Analysis of thermal insulation performance of foamed mixture soil for frozen soil foundation: a case study

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Abstract

Frozen soil foundations are prone to frost heave and thawing under freeze-thaw cycles, which can cause substantial damage to road structures in permafrost areas. The performance of the thermal insulation of the foamed mixture soil subgrade of the S301 highway in Xinjiang was examined as a case study, and the temporal and spatial variation in temperature and strain of the foamed mixture soil subgrade analyzed and compared with those of the original gravel subgrade. The results show that (1) the thermal insulation performance of the foamed mixture soil subgrade is excellent, temperatures tend to stabilize quickly, and changes in amplitude are small—only 8–40% of that of the gravel subgrade; (2) the thermal energy is converted into elastic strain energy for release, which supports the thermal stability of the frozen soil foundation; and (3) a physical model of heat conduction in the foamed mixture soil subgrade structure was established, revealing the mechanism of thermal insulation. This provides a possible solution to help mitigate against frost expansion, thawing, and subsiding of frozen soil foundations.

1 Introduction

The Xinjiang Uyghur Autonomous Region is a key area where frozen soil is encountered in China, comprising approximately 20% of the country's total frozen soil area. As a pivotal point for the "Belt and Road" initiative, Xinjiang's transportation infrastructure has seen rapid advancement in recent decades. An increasing number of highway projects are being constructed in regions where frozen soil is present. However, the engineering behaviour of frozen soil is susceptible to climate variations, external loads, and other influences. The seasonal changes between cold and warm conditions can lead to uneven settlements in frozen soil foundations. This can result in issues such as thermal thaw settlement, subgrade frost boiling, or collapse (Qi and Ma 2010). In recent years, a consensus on the principle of "maintaining frozen foundation" has been reached in the field of frozen soil foundation treatment in China (Ma and Wang 2014). Among various solutions, thermal insulation technology is one of the most important. A prevalent method involves placing a layer of insulating material, such as polystyrene or polyurethane insulation boards, and foamed mixtures of lightweight soil, over the frozen soil foundation. However, due to limitations, such as the thickness of insulation boards, low compressive and flexural strengths, and concerns about long-term durability (Li and Wang 2016), alternative materials, including foamed mixture soil and foamed concrete, have emerged as options for treating frozen soil foundations.

Previous studies have shown that foamed mixture soil is widely used in the field of soft foundation treatment as a lightweight material with high strength and good workability. Simultaneously, due to its condensation and hardening, it forms a porous plate or block with a low thermal conductivity, which is the main characteristic of thermal insulation (Gao et al. 2016). Domestic and foreign scholars have conducted research on the preparation of foamed mixture soil materials and the mechanism of thermal insulation. For example, Hlaváček et al. (2014) prepared a foamed mixture soil with a thermal conductivity ranging from 0.14 to 0.16 W/m/K by adjusting the mix ratio of cementitious materials and adding admixtures. Li et al. (2020) and Batool et al. (2018) studied the influence of bubble content and cement type on the thermal conductivity of foam concrete. She et al. (2013) used X-ray imaging and 3D visualization modeling technologies to reveal the internal mechanism of the micropore structure and thermal properties of foamed concrete. Gao et al. (2023) used CT scanning technology to realize a three-dimensional reconstruction of the pore structure of foamed concrete and established a generalized model to analyze its steady-state heat transfer process. Additionally, for a practical engineering application of foamed mixture soil used to mitigate against roadbed failure in permafrost regions, Lin et al. (2009) pioneered the paving of a test section using a foamed mixture lightweight soil base and roadbed insulation layer within permafrost terrain. The thermal-insulation effect of the base was poor, whereas that of the roadbed was good. However, there are few reports on the application effect of foamed mixture soil subgrade (FMSS) in the treatment of foundation in seasonal frozen soil area, and there are no relevant reports on the long-term thermal insulation performance of FMSS and suitable filling thickness of FMSS.

Therefore, in light of the identified gaps in existing research, this study examined the application of the FMSS test section of the Xinjiang S301 line as a case study. The temperatures and strains of the FMSS and frozen soil foundation were monitored and analyzed, and the time and space variation of the thermal insulation of the foamed mixture soil compared with the original gravel subgrade. By discussing the internal relationship between temperature and strain under two different structural forms of foamed mixture soil and gravel subgrade, a physical model of heat conduction was established. The model aims to simulate the temperature change process of the foamed mixture soil (gravel) subgrade and frozen soil foundation under the

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alternating action of cold and heat to provide a parameter basis and engineering guidance for the treatment of frozen soil foundation using FMSSs.

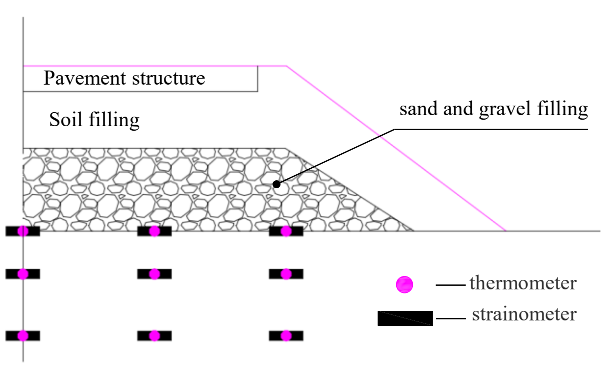
2 METHODOLOGY

The K202+400 – K202+500 section of the S301 line in Xinjiang was selected as the test section for frozen soil treatment of the FMSS. The freezing depth of seasonal frozen soil in this section is approximately 2.3 m, minimum temperature is -20.0 °C, average temperature of the coldest month is -7.9 °C, and the frost heave grade is grade III. Standard specifications, such as the "Technical Code for Design and Construction of Highways in Seasonal Frozen Soil Areas" (JTG/T D31-06-2017) and the "Technical Specification for Foamed Mixture Light Soil Filling Engineering" (CJJ/T 177-2012) were used as a reference. Four types of FMSSs with thicknesses of 0.6, 0.9, 1.2, and 1.5 m were designed, and compared with the original design gravel subgrade. The temperatures and strains within the FMSS and the frozen soil foundation were monitored through the installation of thermistors (*thermometer*) and strain gauges (*strainometer*), respectively. The monitoring scheme for each test section is presented in Table 1, and a monitoring diagram is shown in Figure. 1.

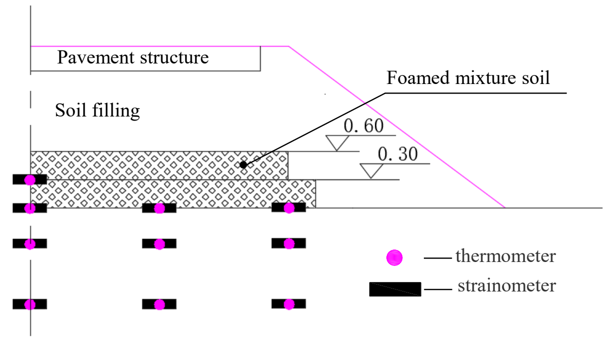
Table 1. Test section monitoring scheme.

Monitoring section pile number	FMSS thickness (m)	Location of monitoring	Depth of monitoring point (m)
K202+475	0（gravel subgrade）	centerline lane	+0.3
K202+415	1.5		0.0
K202+430	1.2	centerline	-0.5
K202+440	0.9		-1.5
K202+465	0.6	shoulder	

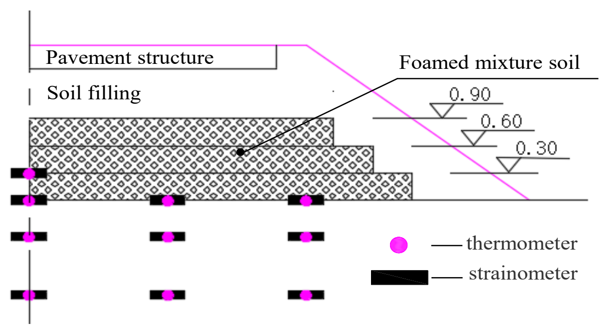
Notes: The depth of the monitoring point is 0 m, which indicates the interface position between the FMSS and frozen soil foundation. A positive value indicates that the interface is above the monitoring depth, whereas a negative value indicates that the interface is below.



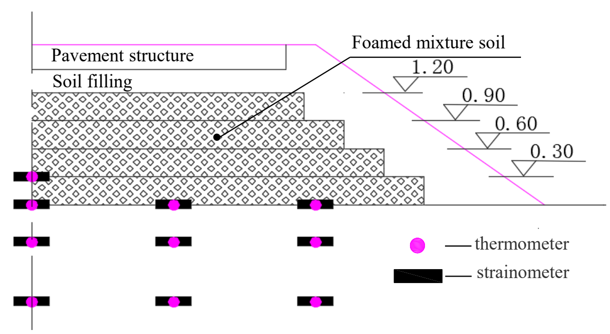
(a) gravel subgrade



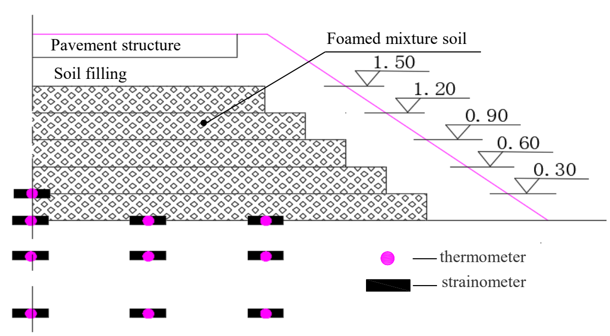
(b) FMSS thickness 0.6 m



(c) FMSS thickness 0.9 m



(d) FMSS thickness 1.2 m



(e) FMSS thickness 1.5 m

Figure 1. Schematic diagrams of monitoring scheme for gravel subgrade and different FMSS configurations.

3 RESULTS

3.1 Temperature Monitoring Results and Analysis

To accurately analyze the thermal insulation effect of the two subgrade forms of foamed mixture soil and gravel in the treatment of a frozen soil foundation, temperatures at the interface between the frozen soil foundation and foamed mixture soil (gravel) subgrade at 0 m, frozen soil foundation at 0.5 m and frozen soil foundation at 1.5 m were selected for comparison. Furthermore, the time-temperature curves are plotted (Figures 2–4).

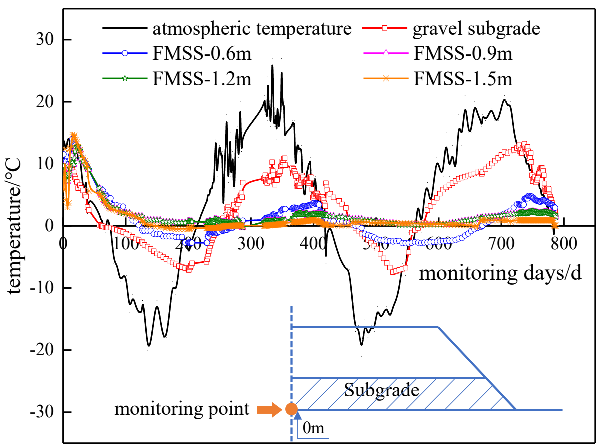


Figure 2. Temperature variation at the interface (0 m) between frozen soil foundation and subgrade.

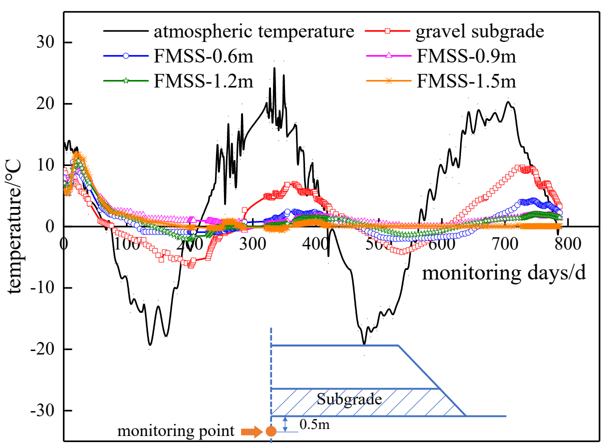


Figure 3. Temperature variation of frozen soil foundation (-0.5 m).

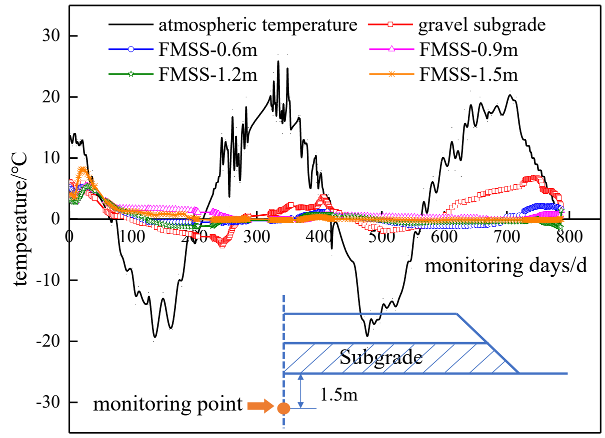
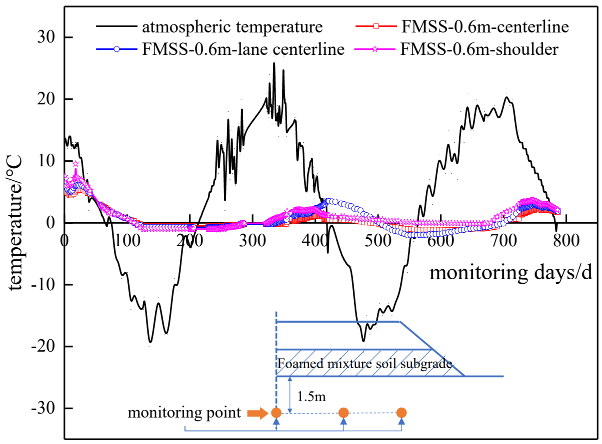


Figure 4. Temperature variation of frozen soil foundation (-1.5 m).

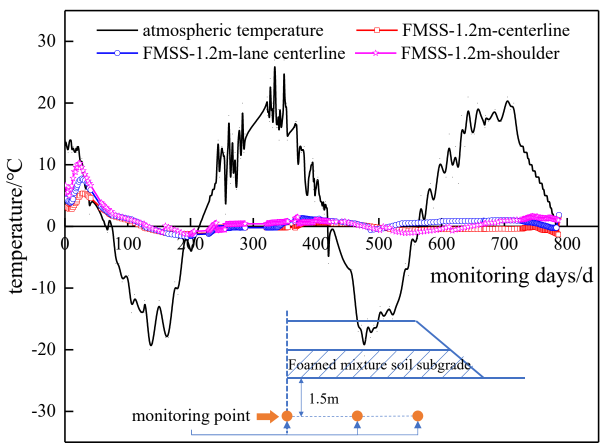
The time-temperature monitoring results for the frozen soil foundation indicate that the temperature variations over time and space beneath the gravel subgrade align with the periodic changes of atmospheric temperature, following a sine function pattern. A noticeable phase difference exists between the peak temperatures of the frozen soil foundation and the atmosphere. Specifically, the foundation's peak temperature lags slightly behind that of the atmosphere. This suggests that while the gravel subgrade offers some thermal insulation, it becomes particularly vulnerable during specific intervals of the heating and cooling cycle. As the freeze-thaw cycles progress, the maximum temperature in the frozen soil foundation under the gravel subgrade increases. This is indicative of an insufficient insulating effect of the gravel impacting the long-term durability of the embankment.

On the other hand, the changes in temperatures in the frozen soil foundation beneath the FMSS are related to the subgrade's thickness. At a thickness of 0.6 m, the temperature patterns in the frozen soil foundation closely mirror the atmospheric temperature's sine function. However, in comparison to the gravel subgrade, the frozen soil foundation beneath the FMSS shows reduced temperature fluctuations and an extended phase duration, indicating the FMSS's superior thermal insulation properties. As the foamed mixture soil thickness increases, the temperature fluctuations within the frozen soil foundation decrease, nearing 0 °C. Furthermore, despite successive freeze-thaw cycles, there is no significant increase in the maximum temperature of the frozen soil foundation beneath the FMSS. This indicates that the FMSS increases the long-term resilience and is resistant to temperature fatigue.

The FMSS, located at the road structure's centerline, demonstrates substantial thermal insulation properties. This suggests that the foamed mixture soil is adept at absorbing and releasing heat—both the heat descending from the road surface above and heat moving laterally from the subgrade's edges toward the centerline. This ability effectively restricts vertical and horizontal heat transfer within the road structure, converging at the centerline, and subsequently ensures that the frozen soil foundation at the centerline remains insulated. To further demonstrate the thermal insulation effect of the FMSS on the frozen soil foundation along the centerline and the shoulder of the road, FMSS structures with thicknesses of 0.6 m and 1.2 m, respectively, are presented (Figure 5).



(a) FMSS thickness 0.6 m.



(b) FMSS thickness 1.2 m.

Figure 5. Temperature variation at different positions of the frozen soil foundation (-1.5 m).

Figure 5 illustrates that temperature fluctuations of the frozen soil foundation (at a depth of -1.5 m) along the road's centerline, lane centerline, and shoulder show freeze-thaw cycles. For a foamed mixture soil thickness of 0.6 m, the most significant temperature shift occurs at the lane's centerline. This suggests that, under the combined influence of vehicle loads and alternating cold and warm (thermo-mechanical coupling), the thermal insulation performance of the FMSS at the lane position is marginally less effective. The temperature amplitude was highest at the road's shoulder, increasing with the progression of the freeze-thaw cycle. This denotes that the shoulder's thermal insulation is the least effective. However, toward the center of the road's cross-section, the insulating properties improve. As the foamed mixture soil's thickness transitions from 0.6 m to 0.9 m, the temperature at all three locations becomes more constant, and the temperature range narrows. This indicates a more consistent and reliable thermal insulation effect.

Based on the aforementioned results, a qualitative simplification was conducted, and schematic models of temperature changes of the frozen soil foundation under two structural forms of gravel subgrade and FMSS are shown in Figures 6 and 7.

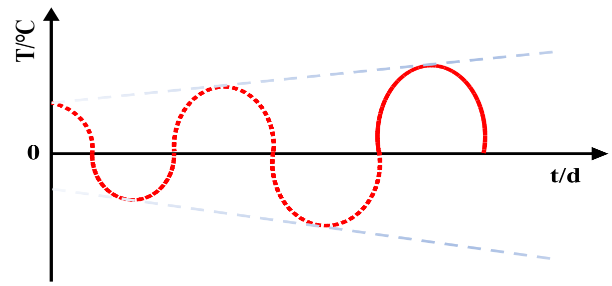


Figure 6. Schematic model of temperature change of the frozen soil foundation under a gravel subgrade.

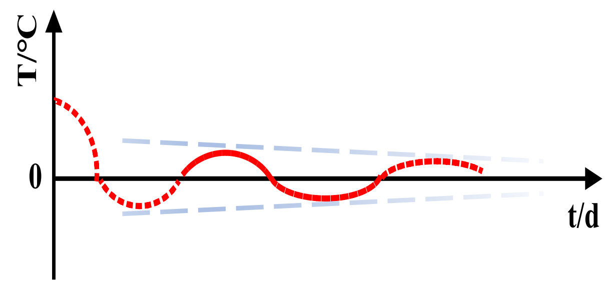


Figure 7. Schematic model of temperature change of the frozen soil foundation under the foamed mixed soil subgrade.

Based on the temperature change curves for the gravel subgrade and FMSS, it is evident that both types of subgrade structures offer thermal insulation. However, there are notable differences in their thermal resistance and long-term durability. The gravel subgrade's thermal resistance and durability exhibit inherent limitations. As alternating cold and heat cycles occur, its insulation capabilities decline. Conversely, the FMSS displays superior thermal resistance and maintains its insulating properties over the long term.

3.2 Strain Monitoring Results and Analysis

To analyze the temporal and spatial variation of the internal strain values of the FMSS and frozen soil foundation, the frozen soil foundation at the centerline of the four different thicknesses of the FMSS was selected at a depth of -0.5 m. Furthermore, the interface with a depth of 0.3 m is compared and analyzed for strain variation, as shown in Figures 8 and 9.

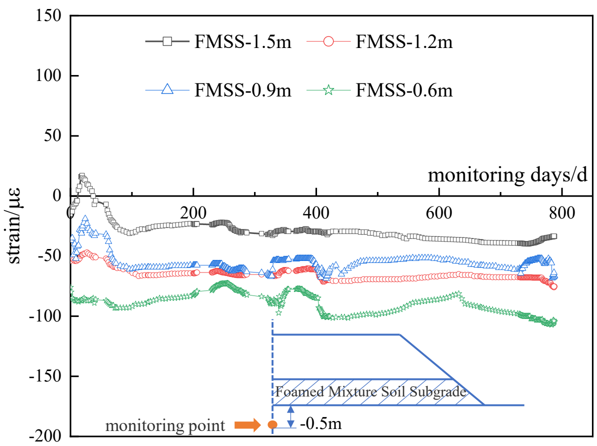


Figure 8. The strain variation curve of frozen soil foundation (-0.5 m).

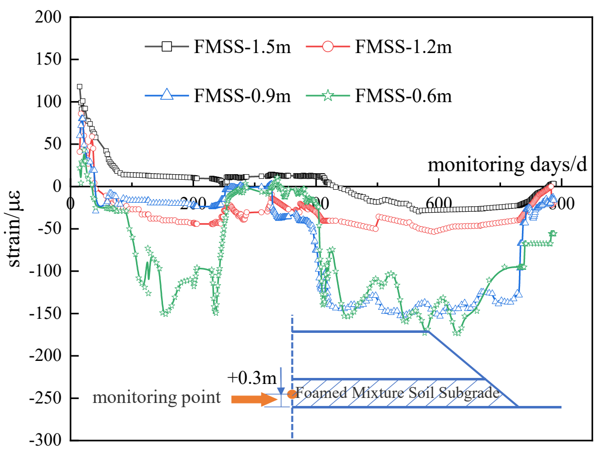


Figure 9. Strain variation curve of FMSS (+0.3 m).

Based on the monitoring results shown in Figures 8 and 9 it can be observed that the strain values of the frozen soil foundation (-0.5 m) under different thicknesses of FMSS exhibit slight fluctuations, and it remains stable after two freeze-thaw cycles. This indicates that the FMSS has significant thermal insulation performance. The frozen soil foundation exhibited negative strain values. As the thickness of the FMSS increases, the strain values decrease. This suggests a positive correlation between the thermal insulation capabilities of the FMSS and its thickness. Furthermore, the strain monitoring results at +0.3 m of the FMAA indicate that during alternating freeze-thaw cycles, the strain values typically follow a pattern: an initial positive increase, then a transition to negative decrease, and finally a negative decline. This trend can be attributed to the heat generated by cement hydration in the raw materials of the foamed mixture soil, leading to an increase in the initial strain monitored. As the freeze-thaw cycles alternated, the FMSS initially experienced cold contraction and compression, resulting in negative strain values. This was later followed by thermal expansion and tension, causing the strain value to offset and gradually approach zero from its previously compressed state. This behaviour demonstrates the FMSS's ability to utilize its porous nature under the influence of thermal cycles, converting external heat energy into elastic strain energy for absorption and release. When the thickness of the FMSS is augmented from 0.9 m to 1.2 m and 1.5 m, respectively, the latter's strain value exhibits a smoother transition, devoid of any abrupt peaks or lows during the cold and heat exchanges. It is hypothesized that a FMSS with a thickness of 1.2 m can satisfy the durability and thermal insulation demands during freeze-thaw cycles.

4 Discussion

4.1 Analysis of the Relationship between Temperature and Strain

Using the K415 monitoring section of the test segment treated with a 1.5-m thick FMSS as an example, temperature and strain data collected 0.5 m below the interface of the FMSS and the frozen soil foundation were examined. Additionally, data from 0.3 m above the interface, situated at the road's centerline, were analyzed for a detailed understanding of the internal variations. These analyses are illustrated in Figure 10.

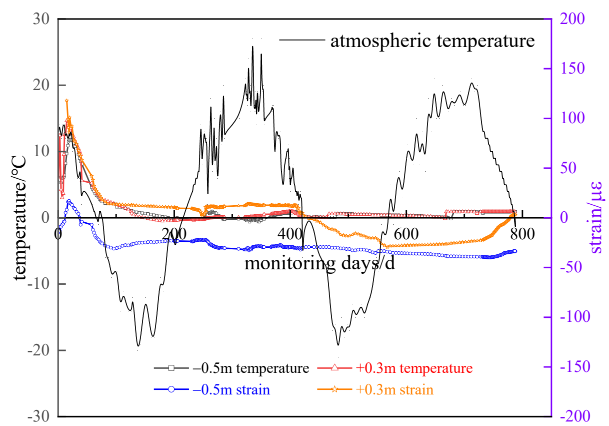


Figure 10. Temperature and strain monitoring of the FMSS and the frozen soil foundation.

As observed in Figure 10, the temperature at the position of the frozen soil foundation (-0.5 m) is consistent with the overall trend of strain. The strain of the original frozen soil foundation increased gradually due to the construction of the subgrade and the pavement structure layer of the FMSS at the initial stage of monitoring. However, the temperature of the frozen soil foundation increased initially because the thermal insulation effect of the foamed mixture soil was not fully exerted owing to the increase in the external temperature. With the decrease in external temperature and the effect of thermal insulation of FMSS, the temperature of the frozen soil foundation gradually tends to 0 °C, and the strain value is stable at -34 με (negative sign represents compression state), which further indicates that there is no significant impact, such as freeze-thaw or frost heave in the frozen soil foundation, after two free-thaw cycles.

There was a correlation and cross phenomenon between temperature and strain in the FMSS (+0.3 m). Figure 10 illustrates that the temperature of the FMSS closely mirrors that of the frozen soil foundation. However, a distinct disparity exists in the strain values at these two locations. This discrepancy primarily arises from the early stages of the foamed soil mixture pouring, where the release of hydration heat elevates the strain value, which then diminishes with a decrease in external temperature. Following a freeze-thaw cycle, the strain value in the FMSS approaches zero. This suggests that the minor expansion from its hydration heat release, the tensile strain from the stress diffusion of the load, and the shrinkage strain due to the external temperature reduction essentially offset each other. After the second freeze-thaw cycle, the FMSS exhibited a pattern of compressive–tensile strain even though the foundation's temperature and strain remained constant. This behaviour can be attributed to the intrinsic properties of the foamed soil mixture as a porous, lightweight elastomeric material. The energy from the periodic external temperature shifts gets absorbed and is transformed into elastic strain energy by the FMSS, thus effectively insulating the frozen soil foundation.

4.2 Analysis of Heat Conduction Physical Model of FMSS

Using the temperature and strain metrics from the previously monitored FMSS and the frozen soil foundation, a comparison was conducted with the gravel subgrade to evaluate the thermal insulation properties of the FMSS. Physical heat conduction models for the two distinct subgrade structures are illustrated in Figures 11 and 12.

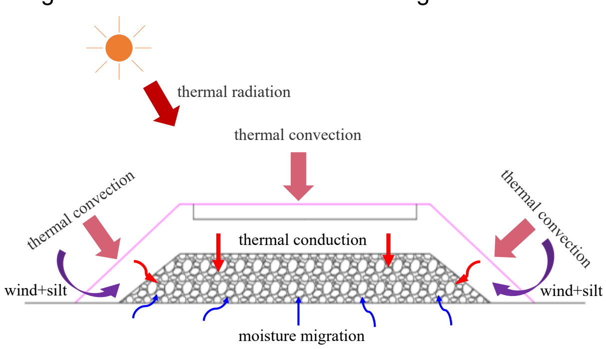


Figure 11. Heat conduction physical model of a gravel subgrade.

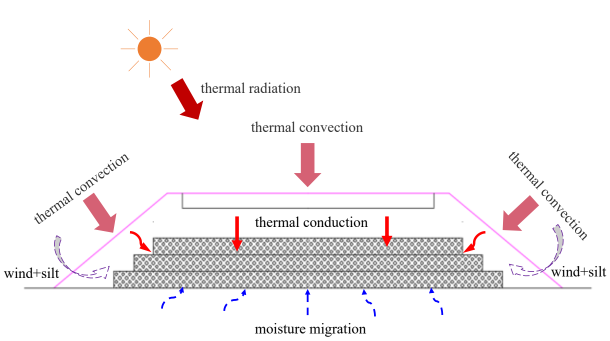


Figure 12. Heat conduction physical model of a FMSS.

Drawing from the research findings of Zhou (2008) and He (2021) and integrating the monitoring data, it can be assumed that, under seasonal freeze-thaw cycles, the frozen soil is primarily influenced by thermal radiation, thermal convection, and heat conduction in the external environment. When using a gravel subgrade, the spaces between the gravels create pores. Due to these pores, heat transfer to the lower part of the subgrade becomes challenging, especially under the influence of cold wind. Hence, the heat entering the permafrost is less than the heat exiting. Over time, wind and sand cause silty sand to accumulate within the gravel subgrade, filling these internal pores. Gradual compaction of the gravel subgrade produces capillary water. Enhanced water migration after multiple freeze-thaw cycles results in issues such as frost heave and thaw settlement within the frozen soil foundation. This underscores the limited long-term durability of the frozen soil foundation using a gravel roadbed. In treating frozen soil foundations with FMSS, its porous structure, minimal thermal conductivity, and high thermal resistance can significantly limit heat energy transmission. Concurrently, its strain monitoring values indicate strong heat storage capabilities. Through freeze-thaw cycles, the foamed mixture soil can transform transferred heat energy into strain energy for dispersal, effectively curtailing heat energy propagation and maintaining the frozen soil foundation's consistent temperature. Moreover, the cementitious plate structure of foamed mixture soil effectively prevents wind driven sand accumulation and condensation and migration of water, mitigating the effects of frost action from freeze-thaw on the frozen soil foundation. Consequently, a FMSS structure addresses the thermal preservation and insulation challenges of frozen soil foundations, enhancing the road structures' long-term durability and performance.

5 CONCLUSIONS

In this study, a test section of a seasonally frozen soil foundation treated with a foam mixture soil was evaluated. The thermal insulation performance of the FMSS applied to a frozen soil foundation, temporal and spatial variation in temperature and strain, and heat conduction transformation processes were analyzed. The main conclusions are as follows:

(1) The temperature of the gravel subgrade changes in accordance with the change in atmospheric temperature, and the change in temperature range is as high as 15.9 °C. At the same depth, the change in temperature range of the FMSS is between 1.4 °C and 6.2 °C, which is 60–90 % lower than that of a standard gravel subgrade.

(2) After two freeze-thaw cycles, the temperature of the FMSS and the frozen soil foundation are constant and trend to 0 °C; and the strain values correspond to compressive strain (in the state of cold pressure).

(3) Physical models depicting temperature variations and heat conduction in the frozen soil foundation for both gravel and FMSSs have been developed. The FMSS transforms externally transmitted heat energy into elastic strain energy while preventing wind, sand, and

water from entering the foundation. This furthers the sustained stability of the frozen soil foundation.

6 ACKNOWLEDGEMENTS

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