Frost resistance of natural stones – a case study from Finland

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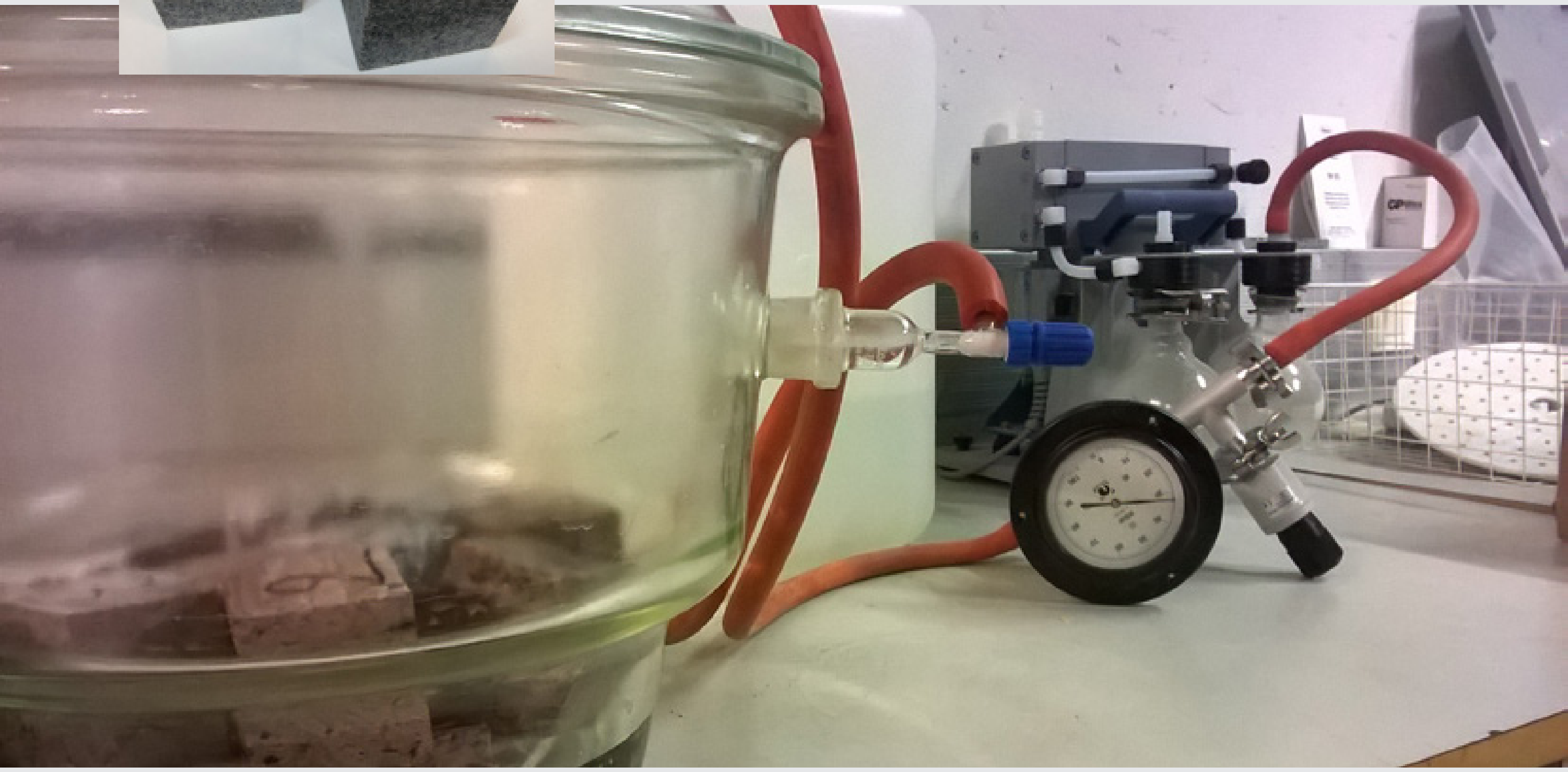

Frost resistance of natural stones – a case study from Finland

Nike Luodes, Heikki Pirinen, Rossana Bellopede and Olavi Selonen

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Frost resistance of natural stones – a case study from Finland

YHTEENVETO: Luonnonkivien pakkaskestävyydestä

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Front cover. Determination of open porosity.
Photo: Nike Luodes. Small photo: Olavi Selonen.
Kansikuva. Avoimen huokoisuuden määritys.
Kuva: Nike Luodes. Pikkukuva: Olavi Selonen.

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CONTENTS

1 INTRODUCTION

Good frost resistance is one of the essential properties of a building material, especially in the cold Nordic climate conditions. Freeze-thaw testing procedure is an artificial weathering process, simulating changing weather by fluctuating the temperature in cycles above and below zero with the presence of water or solutions. It is performed in laboratory and used for forecasting the weathering resistance of a material in use. Mechanical and physical properties of the material are measured before and after the freeze-thaw cycles. See, e.g. Siegesmund & Snethlake (2014).

Based on laboratory tests, according to several authors, e.g. De los Ríos et al. (2005), Delgado (2005), Martínez-Martínez et al. (2013), Freire-Lista et al. (2015a), Freire-Lista et al. (2015b), the main effect of a freeze-thaw weathering of natural stones in presence of salt solution is enlargement of cracks. This will influence the surface resistance to other weathering agents (increased deposition of dust and increased biological growth by action of organic acids), affecting the mineral composition of the rock and by physical interaction increase swelling (Wierzchos & Ascaso 1996, Lee & Parsons 1999, Chen et al. 2000).

Panova et al. (2014) showed that in some cases the material in historical buildings can show visual weathering as increased roughness and deposition of dust. Physical tests indicated increase of porosity, and the material's structure had been affected by light chemical weathering enhanced probably by biological activity (Panova et al. 2014) (see also Chapter 4). During site inspections performed in Finland on historical buildings in the cities of Kuopio, Savonlinna, and Helsinki, Luodes et al. (2014) also found out that, e.g. mechanical cleaning of the façades can increase porosity and the amount of cracks on stone surface.

Durability of the material in use will also be affected by future climate conditions since studies on climate change scenarios highlight the fact that within the next hundred years, there will be warmer climate, increasing the biological activity (including mosses, fungi, and lichens), and there will be more freeze-thaw cycles compared to present in Finland (Kaslegard 2011).

Recently, research on frost behaviour of concrete has been performed in Finland (Kuosa et al. 2013, Ferreira et al. 2014, Ferreira et al. 2015,) while only a few studies have been done on natural stone building products (e.g. Luodes 2007). Natural stone standards and testing in general in the Nordic countries has been described, e.g. by Mesimäki et al. (1984), Mesimäki (1997), Luodes et al. (2005), Luodes (2010), Schouenborg (2011), Sjöqvist et al. (2017), Kuula (2018), and Selonen et al. (2018).

In this study, we evaluate the freeze-thaw resistance of Finnish natural stones in cold climate in presence of de-icing salt (sodium chloride) and discuss the possible correlation between laboratory's accelerated decay and site weathering. Our study aims to understand the changes in the material caused by the combined action of salt and frost by the means of:

- changes in strength, including the use of Schmidt hammer (a non-destructive portable rebound test that can be further used on buildings)
- changes in open porosity, in number of cracks, and in density by physical testing and thin section analysis
- changes in ultrasonic pulse velocity (UPV) (for reference to non-destructive tests that can be performed on site).

The results would help in comprehending the mechanism of weathering and forecasting material durability on site, also affected by maintenance actions, allowing the producers to improve the final product for better performance. Parts of the study have been previously reported by Luodes et al. (2017).

2 MATERIALS AND METHODS

The materials tested in this study included all the main commercial natural stone qualities in Finland (approx. 60 pcs.). They are mainly silicate rocks and can be found on https://www.suomalainenkivi.fi/

en/finnish-natural-stones/. Rock types and codes are shown in App. 1. For these materials, frost resistance was tested according to the EN 12371, and its effects were correlated to fresh material properties by testing density, porosity, flexural strength, and compressive strength, determined according to the European standardized tests as shown in Table 1 as a) group.

In order to study the durability of the material in more detail, a representative selection of Finnish materials was chosen for performing research. The materials were selected so that they would represent the different natural stone types in Finland: granites, schists, and soapstones. Limestones and foreign materials were also added to the weathering tests in order to evaluate visible changes. For this set of representative materials standardized and non standardized methods were applied. Procedures used in site investigations by Luodes at al. (2014) were applied in order to allow a correlation with the results obtained on site. Methodologies are listed in Table 1 as b) group.

The skid resistance and the abrasion resistance, performed according to the European standardized tests (Table 1 c) group), were carried out in order to evaluate the properties of safety and durability of the material in use, and to deepen the knowledge of the materials under study.

3 TEST METHODOLOGIES

All the tests were performed in the Geological Survey of Finland, except for the UPV test, which was done in the Politecnico di Torino in Italy. Site tests in Luodes et al. (2014) were performed in cooperation by the two research entities.

Table 1. Performed tests in the study.

Taulukko 1. *Tutkimuksessa tehdyt testit.*

Standard	**Test method**
a) Standardized tests performed on all the materials in the study. Standardisoidut testit kaikille materiaaleille.	
SFS-EN 12371	Determination of frost resistance, 56 cycles performed with 1 % NaCl according to national specifications - Pakkasenkestävyyden määrittäminen
SFS-EN 12372	Natural stone test methods – Determination of flexural strength under concentrated load - Taivutusvetolujuuden määrittäminen
SFS-EN 1926	Natural stone test methods – Determination of uniaxial compressive strength - Puristuslujuuden määrittäminen
SFS-EN 1936	Determination of real density and apparent density, and of total and open porosity - Tiheyden ja suhteellisen tiheyden sekä huokoisuuden ja avoimen huokoisuuden määrittäminen
b) Tests performed on a selected representative set of materials. Valikoitujen materiaalien testit.	
SFS-EN 14579	Natural stone test methods. Determination of sound speed propagation. Ultraääninopeuden tutkimus.
Schmidt hammer	Indirect strength test. Schmidt-kimmovasaratesti.
CBI internal procedure (*)	Thin section analysis of the crack frequency and features – Instruktionen utförd av Brander och Döse_2014-09-08. Ohuthietutkimus CBI:n mukaan.
c) Standardized set of tests performed to evaluate the properties of the material for future use. Muut standardisoidut testit.	
SFS-EN 14157	Natural stones – Determination of abrasion resistance - Kulutuksenkestävyyden määrittäminen
SFS- EN 14231	Natural stone test methods – Determination of the slip resistance by means of the pendulum tester (on polished surfaces) - Pinnan karheuden määrittäminen heiluritestillä

(*) CBI - Swedish Cement and Concrete Research Institute

3.1 Frost resistance

The frost resistance was performed in accordance with the EN 12371, with 56 cycles of frost in air 6 h (≤-8 °C ≥-12 °C) and thaw in salt water (1 % NaCl) 6 h (≥+5 °C ≤+20 °C). Before performing the freezing cycles, the specimens were saturated in the solution of water and salt. At the end, the specimens were dried to constant mass at 70 °C.

3.2 Apparent density and open porosity

The test was done according to the EN 1936. Six specimens of dimensions 50 x 50 x 50 mm were dried to constant mass, weighted, placed under vacuum for two hours and slowly immersed in water. After 24 hours, the specimens were weighted under water and in air. The density was measured and the open porosity was calculated. See, cover photo.

3.3 Flexural strength

The test was performed according to the EN 12372. Ten specimens of dimensions 50 x 60 x 300 mm were dried at 70 °C until constant mass was reached. The load was applied at a uniform rate following the scheme as shown in Fig. 1. The specimens were brought to rupture, the maximum load was recorded, and dimensions measured. The flexural strength was calculated. Generally, the test is run perpendicular to the foliation planes on the stones that present anisotropies.

3.4 Compressive strength

The test was done according to the EN 1926. Batch of six or even more specimens of dimensions 70 x 70 x 70 mm were dried until constant mass and were measured in three directions. The specimens were loaded uniaxially until rupture (Fig. 2). Even if six samples is the minimum required by the test, larger sample was needed when the material showed higher natural heterogeneities in order to obtain a more representative average value. Compressive strength was calculated. The test can be run perpendicular or parallel to possible foliation planes.

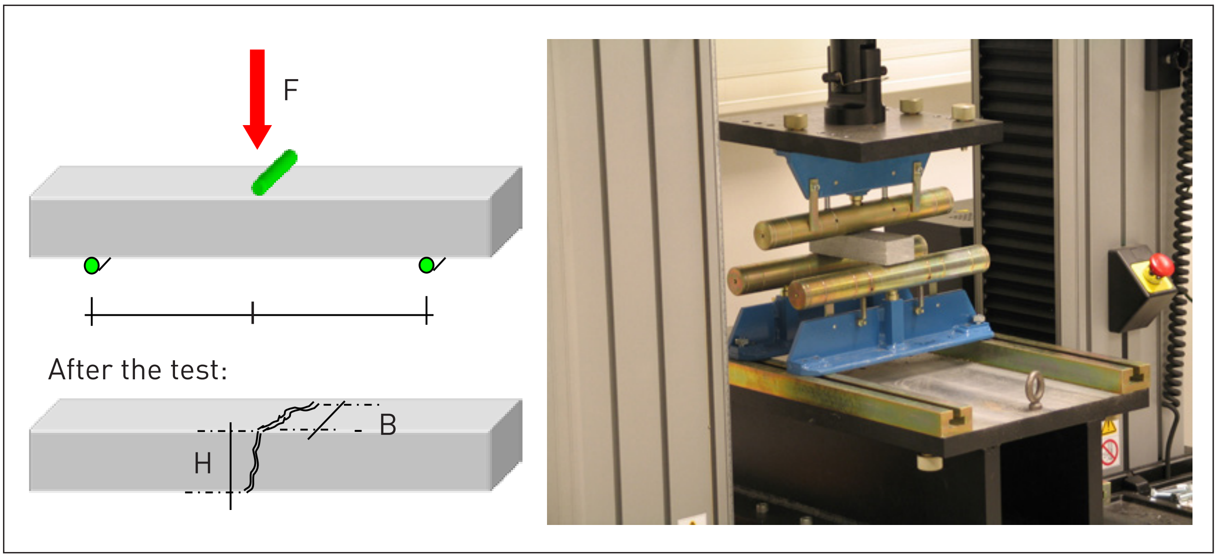

Figure 1. Determination of flexural strength under concentrated load according to the EN 12372. I = distance between the supporting rollers. F = load. B = width of the specimen adjacent to the plane of fracture. H = thickness of the specimen adjacent to the plane of fracture. The flexural strength Rtf is calculated as: 3Fl/2BH2 (MPa).

Kuva 1. *Taivutusvetolujuuden määritys EN 12372 mukaisesti. I = näytettä kannattavien tukien etäisyys. F = kuorma. B = näytteen leveys murtokohdan lähellä. H = näytteen paksuus murtokohdan lähellä. Taivutusvetolujuus Rtf lasketaan 3Fl/2BH2 (MPa).*

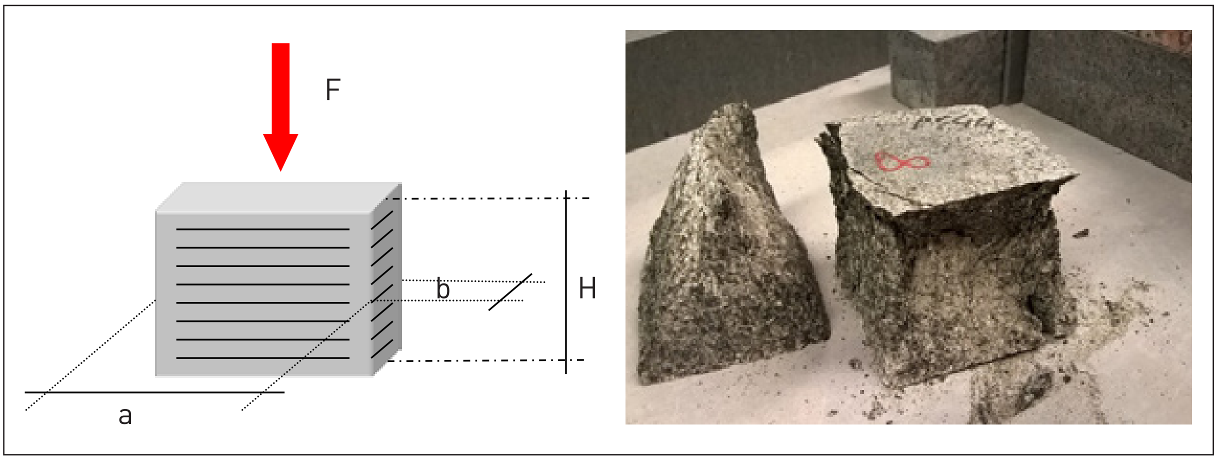

Figure 2. Determination of compressive strength according to the EN 1926. F = load. a, b, H = the three directions of measurement. The compressive strength R is calculated as: F/(a*b) (MPa).

Kuva 2. *Puristuslujuuden määritys EN 1926 mukaisesti. F = kuorma. a, b, H = kolme mittaussuuntaa. Puristuslujuus R lasketaan F/(a*b) (MPa).*

3.5 Determination of sound speed propagation

The ultrasonic pulse velocity (UPV) could represent a reference data for further estimation of stone on building sites. It was evaluated as speed propagation because it is a factor more used on site, compared to attenuation (cf. Cerrillo et al. 2014). Higher velocities can indicate soundness and continuity of the material, whereas slower velocities may indicate material with increased amount of cracks.

The UPV test was performed according to EN 14579 (2005). Direct and surface measurements were taken on the samples in order to evaluate direct and indirect waves. Differences in the velocity of the sound are possible weathering effects. Indirect measurements were performed keeping on place the transmitter and moving the receiver of defined steps (Fig. 3A). Direct measurements were done positioning the transmitter and received on opposites faces of the sample and measuring the fastest wave between the two. Direct waves were measured from the long and short direction of the specimens (Fig. 3B).

Specimens were dried to constant mass at 70 °C before performing the test. Tests were done on fresh material and on the same samples after 56 cycles of frost salt (Fig. 4).

The UPV tests were performed in the Politecnico di Torino in Italy by the third author, using a signal generator and receiver of a Pundit (Portable Ultrasonic Non-destructive Digital Indicating Tester) that is sending and receiving a wave, or train of impulses through the material to be tested. The Pundit is sending the analogical signal to a digitizer NI USB 5133 that sends the digital signal to an oscilloscope installed on a PC for visual evaluation of the waves. The aim is to assess the weathering level of the stone. The data collected can contribute to create a bibliographic reference to evaluate the level of weathering of stones on site.

The transducers used were conical on the surface measurements while the direct measurements were performed with flat transducers with a nominal frequency of 50 kHz (Bellopede 2006, Luodes et al. 2014).

3.6 Schmidt hammer test

Schmidt rebound hammer (Fig. 5) test can be used to evaluate the weathering state of rocks in

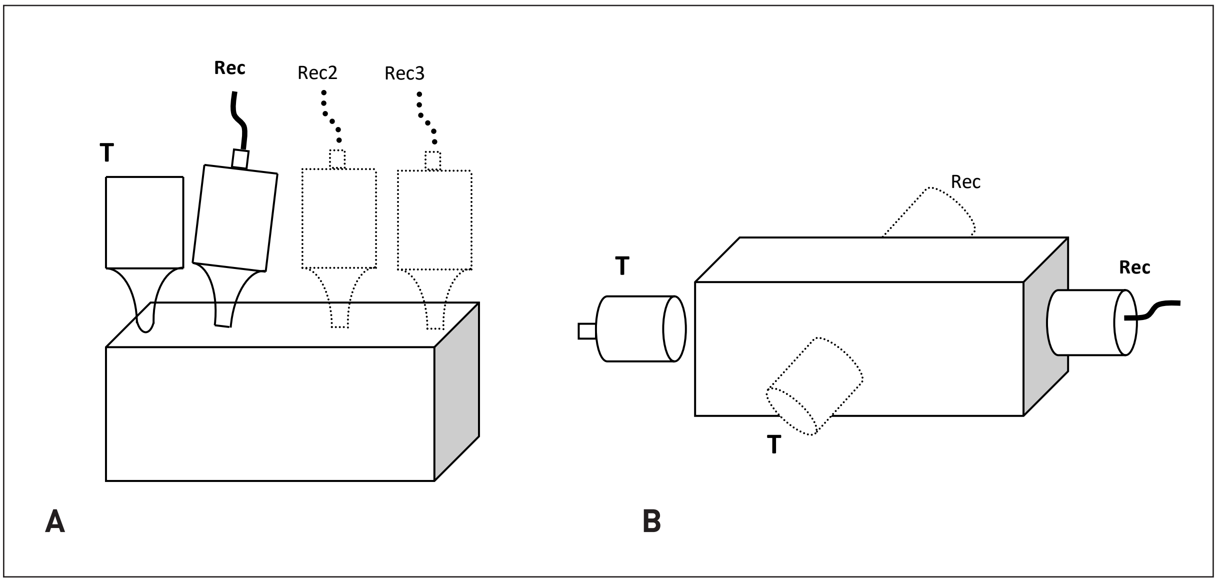

Figure 3. A.,B. Ultrasonic pulse velocity (UPV) test scheme. See text for explanation.

Kuva 3. *Ultraäänipulssin nopeuden mittausjärjestely.*

Figure 4. Ultrasonic pulse velocity (UPV) testing. Photo: Rossana Bellopede.

Kuva 4. *Ultraäänipulssin nopeuden mittaus. Kuva: Rossana Bellopede.*

Figure 5. Schmidt rebound hammer instrument in testing position. Photo: Nike Luodes.

Kuva 5. *Schmidt-kimmovasaratestijärjestely. Kuva: Nike Luodes.*

historical stone monuments and buildings as well as the durability of rocks (e.g. Hashemi et al. 2018).

Schmidt hammer tests were performed using a SADT Model HT225A hammer, performing three set of measurements of a chosen sample from the fresh and weathered material. Each set of measurement were composed by five horizontal rebounds per point, evaluating the average on the sample. The aim was to assess the surface weathering, also possible surface cracks, chipping, or rusting of the minerals. The test were performed keeping the instrument perpendicular to the vertically placed material (Fig. 5), as it had been used in previous site investigations on building walls by Luodes et al. (2014).

3.7 Crack frequency

Freeze-thaw cycles affects the material structure by increasing the frequency of cracks (Freire-Lista et al. 2015a, Freire-Lista et al. 2015b), which is relevant as the formation of cracks can allow, e.g. colonization by biological activity that in local points can concentrate organic acids, weakening the surface structure of the stone.

Optical microscope using Leika microscope and magnification up to 50x was used to perform the first evaluation of cracks in thin sections.

Scanning electron microscope (SEM) was used in some cases to measure the dimension of the cracks (Fig. 6A), but the picture of the material got did not allow to distinguish open and accessible cracks from closed ones. In this case, the section of 15 mm x 25.5 mm was divided into five vertical sections and 17 horizontal measuring lines, and a total length of 255 mm in one direction and 127 mm in the other direction was tested. The results can also be affected by sample preparation and by natural variations of the material.

Optical fluorescent microscope Zeiss Axio Imager A1 was used for counting open cracks (Fig. 6B). Thin sections of approx. 20 mm x 35 mm were prepared with addition of a fluorescent substance. Methodology adopted was based on the one used in the Swedish Cement and Concrete Research Institute CBI for crack frequency. The methodology aims to distinguish material that might suffer weathering from those who might not suffer. The methodology consisted of the count of vertical and horizontal cracks on the thin section along a line of 100 mm in each direction along an imaginary grid. Results are expressed as cracks/mm, and 40x magnification was used. The procedure also evaluate the presence of intergranular cracks

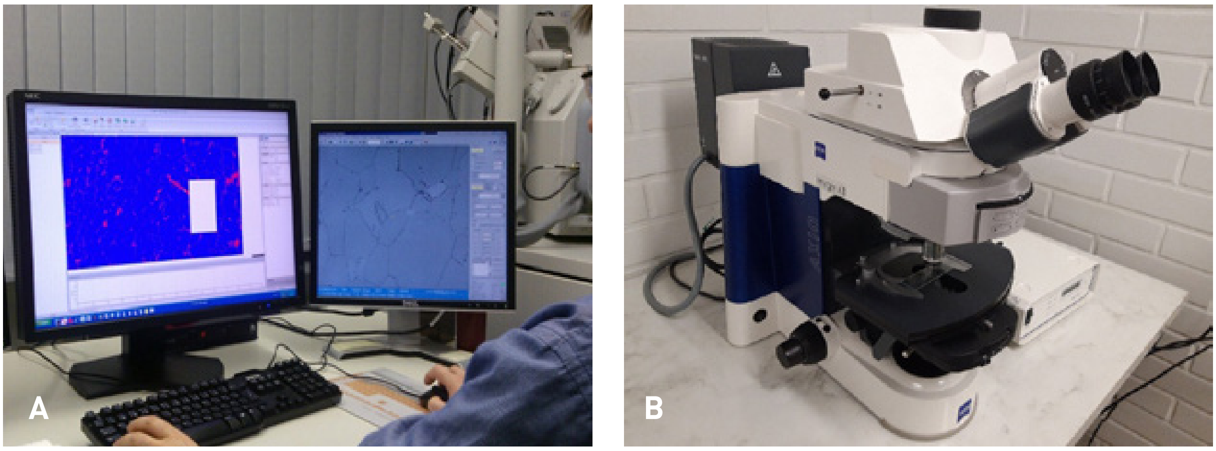

Figure 6. A. Analysis at the Scanning Electron Microscope (SEM). Photo: Nike Luodes. B. Optical fluorescent microscope. Photo: Akseli Torppa. Equipments in the GTK Mintec unit in Outokumpu.

Kuva 6. *A. Pyyhkäisyelektronimikroskooppi (SEM). Kuva: Nike Luodes. B. Optinen fluoresenssimikroskooppi. Kuva: Akseli Torppa. GTK, Mintek Outokumpu.*

that run along grain boundaries (grain boundary cracks), transgranular cracks that cross over two or more mineral grain, and intragranular cracks that are found inside mineral grains, sometimes with a clear relation to cleavage.

3.8 Slip and abrasion resistance

The *slip resistance* test was performed according to the EN 14231 (Fig. 7A). In the dry test, the specimens were kept dry and the test was performed in dry conditions, while in the wet test, the specimens were immersed in water at 20 °C for more than two hours and the test was performed in wet condition. The position of the pendulum tester was controlled adjusting the bubble level, and the zero of the apparatus was calibrated. The specimen were placed, and the height of the pendulum arm was controlled. In the dry test, the pendulum was released and the value on the scale was read. In the wet test, the surface of the stone was spread with water in order to get the surface slippery, then the pendulum was released and the value on the scale was read.

The *abrasion resistance* test was done according to the EN 14157 (Fig. 7B). The specimen was placed against a rotatory wheel and in between was released corundum sand. The wheel rotated 75 times and after that, the width of indentation abraded during the test was measured while the specimens were painted to enhance the contrast for reading the results.

4 RESULTS AND DISCUSSION

Luodes (2009) tested the level of weathering of different Finnish and foreign natural stones (diabases, granites, gneisses, and limestones) reaching 48 cycles at -12 °C temperature, reaching

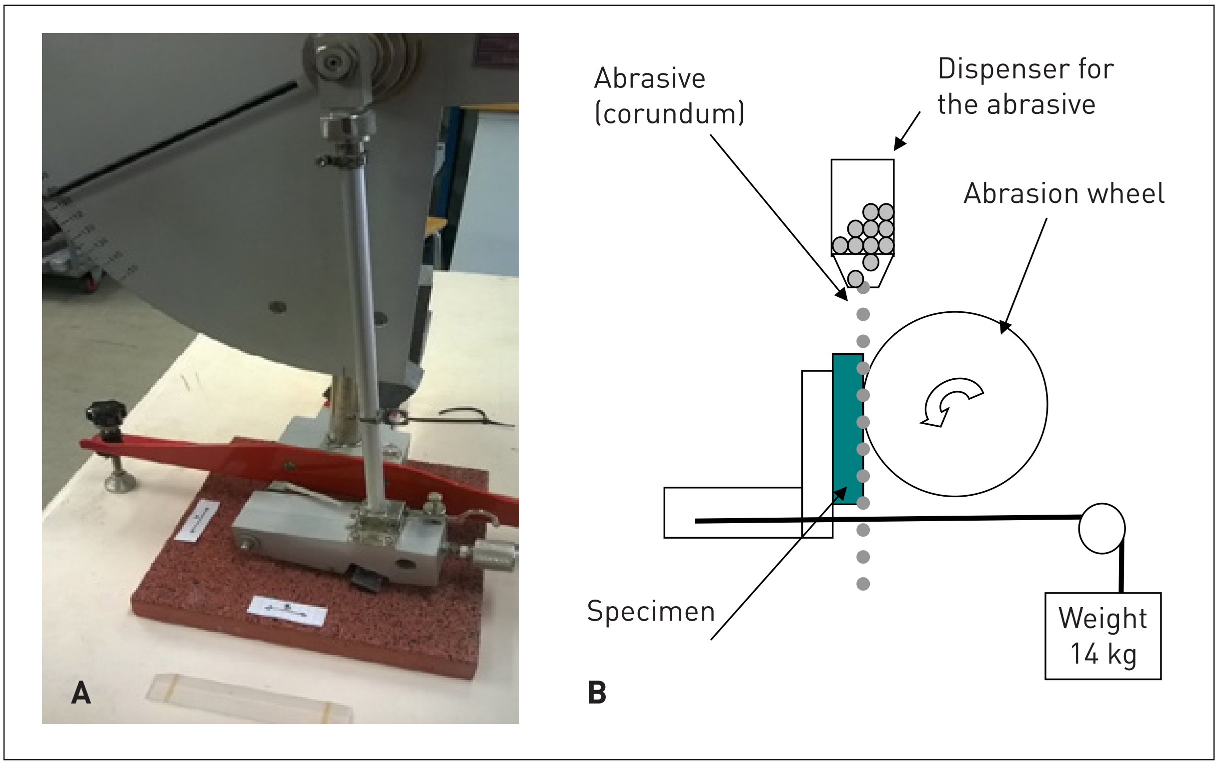

Figure 7. A. Determination of slip resistance according to EN 14231. Photo: Nike Luodes. B. Determination of abrasion resistance according to the EN 14157.

Kuva 7. *A. Pinnan karheuden määritys EN 14231 mukaisesti. Kuva: Nike Luodes. A. Kulutuskestävyyden määritys EN 14157 mukaisesti.*

56 cycles at (-18±2) °C, and reaching 100 cycles at -17 °C in water and in a salt solution. There, as in this study, none of the hard stones tested showed any visual change during tests while limestone showed detachments.

During the study by Luodes (2009), the materials showed a higher decrease of flexural strength after 100 cycles, but for several hard rocks, the loss of flexural strength caused by weathering was small compared to the variation caused by natural heterogeneity of the material itself. Fifty cycles have also been considered relevant for showing deterioration as loss of elastic properties, e.g. by Ruedrich et al. (2011). The European standard had evolved from 48 cycles to 56 also based on these experiences. On the previously listed bibliography, several freezing tests have been performed reaching 100 or 200 cycles, and in the studies of Martínez-Martínez et al. (2013), Freire-Lista et al. (2015a), and Ruedrich et al. (2011), for example, the effects of freeze-thaw on granites are visible later than the 56 cycles performed.

Moreover, in Luodes (2009), materials with porosity lower than 0.5 % and water absorption lower than 0.5 %–1 % showed to be durable. This was not directly transposable to limestone and materials that present a schist structure as slates as these might behave differently during freeze thaw cycles in the long run.

Dimension of the pores affect the durability during the freeze-thaw cycles. Water imprisoned into smaller pores freeze at lower temperatures compared to the one that is into bigger pore sizes, around 10 nm size, and in a material might be present at the same time pores with liquid and frozen water (Chena et al. 2004, Lindqvist et al. 2007, Ruedrich et al. 2011). Enough strong saturation can cause frost damages and considering that capillarity is enhanced by pore dimensions, increasing with smaller size, moving the water at a deeper level into the material (Bell 1993, Takarli et al. 2008), the presence of small interlocked pores can determine the freeze resistance. Solid body (structure and interlocking of crystals) and pore space have been pointed out by Ruedrich et al. 2011 as parameters that effect stress development caused by freeze-thaw cycles. Studies show that a total porosity below 0.5 % measured by SEM represents good frost resistance in pure water and salt solution (Lindqvist et al. 2007). In certain stones, larger pores can allow the draining of the water, and the porosity can be less relevant in the deterioration mechanism. Still some soft, low dense, schistose materials can be affected by freeze-thaw because of other processes of deterioration in act (Wessman 1997).

Physical tests performed according to standardized tests are not so accurate for evaluation of porosity compared to those performed with microscope, but are some basic easy tests to evaluate the compactness of a rock. From the data collected by Luodes (2009), materials with water absorption lower than 0.5–1 % and porosity lower than 3 %, except for the limestones for which water absorption and porosity did not correlate, endured freeze-thaw cycles. Low porosity (<1 %) increasing durability was also seen in studies on hard rocks and sandstones by Hale & Shakoor (2003) and Momeni et al. (2015).

This is anyway not a term to define durability of the rock. It is not directly transposable to limestone and materials that present a schist structure as slates or gneisses as these might behave differently during freeze-thaw cycles in the long run as also visible from studies performed on dolomites, gneisses and sandstone (Rusin et al. 2015). Martinez et al. (2015) showed that tests performed on 102 samples of carbonates subjected to 100 freeze-thaw cycles reaching -20 ºC indicated lower durability of materials with open porosity >10 % (see, also Pápay & Török 2018). Materials that didn't endure the tests in the long term showed granular disaggregation and loss of internal cohesion.

The temperature reached in the freeze-thaw cycles is also affecting the durability, and the freezability of water into nano and micro pores. Studies on concrete have shown that reaching, and going lower than -20 °C, and increasing the freezing time would affect the penetration of frost within the pores (Ferreira et al. 2014).

Artificial weathering is an accelerated weathering that might not correspond to site conditions.

Performances of natural stone might be different on site compared to the laboratory standardized tests. Studies performed in environment affected by salt mist have shown that granites on historical buildings do not present anymore the original characteristics, however still preserving their mechanical function (Baptista-Neto 2006). Accelerated weathering and its effects on the structure of the material is assessed through variation of flexural and compressive strength and can be evaluated also through variation of modulus of elasticity according to the standard. Generally, here the loss of strength is evaluated. Creation of cracks and changes in porosity are visible by microscopic evaluation, and the decrease of velocity in sound speed propagation test.

4.1 Flexural and compressive strength

Most of the tested materials in this study showed a variation of strength between fresh and weathered material lower than 20 %; a percentage defined by the reference standard to discriminate the freeze resistance of a material. Only three of the materials showed a higher variation as visible from graph in Fig. 8.

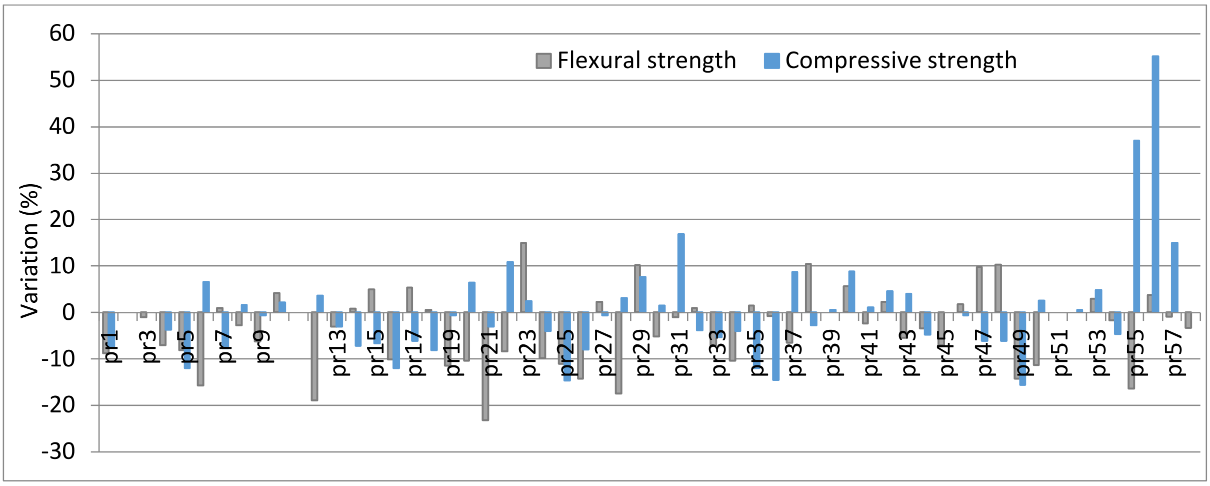

Figure 8. Percentage variation of flexural and compressive strength.

Kuva 8. *Puristuslujuusmittausten (sininen) ja taivutusvetolujuusmittausten (harmaa) prosentuaalinen vaihtelu.*

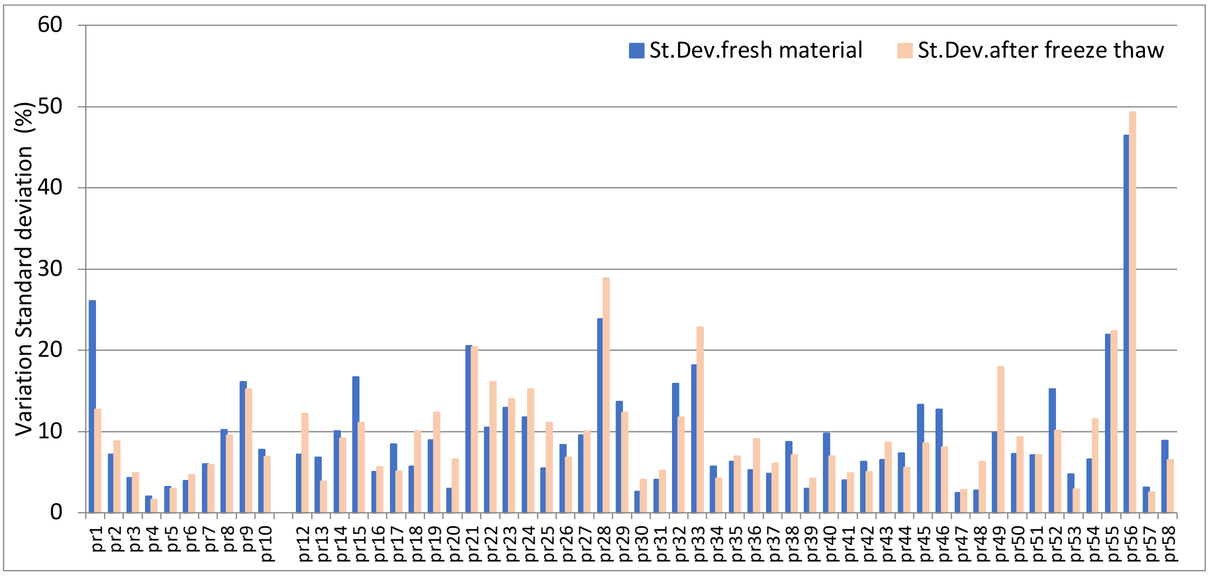

Figure 9. The rate of variation of the standard deviation for flexural strength before and after the freeze thaw cycles.

Kuva 9. *Keskihajonnan vaihtelu taivutusvetolujuusmittauksissa ennen jäädytys-sulamissyklejä (sininen) ja niiden jälkeen (oranssi).*

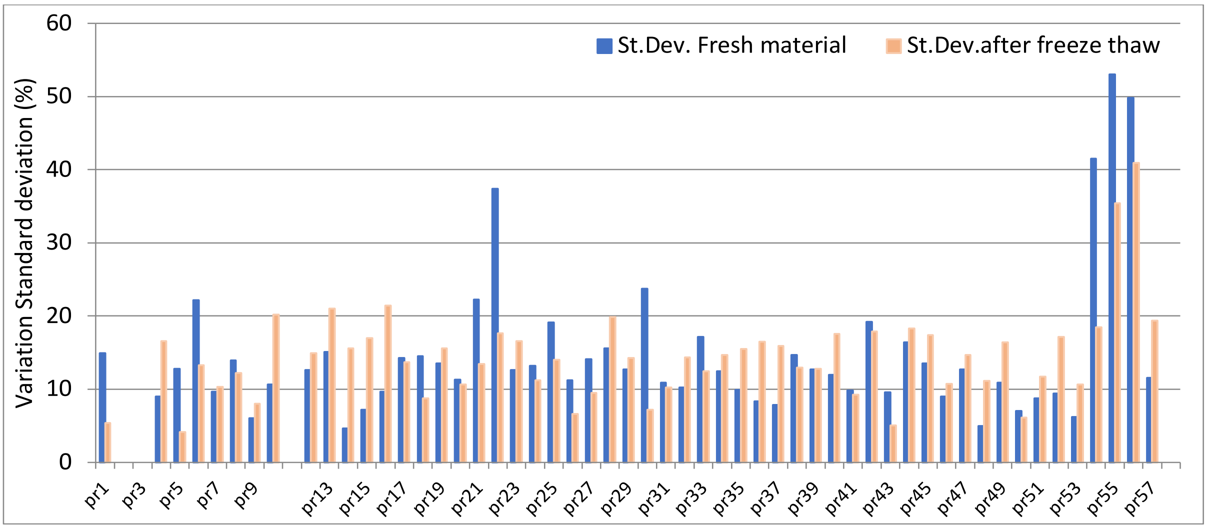

Figure 10. The rate of variation of the standard deviation for compressive strength before and after the freeze thaw cycles.

Kuva 10. *Keskihajonnan vaihtelu puristuslujuusmittauksissa ennen jäädytys-sulamissyklejä (sininen) ja niiden jälkeen (oranssi).*

The variations have not only been loss of strength, but also increase of strength after freeze-thaw cycles (Fig. 8). Sometimes freeze-thaw results are higher compared to fresh material. This is most probably due to natural variation of geological and mineralogical properties of the material that gives a stronger effect compared to the one caused by weathering.

Flexural strength has been more reliable in homogeneity of results compared to compressive strength and, in fact has given lower standard deviation within single batch of materials. This is due to the fact that compressive strength is strongly affected by small variations of planarity.

In the Figs 9 and 10 are shown the standard deviations compared to the relative average strength of the material, calculated as follow for each material:

(Standard deviation (MPa)/average strength (MPa))*100

Standard deviation can be used to show the error as “result ± standard deviation”, in this case it can be seen that for flexural strength half of the material show ±10 %, and most of it show ±10 % regarding the compressive strength. One third of the material even reach 20 % of variation in compressive strength, showing that a loss of 20 % after frost is within the error of the material tested and it might not be due to laboratory weathering effects alone.

4.2 Schmidt hammer test

Small weathering effect might be seen in the Schmidt hammer results for some materials, but in general the average loss was low as visible from the graph of the Fig. 11.

The materials generally showed a small decrease of rebound after the salt frost cycles except for two cases where most probably the results have been affected by the natural mineralogical variations of the material. The Schmidt test is evaluating the strength in a punctual way, and for highly heterogeneous or coarse-grained rocks, the results might differ because of the strength of the single minerals. In our study, the strength of more than one mineral of the stone was evaluated, and the precision in choosing similar minerals before and after the freeze thaw cycle might affect the result.

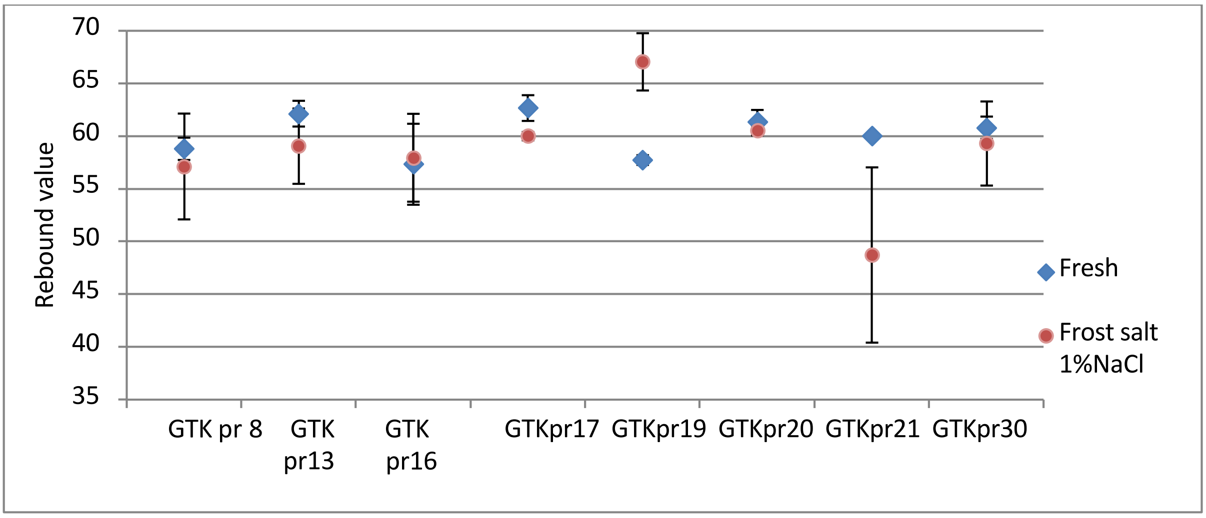

Figure 11. Schmidt rebound values of tests on fresh and weathered samples.

Kuva 11. *Schmidt-kimmovasaratestin arvoja tuoreista (sininen) ja jäädytys-sulamissyklien läpikäyneistä (punainen) näytteistä.*

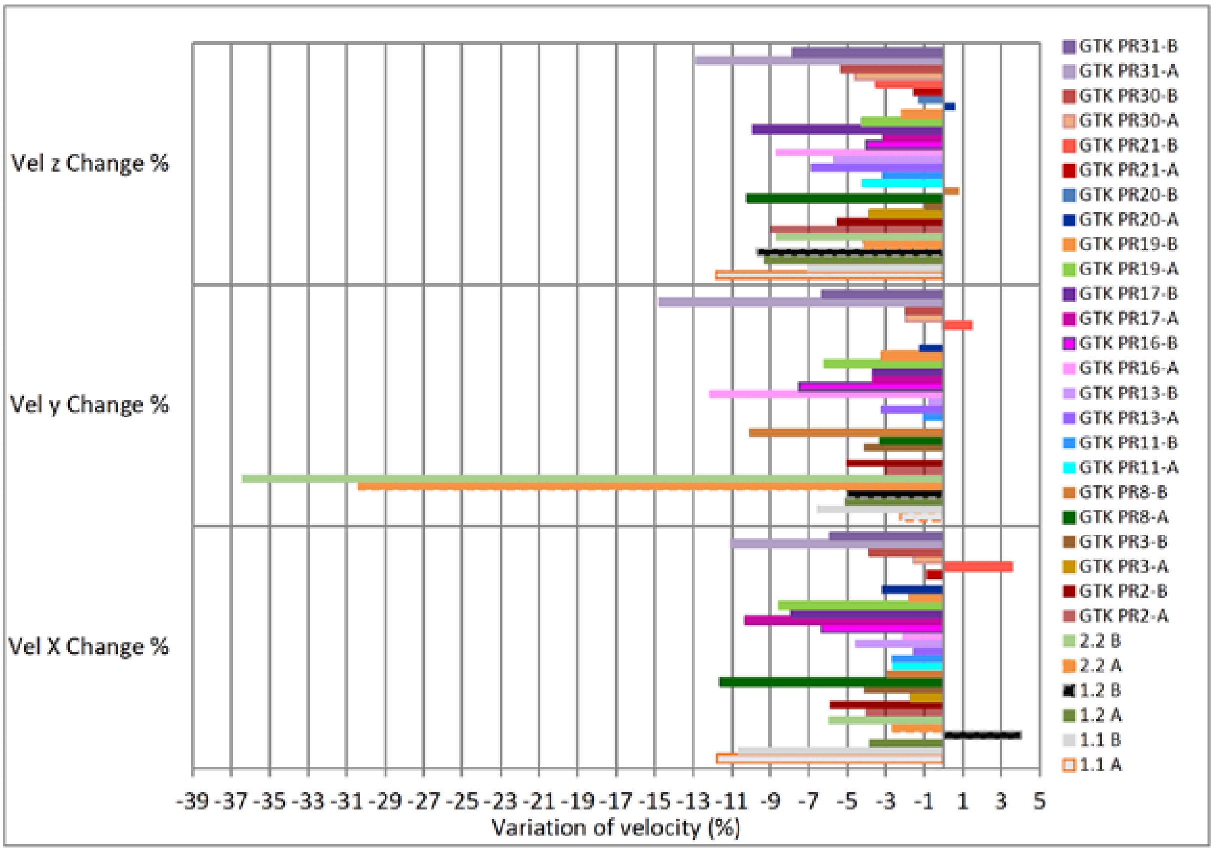

Figure 12. Variation of ultrasonic pulse velocities after weathering cycles.

Kuva 12. *Ultraäänipulssin nopeuden vaihteluita jäädytys-sulamissyklien jälkeen.*

4.3 Ultrasonic pulse velocity (UPV) measurements

Mechanical properties were indirectly evaluated with the UPV measurements as it is a method that shows efficacy in picturing decay (Ruedrich et al. 2011, Momeni et al. 2015, Hashemi et al. 2018).

Changes of velocities between fresh material and weathered one are shown in the graph of Fig. 12. Most of the materials show a decrease of velocity after the weathering cycle, with the higher for soapstones (coded 1.1, 1.2, 2.2) and the lowest for diabase. Each sample had two specimens A and B. Changes in velocities are also effected by uncertainties connected to the natural mineralogical and geological variation of the material.

Fig. 13 shows a comparison between the ultrasonic pulse velocities averaged for each material compared to the flexural strength of the material.

Ultrasonic pulse velocity was obtained by averaging along the three directions the results of the P-waves, and averaging the two specimens tested. Specimens of Pr20, diabase, and Pr21, quartzite, had a bigger change in flexural strength after frost cycles, compared to the changes within the UPV (Fig. 14). The diabase showed consistency of measurements between the two methodologies: high speed and high strength, being a compact homogenous material. The fact that ultrasonic pulse velocity was not diminished, it is an evidence that it is a durable material and loss of flexural strength might be caused by natural heterogeneity of the sample. Results performed on specimen Pr21 might have been affected by foliation. Other measurements show that a loss of flexural strength correspond to a loss of speed, meaning that a slight weathering had occurred in the material. These aspects can also be seen in the diagram of Fig. 14, where the variation of strength against those of speed after frost cycles are compared. The variation are calculated as (Strength after frost-Strength on fresh material)/Strength on fresh material, and (average UPV after frost-average UPV on fresh material)/average UPV on fresh material. Specimen Pr17, a medium-grained granite, shows that there was a deviation between the flexural strengths affected by mineral structure.

4.4 Crack frequency

After the mechanical tests, it was visible that some of the materials endured the weathering cycles without changes, e.g. diabase. At microscopic

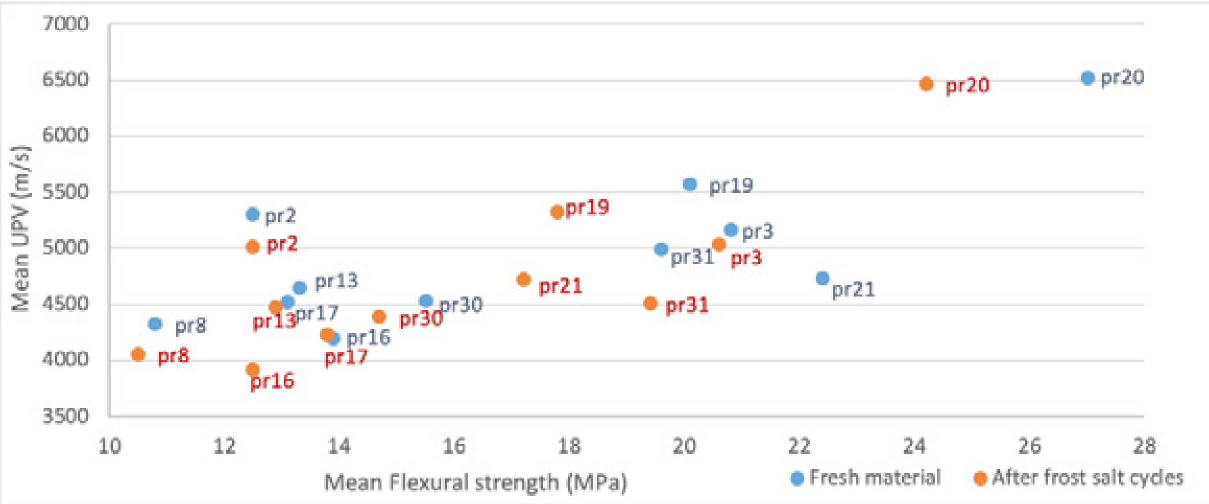

Figure 13. Comparison of average ultrasonic pulse velocity with flexural strength. Soapstone and PR11 was not tested for flexural strength after frost cycles, hence omitted from the graph.

Kuva 13. *Ultraääninopeuden keskiarvojen vertailu suhteessa taivutusvetolujuuteen (sininen=tuore materiaali, punainen/oranssi= jäädytys-sulamissyklit läpikäynyt materiaali). Vuolukiven ja PR11:n taivutusvetolujuutta ei testattu jäädytys-sulamissyklien jälkeen, joten ne puuttuvat kaaviosta.*

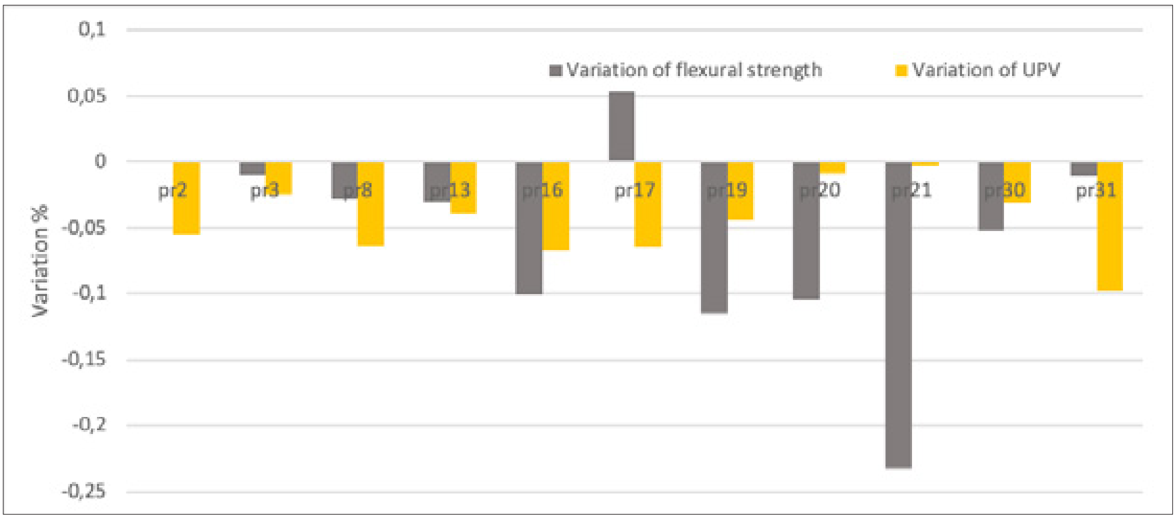

Figure 14. Comparison of variation of ultrasonic pulse velocity and flexural strength before and after frost cycles. See text for explanation.

Kuva 14. *Ultraäänipulssin nopeuden (keltainen) ja taivutusvetolujuuden (ruskea) vaihteluiden vertailu ennen jäädytys-sulamissyklejä ja niiden jälkeen.*

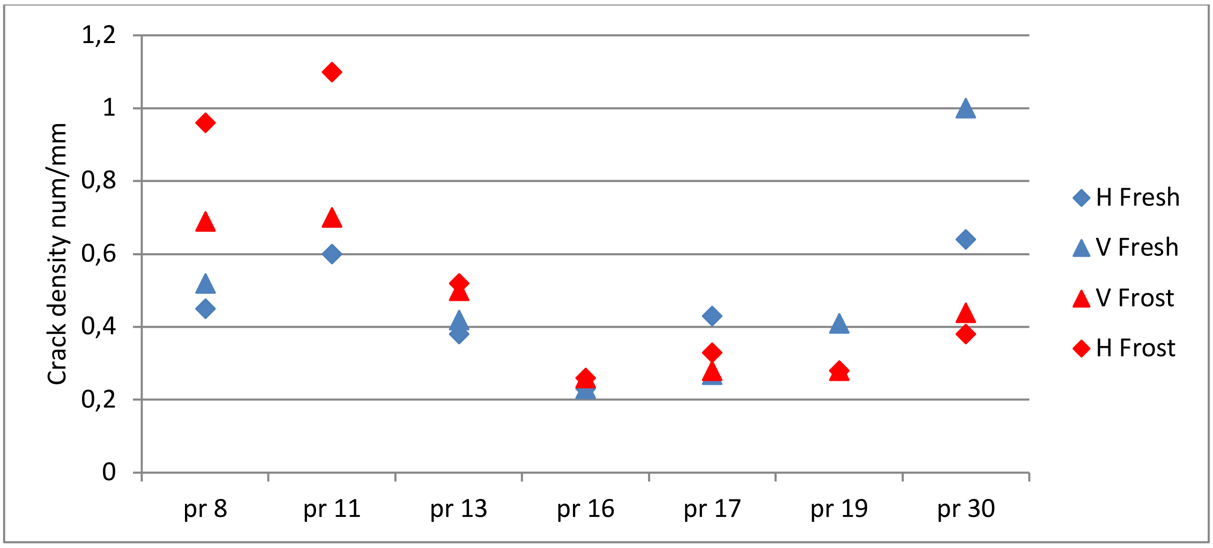

Figure 15. Results of the frequency crack count in two direction of thin section. H=horizontal, V=vertical.

Kuva 15. *Rakotiheys näytteessä pystysuoraan (V) ja vaakasuoraan (H). Sininen = tuore materiaali, punainen = jäädytys-sulamissyklien läpikäynyt materiaali.*

level, performing the linear crack frequency at 40x on fluorescent stained sections, this was also confirmed as there was not visible a weathering effect. Scanning at 200x was done when needed. Some sections of materials that had shown variation of physical properties and that presented visible weathering at microscopic level were chosen to be evaluated for crack frequency by counting at the optical microscope with fluorescent light.

The cracks counted were fine cracks (0.01–0.1 mm wide) and microcracks (<0.01 mm wide) (as defined by Kuosa et al. 2013), and they could be intergranular (developed along the crystals edge), intragranular (within crystals), or transgranular (through the mineral grains) (as defined by Davis et al. 2013).

All the values were under 1.2 cracks/mm that according to Sousa et al. (2005) represent sound material (<1.5 crack/mm) (Fig. 15).

The analysis showed that in some samples there was creation of a subhorizontal fracture within the first mm of thickness exposed to weathering. There was an increase of microcracking along the sample and also in some cases visible vertical fractures even reaching two mm depth.

The freeze-thaw cycles effected the creation of intergranular microcracks, increasing the number of original crack typologies instead on adding new typologies. Several materials had already certain level of original natural weathering and cracking.

Analysis performed with the SEM at 200x magnification (Fig. 16) showed the form of the crystals and the cracks. The process could not be authomatized. Evaluation of open or closed cracks was difficult to perform as it was based on the material of filling, in this case of resin, and the resin was present also elsewhere on the section. The microscope allowed visual analysis and punctual investigation, and it was possible to picture and save the whole section for further examination at the computer. Fig. 16 shows intragranular, intergranular, and transgranular cracks.

Analysis performed with the fluorescent microscope (Fig.17) was an easy and fast method for counting the cracks. The fluorescent substance bring in evidence the fractures. Studying of the images was immediate and the test was performed without the support of the computer.

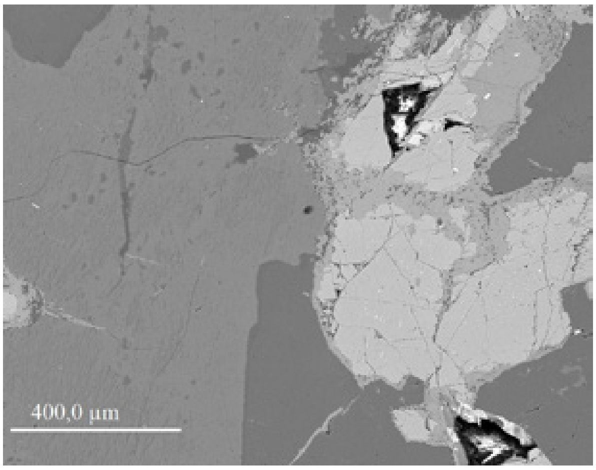

Figure 16. Image from the analysis at magnification 200x performed with the Scanning Electron Microscope (SEM). See text for explanation.

Kuva 16. *Pyyhkäisyelektronimikroskooppikuva (SEM). 200-kertainen suurennos.*

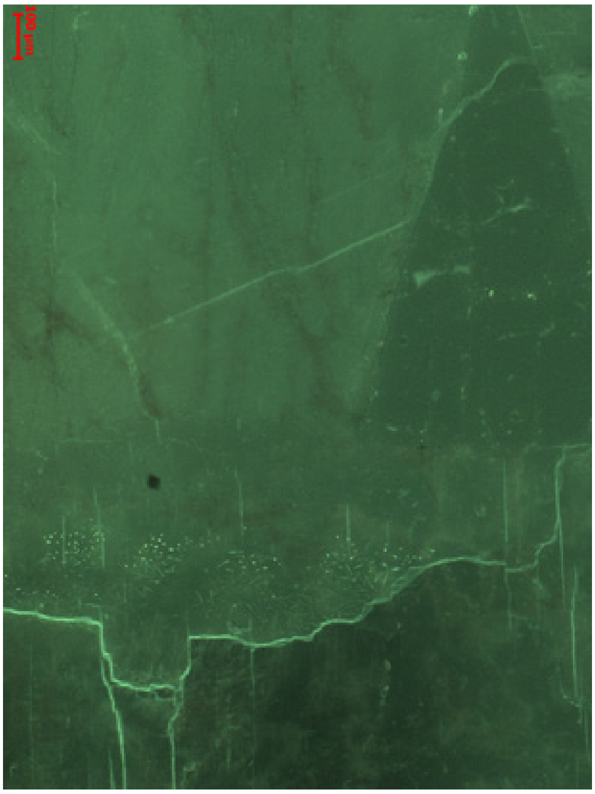

Figure 17. Image from the analysis performed at the fluorescent microscope (40x magnification).

Kuva 17. *Fluoresenssimikroskooppikuva. 40-kertainen suurennos.*

Table 2. Results of apparent density and open porosity of the materials researched, before (upper values) and after (lower values) weathering cycles.

Taulukko 2. *Tutkittujen materiaalien tiheyksien ja avoimen huokoisuuden arvoja ennen jäädytys-sulamissyklejä (ylemmät lukuarvot) ja niiden jälkeen (alemmat lukuarvot).*

	pr2	pr3	pr8	pr11	pr13	pr16	pr17	pr19	pr20	pr21	pr30	pr38
Mean value density – Keskiarvo tiheys m (kg/m^3)	2810	2730	2640	2840	2640	2670	2650	2670	3060	2630	2620	2630
Mean value porosity – Keskiarvo avoin huokoisuus (%)	0.5	0.4	0.5	0.4	0.3	0.4	0.4	0.2	0.1	1.9	0.5	0.3
Mean value density – Keskiarvo tiheys m (kg/m^3)	2840			2860			2640	2670	3040	2660	2620	2630
Mean value porosity - Keskiarvo huokoisuus (%)	0.6			0.3			0.3	0.2	0	0.6	0.5	0.3

4.5 Apparent density and open porosity

Apparent density and open porosity were tested according to European standards on all of the materials. Tests were performed after the weathering cycles on the set of the selected materials in order to evaluate the effects after freeze-thaw cycles.

After 56 cycles, the density had variations lower than 1 % for all the materials examined, and open porosity showed changes caused by natural material variation more than by the weathering effects (Table 2). However, the change might not be yet visible as the newly born cracks might not be yet interconnected, allowing the absorption of more water (Ruedrich et al. 2011).

4.6 Correlation between site performance and laboratory performance

The porosity as well as the density were tested also on site material and results are listed for each building in Luodes et al. (2014).

Site materials of Luodes et al. (2014) showed that even if the surface could had been affected by surface weathering, vegetative growth and deposition of chemicals and dusts, the deeper parts of the cores still preserved sound qualities. The materials used on site and tested were hard silicate rocks and their densities ranged between 2650 and 2850 kg/m^3; typical densities for the rock types. The average density was 2700 kg/m^3 and the average open porosity was 0.39 %, varying from 0.17 % of a diabase or gabbro to 1 % of a rock affected by calcareous deposition in marine environment.

The Schmidt hammer test and the UPV test were used on site as described by Luodes et al. (2014) on hard rocks, and were used in this study in order to evaluate possible correlations between the laboratory tests (fresh material) and the site weathering, and to improve site characterization methodology.

On site, there are several factors that affect the results: surface finishing, the impossibility to reach the material from all the sides, and the humidity and temperature conditions that cannot be ruled (Bellopede 2006, Kartashev et al. 2008).

Performing the laboratory tests, it is visible from Table 3 that all the materials have Schmidt rebound values included between 58 and 64. The granites show heterogeneity of results, but the values are however generally very close and typical for hard silicate rocks.

Table 3. Values of Schmidt hammer test on fresh materials.
Taulukko 3. *Schmidt-kimmovasaratestin tuloksia tuoreelle materiaalille.*

Code	Rock type	Rebound value
Pr1	Granite	58
Pr2	Granite	56
Pr4	Granite	60
Pr5	Granite	60
Pr6	Granite	60
Pr8	Granite	59
Pr9	Granite	59
Pr12	Granite	59
Pr13	Granite	62
Pr14	Granite	60
Pr15	Granite	59
Pr17	Granite	63
Pr22	Granite	60
Pr23	Granite	60
Pr24	Granite	60
Pr25	Granite	60
Pr26	Granite	58
Pr27	Granite	60
Pr28	Granite	58
Pr29	Granite	58
Pr30	Granite	61
Pr31	Granite	60
Pr32	Granite	58
Pr33	Granite	60
Pr34	Granite	60
pr35	Granite	58
pr36	Granite	60
Pr37	Granite	62
Pr38	Granite	60
Pr39	Granite	60
Pr40	Granite	60
Pr41	Granite	64
Pr42	Granite	62
Pr45	Granite	58
Pr46	Granite	62
Pr48	Granite	64
Pr47	Granite	64
Pr49	Granite	62
Pr50	Granite	58
Pr51	Granite	60
Pr52	Granite	58

Code	Rock type	Rebound value
Pr3	Quartzite	58
Pr21	Quartzite	60
Pr7	Diorite	58
Pr10	Diorite	58
Pr16	Granodiorite	61
Pr18	Migmatite	58
Pr19	Migmatite	58
Pr11	Gabbro	58
Pr20	Diabase	61
Pr43	Gabbro	58
Pr44	Gabbro	58

Table 4. Values of Schmidt hammer on freeze-thawed materials.
Taulukko 4. *Schmidt-kimmovasaratestin tuloksia jäädytys-sulamissyklien läpikäyneille materiaaleille.*

	Fresh	St.dev.	Frost salt 1 % NaCl	St.dev.
GTKpr8 Granite	59	1,1	57	5,0
GTKpr11 Gabbro	59	1,1	57	5,0
GTKpr13 Granite	62	1,2	59	3,6
GTKpr16 Granodiorite	57	3,8	58	4,2
GTKpr17 Granite	63	1,2	60	0,4
GTKpr19 Migmatite	58	0,5	67	2,7
GTKpr20 Diabase	61	1,2	61	0,5
GTKpr21 Quatzite	60	0,0	49	8,3
GTKpr30 Granite	61	1,1	59	4,0

Table 5. Schmidt rebound and UPV values on buildings in Luodes et al. (2014).
Taulukko 5. *Schmidt-kimmovasaratestin ja ultraääninopeustestin arvoja Luodeksen et al. (2014) tutkimuksessa.*

Building	Schmidt rebound value	UPV value (m/s)
Niirala school, Kuopio	50–60	2500–2600
Lyceum, Kuopio	48–56	2800–3400
Art Museum, Kuopio	49–58	2293–2833
National Museum, Helsinki	42–56*	2700–3300**

*Higher values on the façade exposed to the south and higher variability on the façade exposed to the east. Values 45–56 were measured on the granite in the entrance to the inner yard of the museum.

**Exception of few blocks where the velocity was lower or higher.

The loss of strength visible from the Schmidt hammer for the samples tested after frost cycles show a loss of 2 or 3 points in general for granites (Table 4); higher variation are visible in migmatite and quartzite probably caused by natural heterogeneity of the material. Diabase endured the frost cycles without changes.

The results got on site with the Schmidt hammer test, showed generally a lower initial rebound values while performing the test on the same spot (Luodes et al. 2014). This might be due to the surface finishing of the material and to the surface weathering (Luodes et al. 2014). Schmidt rebound and UPV values for buildings in the study of Luodes et al. (2014) are shown in Table 5. In the laboratory tests in this study, there was no visible variation between first rebounds and later ones, probably because the specimens were sawn and did not present any detachable fragments.

While comparing the range of superficial velocity of S-waves collected in the laboratory tests on the fresh material and after freeze-thaw cycles (Table 6), except for few samples, possible decay caused by frost cycles is not visible. The ranges after frost cycles are very close to the fresh material. The range is between 2580–3815 m/s after the frost and 2660–3845 m/s for the fresh material. The range on site for the hard silicate rocks tested was between 2500 and 3300 m/s (Luodes et al. 2014). The highest speed was not reached on site, probably because of a certain level of decay, but the lowest speed detected on site was in the same range as the lowest speed measured on laboratory material, meaning the material still preserve characteristics similar to the original (Luodes et al. 2014).

The correlation between laboratory and the site performance is difficult to evaluate, as durability on site is affected by moisture content, temperature,

Table 6. Superficial velocity of S-waves on fresh material and after freeze-thaw cycles.

Taulukko 6. *S-aaltojen nopeuksia tuoreille (vas. sarake) ja jäädytys-sulamiskäsittelyn läpikäyneille materiaaleille (oik. sarake).*

	Velocity of S-waves, fresh material (m/s)	**Velocity of S-waves, material after freeze-thaw with salt (m/s)**
GTKpr2 Granite	3111	3015
GTKpr3 Quartzite	3388	3378
GTKpr 8 Granite	2662	2721
GTKpr11 Gabbro	3331	3255
GTKpr13 Granite	2905	2909
GTKpr16 Granodiorite	2639	2746
GTKpr17 Granite	2661	2581
GTKpr19 Migmatite	3331	3262
GTKpr20 Diabase	3845	3867
GTKpr21 Quarzite	3612	3815
GTKpr30 Granite	2880	2840
GTKpr31 Granite	3242	3047

thermal change, physical and mechanical actions to which the stone has to endure. The environmental conditions might have an impact on the material durability, including the biogenic actions, but the site inspections have indicated that material investigated in Finland has showed slow-decay processes (Luodes et al. 2014).

4.7 Validity of the test methodology for freeze-thaw treatment

Martínez-Martínez et al. (2013) showed that the number of cycles is not enough to visualize the changes given by freeze-thaw for granites. Ruedrich et al. (2011) showed that it is needed at least 50 cycles to notice effects, and Momeni et al. (2015) showed that for granitoids freezing down to -30 °C, the first signs of decay are visible after 50 cycles, and increase until the 300 cycles, lowering material properties in the long term.

The European standard is a compromise that should answer to all the materials, reaches to -18 °C, and considers 56 cycles, but allows to increase the number of cycles for research test. During this study, it was noticed that the methodology adopted, including 1 % NaCl and reaching to -18°C, might not result in showing enough strongly the decay, but on the other hand, the materials performed well on site as well.

Materials here were tested for freeze-thaw cycles according to the European standard. In Luodes (2009), the temperature reached -23 °C. The limestone did not show any flaking in the test when the cycles reached down to -18 °C, while in the test down to lower temperatures, flaking occurred after the first 25 cycles.

Changes in climate might increase the biological growth, which, as seen in the previous studies, can increase surface weathering, but might also diminish the lowest temperature reached, even if increasing passages through the zero.

5 CONCLUSIONS

The effect of freeze-thaw cycles on Finnish hard silicate natural stone materials is low. An initial weathering by increased intergranular cracking can be observed, as well as a slight decrease in the direct ultrasonic pulse velocity. However, the material could still be classified as sound. In comparison with properties tested in the laboratory (UPV, Schmidt, and porosity), site tests showed that surface weathering can occur, but deeper parts of the rock still present properties similar to the average fresh rock. The mineralogical differences between samples had more effect on the test results than the weathering cycles.

In certain conditions, the freeze-thaw method could not give a full picture of the long term durability of the stone material. The correlation between test performance on site and in laboratory is difficult, and it is therefore important to monitor and document site performance in order to better understand the material properties. Documentation of the performance of the material over time on site should become an important aspect of study as it gives actual knowledge of the long-term durability of the stone.

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YHTEENVETO: LUONNONKIVIEN PAKKASKESTÄVYYDESTÄ

Johdanto

Hyvä pakkaskestävyys on rakennusmateriaalien eräs keskeisimmistä ominaisuuksista, erityisesti pohjoisissa kovissa ilmasto-olosuhteissa.

Luonnonkivien pakkaskestävyyttä voidaan arvioida laboratoriossa ns. nopeutetulla rapautumistestillä, jossa lämpötilaa vaihdellaan sykleissä nolla-asteen ylä- ja alapuolelle veden ja/tai suolojen läsnäollessa. Suomessa testi tehdään standardin SFS EN 12371:n mukaan. Siinä suolan ja pakkasenkestävyys määritetään 56 jäädytys- ja sulamissyklillä. Ennen pakkassyklejä näytteitä on imeytetty 48 tuntia vesiliuoksessa, jossa on 1 paino-% suolaa (NaCl). Jokaiseen sykliin kuuluu jäähdyttäminen ilmassa 6 h (≤-8 °C ≥-12 °C) ja sulattaminen vedessä 6 h (≥+5 °C ≤+20 °C). Materiaalien mekaanisia ja fysikaalisia ominaisuuksia mitataan ennen jäädytys-sulamissyklejä ja niiden jälkeen. Tuloksista arvioidaan materiaalien pakkaskestävyyttä.

Ilmaston muuttumisen vaikutuksia on jo havaittu monissa kaupunkiympäristöissä. Tulevaisuuden ennusteisiin kuuluvat lämpötilan nousu, jäädytys-sulamissyklien lisääntyminen ja voimakkaammat tuulet sekä maa-alueilla että rannikolla aiheuttaen rapautumisefektien voimistumista ja etenkin rannikkoalueiden eroosiota. Myös bakteerien ja erilaisten kasvustojen odotetaan lisääntyvän lauhojen talvien myötä.

Tässä tutkimuksessa arvioimme suomalaisten luonnonkivien pakkasenkestävyyttä ym. testin avulla. Tarkastelemme miten kiven lujuus muuttuu suola-pakkaskäsittelyn jälkeen. Lisäksi selvitämme kiven avoimen huokoisuuden ja rakoilun muutoksia sekä ultraääniaaltojen nopeuden vaihteluja kivimateriaalissa.

Tutkimuksemme tavoitteena on karakterisoida kivimateriaalissa tapahtuvia muutoksia, jotka johtuvat suolan ja pakkasen yhteisvaikutuksesta. Tulokset auttavat ymmärtämään säävaikutuksen mekanismia ja ennustamaan materiaalin kestävyyttä käyttökohteessa muuttuvissa ilmasto-olosuhteissa.

Tutkimus

Tässä tutkimuksessa testattiin kaikki tärkeimmät suomalaiset kaupalliset kivilaadut (noin 60 kpl). Ne löytyvät Kiviportaalista suomalainenkivi.fi. Kivilaadut testattiin eurooppalaisten testimenetelmien mukaisesti (Taulukko 1). Testatut ominaisuudet olivat puristuslujuus, taivutusvetolujuus, tiheys, huokoisuus, kulutuskestävyys ja liukkaus. Pakkaskestävyys määritettiin näille kiville nopeutetulla rapautumistestillä EN 12371 standardin mukaisesti puristuslujuuden ja taivutusvetolujuuden muutoksena. Testausten tulokset löytyvät Kiviportaalista.

Tarkempiin pakkaskestävyyden selvityksiin valittiin ryhmä kivilajeja, jotka edustavat tyypillisiä suomalaisia luonnonkivityyppejä: graniitteja, liuskeita ja vuolukiviä. Näiden kivien pakkaskestävyyttä tutkittiin seuraavien menetelmien avulla:

- SFS-EN 14579 Natural stone test methods. Determination of sound speed propagation. P-aaltojen mittauksella karakterisoidaan materiaalin lujuutta, kiinteyttä ja ultraääniaaltojen nopeutta materiaalissa (Kuvat 3 ja 4). Ultraäänen nopeudet ovat suurempia ehyessä materiaalissa kuin rapautuneessa ja rikkoutuneessa materiaalissa. Tietoja voidaan käyttää tutkittaessa luonnonkiven ominaisuuksia rakennuksissa.
- materiaalin lujuuden määrittely Schmidt-kimmovasaratestillä (Kuva 5). Kimmovasaramittaus on menetelmä, jolla voidaan mitata luonnonkiven lujuutta rikkomatta itse materiaalia. Mittaustulos perustuu testivasaran takaisinkimmahduksen matkan mittaamiseen iskettäessä vasaralla kiven pintaan.
- rakojen määrän ja laadun mikroskooppinen tutkimus. Tutkimusvälineinä olivat optinen mikroskooppi, pyyhkäisyelektronimikroskooppi (SEM) ja fluoresenssimikroskooppi (Kuva 6).

Testit ja menetelmät on kuvattu Luvussa 3. Katso myös Taulukko 1.

Tutkimuksen rahoittajina olivat Rakennustuotteiden Laatu Säätiö sr, Kiviteollisuusliitto ry/yritykset ja Geologian tutkimuskeskus. Lukuun ottamatta Italian Politecnico di Torinossa tehtyä ultraäänitestiä, kaikki testit suoritettiin Geologian tutkimuskeskuksessa Kuopiossa.

Tulokset

Puristus- ja taivutuslujuuden muutokset

Suola-pakkassyklien vaikutusta kiven kestävyyteen määritetiin tuoreiden kappaleiden ja suola-pakkastestin läpi käyneiden kappaleiden puristus- ja taivutusvetolujuuden eroina. Kaikki mitatut erot olivat kolmea materiaalia lukuun ottamatta alle 20 % (Kuva 8). Testin läpäisyä varten referenssistandardissa määrätty kyseinen ero saa olla enintään ≤20 %.

Joskus puristus- ja taivutusvetolujuuden arvot olivat korkeampia suola-pakkastestin läpikäyneillä näytteillä kuin tuoreilla näytteillä (Kuva 8). Tämä johtuu todennäköisesti kivien luontaisesta geologisesta ja mineralogisesta vaihtelusta, joka vaikuttaa tuloksiin enemmän kuin varsinainen rapautuminen.

Taivutusvetolujuustestissä saadut tulokset vaihtelivat vähemmän kuin puristuslujuustestissä saadut. Tämä johtuu siitä, että puristuslujuusarvoihin vaikuttaa voimakkaasti testikappaleen pintojen tasaisuus. Jo pienelläkin poikkeamalla voi olla suuri vaikutus tuloksiin.

Schmidt-elastisuustesti

Schmidt-kimmovasaratestin tuloksissa saattaa näkyä pientä rapautumisen vaikutusta joidenkin materiaalien osalta, mutta yleensä keskimääräinen lujuuden aleneminen oli vähäistä (Kuva 11).

Takaisinkimmahdus näytti olevan yleensä hieman heikompi suola-pakkasjaksojen jälkeen paitsi kahdessa tapauksessa, joissa materiaalin luontainen geologinen ja mineraloginen vaihtelu on todennäköisesti vaikuttanut tuloksiin. Schmidtin elastisuustesti arvioi kimmokovuutta pistemäisesti ja karkearakeisten tai monimineraalisten kivien osalta tulokset saattavat vaihdella yksittäisten mineraalien kovuuden vuoksi.

Ultraääninopeuden muutokset

Tuoreen ja pakkaskäsitellyn materiaalin ultraääninopeuden erot on esitetty Kuvassa 12.

Suurimmalla osalla materiaaleista ultraäänen nopeus väheni suola-pakkaskäsittelyn jälkeen, eniten vuolukivessä ja vähiten diabaasissa. Nopeuden muutoksiin vaikuttivat myös materiaalien luonnolliset mineralogiset ja geologiset vaihtelut.

Rakoilun muutokset

Tutkimuksessa havainnoidut raot olivat ”hienoja rakoja” (0,01–0,1 mm leveitä) tai ”mikrorakoja” (<0,01 mm leveitä).

Jotkin materiaalit, kuten diabaasi, kestivät suola-pakkaskäsittelyn ilman rakoilun lisääntymistä. Yleensä kivissä todettiin rapautumiskäsittelyn jälkeen jonkin verran rakoilun lisääntymistä, mutta kaikki lasketut rakotiheydet olivat alle 1,2 rakoa / mm (Kuva 15), mikä edustaa ehjää materiaalia. Materiaalia pidetään ehyenä, jos rakotiheys on <1,5 rakoa / mm.

Tutkimuksessa todettiin, että pakkaskäsittelyn jälkeen joihinkin näytteisiin syntyi rapautumispinnan ensimmäisen millimetrin syvyydelle pinnansuuntaisia vaakasuoria rakoja kun taas toisiin näytteisiin saattoi syntyä rapautumispintaan nähden pystysuoria, enimmillään kahden millimetrin syvyydelle asti ulottuvia rakoja.

Tiheyden ja avoimen huokoisuuden muutokset

Tiheys ja avoin huokoisuus tutkittiin kaikista materiaaleista. Pakkaskestävyys selvitettiin tiheyden ja avoimen huokoisuuden muutoksena ennen ja jälkeen suola-pakkastestin valikoiduille kivityypeille.

56 rapautumissyklin jälkeen tiheyden muutokset olivat pienempiä kuin 1 % kaikilla tutkituilla materiaaleilla (Taulukko 2). Avoimen huokoisuuden vaihtelut johtuivat enemmän kivilaatujen geologi-

sista ja mineralogisista vaihteluista kuin rapautumiskäsittelystä (Taulukko 2).

Laboratorio- ja kenttätutkimusten korrelaatio

Tässä tutkimuksessa oli tarkoitus myös selvittää onko kivien laboratorio-ominaisuksilla (tuore materiaali) korrelaatiota kivien ominaisuuksiin rakennuksissa. Tutkimuksessa pyrittiin vertaamaan tietoa kiven rapautumisesta vanhoissa rakennuksissa ja rakenteissa tuoreen materiaalin ominaisuuksiin. Tässä tutkimuksessa käytettyjä Schmidtin elastisuustestiä ja ultraäänen nopeuden mittaamista käytetään myös rakennusten kivimateriaalien tutkimukseen.

Tutkimuksessa todettiin kuitenkin, että laboratorio- ja kenttätutkimusten korrelaation arviointi on haasteellista, koska kenttätuloksiin vaikuttavat useat tekijät, kuten esim. kiven pintakäsittely, mahdottomuus saavuttaa materiaalia kaikilta puolilta sekä kosteus- ja lämpötilaolosuhteet. Siksi on tärkeää seurata ja dokumentoida kivien suorituskykyä rakennuksissa, jotta materiaalin ominaisuuksia ja pitkän aikavälin kestävyyttä ymmärrettäisiin paremmin.

Ilmastonmuutos

Ilmastonmuutos saattaa lisätä biologisten kasvustojen määrää, mikä, kuten aiemmissa tutkimuksissa on todettu, voi lisätä kiven pinnan rapautumista. Toisaalta ilmastonmuutos saattaa nostaa alinta saavutettua lämpötilaa, vaikkakin samalla se voi lisätä lämpötilasyklien määrää nolla-asteen yli ja ali. Tämä asettaa myös tulevaisuuden haasteita rapautumistestille, jonka pitäisi ottaa huomioon erilaisten kivilajien lisäksi myös muuttuvat ilmasto-olosuhteet.

Johtopäätökset

Jäädytys-sulatusjaksojen vaikutus suomalaisiin koviin silikaattisiin luonnonkivimateriaaleihin on vähäinen. Mahdollinen rapautuminen voi näkyä lisääntyneenä mikrorakoiluna tai ultraääninopeuden laskuna, mutta materiaalia voidaan silti pitää ehyenä.

Kivimateriaalien luonnolliset mineralogiset ja geologiset vaihtelut ovat merkityksellisiä, sillä ne vaikuttivat tuloksiin enemmän kuin rapautumissyklit.

Materiaalien kestävyyden ymmärtämisen kannalta on tärkeää laboratoriotutkimusten lisäksi kenttätutkimuksin seurata ja karakterisoida kivien käyttäytymistä rakennuksissa. Materiaalin historiallisen käytön selvityksestä tulisikin tulla luonnonkiven kestävyystutkimusten olennainen osa, sillä historiatieto osoittaa miten kivi on käyttäytynyt käyttökohteessa, ja se antaa todellista tietoa luonnonkiven pitkän aikavälin kestävyydestä.

APPENDIX

Appendix 1. Rock types and codes in the study.

Pr1	Coarse-grained non-foliated granite with potassium feldspar megacrysts
Pr2	Coarse-grained non-foliated granite with potassium feldspar megacrysts
Pr3	Foliated, variegated medium-grained massive quartzite
Pr4	Fine and even-grained, non-foliated granite
Pr5	Fine and even-grained, non-foliated granite
Pr6	Medium-grained, slightly foliated granite
Pr7	Fine and medium-grained, non-foliated diorite with stripes
Pr8	Medium and coarse-grained non-foliated granite with potassium feldspar megacrysts
Pr9	Medium and coarse-grained non-foliated granite with potassium feldspar megacrysts
Pr10	Medium-grained, non-foliated diorite
Pr11	Medium-grained, non-foliated gabbro
Pr12	Coarse-grained, non-foliated granite with potassium feldspar megacrysts
Pr13	Fine-grained slightly foliated granite
Pr14	Fine and even-grained, non-foliated granite
Pr15	Coarse-grained, non-foliated granite with potassium feldspar megacrysts
Pr16	Coarse-grained, slightly foliated granodiorite with potassium feldspar megacrysts
Pr17	Medium-grained, non-foliated granite
Pr18	Medium and coarse-grained, foliated and variegated migmatite.
Pr19	Medium and coarse-grained, foliated and variegated migmatite.
Pr20	Fine and even-grained, non-foliated diabase
Pr21	Fine-grained, foliated sericite quartzite
Pr22	Coarse-grained, non-foliated granite with potassium feldspar megacrysts
Pr23	Coarse-grained, non-foliated granite with potassium feldspar megacrysts
Pr24	Coarse-grained, non-foliated granite with potassium feldspar megacrysts
Pr25	Coarse-grained, non-foliated granite with potassium feldspar megacrysts
Pr26	Coarse-grained, non-foliated granite with potassium feldspar megacrysts
Pr27	Fine-grained, even-grained, non-foliated granite
Pr28	Coarse-grained, non-foliated granite with potassium feldspar megacrysts
Pr29	Coarse-grained, non-foliated granite with potassium feldspar megacrysts
Pr30	Fine and even-grained, non-foliated granite
Pr31	Fine and even-grained, non-foliated granite
Pr32	Coarse-grained, non-foliated granite with potassium feldspar megacrysts
Pr33	Coarse-grained, non-foliated granite with potassium feldspar megacrysts
Pr34	Coarse-grained, non-foliated granite with potassium feldspar megacrysts
pr35	Medium and coarse-grained, non-foliated granite
pr36	Medium and coarse-grained, non-foliated granite
Pr37	Coarse-grained, non-foliated granite with potassium feldspar megacrysts
Pr38	Coarse-grained, non-foliated granite with potassium feldspar megacrysts
Pr39	Medium and even-grained, non-foliated granite

Pr40	Medium-grained non-foliated granite.
Pr41	Medium-grained non-foliated granite
Pr42	Fine-grained, slightly foliated granite
Pr43	Fine-grained non-foliated gabbro
Pr44	Medium-grained non-foliated gabbro
Pr45	Coarse-grained, non-foliated granite with potassium feldspar megacrysts
Pr46	Coarse-grained, non-foliated granite with potassium feldspar megacrysts
Pr48	Medium-grained, non-foliated granite
Pr47	Fine and even-grained, non-foliated granite
Pr49	Coarse-grained, non-foliated granite with potassium feldspar megacrysts
Pr50	Coarse-grained, non-foliated granite with potassium feldspar megacrysts
Pr51	Coarse-grained, non-foliated granite with potassium feldspar megacrysts
Pr52	Coarse-grained, non-foliated granite with potassium feldspar megacrysts
Pr53	Medium-grained granodiorite
Pr54	Fine-grained foliated phyllite
Pr55	Fine-grained foliated sericite quartzite
Pr56	Fine-grained foliated mica schist
Pr57	Fine and even-grained, non-foliated diabase

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