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Development and Testing of a Temperature-Controlled Triaxial Device for Freeze-Thaw Cycles

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ABSTRACT: The growing instability of permafrost and seasonally frozen soils due to rising global temperatures has heightened the importance of understanding soil behavior under freeze–thaw cycles. Triaxial devices equipped for freeze–thaw testing are costly and limited to a few advanced laboratories. To address this gap, a modified triaxial system was economically developed by integrating a copper coil heat exchanger, a water–glycol confining fluid, and multilayer insulation within a standard triaxial cell, while maintaining compliance with ASTM standards. Calibration tests demonstrated that, without insulation, the system cooled from 24°C to a stable temperature of 2°C in 4 hours while circulating coolant at −10°C. With full insulation, kaolinite specimens achieved and maintained −5°C (± 0.2°C) after 4 hours. After 24 hours of cooling, thermal imaging and specimen sectioning confirmed uniform temperature distribution and ice lens formation. Mechanical calibration of the modified system with Ottawa sand at 50 kPa showed stress–strain responses comparable to standard TruePath and Geotac Sigma-1 systems under conventional test conditions. Further tests at 50 kPa across 23°C, 0°C, and −5°C demonstrated increased strength at lower temperatures due to ice bonding effects. Limitations included sample size constraints (50 mm diameter), temperature losses near couplings, and the need for destructive sampling to assess ice lenses. Future developments will focus on enlarging the copper coil radius to accommodate larger specimens, optimizing insulation to reduce heat loss, and integrating thermo-TDR probes to simultaneously monitor temperature and ice content. Overall, the modified system presents a practical, affordable platform for repeatable freeze–thaw triaxial testing, potentially expanding these capabilities to a wider range of geotechnical research laboratories.

KEYWORDS: freeze–thaw, triaxial testing, thermal imaging, temperature control, ice lens formation, equipment development.

1 INTRODUCTION

Global warming is causing rapid changes in the cryosphere, leading to critical vulnerabilities in infrastructure built on seasonally frozen and permafrost soils. Recent studies have shown that rising global temperatures accelerate permafrost degradation and intensify freeze–thaw cycling, destabilizing foundations, embankments, and other critical infrastructure in cold regions (Chen et al., 2024; Niu et al., 2025). Significant increases in soil temperatures within permafrost regions are changing the hydrothermal conditions, resulting in a decrease in the ground bearing capacity (Duan et al., 2025; Wang et al., 2024). The cyclic weakening of soil caused by freeze–thaw processes is increasingly recognized as a pressing engineering challenge in a warming world, where formerly stable permafrost is now subject to repeated freeze-thaw events (Zhou et al., 2024).

The accurate characterization of the mechanical response of soils under realistic freeze–thaw conditions is vital to predict and mitigate climate-driven infrastructure damage. However, experimental investigation of freeze–thaw effects typically demand advanced triaxial devices equipped with precision temperature control and robust insulation systems (Mohammed and McKenzie, 2024). Such specialized equipment is often expensive and limited to a small number of advanced research laboratories, creating a bottleneck for broader geotechnical testing and model calibration (Esmaeili-Falak et al., 2019).

A range of temperature-modified soil testing systems has been developed to study freeze–thaw behavior, yet each exhibits limitations that restrict accuracy, reproducibility, or accessibility. Early cold-room systems such as that in Da Re et al. (2003) relied on air-cooling and external jackets, producing slow, nonuniform freezing and significant axial and radial temperature gradients. Later designs, including the copper-tube circulation system of Arenson and Springman (2004), improved uniformity but still required bulky insulation and cold-room dependence. More advanced devices, such as the multi-cooling triaxial system of Yao et al. (2013) and the dual-cell true-triaxial system of Ng et al. (2022), achieved tighter thermal control but introduced high mechanical and thermal complexity, costly fabrication, and limited reproducibility. Other apparatuses target narrow objectives such as the soil freezing characteristic curve (SFCC)-focused triaxial system of Mu et al. (2019) uses nonstandard specimen sizes and does not permit full stress-path loading, while the temperature-controlled direct shear box of Emami Ahari et al. (2023) provides effective plane-strain testing but cannot simulate three-dimensional stress states or pore pressure evolution. Cold-room and freezer-based conditioning remains common, but these methods cannot freeze specimens under confining stress and produce large uncontrolled gradients. Across the literature, common limitations include inconsistent temperature fields, incomplete documentation of cooling mechanisms, lack of standardization, and high cost. These gaps highlight the need for an economical, reproducible, and fully documented temperature-controlled triaxial system capable of uniform cooling and realistic thermo-mechanical loading, motivating the development of the device presented in this study.

This study addresses the gaps identified above by presenting the design, calibration, and preliminary testing of an economical, temperature-controlled triaxial device, built to study the freeze–thaw behavior of soils under representative boundary conditions. Through the integration of commercial stress path equipment and custom-fabricated, economical temperature regulation, this system seeks to make sophisticated freeze-thaw soil research more accessible to a greater number of geotechnical research facilities and practitioners. Ultimately, this research intends to improve the capacity to assess infrastructure risk in cold climates by supporting more affordable, consistent experimental data collection.

2 MATERIALS AND METHODS

2.1 *Modified Triaxial System*

The experimental apparatus was developed by modifying a commercial triaxial cell to reliably perform repeated freeze–thaw cycles while maintaining compatibility with relevant ASTM requirements, including ASTM D4767 and ASTM D7181. The central modification involved installing a copper coil heat exchanger within the triaxial chamber as shown in Figure 1.

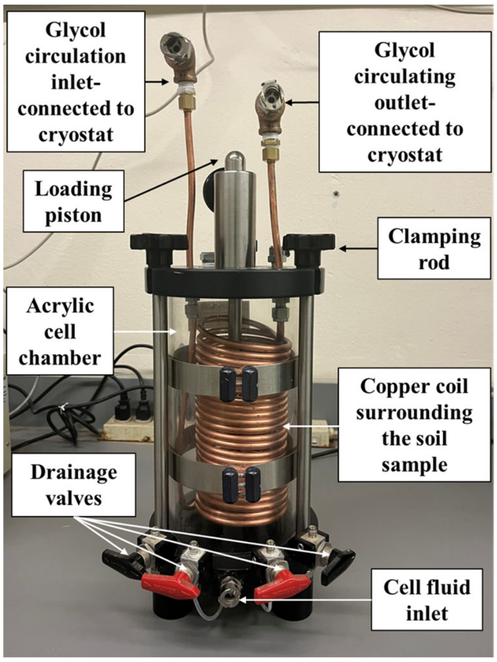

Figure 1. Modified triaxial cell with copper coil heat exchanger.

The modified cell circulates a 50/50 water–glycol mixture supplied by a Polyscience circulating bath unit (chiller). The chiller is equipped with both internal and external resistance temperature detector (RTD) probes to ensure accurate, real-time feedback control and tight temperature regulation throughout testing.

To measure chamber temperature during experiments, an additional gland connector was installed on the top plate of the triaxial cell to accommodate a temperature probe. This gland connector was designed and installed to maintain pressure integrity, avoid leakage, and ensure that the cell could still deliver a uniform confining stress field, consistent with ASTM requirements.

The confining pressure system was operated through the TruePath stress-path platform. The cell pressure pump was also filled with the same water–glycol mixture, providing a consistent confining fluid.

For coolant circulation, low-temperature Tygon clear tubing was used, connected with high-pressure quick-disconnect tube couplings to allow reliable and flexible fluid transfer. The tubing was thermally insulated using flexible polyethylene foam pipe insulation.

To insulate the triaxial cell, a multi-layer thermal barrier was created. First, laminated polyurethane insulation was applied directly to the cell wall. In addition, a custom insulation jacket was constructed from cylindrical concrete paper molds, wrapped in foam strips, and finished with reflective bubble wrap to reduce radiant heat loss. Figure 2 shows the full setup of the modified triaxial system with the various forms of insulation. This layered approach helped stabilize temperatures throughout the entire triaxial chamber, ensuring consistent freeze–thaw cycling with minimal external energy leakage. Figure 3 shows the schematic setup of the triaxial system indicating the simplified operation of the system.

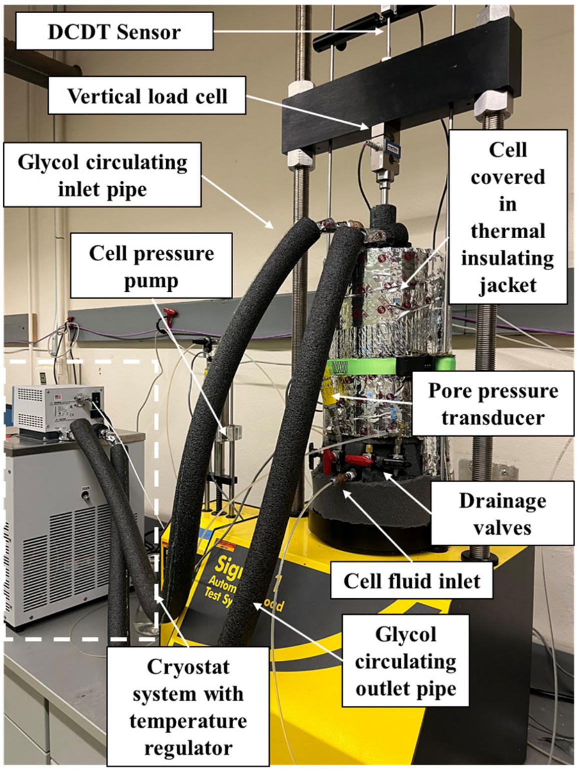

Figure 2. Components of insulation of the temperature modified triaxial system setup.

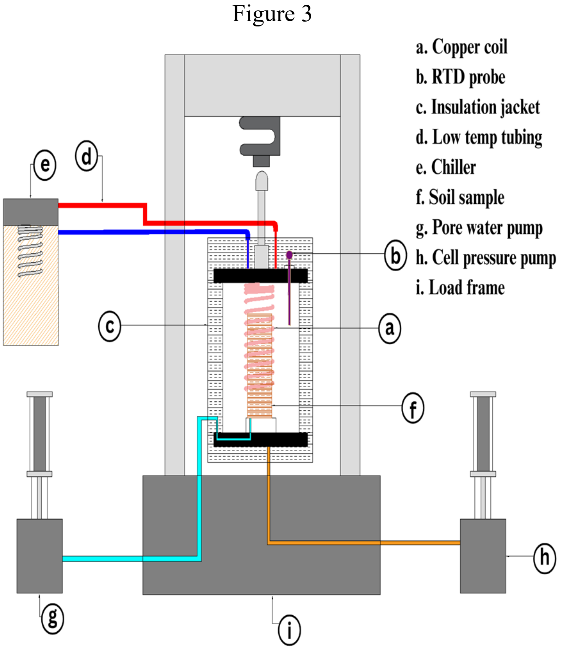

Figure 3. Schematic of temperature modified triaxial system.

2.2 *Soil*

Two soil types were selected to support the calibration and validation of the modified freeze–thaw triaxial testing system. Ottawa sand, conforming to ASTM C778 specifications, was used for strength calibration due to its repeatable mechanical properties. Ottawa sand samples were prepared by gently compacting a constant mass of 391.46 g of dry sand gently into a 1:2 diameter to height ratio at a relative density of 58% with the assistance of a stretched membrane. A commercially sourced kaolinite clay was used to validate temperature control, temperature uniformity, and to observe ice lens formation during freeze–thaw cycles. Table 1 below summarizes the index properties of the kaolinite.

Table 1. Index properties of kaolinite

Test	Value
Particle Size Distribution	25% clay fraction 47.3% silt fraction
Liquid Limit	58.9%
Plastic Limit	29.9%
Plasticity Index	29.0%
USCS Classification	CH
Specific Gravity	2.72

2.3 *Temperature Calibration and Control*

Initial baseline tests were conducted with and without insulation to analyze the effectiveness of the insulation and also determine temperature ranges at which the system is stable in both scenarios. The coolant was circulated at -10ºC in both cases with an average room temperature of 23.5ºC for 8 hours.

Temperature uniformity was validated using a combination of thermal imaging and destructive sampling. Thermographic (infrared) photographs were taken with a FLIR C3 thermal camera after 4, 12, and 24 hours of cooling at -5 ºC (± 0.2) to confirm temperature consistency around the soil specimens. In addition, the specimens were sectioned to evaluate the presence and uniformity of ice lens formation, confirming a stable and uniform freezing front and consistent freezing times across the sample cross section. Vertical and horizontal sections were made with an oven-warmed safety knife. This was done to determine how long it takes the temperature-controlled device to completely perform one freeze - thaw cycle. Also, photographs of the longitudinal and transverse sections were used to confirm the direction of the freezing front.

2.4 *Mechanical Calibration*

Mechanical system calibration was performed using Ottawa sand under consolidated undrained triaxial conditions. Tests were conducted at a confining pressure of 50 kPa using the modified cell (at room temperature with water–glycol as the confining fluid), then compared with identical tests performed in a standard triaxial cell on the TruePath triaxial platform and the Geotac Sigma-1 automated triaxial system (using de-aired water as confining fluid). This was done to ensure the modifications conformed to ASTM standard under normal conditions.

Additional consolidated undrained tests were done on kaolinite specimens tested at a confining pressure of 50 kPa and temperatures of – 5ºC, 0ºC and 23ºC to assess stress development and mechanical consistency under varying thermal conditions. These tests were performed to confirm that the temperature-controlled device could reliably measure changes in soil strength with temperature, an essential requirement for freeze–thaw cycle studies.

3 RESULTS AND DISCUSSION

3.1 *Temperature Control and Uniformity*

3.1.1 *Effectiveness of insulation*

From the initial baseline tests, the coolant cooled from 23°C to -10°C in 45 minutes in the reservoir of the chiller whether the triaxial chamber was insulated or not. However, the minimum achievable stable temperature without insulation was around 2°C. This was achieved in 4 hours indicating substantial external heat losses through the uninsulated cell walls. After insulation (as described in Section 2.1), kaolinite samples were cooled and maintained at −8°C (± 0.1°C) while circulating at −10°C, demonstrating significantly improved temperature stability and reduced thermal losses. Figure 4 shows how the coolant and triaxial chamber temperature changes with and without insulation.

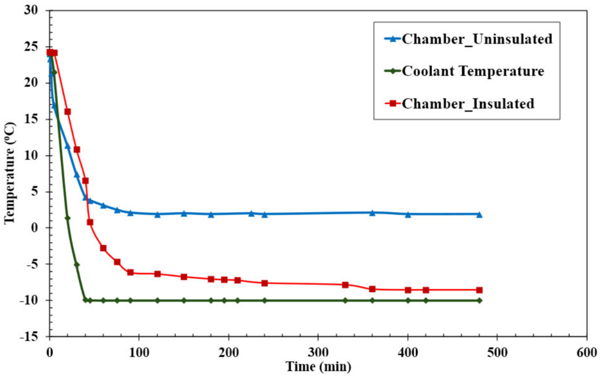

Figure 4. Temperature changes of coolant and triaxial chamber with and without insulation.

3.1.2 *Temperature Uniformity and Freezing Front*

Thermal images of the various cross-sections of the kaolinite samples after 4 hours of cooling showed that the exterior surface of the kaolinite specimens reached a consistent temperature of −5.1°C, while a cut-section measurement across the specimen center indicated an average internal temperature of approximately −3.5°C. The transverse section showed a temperature of -3.7°C between surface and center of the sample indicating the freezing front advances radially from surface towards the center. The differences highlighted an initial temperature gradient from the exterior toward the specimen core, which is expected due to heat transfer lag in the low permeability kaolinite.

After 12 hours, the exterior temperature stabilized at −4.8°C. The internal longitudinal cut section showed an average temperature of −3.9°C. while the transverse cut section shows an average temperature of -4.3°C between the core and surface. This confirms a reduction in the thermal gradient as the freezing front advanced through the specimen.

By 24 hours, both exterior and interior measurements reached a uniform temperature of −4.8°C, as shown in Figure 5, with variations within ± 0.2°C across the sample length. The results demonstrated the successful establishment of steady state freezing conditions throughout the entire soil mass.

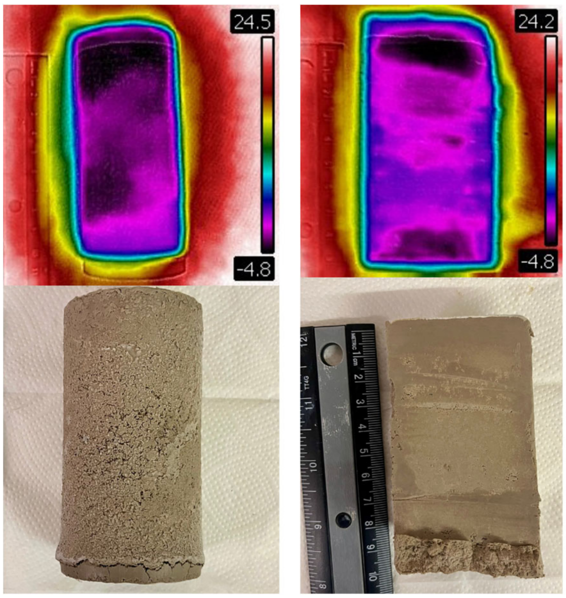

Figure 5. Infrared and visible light images of 24 hr frozen samples showing uniform temperature in uncut and longitudinal section of kaolinite sample.

The fully frozen soil samples were relatively stable such that they maintain an average temperature of -4°C after 15 minutes at room temperature, as shown in Figure 6. Ice particles were also observed at the surface (Figure 5) and in some sections of the core (Figure 6).

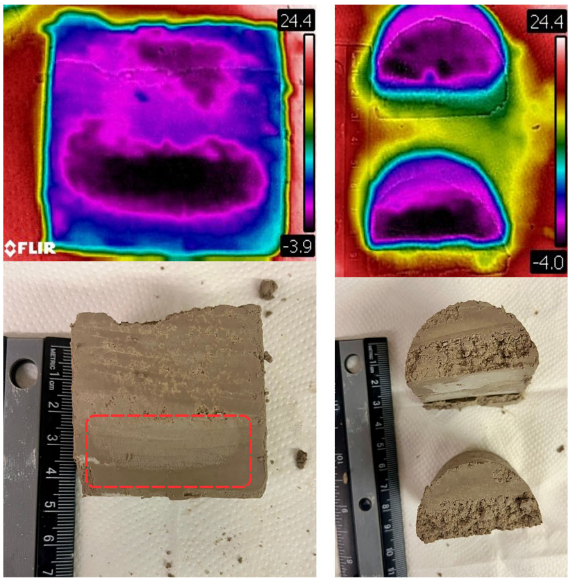

Figure 6. Infrared and visible light images of sections of 24 hr frozen kaolinite samples showing ice particles and temperature stability after 15 minutes of sectioning.

3.2 *Mechanical Calibration*

Stress-strain curves of Ottawa sand specimens tested under identical confining pressures of 50 kPa using three different systems: the modified triaxial cell, a standard triaxial cell on the TruePath triaxial system, and a standard cell on the Geotac Sigma-1 automated triaxial system showed close agreement. The associated results are shown in Figure 7. The systems had comparable peak deviator stresses of 296 kPa, 300 kPa and 312 kPa, respectively, with similar deformation patterns, indicating that the temperature-controlled cell maintained consistent stress path control and reliable data acquisition in line with the standard systems.

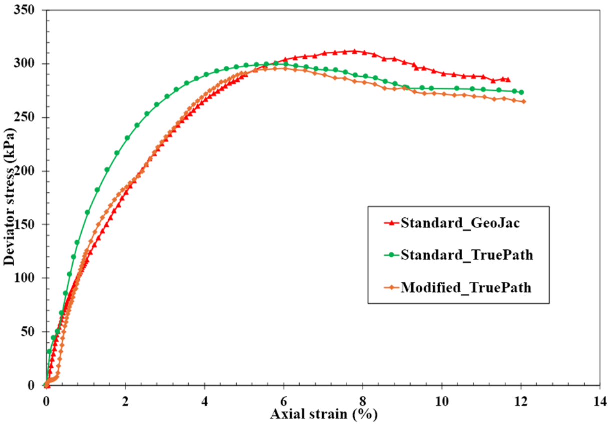

Figure 7. Stress-strain curves of Ottawa sand on different triaxial systems.

Further mechanical tests were performed on kaolinite at a confining pressure of 50 kPa at –5°C, 23°C and 0°C to evaluate the effect of temperature on shearing behavior. As observed in Figure 8, specimens tested at 23°C showed the lowest peak deviator stress of 83 kPa, reflecting the baseline unfrozen strength of kaolinite. Tests conducted at 0°C exhibited a considerable increase in strength with a peak deviator stress of 329 kPa, which is attributed to the initiation of pore water freezing leading to increased interparticle bonding.

The specimens tested at −5°C recorded the highest peak deviator stress of 1394 kPa, demonstrating a clear temperature-strength correlation due to more developed ice lenses at lower temperatures, which act to bind the soil particles together increasing the strength of the soil mass (Ajmera and Emami Ahari 2024; Emami Ahari and Ajmera 2024, 2025). These results validate that the modified triaxial device can reliably capture temperature-dependent mechanical behavior in soils while preserving triaxial loading performance consistent with established equipment.

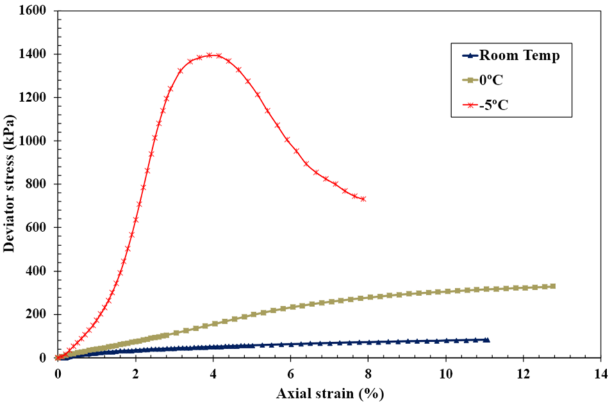

Figure 8. Temperature effects on stress-strain behavior of kaolinite.

The pore pressure responses at room temperature, 0 ºC, and -5 ºC reflect the transition from a water controlled undrained behavior to an ice bonded thermo-mechanical response as temperature decreases. At room temperature, the soil behaves as a normally consolidated material, producing a steady increase in positive excess pore pressure due to contractive deformation and the inability of water to dissipate under undrained loading. At 0ºC, partial freezing reduces the amount of free water in the pores as ice bonding begins and unfrozen water films thin. This creates suction because the soil skeleton carries more of the applied stress and unfrozen water migrates, leading to moderately negative stable values. At -5ºC, the soil structure is strongly ice bonded with only a thin film of unfrozen water, so loading causes immediate and large negative pore pressures as the frozen matrix dilates and develops strong suction. Since ice cannot transmit pressure like liquid water, the pore pressure rapidly becomes highly negative and then stabilizes. The overall trend as observed in Figure 9 shows how decreasing temperature shifts the soil response from contractive to dilative and from positive pore pressure generation to strong suction as ice content increases and the soil skeleton stiffens.

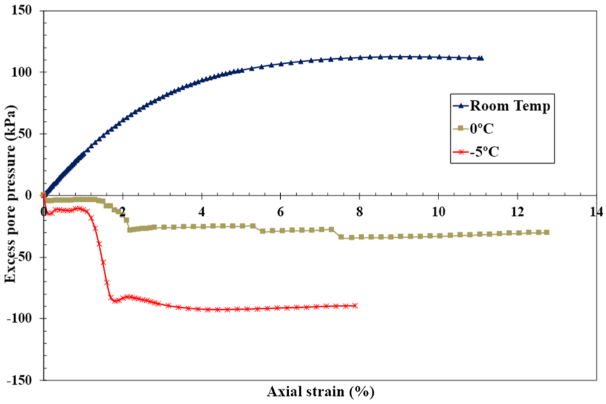

Figure 9. Excess pore pressure behavior of kaolinite during shearing at different temperatures.

3.3 *Limitations*

While the temperature-controlled triaxial system demonstrated reliable temperature control and mechanical calibration, several limitations were identified during its development and testing. Firstly, the specimen dimensions were restricted to 50 mm diameter cylindrical samples due to the spatial constraints imposed by the copper coil heat exchanger installed within the triaxial chamber. This reduced the maximum specimen size relative to standard triaxial systems and may limit the direct comparison to field-scale or larger laboratory specimens.

Secondly, the presence of the copper coil within the chamber, combined with the multilayer insulation jacket, obstructed direct visual observation of the soil sample during testing. As a result, assessments of ice lens formation and soil behavior had to rely on post-test destructive sampling rather than real-time observations during the testing. In addition, the size of the insulation jacket was constrained by the available clearance within the load frame of the triaxial system. This restricted the overall thickness of the insulation, which, together with incomplete coverage at the coupling and elbow sections, resulted in measured temperature losses of -2°C at these specific locations.

While thermographic imaging was an effective tool for assessing temperature uniformity, the time required to drain the cell and extract the specimen introduced additional temperature loss. Furhtermore,the act of handling or cutting the sample could create local temperature gradients. This required extra care to ensure that measurements accurately reflected the in-test temperature conditions.

Overall, while these limitations do not fundamentally compromise the ability of the temperature-controlled triaxial system developed in this study to deliver repeatable freeze–thaw soil tests, they highlight areas for future improvement. These include optimizing the internal layout for larger specimens, enhancing insulation coverage around critical connection points, and developing non-invasive methods to monitor temperature and ice lens formation during the testing process.

4 CONCLUSIONS AND FUTURE DEVELOPMENT

This study developed and validated a modified, economical triaxial system to evaluate soil behavior under freeze–thaw conditions. The device integrates a copper coil heat exchanger, water–glycol-based cooling, and multilayer insulation into a standard triaxial cell. The modified system demonstrated reliable temperature control and mechanical consistency while meeting ASTM standards. Temperature calibration tests confirmed that the system could achieve uniform freezing of kaolinite specimens within 24 hours and maintain a stable thermal environment throughout the testing period. Temperature uniformity was confirmed using thermal imaging and specimen sectioning, with ice lens development observed in clay samples. Mechanical calibration with Ottawa sand and kaolinite further demonstrated that the temperature-controlled system performs comparably to commercial triaxial platforms, effectively capturing temperature-dependent strength variations in frozen soils.

The successful development of this system represents a significant step toward making advanced freeze–thaw soil testing more accessible to a wider range of research institutions, especially those constrained by the high cost of commercial systems. Commercial temperature-controlled triaxial systems generally range from approximately 75,000 to over 650,000 USD, with typical full-system costs averaging around 280,000–300,000 USD once the load frame, pressure controllers, temperature-control chamber, software, and installation are included. These prices place advanced thermal–mechanical testing beyond the reach of most standard geotechnical laboratories. In contrast, the approach developed in this study does not attempt to replace or replicate a complete commercial triaxial system. Instead, it provides a cost-effective modification to an existing conventional triaxial apparatus already present in many laboratories. The added components include the copper cooling coil, tubing and fittings, insulation materials, and a programmable circulating bath total under 8,000 USD, with the cell modification itself costing less than 1,000 USD. This represents a dramatic reduction in the incremental cost of enabling temperature-controlled testing, providing a practical and accessible pathway for laboratories to conduct freeze–thaw triaxial experiments without the financial burden associated with purchasing specialized commercial systems.

Future developments will focus on addressing the limitations identified previously by (1) redesigning the copper coil to allow larger specimens, (2) experimenting with improved insulation materials and geometries to minimize thermal loss, and (3) integrating thermo-time domain reflectometry (TDR) probes to enable simultaneous monitoring of temperature and volumetric ice content. Upgrading to higher-capacity load cells will also be explored to extend the range of stress conditions under which frozen samples can be reliably tested. These enhancements will improve testing accuracy and further align laboratory simulations with real-world geotechnical conditions.

5 ACKNOWLEDGEMENTS

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