Chapter 3
Effects of Moisture Content and Freezing Temperature on the Compressive Strength of Frozen Soils

Yohannes Mulu Birhan, Mewael Daniel Isiet, and Addis A. Kidane

Abstract This paper examines the impact of moisture content and freezing temperature on the compressive response and failure mechanisms of frozen sandy soil at a freezing temperature of -10°C and -20 °C. The sand samples, with a range of gravimetric moisture contents from 10% to 18%, were packed in a cylindrical mold to a nominal density and then frozen for 12 hours. A protocol is developed to compact and freeze sands with different moisture content and freezing temperatures. The samples were subjected to quasi-static compression loading using a universal testing machine and high-strain-rate loading using a split Hopkinson pressure bar. The effects of moisture content and freezing temperature on the material's stress-strain response are investigated. The split Hopkinson pressure bar setup developed for high-strain-rate testing is described; dynamic results are not reported here. In general, the material has a strong dependence on the freezing temperature. For all moisture contents considered, the failure strength increases with lower temperature. The moisture content shows a moderate but consistent effect in expanding the failure stress at lower freezing temperatures. However, at higher freezing temperatures, the increase in strength with moisture content appears to saturate at 16%. The observed variations in stiffness, strength, and ductility are discussed in relation to moisture fraction and loading rate. The data can be used to estimate a moisture-conditioned rate-sensitivity parameter for constitutive modeling. A dataset with uncertainty bounds, including moisture content, freezing temperature, strain rate, failure envelopes, and full-field measurements, will be available and all suitable for validating data-driven constitutive laws.

Keywords Frozen soil · Moisture content · Strain rate · SHPB · Constitutive modeling

Introduction

Building on frozen sandy soils is a significant challenge in cold-region infrastructure, such as Arctic and geotechnical systems, where load-bearing performance depends strongly on both ice content and loading rate. Frozen sandy soil behaves as a complex, multi-phase composite comprising solid mineral grains, pore ice, and unfrozen water. In these materials, small changes in moisture content can shift the dominant load-transfer mechanism from grain-to-grain contact to ice-bonded behavior. In addition, rapid loading can further alter the apparent stiffness, strength, and ductility through rate-dependent ice and interface processes. These coupled dependencies create practical challenges for predicting capacity and failure mode under conditions ranging from slow foundation settlement to impact or blast-type loading. [1–4]. As a result, there is a need for experimentally grounded datasets and failure-mode classifications that span realistic moisture ranges and strain-rate regimes and can directly support the calibration and validation of constitutive models, including emerging data-driven approaches.

Limited experimental efforts in the open literature have focused on understanding the dynamic behavior of frozen soil under different loading conditions [5, 6]. On the other hand, Ravindran et al. [7–9] recently developed and implemented a digital image correlation-based experiment to quantitatively measure the local damage process in granular materials. This work extends the experimental method for understanding the failure mechanism of soil loosening at different temperatures and strain rates. The proposed digital image correlation and Hopkinson pressure bar experiment will provide rich, full-field information, requiring a data-driven, machine-learning approach to effectively understand the fundamental failure mechanisms in freezing soil under different conditions.

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In this study, we focus on frozen sandy soil held at -20 °C and then at -10 °C and test how moisture content (10-18% gravimetric) and strain rate work together to control its compressive response and failure mode. We prepare specimens using a consistent packing and freezing protocol to keep density and thermal history as controlled as possible. Then we load the samples in compression under both quasi-static and high-strain-rate conditions using a universal testing machine and a split Hopkinson pressure bar, respectively.

The primary purpose is to understand the failure mechanisms and their relationship to the stress-strain response at different conditions. The effects of moisture and strain rate on failure mechanisms, such as ice-bond breakage, grain-boundary separation, and shear localization, will be discussed. The experimental data will serve as a starting point for understanding and modeling frozen soil under different moisture, temperature, and strain rate conditions. The data can be used to link mechanics to structure by measuring density/void ratio, saturation/air content, and ice distribution indicators, and evaluate whether these explain the non-monotonic peak behavior at -20 °C. Expand the matrix with additional temperatures, longer conditioning times, and controlled end-friction conditions (lubrication or platen treatment) to separate bonding effects from compaction/friction effects. Validate with complementary observations, e.g., post-test failure patterns, imaging, or mass loss checks, to support interpretations of the result.

Experimental method

Material and specimen geometry

Materials

Specimens were prepared using a uniform silica sand (No. 70, JR Simplot Company) and distilled water. Moisture content was defined on a gravimetric basis by weighing mass. To limit evaporation (and later possible sublimation) and maintain tight moisture control, mixing was performed per specimen. The required sand mass and the corresponding distilled-water mass (and/or volume) were measured for each specimen immediately before compaction. As a basic characterization of the sand gradation, approximately 90% of the material was retained on a 106 μm sieve (No. 140, U.S. standard).

Specimen fabrication and compaction protocol

Cylindrical specimens were formed by compacting moist sand into a small, rigid mold using an energy-controlled procedure, following the principles of ASTM D698 (compaction), adapted to the reduced specimen size. Each specimen was compacted in two layers; each layer received 10 blows from a modified compaction rod dropped from a height of 0.25 ft on a rigid base. The compaction rod mass and tip geometry were selected such that the delivered compaction energy was consistent with the ASTM D698 energy basis. To promote continuity across the layer interface, the surface of the first layer was lightly roughened before placing and compacting the second layer. The specimen ends were used in the as-compacted condition (i.e., no trimming or capping was performed).

Geometry and density

The resulting specimens were right circular cylinders with an average diameter of 19.8 mm (mold diameter tolerance ± 0.2 mm) and an average height of 10.5 mm. A nominal bulk density target of 2.0 g/cm^3 was imposed during fabrication. In practice, this was enforced by selecting the constituent masses of the specimen such that the total wet mass corresponded to the target bulk density for the mold volume; the achieved mean bulk density across specimens was 1.97 g/cm^3. Specimens outside the density tolerance band were rejected before freezing and testing.

Freezing protocol

Immediately after fabrication, each specimen was wrapped in plastic and placed in a sealed bag to minimize moisture loss during freezing. All specimens were frozen at -20 °C and -10 °C for 12 hours before mechanical testing. The specimens were then frozen for an additional 30 minutes at -50°C and -40°C, respectively, for -20 °C and -10 °C batches, conditioned just before the test. The experimental plan included three replicates per condition to assess repeatability.

Quasi-static compression tests were performed on an MTS 858 Universal Testing Machine using temperature-conditioned (pre-cooled) upper and lower platens matched to the specimen temperature to minimize thermal gradients during loading. Specimens were then loaded in displacement control at 5 mm/min (engineering strain rate (around $7.9\text{x}10^{-3}\text{s}^{-1}$) for a 10.5 mm specimen height), with each test lasting $\sim$50 seconds, while an IR thermometer continuously monitored the specimen surface temperature during testing.

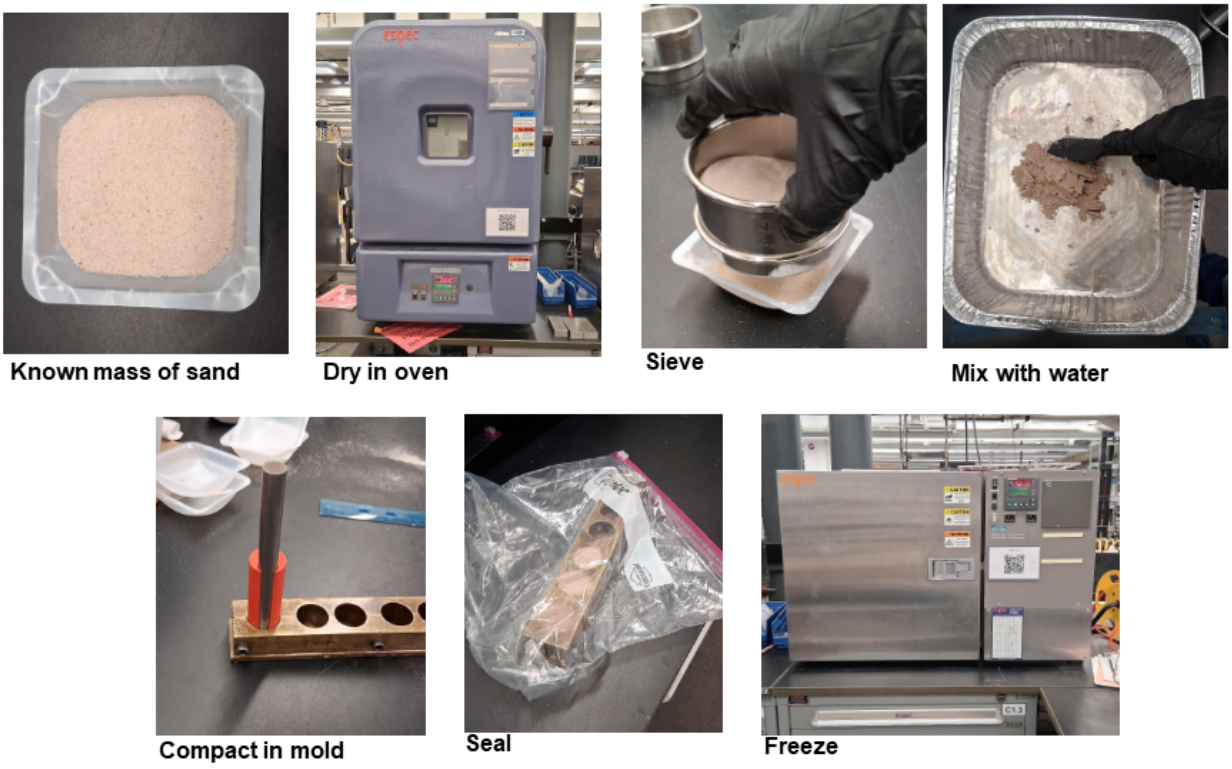

Fig. 1 Specimen preparation.

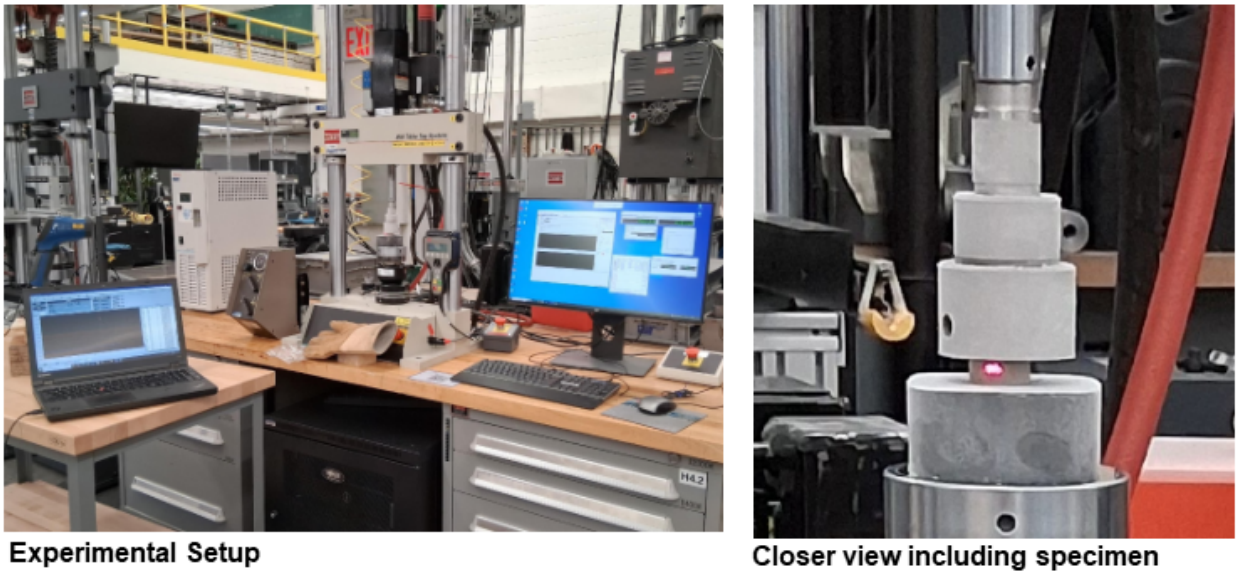

Fig. 2 Quasi-static test setup (left) and specimen while testing (right)(note the loading plates are also frozen to keep the temperature constant during testing).

High-strain-rate testing

A Split Hopkinson Pressure Bar (SHPB) apparatus is used to test the frozen samples at high-strain-rate loading. The setup comprises 1in diameter incident and transmitter bars of identical geometry (1.835 m each), together with a 2 ft striker bar. A

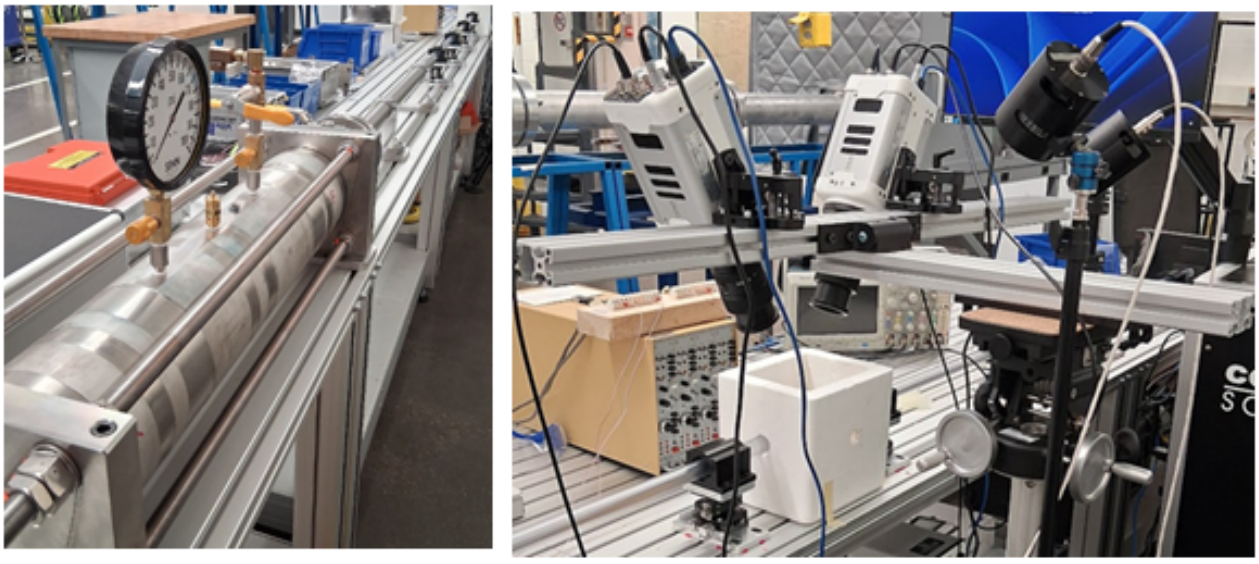

Fig. 3 High-strain experimental setup.

pulse shaper (∼1 mm thick cardboard) is placed on the striker side of the incident bar to condition the incident pulse. Strain gauges (at top and bottom) are mounted on both the incident and transmitter bars at 92.5 cm from the specimen interfaces. Loading intensity (and the resulting strain-rate level) is controlled by adjusting the gas-gun air pressure (starting at ∼5 psi). White lithium grease is applied at the bar-specimen interfaces to reduce friction and promote more uniform loading. A momentum trap/damper is implemented at the free end of the transmitter bar using a steel collar fitted with three ∼1 in rubber elements to mitigate end effects and reduce unwanted reflections. To maintain testing temperature, a copper-coil cooling system coupled to an industrial chiller is being developed.

Result and discussion

Figures 4 and 5 summarize stress-strain behavior for frozen soil conditioned for 12 h at -10 °C and -20 °C across moisture contents of 10-18%. Across both temperatures and all moisture levels, the responses share a consistent shape: a steep initial rise in stress to a distinct peak at small strain, followed by post-peak softening, then a sustained nonzero stress level at larger strain, with partial re-hardening in many curves. This repeatable sequence indicates that, under the present conditions, the material response is not purely brittle; instead, it exhibits a peak-type reaction followed by continued load-carrying capacity at larger strains, and densification at higher moisture content, for example, 18%.

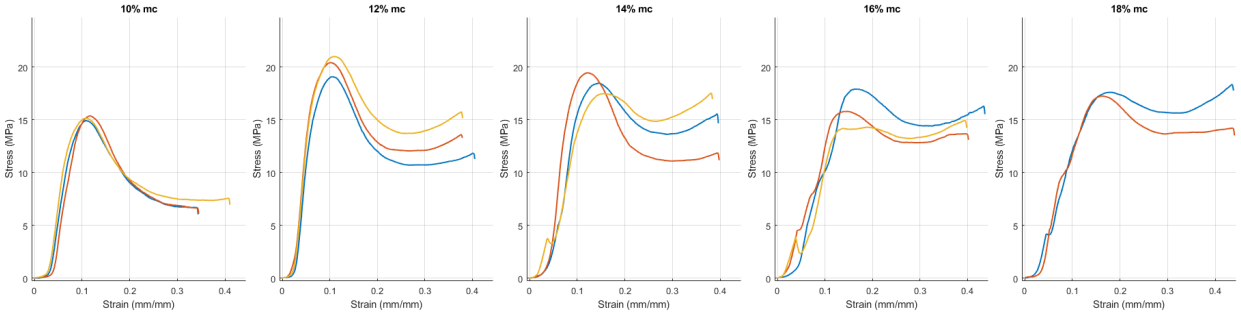

Fig. 4 Stress-strain at -20 °C.

At -10 °C, the curves show a clear qualitative separation between low and high moisture contents. The 10-12% groups exhibit the most pronounced post-peak drops and the lowest stress at large strain, whereas the 16-18% groups maintain

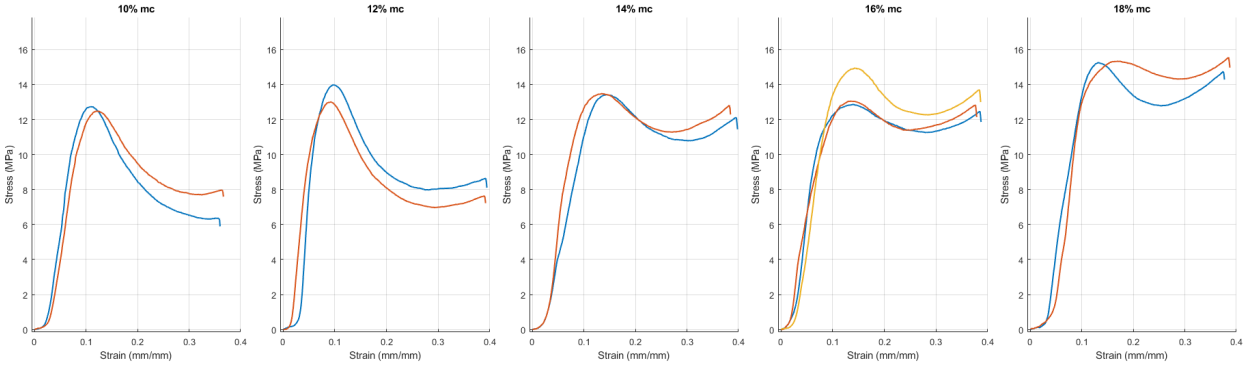

Fig. 5 Stress-strain at -10 °C.

higher stress levels throughout the post-peak regime and commonly show stronger late-stage recovery. The 14% condition is generally intermediate. Replicate scatter is modest at 10-14% and more pronounced at 16%, particularly around the peak and the early post-peak response.

At -20 °C, the overall response shape remains similar, but the moisture dependence is less strictly monotonic in peak stress. The 10% group again shows a strong peak followed by a significant drop to a relatively low residual level. The highest peak stress in this set appears in the intermediate moisture range (notably 12-14%), and several curves display clear late-stage re-hardening. The 16-18% groups still sustain comparatively high post-peak stress, but the mid-to-late strain response shows greater specimen-to-specimen divergence than at lower moisture contents.

Summary

The effect of moisture content and temperature on the stress-strain response of frozen soil was investigated experimentally. A procedure is adopted to compact a specimen and effectively freeze the sample at different temperatures and moisture contents. The quasi-static results can be summarized as;

- Under 12 h freezing at both -10 °C and -20 °C, all specimens exhibit a repeatable peak-softening-residual/re-hardening stress-strain response, indicating continued load-carrying capacity after peak rather than abrupt collapse.
- Moisture content strongly affects post-peak resistance: higher-moisture specimens (especially 16-18%) generally sustain higher stress at larger strain than low-moisture specimens (10-12%).
- The peak stress trend is more evident at -10 °C (higher moisture tending toward higher strength). In comparison, at -20 °C, peak stresses are less monotonic, suggesting increased sensitivity of the peak response to specimen state and to freezing-induced heterogeneity, in addition to moisture content.

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