Evaluation of freeze-thaw behavior of geosynthetics-reinforced base courses

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ABSTRACT
Freeze-thaw (F-T) cycles are a major cause of road damages in seasonal frost regions. Different measures have been implemented to mitigate the F-T damage to roads, which include chemical stabilization (e.g., lime or cement stabilized bases) and physical stabilization (e.g., improving drainage, creating capillary barrier, replacing weak bases with gravels, etc.). Although geosynthetics have been widely applied to enhance the performance of cold regions roads, the beneficial effect of geosynthetics in improving the freeze-thaw resistance of paved and unpaved roads is not well appreciated. This paper aims to fill this research gap through a survey of the state-of-the-art research in literature and presenting the progress results of the authors' research. The survey is focused on the limited cases of field trials and model tests of geogrid, geotextile, and geocell reinforced bases under seasonable F-T cycles while the authors' research is focused on the development of custom-made model test apparatus and the use of it to investigate the F-T responses and bearing pressures of geocell-reinforced base courses after F-T cycles. Both the survey and the experimental tests indicated that geosynthetics could be effective in reducing the frost heave and thaw settlement and improving the bearing pressure of the bases.

RÉSUMÉ
Les cycles de gel-dégel (F-T) sont la principale cause de dommages aux routes dans les régions à gel saisonnier. Différentes mesures ont été mises en œuvre pour atténuer les dommages causés aux routes par les cycles F-T, notamment la stabilisation chimique (par exemple, bases stabilisées à la chaux ou au ciment) et la stabilisation physique (par exemple, amélioration du drainage, création d'une barrière capillaire, remplacement des bases faibles par des graviers, etc.) Bien que les géosynthétiques aient été largement utilisés pour améliorer la performance des routes des régions froides, leur effet bénéfique sur la résistance au gel-dégel des routes pavées et non pavent n'a pas été bien appréciée. Cet article vise à combler cette lacune en faisant le point sur les recherches les plus récentes dans la littérature et en présentant les résultats des recherché des auteurs. L'étude se concentre sur les cas limités d'essais sur le terrain et de tests sur modèle de bases renforcées par des géogrilles, des géotextiles et des géocellules dans le cadre de cycles F-T saisonniers, tandis que la recherche des auteurs se concentre sur le développement d'un appareil de test sur modèle fait sur mesure et sur son utilisation pour étudier les réponses F-T et les pressions portantes des couches de base renforcées par des géocellules après des cycles F-T. L'étude et les tests expérimentaux ont indiqué que les réponses des géocellules aux cycles F-T n'ont pas été évaluées. L'enquête et les tests expérimentaux ont indiqué que les géosynthétiques pouvaient être efficaces pour réduire le soulèvement dû au gel et le tassement dû au dégel, améliorer la pression portante des bases.

1 INTRODUCTION

Roadways, exposed to cyclic freeze and thaw in seasonal frost regions, are prone to performance distress which is mainly attributed to frost heave and thaw weakening. A literature review by Qi et al. (2006) indicates the influences of freeze-thaw (F-T) cycles on soil internal structures, which cause changes to soil's physical and mechanical properties. During the freezing process, the freezing front propagates downwards in soils, resulting in the formation of a freezing fringe, behind which pore water turns into ice (Andersland and Ladanyi, 2004). When an external water supply is available, cryogenic suction mobilizes pore water in the unfrozen zone upwards to the freezing fringe, causing the growth of ice lenses and thus densifying or loosening soil skeletons (Bing et al., 2015; Fredlund et al., 2012). The combined effects of volumetric expansion of water and growth of ice lenses contribute to frost heave and changes in the internal structure of soils, leading to surface irregularities and cracks of pavements. During the thawing process, ices in soils are thawed and the melted water is trapped in the thawing soil layers. The increase of moisture content in soils and the change of soil structure cause a substantial drop in modulus and bearing capacity of the compacted base courses (Simonsen and Isacsson, 1999).

Various engineering countermeasures have been used to improve the durability of pavements in cold regions, including the replacement of frost-susceptible soils with gravels (Li et al., 2017), the installation of the drainage system and the creation of a capillary barrier (Christopher et al., 2000), the stabilization of soils by mixing additives with soils (Hotineanu et al., 2015) and the geosynthetic reinforcement (Henry et al., 2005). Geosynthetics, which have been used to improve the performance of paved and unpaved roads for over 50 years, are also found to be effective in improving the serviceability of roads in cold regions. However, previous research mainly focuses on the geosynthetics induced reinforcement under a normal environment, while little research was performed on F-T behavior of geosynthetics-reinforced soils. To investigate the F-T performance of geosynthetics-reinforced soils, a model test apparatus capable of unidirectional running F-T tests and subsequently performing plate loading tests on geocell-reinforced soils was designed and fabricated by the authors (Huang et al., 2021).

The objective of this paper is to review previous studies on the F-T behavior of geosynthetics-reinforced soils and introduce the model test apparatus developed by the authors and some preliminary results from the model tests.

2 LITERATURE REVIEW

Three conditions are required for the development of frost heave: (1) subfreezing temperature, (2) availability of water supply, and (3) presence of frost-susceptible soils. Various types of geosynthetics have been used in practice to mitigate the effects of the latter two conditions. For example, geosynthetic clay liner (GCL) can be used as a hydraulic barrier to prevent the water from migrating into the upper layers. Hewitt and Daniel (1997) examined the F-T effects on the hydraulic conductivity of GCL and found that no significant changes in hydraulic conductivity of GCL occurred even after three freeze-thaw cycles.

Geotextiles, geogrids, and geocells, installed in the bottom or middle of base courses in road construction, are the popular types of geosynthetics in practice. Han and Yan (2013) summarized the general functions of these geosynthetics, including separation, filtration, drainage, reinforcement, barrier, and erosion protection. Among these functions, reinforcement, drainage, and barrier play an important role in mitigating the F-T-induced damage to roadways. Table 1 gives the functions of corresponding geotextiles, geogrids, and geocell.

Table 1. Geosynthetics functions related to F-T damage mitigation

Geosynthetics type	Reinforcement	Drainage	Barrier
Geotextile	√	√	√
Geogrid	√		
Geocell	√		

This section introduces the previous investigation into the F-T behavior of geosynthetics-reinforced soils with respect to field and laboratory tests.

2.1 Field Testing

A 3.2-km unpaved road was constructed in Iowa by using various improvement measures, including the construction of stone base layers, installation of drainage column, stabilization of cement or bentonite and geosynthetics reinforcement (Li et al., 2017). Falling weight deflectometer (FWD) was performed to examine the F-T effects on shear resistance and elastic moduli of different test sections. Field test data showed that the geotextile reinforcement yielded smaller reduction and greater recovery in elastic modulus of aggregate bases than corresponding unreinforced sections after one F-T cycle. This is due to the drainage of geotextiles which reduced the moisture content at the upper sublayers, resulting in long-term improvement in the serviceability of unpaved roads.

Edil et al. (2002) performed FWD tests on a 1.4 km stretch of a state highway in Wisconsin, which was constructed with foundry by-products or reinforced by geocells, geotextiles, and geogrids. The field results demonstrated that all geosynthetics-reinforced sections showed almost no sign of degradation after one F-T cycle. The use of geocell-reinforced subbases saved subbase materials by about 60% while achieving equivalent stiffness as compared with unreinforced subbases after one F-T cycle.

A comparative study was conducted on two parallel test sections of cement-treated bases and geocell-treated bases in a heavy-volume road in Alberta (Pokharel et al., 2017). It was observed that geocell-treated bases section performed better than the adjacent cement-treated bases section, particularly after 2-3 years of operation of the road.

Henry et al. (2005) performed a field study on an unpaved road in Vermont, in which test sections were reinforced by various geosynthetics, including geotextiles, geogrids, geocells, and geowraps. The geocell-reinforced sections were found to have increased resistance to F-T damages, showing approximately 50% lower pavement distress area and 300% higher CBR than the unreinforced control sections, after a 2-year period of F-T cycles.

Even though field results have demonstrated the effectiveness of geosynthetics reinforcement in improving F-T performance of roadways, these field observations are highly limited to soil conditions and environmental conditions at specific sites, leading to the difficulty in conducting parametric studies. Therefore, laboratory model tests are a necessary complement to the field tests as they can investigate the benefits of geosynthetics and the underlying mechanism under well-controlled conditions.

2.2 Laboratory Testing

2.2.1 Physical properties

Ghazavi and Roustaei (2013) investigated the effects of geotextile reinforcement on the freeze-thaw resistance of clayey soils by using unconsolidated undrained (UU) triaxial tests and computerized tomography (CT) imaging. A layer of permeable geotextile was placed in the middle of the specimens. The unreinforced and reinforced soils were subjected to up to nine F-T cycles in a closed system. After nine F-T cycles, the height change of reinforced and unreinforced soils was 1.75 mm and 1.9 mm, respectively. This indicated that the inclusion of geotextiles slightly reduced the deformation of soils subjected to F-T cycles. However, CT results present the obvious benefits of the geotextile layer in redistributing water into the lower part of soils after F-T cycles as the high permeability of the geotextile layer allowed water freely to flow down. As a result, the upper layer of reinforced soils had a lower water content, which improved its mechanical properties.

Henry and Holtz (2001) performed F-T tests on silty sands reinforced by geotextile and geocomposite under an open system to examine the benefits of such geosynthetics in mitigating frost heave as a highly permeable drainage layer. The results indicated that the use of a layer of geotextiles significantly reduced frost heave by 67% to 83%. However, when the geotextiles were moistened to 30 to 40% saturation, the geotextiles were ineffective in reducing the frost heave of fine-grained soils as a capillary barrier.

Yang et al. (2021) conducted dynamic triaxial tests on expansive geogrid-reinforced soils subjected to seven F-T cycles. The axially vertical deformation of unreinforced and reinforced soils after each F-T cycle was monitored under the confining pressure of 10 and 50 kPa. After each F-T cycle, the soils expanded under low confining pressure (10 kPa) and consolidated under high confining pressure (50 kPa). The use of three-layer geogrids significantly mitigated the development of F-T-induced axial deformation of the soils. After seven F-T cycles, the restraining effect of geogrid reinforcement reduced the soil compression by 9.3% under 50 kPa confining pressure and decreased the expansion by 54.2% under 10 kPa confining pressure, compared with the corresponding deformation of unreinforced soils.

2.2.2 Mechanical properties

Shams et al. (2019) ran a series of CBR tests on clayed sands reinforced by geotextiles located at different soil heights after two F-T cycles in a closed system. The results revealed that the presence of geotextiles closer to the failure area of soils could exert more obvious reinforcement effects on the improvement of soil strength (i.e., an optimum location was 39 mm below the soil surface in this case, which normalized depth was 0.22 with respect to the specimen height). The beneficial effects of geotextile reinforcement in improving CBR of soils were significant at the optimum location (increase by 42% in comparison to the unreinforced soils) after two F-T cycles. However, the reinforcement effect would decrease with the increase of the distance between the geotextile location and the soil failure area. The improvement in F-T resistance of reinforced soils was negligible when the geotextile layer was 78 mm below the soil surface.

The benefits of the application of geotextiles were also confirmed by Ghazavi and Roustae (2013) through a series of UU triaxial tests. The failure strength of geotextile-reinforced soils was reduced by 7% to 14% after nine F-T cycles, compared with the substantial drop by 14% to 43% in unreinforced soils. Meanwhile, the reduction in cohesion was smaller in the geotextile-reinforced soils than in the unreinforced soils: i.e., an F-T induced decrease of 15.6% and 72.3% for the former and the latter, respectively.

3 MODEL TESTS ON GEOCELL-REINFORCED SOILS

The previous laboratory related to F-T tests and mechanical loading almost involved element-scale specimens with heights ranging from 100 to 150 mm and diameters ranging from 50 to 100 mm. However, larger scale model tests pertaining to F-T cycles are rarely reported. This is possibly due to a lack of proper apparatus of this scale that can perform F-T tests and plate loading tests. Therefore, a new model-scale apparatus was designed and fabricated by Huang et al. (2021) to investigate the freeze-thaw behavior of geocell-reinforced soils. This section is to introduce the apparatus setup and to present some preliminary testing results.

3.1 Custom-made model test apparatus

The model test apparatus consists of a freeze-thaw component, a plate loading component and a rail connecting component. A detailed description of this apparatus was introduced by Huang et al. (2021). The freeze-thaw component includes an aluminum box with the dimension of 750 mm $\times$ 750 mm, a square cooling plate with the width of 745 mm, commercial insulation layers and a chiller connecting the cooling plate. During the freeze-thaw test, the cooling plate, placed on the surface of compacted soils, can cool or heat soils by adjusting the coolant temperature in a chiller. To achieve one-dimensional top-down freeze and thaw in soils, a thermal barrier around soils is necessary to prevent soils from absorbing ambient heat in the freezing process. To achieve this condition at room temperature, impractically thick insulation layers are required. Therefore, a thermal sink is created using aluminum walls, which are connected to four aluminum angles tied to the cooling plate in the freezing process. In the thawing process, these aluminum angles are removed to prevent soils from absorbing excessive heat. As a result, the one-dimensional freeze and thaw can be imposed on soils. After the predefined F-T cycles, the insulation forms and cooling plate are removed, and the plate loading tests proceed. The static loading system has a 150-mm diameter loading plate manually driven by a hydraulic cylinder with a maximum static load of 109 kN.

3.2 Preliminary Results

3.2.1 Test materials and instrumentation

Materials

In this study, the base course materials were a mixture of 95% sand and 5% kaolin. The sands were classified as poorly graded sands (SP) according to the Unified Soil Classification System (USCS), which specific gravity was 2.70. The kaolin was commercial EPK kaolin manufactured by Edgar Minerals®, which specific gravity was 2.65. The sand-kaolin mixtures were classified as poorly graded sand with clay (SP-SC), which had a mean particle size (d_{50}) of 0.674 mm with the coefficient of uniformity and curvature of 5.7 and 1.1, respectively. Based on the standard Proctor compaction test (ASTM D698), the maximum dry density and optimum moisture content of the sand-kaolin mixtures were determined as 1970 kg/m^3 and 11.7%, respectively. Geocells used in this study were PRS® novel-polymetric alloy (NPA) Type-C geocells having a tensile strength of 19 kN/m and the coefficient of soil-geocell friction efficiency of 0.95. The 150 mm high geocell walls were perforated. The opening dimension of a single geocell was 245 mm $\times$ 210 mm when it was unfolded.

Instrumentation

Four model tests were performed to investigate the freeze-thaw behavior of geocell-reinforced soils. All soil specimens measured 170 mm in thickness and 750 mm in width and length. The 170 mm thick base underlaid by a rigid box bottom was used to simulate an active layer over permafrost. Specifically, the subgrade was assumed to be perennially frozen where the base layer experienced seasonal F-T cycles. The soils in the model tests were compacted to the dry density of 1970 kg/m^3 with an optimum water content of 11.7%. Four lifts, each 50 mm for the first three layers and 20 mm for the fourth layer, were carried out to compact the soil. After the soil compaction for the first three layers (50 mm, 100 mm and 150 mm height above the bottom), T-type thermocouples were laid out on the finished layer surface to monitor soil temperature evolution, as plotted in Figure 1. T-type thermocouples were also embedded in the box wall, box bottom and the cooling plate.

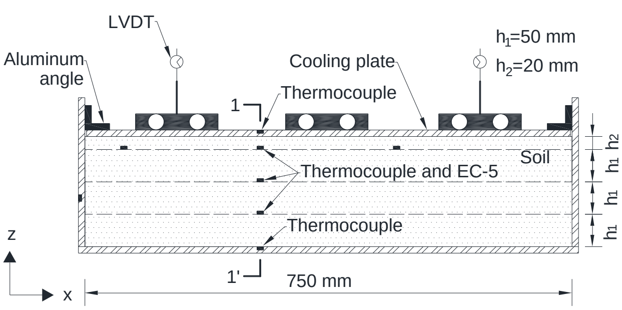
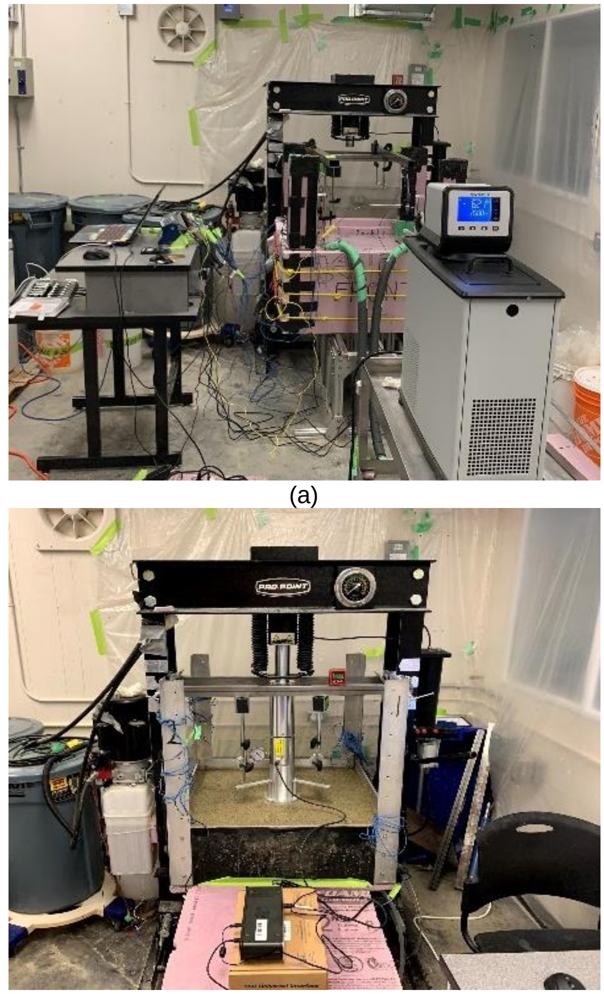


Figure 1. Cross-section instrumentation

Freeze-thaw tests on bases were conducted after the soil compaction. Figure 2(a) illustrates the operation of the freeze-thaw test on soils in the model apparatus. The cooling plate was placed on the surface of sands. The box and cooing plate were then wrapped by the insulation foams. In the freezing process, the chiller temperature was set as -20°C, and the cooling plate was cooled by the coolants circulating from a chiller. The soils were gradually frozen from the top to the bottom by the cooling plate. When the temperature of the box bottom reached -5°C, the freeze was terminated. Immediately after that, thawing process commenced by setting the chiller temperature at 20°C. The cooling plate heated soils from the top to the bottom. When the box bottom temperature reached 15°C, the thawing process was finished. This completed one freeze-thaw cycle. Throughout the freeze-thaw cycles, National Instruments® data logger was used to record the data of T-type thermocouples. Three LVDTs with resolution of 0.01 mm were placed at the tips of screw column on the cooling plate to monitor the frost heave and thaw settlement of soil surface [see in Figure 2(a)]. The readings of thermocouples and LVDTs were recorded every 30 minutes.



(b)

Figure 2. Model test operation of: (a) freeze-thaw test and (b) plate loading test

Plate loading tests were conducted right after freeze-thaw tests. Insulation foams were removed, and the box was moved to the loading frame through the rails. Figure 2(b) shows the operation of the plate loading test on soils in the model apparatus. The circular loading plate connected with the load cell was placed on the center of the soil surface. The piston of the hydraulic cylinder was manually driven downwards to connect the load cell. The pressure transducer was mounted on the load cell and it was monitored by the data logger PASCO® 550 Universal Interface. Three dial gauges spacing 120º were placed on the extensions of the load plate to measure the plate displacement. Incremental loads of 62 kPa were applied by operating the handle of the pump. After each increment, the load was maintained for five minutes before the plate displacement was recorded. The incremental loads were applied until the soils reached failure (e.g., plunging failure or excessive movement equal to 10% plate diameter), and then it was unloaded incrementally to zero. The plate loading test was completed. The precision of the pressure transducer and dial gauges was 1 kPa and 0.001 in (about 0.025 mm), respectively.

3.2.2 Preliminary results

The preliminary results from the model tests are discussed in this section. The results include soil temperature evolutions, vertical movement of soil surface, and plate loading test results.

Temperature evolution

Figure 3 depicts the time-dependent change of soil temperature in the unreinforced and reinforced soils during five freeze-thaw cycles. The temperatures were the readings of T-type thermocouples embedded in the cooling plate, soils and box bottom along section 1-1´ in Figure 1. The temperature of ambient air was also monitored and recorded.

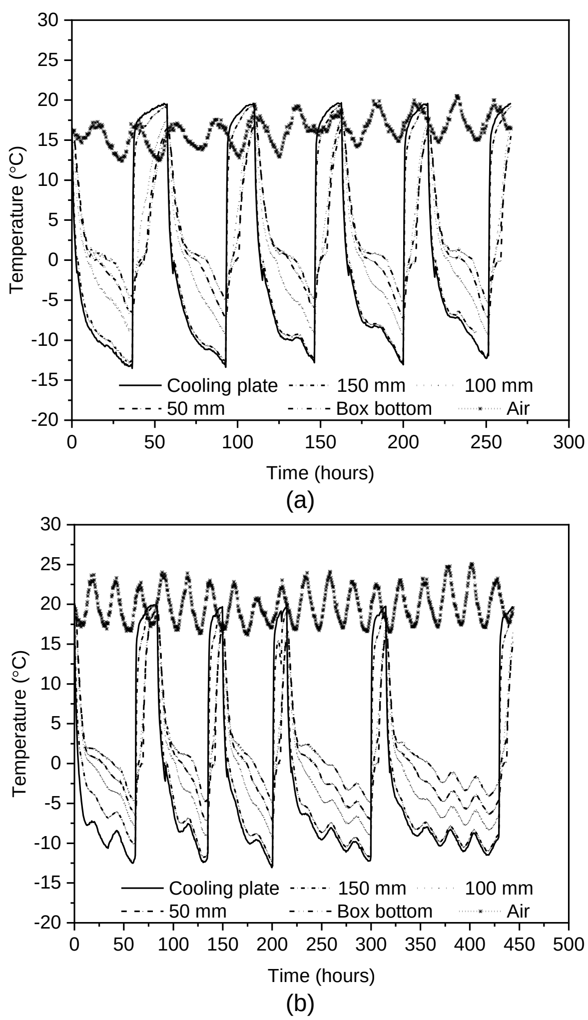


Figure 3. Temperature evolution during five freeze-thaw cycles in: (a) unreinforced soils and (b) reinforced soils

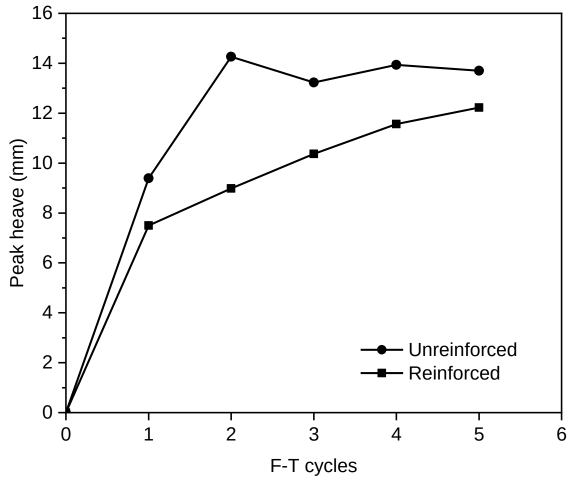
Figure 3 shows that unidirectional freezing progressed downwards in soils as the temperature decreased from the soil surface (cooling pate) to the soil bottom (box bottom). In the freezing process, soil temperature linearly decreased until reached the transient equilibrium at the freezing point. After the pore water was frozen, the temperature continued a linear decrease until the box bottom temperature reached -5°C. Opposite to the freezing process, soil temperature in the thawing process was maintained at the thawing transient phase, with linearly increasing both below and above 0°C.

Figure 3 also shows that reinforced soils experienced a longer subfreezing process than unreinforced soils. This is because the air temperature was higher when reinforced soils were tested. It is also clearly shown that the fluctuation of air temperature resulted in variations in soil temperature during the subfreezing process. This suggests that the entire apparatus would be better placed in a tent equipped with an air conditioner to eliminate the ambient temperature fluctuations.

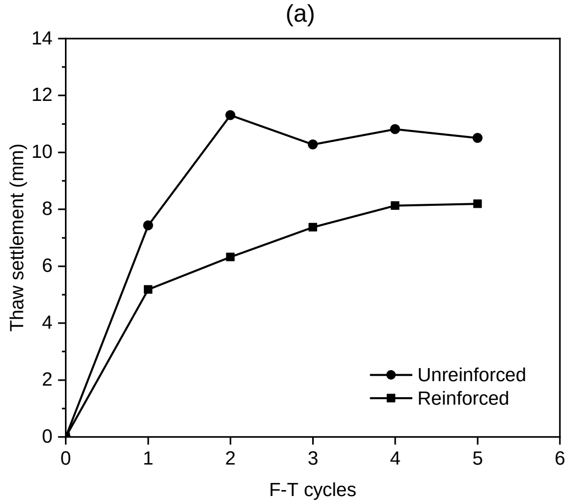
Vertical movement of soil surface

The vertical deformation of soils, including frost heave and thaw settlement, could result in the degradation of road serviceability, such as road bumps and surface cracks. Therefore, the vertical deformation of unreinforced and reinforced soils was monitored to investigate the benefits of geocells in mitigating the F-T induced deformation.

Figure 4 presents the peak heave and thaw settlement of unreinforced and reinforced soils at each F-T cycle. Figure 4(a) presents that the peak heave of unreinforced soils increased drastically at the first and second freeze-thaw cycles, followed by little change in subsequent freeze-thaw cycles. Even though peak heave of geocell-reinforced soils continuously developed as the freeze-thaw cycles increased, geocell-reinforced soils consistently experienced smaller peak heave than unreinforced soils throughout five F-T cycles. After five F-T cycles, the peak heave was reduced by about 11% due to the geocell reinforcement. Similarly, the thaw settlement of unreinforced soils reached its peak of 11.3 mm at the second F-T cycle and kept stable in the following F-T cycles, while the thaw settlement of geocell-reinforced soils continuously increased during five F-T cycles, but the geocell-reinforced soils consistently experienced the smaller thaw settlement throughout all F-T cycles, as indicated in Figure 4(b). The use of geocell decreased the thaw settlement by about 22% after five F-T cycles.



(a)



(b)

Figure 4. Vertical deformation of unreinforced and reinforced soils after each F-T cycle: (a) peak heave and (b) thaw settlement

Plate loading test results

Plate loading tests were performed on soils right after freeze-thaw tests. Figure 5 presents the pressure-displacement curves of unreinforced and reinforced soils subjected to zero and five freeze-thaw cycles. The stiffness was determined as the slope of the initial curve portion. The ultimate bearing pressure is determined as the pressure at a plunging failure (i.e., a distinct inflection point) or determined as the pressure corresponding to the largest curvature.

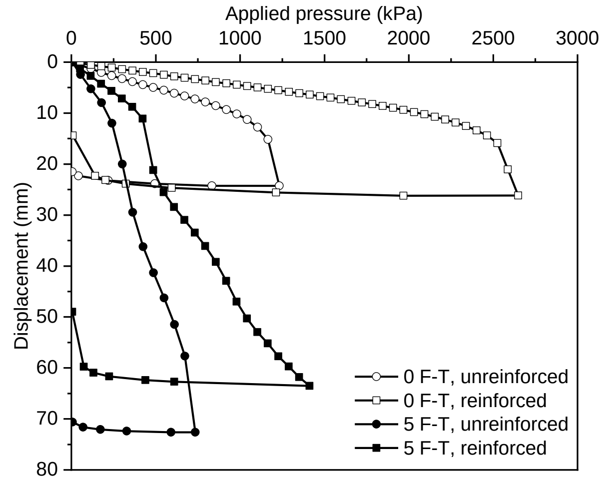


Figure 5. Pressure-displacement curves of plate loading tests on unreinforced and reinforced soils

It is evident that the effect of five freeze-thaw cycles significantly reduced the mechanical properties of both unreinforced and reinforced soils. After five freeze-thaw cycles, the stiffness of unreinforced and reinforced soils was decreased by about 75% and 81%, respectively, while the corresponding decrease of ultimate bearing pressure was 79% and 83%. However, the benefits of polymeric alloy geocell reinforcement in improving the mechanical properties of base courses were significant with and without freeze-thaw cycles. When soils were not subjected to freeze-thaw cycles, the inclusion of geocells increased the stiffness and ultimate bearing pressure by approximately 148% and 117%, respectively. Even though substantial drop in mechanical properties of reinforced soils after five freeze-thaw cycles, the benefits of geocells increased the stiffness and ultimate bearing pressure by about 90% and 73%, respectively after five freeze-thaw cycles, compared with the unreinforced soils.

4 CONCLUSIONS

This paper presents literature reviews on freeze-thaw behavior of geosynthetics-reinforced soils evaluated through field and laboratory tests. A newly designed apparatus capable of performing freeze-thaw tests and plate loading tests in introduced and corresponding preliminary results are discussed in this paper. The following conclusions are draw from this study:

(1) The effectiveness of geosynthetics in improving freeze-thaw performance has been demonstrated in field tests, but the field tests are still relatively scarce.

(2) A number of laboratory element tests were conducted to investigate the F-T effects on engineering properties of geosynthetic-reinforced soils, but these tests were restricted to an element level and hard to reflect the boundary conditions or accommodate the size of geosynthetics.

(3) A model test apparatus capable of performing freeze-thaw tests and plate loading tests was designed and fabricated by the authors. This apparatus could apply

unidirectional freeze and thaw to geosynthetics-reinforced soils.

(4) From the model tests, the use of polymeric alloy geocells could mitigate the development of frost heave and thaw settlement during F-T cycles. The geocell reinforcement reduced the frost heave and thaw settlement by about 11% and 22%, respectively.

(5) The geocell reinforcement could improve the stiffness and ultimate bearing pressure by 148% and 117% respectively after five F-T cycles.

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