

Article

# Analysis of Effects of Rock Physical Properties Changes from Freeze-Thaw Weathering in Ny-Ålesund Region: Part 1—Experimental Study

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**Abstract:** In order to investigate the weathering characteristics of rocks in response to freeze-thaw conditions in northern latitudes, we analysed meteorological data from the Ny-Ålesund region in Norway, and observed changes in the physical and mechanical properties of rocks of dolomite and quartzite. To assess the effects of freeze-thaw weathering on these rock properties, 900 cycles of long-term freeze-thaw tests were conducted for the sampled rocks in two locations. P-wave velocity, absorption, shore hardness, and the uniaxial compressive strength of the sampled rocks were measured at every 150 cycles in order to analyse physical and mechanical mediator variables of freeze-thaw weathering. It was found that an increasing number of freeze-thaw cycle on the sampled rocks decreases uniaxial compressive strength, shore hardness, and P-wave velocity and increases absorption.

**Keywords:** air temperature; freezing-thaw cycle; rock weathering; dolomite; quartzite; rock physical property

## 1. Introduction

The repetition of freeze and thaw of rocks is largely governed by the local climate. In order to investigate rock weathering mechanisms due to freeze-thaw cycles, it is important to reflect the unique properties of the climate and rocks in the region of interest. In addition to reduced strength of the rock structures themselves, the function of rock structures can also be impaired by weathering [1]. Rocks exposed to extremely low temperature environments in northern latitudes are frozen for a considerable time of the year. An accurate assessment of the physical and mechanical properties of these rocks is very important for the evaluation of structural stability to preserve the function of the rock structure. For example, rock weathering from freeze-thaw induces malfunction or instability issues in rock related structures.

Weathered rocks exhibit changes of mechanical, physical, and mineral properties, and more advanced rock weathering results in even significant changes to structure safety. Thus, the extent of rock weathering can be evaluated based on factors such as degradation of the actual mineral particles constituting the rock or weakening of the bonding strength at interface on rocks. Weathering resistance is a form of durability that influences the lifespan of rocks, and as a major mechanical mediator variable, durability is an important physical property for determining the structural stability [2]. At high latitude areas, rocks are exposed to an excessive freezing and thawing environment throughout the year, and this causes gradual freeze-thaw damage. Rock materials used in cold regions are exposed to at least one

cycle of freeze-thaw every year [3]. In particular, freeze-thaw action is one of the strongest mechanisms of physical weathering, and can rapidly change the physical and mechanical characteristics of rocks and reduce their durability [4–8].

Most previous research on the freeze-thaw effects on the mechanical behaviour of rocks has been conducted on rocks with low-to-moderate hardness [7–10]. The response of harder rocks to regular freeze-thaw weathering has generally been ignored due to their high strengths or hardnesses. Meanwhile, freeze-thaw tests have generally been conducted over short periods of time, and researchers have not been interested in long-term freeze-thaw tests due to various difficulties in testing for long time under rigorous control of test environments [11]. Therefore, to evaluate the long-term durability of rock-built structures and to determine suitable maintenance and repair cycles in high northern latitudes, further research is required on the influences of prolonged exposure to freeze-thaw cycles.

Many researchers examined changes of various physical and mechanical properties of rocks in a view of durability with increasing freeze-thaw cycles [7–9,12,13]. Binal and Kasapoglu [7] explored changes of uniaxial compressive strength (UCS) of Selime (Aksaray) ignimbrite resulting from repetition of freeze and thaw. Khanlari and Abdilor [8] conducted research on the effect of freeze and thaw on sand stones. Yavuz et al. [9] developed a model for estimation of rock index characteristics of carbonate rocks after experiencing freeze and thaw cycles. Jamshidi et al. [12] investigated the effect of freeze-thaw cycles on long-term durability of various rock building materials.

Nicholson and Nicholson [14] insisted reduction of strength of 10 different sedimented rocks due to increased freeze-thaw cycle, and Bortz et al. [15] presented correlations among weathered properties of limestone, granite, and marble under freeze-thaw cycles from natural and artificial environments. It was found that the freeze-thaw cycles of 12–16 under artificial condition are equivalent to freeze-thaw effect of one year under natural condition. However, changes of weathered rock properties became obvious after 200, 300, and 500 freeze-thaw cycles for limestone, granites, and marble, respectively.

Other studies also confirmed the changes of rock properties due to freeze-thaw weathering; therefore, further research is necessary to examine long-term rock durability in high latitude regions for effective estimation of maintenance and repair time against freeze-thaw cycles in nature [2,16,17]. The researchers emphasized that experience of freeze-thaw cycles of rocks is one of the most significant physical weathering factors. Therefore, changes of durability and mechanical properties of the rocks were examined with time. Rock weathering from freeze-thaw cycles also induced many engineering problems in roads, railways, energy pile lines, building constructions in cold regions [17,18]. For these reasons, an accurate assessment of durability against rock freeze-thaw weathering is important [4].

Evaluation of reasonable freeze-thaw rock weathering properties are prerequisite for maintain important functions of cultural heritages; and it will bring us many benefits in terms of maintenance of repair of these structures [19]. Especially, protection of cultural heritage sites from freeze-thaw rock weathering is very important to prevent further deterioration of the heritage structures [16]. Most of the heritage structures are made of rocks, and understanding of material properties' changes with time is essential to protect these heritage structures [20]. Hall [21] claimed that main factors influencing freeze-thaw rock weathering are freezing strength, velocity, maintained freeze time, and repetitive actions of freeze and thaw.

In this study, we aimed to investigate the behaviour of rocks collected from Ny-Ålesund, a high latitude region, with changes in rock and air temperatures simulating the Ny-Ålesund region in a laboratory. We collected relatively fresh rock specimens exposed to the surface, and examined changes in their physical and mechanical rock properties of uniaxial compressive strength (UCS), shore hardness, absorption, and P-wave velocity with increasing freeze-thaw cycle.

## 2. Topology of the Survey Area

The survey region is Ny-Ålesund (11°54′41.23″ E, 78°55′31.65″ N), in the northwest of Spitsbergen Island, in the Svalbard Archipelago, Norway, located approximately 1000 km from the North Pole (Figure 1). This region consists of a peninsula to the northwest and a bay to the east, and the mean altitude is 8 m. The mean annual precipitation and air temperature are 364.6 mm and  $-4.1$  °C, respectively. Temperate summers can be experienced due to the northward passage of the warm Gulf Stream, but the winters are very cold. The Ny-Ålesund region used to be a coal-mining region, and the major rock types consist of sandstone, shale, and coal [22]. In order to assess freeze-thaw characteristics of rocks in the Arctic Circle, specimens were collected from Locations A and B in Figure 1, using rocks that had fallen from rocky outcrops protruding over the shore or rock block specimens taken from the outcrops.

Freeze-thaw actions are most active at cold regions, such as high latitude areas including Norway, Alaska, or Canada. Therefore, the study area is selected based on the literature by Dallmann [22] and Buggisch et al. [23]. It was reported that, at the region of Ny-Ålesund, dolomite and quartzite are widely distributed at ground surfaces and are easily sampled minimizing destroy of nature environments. Dolomite and quartzite are formed at the geographical age of middle and upper carboniferous period [23]. There is limited research on these rocks.



**Figure 1.** Location of the study area and topographic map in Ny-Ålesund (map reproduced from the original source [24] with courtesy of the Norwegian Polar Institute).

## 3. Preparation of Rock Specimens

Several types of rock mineral heterogeneity, such as fissures and cracks included in the specimens, influence the mechanical properties of rocks [25–27]. In order to analyse quantitative changes in rock properties during a freeze-thaw tests, the rocks need to be classified into weathering grades. Rock weathering classification has been suggested by a number of researchers [28–30], and can be broadly divided into two methods; qualitative and quantitative methods. In the present study, before specimen preparation, we classified the sampled rocks based on the weathering grades using a qualitative method based on relative hardness, extent of discoloration, and the state of weathering of the constituent minerals proposed by Irfan and Dearman [30]. Rock weathering grades were determined from macroscopy proposed by Irfan and Dearman [30]. The relative hardness presented in Irfan and Dearman [30] indicates difference in hardness between rock surface (weathered portion) and inner rock (unweathered portion). The prepared sample rock surfaces do not exhibit large cracks or pores that may significantly reduce rock strength. The surface colors of the sample rocks were similar to their inner colors. Therefore, the rocks immediately after sampling are classified as fresh rocks.

A laboratory moulding device was used to create cylindrical specimens from rock blocks collected for the freeze-thaw tests. There are difficulties in moulding the specimens due to internal fissures that

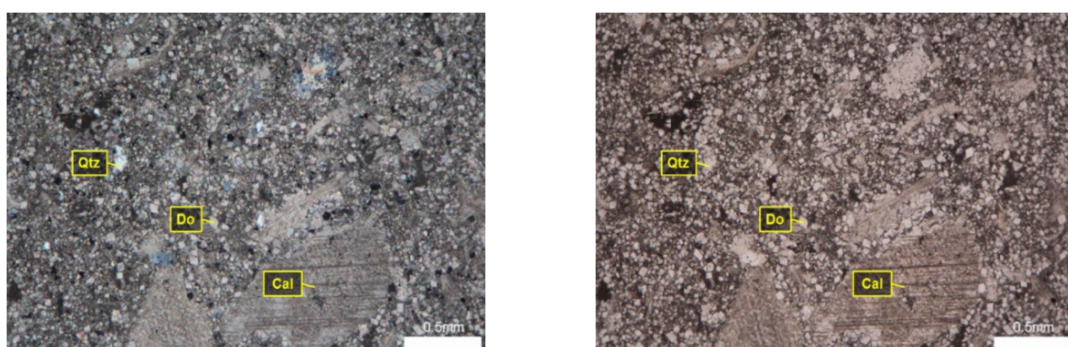
can develop during fabrication. To measure the porosity, absorption, and P-wave velocity of the rocks, 3 specimens of each rock type were fabricated to a size of 49.5 mm (diameter) × 100 mm (length). To measure shore hardness of the rock surface, 3 disk-shaped specimens of each rock type were fabricated to a size of 49.6 mm (diameter) × 60.0 mm (length). To measure uniaxial compressive strength (UCS), 3 specimens of each rock type and every 150 cycles were fabricated to a size of 24.7 mm (diameter) × 50.1 mm (length). The surfaces of all specimens used in the freeze-thaw tests were moulded to flatness errors of less than 0.02 mm for the upper and lower surfaces [ISRM] using a surface grinding machine. In each test, 3 specimens were used in each round of testing (a triplicate test), and physical and mechanical mediator variables were calculated.

#### 4. Mineralogy of Rock Samples in the Survey Area

For mineralogical and textural studies of the sampled rocks, the results of petrographic studies and X-ray diffraction (XRD) analysis of rocks collected from the study area are summarized in Table 1 and shown in Figure 2. Samples for XRD tests were prepared from rock powders from the samples used for uniaxial compressive strength (UCS) tests after their failures. The XRD analysis equipment is XPERT-PRO from Malvern Panalytical Ltd. (located in Malvern, United Kingdom). Scanning interval of XRD tests was  $0.02^\circ$  ( $2\theta$ ), and scanning range is from  $5^\circ$  to  $80^\circ$ . Post processing of the XRD results is conducted using Siroquant program (version 4.0) from Sietronics Pty Ltd. (located in Perth, Australia). In thin section inspection of rocks from Location A, the major constituent minerals were dolomite, calcite, quartz, and opaque minerals were observed. The main rock texture consisted of fine-grained crystals, while there were also calcite crystals of 0.5 mm in size. Equigranular dolomite was also observed as the result of diagenesis or alteration. Some calcite crystals showed cleavage planes. Fine quartz grains showing straight extinction were observed. Due to diagenesis, some calcite had been replaced with dolomite. Some calcite crystals around 0.3 mm in size showed twinning (Figure 2). In XRD analysis (Table 1), the rocks in Location A were classified as calcareous dolomite, consisting of 31.3% calcite, 44.5% dolomite, and 24.2% quartz.

**Table 1.** Results of X-ray diffraction (XRD) in Ny-Ålesund.

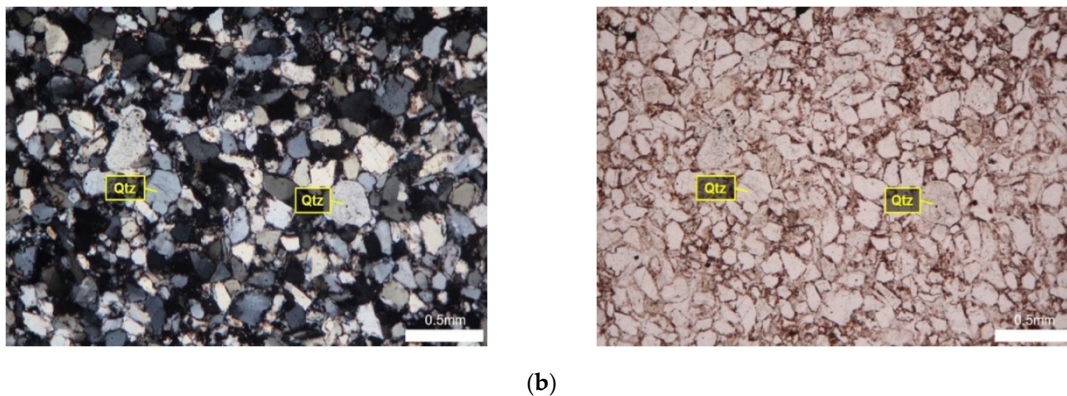
Specimen	Constituents			
	Calcite	Dolomite	Quartz	Dickite
Dolomite (Location A)	31.3%	44.5%	24.2%	-
Quartzite (Location B)	-	-	95.3%	4.7%



(a)

**Figure 2.** Cont.





**Figure 2.** Petrographic images of the sample rocks from (a) Location A and (b) Location B (Qtz = quartz, Do = Dolomite, and Cal = Calcite; left-hand images = crossed polars, right-hand images = parallel polars).

The rocks in Location B consisted of quartz crystals, a small amount of diopside, and opaque minerals. Mineral crystals were mostly quartz crystals of 0.2–0.3 mm on average, and the remaining space was filled with fine-grained crystals. Quartz crystals showing straight extinction and undulose extinction were both observed. The quartz crystals showed a sutured appearance, while there was also a small amount of fine-grained, poikilitic diopside. In XRD analysis, the rocks were classified as quartzite, consisting of 95.3% quartz and 4.7% dickite.

## 5. Changes in Rock Properties with Increasing Freeze-Thaw Cycle

### 5.1. Air Temperature Analysis

In order to examine the freeze-thaw weathering effects on rock properties in the Arctic Circle environment, we collected meteorological field data from Ny-Ålesund and analysed the annual air temperature distribution between 2012 and 2017. We used data measured at an Italian base in Ny-Ålesund. Given the latitude of the study area (78°55′31.65″ N), the summer season in the Ny-Ålesund region is very short and relatively temperate, due to the northward movement of the warm Gulf Stream, and the winter season is very cold and long. Between April and August, the Sun does not set, and between November and January, the Sun does not rise. The reason for analysing this meteorological data is because the change in air temperature is the most important factor increasing physical and mechanical damages to rocks due to freeze-thaw cycles [31].

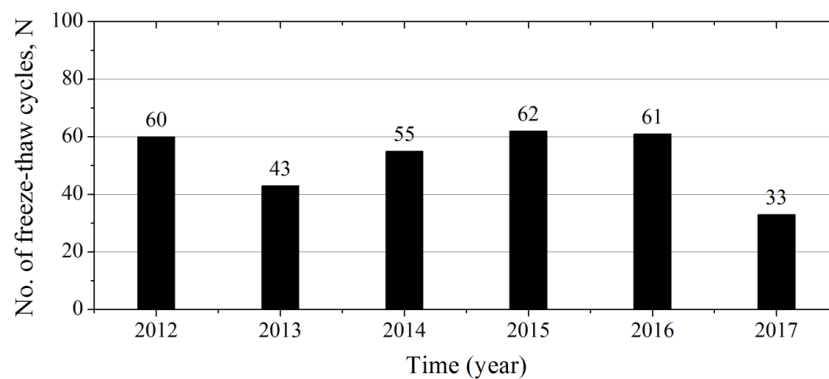
The most basic mediator variable in freeze-thaw damages to rocks is the number of freeze-thaw cycles. This can be determined by the simple method of counting the number of points in a given time interval when the temperature rises above 0 °C [32]. Alternatively, the number of freeze-thaw cycles can be counted by assuming that rocks only freeze when the mean daily temperature is below −3 °C and only thaw when the mean daily temperature is above +1 °C [33]. However, recently, a method has been introduced in which meteorological data is used to analyse the maximum and minimum daily temperatures, and to count the number of freeze-thaw cycles where the temperature goes from above to below 0 °C or below to above 0 °C [31].

In the present study, we used meteorological measurement data to identify cycles in which condensation occurred inside the rocks (the temperature inside the rocks became 0 °C) [31]. We analysed the daily freeze-thaw cycles in terms of minimum and maximum daily air temperatures between 2012 and 2017 and found that freeze-thaw cycles in terms of minimum and maximum daily air temperatures occurred on around 33–62 cycles per year (Figure 3).

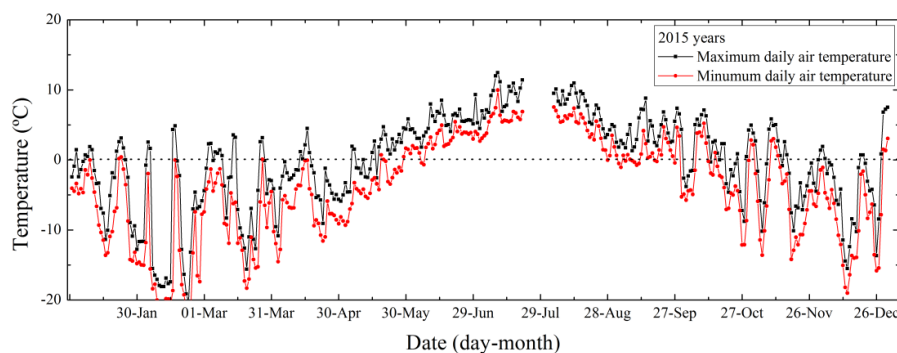
Figure 4 shows the curves of minimum and maximum daily air temperatures in the study area for year 2015 (at which maximum annual number of freeze-thaw cycle was observed) and year 2017 (at which minimum annual number of freeze-thaw cycle was observed). There are several discontinuities

in air temperature measurements. The main reasons of the air temperature measurement discontinuities identified in the sites were shortage of power supply and loss or destruction of sensors due to animal trespass. However, we believe that the missing temperature data do not highly influence on estimation of appropriate annual freeze-thaw cycles. As shown in Figure 4, the change in mean maximum and minimum daily temperatures between above and below zero was most severe in April–May and September–October. In the freeze-thaw process for rocks, the surface of the rock freezes (or thaws) when the minimum and maximum daily temperatures alternate from above to below zero (or below to above zero). Therefore, based on the method proposed by Al-Omari et al. [31], we defined one freeze-thaw cycle of the rock surface as the process of the minimum and maximum daily temperature changing from below to above zero or above to below zero.

However, freeze-thaw cycles of rock may different from that in terms of daily air temperature. For slight changes of air temperature near 0 °C may not lead to freeze-thaw cycles of rock. Brimblecombe et al. [32] also mentioned that air temperature does not exactly represent the rock surface temperature; however, air temperature can be approximately used to estimate the approximate number of freeze-thaw cycles at the rock surface. Freeze-thaw of the rock surface is dependent on the duration of the rock’s internal temperature and the air temperature. Based on changes in the air temperature in the study region, freeze-thaw cycles for the rock surface occurred on 33–62 cycles per year, and the mean number of cycles was calculated to be 52. Therefore, we could conservatively surmise that freeze-thaw weathering occurred at the surface of the rocks at least 33 times per year.

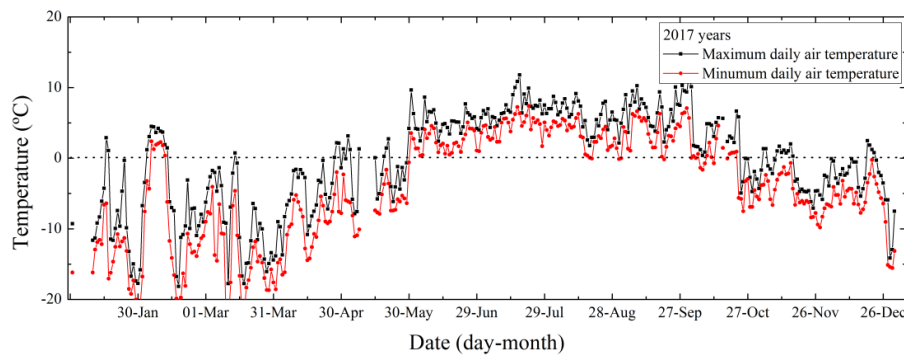


**Figure 3.** Number of freeze-thaw cycles in terms of minimum and maximum daily air temperature measured at Dasan station at Ny-Ålesund.



(a)

**Figure 4.** Cont.



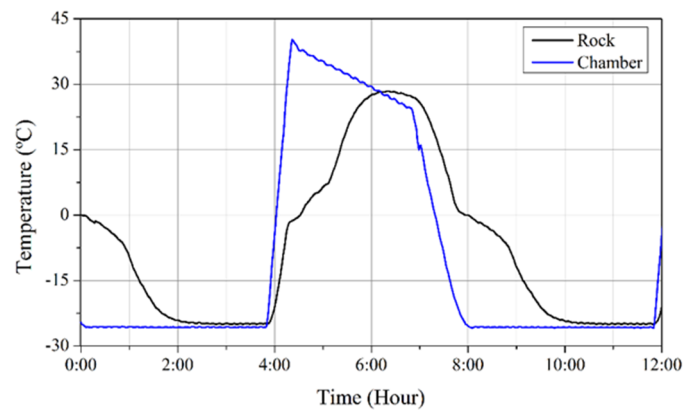
(b)

**Figure 4.** Minimum and maximum daily air temperature variation measured at Dasan station at Ny-Ålesund of years (a) 2015 (maximum freeze-thaw cycles of 62) and (b) 2017 (minimum freeze-thaw cycles of 33).

### 5.2. Determination of Freeze-Thaw Temperature and Time

The freeze-thaw test is an artificial weathering test to reproduce the physical weathering caused by tensile forces that occur during the formation of ice crystals within rocks. The freeze-thaw temperature range and time cycle can be applied differently depending on the study objectives and target region. Freeze-thaw test methods for durability of rocks are described in ASTM D5312 [34]. The temperature range for the freeze-thaw tests proposed by ASTM D5312 [34] is from  $-18 \pm 2.5$  °C to  $+32 \pm 2.5$  °C. Nicholson and Nicholson [14] and Baek and Kwak [27] performed freeze-thaw tests using a temperature range of  $-20$  °C– $+20$  °C. Bortz et al. [15] and Bortz and Wonneberger [35] conducted freeze-thaw tests with a range of  $-22$  °C– $+77$  °C, and Park [36] conducted a test with a range of  $-10$  °C– $+150$  °C. Recently, freeze-thaw tests have been performed to compare climatic conditions at regions where rocks have been collected [10]. Fookes and Hawkins [37] observed the largest effect of decreased hardness due to freezing at a temperature of  $-20$  °C.

For the freeze-thaw temperature range in the present study, we applied a range of  $-25 \pm 2$  °C– $+27 \pm 2$  °C for the temperature inside the rocks, accounting for the air temperatures in the Ny-Ålesund region in the last 5 years (the maximum of  $14$  °C and the minimum of  $-24$  °C). The reason of applying the higher maximum temperature ( $+27 \pm 2$  °C) compared with the five-year maximum temperature ( $+14$  °C) is to consider possible heat transferred from ground and solar radiation to the rock surface. In order to determine the freeze-thaw time, temperature changes inside the rock specimens were measured. For the measurement of rock temperature, small hole of 5 mm (diameter)  $\times$  25 mm (depth) is drilled at both ends of cylindrical rock samples with dimension of 50 mm (diameter)  $\times$  100 mm (length). The t-type thermocouple is firmly attached to center of the hole bottom. Thermal isolation was done by inserting bonding chemicals into the drilled holes. After drilling to the centers of the largest freeze-thaw specimens (diameter of 49.5 mm and length of 100 mm), we inserted a temperature sensor to monitor temperature changes on the inside the rock specimens. After saturating the test specimens in a vacuum chamber for 24 h, the specimens were submerged in individual containers filled with tap water for freeze-thaw. Figure 5 shows the temperature curves inside the rock when the temperature in the freezing chamber was changed in the range  $-25 \pm 2$  °C– $+40 \pm 2$  °C.



**Figure 5.** Temperature change test inside the rock during freeze-thaw cycles.

Although the change in temperature inside the rock sample exhibited some small changes with each freeze-thaw cycle, it took approximately 30 min for the rock temperature to descend from air temperature (+15 °C) to 0 °C, and the freezing temperature (−25 °C) was maintained for around 2 h. The time for the temperature inside the rock to recover from −25 °C to +27 °C was around 2 h 30 min. By measuring the change in temperature inside the rocks, we determined the duration of freeze-thaw cycles. For the freezing phase, in order for the rock temperature to remain at −25 °C for more than 2 h, the specimens were frozen at −25 °C for 5 h. For the thawing phase, the specimens were placed in a chamber for 3 h while the temperature was lowered at a constant rate from +40 °C to +25 °C.

For the freeze-thaw tests, after sample fabrication, all specimens were first subjected to forced saturation in water for at least 24 h using a vacuum chamber. Full saturation of rocks makes for a more severe freeze-thaw environment, as the saturation accelerates freeze-thaw weathering. Therefore, the freeze-thaw weathering of rock in sites may be less significant than those in laboratory. With the rock specimens submerged in water in individual containers, the freeze-thaw process was repeated. For every 150 freeze-thaw cycles, hardness in terms of UCS and shore hardness and physical properties of absorption and P-wave velocity were measured following the methods proposed by the ISRM [38]. For the UCS and shore hardness tests, their values were measured after drying the specimens for more than 12 h at +105 °C. To measure specific gravity, absorption, and porosity, the saturated weight before removing surface water and the weight after drying for more than 12 h at +105 °C were measured. P-wave velocity was also measured in a dry state. After measuring the physical properties of the rocks, the same specimens were submerged within flexible plastic container using tap water and fully saturated at vacuum chamber at least for 24 h. The implemented method in this study is more rigorous than the method proposed by ISRM [38], which saturates rock samples for 12 h under atmospheric pressure followed by an additional 1 h in a vacuum chamber. Then, the saturated specimens were subjected to another 150 freeze-thaw cycles.

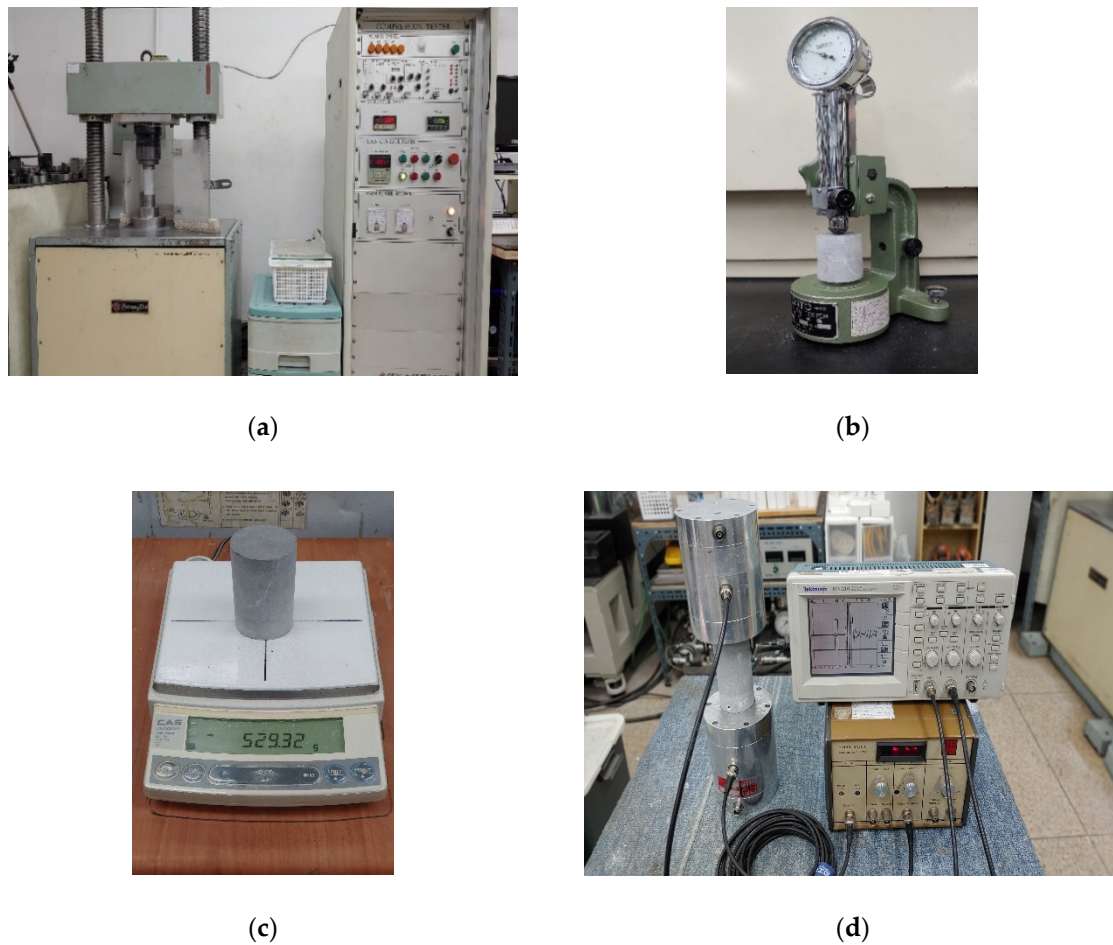
### 5.3. Changes in Physical and Mechanical Properties of Rocks

#### 5.3.1. Baseline Physical Properties of Rocks

The physical properties of the initially sampled rocks are important reference data to provide the criteria for physical changes according to the freeze-thaw process and weathering grade. Baseline properties are defined in this study as reference rock sample properties prior to implement freeze-thaw cycles in laboratory. Table 2 shows the baseline (initial) values for porosity, absorption, P-wave velocity, shore hardness, and UCS of rocks in the northern region of Ny-Ålesund. In order to determine the physical and mechanical properties of rocks, the methods proposed by the ISRM [38] are implemented. Figure 6 shows pictures of the measurement system for the tested samples. The physical and mechanical properties of three rock specimens from each location in the Ny-Ålesund region are summarized



in Table 2. The rocks sampled at Location A relatively show lower porosity, absorption, and shore hardness and higher UCS and P-wave velocity than those properties of the rocks sampled at Location B.



**Figure 6.** Photographs of measurement systems of rock properties: (a) Uniaxial compressive strength; (b) shore hardness; (c) absorption; (d) P-wave velocity.

**Table 2.** Range of rock properties of the pre-test sample specimens.

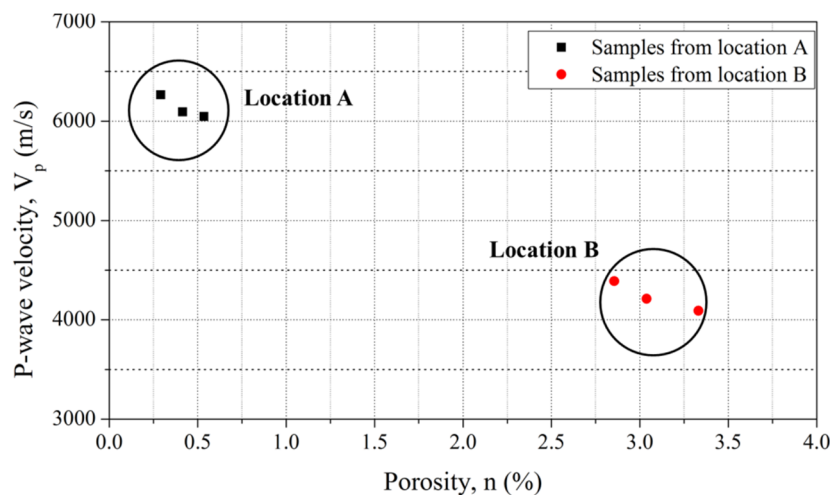
Property	Location A			Location B		
	A-1	A-2	A-3	B-1	B-2	B-3
Porosity (%)	0.291	0.415	0.536	3.332	2.855	3.039
Absorption (%)	0.106	0.151	0.195	1.298	1.136	1.184
P-wave velocity (m/s)	6266	6094	6048	4091	4390	4211
Shore hardness	62.9	66.2	63.8	87.7	90.3	85.0
Uniaxial compressive strength (MPa)	251.6	321.4	311.7	254.8	234.2	190.6

The extent of weathering of each specimen prior to application of freeze-thaw cycles was classified according to the existing grading method of Irfan and Dearman [30]. The weathering grade proposed by Irfan and Dearman [30] classified rock grading into six categories (Table 3). When rock weathering was observed under a microscope, the rocks at Locations A and B showed relatively good preservation of texture and loss or change of colour, and so, in terms of weathering grade, the rocks were determined to be fresh.

**Table 3.** Scale of weathering grades of rock mass (modified from Irfan and Dearman [30]).

Term	Grade	Abbreviation	Description
Fresh	I	F	Rock mass shows no loss of strength, discoloration or other effects due to weathering. There may be slight discoloration on major rock mass defect surfaces or on clasts.
Slightly Weathered	II	SW	The rock mass is not significantly weaker than when fresh. Rock may be discoloured along defects, some of which may have been opened slightly
Moderately Weathered	III	MW	The rock mass is significantly weaker than the fresh rock and part of the rock mass may have been changed to a soil. Rock material may be discoloured and defect and clast surfaces will have a greater discoloration, which also penetrates slightly into the rock material. Increase in density of defects due to physical disintegration
Highly Weathered	IV	HW	Most of the original mass strength is lost. Material is discoloured and more than of half the mass is changed to a soil by chemical decomposition or disintegration (increase in density of defects/fractures). Decomposition adjacent to defects and at the surface of clasts penetrates deeply into the rock material. Lithorelicts or core stones of fresh or slightly weathered rock may be present.
Completely Weathered	V	CW	Original rock strength is lost and the rock mass changed to a soil either by decomposition (with some rock fabric preserved) or by physical disintegration (e.g., talus).
Residual Soil	VI	RW	Rock is completely changed to a soil with the original fabric destroyed (pedological soil).

Although the rocks (prior to implement freeze-thaw cycles) in Locations A and B have the same weathering grade of “fresh” based on the methods of Irfan and Dearman [30], porosity and P-wave velocity were significantly different between the samples from Locations of A and B. Figure 7 shows the relationship between porosity and P-wave velocity in the specimens used in the freeze-thaw test. As shown in Figure 7, there exist clear differences in the physical properties in the relationship between porosity and P-wave velocity. This difference results from the different rock origins, internal structures, properties of minerals. There exists significant difference in porosity and P-wave velocity between rocks from Locations A and B. Figure 7 is provided to show a graphical view of the relationship between porosity and P-wave velocity. Dolomite, which is the smaller porosity, has the denser rock structure compared with quartzite. Therefore, the P-wave of dolomite is higher than that of quartzite.



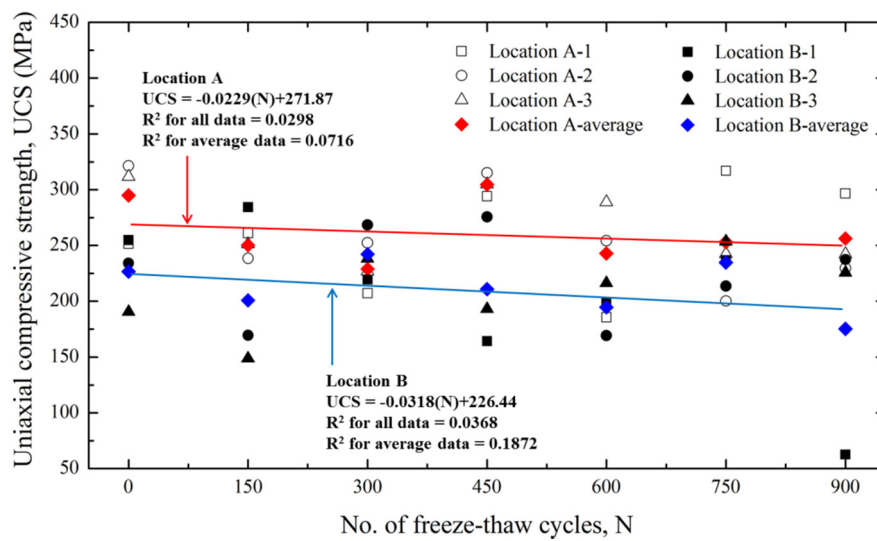
**Figure 7.** Distribution patterns of samples collected Locations A and B in Ny-Ålesund.

### 5.3.2. Changes in Rock Strength

In order to obtain the standardized strengths of the rocks, samples need to be prepared in a standard size, such as core or block samples. The preparation of homogeneous rock blocks or cores is almost impossible due to their inherent heterogeneous properties formed in nature. Especially, the weathered rocks are more difficult to fabricate into homogeneous standardized block or core sizes compared with less-weathered rocks.

In reality, measurement of rock strength inherently has a high uncertainty because of flaws or small cracks inside the rock and relative orientations between major flaws and loading directions. The extent of weathering, fissures, and the distribution of minerals act as factors introducing uncertainty to rock hardness [25–27]. Many researchers found the decrease of rock strength reduction with increasing freeze-thaw weathering from different experiments [6,39–42]. However, because there are large deviations in rock strength also depending on the sampling location, a large number of repetitive experiments of rocks is required to estimate the general UCS of rocks. Consequently, it is not easy to investigate changes in rocks in their natural state by studying artificial changes in rock strength due to freeze-thaw. However, to minimize the effect of inherent non-homogeneity on rock characteristics of freeze-thaw tests, rock samples with relatively consistent mineral composition and extent of fissures were collected for experiments in this study. Specifically, in order to minimizing uncertainty factors of the uniaxial compression test, we prepared test samples by moulding rocks that were homogeneous and, as far as possible, from nearby locations. Because samples after failure cannot be reused in the uniaxial compression test, we fabricated a large number of samples with similar baseline properties.

To reduce the uncertainties of UCS, we measured UCSs of three rock specimens for each freeze-thaw cycle and use their average to capture changes in UCS with increasing freeze-thaw cycle. Figure 8 shows the changes in UCS during 900 freeze-thaw cycles of rocks in the study area. UCS measurements were taken from three rock specimens in each group every 150 cycles, and the coloured points on the graph show the mean UCS of the three specimens. As mentioned earlier, due to the high uncertainty in UCS of rock, it is hard to capture clear decrease of UCS with increasing freeze-thaw cycle. The main reason would be the fact that identical rock specimens could not be used in UCS measurement.

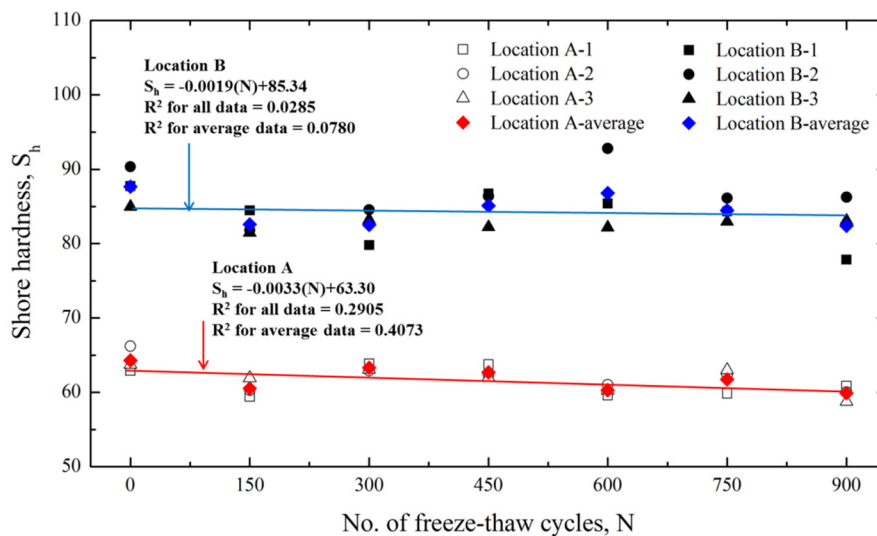


**Figure 8.** Uniaxial compressive strength changes with increasing freezing-thaw cycle of Locations A and B.

The results show an overall decreasing trend for hardness as freeze-thaw progresses, but there are large deviations in some measurement cycles. These deviations in UCS can be considered the result of inhomogeneity on the inside of the rocks [25–27]. The UCS of the rocks from Locations A and B decreased from 295 MPa at baseline to 256 MPa (reduction of approximately 13%) and from 227 MPa at baseline to 175 MPa (reduction of approximately 13%), respectively, after 900 cycles. The rocks from Location A showed a decrease in hardness of  $-0.0229$  MPa per freeze-thaw cycle, and the rocks from Location B showed a decrease of  $-0.0318$  MPa per cycle.

### 5.3.3. Changes in Rock Shore Hardness

In order to investigate the resistance of the rocks to changes in elasticity due to freeze-thaw, the shore hardness was measured on the rock surface. Figure 9 is a graph showing the changes in shore hardness with increasing freeze-thaw weathering. The rocks from Locations A and B showed mean shore hardnesses of 64.3 and 87.7 at baseline, respectively. Thus, the rocks from Location A, mainly consisting of carbonate minerals, showed the higher rebound than the rocks from Location B, primarily consisting of metamorphic quartz.



**Figure 9.** Shore hardness changes with increasing freezing-thaw cycle of Locations A and B.

Shore hardness was measured every 150 cycles of the freeze-thaw process. As freeze-thaw progressed for 900 cycles, the mean rebound of the rocks from Locations A and B decreased by 4.4 and 5.3 (corresponding to reduction by approximately 7% and 6%) from the baseline values, respectively. When the change in shore hardness per freeze-thaw cycle was compared between rock types, the rocks in Location A showed a decrease of  $-0.00329$  per cycle, and the rocks in Location B showed a decrease of  $-0.00185$  per cycle. This indicates that freeze-thaw weathering of the rock surface progressed more rapidly for rocks from Location A than those from Location B. Moreover, as shown in Figures 8 and 9, all rocks showed a decreasing trend in hardness with increasing number of freeze-thaw cycles. However, it is noted that expansion of weathered portion from the rock surface increases small fissures within the rock [26,41,42]. In this study, as mentioned previously, a clear decrease of shore hardness with increasing number of freeze-thaw cycle could not be found due to the inherent uncertainty of shore hardness. The high uncertainty in assessing rock shore hardness was also emphasized in the previous research [12,43].

### 5.3.4. Changes in Absorption

The changes in rock physical properties of absorption during the freeze-thaw test were observed. Figure 10 is a graph of the absorption of the rocks measured every 150 cycles. As shown in Figure 10, absorption showed a clear increasing trend in all rocks with increasing number of freeze-thaw cycles. The absorption of rocks from Locations A and B increased from 0.151% at baseline to 0.365% and from 1.206% to 1.450%, respectively, after 900 freeze-thaw cycles. In terms of the change in absorption by rock type, the rocks from Locations A and B showed increases of 0.000236% and 0.000169% per freeze-thaw cycle, respectively. The higher gradient of the change in absorption for the rocks from Location A compared with those from Location B indicates that the rate of weathering was faster for the rocks from Location A than for the rocks from Location B. The increase in absorption in all rocks with increasing number of freeze-thaw cycles is due to increasing surface porosity with more freeze-thaw cycles. Rocks that are more sensitive to freeze-thaw weathering show a faster increase in absorption due to the increased surface porosity effects.

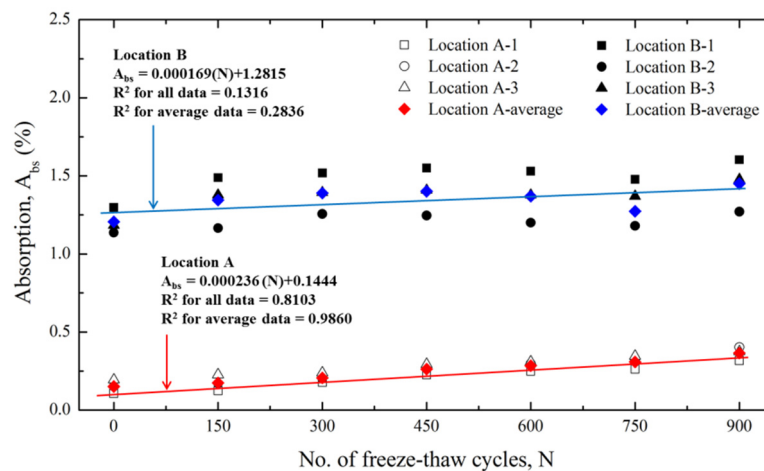


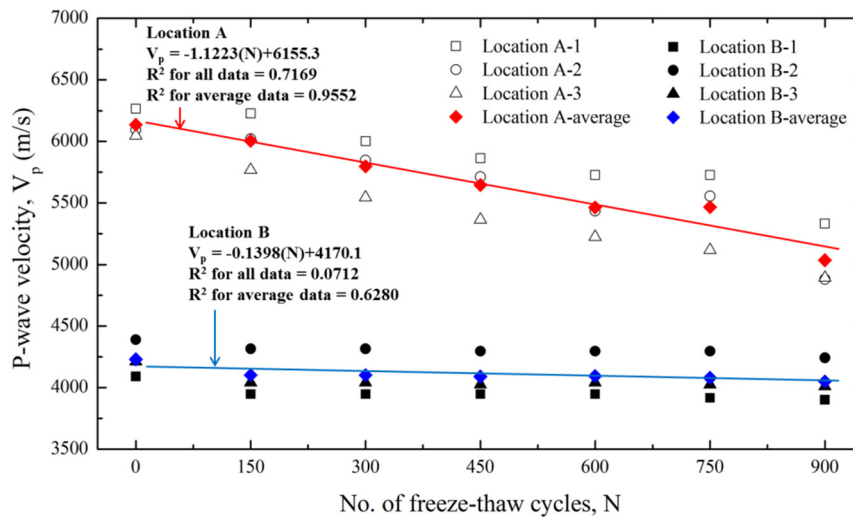
Figure 10. Absorption changes with increasing freezing-thaw cycle of locations A and B.

### 5.3.5. Changes in P-Wave Velocity

Similar to the method used to examine absorption changes with increasing freeze-thaw cycle, P-wave velocities of the rocks were measured every 150 cycles up to 900 cycles. As shown in Figure 11, the P-wave velocity showed a clear decreasing trend in all rocks with increasing number of freeze-thaw cycle. The baseline P-wave velocities of rocks from Locations A and B were 6136 m/s and 4231 m/s, respectively. The mean P-wave velocity of the rocks from Location A after 900 freeze-thaw cycles was 5035 m/s, which was a 17.9% decrease compared to baseline, while that of the rocks from Location



B was 4051 m/s, which was a 4.2% decrease. In average, the rocks from Locations A and B showed decreases of 1.1223 m/s and 0.1398 m/s per cycle, respectively. Thus, the change in P-wave velocity with increasing freeze-thaw cycle was approximately eight times faster for the rocks from Location A than for those from Location B. Such behaviour results from increase of absorption due to increased micro cracks on rock surface with increasing freeze-thaw cycles of absorbed water within the rocks. Therefore, the increased micro cracks induced a reduction of P-wave velocity.



**Figure 11.** P-wave velocity changes with increasing freezing-thaw cycle of Locations A and B.

The P-wave velocity showed an apparent decreasing trend in all rocks with more freeze-thaw cycles because additional micro fissures or cracks developed inside the rocks during weathering. As the size of surface pores becomes larger with increasing freeze-thaw cycle, resulting in increased time for waves to be transmitted through the specimens, or an increase in discontinuities, leading to a decrease in P-wave velocity.

Rocks from Location A relatively have low porosity and high P-wave velocity compared to those of rocks from Location B. The main difference in porosity and P-wave velocity of rocks from Locations A and B results from different mineralogy. From the results from the experiments in this study, porosity and P-wave velocity of rocks from Location A increased by 1.4 times higher and decreased by 8 times lower than that from Location B with an increasing number of freeze-thaw cycles. Therefore, it is inferred that calcite and dolomite dominantly found from rocks of Location A are more susceptible to freeze-thaw weathering compared with quartzite dominantly found from rocks of Location B. A more significant weathering trend of rocks from Location A induced higher  $R^2$  values, compared to that for rocks from Location B. Even relatively small scatters of data from the fitted trend line having small gradient could exhibit small  $R^2$  value.

## 6. Discussion

Regression equations for mean values of rock properties in Figures 8–11, showing the changes of physical properties with increasing freeze-thaw cycle of rocks, were derived based on the experiment results. Table 4 summarizes correlation coefficient ( $R^2$ ) of the relationships between the freeze-thaw cycle and physical properties of UCS, shore hardness, absorption, and P-wave velocity of two rock types from Locations A and B, respectively. As presented in Table 4, UCS and shore hardness show weak correlations that the  $R^2$  of the mean values of UCS and shore hardness were 0.0716–0.4073. Relatively higher  $R^2$  values (0.9860–0.2836) were observed for absorption and P-wave velocity.

**Table 4.** Variation of  $R^2$  due to freeze-thaw test.

Test Type	Average $R^2$ of Location A	Average $R^2$ of Location B
Uniaxial compressive strength	0.0716	0.1872
Shore hardness	0.4073	0.0780
Absorption	0.9860	0.2836
P-wave velocity	0.9552	0.6280

As mentioned previously in this paper, repetitive freeze-thaw actions of rocks induce increases of the number and the sizes of both surface/internal pores and internal micro cracks of rocks. These increases of pores and internal micro cracks of rocks increase rock absorption due to increased voids and void surface areas and decrease P-wave velocity due to delayed wave propagation due to increased voids/micro cracks/fissures within the rock specimens. On the other hand, ideally, UCS and shore hardness may decrease with increasing freeze-thaw cycle due to increases of pores and more developed micro cracks and fissures. However, clear trends of decreases of UCS and shore hardness were not identified because of the impossibility of using the identical sample specimens of rocks. Therefore, randomly distributed major directions of pores/micro cracks/fissures with respect to loading direction significantly influences UCS and shore hardness. Consequently, absorption and P-wave velocity exhibit much higher correction (much higher  $R^2$  values) with freeze-thaw cycle compared with those of UCS and shore hardness. Use of absorption and P-wave velocity is proposed to evaluate degree of freeze-thaw weathering of rocks.

From the analysis of freeze-thaw cycles (Figure 5) in terms of air temperature of the Ny-Ålesund region for 6 years, average and range of annual freeze-thaw cycle was 52 and 33–62, respectively. The 900 freeze-thaw cycles implemented in this study aimed to conservatively simulate 14.5–27.3 years freeze-thaw cycles considering annual freeze-thaw cycle of 33–62 of the Ny-Ålesund region. However, severe conditions of the experiment conducted in laboratory induce more freeze-thaw weathering of rocks as the rock samples are more saturated and typically smaller in sizes compared with rocks in nature state. Smaller sizes of rocks result in higher rock surface area per rock mass. The increased rock surface area per rock mass accelerates freeze-thaw weathering due to the increase exposure of heat changes on rock surfaces. Harsh environments in terms of high temperature change, wind, and salty water of the shore of the Ny-Ålesund region, from which rock samples are obtained, influence the crystallization of salt under coastal weather conditions.

Despite of many other factors describing discrepancy between nature and laboratory conditions, reasonable estimation of freeze-thaw weathering cycle and change of physical properties. Proper estimation of these characteristics enables the prediction of durability and remaining time to repair rock-related structures against freeze-thaw rock weathering.

## 7. Conclusions

This study analysed meteorological data in order to assess the effects of freeze-thaw cycle on the declines of physical and mechanical parameters of rocks in the Ny-Ålesund region, which is a polar region. In addition, we performed an indoor study to examine the freeze-thaw weathering of rocks collected from outcrops. In order to assess changes in rock properties, we measured UCS, shore hardness, absorption, and P-wave velocity. Through the analysis of the measured changes in rock properties and the meteorological data, we quantified weathering characteristics, and used these to correlate the weathering of rocks in the Ny-Ålesund region.

(1) We analysed the changes in annual air temperatures in the region in terms of the daily minimum and maximum temperatures, and evaluated the number of cycles where the temperature changed from above to below zero or from below to above zero. According to the results of the analysis, the numbers of natural freeze-thaw cycle were around 33–62 cycles per year, and the mean number of freeze-thaw cycle was 52 cycles per year.

(2) The rocks in Locations A and B in the Ny-Ålesund region were fresh, showing almost no weathering. The baseline physical properties (absorption, P-wave velocity) showed clear differences between the two groups. Attenuation of weathering over the course of 900 freeze-thaw cycles differed between rocks from Location A and rocks from Location B. In terms of changes in physical properties, the rocks showed decreasing trends for UCS, shore hardness, and P-wave velocity, and increasing trends for absorption.

(3) In order to predict the weathering of rocks in the Ny-Ålesund region, we used  $R^2$  values to compare changes in physical properties of the rocks by the number of freeze-thaw cycles. Changes in physical properties were weakly correlated with the number of cycles. However, the relationships between absorption and P-wave velocity, which is closely correlated with the state of weathering and fissures inside rocks, and between P-wave velocity and UCS showed stronger correlations.

(4) The evaluation of the freeze-thaw weathering cycle using the air temperature and physical properties enables the prediction of durability, remaining life, time of repair of rock-related historical monuments, roadside riprap, railway subgrade, pipelines, built heritage, and buildings using rocks against freeze-thaw rock weathering.

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