Assessment of the Mechanical Response of Road Embankments Built on Permafrost located at Inuvik-Tuktoyaktuk Highway

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Abstract

Road construction on permafrost typically involves using thick granular embankments to provide thermal and mechanical protection for the subgrade. A proper structural design is one of the most important factors to minimize the mechanical impact of roads on permafrost. Additionally, seasonal variability plays a vital role in this regard. This study was conducted as a test section along the Inuvik–Tuktoyaktuk Highway (ITH) by embedding several thermal, moisture, pressure cell, and deformation sensors at different depths and distances in a single location. The instrumentation was done in 2019, and the data was recorded continuously until 2024 for analysis. These results were the outcome of six site visits during two different years, with the goal of recording the properties of the embankment and soil under frost, settlement, and heave conditions. During each site visit, a loaded dump truck was driven over the test section under controlled conditions to record data. The truck was driven at three different speeds (5 km/hr, 15 km/hr, and 25 km/hr) on the centerline of the sensors. Additionally, other testing, such as the Light Weight Deflectometer (LWD), was conducted for further analysis. The results of this research show an increase in permafrost degradation and growth of the active layer, based on the mechanical responses from the embankment and soil. The LWD test shows an improved modulus at the surface of the road, in contrast to a decrease in strength in the deeper layers. The changes in climatic/environmental conditions are also impacting the moisture and temperature in the permafrost region due to increasing temperatures.

Keywords: Unpaved Roads, Permafrost, Cold Region Engineering, Seasonal Analysis, Mechanical Properties

Introduction

Roads and railways in the Arctic began to develop rapidly at the beginning of the 20th century, and this trend continues today with increasing intensity due to the importance of the region[1]. The Canadian Arctic is home to vital ecosystems, infrastructure, and communities. However, the region is experiencing an alarming rate of temperature and climate change, which poses a significant threat to the approximately 3.3 million inhabitants[2,3]. Research from various organizations and researchers indicates that the Arctic's temperature has been rising at a rate of 1.1 °C per decade between 2011 and 2020, and this trend is expected to accelerate by 2050[3,4,5]. Permafrost is defined as soil that remains below 0 °C for more than two consecutive years, with the active layer being the top layer that thaws each summer and refreezes in winter[6,7,8,9]. Furthermore, reports show that the warming rate in the Arctic is two to four times faster than the global average, significantly accelerating the thawing of permafrost[10,11,12]. Additionally, the permafrost region contains approximately 1,300 petagrams of organic carbon—roughly twice the amount currently found in the atmosphere. The release of this carbon due to permafrost thawing could lead to a catastrophic acceleration in global temperature rise[13].

The impact of permafrost on the Canadian Arctic is critical due to the region's importance to the country. Its security and economic interests, along with the deep cultural ties of Indigenous communities to the land, require significant attention to the development of essential and sustainable infrastructure in the region[14,15]. Infrastructure, including roads, highways, and other ground transportation systems, is at risk due to the expanding active layer and weakening soil, which could lead to failure[16,17]. The thawing of permafrost destabilizes the terrain, causing thermal erosion that results in cracked foundations, deformed structures, and structural rutting in roads[17].

In 2017, the Inuvik–Tuktoyaktuk Highway (ITH) was constructed on permafrost, spanning 138 km to connect the city of Inuvik to Tuktoyaktuk and the surrounding communities. Prior to the project, an ice road served as the primary transportation route, reducing the high costs of air travel for part of the year. The ITH project was built during winter, at nighttime, when temperatures were often below –30 °C, due to operational limitations caused by soil strength on construction equipment. The project included around 300 culverts, eight bridges, and approximately 4.8 million cubic meters of embankment material[18]. To minimize damage to the existing permafrost, the vegetation on the tundra was left undisturbed, and the embankment was constructed on frozen ground[18,19,20]. However, since its completion, the thawing permafrost has led to deterioration, necessitating a study of the subgrade properties and the seasonal mechanical behavior of the soil under loading. Changes in soil moisture and temperature over the years have affected the load-bearing capacity of the embankment due to increased saturation[21]. Pavement mechanics depend on factors such as the distribution of the load, soil properties, and layer thicknesses. The deformation caused by loading is critical for pavement design, and analyzing the stresses and deformations is essential for understanding embankment behavior. A cyclic load on the soil produces elasto-plastic responses that must be studied to assess the embankment's performance on permafrost[21]. This study tracks the active layer trajectory of the site from 2019 to 2024, focusing on temperature trends and moisture content, which are key factors in weakening the unbound material exposed to traffic loading. As traffic on the ITH increases due to rising tourism in the region, the resulting structural weakening and pavement distress, along with broader regional disturbances, will pose significant challenges for future pavement design[22,23].

Objective

The objective of this study was to investigate the impact of seasonal environmental changes, particularly variations in temperature and moisture, on the performance of a road embankment constructed on permafrost. This was achieved through continuous environmental monitoring, instrumented sensor measurements (including pressure cells, strain gauges, moisture probes, and thermistors), truck loading simulations, and in-situ testing such as LWD assessments. These methods enabled evaluation of stress, strain, and modulus changes in the embankment and underlying soils under varying seasonal and climatic conditions.

Research methodology

The test section was constructed in 2019 by Université Laval. Several environmental and mechanical sensors were installed in the embankment and soil to collect information for further analysis of active layer behavior and the impact of degradation on the embankment and subgrade. The location of the test section was at Station 81+700, located at coordinates 69.0192° N, 133.2635° W. Figure 1 shows the plan of the road at the test section, as well as the profile at the site. The sensors were located 0.9 m below the wheel path, measured from the top of the embankment (EM) to the point where the natural ground (NG) begins. In addition, thermistors and moisture sensors were also located at various depths within the test section. Table 1 lists the sensors buried in the test section, and Table 2 presents the locations of the thermistors at different depths.

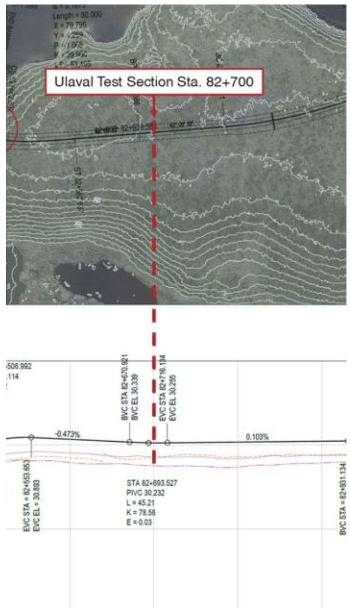

Figure 1 Plan and profile of the section[24,25]

Table 1 Instruments in the ITH test section

Sensor	ID	Depth (m)
Pressure cell	TPC1900003	0.7
Pressure cell	TPC1800003	1.3
Strain gauge	VSG D101	1.3
Thermistor	2610	0.4 to 2.35
Moisture sensor	EC5-035	0.7
Moisture sensor	EC5-779	1.3

Table 2 Thermistor locations in embankment and soil

ID	Depth (m)	Other
T1	0.4	-
T2	0.5	-
T3	0.6	-
T4	0.75	-
T5	0.95	Top of the subgrade (geotextile) at 0.9 m
T6	1.15	-
T7	1.35	-
T8	1.55	
T14	1.55	T14 is installed at the same depth
T9	1.75	Freezing at 1.8 m in September 2019
T10	1.95	-
T13	2.05	T13 is installed between T10 and T11
T11	2.15	-
T12	2.35	-

Environmental data

The moisture sensors and thermistors were installed inside the test section at different depths. The data was recorded continuously throughout the year. The recorded data was stored on-site in a data logger and downloaded during the site visits in 2022 and 2024 for further analysis. The moisture data provided information related to the freezing and thawing of layers, capturing the transitions when ice turned into water. The temperature data indicated the depth and location of permafrost over the years. Figure 2 shows the approximate condition of the road during the site visits, along with the sensor locations and the position of the permafrost in 2022.

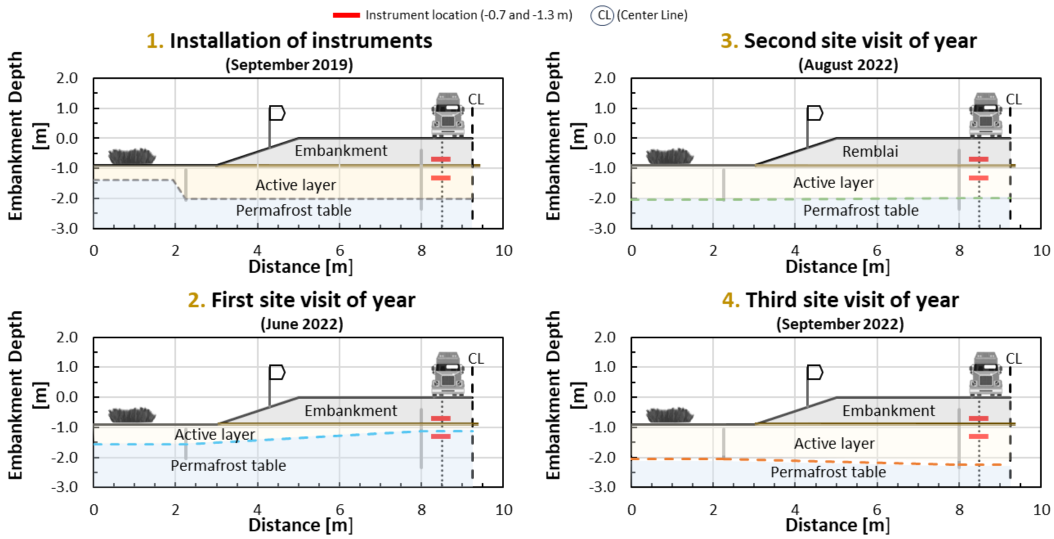

Figure 2 Approximate road profile condition during the site visits

Testing plans after construction

The continuous environmental monitoring provided essential insight into seasonal variations and the evolving state of the active layer and permafrost. This background information was critical for designing and interpreting the subsequent mechanical tests. Building on these environmental observations, the following section describes the testing plan implemented during the site visits, aimed at evaluating how seasonal thawing and moisture fluctuations impact the mechanical response of the embankment structure.

The testing plan was designed to collect data through several site visits in 2022 and 2024. June, August, and September were selected, as they occur during the thaw season when air temperatures start increasing. Each site visit included a series of LWD and mechanical tests. The LWD testing was conducted at nine points located along three lines parallel to the road. These lines were positioned at the centerline (CL), shoulder line (AC), and at the embankment toe (PR). Additionally, the truck test for mechanical sensors was performed using a truck and trailer carrying 20 tons and 40 tons of material, operated at three different speeds (5 km/hr, 15 km/hr, and 25 km/hr). Thermistor and moisture data were also collected, as the sensors recorded continuously throughout the year. Figure 2 presents the testing locations.

Light weight deflectometer

The ASTM E2583 standard was used to perform the LWD test using a Dynatest device. The LWD test provides data related to the resilient modulus (E) of the top pavement layer as a non-destructive test. A loading plate with a 300 mm diameter and a 10 kg drop weight was used, dropped from 48 cm (19 in) and 81 cm (32 in) heights, with six drops for each height. Testing on the CL and AC lines was conducted at eight points, while an additional four points on the PR lane encountered issues due to equipment limitations, as the soft soil underneath caused excessive bouncing in the LWD's deflection sensor. The modulus (E) is used for pavement performance design and for assessing bearing capacity, stiffness, and degree of compaction of the soils[26,27,28]. Correlation formulas were applied to calculate the elastic modulus (Eq. 1), based on assumptions regarding the soil and embankment materials[9].

$$E = \frac{A\sigma_0 a(1-\mu^2)}{d_0} \qquad (1)$$

Where E is the elastic modulus (MPa), σ0 is the applied stress by drop (MPa), a is radius of the plate (mm), μ is the Poisson's ratio for the soil (μ=0.35), A is the stiffness (shape) factor for the soil equal to 2, and d0 is measured settlement of the cone (mm).

Full-Scale Testing on the Road

The structural behavior of the road under load is one of the main properties to be studied for pavement integrity and performance. The repeated loading from vehicles operating on the road results in stress and strain in the layers, which can become problematic during the thaw season. The ITH exists on permafrost, and the layer contains a significant amount of moisture that is frozen during winter. The thawing of ice during summer results in saturated soil being subjected to cyclic loading from traffic. The mechanical testing consisted of driving a truck and trailer half full and fully loaded with materials (20 tons and 40 tons) at three different speeds (5 km/hr, 15 km/hr, and 25 km/hr) along the centerline of the sensors. The data from pressure cells and strain gauges was recorded during each site visit in June, August, and September. The truck and trailer were kept the same across all site visits as much as possible. However, during June 2024, a truck-trailer with six axles and a tridem configuration replaced the five-axle truck-trailer. This variation had a minimal impact on our results, as the data analysis focused specifically on measurements collected from a single designated axle during each test. This approach ensured consistency in the data used for evaluating stress responses, despite the overall difference in axle configurations.

Result and discussion

Environmental data

Figure 3 presents the temperature profile for the embankment and soil under the centerline from 2019 to 2024, using data collected from different depths. Permafrost is defined as a layer in which the temperature remains at or below 0 °C for more than two consecutive years, and Figure 3 illustrates the 0-degree line moving downward over the years from 2019. This implies that the depth of the permafrost table is decreasing at the testing site. Several factors may contribute to this, including climate change, soil disturbance beneath the road, and changes in surface snow cover and water accumulation. Based on data from this study, changes in air temperature, recorded by Environment Canada, have resulted in increased heat transfer from the surface, raising the temperature in the embankment and underlying soil. There is a notable clockwise rotation of the yellow mass in Figure 3, representing areas where the temperature exceeds 0 °C. This shift reflects a more sudden increase in temperature and deeper heat penetration at the onset of the thawing season, followed by a similarly sharp drop at the beginning of the freezing season.

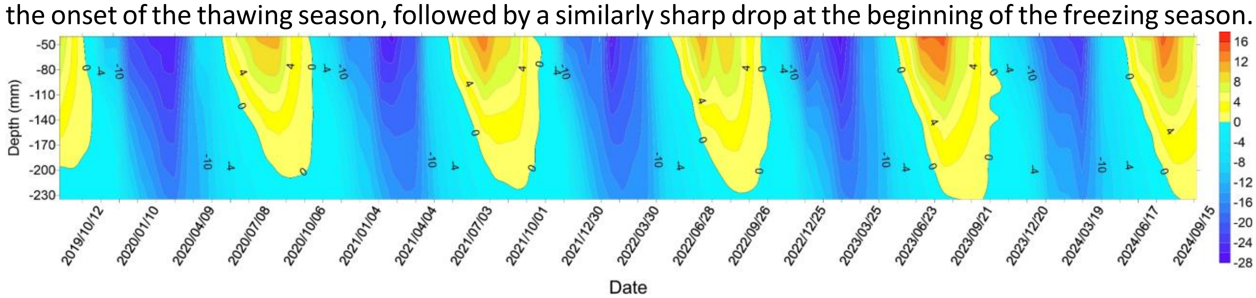

Figure 3 Temperature of the test section for depth from 2019 to 2024

Figure 4 presents the data from moisture sensors. Both sensors at 0.7 m and 1.3 m depths respond to the thawing season, as shown in comparison with the temperature data. The 0.7 m sensor begins thawing approximately three weeks before the 1.3 m sensor, indicating that it takes about two to three weeks for heat to transfer from 0.7 m to 1.3 m and unfreeze the ice in the layer. During the thawing season, melting occurs, resulting in a sharp increase in the graph where the temperature in the layer rises from below 0 °C to above 0 °C. The data presented in Figure 4 only covers the period up to 2022, as the sensors malfunctioned afterward and no additional data is available. Comparing data across the years, a decrease in moisture content in the layers is evident, indicating climate change effects and an increasing trend of soil drainage. Additionally, from June to August and September, there is a noticeable decrease in moisture at 1.3 m, reflecting ongoing moisture loss due to evaporation. At 0.7 m, however, there is a spike in moisture, which may be the result of rainfall or early snowfall penetrating the ground near the end of summer.

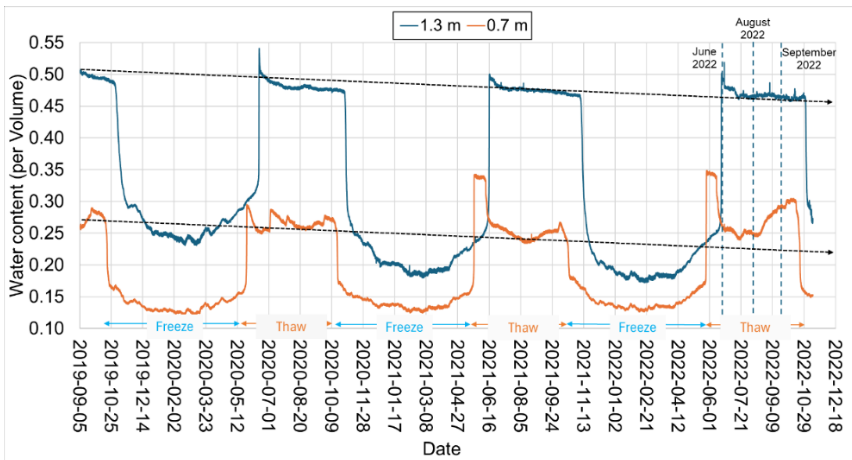

Figure 4 Moisture content of the soil from 2019 to 2022

Light weight deflectometer

The results from the LWD tests conducted in 2022 and 2024 during June, August, and September show several changes in the modulus of the soil. Six drops from two different heights were performed at each of the four points along the CL, AC, and PR lines, and the box-and-whisker plot in Figure 5 presents the results. According to the LWD results from each site visit, the modulus of the layers increases from June to August, then decreases in September, except for the AC lane. Looking at the PR section for both 2022 and 2024, the modulus is approximately 25 MPa across all three site visits, indicating a consistently weak embankment toe. The CL lane, compared to AC and PR, shows the highest values, which suggests better compaction due to consistent traffic along the centerline, improved grading over the years, and possibly reduced water content. A comparison of the modulus values from 2022 to 2024 shows an increase in embankment stiffness, with the modulus rising from approximately 125 MPa to 200 MPa. An increase was also observed in the AC lane, from about 80 MPa to 125 MPa.

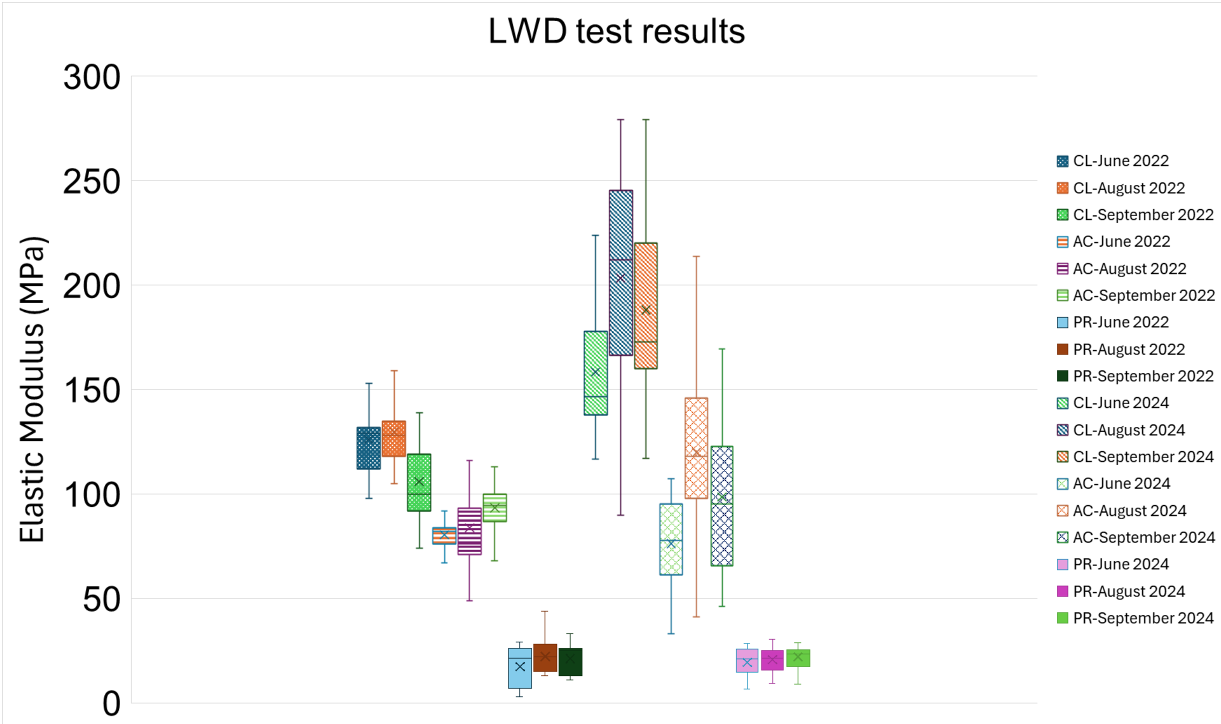

Figure 5 LWD testing for 2022 and 2024 site visits

Full-Scale Testing on the Road

The mechanical testing was conducted using a truck-trailer and it was repeated in all six site visits during 2022 and 2024. The pressure sensors at 0.7 m and 1.3 m collected the data for the pressure of the cyclic load of truck as well as strain gauge near the pressure cells to measure the deformation in the layer. Figure 6, 7, and 8 shows the data related to the stress and deformation under the load for the site visits emphasizing on the speed of the truck. Figure 6 shows the stress values in June, August, and September for a truck driving at various speeds ranging from 5 km/hr to 25 km/hr. Deriving a conclusion from Figure 4 and 6 shows that June and August 2022 has almost similar moisture contents around 0.7 m and the stress values are also closer to each other with speed impact increasing the stress slightly in August and decreasing slightly in June. The stress values for September were highest in 2022 where Figure 4 shows a hike in moisture that could result in pore pressure and internal stress hike observed in Figure 6. Additionally, stress values in 2024 determines September to be the lowest and due to lack of moisture data, we can conclude that the rain fall in 2024 could be lower during this year. The high value of stress for August around 55 MPa, compared to about 43 MPa in June and 38 MPa in September shows a maximum active layer for September and pore water pressure in August due to thawing effect.

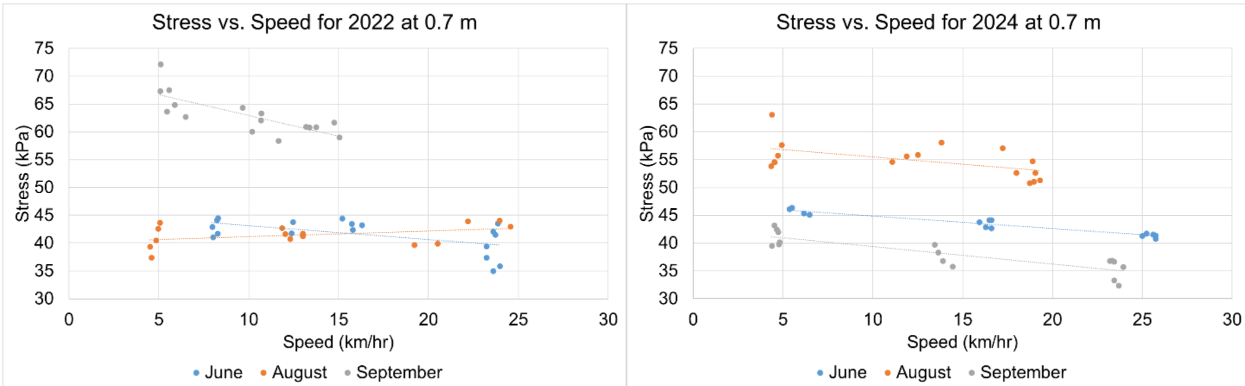

Figure 6 Stress vs. speed for embankment at 0.7 m

The mechanical testing was conducted using a truck-trailer and was repeated during all six site visits in 2022 and 2024. The pressure sensors at 0.7 m and 1.3 m collected data on the cyclic loading pressure from the truck, while strain gauges located near the pressure cells measured deformation within the layer. Figures 6, 7, and 8 show the data related to stress and deformation under load for the site visits, with an emphasis on the speed of the truck. Figure 6 presents stress values for June, August, and September under different truck speeds ranging from 5 km/hr to 25 km/hr. A comparison between Figures 4 and 6 shows that June and August 2022 had nearly similar moisture contents around 0.7 m, and the corresponding stress values were also close—with increasing vehicle speed slightly increasing stress in August and slightly decreasing it in June. The highest stress values were recorded in September 2022. While Figure 4 shows a spike in moisture at this time, the higher measured stress may be attributed to reduced energy absorption in the drier upper layers or stiffer intermediate soils, rather than pore pressure effects, since pore water pressure typically does not increase total stress and may even attenuate load transfer in softer, saturated conditions. Additionally, the stress values in 2024 indicate that September had the lowest readings. In the absence of moisture data for that year, it is possible that lower rainfall or drier upper layers contributed to the higher stress transmission observed in August, around 55 MPa, compared to approximately 43 MPa in June and 38 MPa in September. The peak in August may correspond to relatively stiff and dry upper layers during the peak thawing period, allowing more load to reach the sensor at 1.3 m. The subsequent drop in stress in September could be attributed to further deepening of the active layer, potentially reaching wetter or less stiff soils (e.g., fine-grained or saturated layers), which attenuated the stress more effectively. This pattern may also indicate a seasonal shift in soil behavior due to advancing thaw and evolving permafrost conditions.

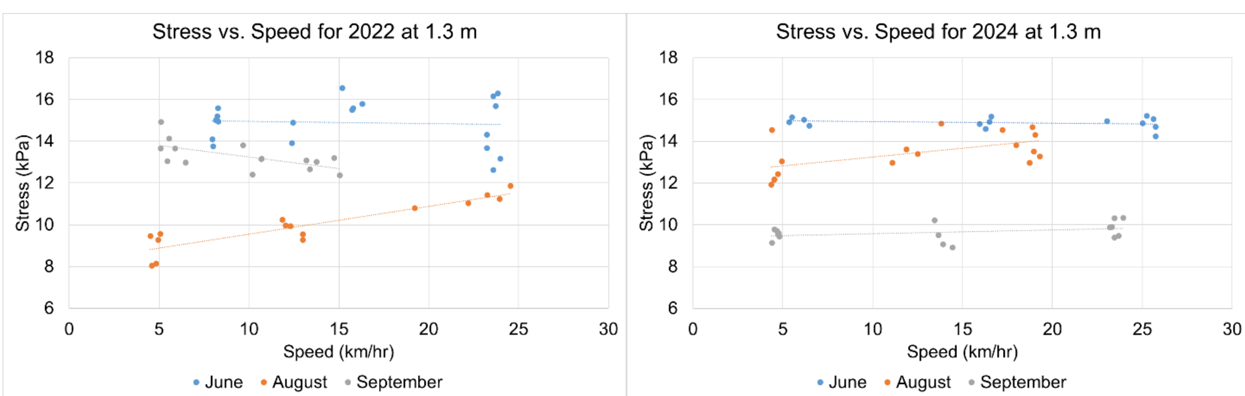

Figure 7 Stress vs. speed for soil at 1.3 m

Figure 8 presents the deformation in the soil at a depth of 1.3 m. The results show that deformation in June 2022 and 2024 consistently decreases with increasing vehicle speed, which is characteristic of frozen soil conditions. At higher speeds, the reduced deformation observed in both years confirms the presence of stiffer, frozen soil layers during testing. In August and September of both years, the soil is thawing, and with softer soil, the deformation becomes largely independent of speed. A comparison between 2022 and 2024 shows higher deformation in 2024, which may indicate a higher thawing rate and weaker soil, as a result of a deeper active layer at the testing site. Both September and August exhibit similar deformation values in both years, with August corresponding to thawed and soft soil, and September representing a saturated and very weak active layer, particularly in 2024.

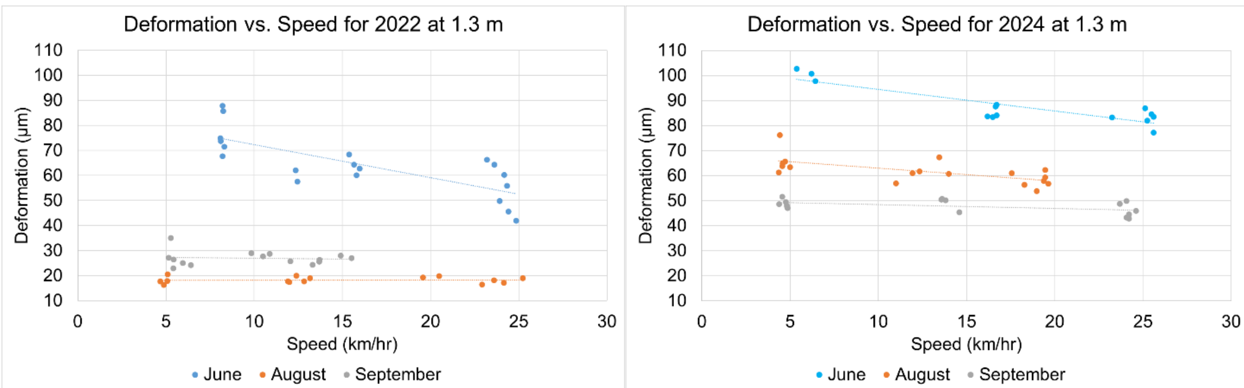

Figure 8 Deformation vs. speed for soil at 1.3 m

Figure 9 shows the elastic modulus of subgrade soil, calculated using the ratio of stress to strain from sensors installed at a depth of 1.3 m. In 2022, the lowest modulus was observed in June, marking the beginning of the thawing season when the soil is moist, soft, and weak. The modulus increased in August and remained relatively high in September as the surface layers dried due to rising temperatures. This suggests that in 2022, frozen soil likely persisted beneath the road surface, effectively supporting the load transferred from the overlying embankment. A similar seasonal trend is observed in 2024, with June showing the lowest modulus due to early thaw conditions and higher moisture content. Modulus values increased slightly in August and September as the soil continued to dry and stiffen, likely due to reduced moisture, improved drainage, and partial re-compaction of the upper layers.

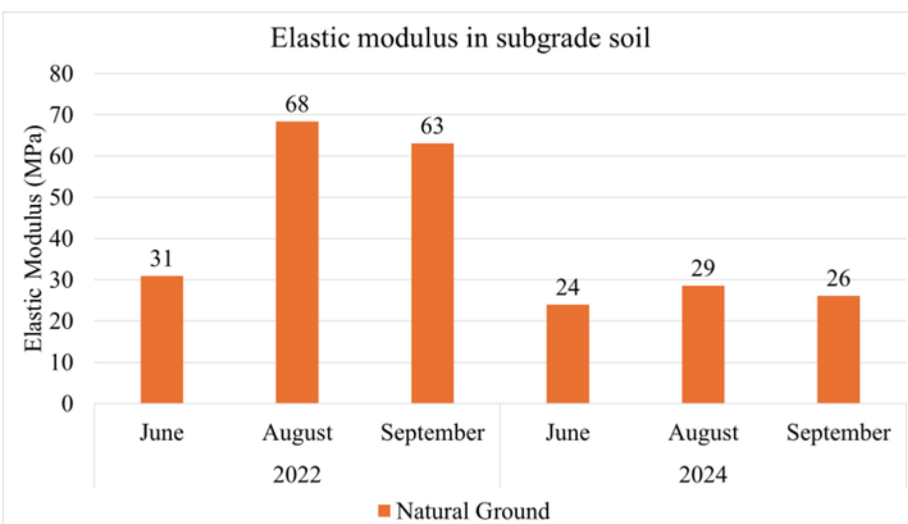

Figure 9 Elastic modulus of the subgrade soil in 2022 and 2024

More importantly, a comparison between the two years reveals critical insights into permafrost degradation. The modulus in June 2024 is lower than in June 2022, with an even more significant reduction observed in August and September. Given that traffic conditions and seasonal moisture trends are assumed to be similar, the notable drop in modulus in 2024 suggests a lowering of the permafrost table. This loss of frozen support beneath the active layer, particularly beyond 1.1 m where clay begins, indicates advancing permafrost thaw and weakening subgrade conditions beneath the embankment.

Discussion

This study highlights the significance of loading and the resulting responses in the permafrost region, especially in the context of climate change and the ongoing rise in temperatures. The mechanical behavior of the ITH, one of the major infrastructure components in the region, is assessed through LWD tests on the embankment, alongside cyclic loading and recording of mechanical responses in the layers. Environmental data, a key factor in interpreting these responses, is also considered.

The LWD results reveal an increase in the modulus of the embankment layers from 2022 to 2024. The modulus at the embankment toe remained almost constant at around 25 MPa. However, the modulus at the embankment's centerline (CL) increased from approximately 125 MPa in 2022 to about 200 MPa in 2024, indicating a drier, more compacted, and stiffer surface. Additionally, the slightly lower modulus observed at the AC (roadside) compared to the CL may be due to less compaction in the AC area, as traffic tends to drive more along the centerline, with maintenance efforts concentrated there as well. Furthermore, the low values in the PR section suggest that the embankment toe, which is closer to the natural ground, contains soil that becomes further weakened as temperatures rise and the season becomes drier.

The environmental data, including temperature and moisture content at various depths, indicates an increase in both temperature and drying effects on the embankment and soil. Over the years, from 2019 to 2024, higher heat transfer has led to increased temperatures at lower embankment levels, causing thawing of the ice beneath these layers and contributing to soil drying. As a result, the active layer has expanded, and its thickness has increased. Moisture content comparisons at two different depths reveal an increasing trend of water drainage during the summer and thawing season, continuing until fall and winter precipitation. At lower depths, the reduced moisture content reflects the thawing of ice-rich layers, which affects the road's performance.

The elastic modulus of the embankment was calculated from the stresses and strains at various depths under cyclic loading. This study measured these stresses at two different depths, and comparison of the values shows the effects of seasonal variations, from the early thaw season in June to the late thaw season in August and September, when drainage of the layers begins. Additionally, the effect of loading frequency, as influenced by truck speeds, was studied. The comparison of these results over several years, alongside environmental changes, led to conclusions about permafrost degradation and the expansion of the active layer. The speed impact on the embankment and soil was more pronounced during the 2022 site visits, when thawing rates were lower and water presence influenced pore water pressure, stress, and deformation levels. In contrast, similar values in 2024, when temperatures and evaporation were higher, revealed a stiffer structure less influenced by changes in loading frequency (speed).

The variation in stress and deformation levels within a single season demonstrated the significant impact of ice thawing on the embankment and soil. The road was subject to considerable stress and strain due to thawing layers until the moisture dried out, resulting in a stiffer structure. The thawing season is a critical period that requires consistent maintenance and careful monitoring. More importantly, the comparison of the elastic modulus of the soil at 1.3 meters in 2022 and 2024 showed a substantial weakening of the soil. These results are inconsistent with the LWD measurements at the surface, which point to an increasing active layer over the years, driven by rising temperatures and permafrost degradation. However, since the LWD primarily measures the modulus of the embankment and layers closer to the surface, while the sensors capture values at greater depths within the soil, this difference can be attributed to the distinct properties of the embankment material and the underlying active layer. The high modulus values in 2022 (approximately 300 MPa) suggest a strong embankment and possibly frozen soil, which dropped significantly in 2024 to around 110 MPa. This indicates that the soil has weakened considerably over two years, reflecting a deeper active layer and progressive permafrost degradation. The contrasting LWD results further support this theory, showing a strong embankment and surface where moisture has dried due to rising temperatures in the years following 2022.

Conclusions and Recommendations

This study aimed to comprehensively evaluate the performance of an embankment located on permafrost. A test section along the Inuvik–Tuktoyaktuk Highway (ITH) was instrumented with embedded pressure cells, strain gauges, moisture sensors, and thermistors to monitor the effects of seasonal variations on the mechanical responses of the infrastructure due to changing environmental conditions. A Light Weight Deflectometer (LWD) test, environmental monitoring, and cyclic loading tests were conducted to assess the modulus of the embankment and underlying soils at different depths. The results from this study revealed several important changes, and the conclusions based on these findings are presented below:

- Rising temperatures resulted in an increased modulus of the embankment from 2022 to 2024, particularly at the centerline (CL), indicating a drier, more compacted, and stiffer surface, while the modulus at the embankment toe remained constant, suggesting that soil closer to the natural ground is weaker.
- Temperature from 2019 to 2024 and moisture data from 2019 to 2022 correlated with the expansion of active layer beneath the embankment.
- Stress and deformation levels vary seasonally, with thawing and water content significantly affecting strain in the embankment, particularly during the thawing season, leading to lower modulus values.
- Truck speed (loading frequency) impacted stress and deformation more in 2022 compared to 2024. In 2022, lower thawing rates and more saturated soil were more sensitive to speed changes, whereas in 2024, higher drainage rates and a stiffer structure made the embankment less affected by speed variation.
- The significant weakening of the subgrade soil at lower depths in 2024 under cyclic loading confirms permafrost degradation and the rapid deepening of the active layer.
- The difference in modulus values between LWD and mechanical analysis is explained by the increasing active layer, which results in a weakened lower layer, while the surface of the embankment retains rigidity, something that LWD can detect. However, mechanical testing at deeper layers provides a more detailed and accurate analysis of the structure, useful for design purposes and long-term performance evaluation.

The results of this study emphasize the importance of climate change and its specific impact on permafrost regions. Enhanced monitoring, beyond simple tests like LWD, should be implemented in these areas through more comprehensive data collection. Regular monitoring of temperature, moisture, and soil stiffness at multiple depths is essential to track the effects of thawing and permafrost degradation. To prevent structural damage, maintenance strategies should focus on seasonal variations, particularly during the thawing season. It is also recommended to incorporate climate change adaptation strategies into the construction and maintenance of infrastructure in permafrost regions.

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