RMSE of λ ranged from 0.032 to 8.450×10^{-5} W/(m·K) and the MRE from 0.086% to 26.92%.

The results of this study indicate that the glass, basalt, and steel fiber-reinforced soil specimens are light in weight, economical, and good thermal insulators. However, the authors suggest using steel and basalt fibers to minimize negative effects arising from temperature changes in the subgrade.

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References

[1] Wansheng Pei, Yu Wenbing, Shuangyang Li, Jiazuo Zhou, A new method to model the thermal conductivity of soil-rock media in cold regions: an example from permafrost regions tunnel, Cold Reg. Sci. Technol. 95 (2013) 11–18.
[2] Pier Paul Overduin, Douglas L. Kane, Wilko K.P. van Loon, Measuring thermal conductivity in freezing and thawing soil using the soil temperature response to heating, Cold Reg. Sci. Technol. 45 (1) (2006) 8–22.
[3] M.R. Yadav, G.S. Saxena, Effect of compaction and moisture content on specific heat and thermal capacity of soils, J. Indian Soc. Soil Sci. 21 (2) (1973) 129–132.
[4] Kathleen M. Smits, Toshihiro Sakaki, Anuchit Limsuwat, Tissa H. Illangasekare, Determination of the thermal conductivity of sands under varying moisture drainage/wetting and porosity conditions: applications in near-surface soil moisture distribution analysis, in: Proceedings from Hydrology Days, Colorado State University, Fort Collins, CO, 2009, pp. 57–65.
[5] Bogusław Usowicz, Jerzy Lipiec, Jerzy B. Usowicz, Wojciech Marczewski, Effects of aggregate size on soil thermal conductivity: comparison of measured and model-predicted data, Int. J. Heat Mass Transfer 57 (2013) 536–541.
[6] Nyle C. Brady, Ray R. Weil, The Nature and Properties of Soils, 14th ed., Prentice Hall, New Jersey, 2002.
[7] Hugh B. Sutherland, Paul N. Gaskin, Pore water and heaving pressures developed in partially frozen soils, in: North American Contribution, Permafrost, Second International Conference on Permafrost, National Academy of Sciences, Washington, DC, 1973, pp. 409–419.
[8] R. Torrance Martin, Rhythmic ice banding in soils, in: Highway Research Board Bulletin 218, Transportation Research Board, National Research Council, Washington, DC, 1959, pp. 11–23.
[9] Pieter Hoekstra, Moisture movement to a freezing front, in: Geochemistry, Precipitation, Evaporation, Soil-Moisture, and Hygrometry, International Union of Geodesy and Geophysics, General Assembly of Bern, 1967, pp. 411–417.
[10] Egbert J.A. Spaans, John M. Baker, The soil freezing characteristic: its measurement and similarity to the soil moisture characteristic, Soil Sci. Soc. Am. J. 60 (1996) 13–19.
[11] Barret L. Kurylyk, Kunio Watanabe, The mathematical representation of freezing and thawing processes in variably-saturated, non-deformable soils, Adv. Water Resour. 60 (2013) 160–177.
[12] Ivan Alekseevich Tyutyunov, M.V. Averochkima, V.P. Titov, Effect of freezing and thawing on the structure, composition and properties of cohesive soil, Physics, Physical Chemistry and Mechanics of Permafrost and Ice. Draft translation, vol. 439, Cold Region Research and Engineering Laboratory (CRREL), U.S. Army Corps of Engineers, Hanover, NH, 1973, pp. 125–132.
[13] Nidal H. Abu-Hamdeh, Thermal properties of soils as affected by density and water content, Biosyst. Eng. 86 (1) (2003) 97–102.
[14] Nidal.H. Abu-Hamdeh, Adnan.I. Khdair, Randall.C. Reeder, A comparison of two methods used to evaluate thermal conductivity for some soils, Int. J. Heat Mass Transfer 44 (5) (2001) 1073–1078.
[15] Mohammad Hossein Jahangir, Seyed Amirodin Sadrnejad, A new coupled heat, moisture and air transfer model in unsaturated soil, J. Mech. Sci. Technol. 26 (11) (2012) 3661–3672.
[16] Hidetoshi Mochizuki, Masara Mizoguchi, Tsuyoshi Miyazaki, Effects of NaCl concentration on the thermal conductivity of sand and glass beads with moisture contents at levels below field capacity, Soil Sci. Plant Nutr. 54 (2008) 829–838.
[17] Abdelmalek Bouazza, Geosynthetic clay liners, Geotext. Geomembr. 20 (2002) 3–17.
[18] State of Ohio Environmental Protection Agency (OhioEPA), Freeze-Thaw Protection During Construction of Recompacted Soil Liners and Recompacted Soil Barrier Layers, Division of Solid and Infectious Waste Management, Ohio Environmental Protection Agency, Columbus, OH, 2007.
[19] Mousa F. Attom, The use of shredded waste tires to improve the geotechnical engineering properties of sands, Environ. Geol. 49 (2006) 497–503.
[20] Martin Christ, Jun-Boum Park, Laboratory determination of strength properties of frozen rubber-sand mixtures, Cold Reg. Sci. Technol. 60 (2010) 169–175.
[21] Li-Wu Fan, Jay M. Khodadadi, Thermal conductivity enhancement of phase change materials for thermal energy storage: a review, Renew. Sustain. Energy Rev. 15 (1) (2011) 24–46.
[22] Duwayne M. Anderson, Pieter Hoekstra, Migration and Crystallization of Interlamellar Water During Freezing and Thawing of Wyoming Bentonite CRREL Research Report 192, AD631150, Cold Regions Research and Engineering laboratory, U.S. Army Corps of Engineers, Hanover, NH, 1965.
[23] Greg P. Newman, Case study: thermal analysis of artificial ground freezing at the McArthur river uranium mine, Geotech. News 21 (2) (2003) 60–63.
[24] Gianluigi Bovesecchi, Paolo Coppa, Basic problems in thermal conductivity measurements of soils, Int. J. Thermophys. 34 (10) (2013) 1962–1974.
[25] Daehoon Kim, Gyoungman Kim, Hwanjo Baek, Relationship between thermal conductivity and soil–water characteristic curve of pure bentonite-based grout, Int. J. Heat Mass Transfer 84 (2015) 1049–1055.
[26] Kunal. Singha, A short review on basalt fiber, Int. J. Text. Sci. 1 (4) (2012) 19–28.
[27] Gail F. Kennedy, Jánis Lielmezs, Heat and mass transfer of freezing water-soil system, Water Resour. Res. 9 (2) (1973) 395–400.
[28] Gabriela Labudová, Vlasta Vozárová, Hot wire and hot plate apparatuses for the measurement of the thermophysical properties, Trans. TSTU 8 (1) (2002) 85–96.
[29] Andrea Carminati, Anders Kaestner, Peter Lehman, Hannes Flühler, Unsaturated water flow across soil aggregate contacts, Adv. Water Resour. 31 (2008) 1221–1232.
[30] Jerzy Lipiec, Mieczysław Hajnos, Ryszard Świeboda, Estimating effects of compaction on pore size distribution of soil aggregates by mercury porosimeter, Geoderma 179 (2012) 20–27.
[31] Cezary Sławiński, Barbara Witkowska-Walczak, Jerzy Lipiec, Artur Nosalewicz, Effect of aggregate size on water movement in soils, Int. Agrophys. 25 (2011) 53–58.
[32] William Woodside, Calculation of the thermal conductivity of porous media, Can. J. Phys. 36 (7) (1958) 815–823.
[33] Tae Sup Yun, J. Carlos Santamarina, Fundamental study of thermal conduction in dry soils, Granul. Matter 10 (2008) 97–207.
[34] Richard Eugene Thalmann, Thermal Conductivity of Dry Soils, University of Kansas, Lawrence, KS, 1950.
[35] Omar T. Farouki, Thermal Properties of Soils, Monograph 81–1, Cold Region Research and Engineering Laboratory (CRREL), U.S. Army Corps of Engineers, Hanover, NH, 1981.
[36] Karl. Terzaghi, Permafrost. J. Boston Soc. Civ. Eng. 39 (1) (1952) 1–50.
[37] G.A. Martynov, Heat and moisture transfer in freezing and thawing soils, in: Principles of Geocryology, Part I: General Geocryology, Chapter VI, Akad. Nauk SSSR, 153–192. Translated by E.R. Hope, National Research Council of Canada Technical Translation, 1959, p. 1065.
[38] N.A. Tsytovich, Instability of mechanical properties of frozen and thawing soils, in: Proceeding of the First International Permafrost Conference, 11–15 November, Lafayette, Indiana, Building Research Advisory Board, National Academy of Sciences-National Research Council, Washington, D.C., 1963, pp. 325–331.
[39] G. Al Nakshabandi, Helmut Kohnke, Thermal conductivity and diffusivity of soils as related to moisture tension and other physical properties, Agric. Meteorol. 2 (1965) 271–279.
[40] V.N. Dimo, Physical properties and elements of the heat regime of permafrost meadow-forest soils, in: Permafrost Soils and Their Regime, Indian Natl Sci Doc Center, New Delhi, 1969. CRREL Bibliography No. 24-2119.
[41] César Juárez, B. Guevara, Pedro L. Valdez, Alejandro Durán-Herrera, Mechanical properties of natural fibers reinforced sustainable masonry, Constr. Build. Mater. 24 (2010) 1536–1541.
[42] Bogusław Usowicz, Statistical–physical model of thermal conductivity in soil, Pol. J. Soil Sci. 25 (1) (1992) 25–34.