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Experimental study on the effect of frost heave prevention using soilbags

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ABSTRACT

This paper introduces a new method to prevent frost heave in cold regions using soilbags (bags filled with soils). The mechanism of the proposed treatment method is introduced. A number of tests of soilbag frost heave, thawing settlement and strength were conducted in the laboratory on soilbags filled with soils. The results showed that soilbags exhibit less frost heave and thawing settlement than soils for the same conditions. In addition, the strength of soilbags was not affected by increasing the number of freeze–thaw cycles. These findings indicate that soilbags can not only prevent frost heave but also inhibit capillary water and film water migration through soilbags.

1. Introduction

The cold regions of the world cover large parts of Asia, northern Europe, Alaska, Canada and approximately a third of the USA. In China, permafrost and seasonal frozen ground cover 68.4% of the land, this area covering 29 provinces, in these regions, foundations, buildings and geotechnical structures are subject to freezing and frost heave in the winter and thaw settlement and weakening in the spring. Freeze–thaw action can cause severe damage to foundations and buildings in northern China. It is estimated that in northern China, some provinces may spend over million US dollars every year in work to repair the damage due to frost heave buildings and foundations. So the management agencies pay a great deal of attention to research work on the prevention of frost heave in engineering.

In recent years, some measures were put forward and investigated in the construction of highway and railway in cold regions, to ensure the stability of railway embankment and protect the underlying permafrost, a series of cooling techniques were employed e.g. duct-ventilated embankment, crushed-rock embankment and thermosyphon embankment (Cheng et al., 2009; Ma et al., 2002), and their cooling effects have been proved by practical engineering (Niu et al., 2006; Sun et al., 2005) different embankment structures and geometries on the underlying permafrost thermal regime along Qinghai–Tibetan Railway were analysed (Zhang et al., 2005).

Soilbags are commonly used to raise embankments during floods and to construct temporary structures during reconstruction after disasters. Soilbags are filled with granular materials such as sand, crushed stone, and recycled concrete. Granular soils wrapped with bags exhibit the typical characteristics of cohesive-frictional materials (Matsuoka and Liu, 2003). In recent years, soilbags have been used primarily for soil reinforcement in permanent or semi-permanent civil engineering works and found to be feasible and effective (Khalili and Khabbaz, 1998; Matsuoka and Liu, 2003). A new earth reinforcement method using soilbags has recently been developed (Matsuoka and Liu, 1999, 2003, 2005; Matsuoka et al., 1998, 2000). The reinforcement mechanism and a three-dimensional (3D) model for the ultimate compressive strength of soilbags have been suggested in these studies. This new model has been used successfully to predict soilbags' compressive strength, and the predicted values have been found to be much closer to experimentally measured values from compressive tests on soilbags than values predicted from two-dimensional (2D) strength models (BAI Fu-qing et al., 2010). A method for reinforcing slope surfaces using soilbags has been developed and used to analyse the stability of an expansive soil slope reinforced with soilbags (Liu et al., 2010). A numerical analysis of soft foundations reinforced with soilbags has been conducted by applying an elasto-plastic finite element analysis. The numerical results show that the predicted values are in good agreement with observed values. The method combines the principles of soilbag reinforcement with an elasto-plastic finite element model (Liu et al., 2012). Matsuoka and Liu (2003) summarised the advantages of reinforcing soil with soilbags, as follows:

(1) Bags are cheap and easy to acquire.
(2) Soilbags have almost the same unit weight as foundation soils.
(3) The materials inside soilbags can be various construction wastes, such as crushed concrete, asphalt and tile wastes. Soilbags thus contribute greatly to the recycling of waste materials.
(4) No special construction equipment is required. Soilbags can be assembled solely by human labour.

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(5) Earth reinforcement using soilbags is environmentally friendly because cement and chemical agents are avoided.
(6) Less noise and vibration are produced by soil reinforcement with soilbags than by the pile-driving method that is commonly used in soft/weak foundation reinforcement.
(7) Soilbags have high compressive strength, approaching 3 MPa, nearly a tenth that of normal concrete.
(8) The bearing capacity of a soft ground can be increased by 5–10 times using soilbags.

They are mainly focus on the effect on the bearing capacity improvement of soilbags, vibration damping effect of soilbags, and improving the stability of an expansive soil slope with soilbags. However, soilbags have not yet been applied to the prevention of frost heave of foundations and buildings in cold regions. In this background, the authors designed frost heave prevention using soilbags in the laboratory.

In this paper, the principle of frost heave prevention using soilbags is introduced. A series of laboratory experiments conducted on soilbags filled with soils to study their frost heave and thawing settlement responses to multiple freeze–thaw cycles are described. Based on the results of the laboratory experiments, a new method for preventing frost heave of foundations and buildings with soilbags is proposed. The soilbags considered in this paper are woven polypropylene bags filled with soils.

2. Experimental investigation

2.1. Specimen preparation and sample freezing–thawing procedure

The moisture content and density of the tested clayey soil in this study were 17.6% and 1.67 g/cm^3, respectively. The engineering properties of the tested clayey soil are listed in Table 1. The grain size distribution for the tested clayey soil is shown in Fig. 1. The saturated moisture content was 38.1%.

In this study, tensile strength tests of soilbags were conducted on an extension–compression apparatus. The tension test results are tabulated in Table 2. To investigate the efficacy of soilbags in preventing frost heave, freeze–thaw cycles were applied to test specimens using a programmed freeze–thaw apparatus. The samples were used in three groups of tests in the laboratory. The three groups of samples were processed as follows.

The soilbags and soil in the first group of samples were placed in a closed system (without an external moisture supply), in which the soils and soilbags were frozen at a temperature of −15 °C for 72 h (Fig. 2). The temperature in the cabinet was then increased to 15 °C so that the samples could thaw for 72 h. The samples were subjected to four freeze–thaw cycles.

The soilbags and soil in the second group of samples were placed in an open system (with moisture supplied from a Mariotte bottle), in which the soils and soilbags were frozen at a temperature of −15 °C for 72 h (Fig. 2). The temperature in the cabinet was then increased to 15 °C so that the samples could thaw for 72 h. The samples were subjected to four freeze–thaw cycles.

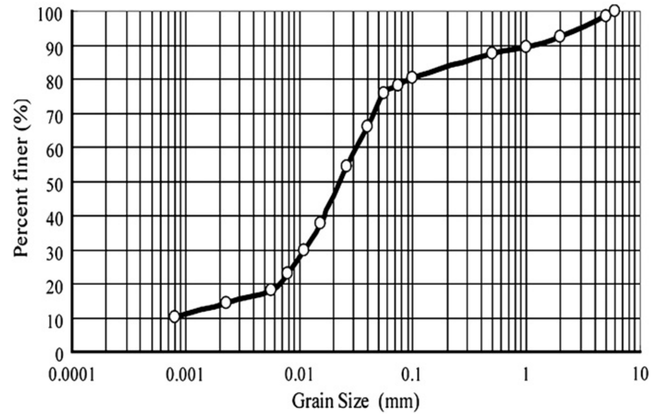

Fig. 1. Grain size distribution for the soil tested.

The third group of samples were woven bags that were placed in a box. The box was injected with water to cover the woven bags, then the box was placed in a freezing apparatus, and the woven bags were frozen at a temperature of −15 °C for 72 h. The temperature in the cabinet was then increased to 15 °C so that the samples could thaw for 72 h. The woven bags were subjected to twenty freeze–thaw cycles.

The prepared samples were placed in two boxes and then put into an environmental apparatus for freeze–thaw testing in closed-system conditions (without an external moisture supply) or open-system conditions (with moisture supplied from a Mariotte bottle). The inner walls of the box were covered with Vaseline to reduce the effect of friction on frost heave and thawing settlement of the samples. The test boxes were covered with insulation materials, and the samples were frozen unidirectionally from the top under a constant temperature. Temperature transducers were placed through small holes into the soil at intervals of 5 cm in the temperature measurement zone, to measure temperatures with 0.01 °C precision. The Mariotte bottle was a constant head device, which provided a moisture supply and capillary water migration for the open system conditions. To record the amount of frost heave and thawing settlement of each specimen, three dial indicators with a precision of 0.001 mm were placed along the diagonal of each specimen. Frost heave and thawing settlement values were taken as the averages of the measurements obtained from the three dial indicators. Freezing rate was 6.7 mm/h. To determine the tensile strength and maximum extension strain of the bags, tensile tests of the bags were conducted on an extension–compression apparatus with an electronic digital control device. The pulling speed was controlled at 20 mm/min. The tensile force-settlement relationship of two woven bags is shown in Table 2. The permeability

Table 1
Physical properties of the soil tested.

Physical parameters	Nanjing clayey soil
Dry density	1.42
Liquid limit W_L(%)	36.4
Plastic limit W_P(%)	16.6
Plastic index I_P(%)	19.8

Table 2
Test conditions and results of woven bags.

Test type	With (mm)	Length (mm)	Tensile force (kN)	Maximum extension (mm)	Tensile strength T (kN/m)	Extension strain λ (%)
Radial	20	10	2.06	44.66	10.3	36.0
	20	10	1.98	31.03	9.9	
	20	10	1.55	32.32	7.75	
Latitudinal	20	10	1.33	25.88	6.65	27.0
	20	10	1.9	27.3	9.5	
	20	10	1.98	27.77	9.9	

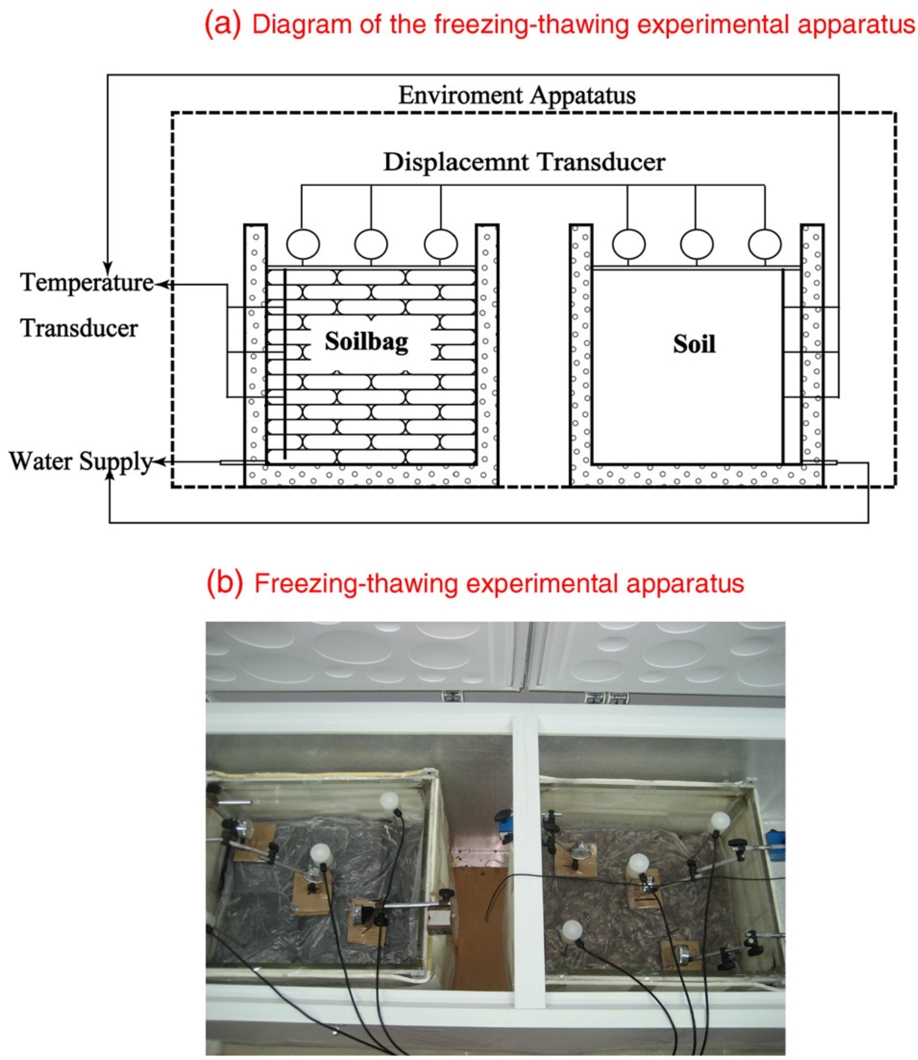

Fig. 2. Freezing–thawing experimental apparatus in the laboratory.

coefficient of the bag is very small, the permeability coefficient of the bag is 1×10^{-11} cm/s.

The testing apparatus has two boxes to hold the samples. The length, width and height of the model boxes are $L\times W\times H=56\times 46\times 32$ (cm). Soilbags were placed in one model box and mutual interlaced with layers of soilbags, and the soil was placed in the other model box. The height of the soilbags and soil was 32 cm, the density of the soil and soilbags was 1.67 g/cm^3. The two model boxes have the same quality of soil. To ensure the specimens were carried out at the same condition. The length, width and height of the soilbags were 20 cm × 20 cm × 2.5 cm ($L\times W\times H$).

2.2. Principle of frost heave prevention with soilbags

Fig. 3 is a schematic illustration of the frost heave prevention mechanism with soilbags. Frost heave prevention with soilbags is mainly attributed to the tensile force T along the bag, which is developed due to the extension of the bag perimeter. For a soilbag, the extension of the bag perimeter is caused by frost heave deforming the soil inside the bag during the freezing process. The tensile force T along the bag enhances the contact between the soil particles inside the bag, resulting in an increase in the normal contact forces N and the frictional forces F between the soil particles ($F=\mu N$, where μ is the friction coefficient). Therefore, the soilbag increases soil strength and frost heave resistance. Thawing leads to a decrease in the volume of the soil. The tensile stress in the soilbag is only induced by the external forces applied.

3. Results and discussion

3.1. Soilbag and soil frost heave for closed-system conditions

Frost heave is an important potential consequence of the freezing of soil. Frost heave sometimes causes severe damage to structures. Freezing rate has a significant impact on frost heave (Chen et al., 2006; Takagi, 1980), this paper does not take into account impact on frost heave of freezing rate.

Fig. 4 shows that the total frost heave of soilbags and soil reaches 2.4 mm and 4.1 mm, respectively, after 48 h. The total frost heave of soil would be much larger than 1.7 mm. For a soilbag, the extension of the bag's perimeter is caused not only by the action of external forces but also by the frost heave deformation of soils during the freezing process. The frost heave of soilbags and soil increased with an increasing number of freeze–thaw cycles. However, the frost heave of

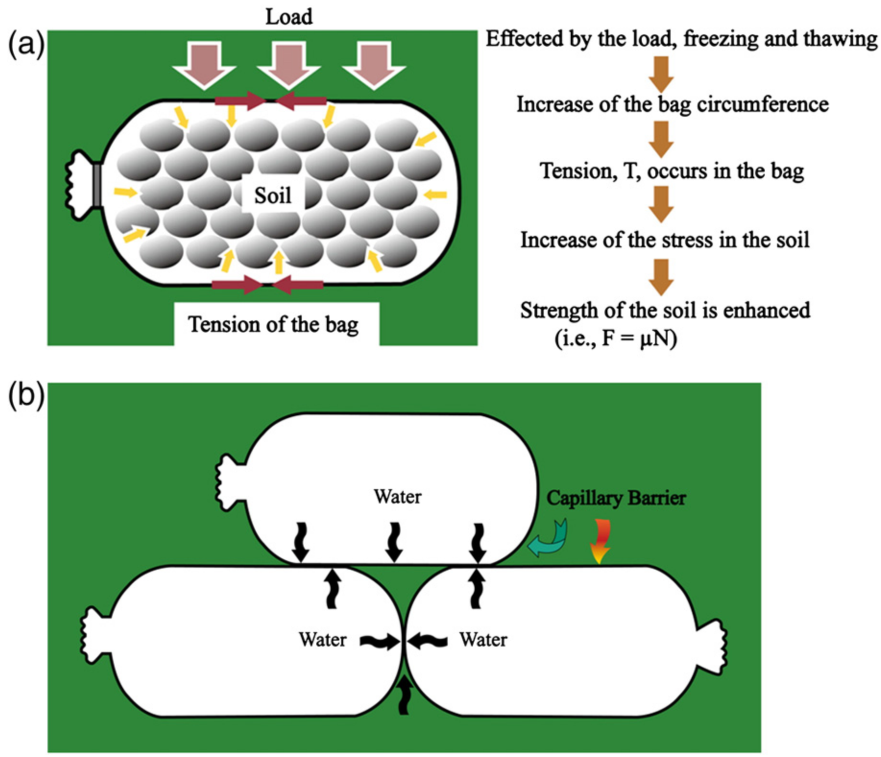

Fig. 3. Frost heave prevention mechanism analysis of soilbags.

soilbags did not change significantly. It is clear from this figure that soilbags have a significant frost heave prevention effect.

A temperature gradient in freezing soil results not only in moisture migration but also in the formation of segregated ice and in complex physico-chemical and physico-mechanical processes. In a closed system, not enough pore water is available to migrate under a temperature gradient, and pore water migration will soon cease (Andersland and Ladanyi, 2004). Ice lenses may form in soil due to freezing of in situ moisture. During freezing, water expands by approximately 9%, which increases the soil volume and the height of the soil. Small ice crystals appear on the surfaces of the samples.

3.2. Soilbag and soil thawing settlement for closed-system conditions

Many researchers have studied the impact of seasonal frost conditions on foundation performance. However, the efforts of previous researchers have been concentrated primarily on freezing phenomena, with considerably less focus on thawing settlement. Fig. 5 shows that the measured soil and soilbag thawing settlement in this study were 4.3 mm and 2.4 mm, respectively. Comparing Figs. 4 and 5 reveals that soil thawing settlement is greater than soil frost heave in a closed system after 4 freeze–thaw cycles. Soil porosity is decreased and soil density increases with an increasing number of freeze–thaw cycles. When the temperature of the apparatus increases, the surface of the sample begins to melt, and during the process of thawing, the core temperature of the sample is always lower than that of the surface, which leads the melted pore water at the surface to migrate toward the centre of the sample. However, this process will cease as the core temperature of the sample increases. With the increase of the sample temperature, the soil ice melts, and the pore volume decreases due to the self-weight of the overlying soil, thus causing the specimen volume to decrease. This process is manifested by the specimen height decreasing after

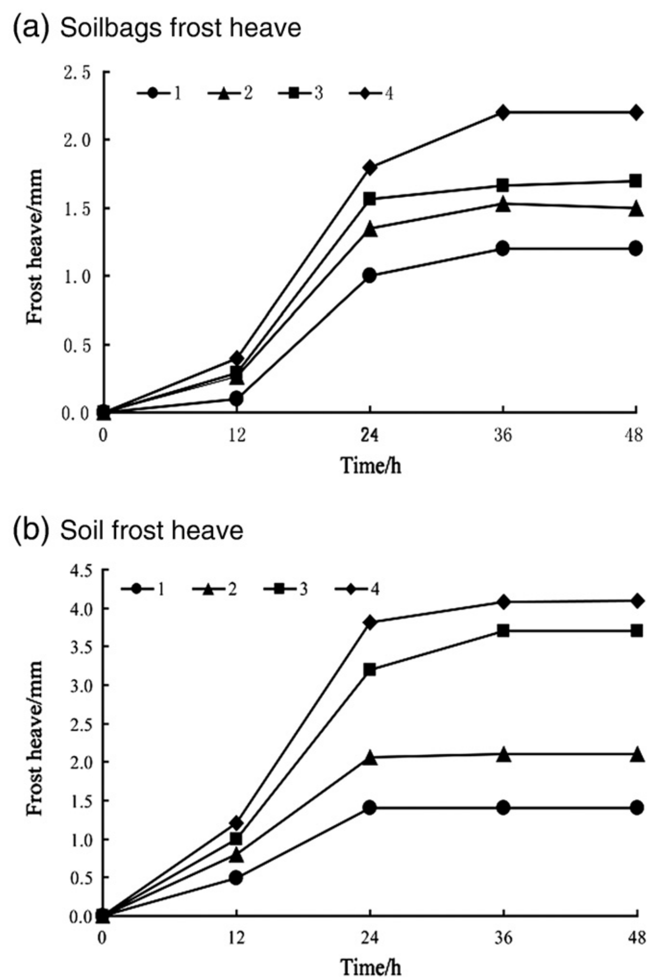

Fig. 4. Frost heave versus the number of freeze–thaw cycles for a closed-system.

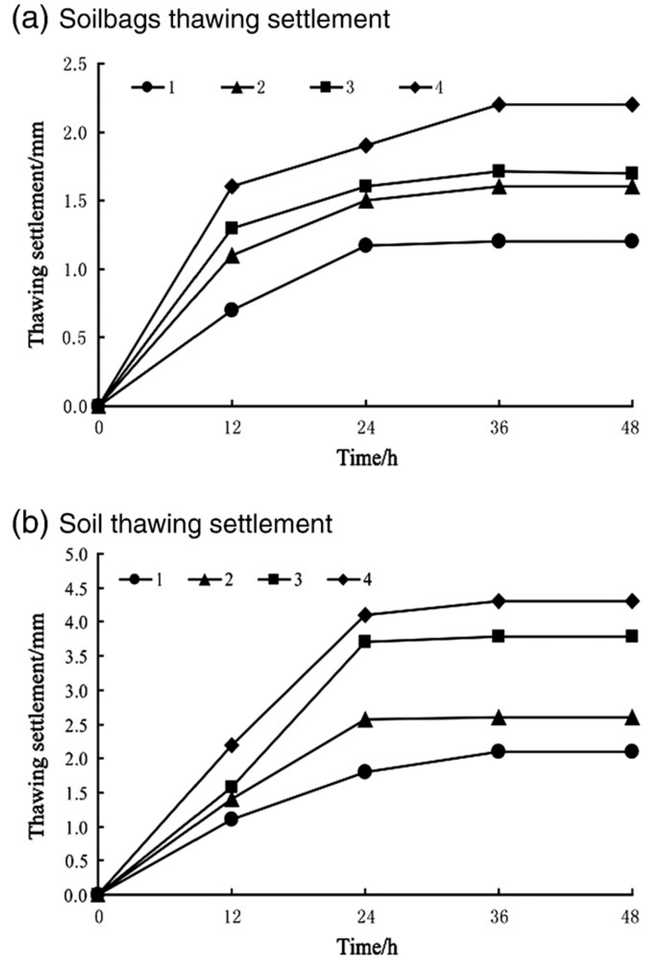

Fig. 5. Thawing settlement versus the number of freeze–thaw cycles in a closed system.

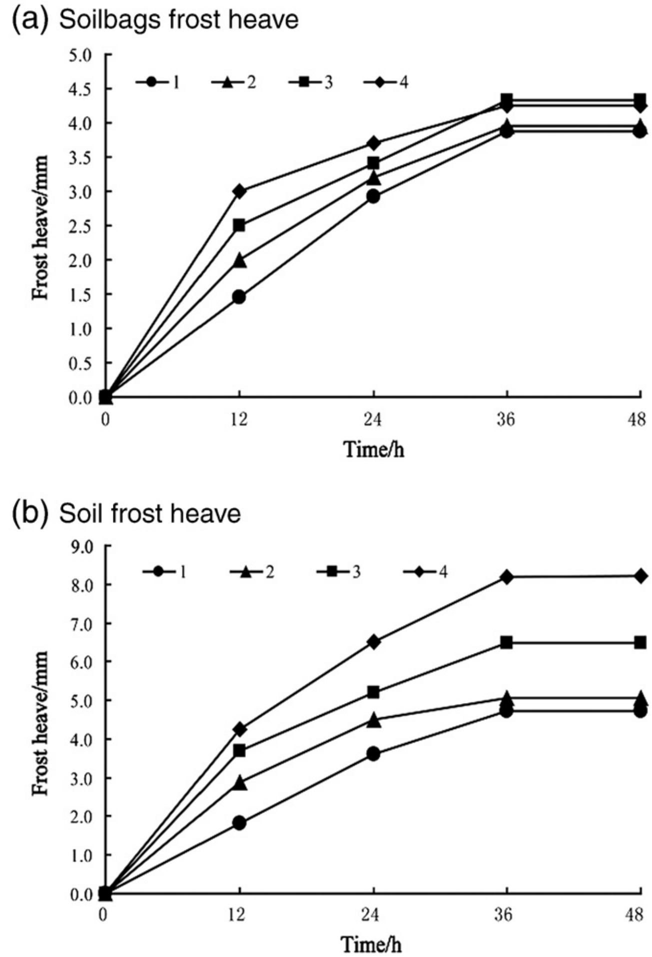

Fig. 6. Frost heave versus the number of freeze–thaw cycles in an open system.

thawing. However, soilbag and soil thawing settlement are equal after 4 freeze–thaw cycles. The soilbags were filled with soil, and the soil was affected by the action of tensile forces during the freezing–thawing. It can be seen that the thawing settlement of the soilbags was not affected by the number of freeze–thaw cycles.

3.3. Soilbag and soil frost heave for open-system conditions

In this experiment, the water table was maintained at 10 mm above the bottom of the specimen, to investigate the effect of soilbags on inhibiting capillary water and film water migration through soilbags.

The frost heave measurements for soilbags and soil, shown in Fig. 6, indicate that the soil frost heave is 1.9 times greater than the soilbag frost heave. The soil frost heave increases with an increasing number of freeze–thaw cycles. The soilbag frost heave changes were not as significant.

From Figs. 5 and 6, it can also be seen that soilbag frost heave in a closed system was not as significant as soilbag frost heave in an open system. This is because the moisture content becomes the most important factor controlling frost heave. In an open system, a temperature gradient is formed between the frozen surface and the unfrozen zone, and moisture is drawn up from a free surface through the soil as the freezing front moves downward. This movement of moisture causes the frost front to migrate. As a result, ice crystals appear on the surfaces of the samples, and increase the height of the soil. However, the soilbags were made of a black woven material that is relatively impervious. The permeability coefficient of the bag is very small, the permeability coefficient of the bag is 1×10^{-11} cm/s. That is why capillary water migration does not occur through soilbags. The capillary water hardly rose inside, and thus, the soilbag frost heave was much smaller than the soil frost heave.

The analyses mentioned above illustrate that the soilbags provide good frost heave prevention. They not only inhibit deformation due to freezing but also inhibit capillary water migration between layers of soilbags.

3.4. Soilbag and soil thawing settlement for open-system conditions

Settlement caused by thawing is attributable to a volume change due to the phase shift from ice to water and the subsequent consolidation of the soil, in which applied loads are transferred from the pore water to the soil skeleton. From Fig. 7, it is seen that the soilbag thawing settlement is less than the soil thawing settlement in an open system. The soilbag thawing settlement amounts after 1, 2, 3, and 4 freeze–thaw cycles were 39 mm, 40 mm, 41 mm, and 43 mm, respectively, while the soil thawing settlement amounts after 1, 2, 3, and 4 freeze–thaw cycles were 45 mm, 51 mm, 57 mm, and 91 mm, respectively. The soil thawing settlement was 2.1 times greater than the soilbag thawing settlement because moisture migration did not occur in soilbags in capillary form. Comparing Figs. 5 and 7, it can be seen that the soilbag thawing settlement in a closed system is less than the soilbag thawing settlement in an open system because

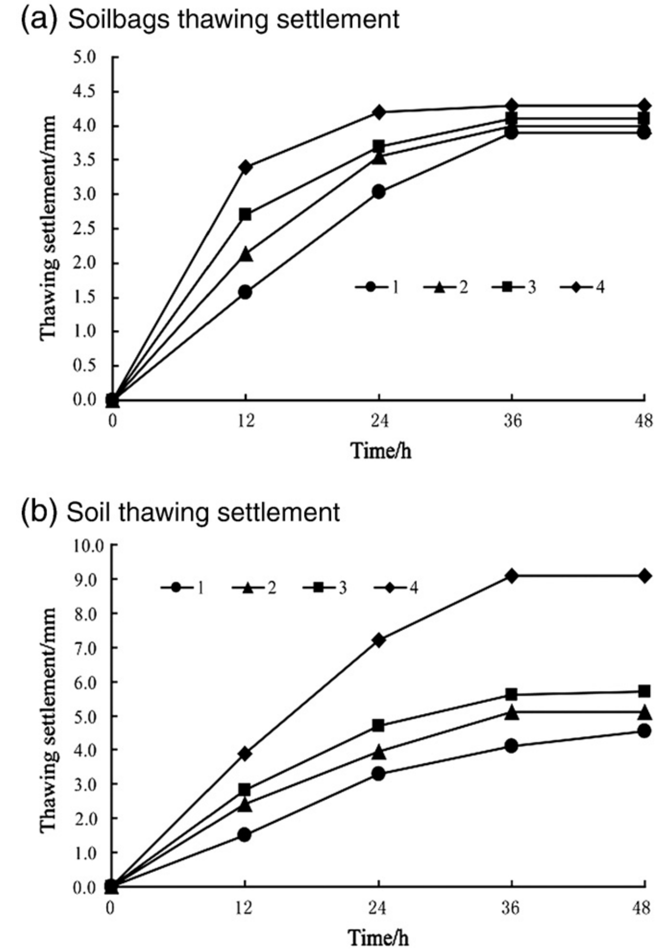

Fig. 7. Thawing settlement versus the number of freeze–thaw cycles in an open system.

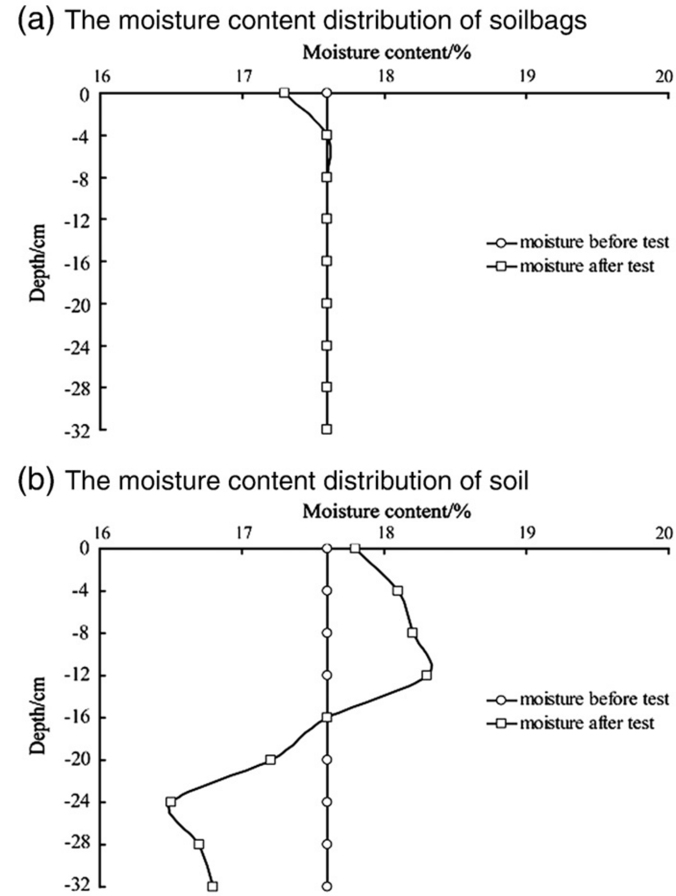

Fig. 8. Moisture content versus the number of freeze–thaw cycles in a closed system conditions.

more water is available in an open system. For a soilbag, the extension of the bag perimeter is caused by the action of external forces during the thawing process. Moisture migration can occur in soils in capillary form during the freezing process. The moisture content of the soil increases with an increase in the soil temperature, the soil ice melts, and the pore volume decreases due to the self-weight of the overlying soil, thus causing the specimen volume to decrease. It can also be seen that the thawing settlement of the soilbags was not affected by the number of freeze–thaw cycles.

3.5. Moisture content changes for closed-system conditions

The measured moisture content results for the specimens are shown in Fig. 8(a). The moisture content at the upper layer changes from the initial value of 17.6% to 17.3%, that is, little moisture content change occurred at the upper layer of the soilbags, and no moisture migration occurred during the freezing procedure.

Fig. 8(b) shows that the moisture contents at depths of 8 mm, 16 mm, 24 mm and 32 mm were 18.2%, 17.6%, 16.5% and 16.8%, respectively. These results reveal that moisture migration did occur in the soil.

Moisture migration can occur in soils in capillary form (capillary water proper) and in film form (weakly bound water). Capillary water migration is mainly volumetric due to meniscus (Laplace) forces. In frozen soils, the migration of bound water usually occurs by film transfer and is comparable to the capillary water transfer in soil micropores, i.e., a mixed capillary-film transfer mechanism can be said to occur. Characteristically, soil moisture migrates in the films from particle to particle (molecular diffusion migration). Naturally, the velocity of film water migration is slower than for capillary water transfer.

3.6. Moisture content changes for open-system conditions

To investigate the capillary water rise and film water transfer, a water table was maintained at 10 mm in the open system. From Fig. 9(a), it can be seen that the moisture contents at depths of 8 mm, 16 mm, 24 mm and 32 mm were 17.6%, 17.6%, 17.6% and 25.1%, respectively. These results indicate that no moisture migration occurred during the freeze–thaw cycle procedure. This is because the capillary water and film water cannot transfer through soilbags. From Fig. 9(b), it can be seen that the moisture contents at depths of 8 mm, 16 mm, 24 mm and 32 mm are 18.8%, 19.2%, 19.7% and 31.1%, respectively. These results indicate that considerable moisture migration occurred during the freezing cycle procedure. It was also observed that many ice crystals appeared on the surface of the soil. For soilbags and soil (Fig. 9), the moisture content at the bottom of the soilbags and the soil changed from 25.1% to 31.1%. This implies that little moisture entered the soilbags. These results prove that soilbags can prevent capillary water rise and film water transfer inside the soilbags.

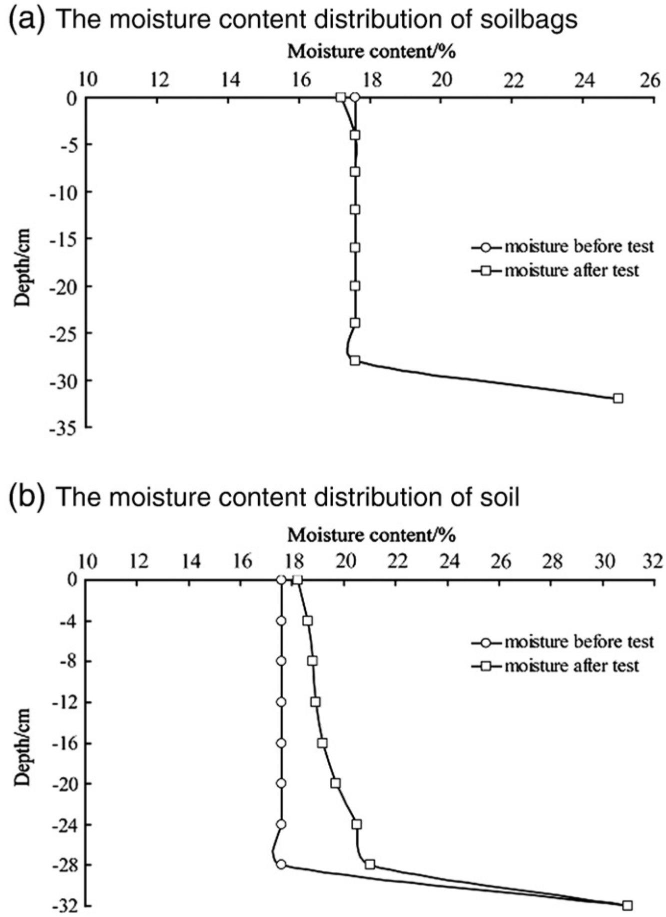

Fig. 9. Moisture content versus the number of freeze–thaw cycles in an open system.

3.7. Effect of the number of freeze–thaw cycles on the tensile strength of soilbags

Another objective of this study was to assess how the tensile strength of soilbags is influenced by freeze–thaw cycles because tensile strength is a key factor in bag quality, and bag quality is related to construction project costs. A series of laboratory extension–compression tests were conducted on soilbags after 0, 5, 10, 15, and 20 freeze–thaw cycles. Fig. 10 shows that the tensile strength of soilbags did not change significantly after twenty freeze–thaw cycles. This also proves that soilbags are an excellent frost heave prevention method.

4. Conclusions

In this paper, a new method is proposed to prevent frost heave in cold regions using soilbags. The frost heave prevention principle is presented, and the effectiveness of the soilbags is verified through a number of laboratory tests. Based on the detailed analyses of the experimental results, the following conclusions can be drawn:

(1) Soilbags filled with soils can prevent frost heave. This capability is mainly attributable to the tensile force T along the perimeter of the bag, which is developed due to the extension of the bag. For a soilbag, the extension of the perimeter is caused not only by the action of external forces but also by the frost heaving deformation of soils during the freezing process.
(2) Soilbags can not only prevent frost heave but also inhibit capillary water and film water migration through soilbags.
(3) The frost heave of soilbags and the thawing settlement of soilbags are smaller than those of soil for the same initial conditions.
(4) The tensile strength of soilbags did not change significantly with an increasing number of freeze–thaw cycles.

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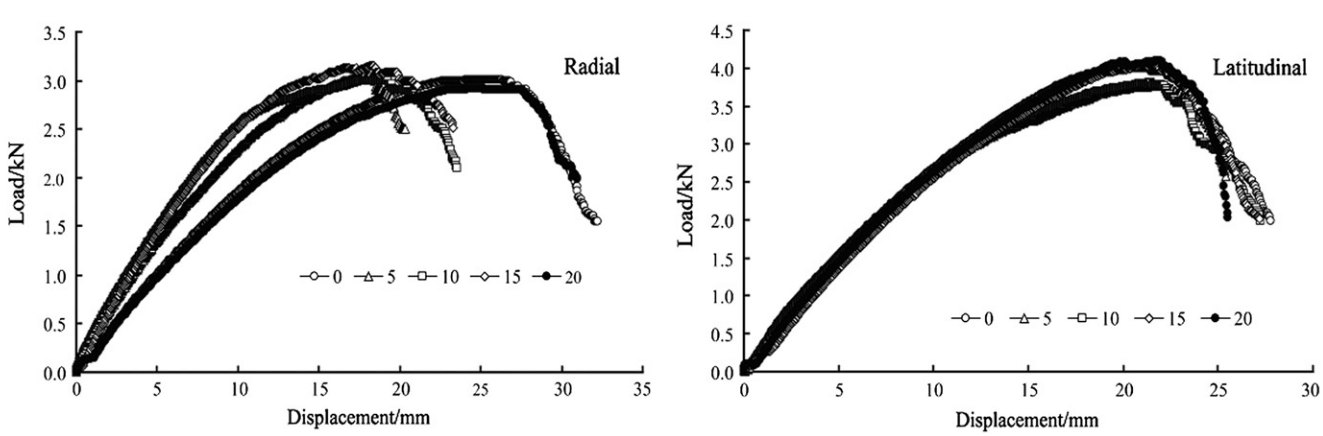

Fig. 10. The strength of woven bags versus the number of freeze–thaw cycles.

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