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Effect of Freeze-Thaw on CBR in Soils with Different Gradation and Mineralogy

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ABSTRACT

Freeze-thaw cycles are prevalent climatic phenomena with substantial effects on soils, leading to alterations in soil strength, stiffness, and hydraulic properties due to disruptions in the soil structure. With the ongoing climate change, weather patterns have grown progressively erratic, resulting in more frequent occurrences of extreme weather events, including heavy snowfall, intense rainfall, and windstorms, even in regions characterized typically with mild climates across the globe. The climate change can potentially threat man-made infrastructure constructed within or upon local soils, regardless of their susceptibility to freezing in temperate climates. The principal objective of this study is to assess the influence of freeze-thaw cycles on the California Bearing Ratio (CBR %) across 12 distinct soils with variations in granulometry and mineralogy. The freeze-thaw cycles resulted in a notable decrease in CBR (%) within the range of 40% to 70%. A strong inverse correlation with D_{50} was observed regarding the decrease in CBR (%). Nevertheless, it was discerned that the decrease in CBR (%) subsequent to freeze-thaw cycles varied among soil samples sharing identical D_{50} and liquid limit characteristics. The aim of this study is to enhance our comprehension of how freeze-thaw cycles can impact the bearing capacity of these soils, thereby providing essential insights for predicting their behavior and potential influence on infrastructure in the context of climate change.

Keywords: Grain size distribution, mineralogy, liquid limit, freeze and thaw, CBR (%).

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1. INTRODUCTION

Permafrost and seasonally frozen soils cover about 24% of the Earth's surface, with global climate change linked to deeper active layers and increased thaw thickness in permafrost regions [1-3]. Climate change has led to unpredictable weather patterns, causing more frequent extreme events worldwide. In areas with seasonal freezing, subgrade and foundation soils are significantly affected by recurring freezing and thawing cycles, disrupting the geotechnical properties of compacted soils and potentially causing structural failures [4-6].

Frost-sensitive soils, vulnerable to frost action, exhibit surface heave, influenced by factors like fines content, specific surface area, and mineralogy. Soils with over 6% fine particle content are more susceptible to frost heave [7-14]. Frost action is influenced by internal and external factors, including soil grain size distribution, structure, specific surface area, chemical properties of pore fluids, confining pressure, water source, and temperature variations. Particularly, the relationship between decreasing particle size and increased susceptibility to frost heave is widely acknowledged [15-21].

Numerous studies have explored the impacts of freeze-thaw cycles on soil mechanical properties. Different dry densities result in varying responses to freeze-thaw cycles, with a critical dry unit weight governing soil behavior [22]. Soil cohesion decreases with freeze-thaw cycles, while the internal friction angle shows varying trends [23-24]. Freeze-thaw cycles affect stress-strain curves differently at various freezing temperatures, influencing resilient modulus and ultimate strength [25-26]. Research on specific soil types demonstrates strain-hardening behavior, declines in elastic modulus, cohesion, and peak undrained shear strength, followed by stabilization after a certain number of freeze-thaw cycles [29-32].

The effect of freeze-thaw on the bearing capacity of subgrade soils has indeed been investigated by some researchers. Kawabata et al [27] investigated the effects of freezing and thawing on the CBR (%) and concluded that freeze-thaw cycles can significantly affect the CBR (%), even in air-dried samples. Factors affecting the CBR (%) after freeze-thaw include changes in particle size distribution, void ratio and water content. Similarly, Işık et al. [28] noted a decrease in the CBR (%) ranging from 21% to 86%, with the maximum change in CBR (%) occurring in the soil characterized by the highest liquid limit.

Various studies have conducted freeze-thaw tests, but there are notable differences in the test conditions between different research reports, as shown in Table 1. These conditions include freezing and thawing temperatures, duration, and number of cycles. While freezing temperature has a minor effect, the researchers in Table 1 emphasize the critical role of the number of cycles. It is suggested that soil changes significantly up to a certain number of freeze-thaw cycles, beyond which soil properties stabilize.

This study investigates the impact of freeze-thaw cycles on the CBR (%) for 12 soils with varying granulometry and mineralogy. While subgrade soil freezing sensitivity is typically considered for cold climates, frost-sensitive local materials may also be used in moderate climates, especially beneath large embankments or roadways. However, with climate change inducing unpredictable weather patterns, even mild climates are expected to experience significant freeze-thaw effects. This poses a risk to critical infrastructure in major cities, leading to substantial damage during adverse weather events, which are becoming more frequent. The study aims to enhance our understanding of how freeze-thaw cycles influence the bearing capacity of these soils. Such insights are crucial for predicting soil behavior and potential impacts on infrastructure in the context of climate change.

Table 1 - Number of freeze-thaw cycles and freezing-thawing temperatures from the literature

References	Temperature (^{0}C)		Duration (h)		Number of test cycles	Threshold cycle
	F	**T**	**F**	**T**		
[22]	-2 to -20	20	until frost heave cease	until thaw settlement cease	1	-
[23]	-5, -15	20	12	12	1, 2, 3, 5, 6, 7, 8, 9, 11, 12	7
	-10	20	12	12	1, 3, 7, 9, 12	
[25]	-5, -10, -15	25	12	12	0,5,10,20,30	-
[26]	-7	14	18	6	1,3,5,7,10,15,21	7
[30]	-10	10	3	3	1, 3, 5, 9	5
[31]	-40	20	12	12	0,1,3,6,9,12,15	6
[32]	-6, -12	15	12	12	0, 3, 6, 9, 12	4-6
[33]	-4, -18	20	24	24	3,6,9	-
[34]	-23	21	24	23	12	-

2. MATERIALS AND EXPERIMENTAL PROGRAM

2.1. Soil Properties

A total of 12 soil compositions were used in this study, formed by adding varying proportions of sand and gravel into three distinct types of fine soil. These fine soils, designated as A, B, and C, exhibited liquid limits determined by fall cone tests as follows: 44%, 78%, and 121.4%, respectively. The corresponding plasticity limits were found to be 26%, 36% and 60% respectively. On the Casagrande plasticity chart, these fine soils are close to the A line (Figure 1). According to the British Soil Classification System (BSCS) [35], the fine soils are classified as CI-MI (A soil), MV (B soil) and ME (C soil).

The mixed soils are identified by the types of fine materials they contain, in addition to varying fine content, which varies from 25% to 75%. The minimum main grain size for all these soils is 0.0009 mm, while the maximum reaches 1.2 mm. The liquid limits of the soils were determined using both the Casagrande test (LL_{CUP}) and the fall cone test (LL_{FC}). The plasticity indexes of the soils range from 13.8% to 63.5%. According to the British Soil Classification System (BSCS), the soil types include MI, CI-MI, MV, CH-MH, MV, ME and SC. In addition, the AASHTO [36] classification identifies the soil types as A-7-6, A-6, A-2-6, and A-2-7. The index properties of the soils are shown in Table 2 and the grain size distribution curves are shown in Figure 2.

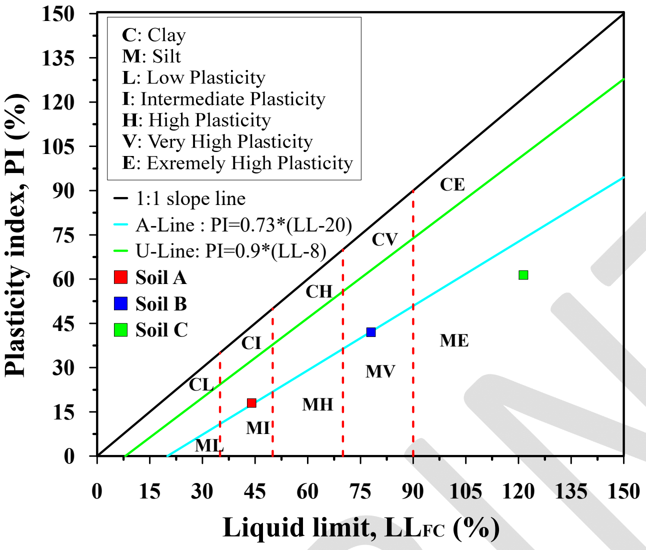

Figure 1 - Locations of soils on Casagrande plasticity chart

Table 2 - Properties of 12 soils

Soil name	Grain-size distribution					Consistency limits				Classifications	
	Clay (%)	Silt (%)	Sand (%)	Gravel (%)	D_{50} (mm)	LL_{CUP} (%)	LL_{FC} (%)	PL (%)	PI (%)	BSCS	AASHTO
A	50.0	50.0	-	-	0.0020	41.0	44.0	26.0	15.0	CI-MI	A-7-6
A1	37.5	37.5	25.0	-	0.0044	37.0	40.0	23.2	13.8	CI-MI	A-6
A2	25.0	25.0	25.0	25	0.0750	33.5	36.5	19.6	13.9	MI	A-6
A3	12.5	12.5	50.0	25	1.2000	33.5	36.5	19.6	13.9	SC	A-2-6
B	45.0	43.0	12.0	-	0.0028	75.0	78.0	36.0	39.0	MV	A-7-6
B1	34.0	33.0	33.0	-	0.0110	69.0	68.0	32.5	36.5	CH-MH	A-7-6
B2	23.0	21.0	31.0	25	0.3200	50.5	51.0	27.8	22.7	SC	A-7-6
B3	12.0	11.0	52.0	25	1.2000	50.5	51.5	27.8	22.7	SC	A-2-7
C	70.0	30.0	-	-	0.0009	123.5	121.4	60.0	63.5	ME	A-7-6
C1	53.0	22.0	25.0	-	0.0013	115.0	113.0	55.1	60.1	ME	A-7-6
C2	35.0	15.0	25.0	25	0.0750	90.0	93.0	44.8	45.2	ME	A-7-6
C3	18.0	7.0	50.0	25	1.2000	90.0	93.0	44.8	45.2	SC	A-2-7

The results of the X-ray diffraction analysis of the soils are visually presented in Figure 3. It shows that soil A is predominantly composed of kaolinite mineral, accompanied by varying quantities of other minerals such as quartz and muscovite. Soil B contains a significant amount of montmorillonite mineral, along with illite and kaolinite, as well as additional minerals such as quartz, anortite, and muscovite. Soil C has a high concentration of clay minerals from the smectite group (montmorillonite) and variable amounts of other minerals.

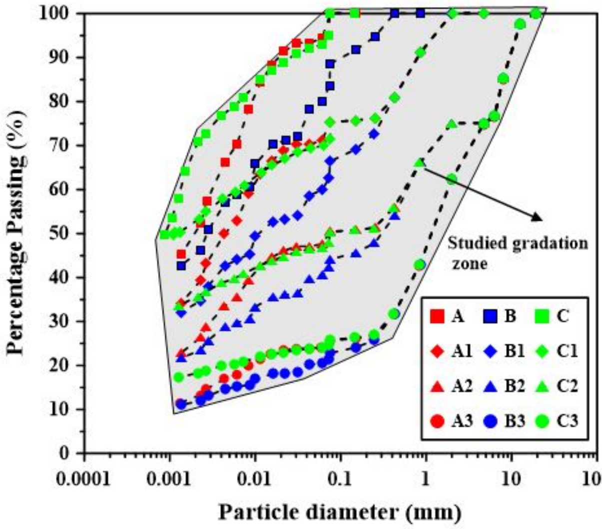

Figure 2 - Grain size distribution curves of soils

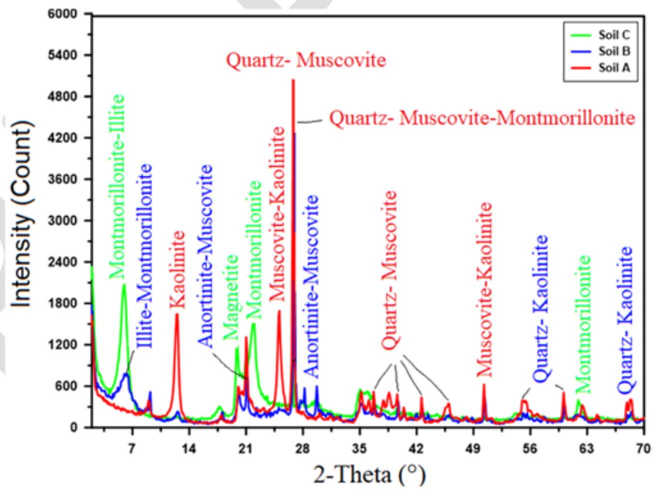

Figure 3 - X-Ray diffraction analysis result of A-B-C soils

Standard Proctor tests were performed on all 12 soils in accordance with ASTM D698 [37]. The results indicated that the maximum dry densities of these soils ranged from 1.2 to 2.2 g/cm^3. Among the tested soils, Soil C had the lowest dry density, while soil A3 recorded the highest dry density. The optimum water contents (w_{opt}) varied between 8.5% and 44. 5% as depicted in Figure 4.

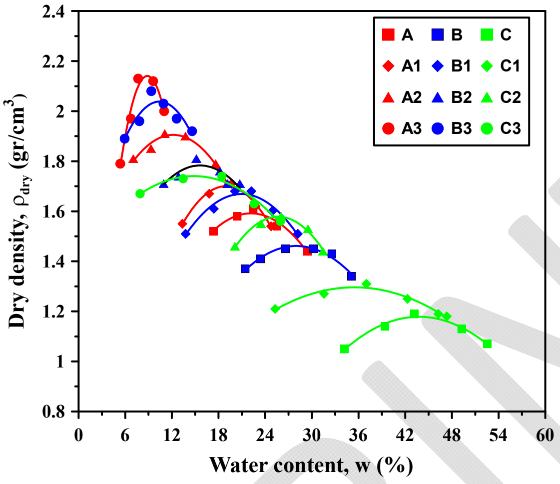

Figure 4 - Standard compaction curves of 12 soils

2.2. Sample Preparation and CBR Test

The specimens were compacted in a CBR mold with a diameter of 152 mm and a height of 178 mm, at the optimum water content and maximum dry density. The volume-mass properties of the compacted soils are shown in Table 3.

The CBR mold was lubricated before compaction to minimize the frictional effect on the movement of the soil mass during saturation and freeze-thaw. Tognom et al. [38] stated that the lubrication process can reduce the angle of friction between the soil and the mold to 5 degrees. It was also observed that the center of the mold exhibited the greatest swelling as it was least affected by friction between the mold and the soil. The displacements measured at this specific point were used for evaluating the extent of swelling and heave.

Table 3 - Volume-mass properties of the compacted soils

Soil	A	A1	A2	A3	B	B1	B2	B3	C	C1	C2	C3
Gs*	2.64	2.65	2.65	2.67	2.63	2.67	2.68	2.71	2.59	2.61	2.62	2.65
w_{opt} (%)	22.5	19 .0	13.2	8.6	29.1	21.6	16.3	10.1	44.3	36.5	26.5	16.7
e**	0.63	0.55	0.39	0.22	0.81	0.59	0.48	0.31	1.16	0.99	0.66	0.51
ρ_{dry} gr/cm^3	1.62	1.71	1.91	2.18	1.46	1.69	1.82	2.08	1.20	1.31	1.58	1.76

*Specific Gravity, **Void ratio

According to ASTM D1883-21 [39], following compaction, a surcharge load of 4.5 kg was uniformly applied to all samples, and the samples were then immersed in tap water for 96 hours to ensure complete saturation. At the end of the saturation (96th h), the height of the samples was measured using a dial gauge to determine the axial strain. The initial set of 12 samples, denoted as the control samples, were not subjected to any freeze-thaw cycle. CBR tests were performed on these control samples after saturation. The second set of samples were subjected to freeze-thaw cycles after saturation.

2.3. Freeze-Thaw Test

In this study, 12 saturated samples were placed in a freeze-thaw chamber and subjected to a closed freeze-thaw test. In ASTM5918 [40], the term 'closed system freeze-thaw' refers to the freezing process taking place under conditions where there is no gain or loss of water within the system. For this purpose, the chamber humidity was set at 80% to prevent evaporation from the soil and maintain the desired moisture level. It was also found that the water contents of the control samples and the freeze-thawed samples were highly consistent. Therefore, there was no change in the water content throughout the freeze-thaw process.

The freezing temperature of -20°C was selected for this study, with a freezing duration of 24 hours. The samples were then allowed to thaw at +20°C, with a thawing time of 24 hours. Control samples were prepared to measure soil temperature during the freeze-thaw cycles. Temperature measurements were taken using a digital thermocouple placed in the sample. The measurements indicate that the cabin temperature and the control sample temperatures are highly compatible (see Figure 5a).

Many researchers have proposed a critical number of cycles beyond which soil properties tend to be less affected or stabilized (Table 1). Therefore, in this particular study, all 12 soil samples were subjected to a total of 10 freeze-thaw cycles, with sample heights monitored using dial gauges at the end of each cycle. (see Figure 5b).

Figure 5 - Freeze-thaw test a) Image showing temperature measurements in control samples using a thermocouple b) images of CBR samples with a dial gauge inside the chamber.

3. RESULTS AND DISCUSSION

3.1. Gradation and Mineralogy Impact on Swelling and Heave

Final swelling measurements were taken for all samples at the end of saturation (at 96 hours). Swelling and final frost heave according to D_{50} and LL_{FC}(%) are presented in Figure 6. The graphs highlights that soils C, B, and A exhibited the highest swelling with recorded values of 5.11 mm, 4.25 mm, and 3.80 mm, respectively. Similarly, the highest final heave was measured at 3.69 mm in soil C, while it was 1.81 mm and 0.59 mm in soils B and A, respectively. It is seen from Figure 6 both swelling and heave increase with increasing liquid limit and decreasing gradation Figure 6. In addition, there is a high correlation (R^2) between the liquid limit and frost heave.

Fine content increases as D_{50} decreases in soil samples. Swelling and frost heave tend to increase as fine content increases. Therefore, Figure 6 illustrates the inverse relationship between D_{50} and swelling and frost heave behavior for all 12 soil samples. As D_{50} values decrease, indicating an increase in fine content, there is typically a coincident increase in frost heave. The primary soil factor influencing frost heave is grain size, and it serves as the fundamental criterion in most frost susceptibility assessments due to its ease of measurement and correlation with frost heave. Soils lacking particles smaller than 74µ typically do not undergo heaving under natural conditions. This recognition dates back to Taber [41], Taber [42] and Casagrande [43] proposed the use of grain size to define frost-susceptible soil limits. Penner [44] determined that soil texture, serving as a measure of particle size gradation, stands out as the foremost crucial physical characteristic of soil when it comes to identifying its frost susceptibility.

In general, soils with high plasticity exhibit greater water retention, swelling, and heave potential. Holtz and Gibbs [45] emphasized the significance of plasticity index and liquid limit as crucial indicators for describing the swelling characteristics of numerous clays. Seed et al. [46] suggested that plasticity index alone serves as a primary indicator in identifying swelling clays. Peck et al. [47] further supported the relationship between clay swelling and plasticity index. Similar results were observed during saturation and freeze-thaw cycles of the samples (Figure 7). Soil C, characterized by a high liquid limit and containing clay minerals from the smectite group such as montmorillonite, tends to have higher water content and greater swelling after saturation. In contrast, soil A, distinguished by a lower liquid limit and swelling potential, primarily contains the kaolinite mineral. Lambe [48] emphasized the significance of mineralogy, especially for clay particles, noting that the nature of the exchangeable ion profoundly affects frost susceptibility. Further studies by Lambe et al. [49] revealed that clay minerals can both enhance and inhibit frost heave. Even minimal concentrations (0.1% to 1.0%) of montmorillonite fines in silt were found to increase frost heave, while higher concentrations led to a decrease.

The primary mechanism responsible for the modification of soil behavior induced by freezing and thawing cycles is thought to be alterations in soil structures [50-52]. The total volume of water-filled pores in the soil skeleton is a major factor controlling the axial strain of saturated soils during freezing and thawing. Therefore, an increase in soil water content, influenced by the high plasticity of the soils, corresponds to an increase in axial strain, primarily attributed to variations in water volume, which can reach up to 9% during the freezing process [53]. As a result, the frost heave of soil C is the highest among the other soil types

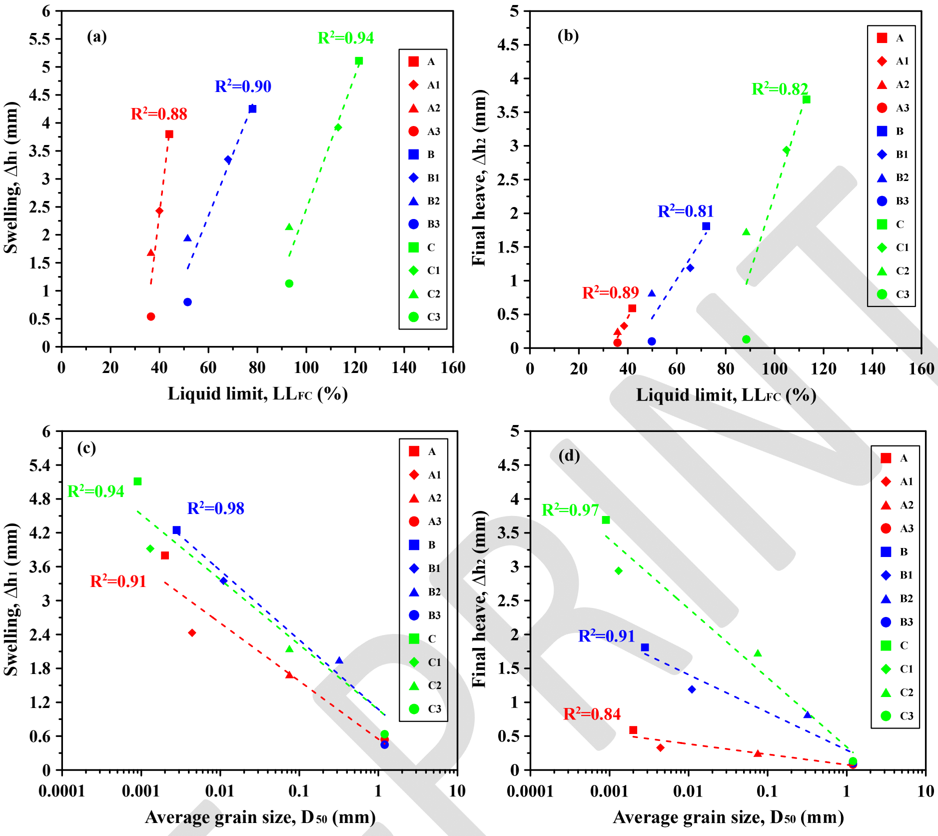

Figure 6 - Swelling and final frost heave according to D_{50} and LL_{FC}(%) a) Swelling-LL_{FC}(%) b) Heave-LL_{FC}(%) c) Swelling-D_{50} d) Heave-D_{50}

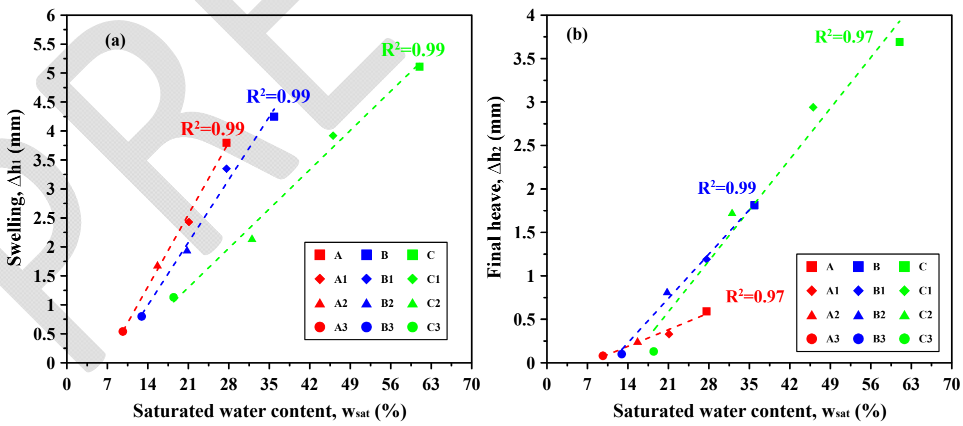

Figure 7 - Swelling and final frost heave according to saturated water content a) Swelling-w_{sat} (%)b) Heave- w_{sat} (%)

The axial strain over 10 freeze-thaw cycles for all soils is shown in Figure 8. To determine the axial strain during the freeze-thaw cycles, the initial height was recalculated taking into account the swelling that occurred during the saturation process. The minimum axial strain recorded was 0.03% for soil A3, while the maximum was 15% for soil C, which indicates a considerable difference in axial strain between these two soil types.

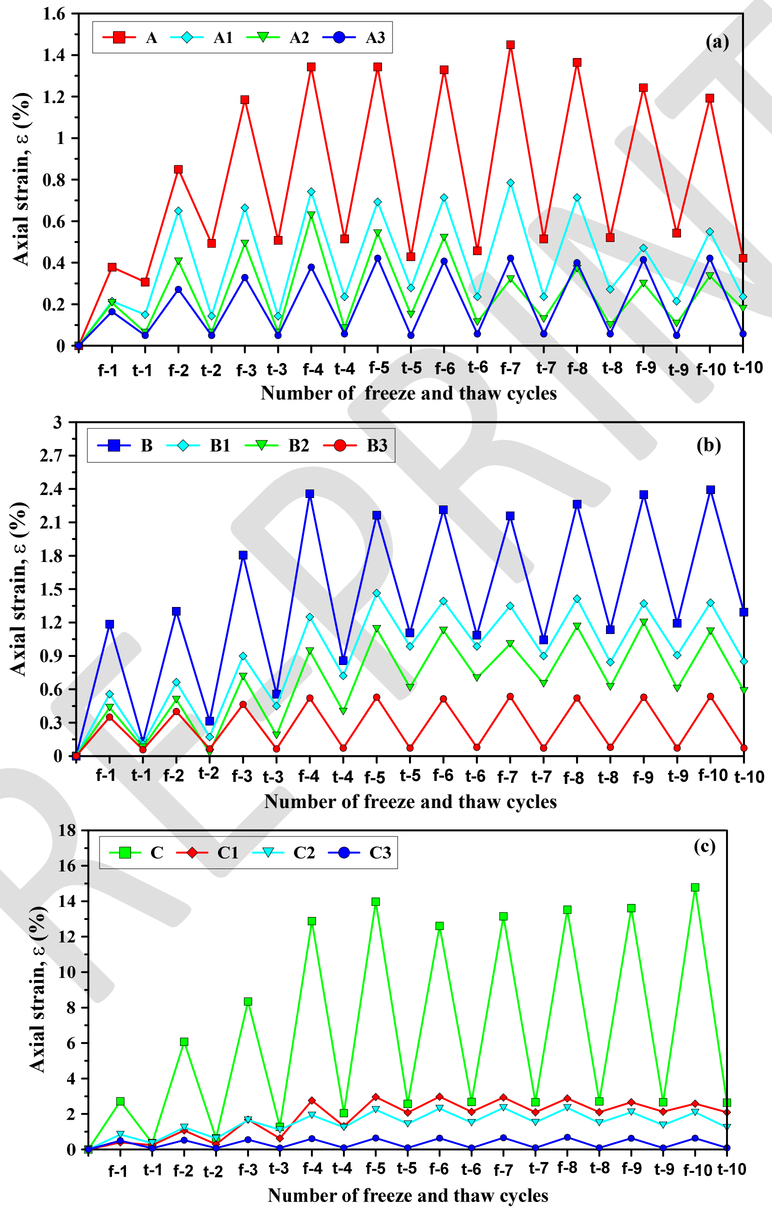

Figure 8 - Axial strains of the 12 soils, during freeze-thaw cycles a) A type soils b) B type soils c) C type soils

For soils A, A1, A2 and A3, the maximum axial strains observed were 1.4%, 0.8%, 0.5% and 0.4% respectively. These soils reached stable axial strains after the 4th freeze-thaw cycle. The coarse material content had a positive effect on the axial strain, with the maximum axial strain decreasing as the coarse material content increased (Figure 8a).

Similarly, the maximum axial strains observed in soils B, B1, B2 and B3 were 2.4%, 1.4%, 1.1% and 0.5% respectively. The reduction in axial strain became more pronounced as the coarseness of the soil increased. After approximately the 5th freeze-thaw cycle, the difference in axial strain between the successive cycles became relatively constant (Figure 8b).

For soils C, C1, C2 and C3 the peak axial strains were 15%, 3% and 2.5% respectively (Figure 8c). The soil skeleton exhibited stabilization after the 5th freeze-thaw cycle as shown in Figure 8c.

As voids within fine-grained soils are exposed to low temperatures, pore-water transforms into ice particles. When the soil is fully frozen (i.e., water within the voids between soil particles are completely frozen), the volume of water increases approximately by 9% resulting in unavoidable cracks in the soil [54]. Freezing water in the soil causes expansion, which exerts significant pressure on pore walls in both soils and rocks, leading to changes in their physical and mechanical properties [31, 55-59]. After thawing, finer particles and fractures attempt to return to their original positions, but complete recovery is difficult, especially for densely compacted soils, and this process repeats with each freeze-thaw cycle [54]. As a result, plastic deformation occurs in the soil.

Figure 9 illustrates the axial strains of soil C, which exhibits the most significant deformation during the freeze-thaw cycles. The highest strain, approximately 14%, occurs during the freezing phase, while the strain during thawing ranges between 2-3%.

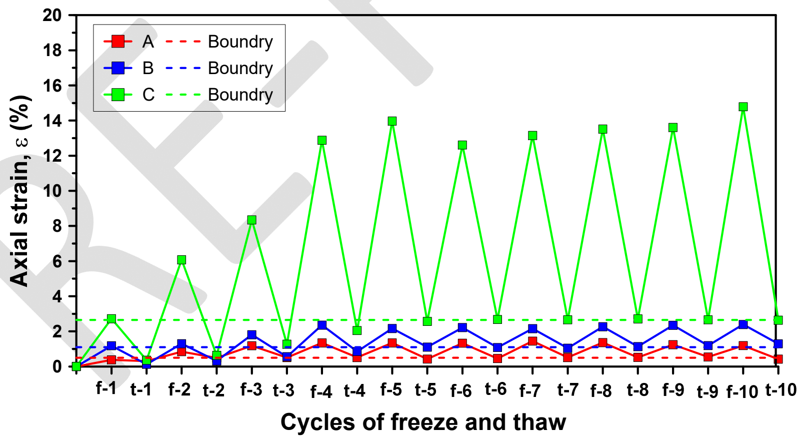

Figure 9 - Plastic deformation boundary for the samples after freeze-thaw cycles

The freeze-thaw process significantly influences the physical-mechanical properties of unfrozen or frozen soils, causing a structural rearrangement of soil particles [32]. This effect persists until a critical number of cycles is reached, beyond which the volume change during freezing no longer significantly affects void volume or particle arrangement [23,26,30-32].

Sherif et al. [60] observed a reduction in frost heave in a silty sand with repeated freeze-thaw cycles, attributing it to diminishing heave potential and compromised continuity of adsorbed water films. This reduction was linked to the loosening and rearranging of particles through successive freeze-thaw cycles.

3.2. Effects of Freeze-Thaw on CBR (%)

CBR tests were conducted on all samples to obtain load-penetration curves. The results, denoted by the symbol ('), represent samples subjected to freeze-thaw (Figure 10). The curves were plotted using the average values derived from the top and bottom test results. The ratio between the CBR (%) values obtained at 2.5mm and 5mm penetration depths was found to be approximately 1.25.

The CBR(%) for groups A, B, and C both prior to and following freeze-thaw cycles are presented in Figure 11. The CBR (%) of Group A soils prior to the freezing and thawing cycles range from 2.28 to 7.2. The A3 sample exhibits the highest CBR (%), while the soil A shows the lowest CBR (%) within this group. Following the freeze-thaw cycles, the CBR (%) for Group A soils are observed to be in the range of 1.15 to 3.98. Similarly, the lowest CBR (%) result is obtained with soil A and the highest with A3 soil. The percentage changes in CBR (%) for the A, A1, A2, and A3 soils are as follows: 59.6%, 55.4%, 44.4%, and 44.7%, respectively (Figure 11a).

Considering the CBR (%) results of the B group soils prior to freezing and thawing; the lowest CBR is obtained from the B3 soil as 2.68, while the highest is 6.64 from the B3 soil. After freezing and thawing, CBR (%) values vary between 1.01-3.48. The percentages of decrease in CBR (%) in B group soils are respectively for B, B1, B2, and B3 soils; 62.3%, 57.3%, 56.9%, 47.6% (Figure 11b).

The CBR (%) values of group C soils were examined before experiencing freezing and thawing. The results showed that C soil had the lowest CBR (%) among all the soils, measured at %2.52. The CBR (%)for C1, C2, and C3 soils were %3.18, %4.05, and %5.95 respectively. After the soils were subjected to the freezing and thawing process, the percentage differences in the CBR (%) were determined. The changes were as follows: 67.1% for C soil, 57.5% for C1 soil, 56.1% for C2 soil, and 48.8% for C3 soil (Figure 11c).

CBR (%) is a significant parameter in assessing the suitability of soils as base, subbase or subgrade material (Table 4). The comparison of the CBR (%) results reveals the adverse effects of freeze-thaw cycles, leading to a substantial reduction in CBR (%), ranging from approximately 40% to 70%. As indicated in Table 4, the CBR (%) results before and after freeze-thaw demonstrate that the reduction in CBR (%)results in a change in the classification of the material. Jessberger and Carbee [61] acknowledged this issue and illustrated through a series of laboratory experiments that freeze-thaw cycling resulted in progressively diminishing CBR (%), especially noticeable in clay soils.

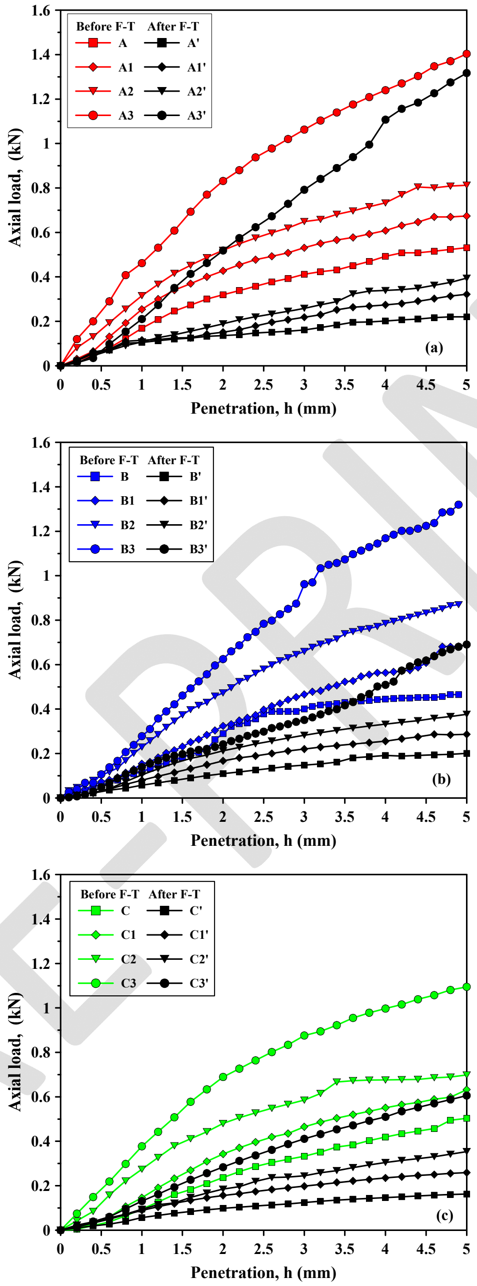

Figure 10 - Load -penetration curves of CBR tests

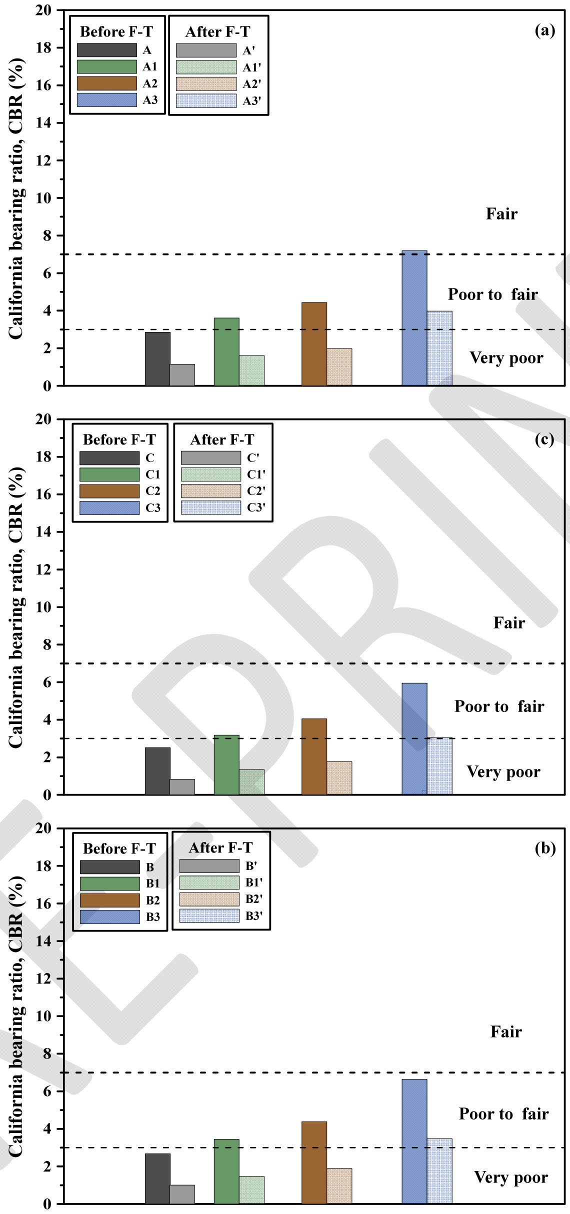

Figure 11 - CBR (%) results before and after freeze-thaw
a) Group A, b) Group B c) Group C

Table 4 - General ratings of soil to be used as a base, subbase, and subgrade material [56]

CBR (%)	General rating	Uses	Classification System	
			Unified	AASHTO
0-3	Very poor	Subgrade	OH, CH, MH, OL	A5, A6, A7
3-7	Poor to fair	Subgrade	OH, CH, MH, OL	A4, A5, A6, A7
7-20	Fair	Subgrade	OL, ML, CL, SC, SM, SP	A2, A4, A6, A7
20-50	Good	Base, Subgrade	GM, GC, SW, SM, SP, GP	A1b, A2-5, A3, A2-6
>50	Excellent	Base	GW-GM	A1a, A2-4, A3

Soils classified as good or poor before freeze-thaw cycles are reclassified as poor or very poor after cycles (Figure 11). Therefore, it is necessary to anticipate the infrastructure challenges that may arise due to climate change in mild or semi-arid regions, taking into account the changes in CBR (%)caused by the freeze-thaw effect .

Frost heave disturbs the integrity of the soil, changing its structure and causing it to become much looser. As a result, the soil becomes unstable and weaker, which adversely affects the stiffness and strength of the soil [22, 24, 31, 32]. In this study, the CBR (%) of the soils before and after freeze-thaw cycles are examined in relation to the gradation and liquid limit (Figure 12).

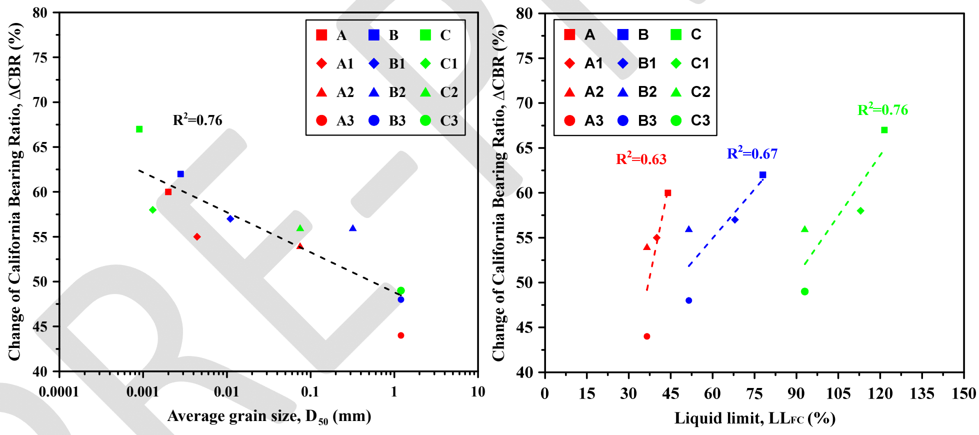

Figure 12 - Change in CBR (%) according to a) D_{50} b) LL_{FC} (%)

The effect of D_{50} (gradation or coarse particle fraction) on CBR (%) was compared even though water content and mineralogy (liquid limit) varied. Figure 12a shows that there is a remarkable relationship between D_{50} and ΔCBR (%). As D_{50} increases, ΔCBR(%) decreases due to the freeze-thaw cycles. It's clear that the ΔCBR (%) values show a relatively similar trend for soils A3, B3, and C3, all of which share the same D_{50} value. However, there are slight variations which probably result from due to the mineralogy of the soils. Furthermore, the correlation between LL_{FC} and ΔCBR (%) was investigated in Figure 12b. The results indicated that the losses in bearing capacity within each soil group increased as the LL_{FC} increased.

4. CONCLUSION

Climate change brings about the potential risk that embankments or native soils below freezing depth in temperate and semi-arid climates may be unexpectedly exposed to freeze-thaw cycles. In such climates, frost effects are so underestimated that local soils may be used for large embankments or roads may be built on frost-sensitive local soils. Therefore, it is important to anticipate the potential problems associated with existing infrastructure caused by a changing climate. To address this concern, our study focuses on investigating the loss of bearing capacity due to freeze-thaw of a wide range of soils with different gradation and mineralogy. The outcomes obtained from the experimental study are presented in the following.

During freezing, the water in the voids of the soil structure expands, forcing the soil particles to change position and breaking the interlocks between them. The soil particles move and form a loose soil structure. During thawing, the soil particles are slightly displaced. However, a permanent structural change occurs in the soil. Nevertheless, these deformations, or changes in the volume, continue until a void ratio is reached where the expansion of water during freezing no longer impacts the soil structure. Within the framework of this study, it was noted that the axial strain stabilized after approximately 4-5 cycles for all soils.

The study results suggest that the axial strain of all soils stabilizes after approximately 4-5 freeze-thaw cycles. These freeze-thaw cycles induce volume changes in the soil, leading to a loose and unstable soil structure. Consequently, the soil demonstrates weakened behavior including reduced strength and stiffness. The findings of this study reveal a remarkable decline in CBR (%), ranging from 40% to 70%, due to the effects of freeze-thaw cycles.

In the existing literature, the adverse effects of freezing and thawing on soils are primarily attributed to the amount of fines present. Nevertheless, this study highlights the importance of not only the fine content but also the properties of the fines themselves. While there is a strong correlation between D_{50} and CBR (%) reduction, a degree of variability was observed in ΔCBR (%) values among soils with the same D_{50}. This suggests that the liquid limit plays a significant role in the structural changes that occur during freeze-thaw cycles.

Moreover, the mineral composition has a significant influence on the frost susceptibility of soils, particularly in terms of specific surface area, cation exchange capacity, and the presence of negative charges on the soil surface – all of which collectively influence the soil's water-retention capacity. In the context of the present study, it was observed that soil C, characterized by the presence of clays of the smectite group, exhibited the most pronounced response to freeze-thaw phenomena, demonstrating significant frost heave and loss of bearing capacity. In contrast, soil A, characterized by the predominance of kaolinite mineral, displayed the least susceptibility to the effects of freeze-thaw cycles.

A strong correlation was observed between the D_{50} and ΔCBR (%) values of all samples. However, variations in the ΔCBR (%) values were observed among soil mixtures having equivalent D_{50} size, particularly in relation to their liquid limits. This observation suggests that soils sharing similar D_{50} values may undergo different change in CBR (%) during freeze-thaw cycles, primarily owing to variations in their mineralogy.

In conclusion, this study underscores the critical impact of freeze-thaw cycles on soil stability, revealing a substantial reduction in CBR (%) ranging from 40% to 70%. The findings emphasize the nuanced influence of factors beyond fine content, highlighting the significance of properties such as liquid limit and mineral composition. The observed correlations between ΔCBR (%) and LL (%) as well as ΔCBR (%) and D_{50} provide valuable insights, emphasizing the need for a comprehensive understanding of soil properties when assessing the effects of climate change on infrastructure stability.

Nevertheless, the outcomes derived from this study are applicable to the designated gradation, mineralogy, and freeze-thaw conditions. To draw more generalized conclusions, additional investigations should be conducted with diverse soils.

Notations and Symbols

CBR: California Bearing Ratio

D_{50}: Average grain size

LL_{CUP}: Liquid limit value by Casagrande Test

LL_{FC}: Liquid limit value by Fall Cone Test

PL: Plasticity limit

PI: Plasticity Index

ML: Low plasticity silt

CL: Low plasticity clay

SC: Clayey sand

MH: High plasticity silt

CH: High plasticity clay

XRD: X-Ray diffraction

w: Water content (%)

ρ_k: Dry unit weight (gr/cm^3)

w_{opt}: Optimum water content (%)

w_{sat}: Saturated water content (%)

w_{ft}: Water content after 10 cycles of freezing and thawing (%)

ε: Axial strain (%)

Δh: Axial displacement (mm)

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