Application of polymeric geocell reinforcement in pavements subject to freeze-thaw cycles

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Abstract

Extreme weather events and shifting precipitation patterns pose a significant threat to the longevity and performance of traditional pavement structures. As climate change continues to exert its influence on infrastructure, the design and maintenance of pavements face unprecedented challenges. With irregular changes in temperature, the pavement layers, including the subbase, tend to lose strength faster. With the fluctuating temperature regime, the band within which the frost depth varies is closer to the subbase and sometimes even reaches base level elevation. The current fluctuation in temperature can lead to multiple cycles of freeze-thaw within the one season thus leading to the early failure of roads and increasing the demand for maintenance.

This paper studies the stress on pavement infrastructure and the progressive loss of strength due to freeze-thaw cycles for a road embankment. This research highlights the inadequacies of conventional pavement designs in adapting to the dynamic nature of changing weather patterns, emphasizing the urgent need for innovative solutions. An innovative solution with novel polymeric alloy (NPA) geocell was used to reinforce the base course of a paved road in Sturgeon County, Alberta and instrumentation was done to obtain real time traffic load measurements and temperature variations along the embankment depth.

A geo-composite was also incorporated into the road application at Sturgeon County to act as a reference for the results of the geocell-reinforced pavement. The performance of the geocell-reinforced and geo-composite-reinforced pavements were continuously monitored through the installation of thermocouples, moisture sensors, and earth pressure cells within the basecourse and subbase of the road structures. Real time data collected through an entire freeze-thaw season highlighted the growing fluctuation in temperatures reaching the subbase leading to multiple freeze-thaw cycles within a single season. Further analysis of the data and field-test results emphasized the efficacy of NPA geocell under multiple freeze-thaw cycles. In this research, the theoretical evaluation was validated with practical data from the instrumentation on site.

The use of high strength, high modulus geocell has shown significant benefit with sustaining the necessary confinement over multiple freeze-thaw cycles. These findings enforce the need for innovative solutions, such as the use of NPA geocell-reinforcement, to combat the increasing freeze-thaw degradation.

Introduction

Pavement degradation and failure is a well-known problem in cold climatic countries like Canada. Freeze-thaw (F-T) cycles introduce weakness within the load bearing structure. Particularly, in the thawing season there is an appreciable drop in bearing capacity (Simonsen et al. (1999)[1]) demanding road bans for heavier traffic. Moreover, F-T action can lead to pavement failures eliciting poor driving conditions and requiring more frequent maintenance. The effect is amplified where there is presence of water within the top 3m of the surface where frost treatment is recommended (Christopher et al. (2006)[2]). With climate change being a looming concern, questions arise as to how this will affect the transportation industry. While bearing capacity loss and road bans typically have occurred in the thawing season at the end of winter, with climate change, freeze-thaw is expected to occur over a larger period throughout the winter months. There are established theoretical models for calculation of frost depth such as those presented in the Canadian Foundation Engineering Manual (5th edition)[3] or the simplified model by Soliman et al. (2008)[4]. Both of these models are heavily dependent on the degree days for which the air temperature remains under zero degrees Celsius (°C) and the long-term air temperature average. While these methods have produced reliable results, with the current sharp temperature variances caused by climate change, these methods need to be re-evaluated. With a reduction in the number of days that the air temperature remains below zero, the seasonal frost depth is expected to get closer to the subbase. The combined effect of increasing air temperatures and sharp temperature variances is expected to create multiple thaw cycles within the pavement base and subbase elevations, resulting in faster pavement degradation. In an analysis of the effects of climate change with regards to road infrastructure, Ede and Oshiga (2014)[5] note how higher temperatures will result in fewer freeze-thaw cycles. While this may be true for certain regions, the opposite effect is theorized for northern climatic regions. Nemry and Demirel (2012)[6] support this through their analysis of the effects of climate change on transportation infrastructure, noting that there is a possibility of transitional increases in multiple freeze thaw cycles. In the past, pavements in northern climactic regions would remain frozen during the winter season, while areas falling within the so called “free/no-freeze zone” were subjected to multiple freeze thaw cycles each year (Jackson and Puccinelli (2006)[7]). Chinowsky and Arndt (2012)[8] state that Canadian roads and other areas experiencing northern climates may face greater infrastructure degradation owing to increased freeze thaw cycles. Bizjak et al. (2014)[9] explains how, because of climate change, repeated periods during the winter season when the pavement surfaces are thawing will become the norm. Thin and unsealed pavements will need upgrading if reliable high bearing capacity is to be provided throughout the winter as the current expectation of seasonally frozen pavement structures will not be achieved.

With these temperature variations, new transportation infrastructure design techniques are needed to combat the expected increases in freeze thaw degradation in northern climactic regions. There have been various attempts on the performance and life improvement of roads in cold regions using soil reinforcement techniques (Helstrom et al. (2006)[10]; Li et al. (2017)[11]). This paper focusses on the effects of geocells in mitigating these problems. The three-dimensional confinement provided by geocell has proven to improve layer stiffness and permanent deformation immensely (Pokharel et al. (2010)[12]). Leshchinsky et al. (2013)[13] highlighted the importance of the modulus of geocell in improving layer stiffness. In a past experimental study, Pokharel et al. (2017)[14] used Novel Polymeric Alloy (NPA) geocell with a high dynamic modulus and high tensile strength in comparison with Cement Treated Base (CBT) within a road subjected to cycles of freeze and thaw. After two F-T cycles it was observed that the CBT section was experiencing severe pavement distresses while the NPA geocell reinforced section did not have any visible rutting or distresses and the surface was smooth for driving. The advantage of reinforcing soil subject to F-T cycles with the three-dimensional confinement of high strength geocell was further investigated by Huang et al. (2022)[15]. The lab-based research concluded that the use of polymeric alloy geocells could mitigate the development of frost heave and thaw settlement during F-T cycles by approximately 11% and 22%, respectively. After five F-T cycles, the geocell reinforcement could also improve the stiffness and ultimate bearing capacity by 148% and 117%, respectively. Further investigation by Liu et al. (2023)[16] into the mechanism of improvement showed that the combined use of geocell and geotextile positively affected the mechanical and hydraulic characteristics of pavement subject to strains developed through F-T cycles. The presence of geosynthetics redirected water away from the road section, thus, reducing the risk of damage from ice-lensing of trapped water. Having a stiffer base-course reduced the pressure on the subbase, thus, minimizing the effect of F-T from the subbase. Also, the additional stiffness within the base-course reduced the degradation parameters. Huang et al. (2023)[17] led a field experimental investigation continuing from the previous laboratory-based tests to investigate the performance of geosynthetic stabilized bases in flexible pavement. From the preliminary results, geocell reinforcement was found to be effective in improving the performance of the flexible pavement.

This paper expands on the in-field research project conducted by Huang et al. (2023)[17], whereby Novel Polymeric Alloy (NPA) geocells were installed in a newly constructed Asphalt Concrete Pavement (ACP) road within Sturgeon County, Alberta, Canada. The goal of this paper is to provide data to support the expectations of increased freeze-thaw cycles within Canada and other northern climatic regions through real-time collected temperature data. Additionally, this paper aims to highlight the effectiveness of pavement reinforcement technologies, specifically geocells, in mitigating this expected increase in freeze-thaw degradation.

Project Overview

A road rehabilitation project along a 1.3km stretch of Township 544 and Range Road 260 near ProNorth Industrial Park in Sturgeon County, Alberta, Canada (Figure 1) was in the initial stages of construction. The expectation was to have the existing, failed paved road rehabilitated to an asphalt paved, two-lane highway. The history of roads in the surrounding area indicated there had been frequent maintenance even where the traffic volume was low indicating that there could be an underlying issue with the native subbase of the area. During construction, saturated subbase and unsuitable materials, not captured in borehole data, were encountered necessitating a required depth of excavation that would cause right of way (ROW) concerns and excess quantities. There was an expected presence of groundwater within 1m from the existing surface along with a regional frost depth varying from 1.8m to 2.7m from existing surface. For a 0.6m conventional road embankment thickness, these factors increase the risk of pavement degradation from freeze-thaw.

Figure 1. Project location

Methodology

The constructed road top width was 9m (4.5m for each lane) with a 4(horizontal):1(vertical) side slope. The initial subbase requirement called for the scarification, conditioning and recompacting of the top 300mm of the natural subbase followed by a proof roll pass with a loaded water truck. While properly designed NPA geocell application can eliminate subbase preparation (Shenouda et al. (2021)[18]; Chatterjee et al. (2022)[19]; Chatterjee et al. (2023)[20]), to make a fair comparison, the subbase preparation requirements for the geocomposite and geocell-reinforced sections followed the initial requirements as set out by the design engineer. The subbase condition remained soft in localized areas even following subbase preparation (Figures 2 and 3), necessitating some excavation and backfill. Construction ran from June to November of 2022.

Figure 2: Subbase condition before preparation

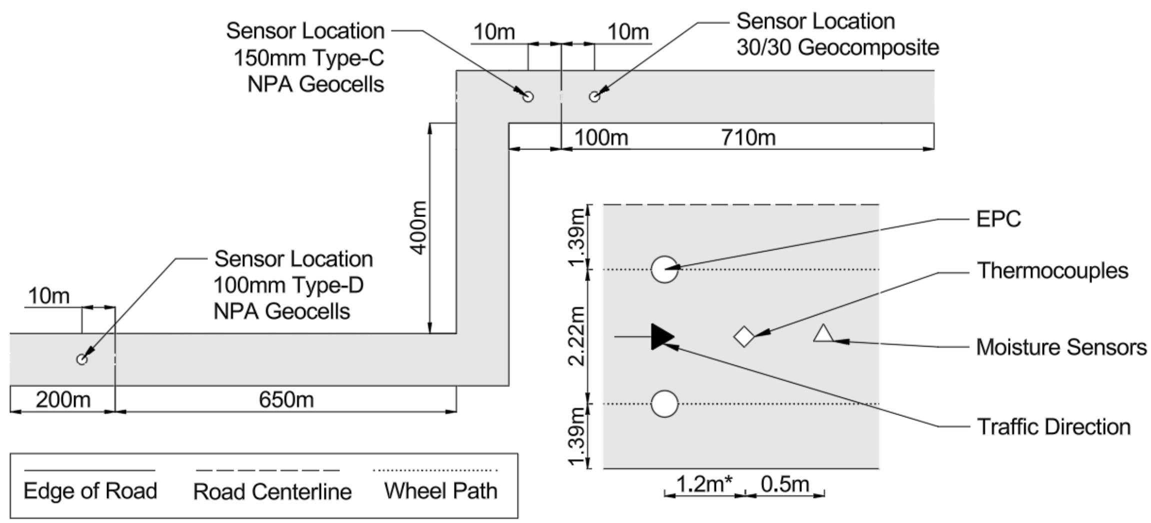
Figure 3: Rut depth before subbase preparation

This field assessment comprised of the installation of three types of sensors: moisture sensors, thermocouples, and earth pressure cells (EPCs). The purpose of the earth pressure cells was to record the effective pressure reaching the subbase so that the reinforcement within each of the test sections could be compared. It is expected that as the structure deteriorates from freeze-thaw related damages, the stress transferred to the subbase will increase. The EPCs were installed in the eastbound lane at the subbase basecourse interface. Two EPCs were installed in each section: one 2MPa cell and one 500kPa cell. The EPCs were installed directly below the expected wheel path. To assess the extent, frequency, and duration of the freeze-thaw cycles, thermocouples were installed at various depths in both the subbase and basecourse providing accurate, real-time temperature profiles. Moisture sensors were also installed at varying depths to determine the correlation between the extent of freeze-thaw degradation and soil gravimetric moisture content. The sensor design was planned for long-term data collection. A singular data acquisition system was implemented for remote, continuous data collection. An in-depth explanation of the sensor and data collection system instrumentation and the installation has been previously presented by Huang et al. (2023)[17]. In conjunction with the continuous data collection, a field-testing plan, developed by Huang et al. (2023)[17], was implemented. Notable field tests include plate loading tests and trafficking tests which have been and will continue to be performed after the final thawing period of each winter season. Currently, the field test has been completed in 2022 following construction of the road (before the first freeze-thaw cycle) and in spring of 2023 following the final thawing period of the first winter season.

Materials and Design

It was expected that, with the use of NPA geocells, owing to its high strength material properties, the strength degradation due to freeze-thaw was largely avoidable. Thus, along with a design solution utilizing this type of geocell, a long-term full-scale study (undergoing several freeze-thaw cycles) was proposed for the road rehabilitation project at Sturgeon County. For the study, three separate test sections were implemented. A biaxial composite geogrid (30/30) section was used as a reference to scale the advantages of using geocells. Properties of these materials are presented in Tables 1 and 2. As opposed to a conventional road section, the geocomposite-reinforced design was chosen to make the comparison more realistic in terms of weak sub-grade application. Along with the reference section, two test sections were constructed using NPA geocell reinforcement – 100mm Type-D and 150mm Type-C. Lengths of the test segments and locations of the sensors are presented in Figure 4.

Figure 4. Section and sensor locations



*1.2m for geocomposite and 150mm geocell; 0.5m for 100mm geocell

Table 1. Properties of Novel Polymeric Alloy geocells

Properties	Type-C	Type-D
Seam weld splitting strength, kN/m	19	22
Tensile strength, kN/m	19	22
Long-term permanent deformation at 65°C, %	3	3
Dynamic modulus at +30°C, MPa	775	800
Coefficient of soil-cell friction efficiency	0.95	0.95
Brittle temperature, °C	-70	-70
Coefficient of thermal expansion, ppm/°C	135	135
Distance between weld seams, mm	330	330
Cell dimensions, mm x mm x mm	245 x 210 x 150	245 x 210 x 100

Upon comparison of the material properties, the Type-D geocell has a higher distribution angle and tensile strength. That, combined with its shorter cell height, promotes the use of Type-D geocells over Type-C in terms of performance and material conservation. However, a major reason for the utilization of Type-C geocell over Type-D geocell is cost. Additionally, based on the subbase conditions, design parameters, and desired infill materials, Type-C NPA geocells can prove to be optimal over Type-D geocells.

The pavement was designed for approximately 2 million ESALs. All design sections consisted of Alberta Transportation and Economic Corridors (TEC) Designation 2 Class 25 Gravel Base Course (GBC) and Asphalt Concrete Pavement (ACP) Mix Type M1. This mix type was selected based on the temperature zone and design ESALs as designated by TEC. The section designs are presented in Figure 5. All measurements are displayed in millimeters. The basecourse and subbase gradation for each section is presented in Figure 6.

Table 2. Properties of 30/30 geocomposite

Properties	Geogrid	Geotextile	Geocomposite
Nominal tensile strength (md/cmd)*, kN/m	30/30	7.5/11.0	-
Elongation at nominal tensile strength (md/cmd), %	8/8	70	-
Tensile strength at 1% elongation (md/cmd), kN/m	6/6	-	-
Tensile strength at 2% elongation (md/cmd), kN/m	12/12	-	-
Tensile strength at 5% elongation (md/cmd), kN/m	24/24	-	-
Grab tensile strength (md), kN	-	-	0.55
Trapezoidal tear strength, kN	-	-	0.26
Puncture force, kN	-	1.67	-
Index puncture, kN	-	-	0.26
Aperture size (md x cmd), mm x mm	32 x 32	-	-
Displacement at static puncture, mm	-	30	-
Characteristic opening size, µm	-	90	-

*md = machine direction; cmd = cross-machine direction

Figure 5: Design Sections; (a) 100mm type-D geocells; (b) 150mm type-C geocells; (c) 30/30 geocomposite

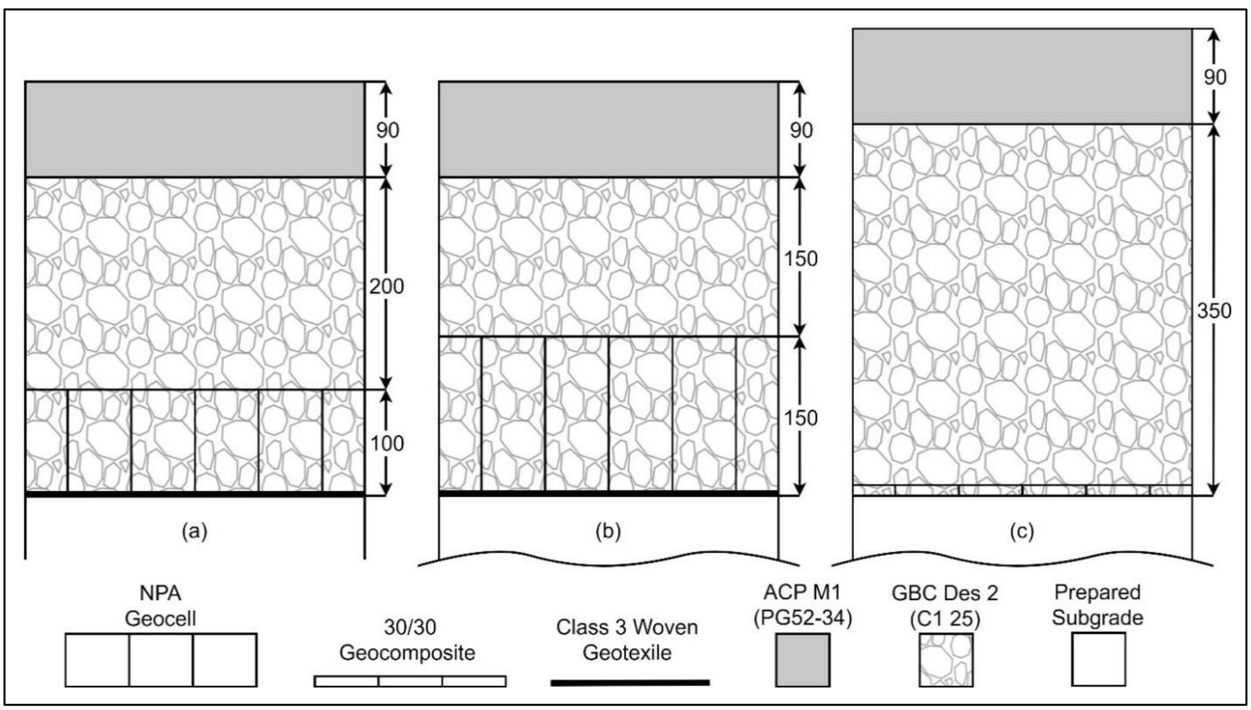
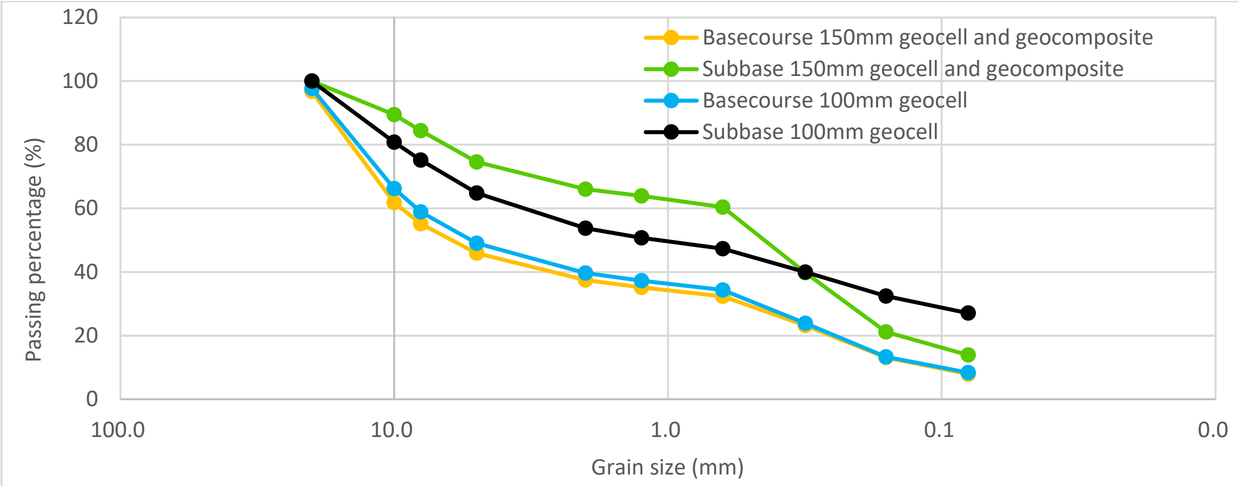


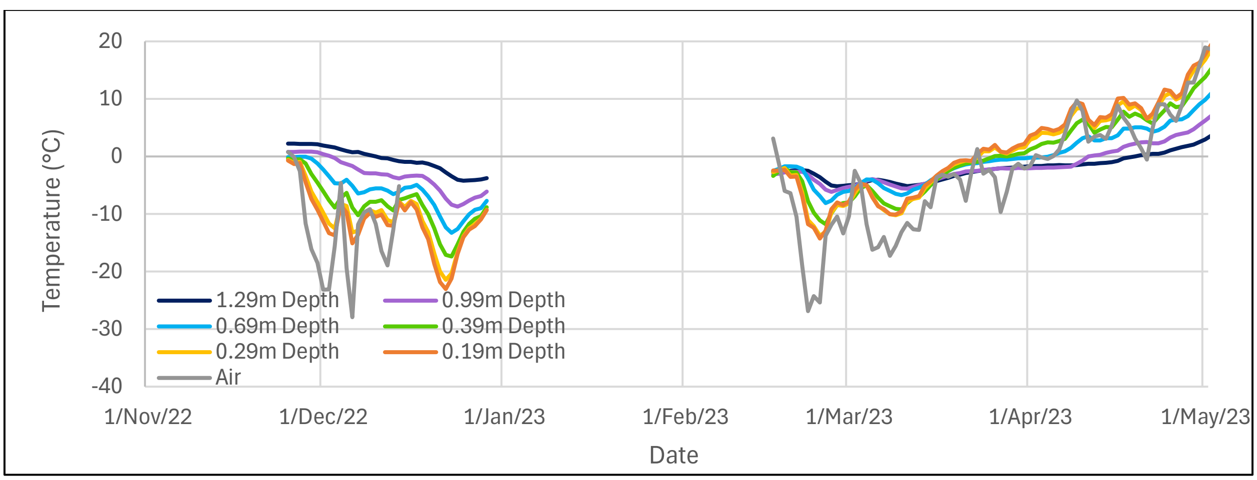
Figure 6: Basecourse and subbase gradation curves



Results

Figures 7 and 8 show the soil temperature profiles of the 150mm geocell and geocomposite sections over the winter of 2022-2023 and 2023-2024. Although thermocouples were gathering temperature data at each of the two sections, the results were comparable; therefore, only the data from the sensors located at the geocomposite-reinforced section is shown. Similarly, the gravimetric moisture content during these times is displayed in Figures 9 and 10. All sensor locations are described in terms of depth from the top of the APC surface. The sensors extend 900mm from the subbase base course interface.

Figure 7: Soil temperature profile (2022-2023 winter)



The datalogger, the most crucial component of the data acquisition systems, was undergoing maintenance through the end of December of 2022 to mid-February of 2023. As such, there is a sizable gap in this data, both for temperature and moisture (Figures 4 and 6).

Figure 8: Soil temperature profile (2023-2024 winter)

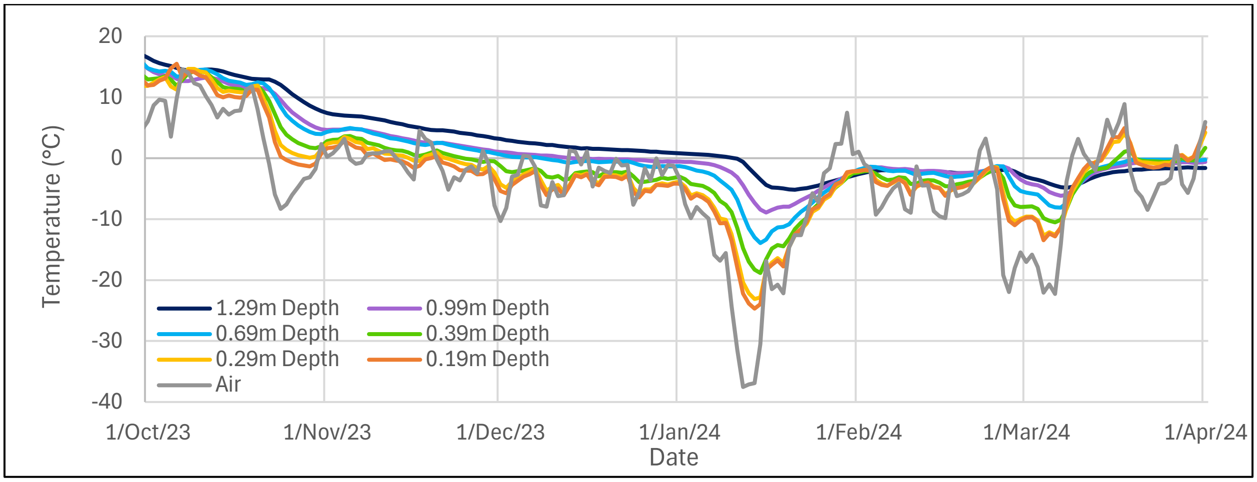


Figure 9: 150mm Geocell gravimetric moisture content profile (2022-2023 winter)

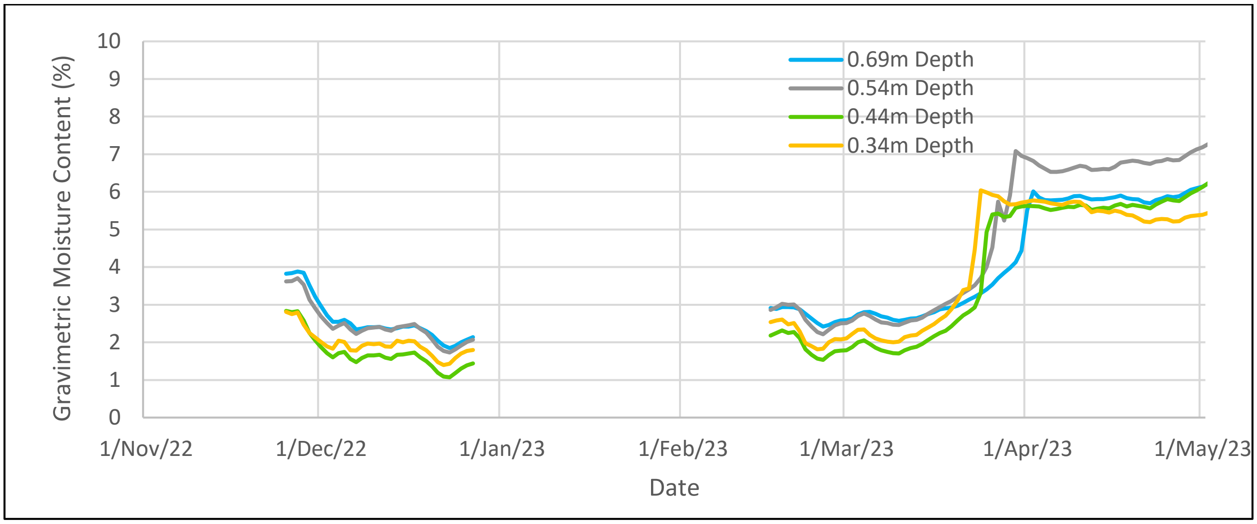
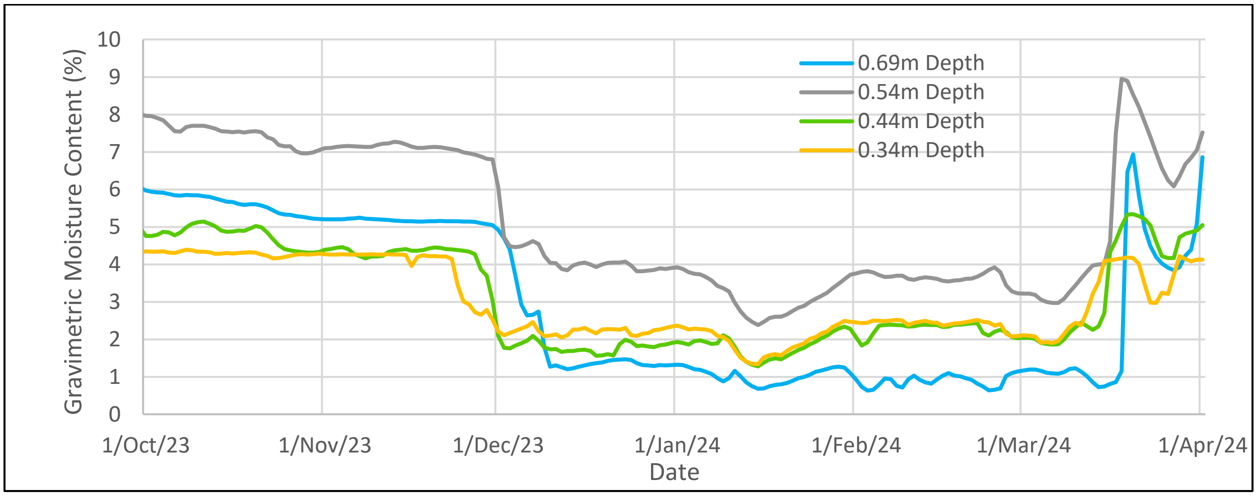


Figure 10: 150mm Geocell gravimetric moisture content profile (2023-2024 winter)



The gravimetric moisture content during the freeze and thaw cycles of both the 150mm geocell and geocomposite-reinforced sections was comparable given the lesser than usual snowfall received in and around the project location in the 2022-2023 and 2023-2024 winters.

From the plate load testing (Figure 12), the effectiveness of geocells in distributing applied pressure to the subbase was calculated in terms of distribution angle. The resulting pressure reaching the subbase based on the distribution angle is presented in Equation 1 and Figure 11, where P_0 is the applied pressure from tire, θ is the distribution angle, a is the tire width, y is the structure thickness, x is the distribution width added by the distribution angle, and P_1 is the pressure applied to the subbase. The distribution angles determined through the plate load testing during each testing period are presented in Table 3.

$$P_1 = \left(\frac{a}{2 \cdot y \cdot tan\,\theta + a}\right) P_0 \qquad (1)$$

Figure 11: Pressure profiles from distribution angle

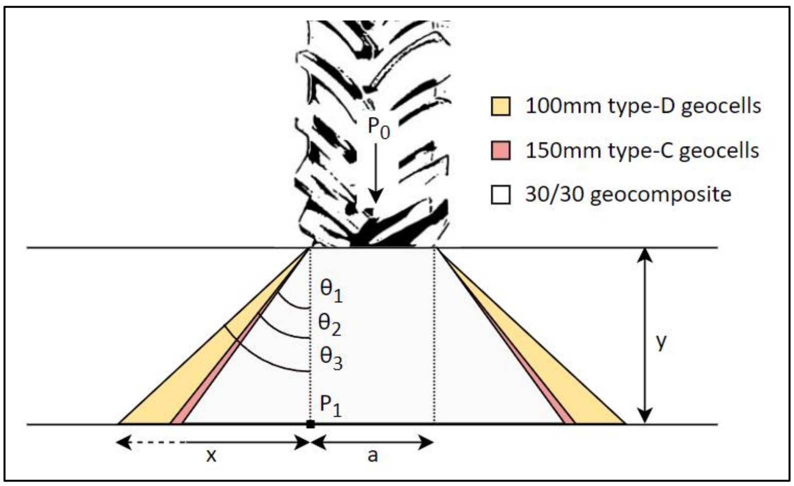


Figure 12: Plate load testing setup at Sturgeon County (May 2023)

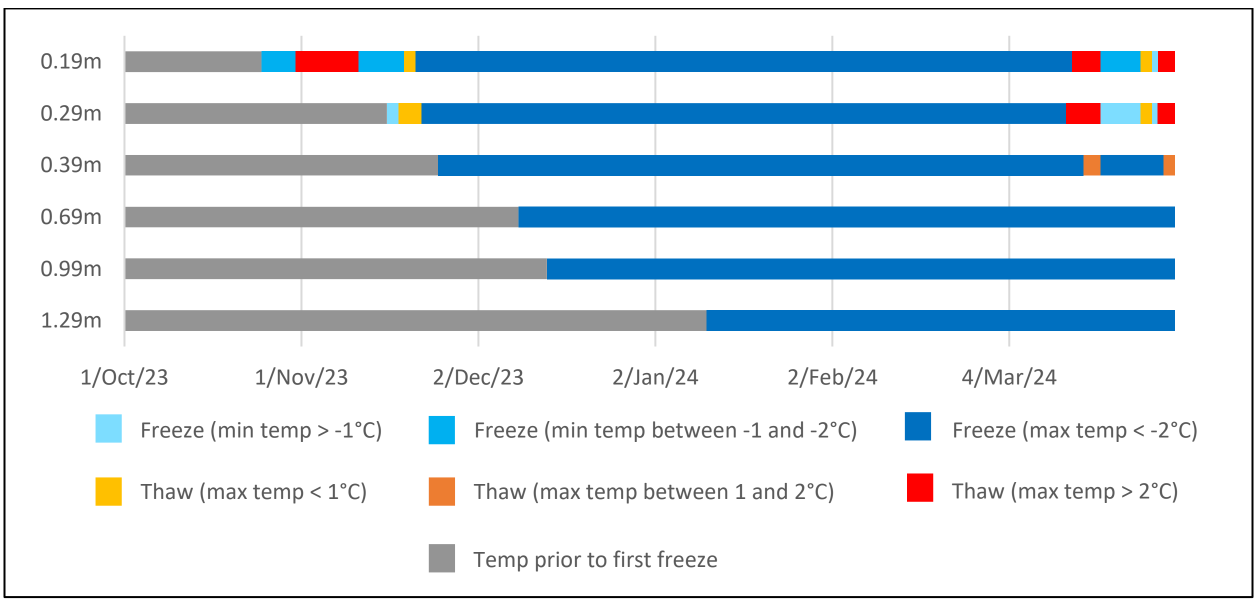
Table 3: Pressure profile from average distribution angles (Figure 9)

Section	Distribution Angle (°)	
	2022 Testing	2023 Testing
100mm type-D geocells (θ_1)	45.36	48.57
150mm type-C geocells (θ_2)	37.55	40.18
30/30 geocomposite (θ_3)	34.66	35.35

Discussion

The soil temperature profile of the winter of 2022-2023, while having some lapses in data collection, shows no apparent instance of multiple freeze thaw cycles. Once the soil temperature falls below 0°C, it does not turn positive until winter's end. Near the end of March 2023, however, it can be seen that the temperature does get within approximately 2°C of crossing that threshold. In contrast, the 2023-2024 soil profile exhibits multiple periods of freeze-thaw within the top 390mm of the road structure. In October and November of 2023, the soil at 290mm depth experienced one minor freeze-thaw cycle whereby the soil temperature fell slightly below 0°C for two days before warming to nearly 1°C. Also, during this time, the soil at 190mm depth experienced two freeze thaw cycles. In mid-March of 2024, the soils at and above 290mm depth experience two additional freeze thaw cycles prior to the final freeze-thaw cycle of the collected data. However, for one of these cycles, the temperature only fell slightly below 0°C for a single day; therefore, this cycle has been omitted from the observations. Also, during mid March of 2024, soils at 390mm depth experienced one freeze-thaw cycle prior to the final thaw of the collected data. In summary, the soils experienced, 4, 3, and 2 freeze-thaw cycles at 190, 290 and 390mm depth, respectively (Figure 13). At this time of this analysis, the collected data had only recorded up to April 1st of 2024, as such, it cannot be said if more F-T cycles had occurred past this time.

Figure 13: Freeze-thaw cycle overview (2023-2024 winter)



The results of the collected gravimetric moisture content data were lower than expected for the area, as the project location experienced less precipitation than usual during the data collection period. Future precipitation more in line with that expected, can result in more sever freeze-thaw degradation. This is because higher moisture content elicits larger ice lenses during the freezing period which results in increased frost heave and lower strength retention as the structure weakens during the thawing season.

It must be noted that the subbase in the 100mm NPA geocell-reinforced section was unable to be prepared to the same extent as the other sections. This was confirmed based on Dynamic Cone Penetrometer (DCP) testing. It was found that the average California Bearing Ratio (CBR) of the 100mm geocell section, as compared to the other sections, differed by 110% to 150%, while the 150mm geocell and geocomposite sections had very similar average CBR. However, based on seasonal influence, the subbase is expected to lose strength until reaching equilibrium, at which time all sections should be balanced. Even though the subbase strength of the 100mm geocell-reinforced section was lesser, the section is performing better based on the acquired distribution angles.

Field testing was conducted prior to and following the 2022 to 2023 winter season. From the plate load testing in 2022, it was found that the 100mm geocell section had a distribution angle that was 10.7° higher than that of the geocomposite section and the 150mm geocell section was 2.89° higher. Following winter, testing in May of 2023 revealed that, in comparison to the geocomposite section, the distribution angles were now 12.22° and 3.83° larger for the 100mm and 150mm geocell sections, respectively. Analyzing these results, it can be seen that following the one freeze-thaw cycle experienced over the 2022-2023 winter season, the performance of the 100mm and 150mm geocell sections increased by 14.2% and 35.2% as compared to the initial test results. These results are promising given the soil temperature variation over the 2023-2024 winter season. With the increased freeze-thaw cycles experienced in 2023-2024, it is expected that the performance of the geocell-reinforced sections, in comparison to the geocomposite-reinforced section, will increase even further. It must be noted that in Table 3 there is slight increase in distribution angle from 2022 to 2023. Though the exact reason behind this is yet to be understood, there can be several possible reasons. These could include migration of fines within the layer leading to higher degree of compaction or a reduced moisture content between the two years (as shown in Figures 9 and 10). This increase in distribution angle has also been reported in other literatures (Pokharel et al. (2010)[21]. Figures 14 to 17 show the road condition prior to rehabilitation, during construction, and following rehabilitation. Figure 15 shows the transition from 100-D geocell to 150-C geocell. Figure 16 shows the transition from geocomposite to geocell. The variance in layer modulus was checked separately to ensure that the changing reinforcement would not produce a stiffness jump leading to a failure prone zone.

Figure 14: Road surface along TWP 544 prior to rehabilitation

Figure 15: 100mm and 150mm Geocell installation along TWP 544

Figure 16: Basecourse fill over 150mm geocell and Combigrid sections

Figure 17. Road surface in 2023 following one winter season (100mm and 150mm geocell-reinforced sections)

Figures 17, 18, and 20 show the condition of the road after the first and second winter seasons with NPA geocell, while Figure 19 shows the geocomposite section following two winter seasons. Based on the images it can be clearly stated that the notable change in moisture content and increased number of F-T cycles did not lead to pavement degradation. From a thermal crack perspective, it can be stated that both reinforcements were tolerant to the climatic degradation. However, considering the improved distribution angle and annual change in distribution angle, it can be commented that the geocomposite section is more susceptible to shorter design life. It is expected that, as the study progresses, and freeze - thaw degradation occurs over multiple winter seasons, visible indicators may present themselves, giving further insights into the effectiveness of these reinforcement technologies. The current condition of the road, following the winter of 2023-2024 is presented below in Figures 18-20.

Figure 18: Current road condition at 150mm geocell section

Figure 19: Current road condition at geocomposite section

Figure 20: Current road condition at 100mm geocell section

Conclusion

Expanding on the in-field research project conducted by Huang et al. (2023)[17], this paper provides data to support the expectations of increased freeze-thaw cycles within Canada and other northern climatic regions while highlighting the effectiveness of using reinforcement in mitigating this expected increase in freeze-thaw degradation. The data collected from the research study location in Sturgeon County, Alberta, Canada, showed that while the 2022-2023 winter season had only experienced a single freeze thaw cycle, the winter season of 2023 to 2024 experienced at least 4 cycles. Although the gravimetric moisture content experienced in the geocomposite-reinforced and 150mm geocell-reinforced section over the testing period was lower than anticipated due to lesser precipitation, future testing is expected to show greater degradation. This is due to the amplification of freeze thaw damages with higher moisture contents. Even still, the NPA geocell-reinforced sections have produced larger distribution angles in comparison with the geocomposite-reinforced section. The Type-D NPA geocell, having 15.8% higher tensile strength and about 3.2% higher modulus than the Type-C NPA geocell, produced a distribution angle that was approximately 20% larger, on a year-by-year comparison, than the Type-C geocell. In contrast, the geocomposite had between 30% and 37% less distribution angle as compared those of the Type-D geocell-reinforced section in 2022 and 2023. This highlights the importance of the three-dimensional geometry and the material properties of the reinforcing material. Through the seasonal cycles, while the distribution of the NPA-geocell increased by approximately 7%, the gain in the geocomposite-reinforced section was barely 1.9%. This shows the higher resilience of NPA geocell structure even when subjected to changing climatic conditions. So far, based on the confinement mechanism for geocell reinforcement and the variance in distribution angle observed between 2023-2024, the NPA-geocell is out-performing the reinforcing effect of the geocomposite. However, further testing and pavement monitoring is proceeding under the continuation of current research work to confirm if this trend will continue over long-term exposure to freeze-thaw cycles. As this study progresses over multiple winter seasons, more concrete findings can be presented to further the development of resilient pavement designs to combat climatic degradations.

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