

INVESTIGATIVE RESEARCH ON FROZEN SOILS

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ABSTRACT

Frozen soils, or permafrost, significantly influence the geotechnical, hydrological, and biological dynamics of polar and subpolar areas. This thesis conducts an investigative study on frozen soils, emphasizing their creation, conduct, and the many elements affecting their stability and long-term performance. The research investigates the physical, chemical, and mechanical characteristics of frozen soils, examining the influence of temperature, moisture content, mineral composition, and external stress on soil structure and consistency under thawing circumstances. The study includes laboratory tests and field research from areas with diverse climatic conditions, including the Arctic, sub-Arctic, and alpine regions. The primary objectives are to comprehend the thermal dynamics of frozen soils, evaluate the effects of seasonal temperature variations, and analyze the potential for thawing and resultant soil degradation, which significantly affects infrastructure development, climate change, and ecosystem stability.

This study significantly emphasizes the behavior of frozen soils under stress, examining the response of frozen ground to loads from anthropogenic activities, such as building, as well as natural factors like earthquakes and thermal cycling. The research examines the environmental issues linked to melting permafrost, which may result in soil subsidence, greenhouse gas emissions, and the disturbance of local ecosystems. The study also examines novel engineering strategies to alleviate the adverse impacts of frozen soil instability, including sophisticated foundation designs and soil stabilizing procedures.

This study enhances the comprehension of frozen soil mechanics, offering crucial insights for engineers, policymakers, and environmental scientists in permafrost-affected areas. The study's results are anticipated to facilitate the creation of more robust infrastructure in frigid places, guide climate adaption methods, and improve our comprehension of an opportunity hazards that climate change presents to frozen soil ecosystems.

This thesis integrates mathematical modeling with real-world evidence to provide a thorough evaluation of the problems and possibilities associated with frozen soils, enhancing scientific understanding and utilization in cold-region design and sustainability management.

Key words: Frozen Soil Mechanics, Soil Parameters, Unfrozen and Frozen States, Porosity, Void Ratio Bulk Density, Soil Freezing

1. INTRODUCTION

1.1 General

Frozen soils, particularly extensive permafrost, are a crucial element of the Earth's cryosphere, profoundly affecting the dynamics of polar, subpolar, and high-altitude ecosystems. These soils persist at or below freezing temperatures for prolonged durations, often exceeding two consecutive years, and are crucial for sustaining the stability of cold-region landscapes. Permafrost covers roughly 25% of the Earth's terrestrial surface, and its stability is essential for the operation of ecosystems, hydrology, and regional temperatures.

The examination of frozen soils is becoming more significant due to rising global temperatures, resulting in the expedited melting of permafrost in many areas. This thawing affects natural ecosystems by releasing previously held greenhouse gasses such as methane and carbon dioxide, while also presenting substantial issues for infrastructure. In regions where human activity interacts with frozen soils, including northern settlements, oil and gas exploration sites, and transportation networks, melting permafrost may lead to ground subsidence, structural damage, and safety issues. As infrastructure in these areas becomes more susceptible, understanding the dynamics of frozen soils amid shifting climatic circumstances is crucial for formulating mitigation solutions and assuring enduring sustainability. This study seeks to tackle these problems, enhancing management and engineering techniques in cold-region situations.

1.2 Behavior of Frozen Soils: Physical, Chemical, and Mechanical Aspects

Frozen soils are characterized by distinct physical, chemical, and mechanical characteristics, influenced by temperature, moisture content, and the presence of salts or other solutes. The freezing of water inside the soil matrix leads to ice formation, which occupies a substantial percentage of the pore space and affects the soil's overall structure and stability. The temperature of frozen soils significantly influences their mechanical characteristics. At subzero temperatures, the soil's strength and stiffness generally augment, enhancing ground stability. As temperatures increase and the ice in the earth melts, these qualities may alter significantly.

A notable property of frozen soils is the formation of ice lenses, which develop during freezing and enhance the soil's

distinctive stratified look. These ice lenses may enlarge during freezing, resulting in frost heave, a phenomenon where the ground surface is elevated owing to ice expansion. This phenomenon may cause considerable disturbances in infrastructure and natural ecosystems. Conversely, thawing may result in the creation of water-saturated soils that may undergo significant subsidence or ground surface collapse. Thawing may modify the chemical makeup of frozen soils, particularly in regions with organic matter. Upon the thawing of permafrost, organic matter decomposes, producing greenhouse gases like carbon dioxide and methane, hence exacerbating climate change.

The mechanical properties of frozen soils are very important in engineering applications. Permafrost serves as a natural substrate for edifices, thoroughfares, and other infrastructure in Arctic and subarctic areas. The melting of permafrost may compromise the structural integrity, resulting in displacement and uneven settlement that may cause damage or collapse. Infrastructure such as roads, pipelines, and airports constructed on permafrost is susceptible to thermal erosion and deformation due to the destabilization of the underlying ground during thawing. Consequently, comprehending the mechanical characteristics of frozen soils under diverse heat and moisture conditions is essential for infrastructure design in these areas.

1.3 Impact of Seasonal Temperature Variations and Thawing on Soil Structure

Seasonal temperature fluctuations in areas with frozen soils enhance the dynamic characteristics of these settings. In several regions characterized by permafrost, temperatures oscillate above and below the freezing threshold year-round. In warmer months, the thawing of the active layer—the uppermost soil layer that undergoes yearly thawing and refreezing—results in substantial alterations to soil structure. These alterations include the flow of water through the soil and the likelihood of heightened erosion, particularly in coastal and riverbank settings. The active layer is often a few meters deep; but, during thaw times, it may become water-saturated, increasing the risk of slumping, landslides, and changes in local hydrology.

The melting of permafrost results in the destabilizing of ice-laden soils, which are susceptible to collapse upon the melting of ice. Thermo-karst formation may result in significant alterations to the terrain, including the development of substantial depressions or sinkholes. The melting of permafrost releases substantial quantities of stored organic carbon, which decomposes and emits carbon dioxide and methane into the atmosphere. This mechanism establishes a feedback loop, intensifying global warming and hastening permafrost melt.

1.4 Human Impact on Frozen Soils: Infrastructure and Environmental Concerns

The interplay between human activities and permafrost has emerged as a significant issue as the impacts of climate change escalate. Human-engineered infrastructure, such as highways, pipelines, airports, and residential zones, often depends on the stability of permafrost. In permafrost locations, infrastructure was traditionally engineered to withstand freezing and thawing cycles. As the temperature warms and permafrost thaws more quickly, the foundations of these constructions are more susceptible to instability.

The melting of permafrost in Arctic locations has already posed issues for people and enterprises. Pipelines and roadways that were previously stable have started to deform and displace owing to the melting and shrinkage of the underlying permafrost. The oil and gas sector, mostly located in areas such as Alaska and Siberia, is especially susceptible to the melting of permafrost. Altered ground conditions jeopardize the integrity of pipelines, potentially resulting in hazardous spills and environmental pollution.

Moreover, the melting of permafrost has extensive environmental ramifications. The melting ice in the permafrost exposes previously unreachable soils and organic matter to decomposition. The emission of greenhouse gases, especially methane, from these thawing regions is a considerable worry because to methane's far greater potency as a greenhouse gas compared to carbon dioxide in the near term. The release of methane exacerbates planetary warming, establishing a feedback loop that accelerates thawing and intensifies global climate change.

2. OBJECTIVES

- Characterize the physical, thermal, and mechanical properties of frozen soils.
- Investigate the impact of thawing permafrost on infrastructure stability.
- Develop predictive models for frozen soil behavior under climate change.
- Assess the environmental impacts of thawing, including greenhouse gas release.
- Propose engineering solutions for mitigating the effects of thawing on infrastructure.

3. LITERATURE REVIEW

Smith and Zhang (2024) examined recent alterations in permafrost temperatures in Arctic locations, emphasizing the relationship between permafrost melt and greenhouse gas emissions. They emphasized that escalating temperatures are causing greater melt depths, resulting in substantial carbon and methane emissions from once frozen organic matter. They

contended that this discharge establishes a strong feedback loop that intensifies global warming. The scientists showed that permafrost melting is not only a result but also a significant catalyst of climate change via greenhouse gas emissions, using a mix of satellite data, field observations, and climate models. Their results underscored the pressing need for climate models to more effectively include permafrost carbon feedback processes, since the likelihood of significant carbon emissions presents a serious threat to the attainment of global climate objectives. This study highlights the crucial significance of permafrost in exacerbating future warming scenarios.

Kumar and Nguyen (2024), in their research "Engineering Challenges in Thawing Soils," analyzed the significant obstacles encountered by civil engineering projects in areas experiencing permafrost degradation. Their study concentrated on the durability of foundations constructed on melting soils, an issue that presents significant threats to infrastructure, including roads, buildings, and pipelines. They said that melting permafrost results in ground subsidence, less load-bearing capacity, and heightened ground displacement, potentially destabilizing buildings and incurring substantial repair expenses. To tackle these issues, the authors offered novel technical solutions, such as using thermosyphons for soil temperature regulation, enhanced insulating materials, and adaptable foundation designs that can accommodate ground movements. Kumar and Nguyen highlighted the incorporation of climate resilience in engineering processes, offering practical ways to reduce risks in permafrost areas, hence promoting safer and more sustainable infrastructure development in the face of evolving climatic circumstances.

Miller and Chen (2023), in their paper "Modelling Heat Transfer in Frozen Soils," used sophisticated simulations to analyse and forecast heat transport mechanisms in permafrost. Their research examined the impact of temperature variations, moisture levels, and other environmental factors on the stability of permafrost throughout time. By including these factors into their models, the researchers enhanced the precision of predictions about thaw depth and the likelihood of ground instability across various climatic scenarios. This study provided essential insights into the thermal dynamics of permafrost, aiding in the prediction of changes in soil behaviour resulting from global warming. The models developed by Miller and Chen proved to be essential instruments for engineering applications, directing infrastructure design and resilience measures in permafrost areas vulnerable to thermal deterioration.

Hassan and Rivera (2023), in their study "Thawing Permafrost and Infrastructure Risk Assessment," examined risk management solutions for northern towns facing risks generated by permafrost thaw. Their research emphasized that melting permafrost compromises essential infrastructure, such as buildings, roads, and pipelines, resulting in safety hazards and economic liabilities. Hassan and Rivera created a thorough methodology to evaluate the susceptibility of infrastructure systems to alterations caused by permafrost. This approach amalgamated geotechnical data, climate forecasts, and engineering evaluations to pinpoint vulnerable sites and prioritize adaption strategies. The authors highlighted measures like strengthening foundations, using thermally durable materials, and establishing continuous monitoring systems to identify early indications of soil displacement. This project sought to improve community resilience and guide policymakers and engineers in addressing the increasing difficulties of permafrost degradation by providing practical tools and risk assessment methodologies.

Nguyen (2022), in his work "Permafrost and Arctic Ecosystem Changes," analysed the ecological transformations resulting from permafrost thaw in Arctic areas. The study examined the cascading impacts of melting permafrost on vegetation, nutrient dynamics, and faunal populations. As permafrost melts, it liberates nutrients that were previously confined in frozen soil, hence modifying nutrient availability and influencing plant development patterns. Nguyen recorded changes in plant species composition, noting that some species thrived due to enhanced nutrient availability, while others, especially those suited to colder climates, were supplanted. These alterations also affect herbivore populations and their dependent predators. Moreover, the thawing process undermines habitat stability, resulting in additional disturbances within local ecosystems. Nguyen's research emphasizes the link between permafrost and Arctic ecosystems, demonstrating that permafrost degradation impacts the physical terrain and induces substantial biological and ecological changes. The research offers significant insights into future Arctic ecosystem dynamics in the context of climate change.

Chen (2021) analysed the extensive social and economic ramifications of permafrost thaw on Arctic communities. The study examined the impact of permafrost deterioration on local infrastructure, resulting in expensive repairs, relocation, and economic losses. The thawing of permafrost destabilizes important infrastructure like as buildings, roads, and pipelines, which are crucial for the livelihoods and transportation networks of northern populations. Chen examined the socio-cultural ramifications, namely migration patterns, when families and communities are compelled to migrate owing to hazardous living conditions and changes to conventional lifestyles. The research highlighted the need for flexible policies and governance structures to tackle these developing concerns. Chen advocated solutions to enhance infrastructure resilience, including investments in adaptable construction methods and the development of more resilient emergency response systems. This study highlights the pressing need for holistic, community-oriented strategies to

alleviate the social and economic repercussions of melting permafrost in the Arctic.

Ivanov and Smith (2020) examined the effects of permafrost melt on hydrological dynamics and its implications for soil and vegetation responses. The research examined the substantial changes in water flow, drainage patterns, and moisture availability resulting from permafrost degradation. As permafrost melts, the once frozen terrain becomes more porous, allowing enhanced infiltration and alterations in surface runoff, so disrupting established hydrological processes. These modifications influence soil moisture levels, thus affecting plant development, with some species flourishing under the new circumstances while others fail. Ivanov and Smith emphasized that these hydrological changes establish a feedback loop, affecting carbon cycling and nutrient availability in Arctic ecosystems. Their study indicated that thaw-induced alterations in hydrology might affect ecosystem services, including water quality and habitat availability, underscoring the need of including permafrost degradation into future climate and ecosystem models.

Vasilenko and Morozova (2019) examined the thermal dynamics of permafrost in Siberia, highlighting the significance of seasonal thawing and refreezing cycles. Their study emphasized the geographical heterogeneity in permafrost reactions to increasing temperatures, indicating that distinct regions of Siberia undergo differing rates of thaw and refreezing influenced by local climatic circumstances and soil properties. The authors emphasized the need of creating localized models to forecast long-term permafrost stability and future carbon emissions, since generalist models may inadequately address these subtle geographical variations. Their research yielded significant data on permafrost temperature changes, elucidating the depth and scope of seasonal thawing, which is essential for comprehending future soil dynamics in a warming environment. The results of Vasilenko and Morozova are crucial for precisely forecasting permafrost deterioration and its effects on greenhouse gas emissions, hydrology, and ecosystem vitality in Siberia.

4. METHODOLOGY

Materials and Equipment

1. Soil: locally available soil is used and sieve analysis is performed on it to classify the soil.
2. Beaker: Cylindrical borosil beakers are used to carry soil into it to create the samples.
3. Weighing balance: A digital weighing balance is used to measure weights of samples.
4. Deep freezer: It is used to freeze the soil sample. The temperatures used are -5, -10, and -15°C

Methodology

The process for this project is clear and uncomplicated. The soil is first oven-dried to remove its inherent moisture, followed by sieve examination to ascertain its classification. This research utilizes sand as the soil medium, concentrating on the examination of its qualities in both unfrozen and frozen conditions, with implications for various soil types. The dirt is then combined with a certain quantity of water to attain a specified moisture content, and then transferred into 100ml cylindrical beakers. The beakers contain soil with variable bulk densities, regulated by tamping the dirt with different quantities of blows using a glass rod. This sample replicates the soil conditions seen on open terrain at ambient temperature. The processed samples are thereafter stored in a deep freezer to replicate the frigid temperatures characteristic of colder locales. The research comprises experimentation at temperatures of 25°C, -5°C, -10°C, -15°C, and -20°C. The parameters of the soil, including porosity, void ratio, bulk density, and dry density, are assessed for the frozen samples at various temperatures. The readings are then compared with those recorded at room temperature. The porosity of frozen soil is modeled as a function of its porosity at ambient temperature, water content, and the measurement temperature. The extent of freezing is similarly assessed using an analogous method. Ultimately, after collecting data from both unfrozen and frozen soil conditions, the correlations between these attributes are examined using Eureka software.

Experimental Procedure

The test methodologies used in the present investigation adhere to Indian Standard codes: IS 2720-2 (1973), IS 2720-Part 3 (1980), and ISO 11272:2017. The process is as outlined below:

- A) Dry the soil in an oven at 105° Celsius for 24 hours according to IS 2720-2(1973). Enclose this soil in plastic bags to prevent moisture absorption from the surroundings, as seen in Figure 4.1.
- B) Extract samples from this soil bag. Classify the soil by sieving, as seen in the diagram 4.2. The soil gradation curve for this project indicates that the soil is well-graded, with C_c and C_u values of 1.09 and 8.33, respectively.
- C) Let the dry weight of soil sample = W_s
Add known amount of water content (2%,4%,6%,8%,40%) $w = (W_w/W_s) \dots\dots (1)$
- D) Independently ascertain the specific gravity (G_s) of soil solids using the pycnometer test and correlate it with equation (2) to get the value of γ_s as seen in Figure 4.3. According to IS-2720-PART-3-1980.

$$G_s = (\gamma_s / \gamma_w) \quad \dots\dots (2)$$

E) Once, γ_s is calculated volume of soil solids will be further calculated by

$$\gamma_s = (W_s / V_s) \quad \dots\dots (3)$$

F) Now, calculate void ratio(e) as per IS: 2720 (Part 2)

$$e = (V_v / V_s) \quad (4)$$

V_v can be calculated by first measuring the total volume (V_t) of soil sample having different bulk densities ($\gamma_{t1}, \gamma_{t2}, \gamma_{t3} \dots$) in measuring container as per **ISO 11272:2017** and then using:

$$V_v = (V_t - V_s) \quad \dots\dots (5)$$

G) Now, place the soil sample container in freezer for various temperatures to record data (- 5, -10, -15, -20 degree Celsius) as shown in Figure 4.5.

H) After 24 hours, remove the sample and measure its weight. Additionally, heights are measured at five distinct sites, with the average calculated as seen in Figure 4.4. Execute this step promptly to prevent errors caused by temperature fluctuations.

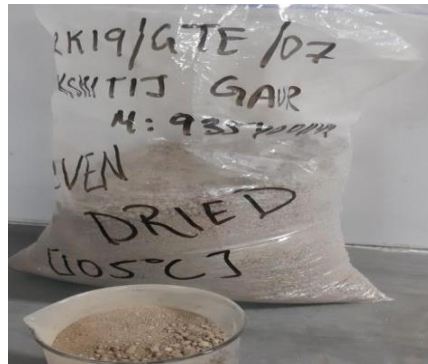


Figure 4.1: Oven dried soil



Figure 4.2: Soil sieving.



Figure 4.3: Pycnometer test



Figure 4.4: Frost soil sample weighing



Figure 4.5: Deep freezer with temperature controls.

5. RESULT

1. The soil gradation curve formed after sieve analysis is shown in figure 5.1.

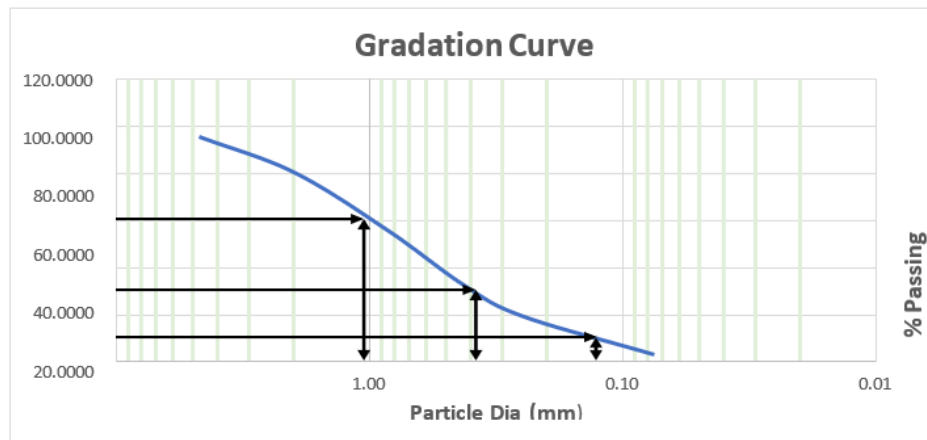


Fig. 5.1 Gradation curve for the soil.

2. The results obtained from sieve analysis are given in table 5.1.

Table 5.1 Results of soil gradation curve

Results					
% gravel	4.54	D60 (mm)	1.053063	$C_u = D_{60}/D_{10}$	8.33
% sand	92.56	D30 (mm)	0.381062	$2 C_c = D_{30} / D_{10} * D_{60}$	1.09
% fines	2.90	D10 (mm)	0.126385		

The soil type is found to be well graded sand (SW) as the coefficient of uniformity is greater than 6 (i.e., $C_u > 6$) and coefficient of curvature is greater than 1 (i.e., $C_c > 1$).

Weight Function

The amount of weight of soil that is frozen may be calculated if the weight of the same material at ambient temperature, its water content, and the temperature at which the weight is to be measured are known. Inputting the experimental data shown in table 5.2 into Eureka software reveals the potential linkages within the dataset. The weight function is as follows:

Table 5.2 Weight of dry vs frozen soil at given temperature and water content.

Wt. of dry soil (gm)	Water content (%)	Temperature (°C)	Wt. of frozen soil (gm)
W_s	w	T	W'
100	6	-5	105.818
100	6	-5	105.862
100	10	-5	109.69
100	10	-5	109.767
100	14	-5	113.665
100	14	-5	113.746
100	18	-5	117.645
100	18	-5	117.771
100	22	-5	121.752
100	22	-5	121.738
100	26	-5	125.672
100	26	-5	125.634
100	30	-5	129.545

100	30	-5	129.65
100	6	-10	105.712
100	6	-10	105.783
100	10	-10	109.595
100	10	-10	109.676
100	14	-10	113.554
100	14	-10	113.641
100	18	-10	117.522
100	18	-10	117.657
100	22	-10	121.605

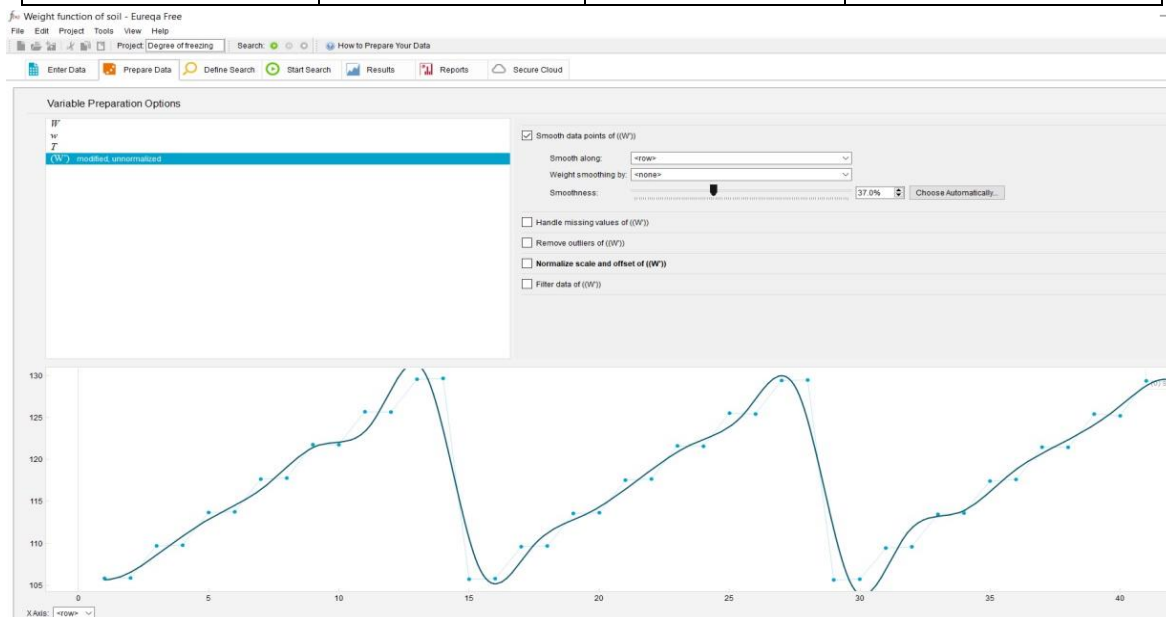


Figure 5.2: Preparing data in eureka software for weight function.

Void Ratio

- 4 Please confirm that the void ratio will vary with temperature due to the increase in water volume when it transitions from a liquid to a solid state. This results in an increase in the number of voids while the volume of soil solids stays constant. Consequently, the void ratio will grow, as corroborated by actual observations. By inputting the data acquired in the laboratory, as shown in Table 4.3, the subsequent connection is derived using Eureka Software.
- 5 $e' = f(e, T)$ (8)
- 6 Where T is in degree Celsius.

Table 5.3 Void ratios for normal (e) and frozen soil (e')

Unfrozen soil void ratio	Temperature	Water content (%)	Frozen soil void ratio	% change in void ratio
e	T	w	e'	y
1.909	-5	6	1.949	2.05
1.667	-5	6	1.688	1.24
1.969	-5	10	1.985	0.81
1.667	-5	10	1.688	1.24
1.607	-5	14	1.708	5.91
1.708	-5	14	1.748	2.29
1.436	-5	18	1.532	6.27

1.778	-5	18	1.829	2.79
0.812	-5	22	0.922	11.93
1.063	-5	22	1.073	0.93
1.194	-5	26	1.204	0.83
1.174	-5	26	1.199	2.09
1.063	-5	30	1.073	0.93
1.265	-5	30	1.386	8.73
1.909	-10	6	1.98	3.59
1.667	-10	6	1.698	1.83
1.969	-10	10	1.99	1.06
1.667	-10	10	1.718	2.97
1.607	-10	14	1.713	6.19
1.708	-10	14	1.808	5.53
1.436	-10	18	1.547	7.18
1.778	-10	18	1.829	2.79
0.812	-10	22	1.033	21.39
1.063	-10	22	1.124	5.43
1.194	-10	26	1.104	8.15
1.173	-10	26	1.174	0.09
1.063	-10	30	1.114	4.58
1.265	-10	30	1.476	14.3
1.909	-15	6	1.98	3.59
1.667	-15	6	1.698	1.83
1.969	-15	10	1.99	1.06
1.667	-15	10	1.718	2.97
1.607	-15	14	1.718	6.46
1.708	-15	14	1.813	5.79
1.436	-15	18	1.567	8.36
1.778	-15	18	1.834	3.05
0.812	-15	22	1.033	21.39
1.063	-15	22	1.124	5.43
1.194	-15	26	1.114	7.18
1.174	-15	26	1.179	0.42
1.063	-15	30	1.114	4.58

1.265-15 30 1.481 14.58

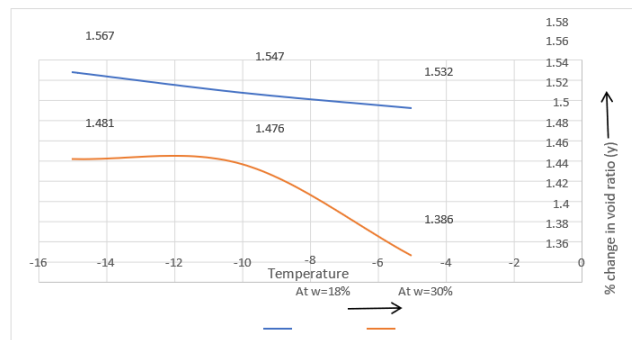


fig. 5.3 Graph of % change in void ratio (y) vs Temperature

6. CONCLUSION

- The formulae established in this study address significant deficiencies in the current literature by providing essential insights into frozen soil and its principal properties. This further information enhances the comprehension of frozen soil behavior and qualities, contributing to a more robust theoretical framework for comprehending soil in cold environments.
- -This work has practical applicability, since the data gathered by the author in a laboratory environment is validated and dependable. Construction projects in frigid places might use these formulae to enhance soil investigations and get a more profound comprehension of frozen soils. The formulae allow engineers to ascertain soil properties at different freezing temperatures using established values at room temperature, or the reverse.
- This study is crucial for assessing the characteristics of frozen soil. By supplying dependable formulae for these characteristics, it establishes a robust platform for further research endeavors and provides instruments that may facilitate further investigation and analysis of frozen soil mechanics and behavior.
- The paper includes extensive references and thorough evaluations of pertinent literature on frozen soil. This comprehensive methodology guarantees that the work is anchored in established knowledge and best practices, offering a nuanced and well-informed analysis of the subject.

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