2.11 Structural considerations

Aim of the study is to find recommendable structural solutions for a natural stone cladding. Special attention is paid to the conditions in the northern climate and especially the specific requirements in the case of Finlandia Hall. Approach is based on techno-economical functionality requirements combined with the structural stability and safety considerations.
The work was divided in the following areas:
- cladding panels
- fixing technology
- physical design principals
- other design considerations

Alternative solutions for the cladding panel were evaluated. Structurally we can divide the alternative panel products into the following types:
- massive stone panel
- thin stone on a light honeycomb backing
- thin stone on a concrete backing
- reinforced stone panel

Alternative solutions were studied both in the field test and in laboratory. main emphasis was given to the durability and technical reliability aspects.

Different technical solutions available today were evaluated based on the new knowledge gained from Mara research. Additional methods were a literature review and a theoretical approach combined with numerous practical experiences obtained in actual conditions. Development and testing of new fixing and installation methods was not included in the research. Collected data was summarised in the form of recommended design principals and examples of acceptable solutions.

3 RESULTS AND DISCUSSION

3.1 Field test

3.1.1 General

The field test was established in order to gain information about the changes appearing in the products included in the test. Being carried out in the natural conditions without any accelerating factors included, it was expected that significant signs of alteration could not be recorded during the two-year period of Mara project. However, evident changes could be measured in some of the samples already during the first year. Clear correlation could be noted between real behaviour of marble samples and that observed in laboratory conditions. This was especially the case with marble type D, which showed the most significant decay of quality during the test.

From the research point of view it is clearly appropriate to continue with the field test during a longer period of time in order to be able to establish more clearly the behaviour of the tested marbles in controlled conditions (Appendix 2).

3.1.2 Colour measurements

The colour of the marble panels chosen for this part of the study was measured 5 times between 23.6.1999 and 8.3.2001 with 5-6 months intervals.

All the marbles were initially white, the L value of the unused panels varying between 80 and 90. Marbles D and E had the highest value and marble K the lowest. The values of the coordinates a and b were close to zero, although all marbles had a slight greenish-blueish hue. The colour coordinate L of marble panels placed on the eastern wall (23) in initial stage (measurement 1) is shown in Figure 20 and the development of the L-value for marble A samples can be seen in Figure 21.

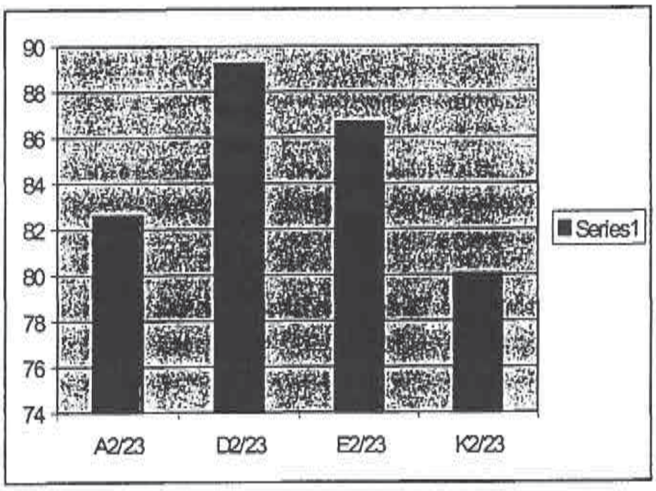


Figure 20. CIELAB colour coordinate L of the marbles. Eastern wall, first measurement 23.6.1999 (1).

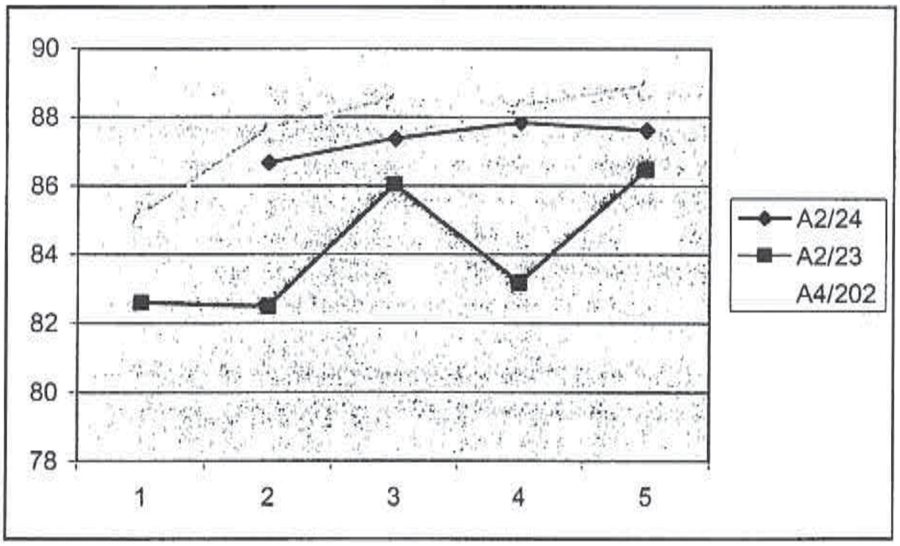


Figure 21. CIELAB colour coordinate L of marble A.

According to the colour measurements the whiteness of the marbles increased. This was evident especially during the first year. After that the changes seem to have been slow, if not negligible. In addition, there has been a slight tendency for the coordinates a and b to move towards more positive values. This means that the marbles are getting more yellow and more red, which could refer to fouling of the marble surfaces. Until now the changes have, however, been small. Results of the measurements of colour coordinates a and b for marble A are shown in Figures 22-23. Detailed results are presented in Appendix 1.

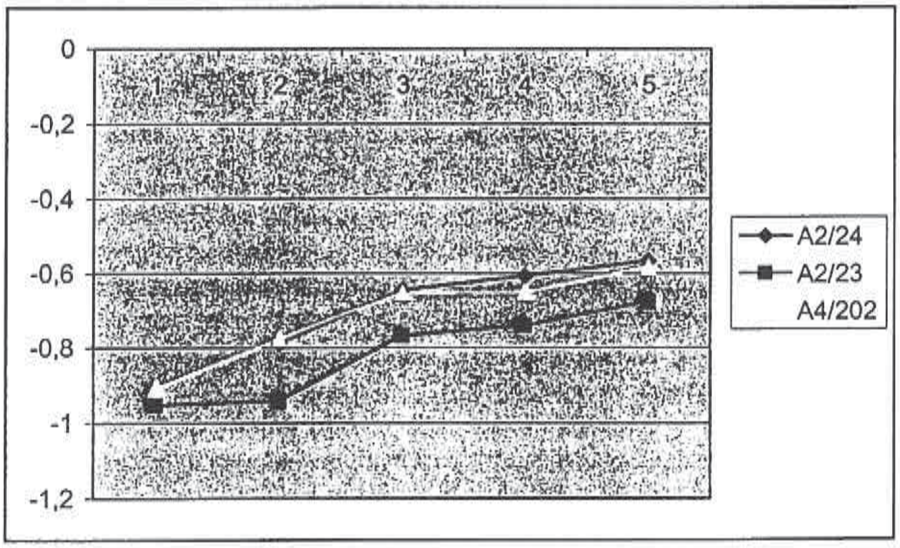


Figure 22. CIELAB colour coordinate a of marble A.

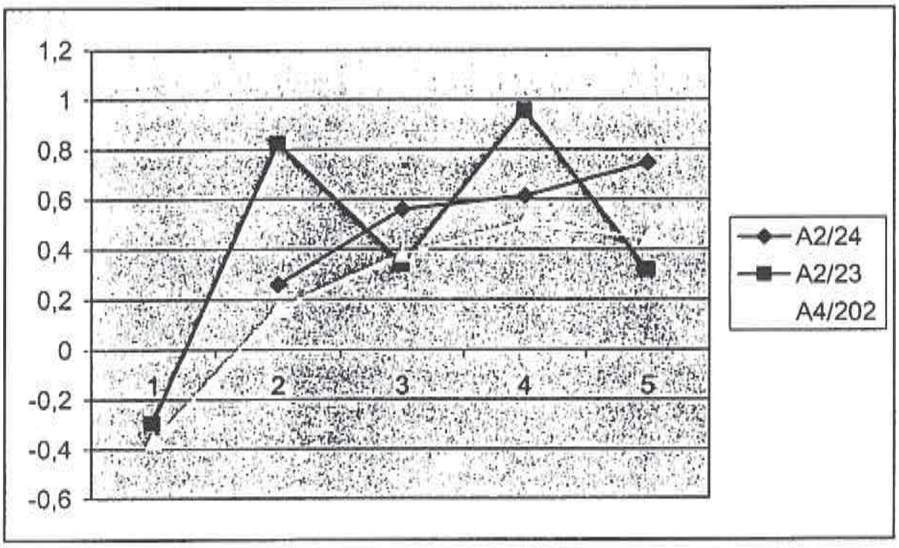


Figure 23. CIELAB colour co-ordinate b of marble A.

3.1.3 Bowing measurements

Straightness of the marble panels was measured five times during the project. The first measurement documented the initial stage of the panels and it was done a few months after completion of the field test façades to ensure that the panels have properly settled to their positions. The panels were measured between 22nd September 1999 and 8th March 2001. Continuation of bowing measurements after this project has not been decided yet, but some kind of monitoring will most certainly continue.

In the beginning it seemed that two years is too short time to notice any differences between the products. The measurements showed this first conjecture to be wrong, very clear differences can be seen in the results (presented more in detail in appendix 9). For example on the wall 24 facing south, massive marble panels have showed very clear bowing (see figure 24).

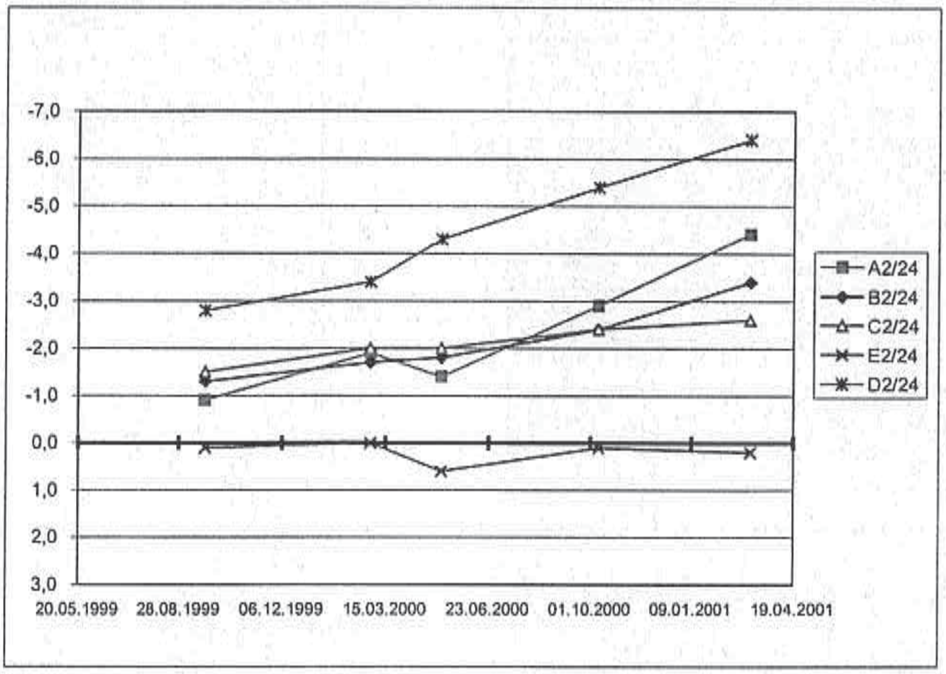


Figure 24. Measured bowings on wall 24. Massive marble panels.

The magnitude of bowing seems to be following the degree of homoblasticity, the most bowed is product D, which is presenting pure homoblastic marbles, and the less bowed –or practically straight- is product E presenting pure xenoblastic marbles. Same phenomena can also be seen on walls 23 and 202, the former facing east and the latter facing south (see figures 25 and 26).

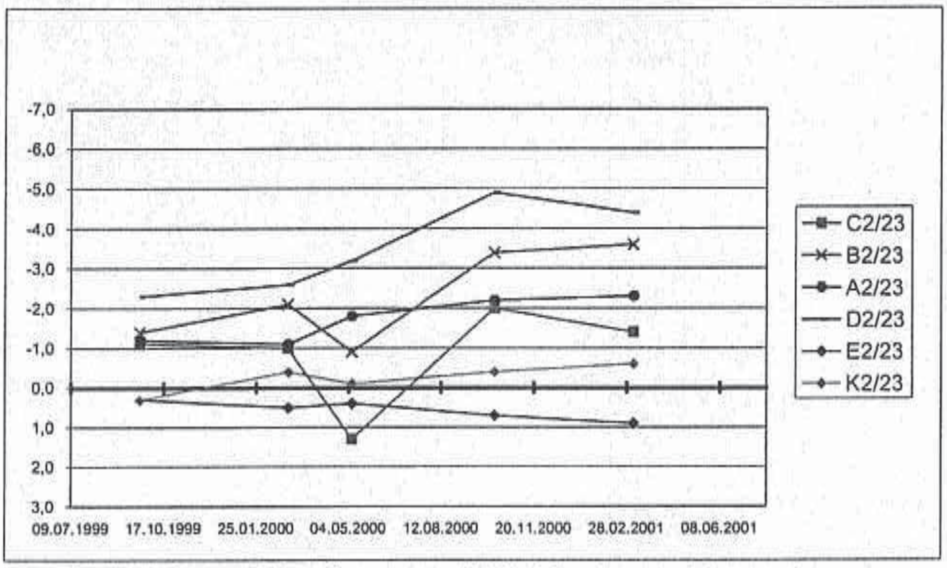


Figure 25. Measured bowings on wall 23. Massive marble panels.

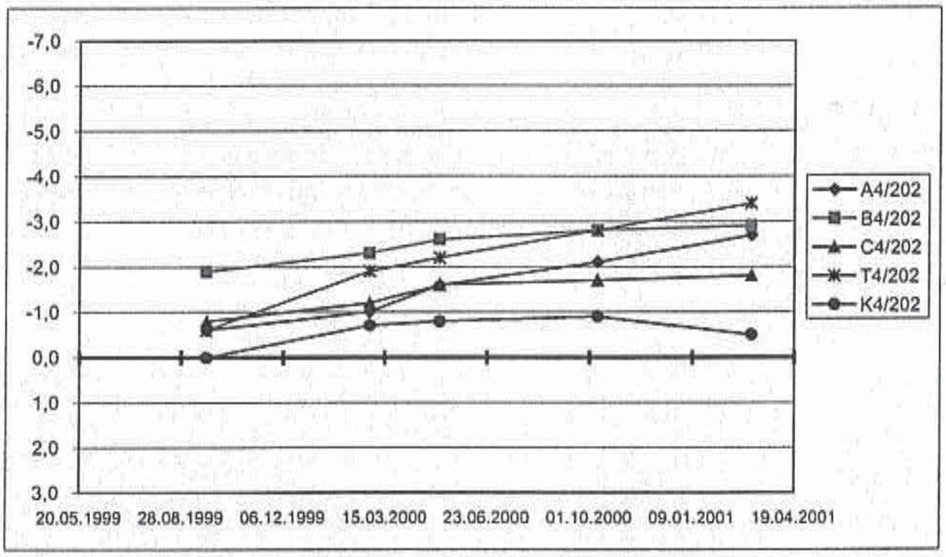


Figure 26. Measured bowings on wall 202. Massive marble panels.

Bowing measurements show also quite clearly the function of two different protective agents. In figure 27 are presented the bowing measurements from the wall 202. Product A is also added in the figure for comparison since products M and O are derived from it by adding protective agent. These measurements confirm, although they can be considered as indicative due to the relatively short observation time, the results introduced later in this report. Protective agent seems not to be able to prevent marble from bowing.

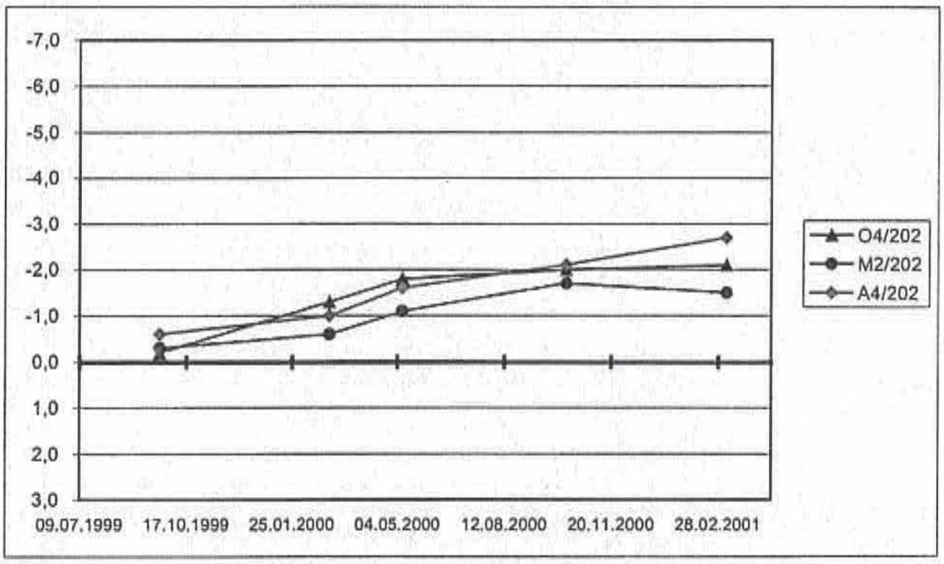


Figure 27. Measured bowings on wall 202. Protective agents.

Also several types of different structural products were included in the field tests. Products present very different structural ideas and also significant differences in their performance can be seen. Also for these products the observation time has been too short to make final conclusions, but some very clear conjuctions can be made already now. Figures 28 and 29 present the results. Also in these figures product A has been added for comparison, although it is not used in the structural products.

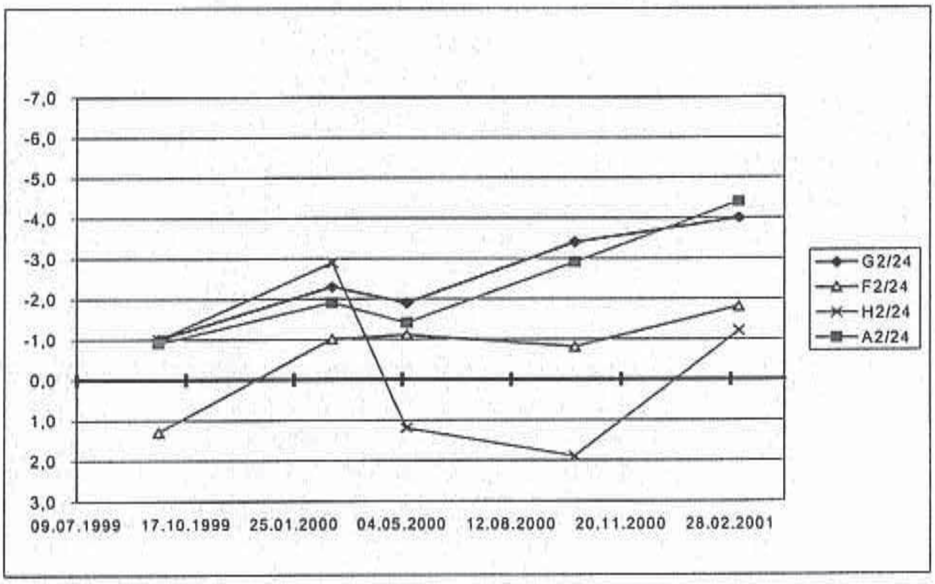


Figure 28. Measured bowings on wall 202. Structural products.

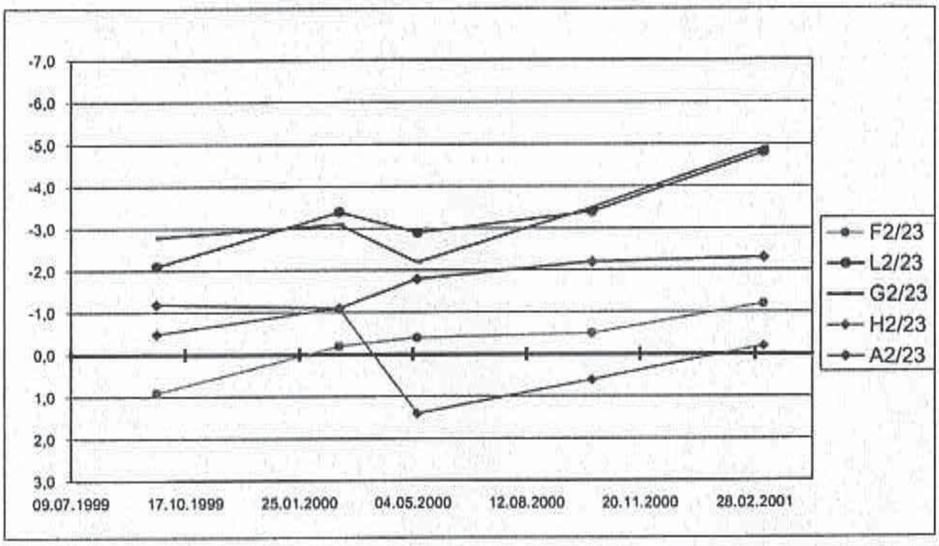


Figure 29. Measured bowings on wall 23. Structural products.

Also three different granites were included in the field tests. Measured bowings are presented in figure 30. Bowing as a word is very much of exaggeration in this context, practically no changes in the straightness of these products can be seen.

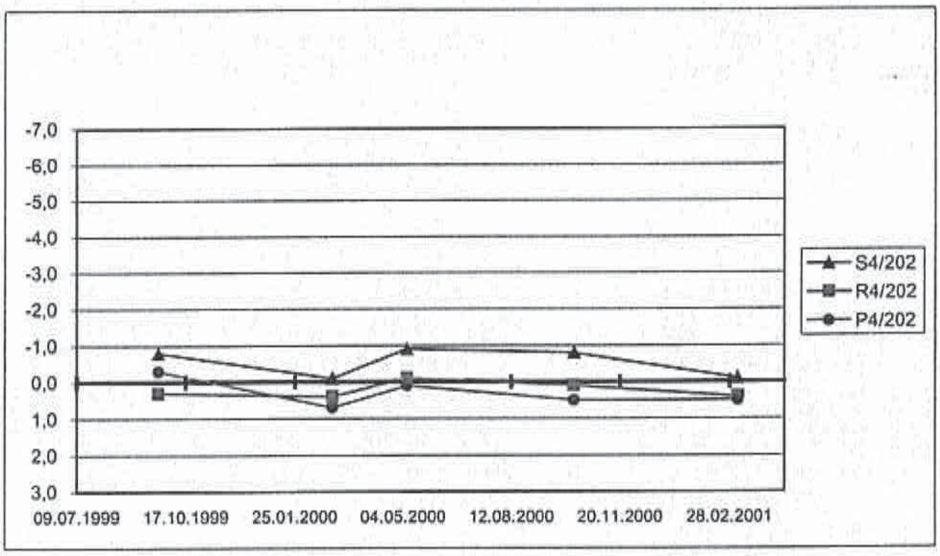


Figure 30. Measured bowings on wall 202. Granites.

3.1.4 Flexural strength

Initial values of flexural strength of marbles A, D, E and K are presented in figure 31. The relative changes of the flexural strengths, ΔR_{tf}, of the marbles that have taken place on the test wall are presented in Table 9. The basis of the comparison is in all cases the flexural strength of the unused marble. Detailed measurement results are shown in Appendix 1.

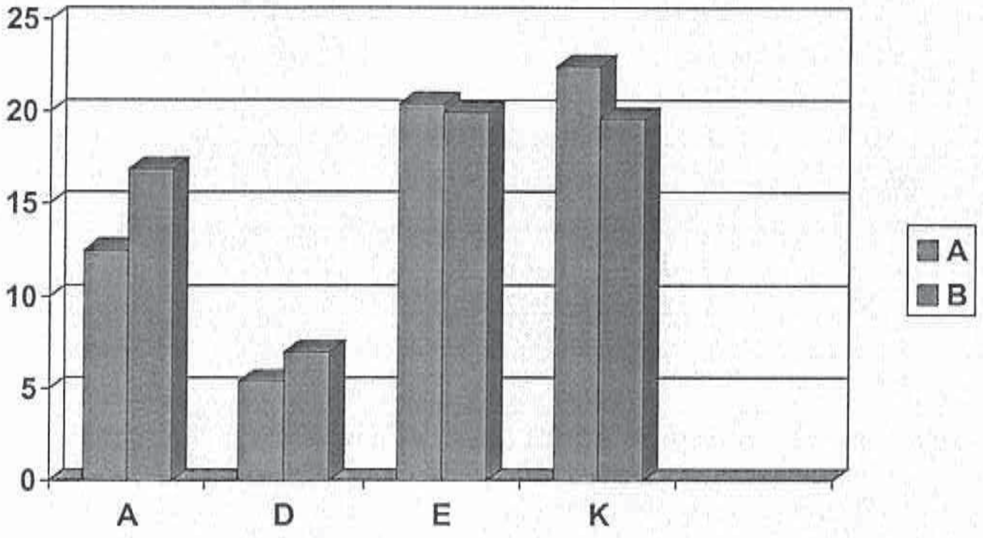


Figure 31. The initial flexural strengths of the marbles (MPa).

Table 9. The relative changes of the flexural strengths of the marbles on the test wall.

Marble type	Δ W 1 year (%)	 1,5 years (%)
A		
direction A	-16	-20
direction B	-17	-17
D		
direction A	-35	-34
direction B	-48	-42
E		
direction A	-17	+11
direction B	+20	+21
K		
direction A	-3	-2
direction B	-2	+4

3.1.5 Water absorption, apparent porosity, bulk density

The water absorption, apparent porosity and bulk density of marble A in initial stage and after 1 and 1.5 years on the test wall at the Finlandia Hall are presented in Table 10. The corresponding values of marbles D, E and K are presented in Appendix 1. The presented results are average values (av.) and standard deviations (s.d.) calculated from the testing data of individual samples.

Table 10. Water absorption, apparent porosity and bulk density, marble A.

	water absorption w-%	apparent porosit vol-%	bulk density kg/m^3
unused			
av.	0.113	0.307	2713
s.d.	0.003	0.009	0
s.d. (%)	2.7	2.9	0
test wall / 1 year			
av.	0.202	0.546	2710
s.d.	0.010	0.027	2
s.d. (%)	5.0	5.0	0.07
test wall / 1.5 years			
av.	0.200	0.540	2706
s.d.	0.018	0.049	1
s.d. (%)	9.0	9.1	0.04

Water absorptions of the marbles are shown in Figure 32.

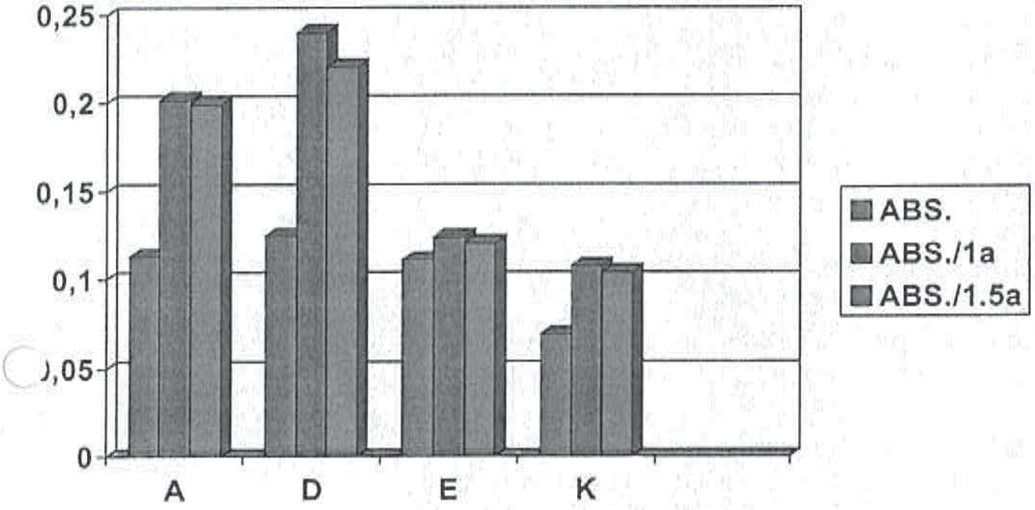


Figure 32. Water absorption of the marbles (w-%).

The relative changes of the water absorption, ΔW, and apparent porosity, Δp_o, of the marbles that have taken place on the test wall are presented in Table 11. The basis of the comparison is in all cases the value of the unused marble.

Table 11. The relative changes of the water absorption and apparent porosity of the marbles on the test wall.

Marble type	Δ W	
	1 year (%)	1,5 years (%)
A	+79	+77
D	+92	+77
E	+12	+9
K	+57	+51

3.1.6 Microscopic research

3.1.6.1 Mineral composition

According to the X-ray diffraction diagram marble A consisted almost entirely of calcite, i.e. calcium carbonate, $CaCO_3$. Quartz, α-SiO_2, and feldspar, Na-K-Ca-aluminium silicate, were also observed. The contents of these accessory minerals were, however, low, at most only a couple of weight percents. Structural products

According to the X-ray diffraction diagram marble D consisted almost entirely of calcite, i.e. calcium carbonate, $CaCO_3$. Quartz, α-SiO_2, and dolomite, $CaMg(CO_3)_2$, were also observed. The contents of these accessory minerals were, however, low, at most only a couple of weight percents.

According to the X-ray diffraction diagram marble E consisted almost entirely of calcite, i.e. calcium carbonate, $CaCO_3$. Marble contained also a substantial amount, probably 5-10 w-%, of dolomite, $CaMg(CO_3)_2$. Quartz, α-SiO_2, was also observed, but its content was low.

According to the X-ray diffraction diagram marble K consisted almost entirely of calcite, i.e. calcium carbonate, $CaCO_3$. Quartz, α-SiO_2, and dolomite, $CaMg(CO_3)_2$, were also observed. The contents of these accessory minerals were, however, low, at most only a couple of weight percents.

The thermal behaviour of all the marbles was practically identical. The thermal curves contained only one phenomenon, the disintegration reaction of calcite in the temperature region of 700°C-950°C. In the curves of the marble E there was, however, a small effect, "a shoulder", at about 750°C. This probably refers to dolomite in which the disintegration reaction includes two separate steps, first of which is comprised of the dissociation of magnesite and the second of the dissociation of calcite. Weight losses of the marbles at 1000°C, Δm_T, and temperatures of the maximum rate of the weight change, T_{max}, taken as the temperatures of the peaks of the DTG-curves as well as the thermal curves of marbles are shown in Appendix 1.

3.1.6.2 Microstructure

Photographs of the microstructure of marble A, unused and after 1 year on the test wall, are shown in Figs. 33-34. Following observations were made:

- groundmass fine-grained, fairly even grained, not oriented, massive
- average grain size 200-300 µm
- slightly porphyroblastic, some larger porphyroblasts (max Ø 6 mm) in the groundmass
- nearly pure carbonate rock, contains only very little opaque minerals
- alteration of the grains insignificant
- no changes observable after 1 year on the test wall

Figure 33. Microstructure of marble A. Unused. Plane-polarized light.

Figure 34. Microstructure of marble A. 1 year on the test wall. Plane-polarized light.

Photographs of the microstructure of marble D, unused and after 1 year on the test wall, are shown in Figs. 35-36. Following observations were made:

- fine-grained, fairly even grained, nor oriented, massive
- average grain size 200-300 µm
- nearly pure carbonate rock, contains very little mica type minerals
- some alteration of the grains
- no changes observable after 1 year on the test wall

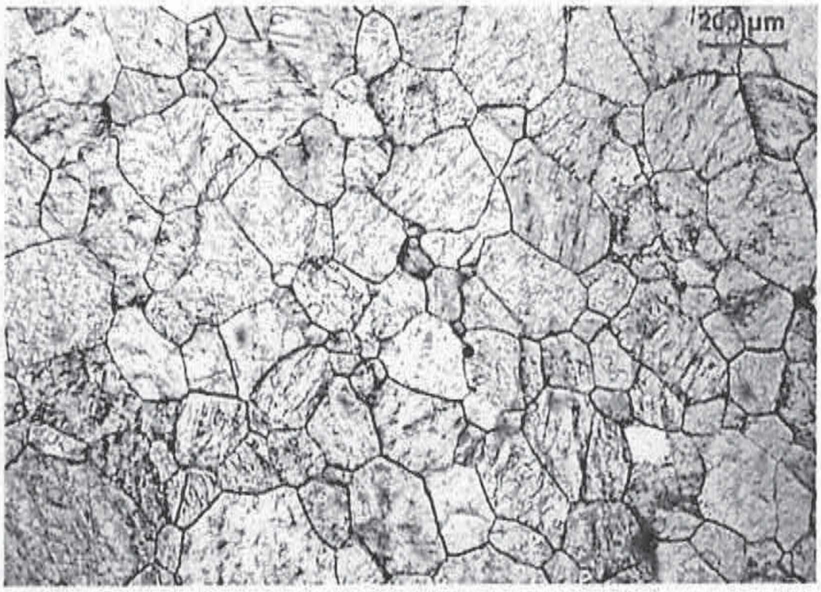


Figure 35. Microstructure of marble D. Unused. Plane-polarized light.

Figure 36. Microstructure of marble D. 1 year on the test wall. Plane-polarized light.

Photographs of the microstructure of marble E, unused and after 1 year on the test wall, are shown in Figs. 37-38. Following observations were made:

- fine-grained, not oriented
- grain size varies from microcrystalline up to 0.8 mm
- very fine-grained (cryptocrystalline) lenses among the groundmass, the lenses pass gradually into groundmass
- nearly pure carbonate, contains some opaque and mica type minerals
- some alteration of the grains
- no changes observable after 1 year on the test wall

Figure 37. Microstructure of marble E. Unused. Plane-polarized light.

Figure 38. Microstructure of marble E. 1 year on the test wall. Plane-polarized light.

Photographs of the microstructure of marble K, unused and after 1 year on the test wall, are shown in Figs. 39-40. Following observations were made:

- fine-grained, not oriented
- average grain size about 200 µm
- very fine-grained (cryptocrystalline) lenses and veins among the groundmass, lense boundaries are distinguished from the groundmass
- nearly pure carbonate rock, contains some opaque minerals
- little alteration of the grains
- no changes observable after 1 year on the test wall

Figure 39. Microstructure of marble K. Unused. Plane-polarized light.

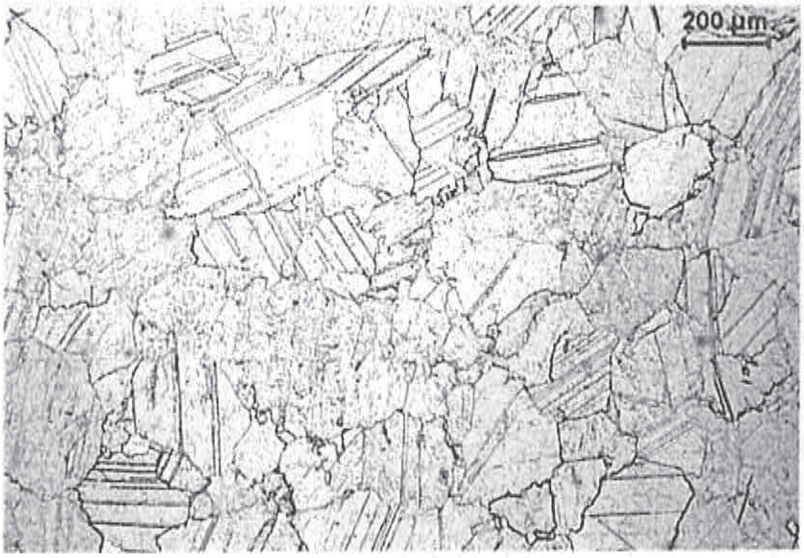


Figure 40. Microstructure of marble K. 1 year on the test wall. Plane-polarized light.

SEM-pictures of fractured surfaces of marble D, both unused and after 1 and 1.5 years on the test wall, are shown in Figs. 41-43. The individual grains can easily be distinguished from each other. Clear cracks can also be noticed between all the grains. These cracks become wider when the marble is exposed to the environmental strains on the test wall. The maximum crack width after 1.5 years on the test wall is around 1 µm. Respective pictures of marbles A, E and K can be found in Appendix 1.

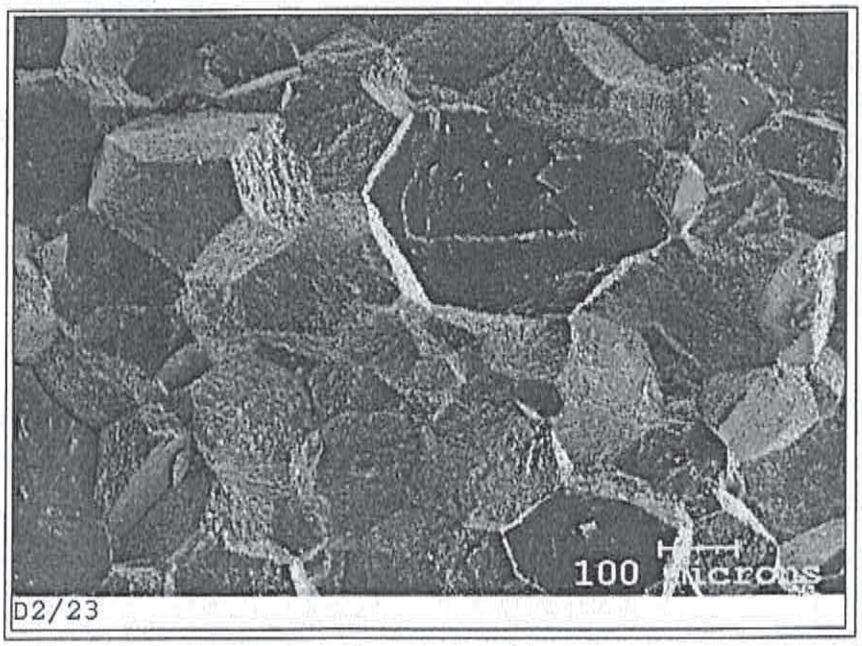
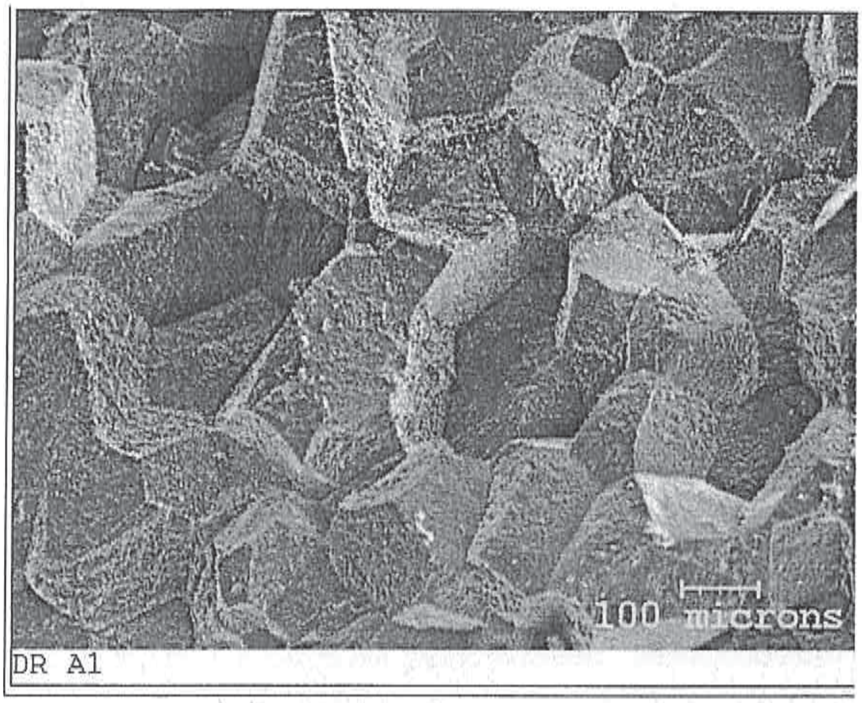
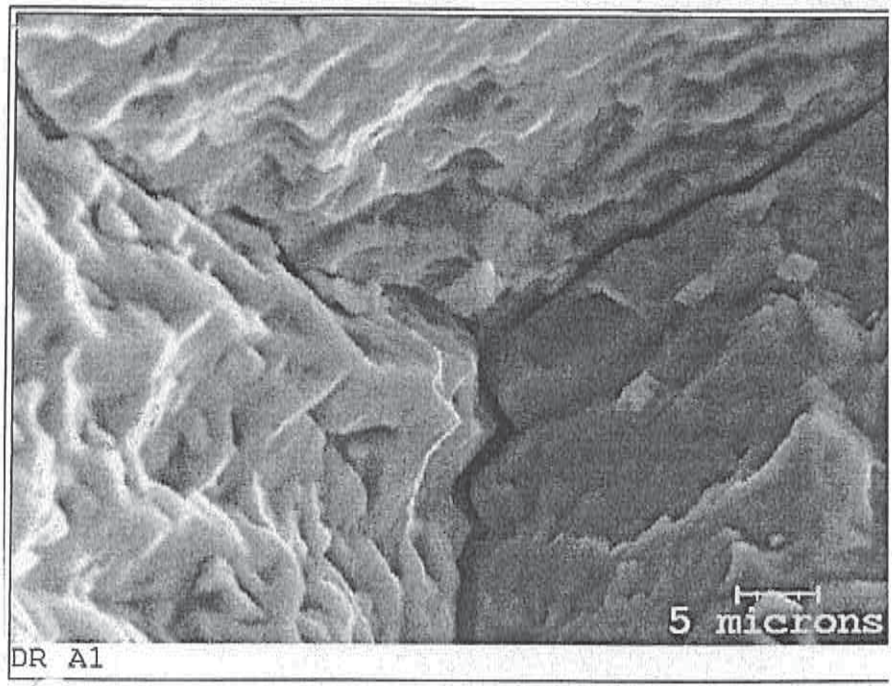


Figure 41. Marble D, unused. SE-image of fractured surface, 100x.


100 microns
DR A1

[illegible]

igure 42. Marble D,1 year on field test. SE-image of fractured surf
00x.



igure 43. Marble D, 1 year on the test wall. SE-image of fractured surfa
500x.

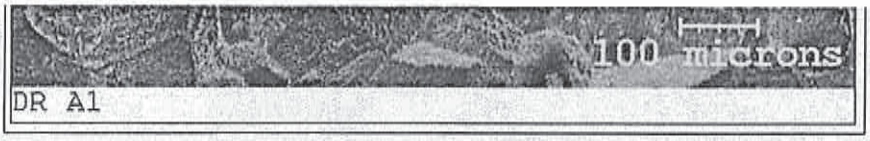


Figure 42. Marble D,1 year on field test. SE-image of fractured surface, 100x.

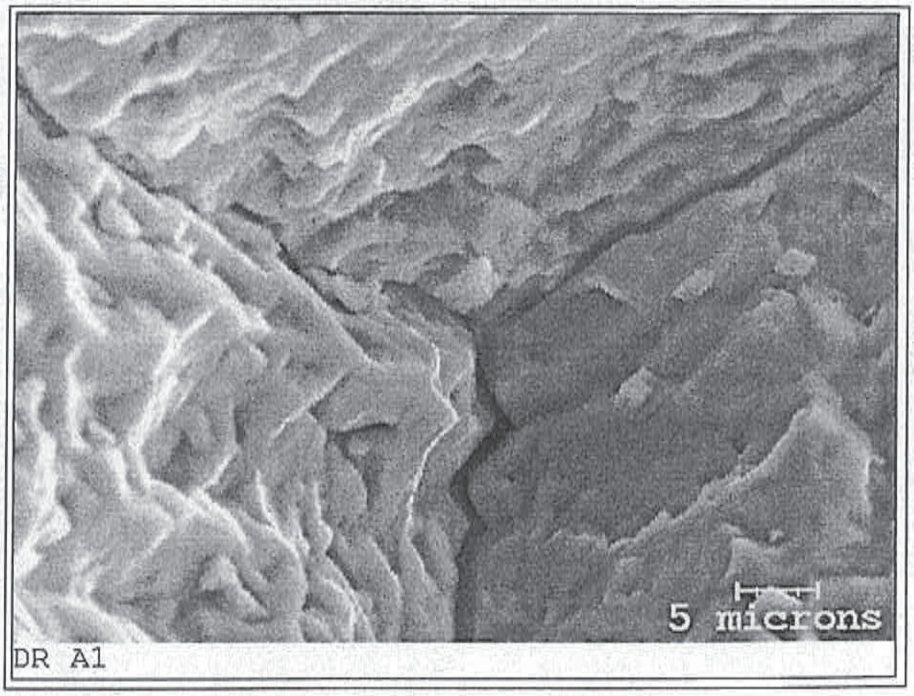


Figure 43. Marble D, 1 year on the test wall. SE-image of fractured surface, 2500x.

3.1.7 Marble coated panels

3.1.7.1 Bond strength

Bond strengths of marbles of the marble clad elements in initial stage and after 1 and 1.5 years on the test wall at Finlandia Hall are presented in Figure 44. Complete measurement results are shown in Appendix 1.

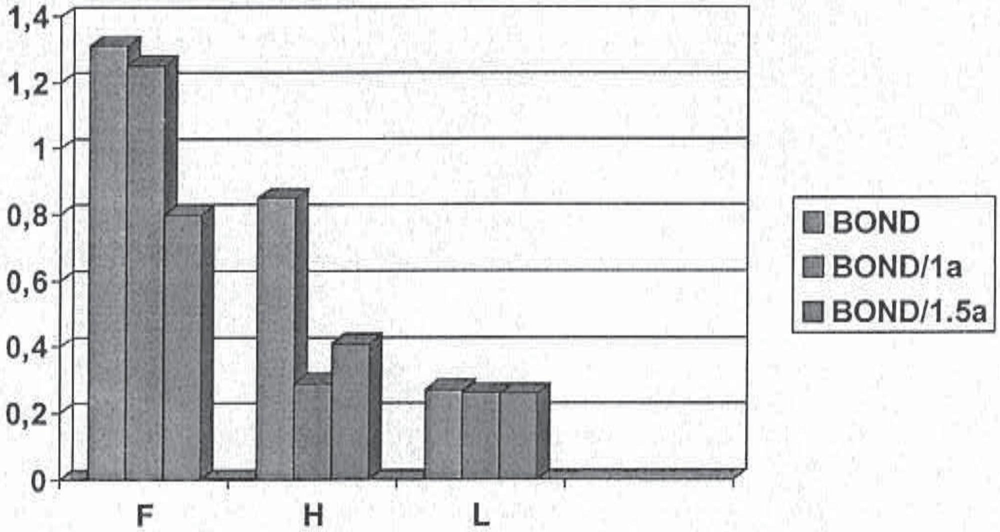


Figure 44. Bond strength of marble in marble clad elements (MPa).

The relative changes of the bond strength that have taken place on the test wall are presented in Table 12. The basis of the comparison is in all cases the bond strength in the unused elements.

Table 12. The relative changes of the bond strengths of marble in the marble clad elements on the test wall.

element type	change of bond strength 1 year %	 1.5 years %
F	-5	-39
H	-66	-52
L	-4	-4

In the element type F the breaking point was usually the interface between marble and concrete. Only in a couple of cases the loosening took place, at least partly, deeper inside concrete.

In the unused element of type H the breaking point was either the interface between marble and the rest of the structure (1/3) or the interface between the glass fiber sheet and the aluminium honey comb structure (2/3). In the elements of type H that had been on the test wall the breaking point was, however, always the interface between marble and the rest of the structure.

In the element type L the breaking point was always the interface between marble and the rest of the structure. Thus, the loosening of marble took place from the top of the glue layer.

3.1.7.2 Microstructure

Photographs of the microstructure of marble clad element F, unused and after 1.5 years on the test wall, are shown in Figs. 45. Following observations were made:

- contact between marble and concrete tight and cohesive
- a narrow layer of third material, probably primer, between marble and concrete
- material (primer) layer rather continuous, though pores are common; thickness of the layer generally 20-30µm, in places even 60 µm
- in the unused element only a few very tiny cracks along the marble/concrete contact zone
- in the element strained for 1.5 years on the test wall some slight and narrow cracking at the marble/concrete contact zone

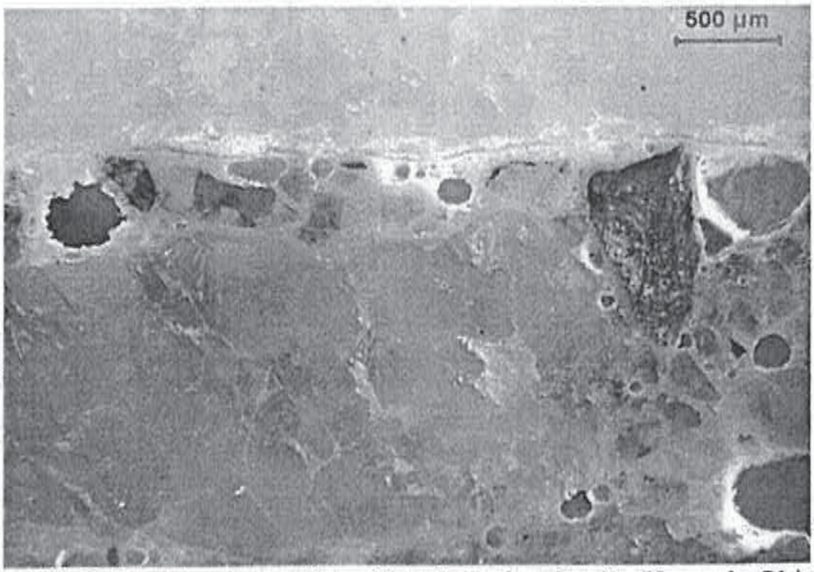


Figure 45. Microstructure of marble clad element F. Unused. Objective 2.5x, oblique illumination.

Photographs of the microstructure of marble clad element H, unused and after 1.5 years on the test wall. Following observations were made:

- a layer of glue between marble and metal structure, thickness of the layer approximately 1 mm
- structure of the unused element partly cracked along the contact zone marble/glue
- in the unused element the upper half of the glue layer tinted yellowish
- in the element strained for 1.5 years on the test wall the upper half of the glue layer tinted brownish
- open crack on about 60 % of the contact zone marble/glue

Photographs of the microstructure of marble clad element L unused on the test wall, is shown in Figure 46. Following observations were made:

- a layer of glue between marble and metal structure, thickness of the layer approximately 0.5 mm
- the glue contains a lot of porosity
- in the unused element the glue layer partly detached from marble
- in the element strained for 1.5 years on the test wall the glue layer rather tightly attached to marble, only minor cracking in some parts of the contact zone

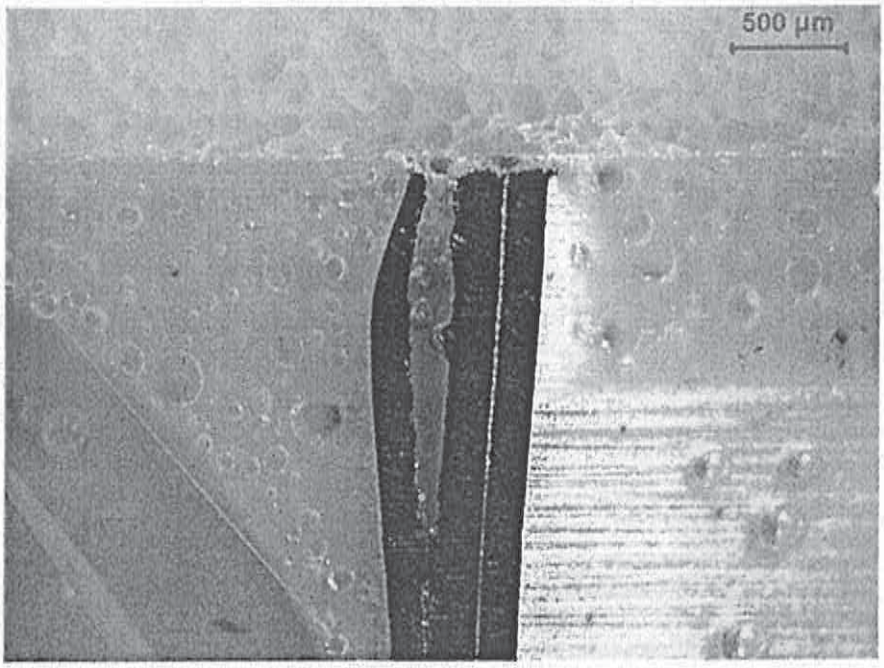


Figure 46. Microstructure of marble clad element L. Unused. Objective 2.5x, oblique illumination.

3.2 Observation of weather conditions

3.2.1 General

Environmental conditions cause various effects on a facade cladding. Temperature changes, gradients over marble panels and the number of freezing and thawing are the most important strains caused by weather. In addition impurities and aggressive compounds found in typical industrial city air are can be mentioned as catalytic factors for the deterioration.

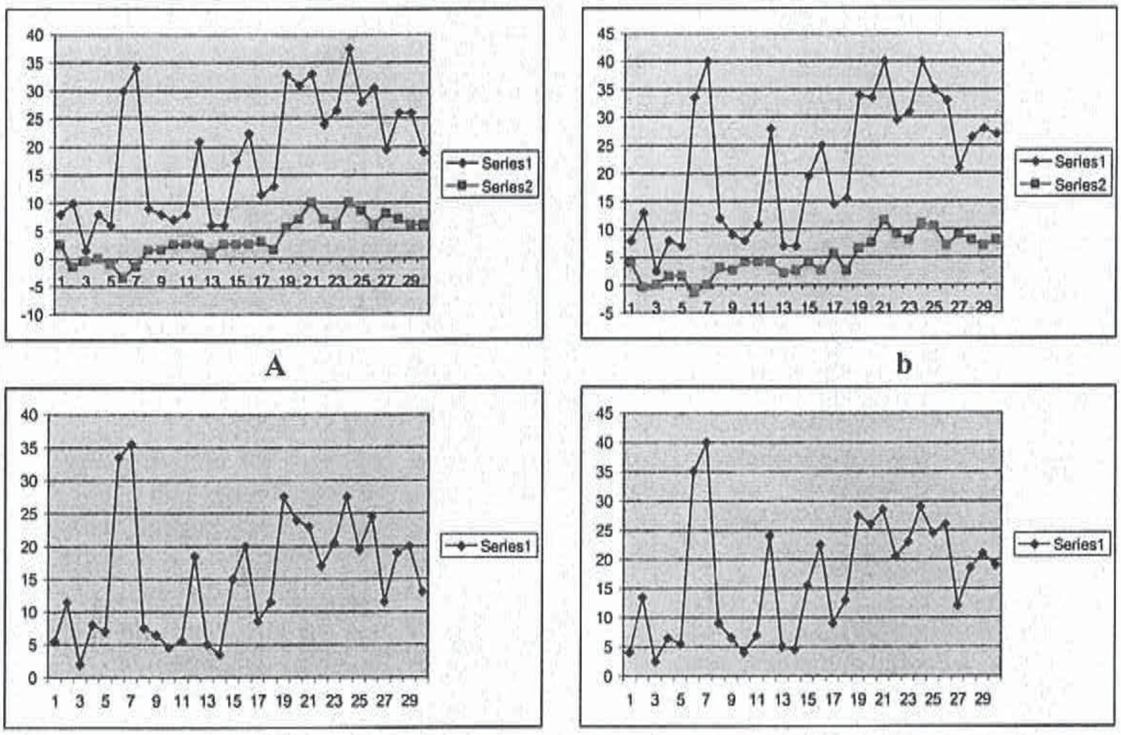
The features of the results which were considered most important considering especially the strains caused by the environmental factors to the marble facade are described more closely in this chapter. In most cases the daily maximum and minimum temperatures are used when examining the results. Complete file of temperature nd humidity measurement data from Finlandia Hall facade is can be found in Appendix 1.

3.2.2 Daily variation of temperature

Daily variation of temperature was studied by using the maximum and minimum temperatures observed daily on outer and inner surfaces of marble panels. Results from measuring point A located on the top of the southern wall, are presented is Figures 47-50. Pictures are grouped in the series of four, each representing the same measurement period. The four pictures in the same series are coded with letters a-d, and they have the following meaning:

a) daily max and min temperatures on outer surface of marble (°C)
b) daily max and min temperatures on inner surface of marble (°C)
c) difference between daily max and min temperatures on outer surface of marble (°C)
d) difference between daily max and min temperatures on inner surface of marble (°C)

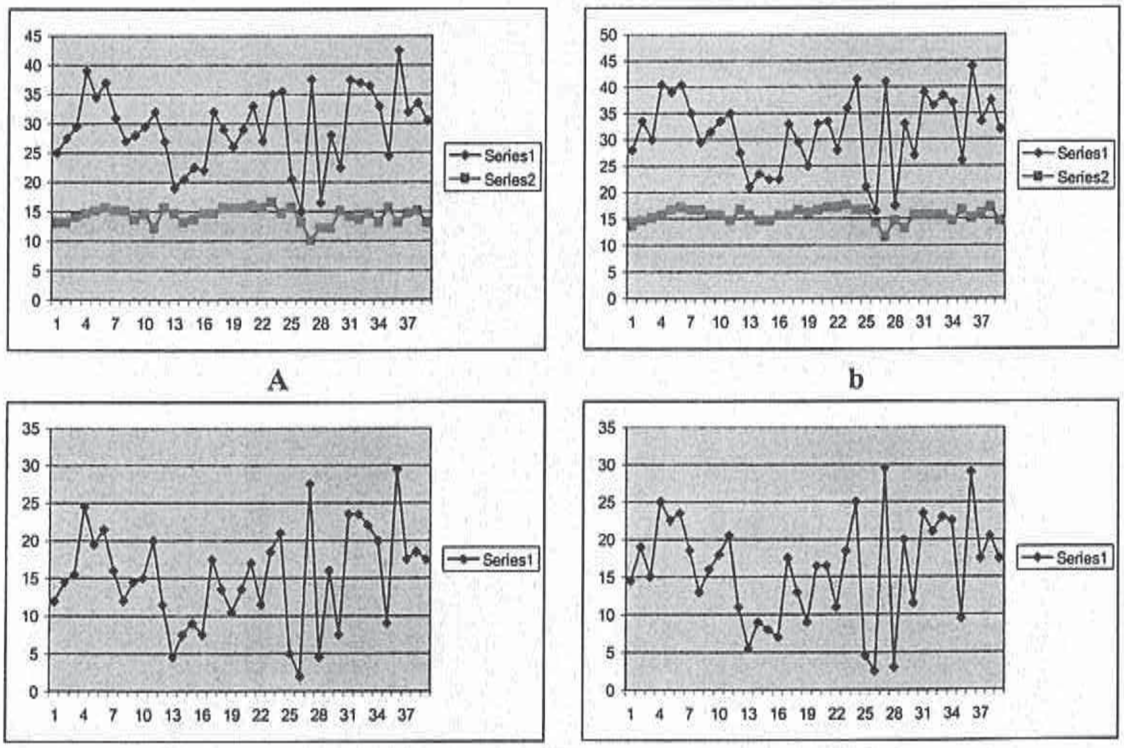
Complete data for all measuring points (A, B, C, D and E) about the daily variations of temperature between the period 26.5.1999 - 28.2.2001.
are presented in Appendix 1.



A b

C d

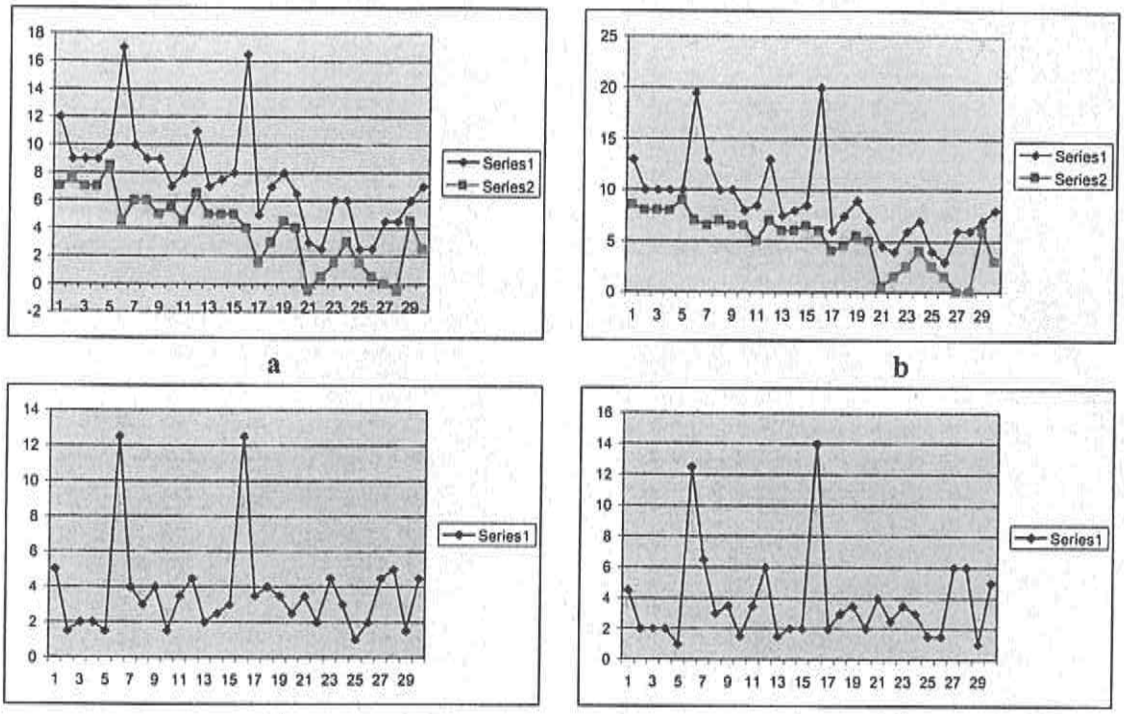
Figure 47. Daily temperature variation during measurement period 1.4.-30.4.2000



A b

c d

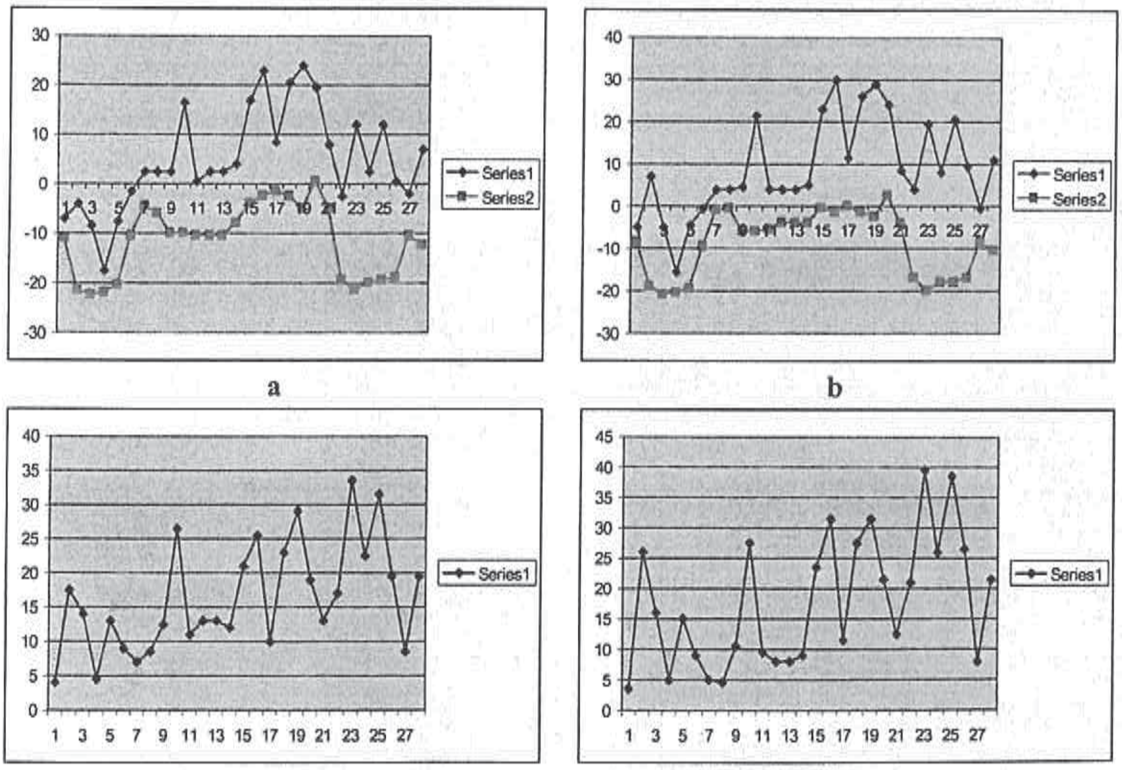
Figure 48. Daily temperature variation during measurement period 1.7.-8.8.2000.



a b

C d

Figure 49. Daily temperature variation during measurement period 1.11.-30.11.2000.



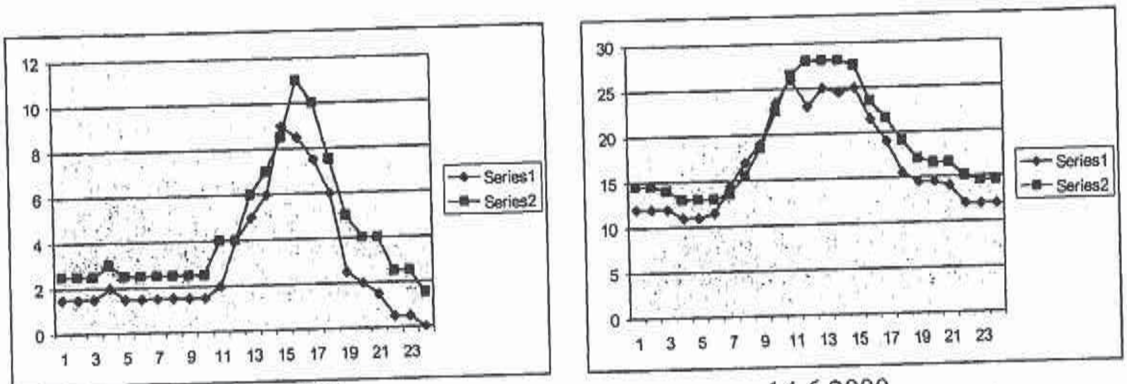
a b

c d

Figure 50. Daily temperature variation during measurement period 1.2.-28.2.2001.

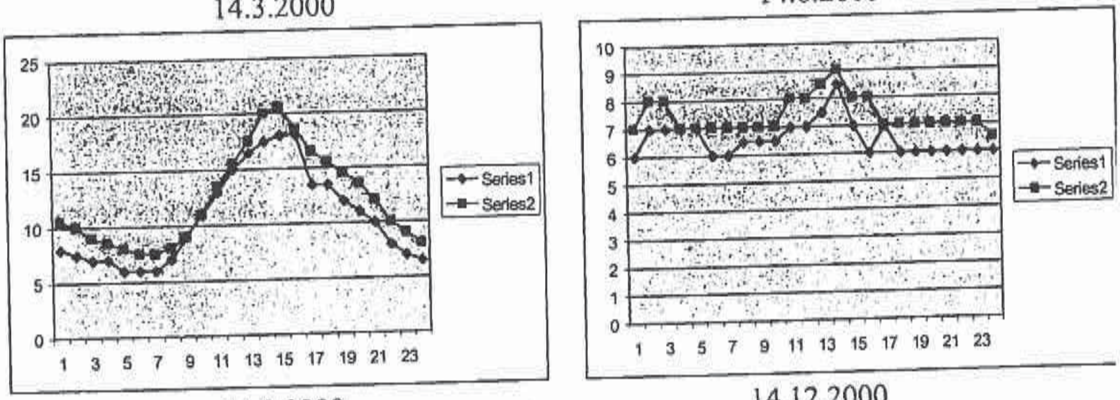
3.2.3 Temperature gradient over the marble panel

Temperature gradient prevailing in the panes was revealed by examining temperatures on the outer and inner surfaces of marble. The results for measuring point A are presented in Figure 51 giving four examples of the daily behaviour of surface temperatures of the measurement panels. The days chosen for the examples represent various seasons. Complete data for all measuring points (A, B, C, D and E) are presented in Appendix 1.



14.3.2000

14.6.2000



14.9.2000

14.12.2000

Figure 51. Temperature of outer (Ser 1) and inner (Ser 2) marble surface (°C) at measuring point A.

3.2.4 Gradient of temperature variation in marble

The gradient of temperature variation over the marble panels was examined as the difference between the range of temperature variation on outer and inner surfaces. The difference is calculated in such a way that the variation on inner surface is diminished from the variation on outer surface. Thus, a positive difference means that the variation has been greater on outer surface and a negative difference that the variation has been greater on inner surface. The results are shown in Figs. 52-55.

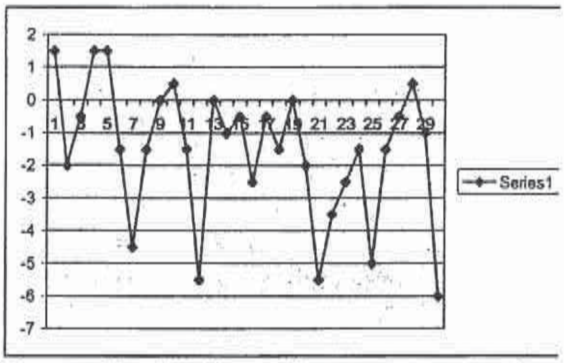


Figure 52. Gradient of temperature variation during measurement period 1.4.-30.4.2000.

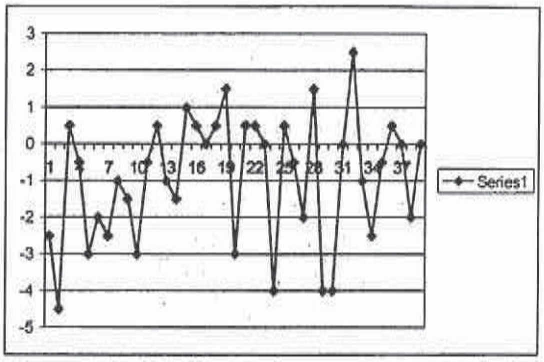


Figure 53. Gradient of temperature variation during measurement period 1.7.-8.8.2000.

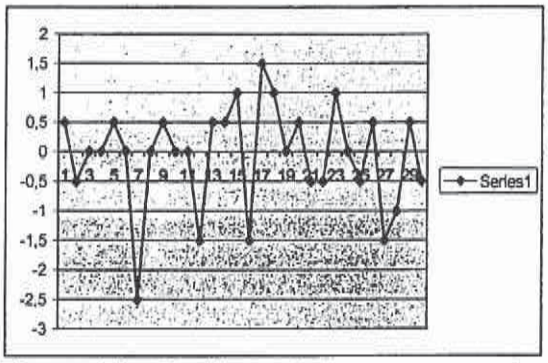


Figure 54. Gradient of temperature variation during measurement period 1.11.-30.11.2000.

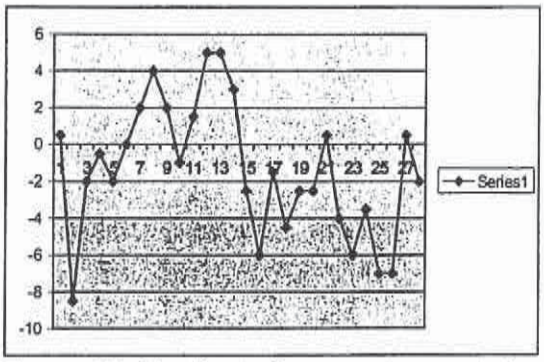


Figure 55. Gradient of temperature variation during measurement period 1.2.-28.2.2001.

3.2.5 Freeze/thaw -cycling of marble

The number of freeze/thaw -cycles occurred on marble surfaces was calculated from the data dealing with the daily variation of temperature. Freeze/thaw-cycle was defined as a day during which the maximum temperature was higher than +0.3°C and the minimum temperature lower than -0.3°C. The number of such days in every month, i.e. the number of freeze/thaw -cycles, on outer (OUT) and inner (IN) surfaces of each measuring panel is presented in Table 13.

Table 13. The number of freeze/thaw -cycles on marble surfaces.

month/year	panel A		panel B		panel C		panel D		panel E	
	OUT	IN	OUT	IN	OUT	IN	OUT	IN	OUT	IN
5/1999	x	x	x	x	x	x	1 7)	1 7)	4 7)	2 7)
6/1999	0	0	0	0	0	0	0	0	0	0
7/1999	0	0	x	x	0	0	0	0	0	0
8/1999	0	0	x	x	0	0	0	0	0	0
9/1999	0	0	x	x	0	0	0	0	0	0
10/1999	1	0	x	x	4 4)	3 4)	1	1	1 8)	1 8)
11/1999	7	5	x	x	x	x	10	9	7	5
12/1999	14	13	x	x	x	x	23	21	15	13
1/2000	4 1)	4 1)	x	x	x	x	16	15	13	14
2/2000	x	x	x	x	x	x	8	3	12	11
3/2000	16 2)	14 2)	x	x	x	x	1	0	25	23
4/2000	5	2	14 3)	8 3)	10 5)	8 5)	0	0	5	4
5/2000	0	0	4	3	0 6)	0 6)	1	1	1	0
6/2000	0	0	0	0	0	0	0	0	0	0
7/2000	0	0	0	0	0	0	0	0	0	0
8/2000	0	0	0	0	0	0	0	0	0	0
9/2000	0	0	1	0	1	0	0	0	0	0
10/2000	2	1	4	3	4	3	2	2	3	2
11/2000	2	0	7	5	6	4	1	1	3	3
12/2000	7	6	1	2	2	2	11	11	5	5
1/2001	21	20	0	0	5	7	9	8	10	11
2/2001	19	20	2	2	1	7	9	10	12	13

x = no results available

1) → 11.1.2000 2) 7.3.2000 → 3) 29.3.2000 → 4) → 20.10.1999 5) 29.3.-12.4.2000
6) 17.5.2000 → 7) 11.5.1999 → 8) 20.10.1999 →

3.2.6 Humidity gradient over the marble panel

The gradient of relative humidity over the marble panels was studied by using the maximum and minimum relative humidities observed daily in outdoor air above the panel and inside the ventilation slot behind the panel. The results from measuring points D and E are shown as pictures presented below. There are four curves in every picture. They are coded with numbers 1-4, and they have the following meaning:

Series 1	maximum relative humidity in outdoor air
Series 2	minimum relative humidity in outdoor air
Series 3	maximum relative humidity in ventilation slot
Series 4	minimum relative humidity in ventilation slot

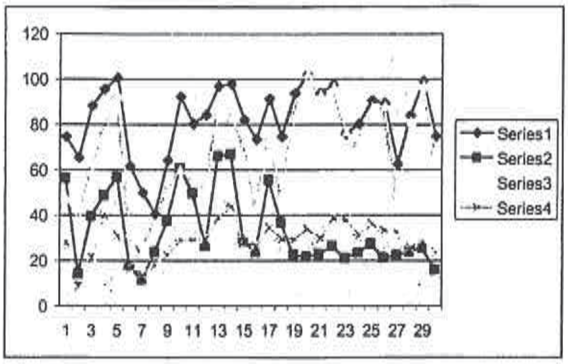


Figure 56. Daily variation of relative humidity during period 1.4.-30.4.2000. Measuring point D.

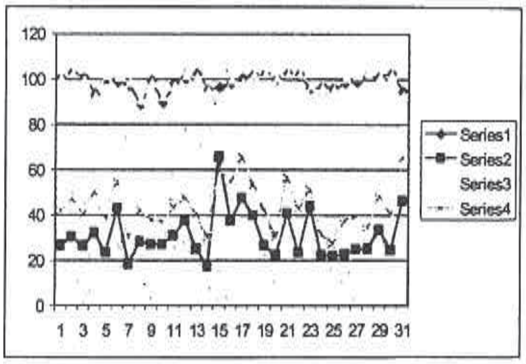


Figure 57. Daily variation of relative humidity during period 1.8.-31.8.2000. Measuring point D.

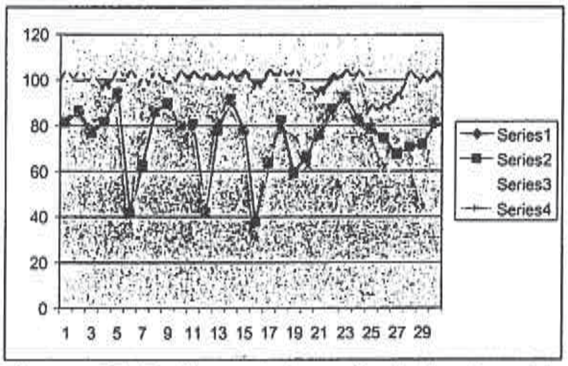


Figure 58. Daily variation of relative humidity during period 1.11.-30.11.2000. Measuring point D.

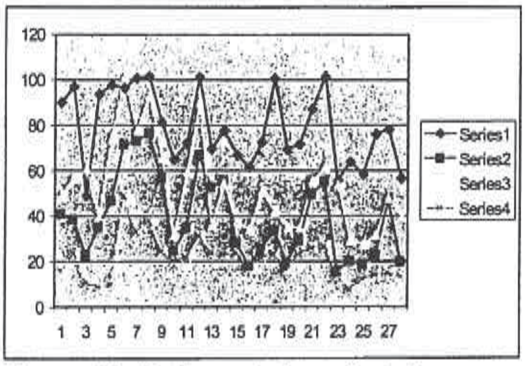


Figure 59. Daily variation of relative humidity during period 1.2.-28.2.2001. Measuring point D.

3.2.7 Acidity of rain water

Finnish Environment Institute has a measurement station at Nupuri, Espoo, about 20 km northwest from Finlandia Hall, where pH of rain water is continuously monitored. Monthly averages from the year 1999 are presented in Table 14.

Table 14. Acidity of rain water at Nupuri measurement station in 1999.

month	pH
January	4.30
February	4.80
March	4.89
April	5.32
May	*
June	*
July	5.34
August	*
September	4.93
October	5.06
November	4.98
December	4.63

* result abandoned due to contamination

The weighted pH-average of the year 1999 was 4.80. It was calculated from the monthly averages by weighing the values presented in Table 15 with the monthly depths of rainfall. The results from the year 2000 were not available by the time of reporting.

3.2.8 Weather conditions

3.2.8.1 Temperature and humidity

Daily maximum and minimum temperatures and corresponding relative humidities in Helsinki area are presented according to the data of Finnish Meteorological Institute in Figs. 60-67. Series 1 represents the maximum values and Series 2 the minimum values.

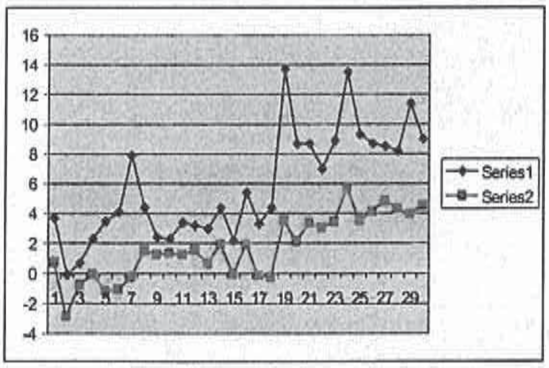


Figure 60. Daily variation of temperature (°C) in Helsinki during period 1.4.-30.4.2000.

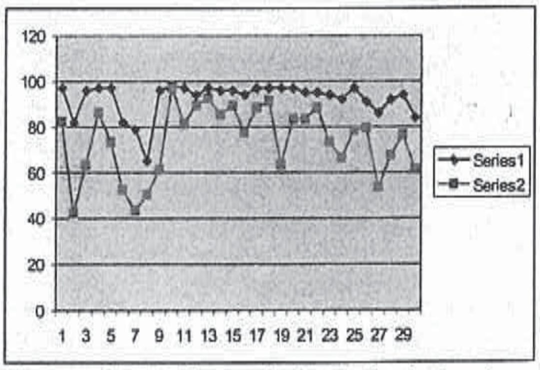


Figure 61. Daily variation of relative humidity (%) in Helsinki during period 1.4.-30.4.2000.

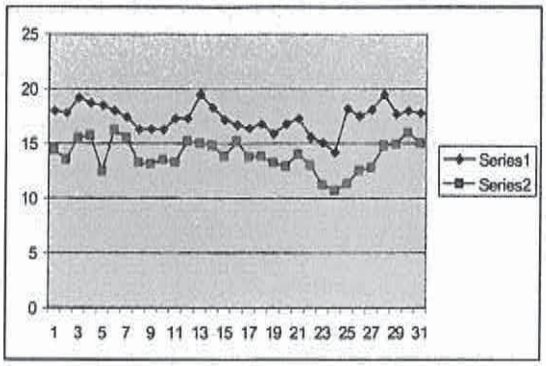


Figure 62. Daily variation of temperature (°C) in Helsinki during period 1.8.-31.8.2000.

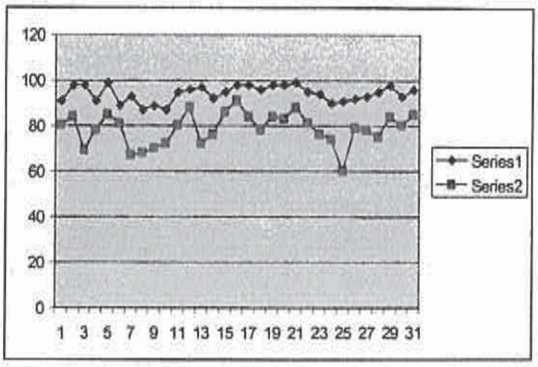


Figure 63. Daily variation of relative humidity (%) in Helsinki during period 1.8.-31.8.2000.

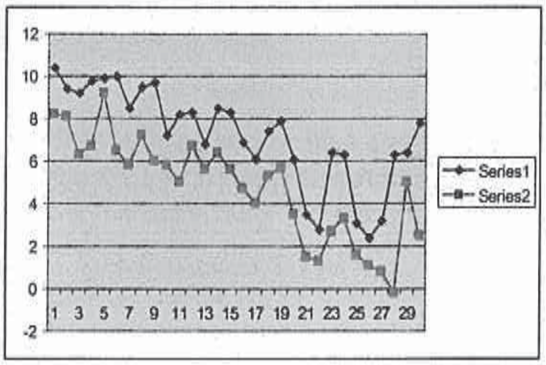


Figure 64. Daily variation of temperature (°C) in Helsinki during period 1.11.-30.11.2000.

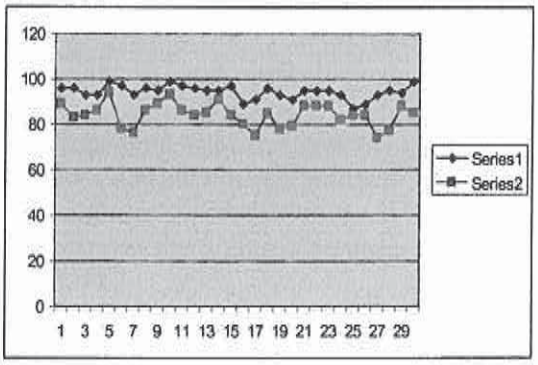


Figure 65. Daily variation of relative humidity (%) in Helsinki during period 1.11.-30.11.2000.

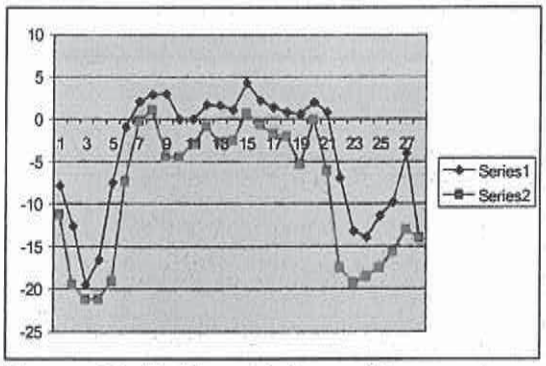


Figure 66. Daily variation of temperature (°C) in Helsinki during period 1.12.-28.2.2001.

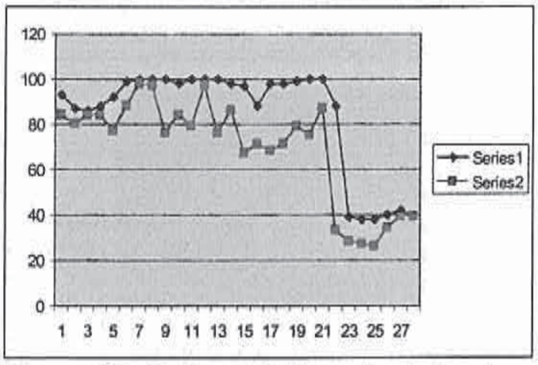


Figure 67. Daily variation of relative humidity (%) in Helsinki during period 1.12.-28.2.2001.

3.2.8.2 Rainfall and sunshine

Daily rainfall and the amount of sunshine in Helsinki area are presented according to the data of Finnish Meteorological Institute in Figs. 68-75.

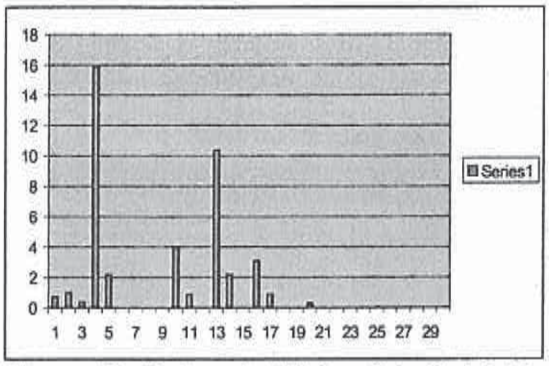


Figure 68. Daily rainfall (mm) in Helsinki during measuring period 1.4.-30.4.2000.

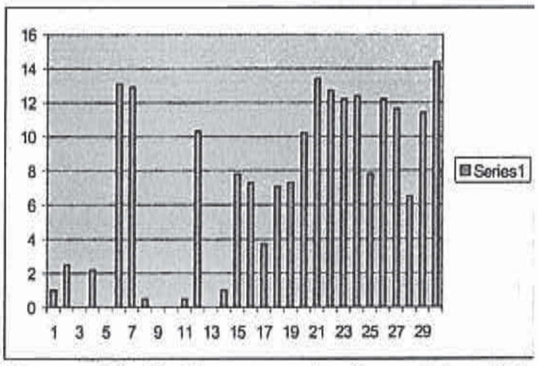


Figure 69. Daily amount of sunshine (h) in Helsinki during period 1.4.-30.4.2000.

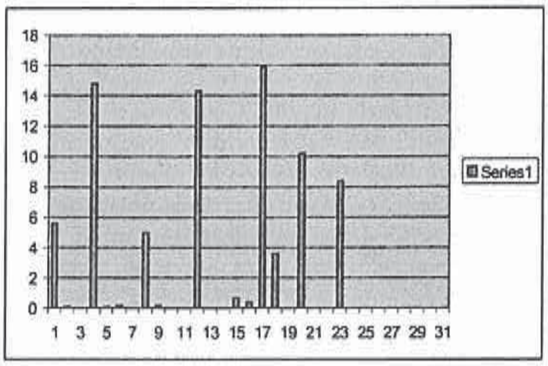


Figure 70. Daily rainfall (mm) in Helsinki during measuring period 1.8.-31.8.2000.

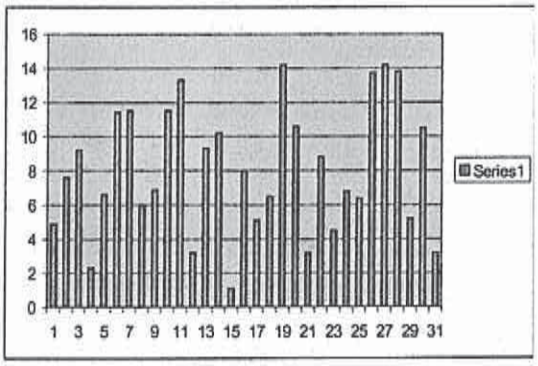


Figure 71. Daily amount of sunshine (h) in Helsinki during measuring period 1.8.-31.8.2000.

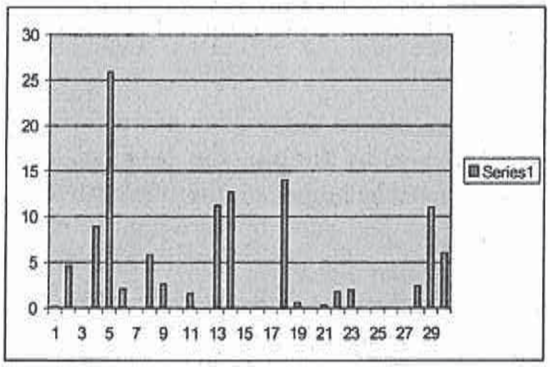


Figure 72. Daily rainfall (mm) in Helsinki during measuring period 1.11.-30.11.2000.

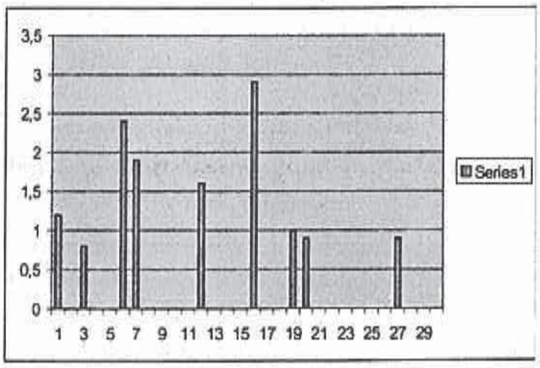


Figure 73. Daily amount of sunshine (h) in Helsinki during period1.11.-30.11.2000.

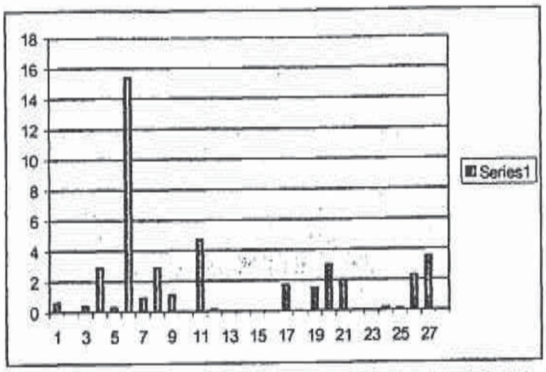


Figure 74. Daily rainfall (mm) in Helsinki during measuring period 1.2.-28.2.2001.

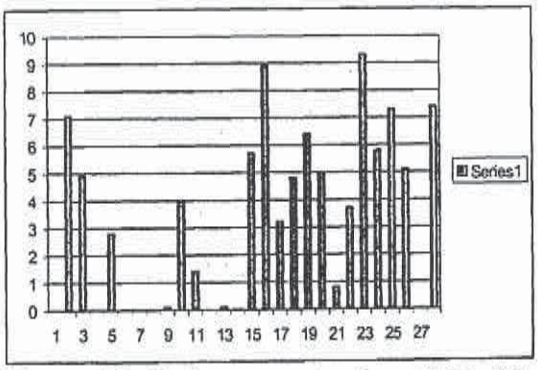


Figure 75. Daily amount of sunshine (h) in Helsinki during period 1.2.-28.2.2001.

3.2.9 Discussion

3.2.9.1 Temperature gradient

According to the temperature data recorded it seems that in general temperature on the inner surface of marble slabs was higher than that on the outer surface. Especially this was the case on western and northern walls, where the inner surface temperature was 1-2°C higher than the corresponding outer surface temperature. Only during the warmest season of the year, June-August, the temperatures were almost the same on both sides of the slab. Occasionally the outer surface temperature was even higher.

On eastern wall the outer surface temperature was usually higher than the inner surface temperature during summer time. The temperature difference varied between 1-4°C. A similar trend was observed in the warmest days of autumn, but then the temperature difference was only about 1°C in favour of the outer surface. For the rest of the year the inner surface was a little warmer than the outer surface.

Measurements from southern wall resembled those from eastern wall. During summer time and the warmest days of autumn the outer surface was warmer, but otherwise the temperature was higher on the inner surface. The temperature differences during summer and autumn were approximately as high as on eastern wall, but during winter the inner surface was about 1°C and during spring even 1-5°C warmer than the outer surface. However, the results from the measuring point A, which was also on southern wall, were different from those presented above. At that point the inner surface temperature was always 1-2°C, during summer time even 2-4°C, higher the outer surface temperature. Because the measuring point A located on top of the wall of the tower part of the building, this could be due to "chimney effect". In that case high inner surface temperatures would be a consequence of the effect of warm air rising up from the roof through the ventilation slot.

3.2.9.2 Daily variation of temperature

The daily variation of temperature of the marble slabs was substantial. It was most prominent during the warm seasons reflecting the natural weather conditions. Except the season the variation depended also on the location of the slab with respect to the cardinal points.

On northern wall the average daily variation of temperature during summer (June-August) was 10-15°C, during spring (February-April) 5-10°C and during winter (November-January) only 2-3°C. In April and in September it was around 10°C and in October around 5°C. The maximum temperature recorded varied accordingly from 30-35°C in summer to around zero in winter. The minimum temperature varied between 5-10°C in summer, but could be as low as -25°C in winter.

On western wall the average daily variation of temperature varied between 15-20°C during the time period from March to September. In winter, from November to January, the variation was only 1-5°C. Between these two periods, i.e. during February and October, the variation was 5-10°C. The maximum temperature varied from 35-40°C in summer to around zero in mid-winter. The minimum temperature was around 10°C in summer but as low as -25°C in winter.

On eastern wall the average daily variation of temperature varied between 15-20°C in summer (June-August), between 5-10°C in spring (March-April) and between 2-5°C in winter (November-January). During May and September it was 10-15°C and during February and October around 5°C. The maximum temperature varied from 35-40°C in summer to about 5°C in winter. The corresponding minimum temperatures were 10°C and -25°C.

On southern wall the average daily variation of temperature varied between 15-20°C in summer (May-September), between 10-15°C in spring (March-April) and between 5-10°C in winter (October-February). The maximum temperature varied from 35-40°C in summer to about 15°C in winter. The minimum temperature was about 10°C in summer and about -25°C in winter. On top of the tower wall (measuring point A) the daily variation during summer and spring times was roughly 5°C higher. Correspondingly, the maximum temperatures were there even 10°C higher than on lower parts of the roof walls. Highest temperatures were measured on the outer surface of black granite slab beside the measuring point A. They were in general 5-10°C higher than the temperatures on the outer surface of the marble slab.

3.2.9.3 Gradient of temperature variation

The daily variation of temperature did not occur evenly in the marble slabs. This can be considered to be significant, because uneven straining of marble could be one of the factors leading to bowing of the slabs.

On northern wall the differencies in the temperature variation between the surfaces were small, and the direction of the gradient changed frequently from one side to another. Most of the time, however, the variation was wider on the outer surface of the slab. Compared to the variation on the inner surface the difference was only 0-1°C.

On western wall the temperature variation was wider on the outer surface of the slab. The difference was noteworthy, 2-4°C, during warm season (April-September), but almost insignificant, 0-1°C, for the rest of the time. In mid-winter the difference between the surfaces in this respect was practically zero.

Also on eastern wall the temperature variation was wider on the outer surface of the slab. The difference was remarkable, 3-4°C, in summer (May-September). During spring (February-April) and late autumn (October) the difference was smaller but clear, 0-2°C. In winter (November-January) the variation was practically the same on both sides of the slab.

On southern wall the temperature variation was wider on the outer surface of the slab except during winter time when the situation was the other way around. In winter (November-February) the difference was 1-2°C, in January even 3-4°C, in favour of the inner surface, but during the rest of the year the difference was 2-3°C, in May-June even 3-4°C, higher on the outer surface. The turning points occurred in October-November on one hand and in March on the other, so that the direction of the difference during these months can be either way.

Again the results from the measuring point A deviated from the trend presented for the southern wall in general. Excluding the mid-winter the variation in that point was wider on the inner surface of the slab. The difference was 2-3°C during February-September and 0-2°C during October-December. In March it was 3-4°C and in September even 5°C. In January the variation was 2-3°C wider on the outer surface. The observed behaviour could be a consequence of the "chimney effect" as discussed in chapter 5.2.

3.2.9.4 Freeze/thaw -cycling

The number of freeze/thaw -cycles during the whole monitoring period of 22 months was amazingly high. The most reliable results were those from the measuring points D and E as their data covered the time period almost completely. The number of freeze/thaw -cycles defined as presented in chapter 4.5 was around 90 in the former and even 110 in the latter. In addition, it must be noted that data from two important months, March and April, were missing from two whole years. These could have meant 20-30 cycles more, which means that the total amount for two years would have been 120-140. Thus the annual amount of freeze/thaw -cycles seems to something like 60-70, while the earlier estimate has been about 20.

The definition of a freeze/thaw -cycle used in this study can be criticised for not being strict enough as the temperature limits were set to -0.3°C for freezing and +0.3°C for thawing. Water in marble probably requires lower temperatures in order to freeze, correspondingly higher temperatures in order to melt. Setting the temperature limits further from zero to both directions would diminish the amount of freeze/thaw -cycles, even considerably if the limits are set far enough. As long as the threshold values for temperatures are not known, the estimates presented here can be used bearing in mind the limitations due to deficiencies in the definition. On the other hand only one cycle per day was calculated in this study as maximum and minimum daily temperatures were used. In reality more than one cycle can occur even in the same day.

The worst directions from the frost resistance point of view seem to be south and east. Considerable amount of data was lacking from north and west walls. The results would indicate that the amount of cycles would have been lower in these directions, although considerable especially on western wall.

The amount of freeze/thaw -cycles seemed to a little lower on the inner surface of the marble slab than on the outer surface. The difference was about 10%. As this causes a higher strain on the outer surface than on the inner this could be one of the factors contributing to bowing of the slabs.

Only during the three summer months, June-August, no freeze/thaw -cycles were observed. The worst period of time in this respect was naturally that from November to March. It seemed that the southern wall was especially strained during November-January while the others suffered most in February-March. During October some cycles were detected in all directions. Excluding the southern wall the situation was the same during April. During May and September some occasional freeze/thaw -cycles were observed on other walls except the southern one.

3.2.9.5 Relative humidity

In general the values of relative humidity were fairly high. During autumn and winter times the average relative humidity values were even higher than during spring and summer. This was due to the fact that the daily minimum rose from the value of about 20%, which was typical of summer time, to 60-80%, or even higher.

On the southern wall there seemed to be a difference between the relative humidity of outdoor air and that of the ventilation slot for the most of the time meaning a humidity gradient over the marble slab. The direction of the gradient was not same all of the time, however. During summer time (May-August) the average relative humidity was higher inside the ventilation slot, though the difference was rather small. It was due to the fact that the minimum value was higher than that of oudoor air and thus the variation of relative humidity was smaller inside.

The situation was exactly the other way around during November-December, when the minimum relative humidity inside the ventilation slot was smaller than that of outdoor air meaning wider variation of humidity inside. However, the the most remarkable difference was observed during January-April. During that time period both the maximum and the minimum relative humidities were higher in outdoor air than in the ventilation slot. Thus, the conditions were considerably more humid on the outer surface of the marble than on the inner surface. Only during September-October the humidity conditions were similar on both sides of the marble slab.

On the eastern wall the humidity conditions were much more even than on the southern wall. There were no great differencies between the relative humidities of outdoor air and that of the ventilation slot. Only during winter time, from January to March, both the maximum and the minimum relative humidities were higher in outdoor air than in the ventilation slot. Thus, the conditions were considerably more humid on the outer surface of the marble than on the inner surface.

The differencies in relative humidity between outdoor air and the ventilation slot causes a higher strain on the outer surface of marble slab than on the inner. Thus, this could be one of the factors contributing to bowing of the slabs.

3.2.9.6 Acidity of rain water

The pH-value of rain water varied between 4.3 and 5.3 during 1999 the weighed average being 4.8. The values of the year 2000 were not available, but most probably the situation was very similar to that in 1999. Although the acidity of rain water has diminished, i.e. the pH-value increased, during the last decade it still acts like a weak acid. Thus, it forms a straining factor to all materials subjected to rain water. Its effect must especially be taken into account when materials like marble which are very reactive in acidic surroundings are considered.

3.2.10 Conclusions

According to the temperature and humidity data recorded the prevailing environmental conditions include several factors that cause strain to the marble facades of Finlandia Hall. The intensity of these factors was not the same everywhere but depended on the cardinal point towards which the walls were directed. It seemed that in general the sum of the straining factors was highest on southern walls and lowest on northern walls.

The annual variation of temperature is one of the straining factors. The minimum temperature recorded during the time period in question was about -25°C on all walls. The corresponding maximum temperature varied from about 35°C on the northern side to about 50°C on top of the southern side of the tower part of the building.

The daily variation of temperature was also considerable. The average variation was highest on southern walls, 15-20°C during summer and 5-10°C during winter time. On northern walls the average variation was lowest varying between 10-15°C during summer and 2-3°C during winter. Occasionally the daily variation could be even twice the average.

Freeze/thaw -cycling caused also strains to marble and facade structures. According to the results the annual amount of cycles can be as high as 60-70. The freeze/thaw -effect was prominent at least on southern and eastern walls, probably also on western walls.

At least two other straining factors were observed: variation of humidity and acidity of rain water. During summer and spring time the relative humidities, especially the daily minimum values, were varying sharply depending whether it was raining or not. During colder seasons the humidity conditions were much more even. The pH-value of rain water varied between 4 and 5 creating acidic conditions that can affect the highly reactive marble.

In addition, three factors causing a higher strain on the outer surface of marble slab than on the inner were observed: the average daily variation of temperature, the number of freeze/thaw -cycles and the relative humidity were higher on the outer surface. The differences were small, but all of them affected in the same direction. Thus, these could be at least some of the factors contributing to bowing of the slabs.

3.3 Effect of protective agent

3.3.1 Laboratory studies

3.3.1.1 Resistance to UV-radiation

According to the colour measurements the whiteness (colour co-ordinate L) increased in the UV-chamber. However, the increase was higher in untreated marble than in protected marble. There was also a clear tendency for the colour co-ordinate a to move towards more positive and for the colour co-ordinate b to move towards more negative values. This means that marble became more red and more blue. The change of the co-ordinate a was small and about the same both in reference and protected marble, but the change of the co-ordinate b was somewhat higher in the protected specimens than in the reference specimens. The detailed results are presented in Appendix 1.

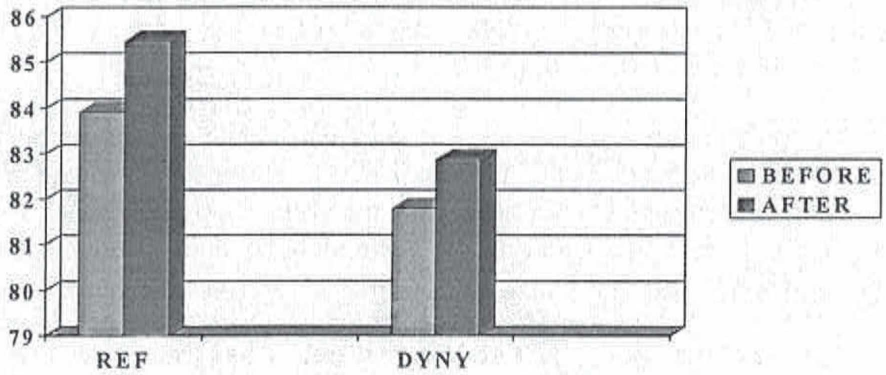


Figure 76. CIELAB colour co-ordinate L of marble A before and after UV-treatment. REF = unprotected, DYNY = protected.

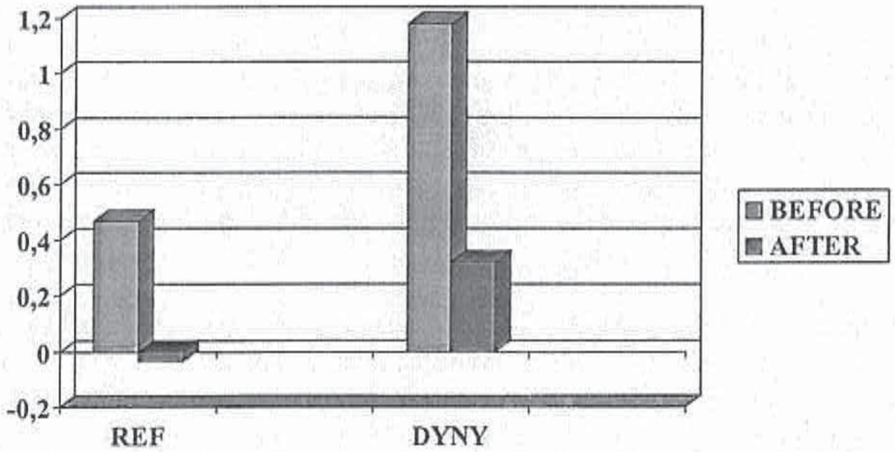


Figure 77. CIELAB colour co-ordinate b of marble A before and after UV-treatment. REF = unprotected, DYNY = protected.

The colour differences, ΔE, of the specimens calculated from the measurements are shown in Table 15. According to the results some colour change takes place by the effect of UV-light. It is notable, however, that the change in the unprotected marble specimens was higher than that in the protected specimens. Also, it must be noticed that the use of the protective agent in itself changes the colour of marble (ΔE = 2.31). Especially, the protective agent seemed to have a decreasing effect on the whiteness of marble. In addition, the colour difference between the unprotected and protected marble increased in the UV-treatment (ΔE = 2.62).

Table 15. Colour change of unprotected and protected (Dyny) marble A in UV-treatment.

	ΔE
unprotected	1.66
protected	1.39

3.3.1.2 Heat resistance

According to the colour measurements the whiteness (colour co-ordinate L) increased in the heat treatments as a function of temperature, i.e. the higher the temperature the higher the value of the co-ordinate L. However, the increase was as high in untreated marble as in protected marble. Instead, no clear tendency for the colour co-ordinates a or b could be observed. Thus, in this respect no change of colour took place in the marble. Detailed results are presented in Appendix 1.

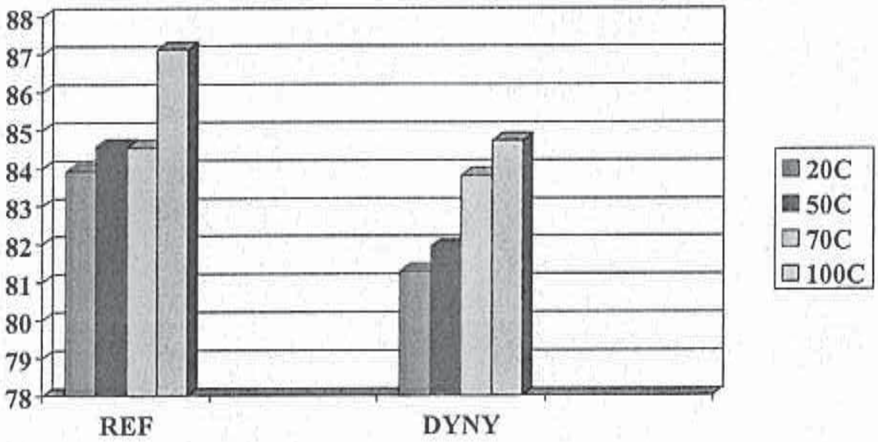


Figure 78. CIELAB colour co-ordinate L of marble A before and after various heat treatments. REF = unprotected, DYNY = protected.

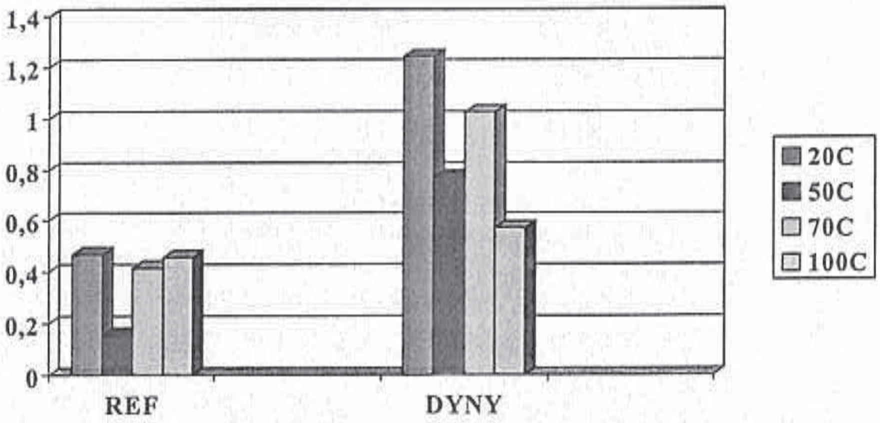


Figure 79. CIELAB colour co-ordinate b of marble A before and after heat treatment. REF = unprotected, DYNY = protected.

The colour differences, ΔE, between the treated and untreated specimens calculated from the measurements are shown in Table 16. According to the results a clear colour change takes place by the effect of heat. It is notable that in the unprotected marble specimens this change was significant only at 100°C. In the protected specimens the change was evident already at 70°C. Also, it must be noticed that the use of the protective agent in itself changes the colour of marble. Especially, the protective agent seemed to have a decreasing effect on the whiteness of marble. However, this colour difference between the unprotected and protected marble did not change in the heat treatments.

Table 16. Colour change of unprotected and protected (Dyny) marble A in heat treatments.

heat treatment	ΔE
unprotected	
50°C	0.73
70°C	0.64
100°C	3.22
protected	
50°C	0.79
70°C	2.53
100°C	3.49

3.3.1.3 Chemical resistance

According to ISO 10545-13:1995 both unprotected and protected (Dyny) samples were treated with the following chemicals:

- hydrochloric acid
- citric acid
- potassium hydroxide

Observations made of the test specimens after the test showed that the protective treatment (Dyny) did not improve the chemical resistance of marble, at least not with respect to the chemicals applied. The resistance classes of marble as specified in the standard are also shown for each chemical. Complete test data is available at Appendix 1.

D. Resistance to stains

Test results were classified according to the ease of removing the particular stain from the surface as well as to the irreversible damage caused to the surface. Following chemicals were applied to both the unprotected and protected (Dyny) samples:

- iodine
- olive oil
- red staining agent

According to the results the protective agent used (Dyny) clearly improved the cleanibility of marble. Especially this seemed to be the case when the stain contained organic compounds. Complete test data is available at Appendix 1.

3.3.2 Test wall studies

3.3.2.1 Flexural strength

A clear decrease of flexural strength could be measured during the test period for the protected samples. Depending on the protective agent used and the testing direction applied the strength values of the protected samples compared with the untreated sample decreased during 1,5 years with 26-32 %. In Figure 80 test result with protective agent Dyny are presented. The measurement results are shown in detail in Appendix 1.

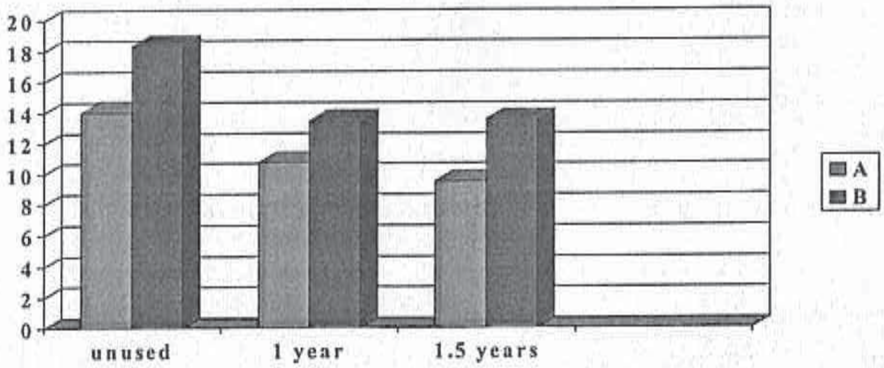


Figure 80. Flexural strength of marble A protected with Dyny (MPa).

3.3.2.2 Water absorption, apparent porosity, bulk density

The water absorption and apparent porosity of marble type A protected with the tested agents at initial stage and after 1 and 1.5 years on the test wall at Finlandia Hall are presented in Figures 81 and 82. A significant increase of the values could be measured during the test period for the protected samples. Depending on the protective agent used and the testing direction applied the strength values of the protected samples compared with the untreated sample increased during 1,5 years by 65-74 %. The measurement results are shown in detail in Appendix 1.

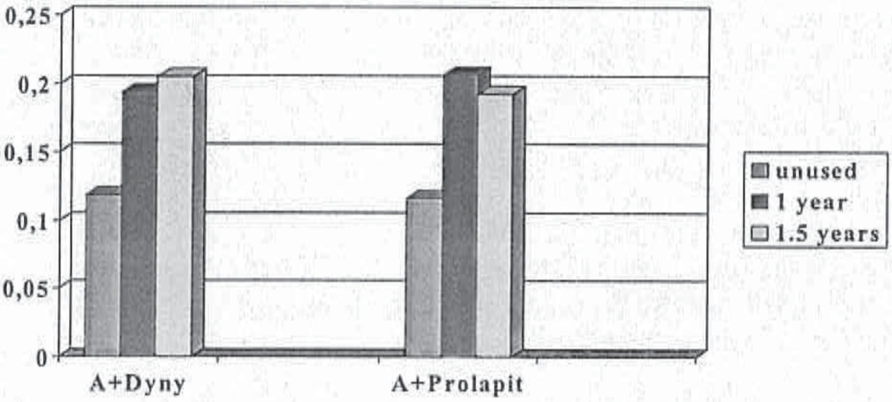


Figure 81. Water absorption of the protected marbles (w-%).

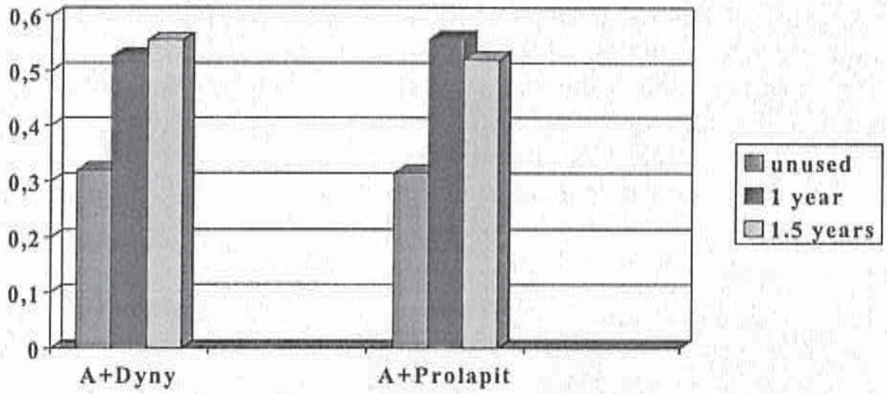


Figure 82. Apparent porosity of the protected marbles (vol-%).

3.3.2.3 Microstructure

A. Thin section study

Microstructure photograph of marble A protected with "Prolapit" after 1 year on the test wall is shown in Figure 83. The following observations were made:

- groundmass fine-grained, even-grained, not oriented
- average grain size 200-300 µm
- nearly pure carbonate rock, some quartz and little opaque minerals were detected
- no signs of deterioration observable

Figure 83. Microstructure of marble A protected with Prolapit. 1 year on the test wall. Plane-polarized light.

B. SEM-study

BSE- and SE-images of marble A protected with the agents "Dyny" and "Prolapit" after 1 year on the test wall show that grain boundaries can partly be distinguished. No signs of deterioration could be seen in the structure of marbles. Protective agents formed a layer on the surface of the marble panels. The layers seemed unaltered after 1 year on the test wall. The layer thickness was 15-30 µm with the agent "Dyny" and 10-15 µm with the agent "Prolapit". Detailed results are presented in Appendix 1.

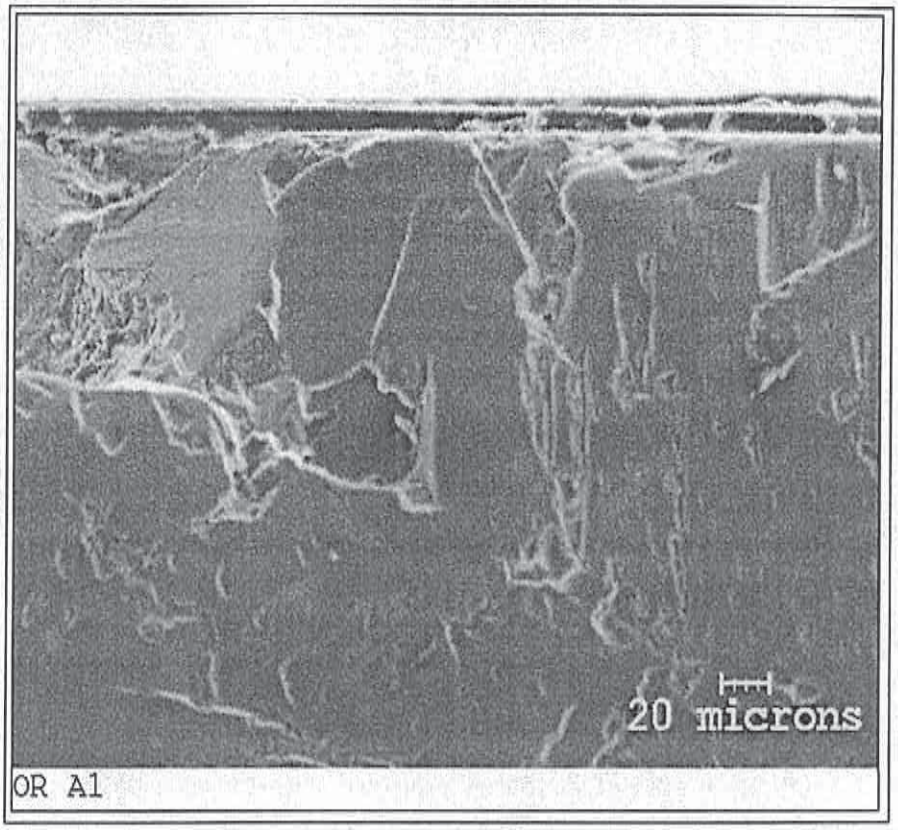


Figure 84. Marble A + Dyny. A layer of protective agent on the surface of the panel having a thickness 15-30μm. 1 year on the test wall. SE-image, 300x.

SEM-pictures of fractured surfaces of marble A protected with agents "Dyny" and "Prolapit" after 1 and 1.5 years on the test wall are shown in Figs. 85-86. The individual grains can, at least for the most part, be distinguished from each other. Cracks can be noticed between some of the grains. The maximum crack width observed in the specimens was around 0.6-0.7 μm.

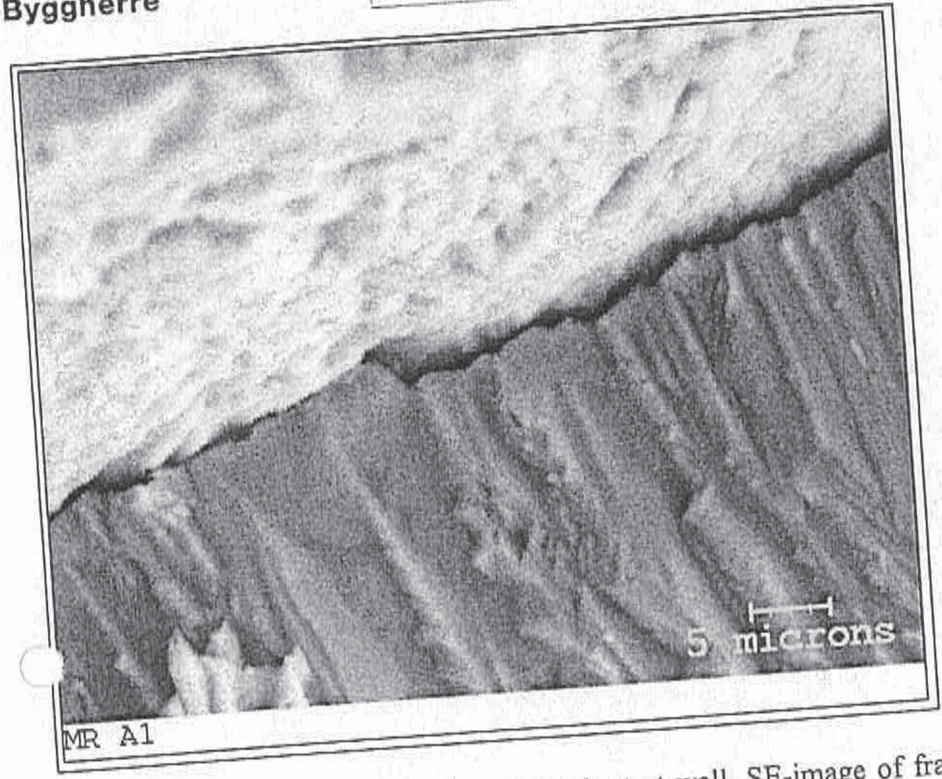
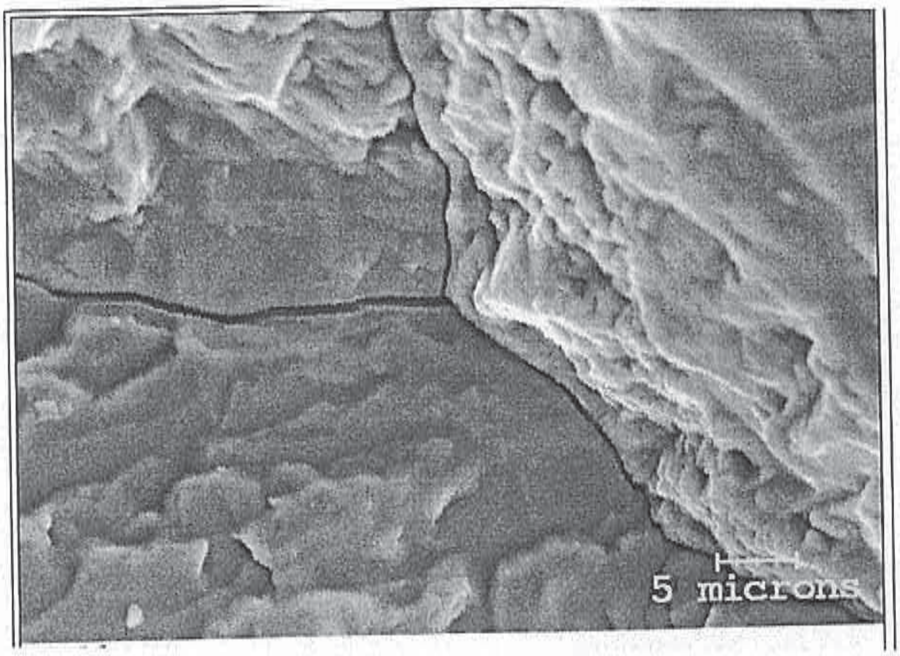


Figure 85. Marble A + Dyny. 1 year on the test wall. SE-image of fractured surface, 2500x.


5 microns

3.3.2.4 Colour measurement

The colour of the protected marble panels chosen for this part of the study was measured 5 times during the project between 23.6.1999 – 8.3.2001. Marbles with both of the protective agents were white, the L value of the unused panels varying between 81 and 83. The values of the co-ordinates a and b were near zero, even though the marbles had a slight greenish hue. Compared to unprotected marble A, the value of the co-ordinate L was a little lower and that of the co-ordinate b a little higher.

According to the colour measurements the whiteness of the marbles increased. The increase was fairly even. Also, there was a clear even if slight tendency for the co-ordinates a and b to move towards more positive values. This means that the marbles are getting more yellow and more red, which could refer to fouling of the marble surfaces. So far the changes have, however, been small. As a whole, the behaviour of the protected marble panels was similar to that of the unprotected panels. The results from the colour measurements for all the marbles are shown in Appendix 1.

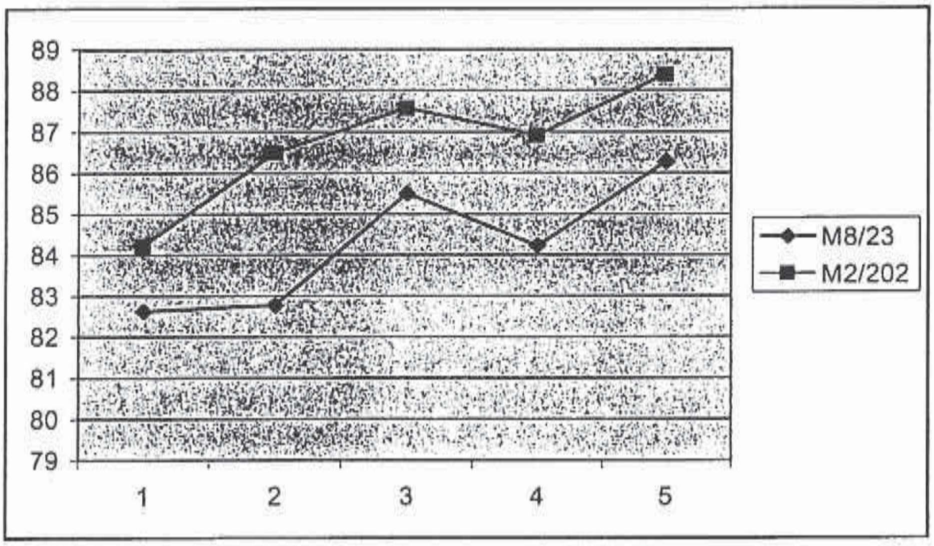


Figure 87. CIELAB colour co-ordinate L of marble A + Dyny.

The colour differences, ΔE, of the protected marbles calculated from the values of the first (1) and the last (5) measurements are shown in Table 17. According to the results the colour change of protected marbles is evident. However, the change is of the same order of magnitude as the change observed with unprotected marble A.

Table 17. Colour change of the protected marbles in time period 6/99-3/01 (CIELAB).

marble	wall	ΔE
A+Dyny	23	3.66
	202	4.18
A + Prolapit	23	3.92
	202	4.17

3.3.3 Discussion

3.3.3.1 Resistance properties

According to the colour measurements the protective agent used in the laboratory studies (Dyny) altered the colour of marble. It decreased the whiteness of marble, in marble A the L value of CIELAB co-ordinates dropped from about 84 to 81-82, and increased the yellowish hue, in marble A the value of co-ordinate b rose from about 0.5 to about 1.2. The colour difference caused by these changes was fairly obvious.

Treatment in the UV-chamber increased the whiteness of protected marble. Because it increased the whiteness of unprotected marble as well, the change was most probably not due to chemical degradation of the protective agent but a consequence of the deterioration of marble itself. As discussed in the report of the subproject "Test wall" thermal treatment is used to increase the whiteness of marble, and the process is presumably based on the microstructural cracking accomplished by thermal variations. Thus, the increased whiteness in the UV-chamber is not directly caused by radiation but elevated temperature it generates at least on the surface of marble.

On the other hand, UV-radiation dropped the value of co-ordinate b of protected marble almost to the same level as that of unprotected marble. This indicates that the protective agent is, at least to a certain extent, sensitive to UV-radiation and may show some degradation when subjected to it.

Heat treatments had the same effect on the whiteness of protected and unprotected marble as UV-radiation. Most probably also the reason for the increase was the same, i.e. microstructural cracking of marble caused by thermal variation. However, a decrease in the value of co-ordinate b was also observed in protected marble. As above this refers to some sort of degradation of the protective agent due to heat. The colour change taking place for this reason was almost insignificant, though.

The protective agent used in the studies was resistant against alkalies, but it could not protect marble from the etching effect of acidic compounds. It must be noted, however, that the test used to evaluate the behaviour of the agent was not very suitable for the purpose, because in this test specimens were immersed as whole in the chemical. Thus, the potential protective effect of the agent got covered by the very vigorous reaction of marble itself. In any case, there were some signs that the protective agent didn't take part in the reaction. Its resistance against acidic compounds should be studied again by using a method in which only the surface with the protective agent is subjected to acids.

The protective agent used in the studies improved considerably the resistance of marble to stains of organic nature. The mechanism of protection seemed simply to be that it prevented the organic compounds from intruding into marble, which made marble surface relatively easy to be cleaned. However, most probably there are some organic compounds that can react with the protective agent and can in that way cause a stain which is much more difficult to remove. This kind of signs was to be observed when the only inorganic chemical of the test, iodine, was applied on the protected surface, even if it could be cleaned as easily as from unprotected marble.

3.3.3.2 Strength properties

The initial flexural strength of protected marble (type A) varied between 14 and 19 MPa.The lowest values were measure in testing direction A and the highest in testing direction B, the strength ratio A/B varying between 0.7-0.8. This refers to some kind of schistosity in stone structure. The results of unprotected marble A in the subproject "Test wall" were similar to those determined here.

The strength of protected marble decreased considerably on the test wall, which most probably is a sign of the effect of some sort of a deterioration process. The loss of strength was 25-30%, and it was about the same in both directions and with both protective agents. The results in the subproject "Test wall" were precisely parallel to those discussed here. Thus, the loss of strength can be considered to be a real phenomenon, and it can't be explained to be due to sampling or random variation of strength. In fact, the strength losses detected in protected marble were somewhat higher than those determined for unprotected marble. If the difference is real, there must a factor in the deterioration mechanism that is affected by the changes in marble properties due to protective agents in an accelerating way. At least, the difference can't be explained with difference in the strain level accomplished by environmental conditions, as both protected and unprotected marble slabs were placed on the same test wall for the same period of time.

The fact that the strengths were of the same order of magnitude after 1 and 1.5 years on the test wallwas also a very noteworthy feature in the results. This would indicate that the loss of strength on the test wall happened very soon after the slabs were installed, and after that the deterioration process proceeded only slowly. Also in this respect the results were parallel to those of unprotected marble.

According to the results of the strength measurements the protective agents used in the study can't prevent the loss of strength taking place in marble when subjected to environmental strains. Thus, the deterioration mechanism in question is not dependend on at least any straigth reaction of e.g. water and/or acidic compounds or other impurities with marble surface.

3.3.3.3 Water absorption properties

Protected marble was very dense. The water absorption was about 0.12 w-%, apparent porosity 0.31-0.32 vol-% and bulk density 2712-2715 kg/m^3. The results were similar to those of unprotected marble. This is explained by the nature of the test which was used in the measurements, because in the test the specimens are totally immersed in water instead of subjecting water only to the surface treated with the protective agent. Thus, the test is not able to evaluate the protective capability of the agent.

The water absorption and apparent porosity of protected marble increased considerably, around 65-75%, on the test wall. The increase observed in unprotected marble was practically the same. No further increase in the values of the water absorption properties could be observed between 1 and 1.5 years on the test wall. Thus, the results in this respect were in line with those from the strength determinations.

The fact that porosity of marble increases when subjected to environmental strains refers to a deterioration mechanism that causes cracks to marble structure. These cracks can go either straight through the individual grains or, more probably, along the grain boundaries.Emergence of cracks to marble structure would also explain the loss of strength observed. It seems, however, that at least a certain amount of cracks appears almost immediately when marble is subjected to strains but then the process slows down and the degree of cracking stays more or less at same level. Also, it seems likely that the mechanism causing the cracks is not affecting through reactions occurring on the outer surface of marble, as already discussed above.

3.3.3.4 Microstructure

According to the definition by prof. Royer-Carfagni from University of Parma marble structures can be classified along the axis of xenoblastic-homoblastic. Xenoblastic marble structure is characterized by interlacing of irregular grains that are closely fitted to each other along their wavy contours. On the other hand, homoblastic marble structure is characterized by regular-shaped grains with straight or gently curving boundaries. Thin section study of the protected marbles revealed that the structure was intermediate, i.e. it was between the two extremes showing both xenoblastic and homoblastic features. Marble was fairly even-grained, and the average grain size was around 0.2 mm. The results were similar to those observed for unprotected marble in the subproject "Test wall".

No changes could be observed in the microstructure of protected marbles taken from the test wall with SEM-study of polished marble sections. As thin sections polished sections can be used to reveal the structure type of marbles, but the method is not sensitive enough to monitor the changes taking place in the microstructure due to environmental strains. Also, polished marble fractions can be used to determine the condition of the layer of the protective agent on marble surface. According to the observations made the protective layer of both of the agents seemed unaltered after 1 year on the test wall. The layer thickness of the agent "Dyny" was 15-30 µm and that of the agent "Prolapit" 10-15 µm.

The structural type of marble could be identified also in the SEM-study of fractured surface specimens of protected marbles. As already stated above, the structure of marble was intermediate: in part the individual grains could be easily seen, in part no grain boundaries could be distinguished in the structure.

SEM-study of fractured specimens revealed also cracks in the specimens of marbles that had been on the test wall. The maximum crack width observed was about 0.6-0.7 µm, though in general the cracks were narrower. The behaviour of the protected slabs was exactly the same as that of the unprotected marble. Thus, protective agents can't prevent marble from cracking.

Crack formation is a clear sign of deterioration occurring in marble. The fact that the cracks go along the grain boundaries, not straight through the grains, indicates to a mechanism that tends to separate the grains from each other. Thus, cracking can be a consequence of thermal variations taking place in marble slabs as the thermal expansion behaviour of calcite crystals of which the grains of marbles are composed is anisotropic, i.e. the expansion coefficient is higher in the direction of one crystallographic axis than in the other perpendicular to the first one. This kind of a deterioration mechanism would also explain the inefficiency of protective agents to prevent marble from damaging when subjected to thermal variations.

Another possible explanation can be the freeze/thaw effect which tends to widen the cracks already existing in marble structure and also in this way to create new. Naturally, both of the mentioned mechanisms can act simultaneously. It seems, though, that freezing and thawing is of minor importance as it could be expected that protective agents could at least retard the effect of that type of a deterioration mechanism. As stated, nothing of the kind could be observed.

3.3.3.5 Colour measurements

According to the colour measurements the protective agents didn't alter the colour of the marble to a considerable extent. The initial value of CIELAB co-ordinate L (whiteness) of the protected slabs was around 83, which was only slightly lower than that of the unprotected marble. In the laboratory tests discussed in chapter 5.1 the darkening effect of the protective agent was much more obvious. Also, the agents didn't change the slight greenish hue of marble with the value of co-ordinate a of about -1, but they had a small effect in the axis of blue-yellow, as they altered the original blueish hue to neutral or even to a little bit of yellow with the value of the co-ordinate b varying between 0 and 0.1.

The whiteness of the protected marbles increased when the slabs were subjected to environmental strains on the walls of Finlandia Hall. Presumably this is a sign of the deterioration process taking place in marble. It is common knowledge in the manufacturing of marble products that their whiteness can be increased by thermal treatment. As it is obvious that variation of temperature causes granular decohesion in marble, it seems plausible to suppose that it is just this deterioration that is reflected also in the colour of marble as increased whiteness. This theory of the reason for increasing whiteness on the walls is supported by the observation that the colour change was evident especially during the first year, but after that the rate of change seem to have slown down. A similar time-dependent behaviour was observed in the strength and water absorption properties, which without any doubt are directly connected to deterioration.

A minor but clear tendency for the co-ordinates a and b to move towards more positive values was observed in the protected marble slabs. This means that they are turning more red and more yellow, which could refer to fouling of marble surfaces.

It is noteworthy that the behaviour of the protected marble slabs also in this respect was similar to that of the unprotected marble. Thus, the protective agents haven't had any effect on the colour change of marble. So far this changes has, however, been small, and in addition most of it is due to increased whiteness, not to change of the other co-ordinates. The time period of monitoring the colour changes, about 20 months, has been so short that no definite conclusions can yet be made. For good reason it can be expected that the effect of the protective agents, if any, will be seen only during longer periods of time, as the outer surface of unprotected marble starts to lose its gloss and gets more apt to fouling.

3.3.4 Conclusions

According to the studies made the deterioration of marble structure taking place when subjected to environmental strains is caused by granular decohesion, which forms cracks along the grain boundaries. Granular decohesion seems to be a consequence of the anisotropic thermal expansion behaviour of calcite crystals. For this reason marble grains that are composed of calcite crystals break away from each other when thermal variations occurring naturally affect the material, e.g. in facades. The strain caused by freezing and thawing may have an accelerating effect on the deterioration process after it has started and enough cracks have been formed.

The results achieved show that the damaging of marble structure takes place very soon after it has been subjected to environmental strains, probably already during the very first cycles of thermal variation. After that the deterioration process slows down, and the properties of marble will stay more or less stable. Thus, in order to predict the behaviour of marble for any longer periods of time a longer period of time for monitoring the marble properties would also be required. A reliable view e.g. of the rate of strength decrease as an indication of the progress of the deterioration process can be acquired only in that way.

Because of the nature of the deterioration mechanism described above it can't be influenced by the use of protective agents. If other factors, e.g. freeze/thaw effect and chemical degradation, have a significant contribution to the deterioration process during later stages, these might be retarded with the use of some sort of a protection on the outer surface of marble. More long-term studies dealing with thsi issue would, however, be needed.

Measurements of marble colour can be used to monitor the fouling of marble surfaces. So far protected marble has shown similar behaviour as unprotected marble. However, in order to get a reliable picture of the effect of possible protective treatments on the fouling behaviour the period of time used for monitoring the colour should be much longer than that used in this project, probably at least 5 years.

According to the laboratory studies marble surface can be protected against stains and certain types of chemical effects by the use of protective agents. They are especially effective against stains of organic nature. The agents themselves, however, seem to be affected by UV-radiation and thermal strains. Thus, their service life is limited. Long-term monitoring of the resistance of the protective layer on marble surface would be needed in order to determine the proper period for renewal of the protection procedure

According to the measurements the walls of Finlandia Hall have already deteriorated. The strength decrease of marble about two years after installing the slabs is 20-30%. Continuous monitoring of the microstructure and the strength properties as well as the colour of the wall marble is recommended.