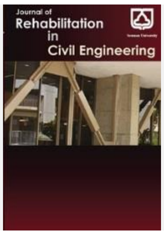

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Experimental Study on Frost Heaving of Soils under Unidirectional Freezing Considering Varying Percent Fines and Moisture Content

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ABSTRACT

Frost heaving is a significant geotechnical concern in cold regions, where subgrade soil is exposed to freezing temperatures. This phenomenon arises when water migrates to the freezing zone within the soil and forms ice lenses, causing volumetric expansion and upward soil displacement. The resulting heave poses serious challenges for infrastructure, affecting roads, pavements, and foundations, and often leading to costly repairs and structural failures. This study investigates the frost-heaving behavior of fine- and coarse-grained subgrade soils through controlled unidirectional freezing experiments, simulating in situ conditions found in frost-prone areas. Based on the preliminary geotechnical laboratory test results, the soil samples were classified for frost susceptibility using established frost susceptibility classification systems. Further, using a specially fabricated insulated mold, unidirectional freezing tests were performed in a controlled setup. Fine-grained soils were tested by changing the moisture content from 20 to 50%, while coarse-grained soils were tested by adding different amounts of fine particles ranging from 5 to 25%. The frost heave ratio (FHR) was measured over 48 h of freezing. The study found that moisture content of about 45% or more significantly increases frost heave in fine-grained soils. Whereas in coarse-grained soils, the frost-heave ratio rises with fines content up to 20%, beyond which it decreases. The study further recommends that increasing the thickness of pavement layers is an effective measure to mitigate frost heaving in cold climate regions.

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1. Introduction

Frost heaving can significantly influence infrastructure, such as roads and foundations, depending on the type of soil and its capacity to retain and transport water. Fine-grained soils, such as silts and clays, are commonly known for higher susceptibility to frost-heaving due to their water-retention properties, while coarse-grained soils (CGS), such as sands and gravels, exhibit lower frost-heaving potential. Researchers have shown that CGS experiences minimal frost heave when fines content is within a certain limit, beyond which, these soils also exhibit significant frost heaving. Laboratory freezing tests on crushed stones with different amounts of fine particles (5–15%) and clay (kaolinite) content (10–100%) showed that the risk of frost damage increases as the amount of fines and clay goes up. The frost effect keeps increasing steadily until fines go over 15%, at which point the fine material forms a packed layer around the larger particles [1]. A series of unidirectional freezing tests found that the frost heave susceptibility of well-graded gravels is affected positively by moisture content and percent fines [2]. A study on coarser soils with 5 to 45% fine particles highlighted that initially frost heave increases with fines content, reaching the highest point around 20% fines, then starts to decrease [3]. Based on a laboratory study on 47 samples with different fines content, dry density, overburden pressure, and water supply (open or closed) it was revealed that having 9% fines in coarse-grained soils is ideal for reduced frost heaving and effective compaction [4]. U.S. Army Cold Regions Research and Engineering Laboratory tests showed that frost heave in crushed limestone increases steadily as fines increase. Soils with 8% fines or less performed well, but those with more than 8% fines did not meet the required standards [5]. Frost heave in coarse-grained soils is found to be affected by fines content (2.7-16%) and other factors such as freezing temperature (-5 °C to -15 °C) and water availability. In open systems, freezing at -15 °C delayed the ice formation by 17 h, while fines caused a 5-h delay [6]. A series of 1-D freezing experiments conducted to simulate frost heave in saturated coarse-grained soil with variable fines content showed that coarse soils with 6% or more fines can develop frost heave when fully saturated due to the formation of ice lenses [7] Investigations into water table height revealed that lowering of water levels reduce frost heave and water intake rates in silty soils [8]. Thus, findings based on the available literature principally suggest a linear increase in frost heave with rising fines content and presence of water in the soil.

Structural improvements in the form of embankments consisting of geotextile, crushed-rock layer, and geomembrane have effectively reduced frost penetration and thaw depth compared to conventional CGS fills [9]. Additionally, soil stabilization using waste materials (e.g., fly ash, slag) and fiber-reinforced cement-treated sand can enhance frost resistance by improving strength and reducing water permeability [10]. High-volume GGBFS (Ground Granulated Blast Furnace Slag) in concrete pavement further mitigates frost heaving by lowering thermal conductivity and minimizing ice lens formation [11]. These sustainable techniques offer cost-effective solutions for frost-susceptible subgrades in cold regions.

Studies have reported that frequent freeze-thaw cycles often lead to depressions or upward deformation in the pavements [12]. Fig 1. shows typical pavement conditions in frost-affected regions during the winter season [12]. In the Indian context, similar conditions are prevalent in cold regions like Jammu and Kashmir. Despite significant progress in understanding frost heaving worldwide, readily available studies on frost heave behavior of soils in India are limited. Thus, the present study aims to understand the frost heave behavior of soils from the Kashmir region to freezing, considering two important factors, namely, percent fines and in situ moisture content. The soil samples collected from the Kashmir region are used in performing unidirectional freezing (i.e., freezing exclusively from top to bottom) experiments to study the frost-heaving ratio in both fine- and coarse-grained soils.

a) Cracks on pavement due to frost heaving b) Upward bulge in pavement surface

Fig. 1. Typical pavement conditions in frost-affected region during winter season [12].

2. Description of study area

The typical composition of soil in the Kashmir Valley, particularly in the Srinagar region, is predominantly fine-grained, which can be classified as silty or clayey, having intermediate to high plasticity. Further, due to the presence of Quartz and either Illite or Kaolinite clay minerals, these soils normally have low swelling potential and low activity. A detailed description of geotechnical characterization and mineralogical evaluation of soils in Jammu and Kashmir is readily available in the literature (e.g., [13,14]). Topographically, Srinagar is situated at an average height of 1719 meters above sea level and is situated between 74°39' and 75°79' East longitude and 33°52' and 34°45' North latitude. The area receives an average annual rainfall of 650 mm, and winter temperatures range between -2 °C and 8 °C [15]. According to [16,17], the road network in Jammu and Kashmir has expanded significantly in recent years. However, despite this progress, many roads remain in poor condition due to a lack of proper maintenance. As mentioned earlier, existing studies show that frost-related problems, such as frost heave and differential settlements, are common in cold regions. Fig. 2 presents the geographical map of the study area. Fig. 2 provides a depiction of the topography and climatic conditions of the region that are critical to frost-related behavior. Rashid et al [18] identified frost heaving as a major concern in several regions in the Kashmir valley. The present study seeks to further explore and comprehend the occurrence of frost heaving in the local soil.

2.1. Frost susceptibility classification of the study area

A crucial step in understanding behavior under freezing conditions is to first classify soils in the study area based on their frost susceptibility. By prioritizing this classification, the research effectively targets soils with high frost-heaving potential, optimizing the relevance and impact of subsequent experiments. The classification evaluates the frost-heaving potential of diverse soil types, focusing on the differentiation between fine-grained soils (e.g., silts and clays) with high frost susceptibility and coarse-grained soils (e.g., sands) with relatively lower susceptibility. Before the frost susceptibility classification, soil samples were also classified as per the IS Soil Classification System [19]. To ensure a comprehensive and reliable assessment, three established frost-susceptibility classification systems were used, including the IRC SP48 [20], Swiss Susceptibility Criteria [21], and US Army Corps of Engineers [21]. The IRC SP48 [20] provides guidelines tailored to Indian conditions, making it particularly relevant for the study region, the Swiss Susceptibility Criteria [21] is widely recognized for its precision in identifying frost-prone applications soils in cold climates, while the US Army Corps of Engineers classification [21] is a globally accepted standard known for its reliability in evaluating frost heave potential. Table 1 summarizes the criteria used to classify soil frost susceptibility by different international standards. In this study, a soil sample is regarded as frost susceptible if it conforms to the susceptibility criteria specified by any of the adopted frost-susceptibility classification systems.

Fig. 2. Geographical map of the study area (Source: Google Maps 2024).

Table 1. Soil classification and frost susceptibility criteria according to various international standards.

Soil Type	Grain Size (mm)	Soil Classification	Frost Susceptibility Classification		
		IS: 1498-1970 [19]	IRC SP48 [20]	Swiss Susceptibility Criteria [21]	US Army Corps of Engineers [21]
Clay	<0.002	CI, CH (Clay of Intermediate/High Plasticity	Frost Susceptible	Frost Susceptible (High Plasticity)	Frost Susceptible (High Frost Risk)
Silt	0.002-0.075	MI, ML (Silt of Intermediate/Low Plasticity)	Highly Frost Susceptible	Highly Frost Susceptible	Frost Susceptible (High Frost Risk)
Silty Sand	0.075-0.425	SM (Silty Sand)	Moderately Frost Susceptible	Moderately Frost Susceptible	Moderately Frost Susceptible

Following IRC-37 [22], soil samples were collected at depths of 25 cm to 45 cm, from various locations across Badgam and Srinagar districts in the Kashmir region. As a preliminary requirement for frost susceptibility classification, particle size analysis was done for a set of soil samples. Based on the typical observations from the particle size distribution curves, Soil sample A collected from the Budgam district was found to have more granular fraction, representing a lower frost susceptibility soil, while Soil sample B obtained from the Srinagar district with a higher fine-grained fraction was anticipated to have higher frost susceptibility. Fig. 3 shows the typical particle size distribution curves for Soil Sample A and Sample B.

As it is evident from Fig. 3, soil sample B reveals its likely composition as silt or clayey silt, based on its high percentage of fine particles (<0.075 mm). Fine-grained soils such as silt are particularly prone to frost susceptibility due to their ability to retain water within their small pores. Following the relevant Indian Standard, additional geotechnical tests were performed to check the index properties of the soil samples. Table 2 shows geotechnical index properties of the soil samples.

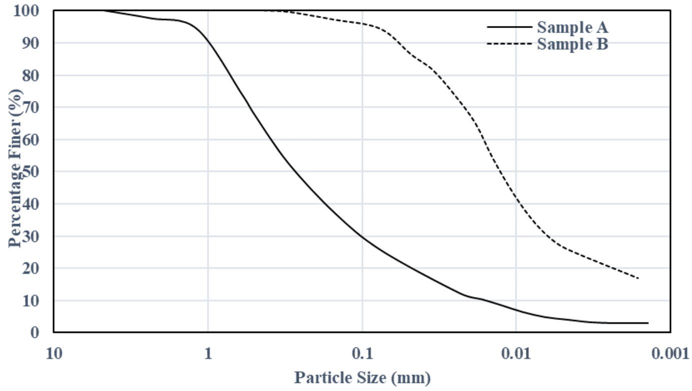

Fig. 3. Particle size distribution curves of soil samples A and B.

Table 2. Geotechnical index properties of soil samples A and B.

Parameter	Soil Sample A	Soil Sample B
Specific Gravity	2.67	2.45
Soil Fraction < 0.075 mm (%)	25	94
Soil Fraction < 0.02 mm (%)	12	73
Liquid Limit (%)	22	27
Plastic Limit (%)	18	19
Plasticity Index (%)	4	8

Thus, based on the index geotechnical properties of soil samples A and B shown in Fig. 3 and Table 2, it can be concluded that soil sample B exhibits characteristics consistent with frost-susceptible soils. The properties of soil sample B suggest that it has the potential to retain moisture and undergo frost heave under freezing conditions, making it highly susceptible to frost action. Table 3 presents a comparison of soil sample B with frost susceptibility requirements for different classification systems. From Table 3, evidently, Soil sample B is classified as highly susceptible as per the frost susceptibility classification systems considered.

Table 3. Comparison of frost susceptibility classification systems and evaluation of soil sample B.

Classification System	Criteria for Highly Frost Susceptible Soils	Details for Soil Sample B
IRC SP48 [20]	Fine-grained soils with high silt content (e.g., silts or silty clays) and a Plasticity Index (PI) <10.	Liquid Limit = 27%, Plastic Limit = 19% and PI = 8%, Fines content = 94%, fits as highly frost susceptible.
Swiss Susceptibility Criteria [21]	Soils with grain size <0.02 mm exceeding 15%.	Grain size distribution shows significant proportion <0.02 mm is 73%, making it highly frost susceptible.
US Army Corps of Engineers [21]	Fine-grained soils such as silts or clayey silts, characterized by low permeability and high moisture retention.	Specific gravity = 2.45 (indicative of silty soils), with characteristics supporting frost susceptibility.

3. Experimental program for studying frost heave

The experimental program for studying frost heave included two stages. In the first stage, the mold for conducting experiments is prepared and calibrated to ensure accurate testing, and in the second stage, soil samples are prepared & tested for frost behavior. To ensure unidirectional freezing, a low-cost experimental set-up was fabricated. Geotechnical index properties such as specific gravity, liquid limit, plastic limit and grain size distribution were determined to classify soil samples. During the freezing process, parameters such as temperature and heave displacement have been monitored and recorded at regular intervals. Post-experiment, frozen samples have been analyzed for frost heave ratio to assess the frost susceptibility of the soil. This systematic framework ensured a comprehensive evaluation of frost heaving characteristics under unidirectional freezing conditions. Fig. 4 outlines the process of the experimental programmer for frost heaving analysis.

3.1. Preparation of mold

The experimental setup and procedure were developed based on the methods drawn from existing literature [2,4]. For conducting frost heave experiments, a double-layer thermo-steel cylindrical mold was utilized to ensure controlled and consistent unidirectional freezing from the top side. Fig. 5 shows the mold, designed with a dual-layer thermos-steel structure, having a length of 17 cm, an external diameter of 9 cm, and an internal diameter of 8 cm. The gap between the inner and outer layers, measuring 0.5 cm, was filled with thermocol insulation to reduce heat transfer and better isolate the cooling direction, thereby facilitating unidirectional freezing during the tests. Four linear measurement scales were placed diametrically opposite to each other inside the mold to measure the average heaving in soil samples. Fig. 6 illustrates various aspects of the testing setup, including: (a) freezing chamber capable of reaching temperatures below -12 °C, (b) mold calibration, (c) the mold structure and (d) the placement of the soil sample inside the mold.

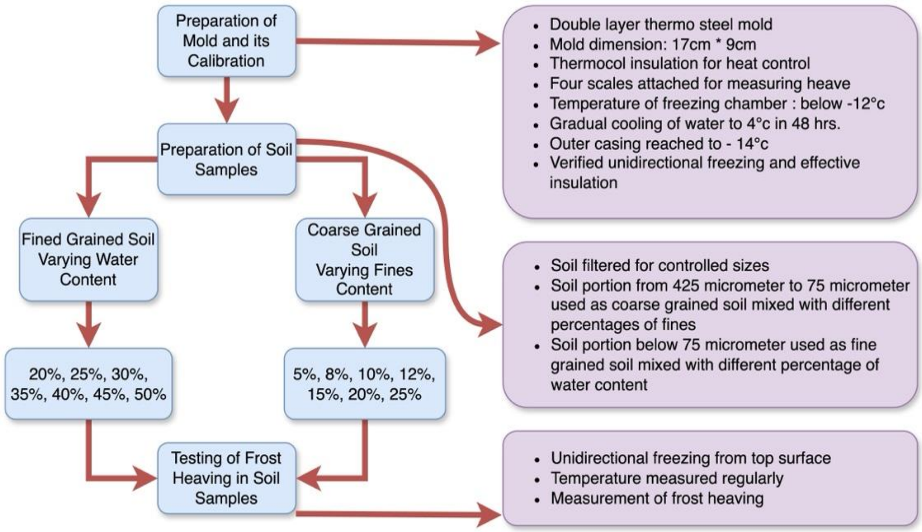

Fig. 4. Flowchart of experimental procedure for frost heaving analysis.

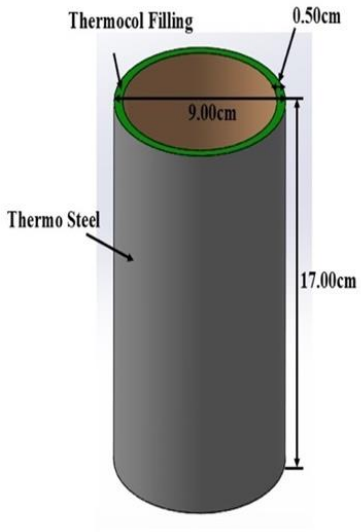

Fig. 5. Cross-sectional design of frost heave test mold with thermocol insulation and steel casing.

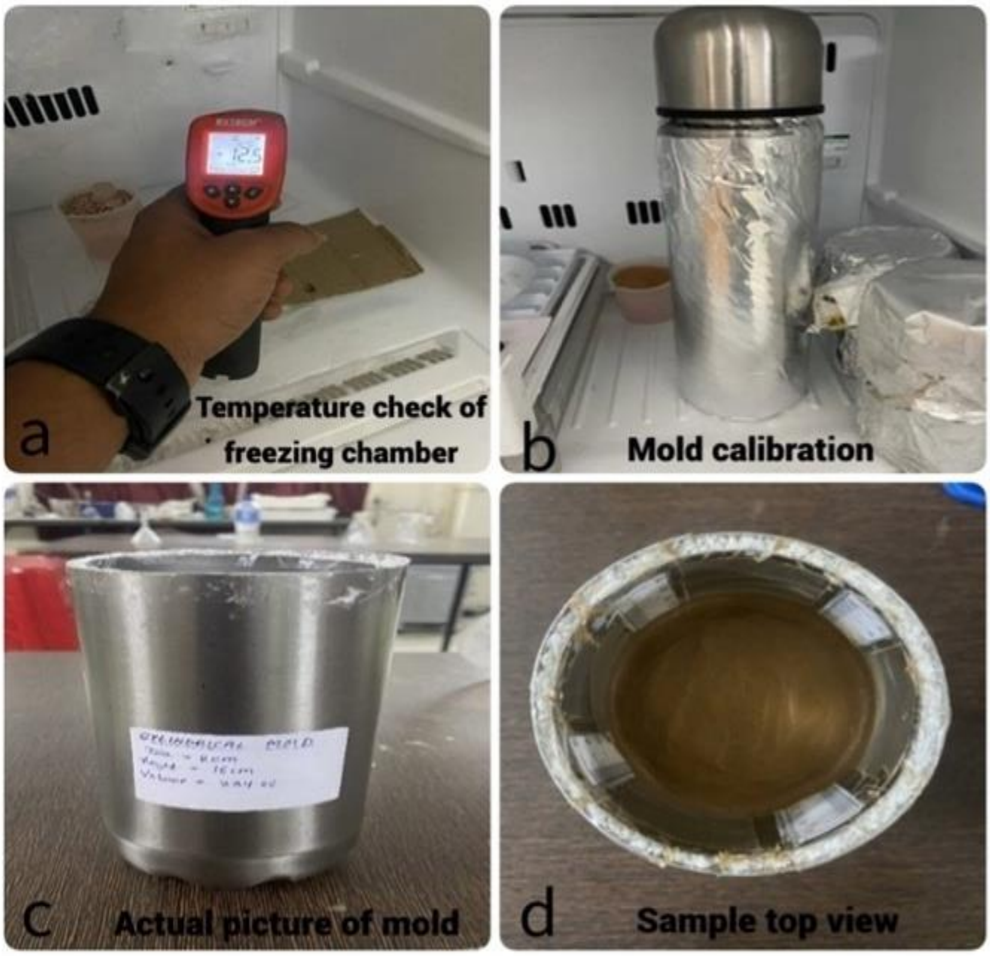

Fig. 6. Laboratory setup for unidirectional freezing test: a) freezing chamber temperature calibration, b) mold calibration c) mold preparation, d) assembled mold with sample (top view).

3.2. Mold calibration

Mold calibration is an important step to confirm its efficiency to support unidirectional freezing. For calibration, water was filled into the mold and placed with its top face open in the freezer of the cooling device. Three such trials were conducted. The temperature readings from all three trials indicated a steady drop in the outer casing temperature over time, which means the cooling system and insulation worked well. The water inside the mold also cooled gradually and reached up to 4 °C by 48 hours but did not freeze, showing that the freezing process was controlled and effective. By the end of the trials, the outer casing temperatures were between -12 °C and -14 °C, proving that the mold could create the right thermal conditions for unidirectional freezing. Table 4 summarizes temperature data monitored during mold calibration. From the mold calibration test data shown in Table 4, it is evident that the mold is well-suited for unidirectional freezing experiments.

Table 4. Temperature monitoring during mold calibration for unidirectional freezing.

Trial 1			Trial 2			Trial 3		
Time (h)	Temperature of Mold - Outer Casing (ºC)	Temperature of Water (ºC)	Time (h)	Temperature of Mold - Outer Casing (ºC)	Temperature of Water (ºC)	Time (h)	Temperature of Mold -Outer Casing (ºC)	Temperature of Water (ºC)
00	16	22	00	13	22	00	13	24
24	-5	10	24	-8	9	24	-9	9
30	-8.5	7	30	-10	6	30	-12	7
48	-12	5	48	-14	4	48	-14	5

3.3. Sample preparation and frost heave testing

As described earlier, the frost susceptibility classification of soil samples A and B from the Kashmir region revealed that the soil sample B from Srinagar district has been found as most susceptible to frost heave, showing characteristics typical of fine-grained soils with a high silt content. Therefore, soil sample B is used for further experimentation to study frost heave behavior. To study the effect of varying fines content in coarse-grained soil, the coarser fraction of the soil sample B is used for frost heaving. For this purpose, soil sample B was carefully sieved to have particles that passed through a 425-µm sieve but were retained over a 75-µm sieve. This ensures the soil particles are mainly fine-grained sand or silt. The chosen particle size likely affects the ability of soil to draw in and hold water, which are key factors deciding the soil behavior when exposed to freezing conditions. Further, to study the effect of water content on frost heaving in soil, the fraction of the soil sample B below a 75-µm sieve was used for the preparation of fully saturated specimens. To ensure full saturation, sufficient water was added to the specimens so that it yields a water content higher than the optimum moisture content (i.e., 18%). Knowing the bulk unit weight of the specimen and its actual water content, the dry density of the specimen was back calculated. The Frost Heave Ratio (FHR) was calculated to quantify soil displacement during freezing [2], expressed as:

$$\mathrm{FHR}(\%) = \left(\frac{\Delta \mathrm{H}}{\mathrm{H_0}}\right) \times 100 \quad (1)$$

where ΔH = average change in soil height after freezing obtained by taking an average of readings of four measurement scales placed inside the mold, and $\mathrm{H_0}$ = initial soil height specimen in the mold before freezing.

4. Results and discussion

In the present study, the behavior of soil from the Kashmir region (i.e., sample B from Srinagar district) is studied under unidirectional freezing conditions. Experimentation was conducted using a double-layer thermo-steel mold, which was carefully calibrated to ensure consistent and controlled freezing conditions. A set of experiments has been performed on fine fractions (-75 µm) of the soil sample B by adjusting the water content, and on coarse-grained fractions (-425 µm to +75 µm) of the soil by changing the fines content, to understand the effect of these factors on frost heaving. The observations and results of the experimentation are discussed below.

4.1. Study on the influence of water content on frost heave

In this series of experiments, a fine-grained fraction of soil sample B was selected, and fully saturated specimens were tested at water content in the range of 20 to 50% to investigate the impact of in situ moisture on frost heaves. The change in soil volume has been measured at specific time intervals: 0, 24, 30, and 48 h. This approach helped to observe how different moisture levels and freezing durations affected the expansion of soil during the frost heave process. Table 5 summarizes the experimental observation data on frost heaving behavior of fined-grained soils with varying water content. Table 5 also indicates the interaction between water content, freezing time, and the resulting soil volume changes. The dry density values indicated in Table 5 are determined using the bulk density and water content of the tested specimens. The results demonstrated that moisture content significantly impacts the degree of frost heaving. Soil samples with 20 and 40% water content showed minimal or no volume change during freezing. The lack of frost heaving happens because there is not enough extra water in the soil to form continuous ice layers.

Table 5. Frost heaving behavior of fined grained soil with varying water content.

Water Content (%)	Dry Density (g/cm³)	Time (h)	Temperature of Soil Sample (ºC)	Height of Soil Sample (cm)	Change in Height (cm)	FHR (%)
20	1.64	0 24 30 48	15.3 -10 -12.6 -14	11 11 11 11	0	0
25	1.52	0 24 30 48	16 -11.5 -13.8 -15.5	11.5 11.5 11.5 11.5	0	0
30	1.41	0 24 30 48	18.7 -13 -13.5 -15	11.5 11.5 11.5 11.5	0	0
35	1.32	0 24 30 48	17.6 -14.3 -16 -16.5	11.5 11.5 11.5 11.5	0	0
40	1.23	0 24 30 48	16 -15 -17 -17	11.8 11.8 11.8 11.8	0	0
45	1.16	0 24 30 48	18 -13 -16 -16	12.2 12.2 12.3 12.3	0.1	0.81
50	1.10	0 24 30 48	13 -12 -11.6 -11.8	12.5 12.5 12.7 12.8	0.3	2.4

At these water levels, the water freezes at its location without moving to create separate ice lenses, which prevents the soil from expanding. However, at higher moisture levels (45 and 50%), frost heaving became more obvious, with the sample at 50% moisture content exhibiting the greatest frost heave ratio and a notable increase in height after 48 h of freezing. These findings suggest that, irrespective of their mineralogical composition, at higher water content (45% or above), fine-grained soils are susceptible to frost heaving.

4.2. Study on the influence of fines content on frost heave

In this series of experiments, a coarser fraction of the soil sample B (referred to as coarse-grained soil) was tested for frost heaving behavior by varying the fines content within the soil. The percentage of fines added to the coarser fraction was incrementally adjusted from 5-25%. This range was selected to analyze the effect of low to moderate fine content on the frost heaving ratio, as even small amounts of fines can significantly influence water retention and freezing behavior. For each variation in fine content (5%, 8%, 10%, 12%, 15%, 20% and 25%), the fully saturated soil specimens were prepared and subjected to unidirectional freezing in the thermo-steel cylindrical mold at constant water content of 45% with dry density of 1.16 g/cm³. Table 6 summarizes the experimental observation data on frost heaving behavior of coarse-grained soil under varying fines content.

From Table 6, it is evident that no significant vertical displacement or frost heaving was observed corresponding to 5%, 8%, and 10% fines content, and FHR values are negligible. The absence of frost heaving in soils with up to 10% fines content can be attributed to the insufficient availability of fines to form a continuous, interconnected matrix that can effectively retain and transport water under freezing conditions. Fines, primarily consisting of silt and clay particles, have a high specific surface area and a strong affinity for water. However, when present in low proportions (up to 10%), they are dispersed within the coarser soil matrix, limiting their ability to significantly influence the hydraulic and thermal properties of soil.

Table 6. Frost heaving behavior of coarse-grained soil with varying fines content.

Fines Content (%)	Time (h)	Temperature of soil sample (ºC)	Height of Soil Sample (cm)	Change in Height (cm)	FHR (%)
5	0	15.3	14	0	0
	24	-12	14		
	30	-12	14		
	48	-16	14		
8	0	16	11	0	0
	24	-11.5	11		
	30	-13.5	11		
	48	-15	11		
10	0	17	9.5	0	0
	24	-12	9.5		
	30	-13	9.5		
	48	-15	9.5		
12	0	17.5	11	0.2	1.8
	24	-15	11		
	30	-16	11.2		
	48	-16.5	11.2		
15	0	16	9.5	0.5	5.2
	24	-14	9.6		
	30	-16	10		
	48	-17	10		
20	0	-15	9.8	0.6	6.1
	24	-16	10		
	30	-15	10.4		
	48	-18	10.4		
25	0	-16	10.1	0.5	4.95
	24	-16.5	10.1		
	30	-16	10.6		
	48	-17	10.6		

At 12% fines content, a change in the height of the soil sample was observed, with an increase of 0.2 cm at the start of the freezing process, and the FHR reached 1.8% by the 48th hour of freezing. At 15% fines content, the vertical displacement was more noticeable, with an initial change in height of 0.5 cm and a final FHR of 5.2% after 48 hours. This suggests that the increased fines content has started to influence water retention, leading to frost heaving. These results indicate that as the fine content increases, the water-holding capacity of soil increases, causing noticeable frost heaving. However, the displacement is still moderate, reflecting a balanced effect between the coarse and fine soil fractions. At 20% fines content, the FHR reached 6.1%, with an initial height change of 0.6 cm. This shows a further increase in frost heaving as more fine particles are introduced into the soil. At 25% fines content, however, the FHR dropped to 4.95%, with a smaller height change of 0.5 cm. This decline suggests that beyond a certain limit (around 20% fines content), the ability of the soil to retain water for frost heaving may begin to decrease. Fig. 7(a-c) shows the evidence of soil expansion in coarse-grained soil samples after 48 hours under freezing temperature at different fines content. Fig. 7(b) shows maximum expansion in the soil sample at 20% fines content.

4.3. Discussion and comparison of findings with literature

Based on the observations of unidirectional freezing presented in the previous sections, the two major findings of the study are: (a) higher water content (i.e., about 45-50%) in fine-grained soils lead to a significant increase in frost heaving, and (b) minimal frost heave is observed in coarse-grained soils with ≤10% fines, but susceptibility increases at 20% fines. Both these findings compare well with existing literature. Konrad and Lemieux [1] observed significant heave at 15% fines, Wang et al. [3] reported a maximum of 9% fines for frost susceptibility mitigation, Tester and Gaskin [5] noted 8% as the critical limit for fines beyond which excess fines results in significant frost heaving. Likewise, Hermansson.[8] showed that moisture content and water table height are critical to reduce frost heave up to 32.5%. Thus, previous studies confirm the findings of the study and suggest keeping fines content and moisture within certain limits to reduce frost problems.

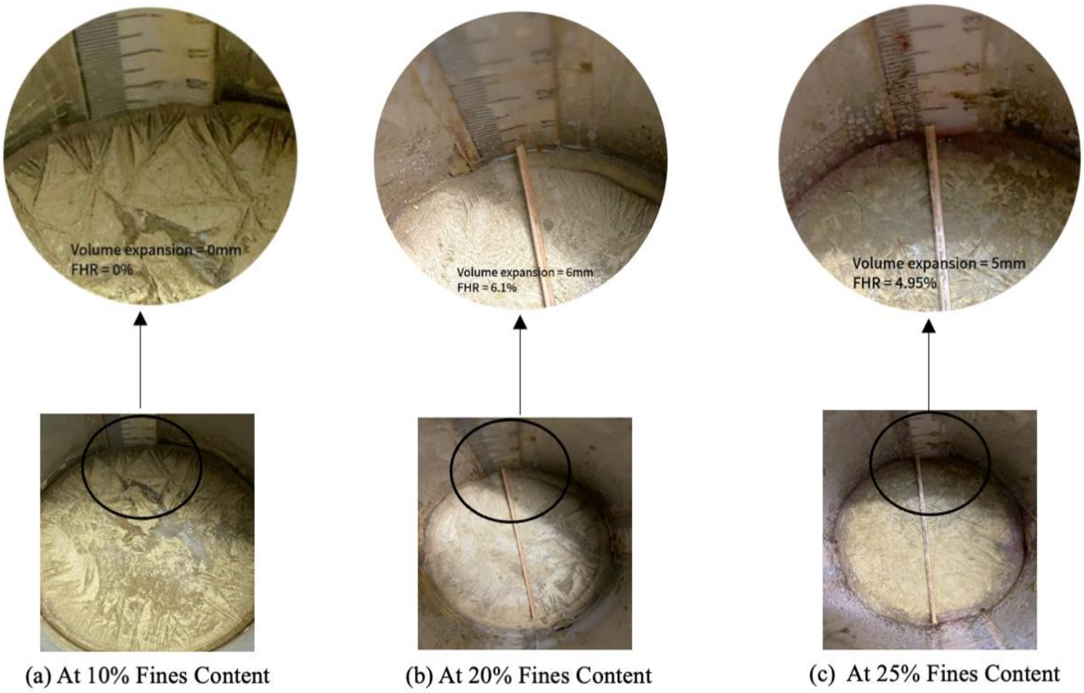

Fig. 7. Coarse-grained soil samples after 48 hours under freezing temperature at different fines content.

5. Strategy to mitigate the effect of frost in the soil

While designing pavements in frost-prone regions, the effects of frost action must be carefully considered to ensure long-term durability and performance. Lai et al. [9] emphasized structural embankment layers to reduce frost penetration. According to the IRC-37 [22], to mitigate frost effect, a minimum total pavement thickness of 450 mm is recommended even when the CBR value of the subgrade warrants a smaller thickness. In the present case, a frost heaving ratio of 6.1% suggests a significant risk of frost heaving, which may affect the pavement structure. To mitigate the frost action, the design should include an adequate thickness of granular sub-base (GSB) material above the subgrade to prevent frost penetration and minimize heaving. A thicker GSB layer helps stop the frost from reaching the frost-susceptible soil by slowing down the movement of cooling and water. This way, the pavement structure remains stable during freezing and thawing cycles. Fig. 8 shows the minimum required pavement thickness for frost-susceptible and non-susceptible zones [22].

6. Concluding remarks

This study provided valuable insights into frost heaving behavior of fine- and coarse-grained soils, specifically highlighting the critical role of water content and percent fines. In fine-grained soils, frost heave became noticeable when the moisture content reached 45% or more, with the peak movement seen at 50% water content. This aligns with the optimum moisture content (OMC) of 18% for these soils, showing that water content greater than OMC greatly increases the risk of frost heaving. Further, coarse-grained soils exhibit minimal frost heaving up to 10% fines content, but as the fine content increases to 20%, frost heave becomes more pronounced, followed by a decline, indicating an optimal range for fines. Given the significant frost heave ratio of 6.1%, design measures should include adequate frost protection,

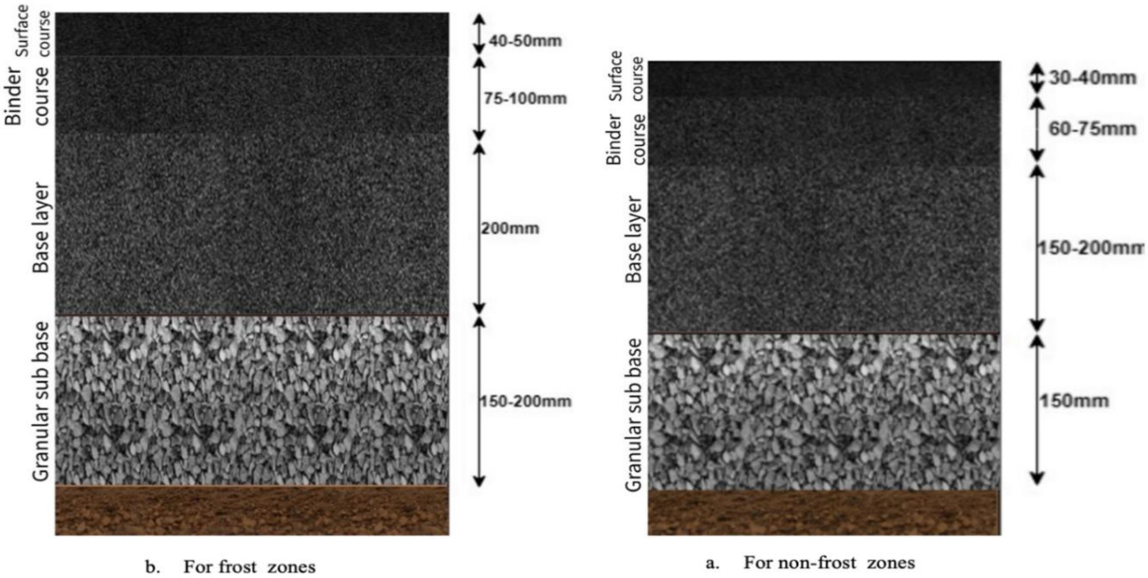

Fig. 8. Pavement cross-section recommendations for frost and non-frost zones [22].

such as a sufficient thickness of granular sub-base material to prevent frost penetration. The present study primarily investigated the frost heave under bare soil conditions subject to unidirectional freezing, without explicitly simulating pavement layers. Despite a few limitations, including a small-scale experimental setup, omission of the effect of pavement layers and surcharge loading, the present study provided a valuable insight into the frost heave behavior of soils in Indian conditions and apprised the significance of considering frost heaving while designing pavements in cold weather regions.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors contribution statement

Shahrukh: Methodology; Sample collection; Experiments; Writing.

Vikas Pratap Singh: Writing- review and editing; Conceptualization; Methodology; Overall supervision.

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