Analysis of Effects of Rock Physical Properties Changes from Freeze–Thaw Weathering in Ny-Ålesund Region: Part 2—Correlations and Prediction of Weathered Properties

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Received: 5 February 2020; Accepted: 11 May 2020; Published: 14 May 2020

Abstract: From the examination of rock physical parameters’ changes of compressive strength, shore hardness, water absorption, P-wave velocity with increasing freeze–thaw cycles, correlations of these parameters were investigated. Rock samples were collected from Ny-Ålesund region in Norway. As compressive strength and shore hardness inherently have high uncertainties due to inhomogeneous rock composition and internal fissures and cracks, only the relationship between water absorption and P-wave velocity revealed high correlations, providing meaningful linear fitting equations. From the correlation analysis results and clear trends of increasing water absorption and decreasing P-wave velocity with increasing freeze–thaw cycle found in part one of the companion study, prediction equations of future changes of rock physical parameters are proposed using P-wave velocity or water absorption. In addition, future rock weathering grade changes with time can be predicted from estimation of water absorption or P-wave velocity change due to freeze–thaw cycles.

Keywords: rock weathering; rock weathering grade; freeze–thaw cycle; air temperature; P-wave velocity; water absorption; regression analysis

1. Introduction

Prediction of physical changes and rock weathering during the freeze–thaw cycle is important because it plays an important role in controlling the long-term global climate, and influences the development landscapes, the formation of soil and the preservation of buildings and monuments [1–6]. The changes in rock durability can cause reduced shear strength of the rock and discontinuities (or joint surfaces), leading to issues such as overall slope failure or localized rockfall, and contributing to the gradual destruction of the structure [7]. Prediction of the durability of rocks allows the limit of validity to be estimated, which makes it possible to decide the appropriate time for maintenance and repair of rock-based historical monuments, roadside riprap, railway subgrade, pipelines, built heritage and buildings [8]. These structures are exposed to the variable atmosphere changes for long periods of time. Exposure to long-term environmental changes could result in cumulative damage to the rocks.

In the process of rock weathering, climate can be considered as a major factor in inner structure or built structure damages due to possible wear and disintegrate of rocks. Brimlemcombe and Grossi [9,10] investigated climate change effects on cultural heritage weathering and suggested solutions for their conservation and survival. In addition, Grossi et al. [11] stated that temperature increase due to
climate change could melt the upper frozen soil layer and decrease number of freeze–thaw cycles; therefore, problems of structural safety of building, road, and buried pipes could occur. However, experts, such as architects and geologists, centuries ago were not likely to make the connection between rock weathering and most built structural damages, including collapse and abrasion [12].

High temperature variation (freeze–thaw actions) of rocks and presence of water are major factors influencing weathering of rocks in polar regions. However, the rock temperatures are not easy to track continuously. For this reason, air temperature near the Earth surface is generally used to indirectly estimate exposed rock temperature [13,14], even the air temperature in polar regions is not representative of the temperature of rocks exposed to the Earth surface. The difference in temperature between the exposed rock and adjacent air result from different solar radiation and specific heat of the air and rock. Generally, when the air temperature is below zero degrees Celsius in polar regions, the temperature of rocks at the surface is slightly higher due to solar irradiation [15]. Although the air temperature does not accurately represent rock temperature, in terms of freeze–thaw, counting freezing cycles based on temperature below zero degrees Celsius can have a large effect on the number of valid freeze–thaw cycles [15–17]. Since, the method of using air temperature to determine the number of freeze–thaw cycles was utilized by various studies [9–11,18], it is necessary to investigate future and past rock properties’ changes from freeze–thaw weathering based on air temperature changes [11].

There are many studies [17,19–26] on the effect of natural or artificial freeze–thaw cycles on rock weathering. Celik [19] investigated water saturation effect resulting from rock weathering due to freeze–thaw cycles. Heidari et al. [20] estimated degree of freeze–thaw rock weathering under natural condition. Momeni et al. [21] examined engineering properties of rocks based on physical and mechanical parameters under repetitive freeze–thaw conditions. Al-Omari et al. [17] assessed freeze–thaw environment in nature and reflected the results on estimation of physical and mechanical rock properties. Khandlari et al. [22] studied on degradation of engineering properties of sandstone; while Yu et al. [23] investigated basic engineering properties of rocks and the effect of rock strength reduction due to freeze–thaw cycles. Hall [24] performed weathering tests of paving bricks in the northern region of Canada and found that freeze–thaw rock damage is influenced by freezing strength, rate and sustained time. McCabe et al. [25] showed different weathering status between the surface and the core based on the shore hardness and uniaxial compressive strength (UCS) properties. Yurdakul and Akdas [26] modeled uniaxial compressive strength of building stones using non-destructive test results using neural network analysis.

This study, part two of two companion papers, uses experimental data of rock properties’ changes due to freeze–thaw weathering to analyze correlation and prediction of weathered rock properties. The rock samples were obtained in Ny-Ålesund regions in Norway. The detailed explanation of the site, rock samples and environmental data are available in part one [27] of two companion papers. The use of UCS, as proposed by International Society for Rock Mechanics (ISRM) [28], to quantify weathering characteristics is more practical and appropriate; however, the high uncertainty in UCS estimation resulting from sampling induces difficulty in assessment of accurate in situ rock strength on site. Consequently, the changes of water absorption and P-wave velocity with increasing freeze–thaw cycle were examined, and rock weathering grade proposed by Iliev [29] for weathering grades is applied in this study. From the analysis of rock weathering properties’ changes with increasing freeze–thaw cycles along with the average annual numbers of freeze–thaw cycle, prediction is made on future physical properties’ changes resulting from freeze–thaw weathering to estimate remaining time to change of rock weathering grade. Estimation of remaining time of rock weathering grade change is important to prepare conservation plan of rock-built structures.

2. Summary of Part One [27] of the Companion Papers

This study is part two of two companion papers. Part one [27] of the companion papers describes details of experiments of rock physical properties of uniaxial compressive strength (UCS), shore hardness, porosity, water absorption and P-wave velocities, and their changes with increasing freeze–
thaw cycle. Two different types of rocks (dolomite from Location A and quartzite from Location B in Figure 1) were sampled in Ny-Ålesund (11°54′41.23″ E, 78°55′31.65″ N) in the Svalbard Archipelago.

Climate in summers is generally temperate due to the northward passage of the warm Gulf Stream; however, it has very cold weather in winters. Based on XRD results, rocks from Location A (approximately six kilometers from Ny-Ålesund harbor to southeast direction) mainly consist of dolomite (44.5% by weight percentage), calcite (31.3%) and quartz (24.2%); while major minerals of rocks from Location B (approximately 8.7 km from Ny-Ålesund harbor to northwest direction) are quartzite (95.3%) and dickite (4.7%).

![Figure 1](image)

Figure 1. Study area and locations of rock sample areas in Ny-Ålesund (map reproduced Figure [30]. with courtesy of the Norwegian Polar Institute).

Triplicate tests were conducted for determination of UCS, shore hardness, porosity, water absorption and P-wave velocity. Details of sample sizes and sample preparation are explained in part one [27] of the companion papers. Properties of UCS, shore hardness, porosity, water absorption and P-wave velocity are obtained using the method proposed by ISRM [31]. The physical parameters of UCS, shore hardness, water absorption and P-wave velocity were examined under completely dried condition. Freeze–thaw cycles of temperature range of −25 ± 2 °C → 27 ± 2 °C were applied for samples.

The extent of weathering of rocks cannot be clearly distinguished based on differences in physical properties. Since rocks show changes in physical properties depending on differences in the extent of weathering [32–34], it is important to determine reference physical properties (or baseline properties). In freeze–thaw tests of rocks because differences in initial (or baseline; which means the state prior to applying freeze–thaw cycle experiments) mechanical properties can occur as a result of the distribution of micro fissures and joints that develop inside the rocks.

In order to determine the durability of the rocks, it is essential to have quantitative data classifying the rocks by hardness and the extent of weathering. Representative research on these topics are the studies of ISRM [28] and Iliev [29]. ISRM [28] used UCS to classify rocks into the grades of R0–R6 (Table 1). Meanwhile, Iliev [29] suggested weathering grades to classify the extent of weathering based on P-wave velocity (Table 2). The rocks tested in this study were relatively very strong rocks or extremely strong rocks based on the classification proposed by ISRM [28] and the mean baseline rock UCSs from Locations A and B were 295 MPa and 226 MPa, respectively. Stress-controlled UCS tests were conducted with a stress rate of 0.5 MPa/s. When the rocks were graded using the baseline UCS, the rocks from Location A were classified as extremely strong rock (R6), while the rocks from Location B were classified as very strong rock (R5). The mean UCSs of rocks from Locations A and B after the 900-cycle freeze–thaw test were 256 MPa and 175 MPa, respectively.
Based on the weathering grades proposed by Iliev [29], the baseline weathering grade for rocks from Location A was fresh (P-wave velocities ≥ 6000 m/s), with a mean P-wave velocity of 6136 m/s, while the baseline grade for rocks from Location B was slightly weathered (P-wave velocities ≥ 4000 m/s), with a mean P-wave velocity of 4231 m/s.

The rock weathering grade results by Iliev [29] is different from those by Irfan and Dearman [35]. As shown in part one [27] of two companion papers, based on the six weathering grades (fresh; slightly weathered; moderately weathered; highly weathered; completely weathered; and residual soil) of rocks proposed by Irfan and Dearman [35], all the rock specimens from Locations A and B immediately after their sampling in our study were classified as fresh. Irfan and Dearman [35] uses observation of large cracks, pores and surface/inner color similarity of the sample rocks to classify rock weathering grade. The rock weathering grade by Iliev [29] is used in this study to implement more objective and quantitative measure of P-wave velocity. Irfan and Dearman [35] method is more subjective because it relies on eye and microscopic observation of large cracks, pores and surface/inner color similarity of rocks. The purpose of this study is to provide quantitative physical properties of rock for estimation of freeze–thaw rock weathering.

The five weathering grades proposed by Iliev [29] in Table 2 were initially developed for granite rocks; however, the weathering grades are also implemented for rocks with similar strength and stiffness [36]. The weathering grades are used to examine degrees of rock weathering for evaluation of rock strengths on site [36–38]. As mentioned in details later in this study, the strength and stiffness ranges of typical granites are comparable with the identified strength ranges of the sampled rocks in this study and the stiffness ranges founded from literature. As the strength and stiffness ranges of the sampled rocks are not significantly different from those of typical granites, in this study, the weathering grades of the sampled rocks can reasonably be evaluated from P-wave velocity following the criterion by Iliev [29]. Based on the correlation between water absorption and P-wave velocity, the results of changes of these properties with increasing freeze–thaw cycle are used to estimate the remaining time to change current rock weathering grades for given average annual freeze–thaw cycle.

Table 1. Rock strength classification using uniaxial compressive strength for estimation of rock durability proposed by International Society for Rock Mechanics (ISRM) [28].

| Rock Strength Description       | Uniaxial Compressive Strength (MPa) | Symbol |
|---------------------------------|-------------------------------------|--------|
| Extremely strong rock           | higher than 250                     | R6     |
| Very strong rock                | 100–250                             | R5     |
| Strong rock                     | 50–100                              | R4     |
| Medium strong rock              | 25–50                               | R3     |
| Weak rock                       | 5–25                                | R2     |
| Very weak rock                  | 1–5                                 | R1     |
| Extremely weak rock             | 0.25–1                              | R0     |

Table 2. Granite rock weathering grade based on P-wave velocity proposed by Iliev [29].

| Rock Weathering Grade           | P-Wave Velocity (m/s) |
|---------------------------------|-----------------------|
| Fresh rock                      | higher than 5000      |
| Slightly weathered rock         | 4000–5000             |
| Moderately weathered rock       | 3000–4000             |
| Strongly weathered rock         | 2000–3000             |
| Very strongly weathered rock    | less than 2000        |
3. Relationship of Physical Parameters of Rocks Evaluated during Freeze–thaw Cycles

Figure 2 shows relationship between UCS and shore hardness (S_h) of samples from Locations A and B estimated for different freeze–thaw cycles. Triplicate tests (A-1, A-2 and A-3 for Location A; and B-1, B-2 and B-3 for Location B) were conducted for estimation of each physical parameter. Different colors were used to express different numbers of freeze–thaw cycles of 0, 150, 300, 450, 600, 750 and 900. There exists a trend of increase of UCS with increasing shore hardness; however, high scatter of data points indicates poor correlation (R^2 values of 0.0568 and 0.1083 for rocks from Locations A and B, respectively) between UCS and S_h. In addition, from a close examination of different colors, there was not a clear pattern of increase of UCS or S_h with increasing freeze–thaw cycle. As mentioned earlier in this study and in part one [27] of two companion papers, the poor correlation between UCS and S_h results from high uncertainties in measurement of UCS and S_h due to inhomogeneity of fissures, cracks and mineral compositions [39–42].

![Figure 2](image)

**Figure 2.** Relationship between uniaxial compressive strength and shore hardness for every 150 freeze–thaw cycles and initial state prior to freeze–thaw test: (a) location A and (b) location B.

Figure 3 represents relationship between UCS and water absorption (Abs) of rock samples from Locations A and B estimated for different freeze–thaw cycles. There was a weight loss (in terms of dry weight) identified during porosity, water absorption tests with increasing freeze–thaw cycle. The dry weight of rock samples was measured at every 150 freeze–thaw cycle. Average dry rock weight losses per 150 freeze–thaw cycle for Locations A and B were 0.1 g (dry weight loss of 0.0191%) and 0.05 g (0.0102%), respectively. The dry weight losses of rocks may result from detachment of small rock fractions during freeze–thaw actions. However, calculation of Abs at each 150 freeze–thaw cycle reflects dry weight loss of the samples. There is a trend of slight decrease of UCS with increasing Abs; however, due to a high inherent uncertainty in UCS and its measurement, the correlation between UCS and Abs is low. R^2 values for UCS and Abs correlation are 0.0124 for Location A and 0.0673 for Location B.

Relationship between S_h and Abs is presented in Figure 4. Similar to the relationship between UCS and Abs, a slight decrease of S_h with increasing Abs and their low correlation are observed. The higher values of R^2 of 0.1656 for Location A and 0.3014 for Location B in Figure 4 are found compared with those in Figure 3. The higher correlation (the higher R^2) may result from the lower uncertainty in S_h compared with that in UCS. However, the correlation between S_h and Abs is not sufficiently high enough to estimate S_h using Abs or Abs using S_h.
Figure 3. Relationship between uniaxial compressive strength and water absorption for every 150 freeze–thaw cycles and initial state prior to freeze–thaw test: (a) location A and (b) location B.

Figure 4. Relationship between shore hardness and water absorption for every 150 freeze–thaw cycles and initial state prior to freeze–thaw test: (a) location A and (b) location B.

Figures 5–7 show changes of UCS, $S_h$ and $A_{hs}$ with changes of P-wave velocity ($V_p$). Increases of UCS and $S_h$ and decrease of $A_{hs}$ are observed with increasing $V_p$. The correlation between UCS and $V_p$ is the lowest showing $R^2$ values of 0.017 for Location A and 0.0478 for Location B; while the highest correlation was found for the relationship between $A_{hs}$ and $V_p$ exhibiting $R^2$ values of 0.935 for Location A and 0.8974 for Location B.

From a close examination on symbol colors in Figure 7, it is noted a clear consistent pattern of increase of $A_{hs}$ with increasing freeze–thaw cycle. However, there exists no reliable decrease trends of UCS and $S_h$ with increasing $V_p$ because of high uncertainties of UCS and $S_h$ measurement. The highly correlated relationship between $A_{hs}$ and $V_p$ results from the followings: (1) $A_{hs}$ and $V_p$ are measured and tracked with increasing freeze–thaw cycle using the same samples; and (2) Reuse of samples in $A_{hs}$ and $V_p$ is possible because their measurements are from nondestructive tests. Reuse of nondestructive tests should be conducted with special care, as the changes of measured physical properties are very small [43–46]. In particular, reuse of rocks for nondestructive is recommended in the correlation analysis of resulting physical properties to avoid possible erratic data [47–52].

On the other hand, reuse of samples for estimation of UCS and $S_h$ is impossible as their measurements are obtained from destructive tests. Changes of samples in estimation of UCS and $S_h$
induce high uncertainties in these parameters. Different samples have different spatial and orientation distributions of internal pores, fissures, cracks and mineral compositions; and these factors highly influences UCS and shore hardness.

Figure 5. Relationship between uniaxial compressive strength and P-wave velocity for every 150 freeze–thaw cycles and initial state prior to freeze–thaw test: (a) location A and (b) location B.

Figure 6. Relationship between shore hardness and P-wave velocity for every 150 freeze–thaw cycles and initial state prior to freeze–thaw test: (a) location A and (b) location B.

Figure 7. Relationship between water absorption and P-wave velocity for every 150 freeze–thaw cycles and initial state prior to freeze–thaw test: (a) location A and (b) location B.
In Figure 7, as the number of freeze–thaw cycles increases in the same direction as the dotted arrows, \(V_p\) is decreased and water absorption is increased. In Figure 7 especially, specimens of the same rock type are located on the fitting line for attenuation of physical properties, showing decreasing \(V_p\) and increasing \(A_{bs}\) with increasing number of freeze–thaw cycles (gray solid arrow). The cross-plot of \(A_{bs}\) against \(V_p\) allows the attenuation characteristics of weathering to be calculated directly according to the number of freeze–thaw cycles; therefore, the authors surmise that the time of changes in weathering grade could be derived from the \(A_{bs}-V_p\) curves.

Table 3 summarizes the linear regression equations and their \(R^2\) values. Only the \(R^2\) values for relationship between \(A_{bs}\) and \(V_p\) for Locations A and B are significantly higher than those of other relationships. The linear equations in Table 3 may be effective for reasonable ranges of physical parameters of UCS, \(S_h\), \(A_{bs}\) and \(V_p\).

| Location | Regression Equations                                      | \(R^2\) |
|----------|-----------------------------------------------------------|---------|
| A        | UCS = 5.180\((S_h)\) − 58.68                            | 0.0568  |
|          | UCS = −56.313\((A_{bs})\) + 275.67                       | 0.0012  |
|          | \(S_h\) = −9.480\((A_{bs})\) + 64.19                    | 0.1656  |
|          | UCS = 0.013\((V_p)\) + 187.93                            | 0.0170  |
|          | \(V_p\) = 91.881\((S_h)\) − 29.663                      | 0.1791  |
|          | \(V_p\) = −4890.7\((A_{bs})\) + 6875.5                  | 0.9350  |
| B        | UCS = 4.968\((S_h)\) − 207.71                            | 0.1083  |
|          | UCS = −92.304\((A_{bs})\) + 337.45                       | 0.0673  |
|          | \(S_h\) = −12.940\((A_{bs})\) + 102.08                   | 0.3014  |
|          | UCS = 0.069\((V_p)\) − 71.89                            | 0.0478  |
|          | \(V_p\) = 26.820\((S_h)\) + 1840.5                      | 0.3156  |
|          | \(V_p\) = −1066.0\((A_{bs})\) + 5554.3                   | 0.8974  |

There are studies [53–55] showing clear trends of strength drop with increasing freeze–thaw actions. However, relatively fresh rocks having UCS higher than 200 MPa do not show significant UCS decrease with increasing number of freeze–thaw cycle [56,57]. There is a limitation on model development for estimation of one physical property of relatively fresh rock from other properties of the rock due to relatively low correlations among the physical properties. Low correlations among mechanical and physical properties of rocks are also reported from other research [57,58].

In reality, because UCS of rock decreases with increasing weathering compared to its initial strength; therefore, UCS is often used as a good indicator of the extent of rock weathering. At the same time, UCS also is used to predict other rock properties such as Young’s modulus or Poisson’s ratio. The highly weathered rocks with higher porosity, larger particle size, and more-developed micro joints are likely to have more rock discontinuities. The increased surface area of highly weathered rock resulting from weathering accelerates overall weathering of the rock [41,59–61]. In addition, as UCS is an important factor in estimation of durability of rock, research on UCS degradation with increasing freeze–thaw cycle is required for its practical use for engineers.

If this study were performed for much larger number of freeze–thaw cycles and samples or implemented nondestructive tests for estimation of rock strength, more clear gradual weathering patterns in the form of destruction were observed; therefore, quantitative degrade of freeze–thaw weathering could become more apparent. However, because not all weathering processes can be assessed from laboratory tests, it will be necessary to implement a logical quantification process using existing data. In this discussion, the authors aim to analyze the required additional number of freeze–
thaw cycles for chain in rock weathering grade by quantification of weathering using physical properties of rocks and the relationships.

4. Correlation Analysis Result Summary

As mentioned previously, weathering grade system proposed by Iliev [28] can be implemented for rocks with similar strength and stiffness of granite. Granite is one of the mostly distributed rock types. Due to its wide distribution mixed with other rock minerals, granites have wide ranges of compressive strength and stiffness. The uniaxial compressive strengths of granites are reported within ranges of 26–485 MPa [62–71] and elastic modulus exists within a range of 20–81 GPa [62,64–68,70–75]. Dolomite has uniaxial compressive strength of 32–500 MPa [62,64,76–81] and elastic modulus of 38–70 GPa [62,64,79,81], while quartzite has uniaxial compressive strength of 215–320 MPa [62,82] and elastic modulus of 88.3 GPa [62]. Therefore, the weathering grades suggested by Iliev [29] can be also implemented for the samples (dolomite and quartzite) used in this study and this classification is used in the prediction of weathering by rock type, discussed in the next section.

As shown in Figures 2 through 4, R² values of relationships among UCS, S₀, and A₀, exhibit weak correlations. This weak correlation of observed mechanical and physical properties has also been reported by other investigators [57,58], suggesting the need for quantification using a coefficient other than freeze–thaw cycles in order to predict the course of weathering as freeze–thaw progresses. From the correlation analyses of rock properties’ correlations during freeze–thaw weathering, it was found that the relationships (Figures 5 and 6) of USC and S₀, which parameters showed high uncertainties, with Vₚ provide a slightly better correlations compared to those (Figures 3 and 4) with A₀. Figure 7 is the cross-plot showing the correlation between A₀ and Vₚ measured in the same specimens every 150 cycles. As shown in Figures 2 through 6, the relationships among A₀, Vₚ, S₀, and UCS showed large variance, whereas Figure 7 of A₀ against Vₚ and Figure 8 of UCS against Vₚ/UCS presented relatively constant attenuation with less uncertainty as freeze–thaw progressed.

Despite of poor correlation between UCS and Vₚ in Figure 5, effort was made to find a good equation representing their relationship (equations in Figure 8) for Locations A and B. The plot of UCS against UCS/Vₚ in Figure 8 shows a relatively steep slope compared to the graph in Figure 5, and R² for rocks from Locations A and B are 0.8974 and 0.9858, respectively, demonstrating strong correlations. The inconsistent attenuation of changes in physical properties with increasing number of freeze–thaw cycles is thought to reflect the variance in UCS in Figures 2, 3 and 5. Thus, the cross-plot of UCS against UCS/P-wave velocity has the drawback that it is difficult to directly calculate hardness characteristics and the attenuation of freeze–thaw weathering from the number of freeze–thaw cycles.

![Figure 8](image-url)

**Figure 8.** Relationship between uniaxial compressive strength and “normalized P-wave velocity with uniaxial compressive strength” for every 150 freeze–thaw cycles and initial state prior to freeze–thaw test.
5. Prediction of Weathering Based on the Freeze–thaw Process by Rock Type

High correlation between $A_{bs}$ and $V_p$ in Figure 7 can be implemented in development of an equation predicting the attenuation of weathering due to physical changes in relation to freeze–thaw. The arrows towards to the upper left show freeze–thaw weathering progresses of the rocks in Locations A and B. Clear patterns of changes in $A_{bs}$ and $V_p$ with increasing freeze–thaw cycle enable estimation of rock weathering grade with changes of freeze–thaw cycles (or time if average freeze–thaw cycle number per year is known.)

Equations (1) and (2) present changes of $A_{bs}$ and $V_p$ with increasing freeze–thaw cycle, which are the results from the P [27] of two companion papers. These equations can be used to calculate the average amount of weathering attenuation cycles for each location, as different coefficients are given in Table 4 for each location.

$$A_{bs} = \alpha N + A_{bs,N0} \tag{1}$$

where $\alpha$ is the gradient of the linear relationship between $A_{bs}$ and the freeze–thaw cycle number $N$ and $A_{bs,N0}$ is the $A_{bs}$ values when $N = 0$.

$$V_p = \beta N + V_{p,N0} \tag{2}$$

where $\beta$ is the gradient of the linear relationship between $V_p$ and $N$ and $V_{p,N0}$ is the $V_p$ values when $N = 0$. From the given Equations (1) and (2), the remaining number ($\Delta N_{\text{remaining}}$) of freeze–thaw cycle from current and target freeze–thaw cycles ($N_{\text{Current}}$ and $N_{\text{Target}}$) using $A_{bs}$ and $V_p$ can be estimated using the following equations, respectively:

$$\Delta N_{\text{remaining, } A_{bs}} = N_{\text{Target}} - N_{\text{Current}} = \frac{A_{bs, \text{Target}} - A_{bs, \text{Current}}}{\alpha} \tag{3}$$

Where $\Delta N_{\text{remaining, } A_{bs}}$ is $\Delta N_{\text{remaining}}$ estimated in using $A_{bs}$ and $A_{bs, \text{Target}}$ and $A_{bs, \text{Current}}$ are the target and current $A_{bs}$ values.

$$\Delta N_{\text{remaining, } V_p} = \frac{V_{p, \text{Target}} - V_{p, \text{Current}}}{\beta} \tag{4}$$

where $\Delta N_{\text{remaining, } V_p}$ is $\Delta N_{\text{remaining}}$ estimated in using $V_p$ and $V_{p, \text{Target}}$ and $V_{p, \text{Current}}$ are the target and current $V_p$ values. Equation (5) shows the relationship between $A_{bs}$ and $V_p$ in Figure 7 with different coefficients of $\gamma$ in Table 4. Equation (5) can be used to convert $A_{bs}$ to $V_p$ or vice versa when one property is missing. However, conversion one property from the other property using Equation 5 may induce higher uncertainty in estimation of $\Delta N_{\text{remaining}}$.

$$A_{bs} = \gamma V_p + A_{bs,Vp0} \tag{5}$$

where $\gamma$ is the gradient of the relationship between $A_{bs}$ and $V_p$ and $A_{bs,Vp0}$ is the $y$-intercept when $V_p = 0$.

Table 4. Coefficients and reference parameters of fitting parameters of the linear regression equations from (1) to (5).

| Location | $\alpha$     | $\beta$     | $\gamma$ | $A_{bs,N0}$ | $V_{p,N0}$ | $A_{bs,Vp0}$ |
|----------|--------------|-------------|----------|-------------|------------|--------------|
| A        | 0.000236     | -1.1223     | -0.0002  | 0.1444      | 6155.3     | 1.3307       |
| B        | 0.000169     | -0.1398     | -0.0008  | 1.2815      | 4170.1     | 4.8151       |

Using Equations (1) and (2) to quantify physical changes in each rock type due to freeze–thaw weathering, prediction of the duration (remaining time) of freeze–thaw to change weathering grades based on $V_p$ for rocks from Location A was found to be shorter than that of rocks from Location B. This means that physical properties of rocks, such as $A_{bs}$ and $V_p$, show attenuation effects due to weathering at the rock surface, and that weathering occurs more rapidly for rocks from Location A compared to rocks from Location B. The rocks from Location A mostly consisted of fine-grained...
crystals, while the rocks from Location B mostly consisted of quartz crystals. Moreover, in the rocks from Location A, fine-grained crystals were dominant, and mostly calcite and quartz crystals were present. Consequently, the authors deduced that, for rocks from Location A, weathering progresses more rapidly at the surface than on the inside of the rocks.

6. Difference between Laboratory and Nature Environment and Ideal Assumptions of the Model

Artificial freeze–thaw weathering tests in a laboratory may produce different degrees of weathering than natural freeze–thaw weathering due to factors such as saturation of rock pore water and the size of the specimens. Because the rocks in the study area are exposed to extreme temperature conditions and are close to the coast, compared to the freeze–thaw test, they will be influenced more by salt crystallization weathering due to the air temperature, wind and seawater. Due to these complex factors, it is very difficult to elucidate the relationship between freeze–thaw weathering in the laboratory and the nature environment. Assuming that the rock durability parameters including strength and stiffness of artificial weathering and natural weathering are similar under reasonable application of temperature variation; the extent of rock weathering in the laboratory freeze–thaw test can be also assumed to be closely related to the number of freeze–thaw cycles in nature. In cool and temperate climate regions at high latitudes, frequent freezing and thawing during the year can be the greatest cause of rock weathering [24].

The rock damage caused by freeze–thaw, in both damaged and undamaged rocks, mostly consists of granular disintegration and flaking as a result of mechanical stress leading to microfissures [83,84]. The typical damage process begins with volumetric expansion or ice separation caused by the meteorological environment. Generally, the inside of the rocks can become weakened by a single freeze–thaw cycle, but several cycles are required before signs of weathering or damage become visible [85]. This freeze–thaw damage is used to estimate the likelihood of freeze–thaw structural damage to buildings and civil super structures founded on rocks.

As shown in part one [27] of two companion papers, when the daily mean temperature was analyzed in the study area throughout the year, the authors found that freeze–thaw could occur at the rock surface tens (33–62 cycles) of times per year. These changes were mostly freeze–thaw in seasonally frozen ground, and rocks exposed to the surface underwent more freeze–thaw than rocks buried in the ground.

Future changes in the extent of weathering can be examined by looking at changes in the weather, based on the same logic as using past weather data to estimate the number of freeze–thaw cycles for previous weathering [18]. The general decrease in freeze–thaw cycles in northern regions could be due to the effects of rising temperatures in Europe since the 18th century, but there could also be changes in the number of freeze–thaw cycles due to increased urban heat island effects, which are especially important for buildings [11]. The predicted rise in global temperature during the current century means that freezing will decrease in most European regions, and diminished physical properties of rocks due to freeze–thaw will be less likely. Nevertheless, increased air temperatures in the Arctic Circle could lead to structural loss and collapse due to its effects on archaeological heritage sites preserved in the permafrost layer. Freeze–thaw cycles can cause landslides due to their effects on the foundations of structures. In addition, the frequency of freeze–thaw cycles for cultural heritage and the duration of changes in weathering can support administrators’ strategic decision-making regarding maintenance, repair and prevention of collapse of cultural heritage.

When freeze–thaw of the rock surface was analyzed using changes in daily minimum and maximum temperatures for 5 consecutive years in the study area, the minimum and maximum air temperature were found to change from below to above zero on 33–62 times per year. When estimating freeze–thaw of the rock surface, the authors assumed that natural freeze–thaw will have occurred similar to 33–62 times per year at the rock surface and at a depth of 25 mm, which was the maximum depth of the rocks tested in this study.

When $V_p$ of fresh granite decreases by half, the granite is graded as weathered rock [29]. The rocks in the present study had a baseline P-wave velocity of ≥ 5000 m/s, and so could be considered fresh. Considering the upper limit of $V_p$ for very strongly weathered rock category proposed by Iliev
[29], $V_p \leq 2000$ m/s is set as the threshold of becoming a very strongly weathered rock. Using Equation 4, the average number of freeze–thaw cycles to become very strongly weathered rock are calculated as 3551 cycles for Location A and 7704 cycles for Location B. The time required for natural freeze–thaw to cause the weathering grade to decline to very strongly weathered rock was 57–108 years for rocks from Location A and 124–233 years for rocks from Location B (Table 5). Because weathering of rock surfaces in the study area is mostly caused by changes in air temperature at short intervals, calculation of weathering attenuation using changes in physical properties ($A_{\text{abs}}$ and $V_p$) is even more meaningful.

| Location | P-Wave Velocity Decrease Per Cycle | Freeze–thaw Cycles of Variations up to 2000 m/s from Initial Value | Variation Years by 33 Freeze–thaw Cycles | Variation Years by 62 Freeze–thaw Cycles |
|----------|-----------------------------------|---------------------------------------------------------------|----------------------------------------|----------------------------------------|
| A        | 1.164 m/s                         | 3551 cycles                                                 | 108 years                              | 57 years                               |
| B        | 0.289 m/s                         | 7704 cycles                                                 | 233 years                              | 124 years                              |

The depth of freeze–thaw inside rocks shows diverse results, depending on the air temperature, solar irradiation, the direction lighting, rock water content and the interval between temperature measurements [6]. However, if changes in the freeze–thaw depth inside rocks were tested with varying persistence of air temperature, which is the largest factor in weathering except for freeze–thaw variables, the authors anticipate that the cumulative freeze–thaw weathering attenuation at a rock depth of 25 mm [27] could be rapidly and accurately calculated according to the persistence of air temperature and the relationship between artificial weathering and natural weathering could be analyzed more precisely. In addition, because it will be possible to logically measure the durability and limits of use of structures such as historical monuments, roadside riprap, railway subgrade, pipelines, built heritage and buildings, appropriate times and durations of structural maintenance and repair could be determined. In particular, by extending the durability of structures to freeze–thaw damage, it would improve the sustainability of the present state of structures.

7. Conclusions

Correlation analysis of physical parameters of freeze–thaw weathering induced rocks collected from Ny-Ålesund region of Norway was conducted in this study. From the analysis, prediction of future physical properties’ changes resulting from freeze–thaw weathering and estimation of remaining time of rock weathering grade change is possible. The followings are key findings from this study:

1) Among the physical parameters considered in this study, water absorption and P-wave velocity are effective parameters for estimation of rock weathering due to freeze–thaw actions. The rock weathering degree due to freeze–thaw cycles is highly dependent on rock mineralogy composition considering rock mineralogy differ from location to location. Further research is necessary to examine the effect of rock mineralogy on rock freeze–thaw weathering.

2) High correlation between water absorption and P-wave velocity with increasing freeze–thaw cycles enables indirect estimation of remaining time of weathering grade estimated freeze–thaw cycles from the changes of regional air temperatures.

3) We proposed equations to predict the progression from fresh rocks in the study region to weathered rocks and made calculations using these equations. Freeze–thaw weathering of rocks from Location A was predicted to take $\geq 3551$ cycles and of rocks from Location B was predicted to take $\geq 7704$ cycles. Thus, the weathering duration for rocks from Location A was 191–358 years and for rocks from Location B was 159–298 years. The time for the weathering grade of the rocks to be weathered rocks as a result of natural freeze–thaw was 57–108 years for rocks from Location A and 124–233 years for rocks from Location B.
4) The developed predictive equations make it possible to rapidly and accurately predict rock weathering, in order to logically measure the structural durability and limits of use of structures containing rocks. Therefore, these equations will help to determine appropriate times and durations of structural maintenance and repair, improving the sustainability of the current state of structures. However, further studies are needed on the production of spatiotemporal information related to variation in rock physical properties in broad regions and on the effects of past climate change trends on rock weathering.

**Author Contributions:** Conceptualization, K.P. and D.K.; methodology, K.P.; validation, B.Y.L. and K.L.; investigation, K.P., B.Y.L. and K.L.; resources, B.Y.L.; data curation, K.P. and K.L.; writing—original draft preparation, K.P. and D.K.; writing—review and editing, D.K.; visualization, K.L.; supervision, D.K. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was supported by the National Research Foundation of Korea Grant from the Korean Government (MSIT; the Ministry of Science and ICT) (NRF-2016M1A3A1901769; KOPRI-PN20081) (Title: Circum-Arctic Permafrost Environment Change Monitoring, Future Prediction and development Techniques of useful biomaterials; CAPEC Project), Industrial Facilities & Infrastructure Research Program (IFIP) funded by Ministry of Land, Infrastructure and Transport of Korean government (19IFIP-B089075-06;19IFIP-B089084-06; KOPRI-PN19110) and Incheon National University Research in 2019–2020.

**Acknowledgments:** The authors acknowledge the support by the National Research Foundation of Korea, the Ministry of Land, Infrastructure and Transport of Korean government and Incheon National University, Korea.

**Conflicts of Interest:** The authors declare no conflict of interest.

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