



Table 54. Characterisation of the sample E marble resistance, each 25 cycles of freeze/thaw

Resistance characterisation	Each 25 cycles of the freeze/thaw							
	28	46	74	102	150	174	202	216
Resist. to Compression (Mpa)	104.7	112.5	116.9	106.9	112.5	118.6	120.2	120.3
Water Absorption at PtN (%)	0.13	0.16	0.16	0.16	0.17	0.17	0.16	0.17
Open Porosity (%)	0.30	0.40	0.29	0.29	0.37	0.43	0.44	0.40
Volumetric Mass (Kg/m ³)	2656	2601	2656	2648	2650	2682	2676	2675
Resonance Frequency (HZ)	2127	1887	1717	1848	1980	2225	2283	2647
Ultrasonic Propagation Speed (x10 ⁻² m/s)	6.1	6.1	6.0	6.0	6.0	6.0	6.1	5.9
Thermal Shock	No visual remark							
Dynamic Modulus of Elasticity (x10 ⁹ N/mm ²)	4.3	3.3	2.8	3.3	3.7	4.8	5.0	6.7
Microscopic Observation	See report in annex							
Resistance to Flexural Strength under conc. Load (Mpa)	14.8	16.4	13.2	13.4	11.7	13.9	13.0	12.3

The Crystallisation tests were made in the beginning and after 216 cycles of freeze/thaw. The results obtained were the same, just tarnished appearance. But no colour or structural changes on the samples were noticed (see photo 1 and 2)

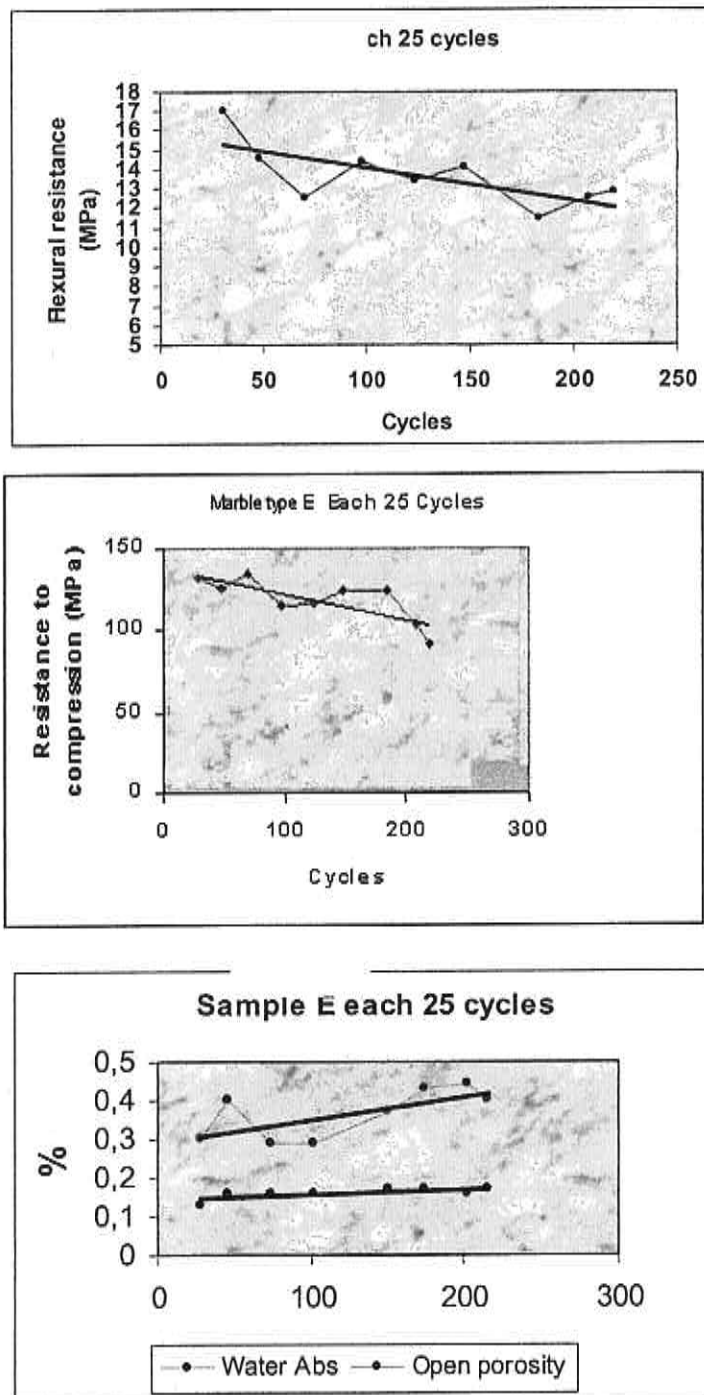
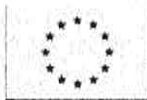


Figure 153. Interpretation of marble E test results.



It's a marble with highest mechanical resistance, to flexural and compression, and to freeze/thaw environments.

After 240 cycles of freeze/thaw, no visual alteration appeared, nor loss mass. The physical tests have given basically constant results, so it is possible to conclude that no alteration in the structure occurred, this is supported by the results obtained by microscopy (see report in annex).

3.12.4 Marble type K

Table 55. Initial characterisation of sample K (cut against)

Initial Characterisation	Sample K (cut against)	
	Average	Standard deviation
Resist. to Compression (Mpa)	79,6	7
Water Absorption at PtN (%)	0,05	0,01
Open Porosity (%)	0,15	0,00
Volumetric Mass (Kg/m ³)	2715	2
Resonance Frequency (HZ)	1748	-
Ultrasonic Propagation Speed (m/s)	6,5x10 ⁻²	-
Thermal Shock	No visual remark	-
Crystallisation Test	No alteration	
Dynamic Modulus of Elasticity (x10 ⁹ N/mm ²)	3,0x10 ⁹	-
Microscopic Observation	See report in annex	
Resistance to Flexural Strength under conc. Load (Mpa)	23,1	2,1

Table 56. Initial characterisation of sample K (cut in favour)

Initial Characterisation	Sample K (cut in favour)	
	Average	Standard deviation
Resist. to Compression (Mpa)	111,5	3,4
Water Absorption at PtN (%)	0,05	0,01
Open Porosity (%)	0,15	0,00
Volumetric Mass (Kg/m ³)	2715	2
Microscopic Observation	See report in annex	
Resistance to Flexural Strength under conc. Load (Mpa)	21,4	0,6

Table 57. Characterisation of the sample K marble resistance, each 25 cycles of freeze/thaw

Resistance characterisation	Each 25 cycles of the freeze/thaw								
	30	48	70	98	124	148	184	208	220
Resist. to Compression (Mpa)	132,2	125,1	134,6	114,3	115,6	123,0	123,9	102,6	92,0
Water Absorption at PtN (%)	0,10	0,11	0,13	0,12	0,13	0,13	0,13	0,15	0,13
Open Porosity (%)	0,25	0,30	0,35	0,26	0,33	0,31	0,28	0,25	0,31
Volumetric Mass (Kg/m ³)	2737	2716	2717	2709	2693	2711	2689	2689	2684
Resonance Frequency (HZ)	1920	2000	1974	1607	1712	1917	1942	1582	1712
Ultrasonic Propagation Speed (x10 ⁻² m/s)	6,2	6,3	6,2	6,2	6,2	6,2	6,2	6,2	6,1
Thermal Shock	No visual remark								
Dynamic Modulus of Elasticity (x10 ⁹ N/mm ²)	3,6	3,9	3,8	2,5	2,8	3,6	3,7	2,4	2,8
Microscopic Observation	See report in annex								
Resistance to Flexural Strength under conc. Load (Mpa)	17,0	14,6	12,5	14,4	13,4	14,1	11,5	12,5	12,8

The crystallisation tests were made in the beginning and at the end of 220 cycles of freeze/thaw. The results were generally, tarnished appearance and no loss mass.

The loss of material, during the initial characterisation test was of 0,25% and after the 220 cycles, was of 0%, this may be a consequence of no significant increase on the porosity and consequently of the water absorption.

It's possible to conclude that marble, when submitted to thermal variations, and in presence of salt mist, wasn't shown alterations.

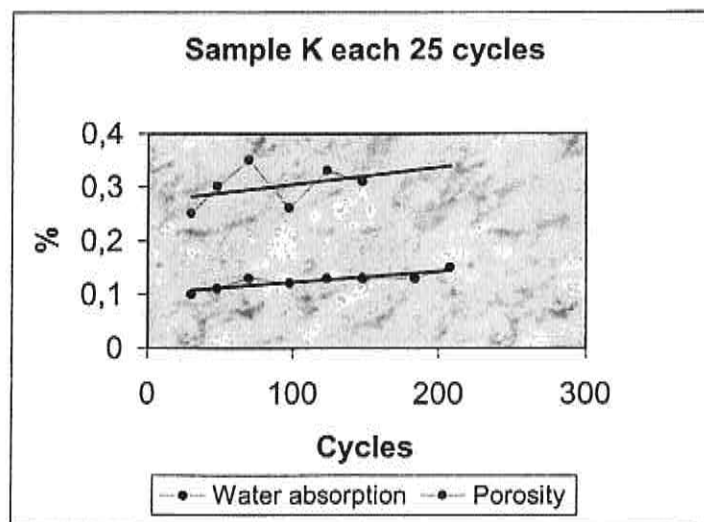
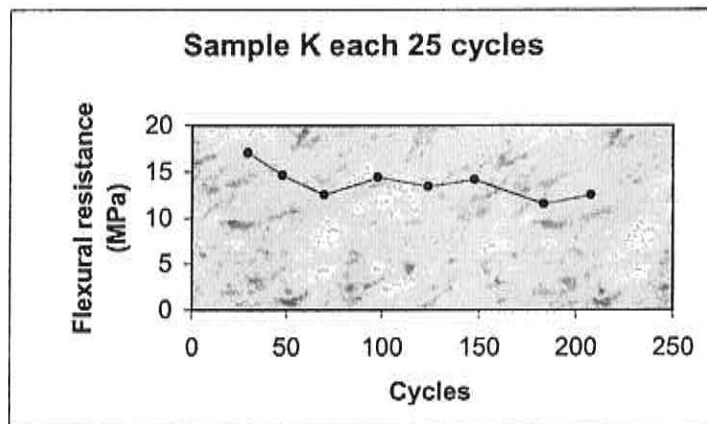
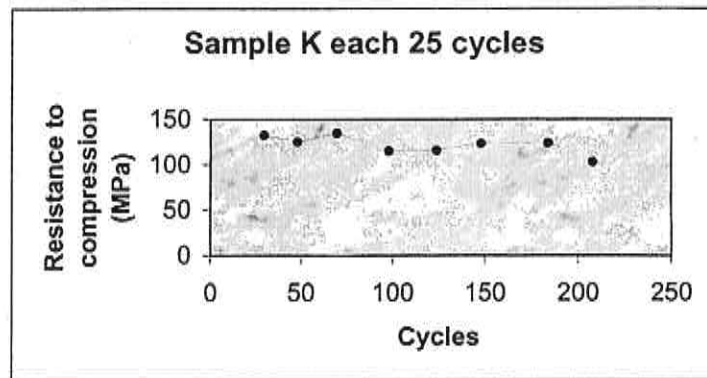


Figure 154. Interpretation of marble K test results.



According to the graphics, it's possible to conclude that the Italian marble sample K, is the most resistant sample of all the tested proposed samples for this project.

Thus, it can be said that in terms of physical and mechanical characterisation this marble presents a good behaviour when submitted to the temperature of freeze/thaw cycles, used in this project.

The interpretation of the compression and flexural resistance results, show that this marble doesn't present relevant alterations showing a slight decrease of resistance, although no conclusive.

Relatively to the absorption of water and open porosity the results also showed a certain tendency for the increase of the porosity, although not significant.

3.12.5 Case studies

3.12.5.1 The use of marble in facades in the North of Portugal.

Buildings

Being the north of Portugal, a region rich in granite, it is normal that the buildings are mainly built in this material. However during the 60's it was very common to have concrete buildings with the facade of the lower floor in marble.

Today these buildings are not in very good conditions, many slabs have fallen down and they need urgent renovation. In the modern buildings the architects are using more and more Portuguese limestone.

Gravestones

During the times stone has always been used for the building of graves. In Portugal marble, granite and limestone are very much applied in the tombs and mausoleums. In this field we can find some applications of Carrara Marble. The use of this material was always a sign of richness. It was used not only in graves on the ground and mausoleums but also in graves on the walls.

3.12.5.2 Stone companies

Company A

This is an importer of Carrara marble but never applied in outside facades.



The types that are usually imported are Gioia, Didora, CD, Semap and Statuario. In interior walls, the only problem are yellow stains that can appear. To avoid this problem they use a special kind of glue.

This company once applied a Green greek marble with white veins that also started to bow. This material had to be substituted by other material. For exterior they always use Portuguese marble.

Company B

This company uses Carrara Marble but never applies it in outside facades. In the inside works they never had problems. Is not a direct importer, buys the marble from other Portuguese importers.

Company C

Never applied **Carrara Marble** in outside facades, but 20 years ago this company was responsible for the building of a **Carrara Marble** grave in a graveyard near Porto. Our days this grave is completely bowed.

Company D

Being located in the south of Portugal, this company is used to build facades in marble and limestones. Never had any problems with the facades built until now. Uses **Carrara Marble** in interiors

Compagny E

Is a company specialist in gravestones (graves and mausoleums). These graves are built either in granite or marble. Never used Carrara Marble. The mausoleums are general built by one single wall, with 8 cm of thickness and 280 cm length and 60 cm.

3.12.5.3 Architects

The architects contacted never used **Carrara Marble** for outside facades. The reason it is the high price and not the problems related with the application of this material. In most of the cases they never had heard about the problems related with bowing, and some knew the Finland Hall case. In this moment, most of the architects are using for outside facades of important buildings Portuguese limestones.

In the 19th century, in the graveyards Portuguese marble was not applied for the graves. The most common marble was **Carrara Marble**. The restoring that she usually does to grave stones is gluing small pieces and cleaning but in Braga graveyard there are some graves on the walls that show bowing as we can see in the pictures (Figure 155).



3.12.5.4 Examples of objects

ATRIUM SALDANHA

- **Location** - Lisbon
- **Outside Facade** – Estremoz Marble
- Ventilated facade with mechanic fixation
- Bushammered
- 3 cm
- 80 cm/ 120 cm
- 12 000 m²
- Protected with Grafitix
- The outside facade was meant to be built in Giallo Dorato.
- **Inside** – Greek marble

The only problem with façade is the dirty, and never appear bowing problems. This building company never applied Carrara in outside facades

OPORTO BUILDING

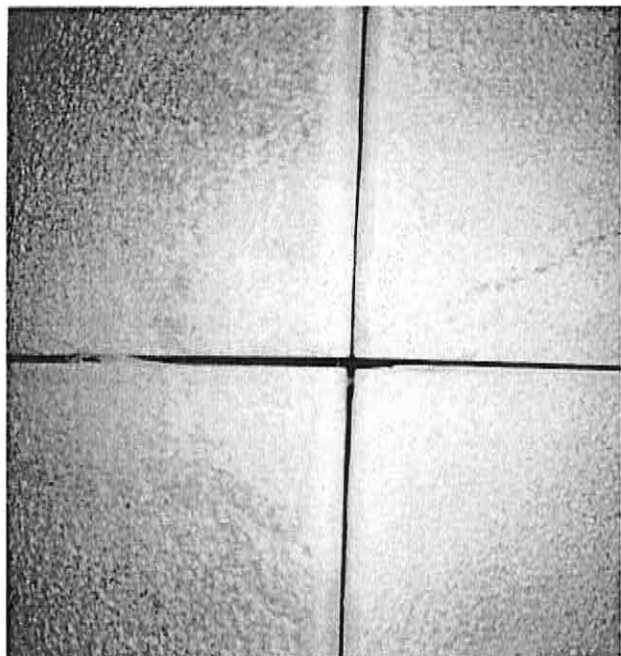
- **Location** – Porto
 - **Outside Facade** –Estremoz Marble
 - Bush hammered
 - Halfen fixings
 - Stone thickness 3 cm
 - Granite Yellow Boticas Polished
- No problems with this façade (Figure 156).

3.12.5.5 Centro tecnológico da piedra

To complete our research we contacted other Technological Centres in other countries. We contacted a Technological Centre in Spain (Macael) region . In this spanish area there are many buildings with outside facades in Macael marble, and even the Technological Centre building is in Macael marble. Never bowing problems in this buildings, only problems with some braked? stones in facades with mechanical fixation. In this centre there is an investigation going on to try to find the reason of the breaking stones on floors built with rectangular tiles (2m x 1 m). These tiles appear broken in the middle 2m x 1m. When they are square that doesn't happen. Until now they think that this phenomena is due the calcite orientation .



Figure 155. A gravestone in Braga (North Portugal) showing clear warping.





4 PRACTICAL APPLICATIONS

4.1 Instructions for constructing a durable marble façade

4.1.1 General

This research has indicated quite clearly that deterioration of marble panels is due to the granular decohesion of calcite grains. According to Royer (see annex 7) thermal variations are causing granular decohesion even when uniformly distributed throughout the specimen. Very low temperatures (-20°C to -30°C) seem to be more damaging, even without frost effect. But also temperatures from $+30^{\circ}\text{C}$ to $+50^{\circ}\text{C}$ are causing permanent changes in the microstructure of some marbles. This kind of surface temperatures can be quite easily measured also in Nordic climates as Koskinen has showed. Weathering agents i.e. humidity and acid rain, are accelerating, rather than starting the degradation process.

Deterioration can be divided in two main categories; physical and esthetical. The latter can be very easily seen as bowing and changes in colour. This phenomena changes the appearance of the façade to somewhat different from architect's original idea. The former is more difficult to see and also more dangerous. The material is, as discussed in previous chapters, gradually losing it's strength, which may cause a considerable safety risk if not recognised early enough.

4.1.2 Selection of marble

Marble is nowadays used in the façades for esthetical reasons. Therefore, the selection of material should start from selecting a few (5..10) possible qualities for further studies according to the desired appearance; colour, veining etc.

These selected marbles shall then be examined more carefully under microscope. Recent studies have shown clearly that many material properties are influenced by the microstructure. Therefor the texture of each marble should be defined comprehensively and only those of xenoblastic or intermediate microstructures are qualified for further studies. Texture of each marble is defined by indicators A/P^2 and A/S^2 (see Royer, annex 3).

In this stage also the flexural strength for virgin specimen is tested and those below 12 MPa are rejected. Bending should be done according to EN12372 with the modification of drying temperature, which should not exceed $+40$ degrees centigrade. This modification is essential since higher temperatures may cause serious damage for the studied material and thus distort the results.

Those qualities passed these preliminary tests shall proceed to further examinations which include testing certain physical properties for virgin, un-



conditioned samples and thermally treated samples. Thermal treatment is done for dry samples as thermal cycles from -25°C to +50°C. Control of the weathering chamber should be done by measuring the actual temperature inside a few samples being located in the chamber so that they give representative picture of the temperature of all of the samples. This is a very easy and reliable way to ensure that samples are actually induced to the desired thermal stress.

Dry samples can be used because driving force for deterioration seems to be thermal changes and humidity is "only" accelerating the process. Using dry samples gives us more certainty that all different qualities are in exactly the same conditions, which is vitally important when comparing materials. Marble classification form can be summarised as below (modified from Royer, annex 3):

Marble type:		
Texture: (xenoblastic or homoblastic) $A/P^2=...$, $A/S^2=...$		
Test	Unconditioned samples	After 20 cycles from -25°C / +50°C
Bending strength	12 MPa	10 MPa
Water absorption	0,12	0,2

Values filled in the form represent the requirements for material to be used in the case of Finlandia Hall. For other cases these threshold values must be reconsidered according to the conditions the façade must tolerate.

4.2 Technical specifications for a stone cladding

4.2.1 Functional considerations

Apart from the right choice of stone material it is essential for the desired function of a natural stone cladding to use the correct solutions for structural implementation of the object. A modern stone facade is many ways quite different from the historical buildings. Throughout the history of architecture stone has been used as a massive, load-bearing structure. In the modern facade construction, however, stone has typically the role of giving the building its final appearance and a shelter against weathering agents. Stone is in the modern applications cut in thin panels and fixed in the building with mechanical anchors.

Change from massive structures to thin veneers has brought along many new technical and functional requirements. With respect to the stone itself it is evident that used as a thin veneer the importance of weather resistance properties is emphasized because of the slenderness of the stone panels. This is in fact one of the reasons giving rise to the severe nature of the



problems with marble facades. On the other hand technical solutions for fixing the stone to the building must be designed taking into account both the requirements coming from the modern building technology as well as the aspects related to the stone cladding itself. In modern construction stone cladding is normally built with thin stone panels of 30-50 mm thickness.

Important design consideration is the physical functionality of the stone veneer. This is especially important in northern climate areas where the temperature gradient between inside and outside of the building is greater than in the southern areas. Main aspects to be taken into account in the physical design of the facade cladding are the thermal and humidity conditions and the expected deformations in materials and structures.

In order to secure the desired quality of the stone material and the installation work a specific quality control system for the building project is needed. Quality control measures are to be taken

- at the quarry
- at the processing plant
- at building site

Controlling laboratory testing of the material properties shall be carried out according to the quality assurance plan of the project.

4.2.2 Structural design principals

The approach was divided into design and dimensioning aspects in the following four areas:

- connection between panel and fixing
- fixing anchor / secondary frame structure
- connection between fixing anchor and a secondary frame structure
- connections into the concrete/steel frame of the building

As a conclusion following structural principals are recommended to be applied for a natural stone cladding:

- panels are fixed independently to the frame of the building using load bearing and restraint anchors of stainless steel or aluminium (figure T1)
- anchors are placed in the joints between stone panels and fixed to the edges of the stone panel with stainless steel pins (figure T2)
- load bearing anchors, placed in the lower part of each panel, carry the weight of the stone panels and part of the wind forces;
- restraint anchors, placed in the upper part of each panel, take only wind forces

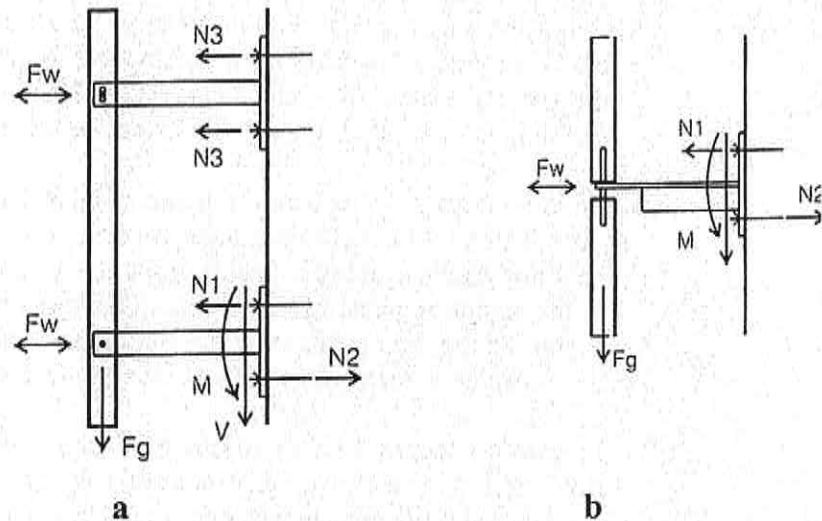


Figure T1. Static principals of a natural stone cladding. Vertical fixing (a), horizontal fixing (b).

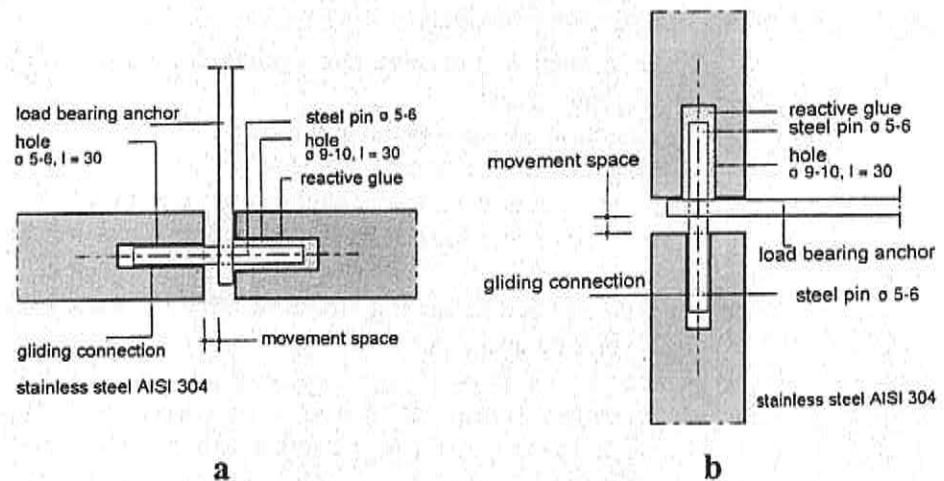


Figure T2. Connection between stone panel and the fixing anchor. Vertical fixing (a), horizontal fixing (b).

4.2.3 Building physical design principals

The approach was divided into design and dimensioning aspects in the following four areas:

- water permeability/tightness
- jointing method
- ventilation of the facade structure



- deformations due to temperature, humidity and movements
- protective impregnating treatments

As a conclusion following physical design principals shall be applied for a natural stone cladding:

- stone cladding shall be jointed by elastic mass to prevent rain penetration and to allow small deformations of structural elements without a risk for internal strains
- humidity in the wall structure shall be led out using a ventilation gap placed behind the stone cladding; proper function of the ventilation gap is arranged by using sufficient openings for both air going in and coming out
- connections between panels are designed elastic to allow deformations due to thermal expansion
- internal stresses, due to fixings and deformations between structural elements, are eliminated by proper design of the fixings
- protective agents shall be considered if there is a need to protect the cladding against environmental impurities

4.3 Monitoring the physical state of an existing façade

4.3.1 General

Monitoring of the physical state of façades should be included in every real estate's maintenance program. Considering marble façades, designing of the monitoring program starts from recognising the most critical part of the façade where the climatical stresses are the most severe. Typically the highest temperatures can be measured in the façades facing south, south-west and west. In Nordic climates these are also the compass directions where temperature changes are the strongest. The focus of monitoring should be on these parts of a façade, but of course also other parts of façade must be monitored, possibly less intensively.

The first and easiest inspection should be visual inspections. Changes in colour and appearance should be followed carefully.

4.3.2 Bowing measurements

A practical way of monitoring the process of granular decohesion is to measure the bowing of panels. As Royer explains in his report (annex 3), bowing is caused by differences in the level of granular decohesion through the thickness of a marble panel. By measuring the bowing we can thus notice the starting decohesion and later follow the progress of deterioration.

Measuring can be done with different types of "rulers", but essential is that bowing in both directions, concave and convex, can be measured with the same apparatus. According to our experiences from measurements, an accuracy of 0,1 mm is enough for following the development of bowing and also



practically reasonable. Bowing measurements are recommended to be done in the first stage in every six months; time period can later be adjusted if needed.

4.3.3 SEM -analyses

In addition to bowing measurements also more accurate methods are needed. These methods include SEM -analyses and testing the flexural strength of the panels on the façade continuously during the lifetime of the façade. Samples for the former should be taken from the previously defined most critical part of the façade. These samples can be very small and so the traces of sampling are easily hidden from spoiling the view. The amount of the samples must be considered regarding the façade in question, but for Finlandia Hall –case two samples every second year should be enough. The idea of these samples is to actually peek inside the panels and to verify the condition of them. Also the openings between the calcite grains can be measured and their importance can be interpreted.

4.3.4 Flexural strength testing

Sampling for the flexural testing is more difficult, but this testing is considered to be essential. The only possible way of sampling- due to the amount needed for statistically reliable results- is to release complete panels from the façade. This requires a bit of arrangements since estate owner should stock spare panels for the ones decided to be tested and also since the initial strength of the panels tested must be known in order to define the decrease of the strength. Practical solutions for the latter are numerous, but one recommendation is to select one block for the monitoring, test the strength of it and then install the rest of the panels made of it. These panels should be marked clearly for later identification. Samples are then taken (and tested) from these panels once every five years.

4.3.5 Criteria for façade renovation

From the above described method can be derived very easily otherwise very difficult decision to be made: when to renovate the façade. One must set, when designing the façade, certain threshold values allowed for bowing and loss of strength. When monitoring is giving values close to these values, planning of the renovation should be started and when those values are exceeded, renovation works should be started.

4.4 Recommended actions for façade maintenance

Because of the nature of the deterioration process, even the most careful maintenance cannot prevent the panels from bowing and loosing their strength. Therefore, the effort should be put on upholding the outlook of the façade as long as possible. This is done by cleaning the panels with suitable method according to the amount of dirt accumulating on them. When cleaning the panels also the state of the joint sealings can be easily checked and fixed if needed. This is essential to prevent the frost damage the water leaks into the façade could otherwise produce.



The physical state of fixings should be checked every once and a while. Even stainless steel can be subjected to corrosion in some conditions, which may lead to serious accidents if not recognised early enough.

APPENDIXES

1. VTT Building and Transport, Environmental conditions
2. VTT Building and Transport, Test wall
3. VTT Building and Transport, One-sided weather resistance test
4. VTT Building and Transport, Protective agent
5. Helsinki University of Technology, Laboratory of Engineering Geology and Geophysics
6. Helsinki University of Technology, Laboratory of Rock Engineering
7. University of Parma
8. Cevalor
9. Bowing measurements
10. Financial report

