Freeze-Thaw Performance of Geosynthetics-Reinforced Pavements: Field Tests After Four-Year Operation

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Abstract

Freeze–thaw (F–T) cycles are a major cause of pavement deterioration in cold regions, as repeated seasonal freezing and thawing weaken foundation support and reduce long-term performance. The increasing frequency of extreme weather events and irregular temperature fluctuations further intensify freeze–thaw activity, accelerating pavement degradation and increasing maintenance demands. Although geosynthetic reinforcement systems are increasingly applied in practice, comparative long-term field evidence on their load distribution behavior remains limited. This study presents a four-year field evaluation in Alberta, Canada, investigating pavement test sections reinforced with two types of novel polymeric alloy (NPA) geocell (Types C and D) and geogrid–geotextile composite systems. Annual plate load tests were conducted from 2022 through summer 2025, and the stress distribution angle was evaluated. Results show that the higher strength geocell (Type D) section exhibited the most stable load-spreading response, followed by Type C geocell section, while the geogrid composite section remained comparatively lower with minimal change across years. Overall, the findings provide multi-year field evidence supporting geocell reinforcement in load bearing applications as a practical approach for improving pavement performance under seasonal freeze–thaw exposure.

Introduction

Freeze–thaw (F–T) cycles are a major contributor to pavement deterioration in cold regions, where seasonal temperature fluctuations induce repeated freezing and thawing of moisture within pavement layers. In pavements underlain by frost-susceptible soils, these processes can lead to frost heave during freezing and significant strength loss during thawing, ultimately reducing structural capacity and accelerating surface distress. The increasing variability in climate conditions, including more frequent temperature fluctuations around the freezing point, further intensifies F–T activity and poses additional challenges for maintaining pavement performance and serviceability. . During freezing, water migration and ice lens formation in frost-susceptible soils alter the soil's physical properties and internal structure, resulting in changes to void ratio, particle bonding, and soil fabric(Qi et al. (2006)[1], Viklander (1998)[2]).

Various approaches have been investigated to mitigate freeze–thaw damage and enhance roadway performance in cold regions, including the use of chemical stabilizers, replacement of frost-susceptible soils with granular materials, installation of drainage or capillary barrier systems, and reinforcement of base layers using geosynthetics such as geocells, geogrids, and geotextile composites (Christopher et al. (2000)[3], Henry and Holtz (2001)[4], Pokharel et al. (2016)[5]). Among these, geocells provide three-dimensional confinement to aggregate layers, enhancing load distribution and reducing stress transmission to the subgrade, while geogrid–geotextile composites offer planar reinforcement and filtration benefits. Previous studies have demonstrated the effectiveness of geosynthetics in improving bearing capacity, reducing deformation, and enhancing pavement durability. However, most of these investigations have been limited to laboratory-scale experiments or short-term field observations, often lacking detailed mechanistic evaluation of load transfer behavior under long-term F–T exposure.

Recent full-scale field studies have begun to address this gap by incorporating instrumentation to monitor temperature, moisture, and stress responses within pavement systems. These studies have shown that F–T cycles significantly influence stress distribution and load transfer characteristics, particularly during thaw periods when subgrade weakening occurs. Nevertheless, many existing field investigations rely on indirect performance indicators such as surface distress, deflection measurements, or limited load testing, with relatively little emphasis on quantifying the evolution of stress distribution mechanisms over time.

A critical aspect that remains insufficiently explored is how different reinforcement systems influence the distribution of stresses within pavement layers under repeated loading and seasonal degradation. In particular, the concept of stress distribution angle (θ) provides a direct measure of load-spreading behavior, offering a more mechanistic understanding of how reinforcement systems modify stress transfer paths. Unlike conventional indicators such as load transfer ratio (LTR), which quantify stress transmission at discrete points, the distribution angle captures the geometric spreading of stresses and can provide deeper insight into structural performance.

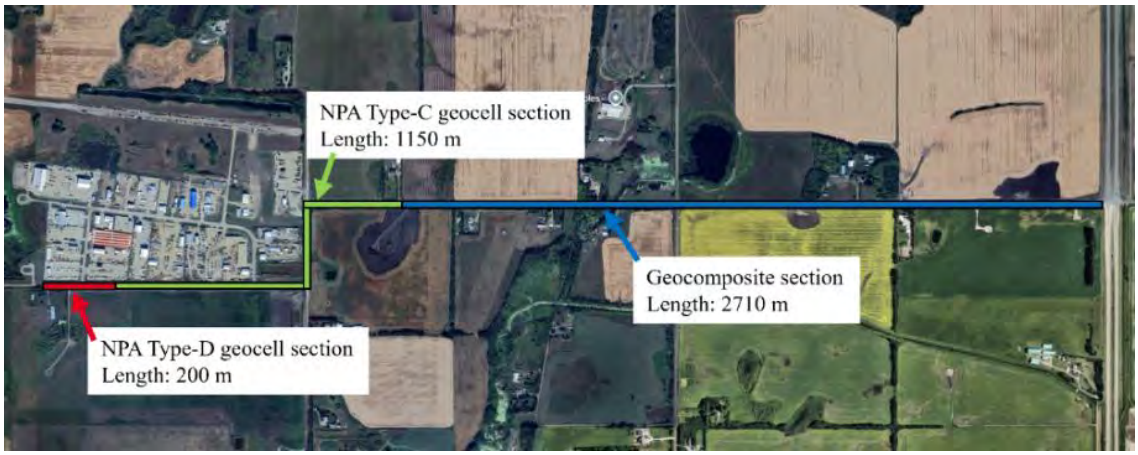
To address this gap, this study presents a four-year field evaluation of geosynthetics-reinforced pavement sections in Alberta, Canada, incorporating annual plate load tests conducted from 2022 to 2025. The investigated sections include two types of novel polymeric alloy (NPA) geocells (Types C and D) and a geogrid–geotextile composite system. The primary objective is to examine the evolution of load transfer behavior using the stress distribution angle derived from field measurements and to compare the response of different reinforcement systems under repeated freeze–thaw cycles.
The analysis is based on multi-year full-scale field data and focuses on assessing long-term performance under realistic traffic and environmental conditions. By comparing three-dimensional geocell systems with planar geocomposite reinforcement, the study provides insight into differences in load distribution characteristics and contributes to a better understanding of load transfer behavior in reinforced pavements.

Field Program

Project Site Description

The field study was conducted on a full-scale test section located in Sturgeon County, Alberta, Canada, a region characterized by a northern continental climate with pronounced seasonal temperature variations. The area experiences long, cold winters with temperatures frequently dropping below −30 °C and warm summers, resulting in seasonal freeze–thaw cycles that affect both the pavement structure and the underlying frost-susceptible subgrade. Precipitation is concentrated during late spring and early summer, contributing to increased moisture availability during the thaw period. These environmental conditions make the site highly suitable for evaluating pavement performance under combined thermal and moisture-induced deterioration. The test road consists of a reconstructed flexible pavement section designed to support heavy industrial traffic. The subgrade soil is predominantly fine-grained silty clay with moderate plasticity, known to be frost-susceptible and prone to strength loss during thawing. To investigate the influence of reinforcement systems, three pavement sections were constructed using different geosynthetic configurations: Type-D geocell, Type-C geocell, and a geogrid–geotextile composite. The site has been monitored since 2022, providing a unique opportunity to assess long-term structural response under real traffic loading and environmental exposure. This setup follows the framework established in prior research on this site by Huang et al. (2025)[6]. Test sections are shown in Figure 1.

Figure 1. Location of the test sections in Sturgeon County, Alberta, Canada (Huang et al., 2025).



Test Sections

The reconstructed pavement includes three full-scale test sections incorporating different geosynthetic reinforcement systems: (i) Type-D geocell (100 mm height), (ii) Type-C geocell (150 mm height), and (iii) a geogrid–geotextile composite (combigrid). Table 1 and 2 summarize the basic properties of geocells and geocomposites, respectively (Huang (2025)[6]).

All pavement sections consisted of a 90 mm asphalt concrete (ACP) layer, a 300 mm subbase, and a 1000 mm pit run backfill over the native subgrade. The reinforced sections differed in the base layer configuration. The Type-D and Type-C geocell sections incorporated 300 mm base courses, reinforced with 100 mm and 150 mm high geocells, respectively, while the geocomposite section consisted of a 350 mm base course reinforced with a geogrid–geotextile composite. The geosynthetic reinforcement was installed at the base–subbase interface. . Although an unreinforced control section was initially considered during the project planning stage, it was not constructed because of concerns regarding premature failure under heavy industrial traffic and the operational requirement to keep the roadway open. Consequently, this study compares the long-term field performance of three geosynthetic-reinforced pavement sections constructed under identical pavement configurations, where the reinforcement type is the primary experimental variable (Huang (2025)[6]).

The geocell systems provide three-dimensional confinement to the base materials, enhancing load distribution and limiting lateral deformation. In contrast, the combigrid system offers planar reinforcement through tensile interaction and separation. The use of consistent materials and construction procedures across the sections allows direct comparison of the influence of reinforcement type on load transfer behavior under repeated loading and environmental exposure (Ikra (2026)[7]).

Table 1. Properties of NPA geocells

Properties	Values	
	Type-C	Type-D
Tensile strength, kN/m	19	22

Dynamic modulus, MPa		
+30°C	775	800
+45°C	675	700
+60°C	525	650
Distance between seams, mm	330	330
Open cell dimensions, mm × mm	245 × 210	245 × 210

Table 2. Properties of geocomposite

Properties	**Values**		
	Geogrid	**Geotextile**	**Composite**
Tensile strength (md/cmd)[1], kN/m	30/30	7.5/11.0	-
Grab tensile strength (md), kN	-	-	0.55
Trapezoidal tear strength, kN			0.26
Aperture size (md/cmd), mm × mm	32 × 32	-	-
Characteristic opening size, µm	-	90	-

[1]md is machine direction; cmd is cross machine direction.

Plate Load Testing Methodology

Plate load tests (PLTs) were carried out in all test sections to assess the mechanical response of the pavement structure under controlled loading conditions. The tests were performed on the asphalt surface at locations aligned with the installed earth pressure cells to allow direct correlation between applied surface loads and measured stresses within the pavement layers. The testing program included a standard plate load test conducted in accordance with ASTM D1195/D1195M, together with monotonic and cyclic loading tests to evaluate pavement behavior under high and repeated loading conditions (Huang (2025)[6]). . A circular steel loading plate with a diameter of 300 mm was placed on a leveled sand bedding layer to ensure uniform contact between the plate and the pavement surface. Vertical loads were applied through a hydraulic jack system, reacting against a rigid frame mounted on a support vehicle. A seating load was applied prior to testing to stabilize contact conditions and record any initial deformation.

The loading procedure consisted of incremental loading and unloading stages, with applied pressures increased stepwise (e.g., 200, 400, 800, and 900 kPa), followed by unloading in predefined stages. At each load increment, the load was maintained until the rate of displacement became negligible before proceeding to the next stage. Surface displacements were measured using dial gauges placed symmetrically on the loading plate, while the applied pressure was monitored using a digital pressure gauge.

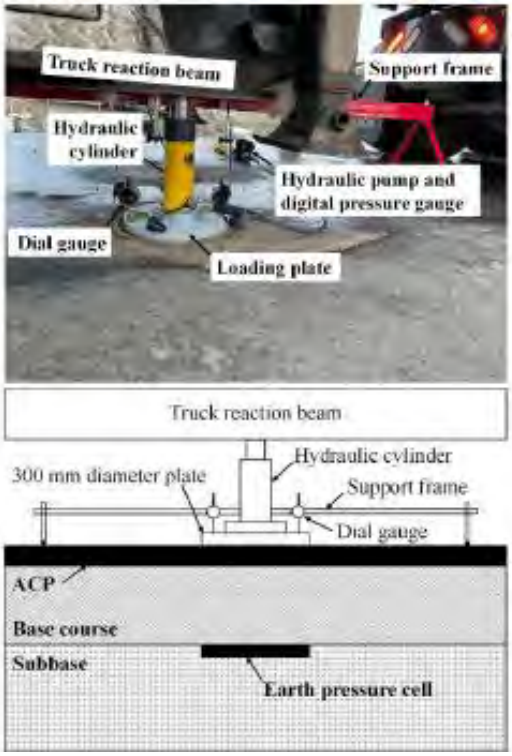
The asphalt concrete layer was 90 mm thick in all three test sections, while the base course thickness was 300 mm in the Type-C and Type-D geocell sections and 350 mm in the geocomposite section, as described in the Test Sections subsection. Vertical stresses at the base–subbase interface were recorded simultaneously using earth pressure cells connected to a data acquisition system. The synchronized measurements of applied load, displacement, and transmitted stress provide the basis for evaluating load transfer behavior within the pavement structure. Figure 2 illustrates the setup of a PLT.

The load transfer ratio, defined as a ratio of the measured stress at the base-subbase interface to the applied stress on the pavement surface, was therefore utilized to understand the load transfer in the pavements. To normalize the effect of base course thickness and to quantify and estimate the effectiveness of geosynthetics-stabilized base courses in distributing applied pressure over subbases, the stress distribution angle was defined. The distribution angle θ, was determined using Equation 1 ((Giroud and Han, (2004)[8]).

$$tan\theta = \frac{b}{2h}\left(\sqrt{\frac{p_0}{p_1}} - 1\right) \qquad [1]$$

where,
θ is the distribution angle, (°).
b is the diameter of the loading plate, mm.
h is the depth between the pavement surface and the subbase surface, mm.

Figure 2. Photographs of plate loading tests



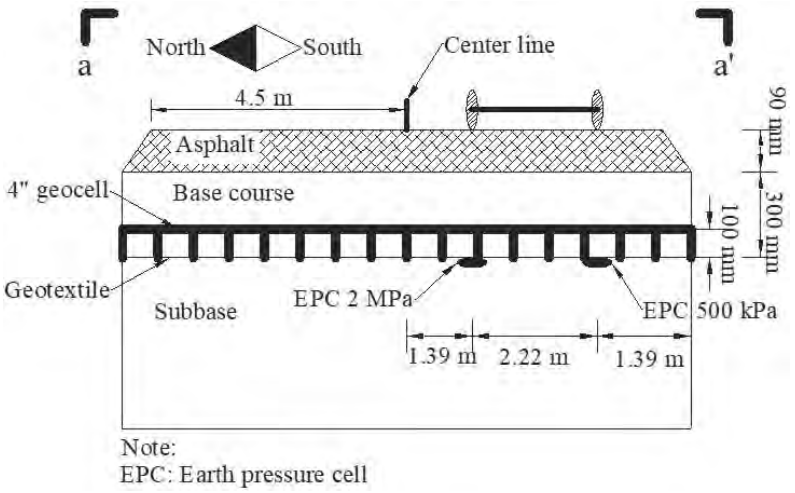
Instrumentation and Measurement System

The pavement sections were instrumented to measure the stress response under applied loading using earth pressure cells (EPCs). These sensors were installed at the base–subbase interface to capture the vertical stress transmitted through the reinforced layers.

Each section was equipped with two EPCs (RST Instruments® LPTPC12-S) with measurement capacities of 500 kPa and 2 MPa, respectively. The sensors were positioned approximately 2.22 m apart, corresponding to the typical axle spacing, to capture stress responses under representative wheel loading paths. The EPCs were embedded during construction by preparing level cavities at the interface, followed by careful placement and coverage to ensure uniform stress transfer and minimize disturbance effects.

The PLTs were conducted directly above the location of the EPCs, enabling simultaneous measurement of applied surface load and transmitted subgrade stress. This configuration establishes a direct relationship between loading and stress response, forming the basis for evaluating load transfer characteristics. The recorded stress data were subsequently used to compute performance parameters, including load transfer ratio (LTR) and stress distribution angle (θ), which are used to assess the efficiency of load distribution in the reinforced pavement sections. Figure 3 shows the sensor locations of Type-D geocell section.

Figure 3. Sketch of sensor location in Type-D geocell section of earth pressure cells



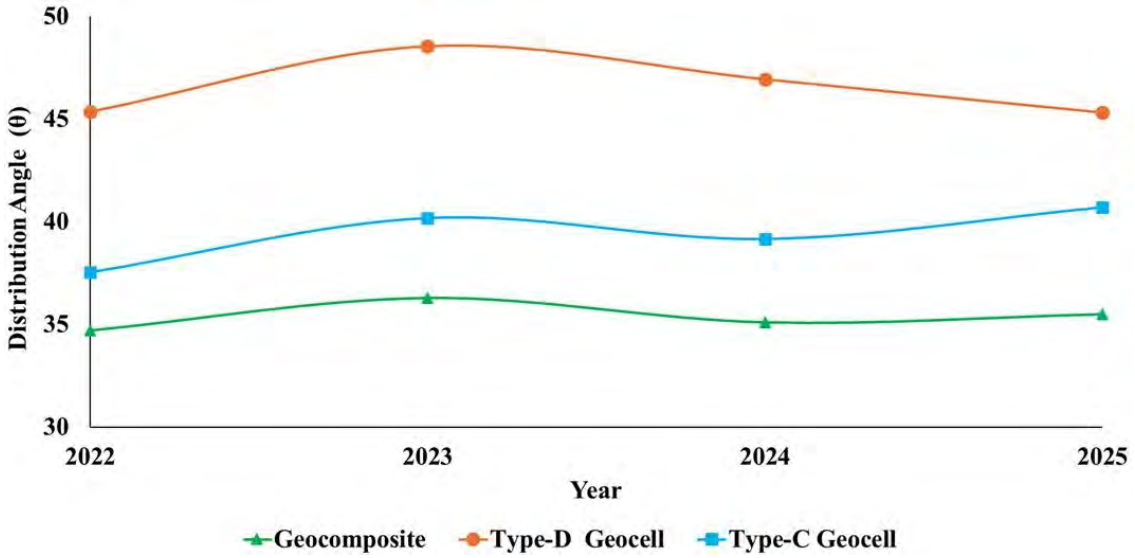
Results and discussion

Evolution of Stress Distribution Angle

The annual PLTs from 2022 to 2025 were conducted within a consistent late-spring testing window (May–June), following seasonal thaw. No PLTs were conducted under freezing conditions. Figure 4 presents the variation in stress distribution angle (θ) for the three pavement sections between 2022 and 2025. The Type-D geocell section shows the highest θ values across all years, ranging from approximately 45° to 49°. The Type-C geocell section exhibits intermediate values between about 37° and 41°, while the geocomposite section remains within a narrower range of approximately 34° to 36°. A similar temporal pattern is observed in all sections, with an increase in θ from 2022 to 2023, followed by a slight reduction

in 2024 and minor variation in 2025. Despite these changes, the relative ranking of the sections remains unchanged. The higher θ values in the geocell-reinforced sections indicate a wider spread of stresses within the pavement structure compared to the geocomposite section. The Type-D geocell section maintains this response with minimal variation over time, while the Type-C geocell section shows moderate change. The geocomposite section exhibits comparatively smaller variation throughout the monitoring period. These trends are consistent with observations reported in previous studies (e.g., Divakar et al. (2024)[9], Pokharel et al. (2010)[10]).

Figure 4. Variation of Stress Distribution Angle (θ) over Time for Different Reinforcement Sections (2022–2025)



Change in Stress Distribution Angle

To quantify the variation in load distribution behavior over time, the change in stress distribution angle (θ) between 2022 and 2025 was calculated for each section, as summarized in Table 3. The results indicate that the magnitude of change in θ varies among the reinforcement systems. The Type-C geocell section exhibited the largest increase in θ, with a change of approximately +8.38%, indicating a noticeable shift in load-spreading behavior over the monitoring period. In contrast, the Type-D geocell section showed minimal variation, with a change of approximately 0%, suggesting that its load distribution performance remained relatively consistent over time. The geocomposite section exhibited a small increase of approximately +2.47%, indicating limited variation in its load-spreading response. Although the annual tests were conducted within a consistent seasonal window, variations in temperature and moisture conditions may have contributed to the observed changes in stress distribution angle. The individual effects of freeze–thaw processes and other environmental factors were not independently assessed in this study.

These results suggest that while the Type-D geocell section maintained stable performance, the Type-C geocell section experienced a measurable change in stress distribution behavior. The relatively small change observed in the geocomposite section indicates that its load distribution characteristics remained largely unchanged over the monitoring period.

Table 3. Change in Stress Distribution Angle (θ) Between 2022 and 2025

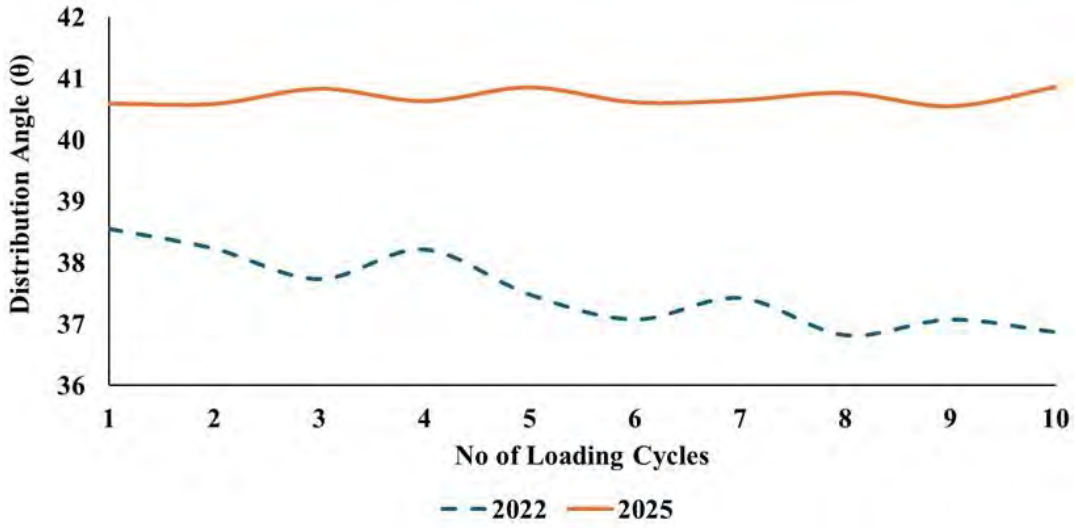
Section	θ (2022)	θ (2025)	Change (%)
Geocomposite	34.66	35.52	+2.47
Type-D Geocell	45.36	45.31	~ 0
Type-C Geocell	37.55	40.70	+8.38

Load Response under Cyclic Loading

The variation of stress distribution angle (θ) with loading cycles is presented in Figure 5 for the Type-C geocell section for two testing periods (2022 and 2025).
The results show that θ values obtained in 2025 remain relatively consistent across the loading cycles, with only minor fluctuations around approximately 40.5°–41°. In contrast, the 2022 results exhibit a gradual decreasing trend with increasing number of cycles, along with greater variability. The θ values in 2022 decrease from approximately 38.5° at the initial cycle to below 37° in the later cycles.
This difference suggests that the load distribution response in 2022 was more sensitive to repeated loading, whereas the response in 2025 appears more stable under cyclic conditions. The reduced variation observed in the later testing period indicates a more consistent stress distribution behavior during repeated loading.

The results do not indicate a significant change in the absolute magnitude of θ within a single test; however, the difference in trend between the two years highlights a change in how the pavement responds to cyclic loading over time. This observation is consistent with the overall trend discussed in the previous sections, where the Type-C geocell section showed a measurable increase in θ over the monitoring period. The Type-C geocell section is presented here as a representative case due to its noticeable variation in stress distribution behavior over time compared to the other sections.

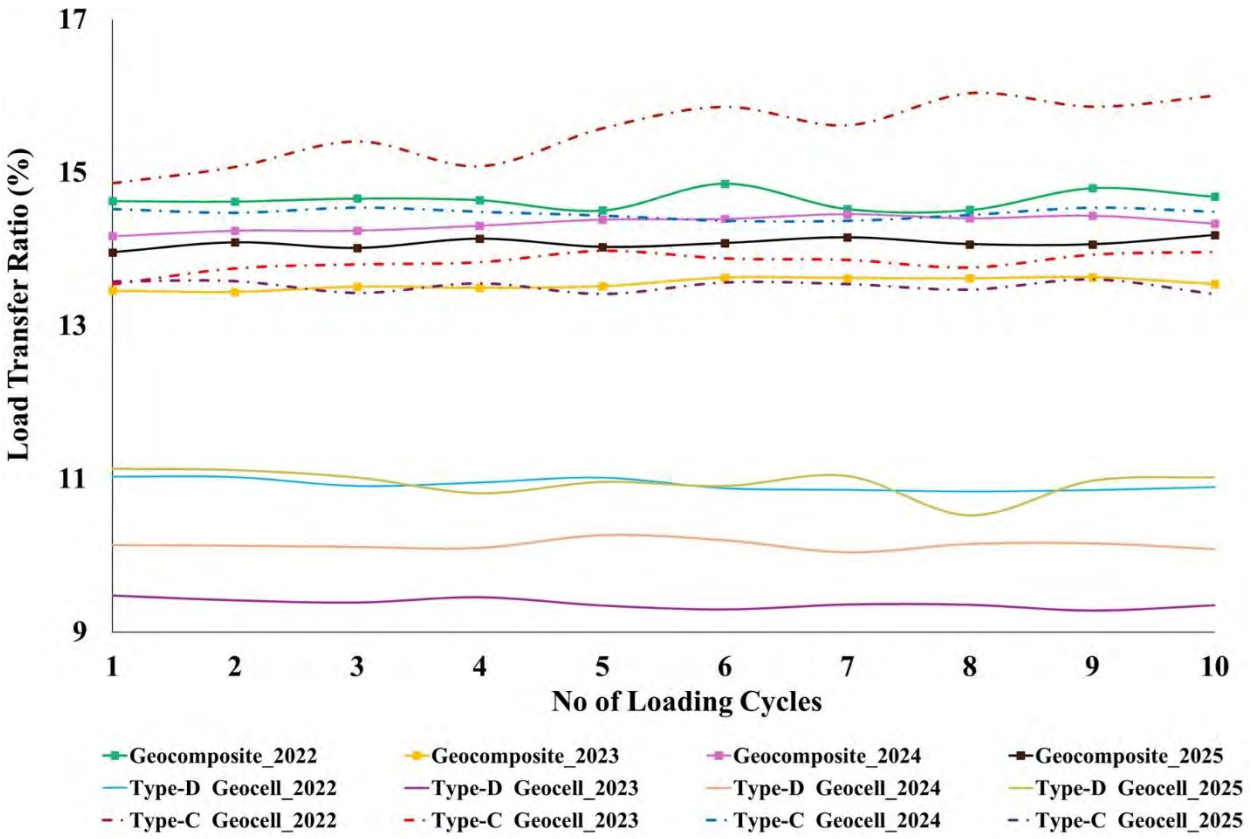
Figure 5. Variation of Stress Distribution Angle (θ) with Loading Cycles for Type-C Geocell Section (2022 and 2025)



Load Transfer Ratio under Cyclic Loading

The variation of load transfer ratio (LTR) with loading cycles is presented in Figure 6 for all sections and testing years. The results show that LTR values remain relatively stable across loading cycles for all sections, with only minor fluctuations. The Type-D geocell section consistently exhibited the lowest LTR values, indicating reduced stress transmission to the base–subbase interface. The Type-C geocell section showed intermediate values, while the geocomposite section generally exhibited higher LTR values.
Across different years, no significant variation in LTR trends with respect to loading cycles is observed. The relatively stable behavior suggests that cyclic loading within a single test does not substantially alter the stress transfer characteristics. However, differences between reinforcement types remain evident, with geocell sections demonstrating lower LTR compared to the geocomposite section.

Figure 6. Variation of Load Transfer Ratio (LTR) with Loading Cycles for All Pavement Sections (2022–2025)



Overall, the results indicate that the type of reinforcement influences both stress distribution and stress transmission within the pavement structure. The Type-D geocell section consistently exhibited higher stress distribution angles (θ) and lower load transfer ratios (LTR), indicating a greater extent of load spreading and reduced stress transmission to the lower layers. The Type-C geocell section showed moderate performance with a noticeable increase in θ over time, suggesting variation in load distribution behavior during the monitoring period. In contrast, the geocomposite section exhibited comparatively

lower θ values and higher LTR, indicating more limited load redistribution within the base layer. These observations are consistent across both temporal trends and cyclic loading behavior, highlighting differences in how reinforcement systems influence load transfer characteristics under field conditions.

Conclusions

This study evaluated the load transfer behavior of geosynthetics-reinforced pavement sections using plate load testing combined with stress measurements. The results show that the type of reinforcement influences both stress distribution and stress transmission within the pavement structure.
The Type-D geocell section consistently exhibited higher stress distribution angles (θ) and lower load transfer ratios (LTR), indicating more effective load spreading and reduced stress transmission to the base–subbase interface. The Type-C geocell section showed moderate performance, with an increase in θ over the monitoring period, suggesting variation in load distribution behavior over time. The geocomposite section exhibited comparatively lower θ values and higher LTR, indicating more limited load redistribution within the pavement layers.

The analysis of cyclic loading showed that stress distribution behavior remained relatively stable within individual tests, while differences between reinforcement systems persisted. Overall, the results highlight the influence of reinforcement type on load transfer characteristics under field conditions.

References

[1]Qi, J., Vermeer, P. A., and Cheng, G. (2006). “A review of the influence of freeze–thaw cycles on soil geotechnical properties.” Permafrost and Periglacial Processes, 17(3), 245–252.

[2]Viklander, P., 1998. Permeability and volume changes in till due to cyclic freeze/thaw. Canadian Geotechnical Journal, 35(3), pp.471-477.

[3]Christopher, B. R., Hayden, S. A., and Zhao, A. (2000). “Roadway base and subgrade Geocomposite drainage layers.” Testing and Performance of Geosynthetics in Subsurface Drainage, ASTM International, 35–51.

[4]Henry, K. S., and Holtz, R. D. (2001). “Geocomposite capillary barriers to reduce frost heave in soils.” Canadian Geotechnical Journal, 38(4), 678–694.

[5]Pokharel, K. S., Norouzi, M., Martin, I., and Breault, M. (2016). “Sustainable road construction for heavy traffic using high strength polymeric geocells.” Proc., Resilient Infrastructure 2016, Canadian Society for Civil Engineering, London, ON, Canada, 1–9.

[6]Huang, M., Liu, J., Pokharel, S. K., Dagenais, T., Chatterjee, A., and Lin, C. (2025). “Full-scale testing and monitoring of geosynthetics-stabilized flexible pavement in Alberta, Canada.” Geotextiles and Geomembranes, 53, 427–444.

[7]Ikra, B.A., Gao, Y., Liu, J., Dagenais, T., Chatterjee, A., Pokharel, S., Sun, M., and Lin, C. “Evaluating pavement resilience to freeze–thaw cycles using geocell and geocomposite reinforcements: A two-year field study.” Geo-Congress 2026. American Society of Civil Engineers (ASCE). https://doi.org/10.1061/9780784486764.005 (2026).

[8]Giroud, J.P., Han, J., 2004. Design method for geogrid-reinforced unpaved roads. I. Development of design method. J. Geotech. Geoenviron. Eng. 130 (8), 775–786.

[9]Divakar, M., Gottumukkala, B., Swarna, S.T., Prasad, P.S., Arunkumar, G., 2024. Performance evaluation of geosynthetic reinforced marginal material as base layer over weak subgrade. Int. J. Pavement Eng. 25 (1), 2318605.

[10]Pokharel, S. K., Han, J., Leshchinsky, D., Parsons, R. L., and Halahmi, I. (2010). “Investigation of factors influencing behavior of single geocell-reinforced bases under static loading.” Geotextiles and Geomembranes, 28(6), 570–578.