ERDC/CRREL TR-18-2

Cold Regions Research and Engineering Laboratory

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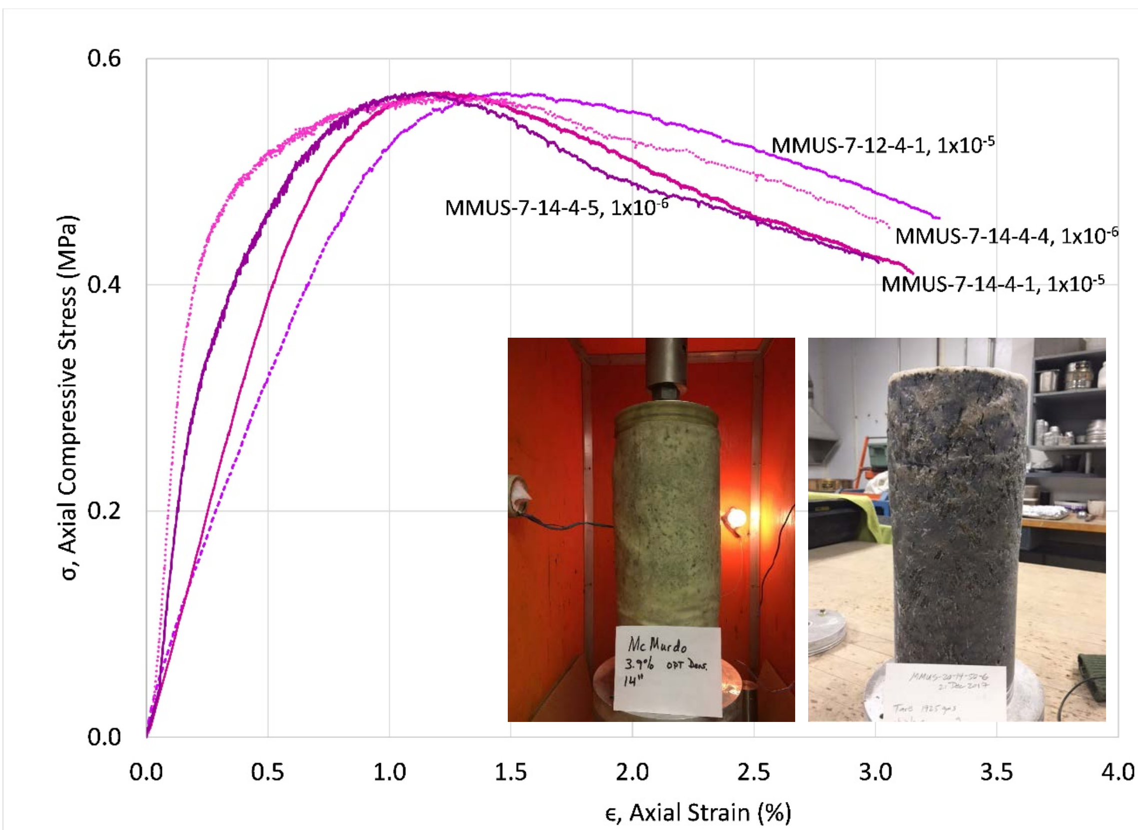
Engineering for Polar Operations, Logistics, and Research (EPOLAR)

Compression Strength of Frozen Gravel Materials from McMurdo Station, Antarctica

Rosa T. Affleck, Terry Melendy, Amelia Menke, Andrew Bernier, and Charles Smith

March 2018



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EP-ANT-17-65, “Laboratory Tests to Quantify the Strength Properties of McMurdo Ground Materials”

Abstract

The plan to modernize McMurdo Station involves constructing large buildings for more efficient facilities and infrastructure. Foundation design for these large buildings will require understanding of the mechanical properties of the native soil. This study is the first that we are aware of to conduct uniaxial compression tests on materials from McMurdo Station in their frozen state. The testing used in this study emulates specific ground conditions measured on-site.

Reconstituted specimens of well-graded gravel basalt were compacted at 4% and 20% by weight moisture contents and frozen at temperatures of −7°C and −20°C. Test results determined that higher moisture content combined with lower ambient temperatures resulted in increased strengths compared to optimum moisture and compaction testing results.

If new building foundations will be in direct contact with the ground and allow heat transfer to take place, then the base material should be placed and compacted at the optimum moisture content. This will reduce the potential effects of thaw degradation under the foundation, especially on ice-rich ground.

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Preface

This study was conducted for the National Science Foundation (NSF), Office of Polar Programs (OPP), under Engineering for Polar Operations, Logistics, and Research (EPOLAR) EP-ANT-17-65, "Laboratory Tests to Quantify the Strength Properties of McMurdo Ground Materials." The technical monitor was Ms. Margaret Knuth (program manager), NSF-OPP, U.S. Antarctic Program; she also provided logistical guidance and technical supervision.

The work was performed by the Force Projection and Sustainment Branch (CEERD-RRH) and the Engineering Resources Branch (CEERD-RZE) of the Research and Engineering Division (CEERD-RR), U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL). At the time of publication, Ms. Erin Bodie was Chief, CEERD-RRH; Mr. Jared Oren was Chief, CEERD-RZE; Mr. J. D. Horne was Chief, CEERD-RR; and Ms. Janet Hardy was the program manager for EPOLAR. The Deputy Director of ERDC-CRREL was Dr. Lance D. Hansen, and the Director was Dr. Joseph L. Corriveau.

The authors also thank the following CRREL staff for their contributions: Glenn Durrell (retired CRREL technician) for conducting the second phase of MTS testing and Ms. Renee Melendy for providing superb office administrative and logistical support. Ms. Emily Moynihan provided our editing support. Technical reviews were provided by Mr. Kevin Bjella and Dr. Wade Lein.

COL Bryan S. Green was Commander of ERDC, and Dr. David W. Pittman was the Director.

Acronyms and Abbreviations

CRREL	Cold Regions Research and Engineering Laboratory
EPOLAR	Engineering for Polar Operations, Logistics and Research
ERDC	U.S. Army Engineer Research and Development Center
GW	Well-Graded Gravel
MPT	Multipurpose Testware Suite
NSF	National Science Foundation
OPP	Office of Polar Programs
USAP	U.S. Antarctic Program
USCS	Unified Soil Classification System

Unit Conversion Factors

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
degrees (angle)	0.01745329	radians
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
foot-pounds force	1.355818	joules
inches	0.0254	meters
pounds (force)	4.448222	newtons
pounds (mass)	0.45359237	kilograms

1 Introduction

1.1 Background

The strengths of frozen soils depend on their actual composition (Andersland and Ladanyi 1994) and numerous other factors, such as loading, grain size, mineralogy, salinity, location, and geological history (Anderson and Tice 1972; Anderson et al. 1973; Arenson and Tice 2006; Patterson and Smith 1985; Williams 1963; Zhang et al. 1998). Published literature presents the strength properties and the stress–strain behavior of frozen fine-grained and sandy soils (Baker 1978; Bragg and Andersland 1981; Sayles and Carbee 1980; Diekmann and Jessberger 1982; Sayles 1973; Zhu and Carbee 1984). These studies indicate that the strength of frozen soil is also dependent on density, temperature, pressure, strain rate, ice content, and crystal orientation. At very high ice contents (ice-rich soils), frozen soil under load behaves similarly to ice. The strength of frozen soil is influenced by bonding of particles by ice. This means that when ice fills most of the pore space, there is a strong material bond, and the mechanical behavior of a frozen soil will reflect closely that of the ice.

Typically, the compressive strength of frozen soil increases with increasing moisture contents. Likewise, the compressive strength of frozen sands and silty soils increases with decreasing temperature until a point at which the frozen material becomes brittle. At very low temperatures, the release of the ice–soil bond and the maximum microstructural damage occur (Andersland and Ladanyi 1994). For example, under uniaxial loading at 3×10^{-5} sec^{-1}, the release of the ice–soil bond for frozen sand occurs after −60°C, and the maximum microstructural damage occurs at a temperature of approximately −100°C; below that temperature, its strength gradually decreases (Andersland and Ladanyi 1994; Bourbonnais and Ladanyi 1985). The cryogenic temperatures at which the ice–soil bond releases and the maximum microstructural damage occurs for frozen gravel are not available in published literature.

Gravelly materials are normally dense, particularly those with well-graded grain distribution. They usually have good permeability and high bearing capacity. Studies on the mechanical properties of unfrozen gravel materials far outnumber those concerning frozen gravels. The mechanical properties of frozen gravelly materials, and igneous basalt specifically, have not been well investigated. It is of utmost importance to examine the mechanical behavior of ice-cemented basalt because it will serve as bearing strata for pile or mat foundations for important structures at McMurdo Station.

The current plan at McMurdo Station involves a large development of engineered structures to modernize the facilities by building a more efficient infrastructure. This modernization plan encompasses significant and drastic changes to the topography and extensive site preparation to construct foundations for large buildings and to improve existing infrastructure. Although there have been several extensive studies on soils in continental Antarctica, there has been little focus on the geotechnical information at McMurdo Station, particularly frozen characteristics of the materials. The ground conditions of perennial frozen materials at McMurdo Station are subjected to the Antarctic extreme subfreezing temperatures. The soil-ice structure are heterogeneous and consist of ice-rich fill, fractured volcanic bedrock, permafrost, excess ice, and buried anthropogenically generated debris, each of which must be considered during future construction (Affleck et al. 2017; Campbell et al. 2018). Even the terrain of fractured rock layers containing massive ice or ice-rich materials (similar to the materials found at McMurdo) when thawed by changing the regime state will lead to deferential settlement. Therefore, the selection of foundation design depends on the behavior of the ground materials.

1.2 Objectives

To our knowledge, this study is the first uniaxial (unconfined) compression tests to test the frozen basalt materials from McMurdo Station. Because of the remote site, ordinary in situ tests were not possible; and obtaining undisturbed frozen samples for laboratory testing is logistically challenging. Therefore, reconstituted specimens were manufactured at two selected moisture conditions and frozen at two specific temperature points that resemble the ground conditions measured on-site. The objectives of this study were (1) to quantify the strength properties of the material and (2) to develop broad-scale recommendations for the foundation design based on the strength properties and physical characteristics of the material.

1.3 Approach

The representative gravel materials of approximately 100 kg was shipped to CRREL from McMurdo Station. This material was taken from the stockpile screened with a 50 mm industrial screen to maintain the natural distribution of material sizes. Section 2 describes the general characteristics of the McMurdo Station landscape, and section 3 highlights the physical characteristics of the gravel materials. Section 4 discusses the experimental design of the study and describes the sequence of the samples' fabrication and testing. The report then describes the mechanical behavior that resulted from the stress–strain responses and compares it with other tests (i.e. frozen sands and unfrozen gravel of similar test characteristics). The summary and conclusions include discussions of the test limitations, the risks of the presence of alkaline silica reaction on the aggregate, and the existence of hydrocarbon in places at McMurdo Station.

2 General Site Description

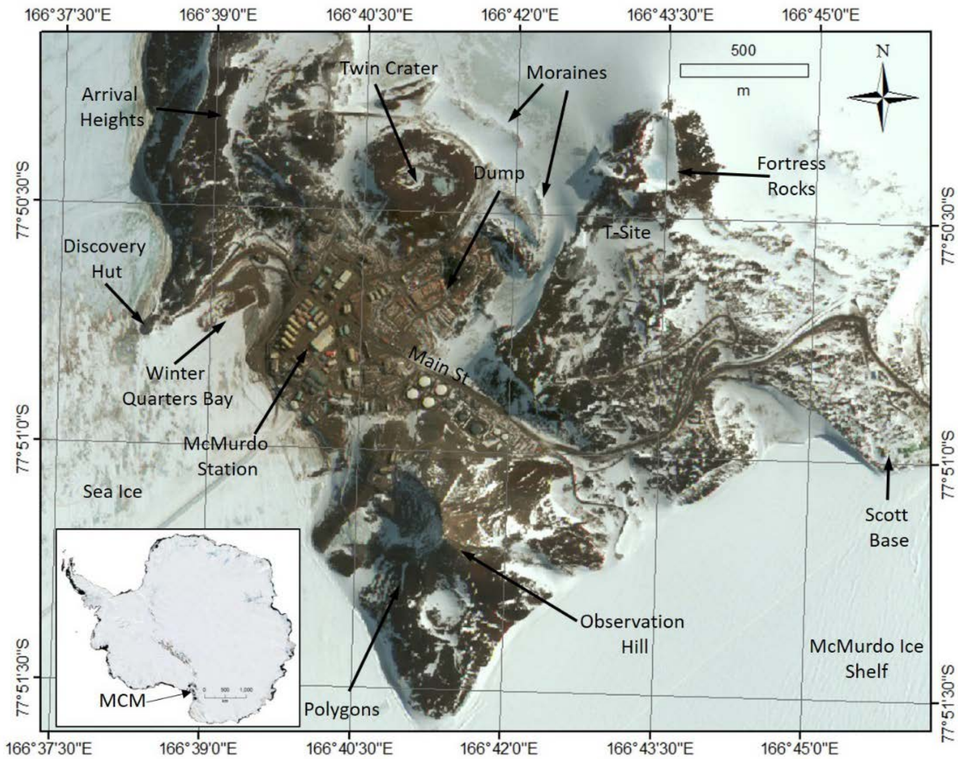
McMurdo Station, located on Hut Point Peninsula of Ross Island, is a research facility and logistics hub of the U.S. Antarctic Program (USAP) with a large operational component that supports research in the region and around the continent (Figure 1). McMurdo Station's existing facilities were constructed on an outcrop of barren volcanic rock on a series of constructed flat fill platforms, resulting in terraced-like topography. Although the terrain at McMurdo Station has been altered to accommodate the increase of science support activities (Klein et al. 2004, 2008; Kennicutt et al. 2010), the landscape at McMurdo Station still features the high ridges and sloping hills of barren volcanic rock, frozen ground, and perennial snow and ice fields. Early literature described the terrain at McMurdo Station and in the surrounding area as having polygonal and sand-wedge features indicative of a typical permafrost landscape (Péwé 1959, 1991; Bockheim 1997). Péwé (1959) suggested that the formation of

> polygons and sand wedges is similar to the origin of foliated ice wedges and polygons in the Arctic. Periodic contraction cracks in the perennially frozen ground around McMurdo Sound, cracks produced by the great change in temperature from summer to winter, are gradually filled with clean sand which filters down from above in the spring and summer.

These features are still visible in a few small places, including the escarpment on Arrival Heights and Observation Hill (Klein et al. 2004), but most of the sand-wedge polygons in the area are indiscernible because of significant landscape disturbance and human activity.

In the summer months, the maximum active layer is approximately 0.26 m and 0.37 m in a partially shaded area and in an open area, respectively (Affleck et al 2017). The ground temperature gradually loses heat sometime at the end January as lower air temperatures advance, causing the ground to refreeze. The ground condition is fully frozen in mid-May and mid-October with subfreezing temperatures at well below −20°C down to 1.22 m below the surface (Affleck et al. 2017; Tumeo and Cummings 1996). In other places at McMurdo Station, the ground temperatures from April to September are approximately between −17°C and −16°C at 8 and 12 m below the surface, respectively (Affleck et al. 2017; Oswell et al. 2010).

Figure 1. Map of Hut Point Peninsula on Ross Island, Antarctica, showing McMurdo Station (MCM) relative to other major geographic features. (The background is from DigitalGlobe, Inc., satellite image WorldView-3 taken from the 6 December 2015 panchromatic band.)



The water contents of near-surface permafrost horizons (layer between 0.5 m and 1 m below the ground surface) ranged from 64% to 150% by weight. These indicated significant amounts of segregated ice interlayered with soil in the horizon (Affleck et al. 2017). However, the lower portion of the permafrost horizon exhibited lower moisture contents (between 10% and 55%) than in the upper horizons in the permafrost layer. Similarly, the measured values for total volumetric ice content (V_{ice}) ranged from 21% to 83% and varied with depth below the permafrost table within the ice-rich layer (Affleck et al. 2017). The moisture variations depended on the deposition and conglomeration of the frozen materials. These values are similar to those measurements in the ice-cemented layers in the undisturbed and disturbed sites at the Scott Base area (Campbell et al. 1994).

3 Soil

Earlier studies classified the soils in that Antarctic region as "cold desert zone" (Tedrow and Ugolini 1966; Tedrow 1977; Ugolini and Bockheim 2007). More recently, the soils within the Ross Sea region were classified as Cryosols (International Union of Soil Sciences 2006) or Gelisols (Soil Survey Staff 2010) with a wide range of soil properties based on the climate and glacially ablated parent (geologic) materials (Campbell and Claridge 2004, 2009). Organic matter is very minimal with isolated mosses and lichen in a few places. The ablated or barren surface of McMurdo Sound is composed of boulders, rock, and coarse-grained soils from weathered volcanic flows. These materials are single-grained structures with lithochromic grayish colors reflecting the parent materials and some reddish materials due to oxidation of iron minerals. The presence of ice-cemented permafrost within Ross Island is common (Balks et al. 2013). The general summary of key soil properties in the Ross Sea region indicated that the material is predominantly gravelly sands with a single-grained structure (Affleck et al. 2017; Balks et al. 2013). Observations of active layers during summer indicated that the ground thaws between 0.15 m in partially shaded area or near buildings and 0.30 m on flat or open areas at McMurdo Station (Affleck et al. 2012; 2017) and on a hillside 100 m from the building at Scott Base (Adlam et al. 2010; Seybold et al. 2010).

The predominant geologic features of the ice-free surface of McMurdo Station are characterized as basaltic and pyroclastic flows interbedded with widespread tills (Cole et al. 1971). In general, the fractured rocks and boulders are classified as (olivine-augite) basalts (Cole et al. 1971) at Fortress Rock, Arrival Heights, and Crater Hill, including trachytes rocks at Observation Hill (Figure 1). Because Fortress Rock, Arrival Heights, Crater Hill, and Observation Hill are within 1 km of each other, the general description of the surface geology of McMurdo Station is varying amounts of scoria and basalt fragments in ice matrix and fractured basalt bedrock. These materials are mineralogically similar and are composed of pyroxene, olivine, plagioclase feldspar, magnetite, and glass (Hoffman 1979). These fractured basalts can vary from compact (dense gray rock) to vesicular basalts (rocks with tiny holes). Some rocks have a redder color owing to oxidation of iron minerals and are differentiated as scoria. Compact rocks from much harder crystalline flows are found at deeper depths and at various locations. The fine-grained materials exist due to the physical and natural (thermally and cryogenically) changes with time.

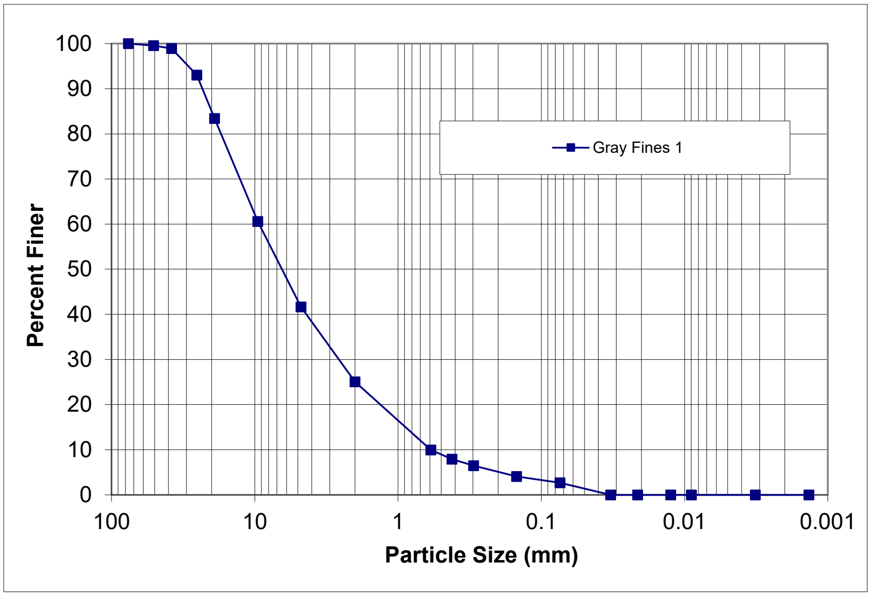
A certain amount of rock materials is constantly harvested from nearby hillsides for various purposes, including new projects, infrastructure improvements, fill, maintenance or road repair, pads, and landscaping around or under buildings (Knuth and Melendy 2012). The dry densities of reddish and gray (solid) rocks were recorded with approximate values of 1.96 g/cc and 2.48 g/cc, respectively (Affleck et al. 2017). The gray soil (being denser and harder material than the reddish material) is used primarily on roads and pads and for foundation while the reddish materials are used surfacing the pier and in less trafficked areas. The permeability of the gravelly sand samples from McMurdo Station ranged from 0.07 to 0.11 cm per second (Affleck et al. 2012). With these permeability values, the soil is classified as a good drainage material for sandy gravel soil (Holtz and Kovacs 1981). Thus, the active layer is porous and permeable, allowing melt water to flow both through the interstices and laterally along the permafrost table or pond and to refreeze at the permafrost table.

We selected the gray coarse-grained material for this laboratory testing because this material was found to be the best available rock for construction (Knuth and Melendy 2012; Hoffman 1979). We took this gray material from a representative stockpile collected above Gasoline Alley (the stockpile passing the 50 mm screen with the distribution of material consisting of less than 50 mm) and shipped it to the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) in a metal drum.

3.1 Gradation

CRREL conducted a grain size analysis for the material (ASTM 2009 [ASTM D6913-04]) as characterized based on Unified Soil Classification System (USCS) engineering identification. The typical gradation is classified as well-graded gravel (GW) and is commonly used for construction materials (Figure 2). These coarse-grained materials are typified as angular and subangular grains with relatively low silt contents (Affleck et al. 2017), with 2.7% passing 0.075 mm (200 sieve).

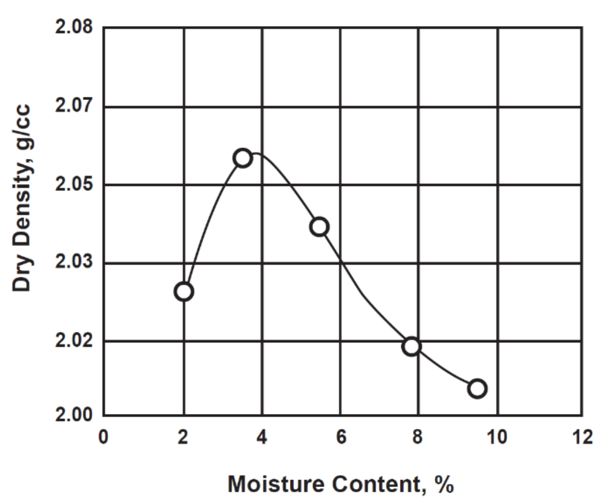
Figure 2. Test specimen grain size distribution. The median grain size (D_{50}) = 6.42, coefficient of uniformity (C_u) = 16.66, and specific gravity = 2.75.



3.2 Compaction

The compaction properties of the material were tested by using standard test methods ASTM D698-12 (ASTM 2015) and Department of the Army TM 3-34.43 (2015) to determine the relationships between molding water content and dry unit weight. From the compaction test, the maximum dry density and moisture of the soil were 2.06 g/cc and 4% (by weight at a saturation of 28.7%), respectively (Figure 3).

Figure 3. Compaction curve for McMurdo well-graded gravel.



4 Experimental Program

We selected two sets of moisture contents: the optimum moisture represents the condition if construction uses compaction while the saturated samples represent a high ice condition. Table 1 summarizes the experimental design. Description of the testing for the material follows.

4.1 Specimen fabrication

For this test, the material from McMurdo Station was separated into various sieve sizes. To fabricate each sample with consistent gradation (in Figure 2), the percentage of the total amount of the material needed in each mold was combined together. Samples were fabricated in replicates of two in cylindrical (aluminum-split) molds of either 305 or 356 mm high with a 152 mm diameter. The 152 mm diameter molds were used because the gravel included the 19 mm (¾ in.) diameter size, which follows TM 3-34.43 (Department of the Army 2015). The molds were custom manufactured for the desired lengths due to the unique requirements of the testing. These molds were radially lined with a rubber membrane connected to a vacuum system (Figure 4) to prevent loss of moisture content from the sample. The samples were fabricated with test conditions described in Table 1. This includes freezing of the samples at −7°C and −20°C. The tests at −7°C resemble the temperature of the ground in the summer months just below 0.61 m while the tests at −20°C resemble the approximate ground temperature (from surface to 12 m) in April or October (Affleck et al. 2017).

The first set of samples was fabricated at ambient (22°C) temperature with optimum soil moisture and density. Targeting 4% by weight of moisture and density of 2.06 g/cc (Figure 3), the precise amount of water was added into the dry soil. The soil was compacted in the molds in five lifts with 12 blows per lift using the 10 lb hammer. Then the samples were allowed to cold sink in the cold rooms at target temperatures. To ensure that the temperature was uniform throughout the volume, four sets of samples were frozen at −7°C for five to seven days, and the other four samples were frozen at −20°C for a similar length of time.

Table 1. Experimental design for the specimens with uniaxial compression.

Temperature Ranges	Water Content (% by Weight)	Loading Conditions	Number of Replicates
2 settings (−7 °C and −20 °C)	Optimum and high ice contents (4% and 20%)	Constant-strain rates: 1×10^{-5} and 1×10^{-6}	Two per test

Figure 4. Mold setup and sample fabrication with vacuum hookup.

High-moisture-content samples were manufactured with contents ranging from 19% to 30% by weight of dry soil in the cold room. Water was added to the material to achieve the desired moisture content, but the sample was not required to equilibrate to the moisture content due to be being graded as a GW (ASTM 2009 [ASTM D6913-04]). The material then was brought down to the desired test temperature by allowing it to sit in the cold rooms. For each specific mold, the material at the required moisture content was divided into five portions to be evenly distributed into five layers. The fabrication process started with spraying the bottom of the mold to create a thin layer of ice. This step ensured an ice seal at the bottom of the sample to reduce the drainage of water at high moisture contents. With a thin layer of ice on the bottom of the mold, the first layer of saturated material was placed and spread evenly into the mold. This process was particularly difficult because the material was required not to form ice lenses in-between the layers. When excessive forming of ice lenses between layers occurred, the resulting data skewed weaker. This is because of the bond strength of the differing materials forming horizontal sections in the frozen samples; the ultimate strength capability of the material is reduced due to the smooth, hard surfaces that form at these ice interfaces. To avoid these issues in this experiment, the standing water on top each layer was allowed to freeze by sprinkling or seeding it with soil less than 5% of the next layer, creating an interface at the top of the layer that is composed of the gravel and not just water. Once each lift was compacted and seeded, the mold was kept in the cold room at either −7°C or −20°C. Total freeze time depended on the ambient temperature of the material being tested but would range from three to seven days per sample. All the samples were fabricated under a vacuum for the duration of the manufacturing process in the cold room; then the vacuum was removed from the aluminum-split molds. Leaving the membrane intact, the sample was tested on the uniaxial compression machine.

4.2 Loading tests

Uniaxial (unconfined) compression tests of the fabricated samples used a hydraulic universal load frame (MTS, Minnesota, USA) equipped with two actuators and three electronically controlled servovalves. The bottom actuator is capable of reaching 250,000 lbf across a 9 in. loading surface while the top is able to reach 22,000 lbf across a 2.5 in. loading surface. The top actuator can be controlled by a two-stage or three-stage servovalve. These features allow the top actuator to have a specific loading setting for a test, such as low load, low displacement, or high-speed loadings The system is controlled by an MTS FlexTest SE, which is connected to a computer running MTS 793 software with the Multipurpose Testware Suite (MPT) for test procedure design. The 793 software with MPT allows the user to program ASTM-style testing procedures for repeatable testing and data collection described in ASTM D7300-11 (ASTM 2012). The stress and strain responses were quantified using a constant strain rate under the set boundary conditions (Table 1). The frozen specimen with the rubber membrane intact was placed in the thermal-controlled MTS chamber (Figure 5). Each test was conducted at an applied strain rate of either 1×10^{-5} or 1×10^{-6} sec^{-1} and the corresponding test temperatures were held in the chamber while testing. Testing was stopped when the compressive stress dropped 20% or when 5% additional axial strain occurred after the compressive stress had peaked. After the specimen was removed from the chamber, any observable failure was noted; and the entire sample was weighed and dried for moisture content determination (Figure 6).

Figure 5. Compression test setup.

Figure 6. Failure mode and deformation for an optimum specimen (*left*) and higher moisture content (20%, *right*).

5 Results

5.1 Stress–strain responses

The results of the stress–strain responses are presented in Figures 7–10. The compressive-strength responses for each test in Table 2 are summarized according to initial physical properties based on the experimental design with associated test names. In addition, the compressive-strength responses are characterized in terms of maximum or ultimate strength, the corresponding strain at failure, and yield bearing capacities at 0.5% strain. In this case, the yield bearing capacities at 0.5% strain was chosen as that is when the material will likely have no permanent deformation.

The changing curves of strength for the optimum moisture specimens frozen at −7°C show similar patterns for both strain-rate loads with consistent maximum axial compressive strength at approximately 0.57 MPa (Figure 7). The maximum axial compressive strength for these frozen (at −7°C) optimum compacted gravel specimens occurs at strain between 1.34% and 1.44% with the strength failure decreasing with increasing strain, showing plastic deformation.

Figure 7. Stress–strain responses for samples fabricated at optimum moisture content (from 3.7% to 4.1%, by weight) and density, frozen at −7 °C, and with constant loading rates of 1×10^{-5} and 1×10^{-6} sec^{-1}.

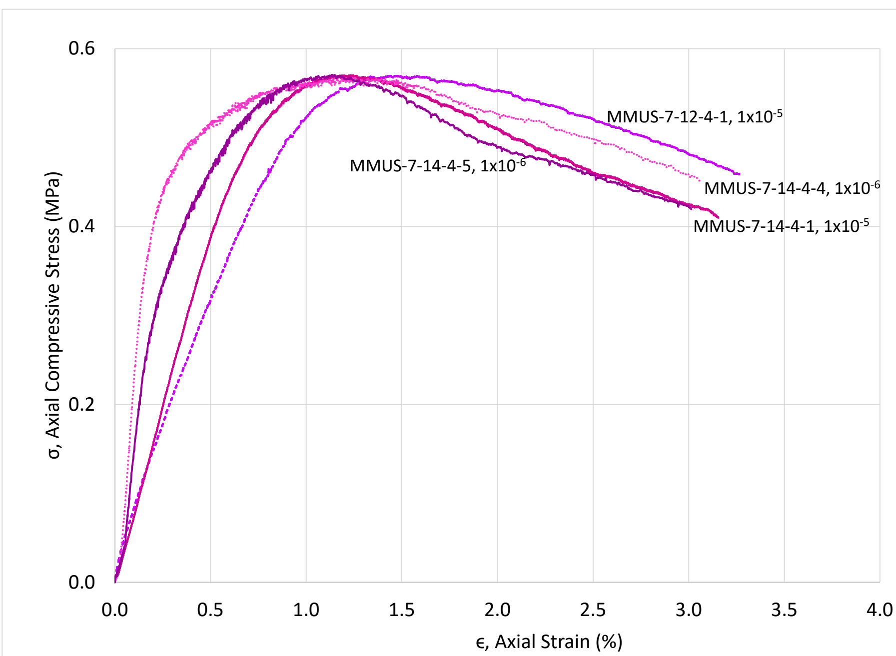
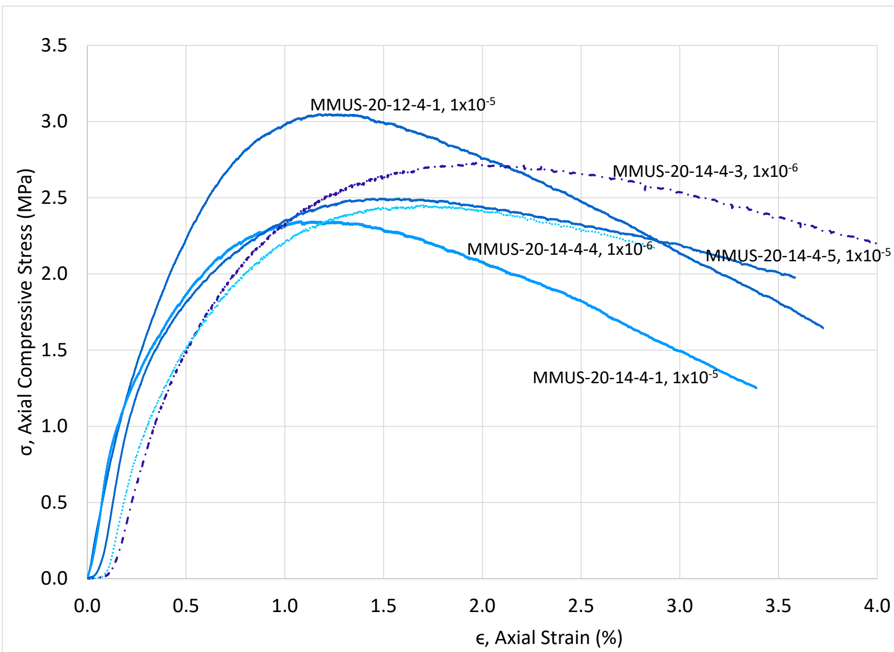


Table 2. Physical properties and compressive strength of test specimens.

Specimen Name	Dry Unit Weight (g/cc)	Water Content (%)	Void Ratio	Porosity (%)	Saturation (%)	Freezing Temperature (°C)	Length of Freezing (days)	Strain Rate (s^{-1})	Max Corresponding Strain (%)	Max (Ultimate) Compression (MPa)	Yield Bearing Capacity at 0.5% Strain (MPa)
MMUS-7-12-4-1	2.0	4.1	0.36	26.4	31.1	−7	5	1×10^{-5}	1.44	0.57	0.32
MMUS-7-14-4-1		3.9				−7	5	1×10^{-5}	1.24	0.57	0.39
MMUS-7-14-4-4	2.0	4.0	0.35	26.1	31.1	−7	6	1×10^{-6}	1.24	0.57	0.52
MMUS-7-14-4-5	2.0	3.7	0.35	26.1	28.8	−7	5	1×10^{-6}	1.14	0.57	0.46
MMUS-20-12-4-1	2.1	3.7	0.34	25.1	30.1	−20	1	1×10^{-5}	1.17	3.05	2.22
MMUS-20-14-4-1		4.0				−20	6	1×10^{-5}	1.08	2.35	1.86
MMUS-20-14-4-3	2.0	3.6	0.35	25.8	28.8	−20	3	1×10^{-6}	1.91	2.73	1.50
MMUS-20-14-4-4	2.0	3.7	0.35	25.8	29.4	−20	3	1×10^{-6}	1.69	2.45	1.50
MMUS-20-14-4-5	2.0	3.6	0.35	25.9	28.7	−20	3	1×10^{-5}	1.48	2.50	1.81
MMUS-7-12-50-1	1.7	19.4	0.59	37.1	90.4	−7	6	1×10^{-5}	2.82	2.17	1.29
MMUS-7-14-50-1	1.7	19.4	0.58	36.8	92.0	−7	6	1×10^{-5}	1.44	1.64	1.03
MMUS-7-14-50-2	1.8	19.0	0.52	34.4	100.0	−7	7	1×10^{-6}	1.32	1.90	1.63
MMUS-7-14-50-3	1.8	18.9	0.52	34.3	99.5	−7	7	1×10^{-6}	1.55	1.89	1.55
MMUS-20-14-50-2	1.6	24.1	0.68	40.5	97.2	−20	8	1×10^{-5}	1.04	5.26	3.60
MMUS-20-14-50-3	1.6	25.0	0.70	41.1	98.5	−20	8	1×10^{-5}	1.27	6.04	4.92
MMUS-20-14-50-4	1.8	19.3	0.56	35.8	95.0	−20	3	1×10^{-6}	1.04	5.47	4.28
MMUS-20-14-50-5	1.6	25.6	0.73	42.3	96.1	−20	6	1×10^{-6}	1.12	4.44	3.62
MMUS-20-14-50-6	1.8	18.7	0.51	33.7	100.0	−20	3	1×10^{-5}	1.16	6.75	4.79

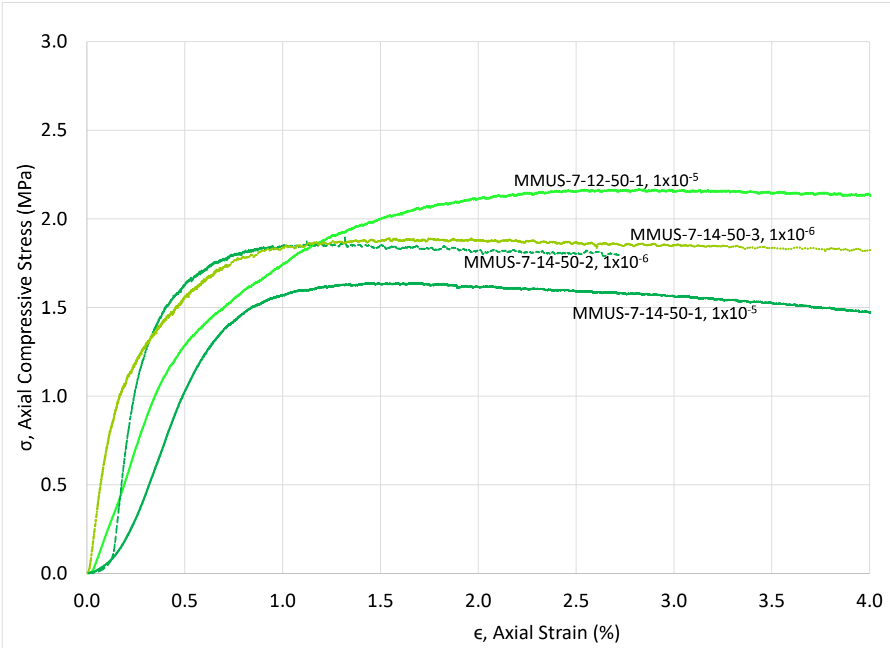
Similarly, Figure 8 demonstrates that the changing curves of strength show a distinct parabolic pattern for optimum moisture specimens frozen at −20°C and loaded at both strain rate loads. The strength increases to a maximum value and then decreases with increasing axial strain. The maximum axial compressive strength ranged from 2.35 to 3.05 MPa at corresponding axial strain between 1.08% and 1.91%. Failure for the optimum moisture specimens of the frozen samples is in the form of breaking and disintegrating of particles where bulging occurs near the top middle of the samples.

Figure 8. Stress–strain responses for samples fabricated at optimum moisture content (from 3.6% to 4%, by weight) and density, frozen at −20 °C, and with constant loading rates of 1×10^{-5} and 1×10^{-6} sec^{-1}.



The fabricated samples with moisture contents of approximately 19% (by weight) and frozen at −7°C show variable stress–strain responses (Figure 9), particularly for samples tested at a 1×10^{-5} strain rate. These specimens produced maximum compression strengths of 1.64 and 2.17 MPa. The variability is likely due to the material distribution of ice and gravel within the specimens. However, both of the stress–strain curves for the 1×10^{-6} tests showed similar maximum strength values (i.e., 1.90 MPa) with corresponding failure strain between 1.32% and 1.52%. These tests are exhibiting a viscoelastic behavior in which, as the strength peaked, the stress is very gradually decreasing with increasing axial strain (Figures 7 and 8), and the samples deformed instead of breaking apart.

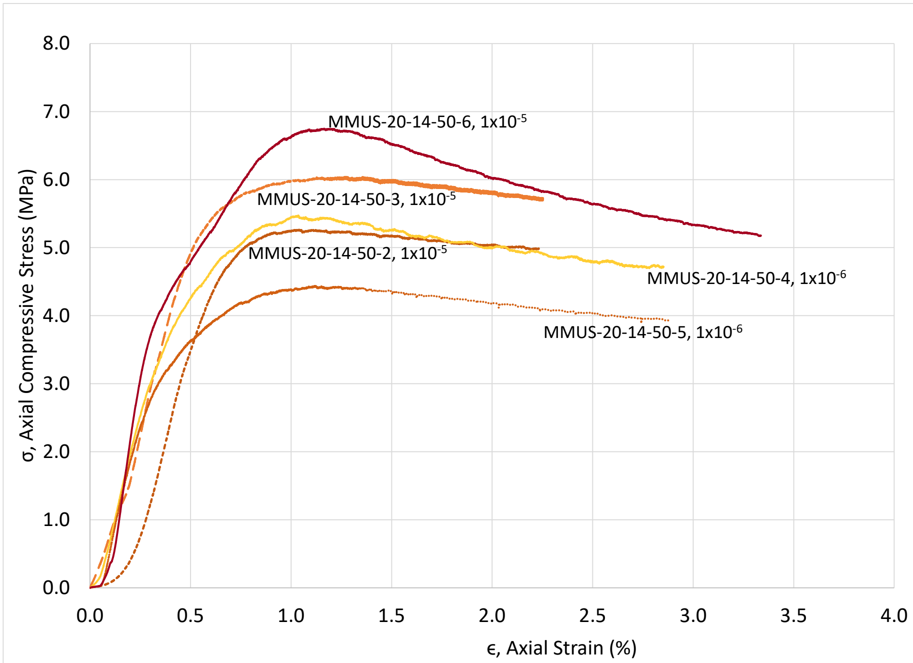
Figure 9. Stress–strain responses for samples fabricated at a moisture content of approximately 19% (by weight), frozen at −7 °C, and with constant loading rates of 1×10^{-5} and 1×10^{-6} sec^{-1}.



The stress–strain curves for the fabricated samples with moisture contents between 19% and 20% (by weight) and frozen at −20°C show varying maximum compression strength (Figure 10) regardless of the loading strain rates. The maximum compression strength ranged from 4.44 to 6.75 MPa. Again, the variability is likely due to the material distribution of ice and gravel when the specimens were fabricated. However, the corresponding strain at failure is approximately between 1.04% and 1.27% where bulging deformation formed near the top half of the specimens.

Unfrozen triaxial drained shear studies with confining pressure at 100 KPa on reconstituted saturated rock basalt materials showed that the compression strength (peak deviatoric stress) is close to 1.2 MPa, and the axial strain is approximately 2% at failure (Charles and Watts 1980). In frozen soil, the strength is influenced by bonding of particles by ice and physical properties, such as density, temperature, pressure, strain rate, grain size, ice content, and crystal orientation (Zhu and Carbee 1984; Sayles and Carbee 1980; Diekmann and Jessberger 1982; Bragg and Andersland 1981; Baker 1978; Sayles 1973). Additionally, at very high ice contents (ice-rich soils), frozen soil behavior under load is similar to that of ice.

Figure 10. Stress–strain responses for samples fabricated at a moisture content between 19% and 20% (by weight), frozen at −20 °C, and with constant loading rates of 1 × 10^{-5} and 1 × 10^{-6} sec^{-1}.



5.2 Temperature and moisture

The temperature and moisture of the fabricated samples influence the strength of the gravel (Figure 11) regardless of strain rates. When the specimens are compacted at optimum (i.e., 4%) moisture content, the maximum strength of the specimens frozen at −20°C increases between 4 and 5 times higher than the specimens frozen at −7°C. This means that as the temperature decreases, the strength significantly increases. In the frozen state, the maximum strength linearly increases with increasing moisture content. These experimental relationships between the uniaxial compressive strength and temperature at different water contents for frozen gravel correspond well when compared to the test results of frozen sand (Kuribayashi et al. 1985; Andersland and Ladanyi 1994), as shown in Figure 12. As the temperature decreases, the relationships represent varying slopes at various moisture contents. The gravel specimens compacted with moisture contents between 3.6% and 4.1% are slightly lower in strength than the sands with moisture contents of 6%–7%. Similarly, the gravel specimens compacted with moisture contents between 18.7% and 25.6% are significantly lower in strength than the sands with moisture contents of 18%–19%.

Figure 11. Relationship between uniaxial compressive strength and frozen soil moisture content (MC).

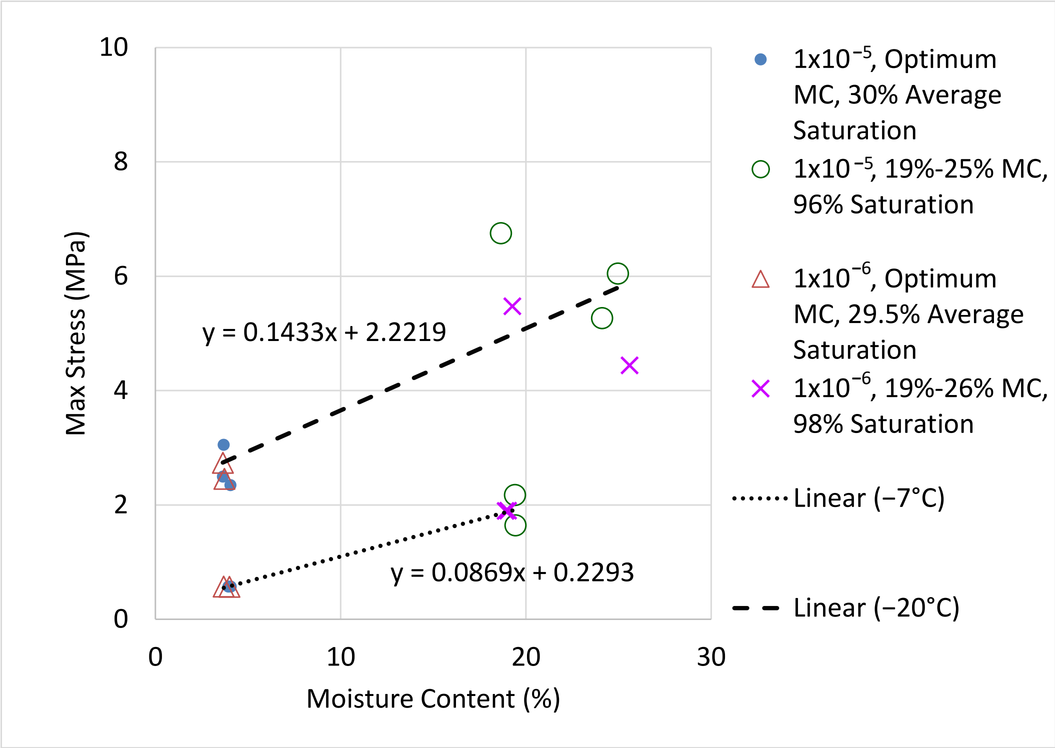
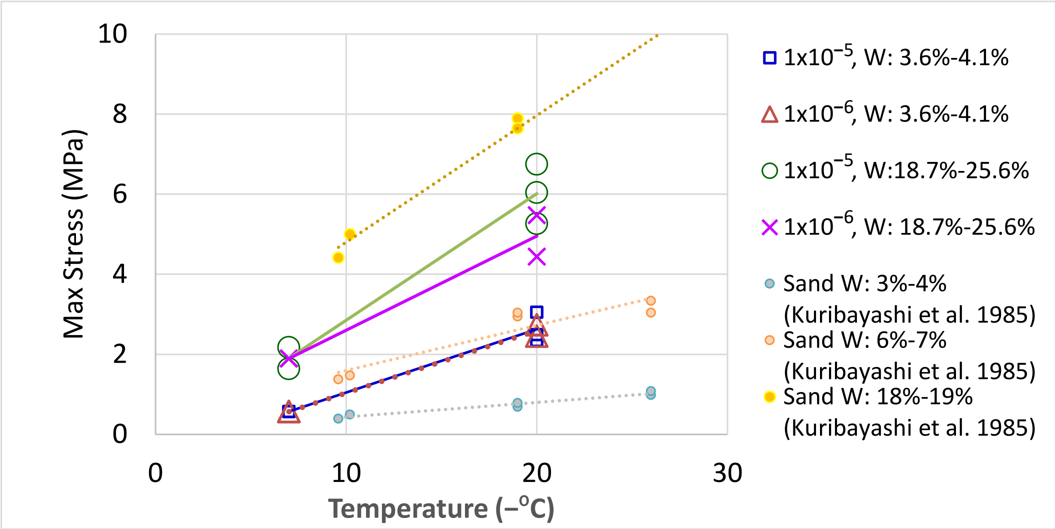


Figure 12. Relationship between uniaxial compressive strength and temperature and moisture compared with existing data from frozen sand. *W* means water or moisture content of the specimens.



6 Discussion

6.1 Limitations

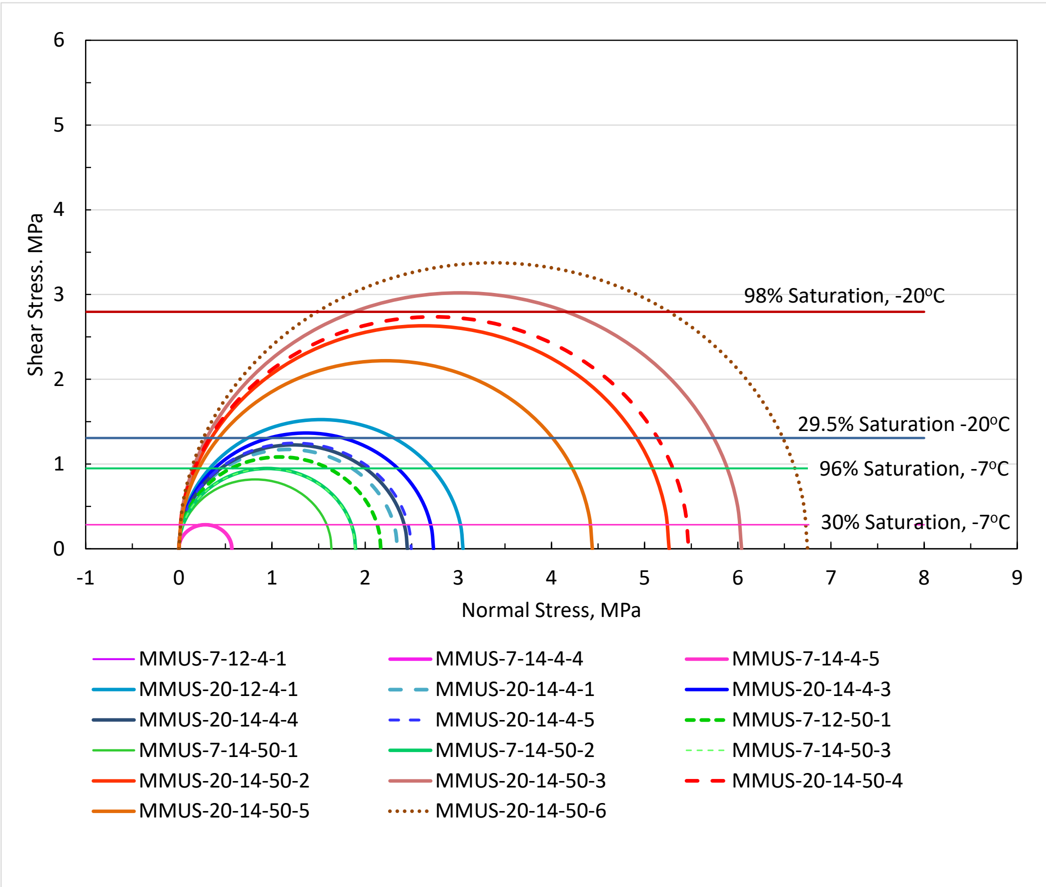
A minimum of 15 specimens for each selected temperature- and moisture-content combination is needed to determine the uniaxial compression strength properties of a given frozen soil for taking into account a possible scatter of experimental results (ASTM 2011 [ASTM D7300-11]). In addition, having a sufficient number of compression tests (i.e., testing with more than two strain rates and conducting confined compression or triaxial tests) would provide a common basis for comparing the behavior and the mechanical properties of the material.

In this study, the tests are limited to two replicates primarily because it is not feasible and it is too costly to produce multiple specimens. Likewise, it is not feasible and is too costly to produce multiple specimens that have uniform physical properties. Any variations observed in the data are possibly due to the nature of the frozen specimen and laboratory testing disparities.

Frozen and ice-rich soils tend to behave like rocks or granular materials, showing a failure envelop in a parabolic shape (Andersland and Ladanyi 1994). This is likely because higher-ice-content materials tend to have a viscoelastic behavior. Studies on unfrozen gravel have shown nonlinear failure envelops with drained friction angles ranging from 32° to 45° at normal stresses between 35 kPa and 1400 kPa (Agha and Masood 1997; Indraratna et al. 1993). A direct shear on unfrozen, reconstituted basalt gravel of similar gradation as McMurdo basalt resulted in an effective friction angle of 58.7°, and this value is much higher than for other gravel (Charles and Watts 1980). A triaxial tests by Goto et al. (1994) for alluvial gravel (fines less than 1.0% and dry density between 1.9 and 2.1 g/cc) showed an internal friction angle of approximately 40° on undisturbed and reconstituted frozen gravel specimens thawed under a confining pressure of 29.4 kPa. Aggregate angularity or roundness will have a strong effect on friction angle.

For this study, it is simplest to plot the Mohr failure envelopes from the tests (Figure 13). But because these tests are limited to uniaxial (unconfined) compression tests, the only component holding these samples together without changing confining pressure is the cohesion. The cohesion values are equivalent to 0.28 and 0.95 MPa for reconstituted samples at −7°C with saturation of 30% and 96%, respectively. The average cohesion for frozen samples at −20°C and reconstituted at 30% and 96% saturation, resulted with values of 1.31 and 2.8 MPa, respectively. The equivalent cohesion values are associated mainly with the responses of the materials due to the bonding of particles by ice, the temperature, and to some extent the grain size. Future studies should examine the exact failure envelops under static and dynamic loading as well as volumetric consolidation, creep, and relaxation effects.

Figure 13. Mohr circle for the test specimens.



6.2 Corrosion risk

Igneous rocks with the presence of naturally occurring opal and feldspar can have alkaline elements. Previous petrographic examination from rock samples taken from McMurdo Station indicated the presence of opaline (soft, white, powdery) particles or specks on the basalt rocks (Hoffman 1979). Opal is a form of silica that may be found within vesicles and cavities of volcanic rocks. Likewise, feldspars are common minerals that crystallized from a wide spectrum of magmas (Klein and Dutrow 2008; Harker 1902). When crystallized at high temperature, the minerals formed are called alkali feldspars (Deer et al. 1992; Harker 1902). The alkaline elements of the materials can have implications when they are exposed to or are in contacted with a structural element, such as a reinforced concrete foundation. The presence of opal in aggregates is associated with an alkali-silica reaction in concrete, which causes excessive expansion (ASTM 2016 [ASTM C33]). This reaction increases the risk of premature degradation and failure of the reinforced concrete foundation unless preventive measures are used.

Also, conductivity analysis documented in Fenwick et al. (2017) showed the presence of salt (sodium chloride) on the soil. The salts precipitated within the vesicles and joints of the gravel and rocks. The presence of salt is expected due to McMurdo Station's proximity to the ocean and indicates high conductivity of the soil. Concrete that will be in contact of the native aggregates will need to be specified to resist corrosion under contact with soil having these chemical reactions.

The formation of rust corrosion in the metal drum that was used to ship the gravel material to CRREL was caused either by the presence of salt or from an alkaline reaction. The gravel material when shipped to CRREL was stored in the metal drum for approximately four months from collection to delivery. This study did not test for reactivity of the soils; however, the presence of alkali-reactive minerals specifically in aggregates is problematic for cement* and embedded reinforcing steel (ASTM 2016 [ASTM C33]). Interestingly, the concrete footings and steel beams on-site (Figure 14) have shown an unspecified amount of deterioration with soft, white, powdery particles visible; the deterioration is likely due to the exposure of alkaline or corrosive reactions with native material. Most concrete footings on buildings at McMurdo Station are typically imported precast and brought on-site. Unmeasured evidence has indicated that the deterioration found on the concrete footings and steel beams on-site (Figure 14) is due to the excess water from washing vehicles, which has seeped through the floor cracks, pooling onto the ground underneath the building.† If the ad-

* Barna, L. A., personal communication on deterioration due to rust under the building, 7 February 2018. Hanover, NH: U.S. Army Engineer Research and Development Center.

† Barna, pers. comm., 2018.

ditional water is from washing equipment, then the water would also activate the reactions in the localized area. Nonetheless, the ramification of having the foundation elements exposed to the reactive soil would have significant structural issues for the new foundation structures.

Figure 14. Rust on a steel support (*left*) and an existing concrete footer with deterioration (*right*) under the Building 143 (courtesy of L. Barna).

Concrete in contact with the gravel at McMurdo should use Type V cement or appropriate admixtures for high sulfate resistance (ASTM 2017 [ASTM C150]). If the gravel is to be used as a concrete aggregate, preventive measures must be taken to ensure structural integrity. The Standard Specification for Concrete Aggregates (ASTM 2016 [ASTM C33]) prohibits use of aggregates containing materials that are deleteriously reactive with the alkalies in cement, except when appropriate precautions are taken.

> Coarse aggregate for use in concrete that will be subject to wetting, extended exposure to humid atmosphere, or contact with moist ground shall not contain any materials that are deleteriously reactive with the alkalies in the cement in an amount sufficient to cause excessive expansion of mortar or concrete except that if such materials are present in injurious amounts, the coarse aggregate is not prohibited when used with a cement containing less than 0.60 % alkalies calculated as sodium oxide equivalent (Na_2O + 0.658K_2O), if there is a satisfactory service record evaluation, or with the addition of a material that has been shown to prevent harmful expansion due to the alkali-aggregate reaction (ASTM 2016 [ASTM C33, Section 11.2]).

6.3 Hydrocarbons and contaminant

Hydrocarbons in soil or light, nonaqueous phase liquids (such as gasoline, diesels, and other petroleum products) are also prevalent at McMurdo Station from accidental or historical human activity (Affleck et al 2017). The gravel used for this test was collected from newly harvested (clean) stockpile site. There should not be significant compressive-strength difference that we are aware of between natural (uncontaminated) gravel and hydrocarbon-contaminated gravel of the same grainsize distribution. However, hydrocarbon-contaminated soils need to be examined in foundation design because of possible chemical incompatibility with build materials and potential leaching or migration during construction or excavation of soil.

7 Summary

Test results of the mechanical properties, within the bounds of the test design, determined that higher moisture content (18.7%–25.6%, or between 96% and 98% saturation) combined with lower ambient temperatures resulted in increased strengths compared to optimum moisture and compaction testing results. The decrease in temperature from −7°C to −20°C consistently resulted in an increase of maximum axial compressive strength. For samples at high moisture content (96% and 98% saturation), the strength increased by a factor of 2 to 4. The increase was more significant at optimum moisture (30% saturation), when strength increased by a factor of 4 to 5. If the natural material meets strength requirements at near-freezing temperatures, we can reliably expect the soil to satisfy strength requirements as temperatures drop. In addition, we recommend engineering controls to ensure non-frost-susceptible soil is emplaced.

Maximum axial compressive strength increased with an increase in moisture content at both temperatures tested. Between optimum moisture content and high moisture content, strength increased by a factor of 2.8 to 3.8 at −7°C and by a factor of about 1.5 to 3 at −20°C. This strength gain is also influenced by ice bounding, such that the materials are weakly bounded at optimum moisture content or ice-poor conditions and are strongly bounded at high moisture content or ice-rich conditions. When ice fills most of the pore space, the mechanical behavior of a frozen soil will closely reflect that of the ice. However, depending on the loading rate and the grain size, the frozen soils become brittle and the ice–soil bond is released at extremely low temperature. The strength decreases with decreasing temperature once the maximum microstructural damage occurs. These mechanical behaviors are well defined for silty sands and sands. At temperatures of −7°C and −20°C, the frozen gravel samples reconstituted between 18.7% and 25.6% moisture content showed slightly lower strength than the sands with the same moisture content. At these limited temperature regimes tested for this study, the observed mechanical behavior of the frozen gravel potentially linearly resembles that of the frozen sands. The strength behavior of the frozen gravel would likely be attenuated at lower temperatures, releasing ice-grain bonds and damaging the microstructure of the materials.

The natural-state water contents of near-surface permafrost horizons ranged from 64% to 150% by weight (with maximum saturation of 110%, Affleck et al 2017), which are much higher than the maximum moisture contents in the tests at 25% by weight (98% saturation). This natural layer with much higher moisture contents would likely exhibit significantly more strength, if remaining frozen, than samples of the same material at 25% by weight and at optimum moisture content. However, ice-rich material will be exposed to the effects of creep and relaxation. Creep would be significant when moisture saturation values are greater than 110%. Further testing should be completed to understand the long-term effects of this material under load.

Testing results did not demonstrate a significant difference in strength between the two selected strain rates of 1×10^{-5} and 1×10^{-6} sec^{-1}. The failure mode for the optimum moisture specimens is in the form of breaking and disintegrating of particles near the top middle of the samples due to the limited bonding between the grain and ice. However, the failure mode for specimens with moisture contents between 19% and 25.6% is in the form of bulging deformation formed near the top half of the specimens. This is typical of viscoelastic deformation, which is indicative of soils tending toward creep behavior.

The natural state of the material at high frozen water content is sufficient for use as a construction material if structures are designed with an elevated foundation type. However, if moisture values are high resulting in significant segregation-ice creation, differential settlement from creep will result. More importantly, foundations that allow heat transfer to take place at the soil-interaction horizon should be placed only on material compacted at optimum moisture to reduce the potential for differential settling.

Alkali-reactive elements are present in the natural material found at McMurdo Station. The alkali-reactive elements may not directly influence the material strength of the natural material. However, the design of foundations that are in contact with the natural material should account for the possibility of a destructive reaction, which could degrade the long-term performance of the foundation.

8 Recommendations and Conclusion

A conclusive result of this study was that the frozen natural material found at McMurdo Station should be used in its current state as a foundation base material if the foundation is to be elevated and not allow heat transfer to take place. However, ice-rich material will be exposed to the effects of creep and relaxation, and ice-rich fill and sediments should be excavated and replaced with select fill to avoid thaw degradation. If the foundation to be used is in direct contact with the ground and allows heat transfer to take place, the base material should be removed down to the structurally competent ice-poor layer and a new structural base layer should be installed at optimum moisture content and compaction. This will reduce the potential effects of frost thaw, especially of ice-rich ground, under the foundation.

From this study, we conclude that further research will need to be conducted in the area of contact exposure and degradation of building materials that are subjected to the native materials found at McMurdo Station. These studies should include but not be limited to oxidation of metals, concrete decomposition, and severity of the alkali–aggregate reaction dependent on the quantity of water. We have evidence of existing issues that can be associated with the reaction outlined in this study.

Treatment and remediation of the alkali-aggregate should be researched to determine if a reliable cost-effective option is available off the shelf. If no off-the-shelf options exist, alternatives to reduce the effect of the reaction should be used and compared.

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14. ABSTRACT
The plan to modernize McMurdo Station involves constructing large buildings for more efficient facilities and infrastructure. Foundation design for these large buildings will require understanding of the mechanical properties of the native soil. This study is the first that we are aware of to conduct uniaxial compression tests on materials from McMurdo Station in their frozen state. The testing used in this study emulates specific ground conditions measured on-site.

Reconstituted specimens of well-graded gravel basalt were compacted at 4% and 20% by weight moisture contents and frozen at temperatures of −7°C and −20°C. Test results determined that higher moisture content combined with lower ambient temperatures resulted in increased strengths compared to optimum moisture and compaction testing results.

If new building foundations will be in direct contact with the ground and allow heat transfer to take place, then the base material should be placed and compacted at the optimum moisture content. This will reduce the potential effects of thaw degradation under the foundation, especially on ice-rich ground.

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