APPENDIX 2

VTT BUILDING AND TRANSPORT

RESEARCH REPORT

Developing long term durability of marble facades

Subproject "Test wall"

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Encl.: Final report (91 pages + 4 Appendices with 22 pages)

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1 BACKGROUND

The need for conserving, restoring and protecting stone buildings and monuments throughout the world is growing continuously. This is particularly actual in the historic cities of Europe where marble and other calcareous stones have been commonly used. The decay of old stone structures is becoming a remarkable technical and economic problem. Deteriorated stone facades may in some cases even represent a considerable safety risk. The durability problems have led to a strong decrease in the use of marble for outdoor applications.

One of the most important reasons for the deterioration and fouling of natural stones is the rising amount of acid compounds and other impurities coming mainly from industrial and traffic sources. Today stone structures are exposed to harsher environmental conditions than ever before. Thin stone veneers that are commonly used nowadays are even more sensitive for weathering than traditional massive stone structures.

Carrara marble was used as the original facade material for Finlandia Hall. In the early 1980's the marble plates began to warp. Warping was especially noticeable in larger plates because of lapping. It also became apparent that the plates' inner strength was rapidly weakening. Extensive studies were undertaken to determine the cause of the deterioration. The conclusion was that the phenomenon was mainly due to climatic factors and especially to acid rain, which gradually converts marble to gypsum.

The badly damaged marble facade of Finlandia Hall was renewed during the autumn of 1998 and the spring of 1999. In connection with the refurbishment, the City of Helsinki launched the research project "Developing long-term durability of marble facades" known as "MARA-project". The main aims of the project were to extend the service life of the new facade, to formulate an appropriate maintenance strategy and to create reliable technical criteria and methods to assess the suitability of marble for facade applications.

As already stated above the degradation of marble is a universal problem, which has been especially highlighted by recent cases of damage to old buildings and historic monuments. However, in Europe there are also a number of other architecturally significant new buildings that have fallen victim to the same kind of deterioration as Finlandia Hall. Because research results can therefore be widely exploited, the MARA-project received financial support from the EU's Raphael cultural heritage programme.

VTT Building and Transport was responsible for four subprojects of the main study. The primary goals of these subprojects were to determine the deterioration mechanism of marble, to set requirements for a durable marble facade structure and to develop a reliable method for testing marble quality. The subprojects also included studies of the environmental conditions at Finlandia Hall and of the stresses these cause to marble, of the durability of different types of marble, of the performance of alternative structural solutions and of the possibilities of using protective treatments. The studies were made in co-operation with Helsinki University of Technology, Parma University in Italy and Cevalor in Portugal.

2 OBJECTIVE

The aim of the subproject "Test wall" was to determine the durability of various marbles in the facades of Finlandia Hall and to study the connection between their real behaviour and that observed in laboratory conditions. In addition, the aim of the subproject was to examine the behaviour of various structural solutions.

In order to achieve the goals set for the subproject it was divided into four tasks:

- the effect of the environmental stresses prevailing at Finlandia Hall on the strength properties of marbles and marble clad elements
- the effect of the environmental stresses prevailing at Finlandia Hall on the microstructure and the composition of marbles
- the effect of the environmental stresses prevailing at Finlandia Hall on the colour and the appearance of marbles
- reporting of the results and conclusions made from them

3 EXPERIMENTAL

3.1 General arrangements

The marbles for the project were chosen by the representatives of the City of Helsinki. Four different types of marbles were used in the studies, and they were coded with letters A, D, E and K. All the marble types were white and originated from the area of Carrara in Italy (Carrara Bianco). One of the marble types (A) was the same that was used for the renewal of the facades of Finlandia Hall. According to a general assumption formed from practical experiences two of the marble types (E, K) should show a relatively good durability in outdoor applications. Correspondingly, one of the marble types (D) was thought to be not durable and thus unsuitable for facades.

The City of Helsinki delivered one unused slab of each marble type for the laboratory studies. The measures of the slabs were approximately 30x800x1200 mm^3. In order to study the effect of the prevailing environmental conditions on the properties of the marbles a test wall was constructed on the roof of Finlandia Hall. The test wall was a simple wooden frame that supported the test slabs from lower and upper edges of the slabs and prevented them from falling. Air could circulate freely around the slabs. The frame was placed on the roof in such a manner that the faces of the slabs were directing towards south.

One slab of each marble type was installed on the test wall in May 1999. In May 2000 the slabs were cut vertically in half. The other halves were taken to laboratory while the others were left on the test wall for another 6 months. These were taken for the laboratory studies in November 2000.

The City of Helsinki delivered also three marble clad elements, which were coded with letters F, H and L. The element F, measuring about 40x800x1200 mm^3, consisted of a thin (10 mm) marble plate and a thick (30 mm) concrete background. The element H, measuring about 25x800x1200

mm^3, consisted of a very thin (5 mm) marble plate glued on an aluminium honeycomb structure (20 mm). The honeycomb structure was covered with thin glass fiber sheets. The element L, measuring about 23x800x1200 mm^3, consisted of a thin (11 mm) marble plate glued on a steel honeycomb structure (22 mm). Marbles for the elements were chosen by the manufacturers, and their types or qualities have not not been made public.

One element of each type was installed on the test wall at the same time as the marble slabs. The sampling procedure was similar to that of the marble slabs described above.

3.2 MARBLES

3.2.1 Flexural strength

The flexural strength of the marbles was determined by using the slabs taken from Finlandia Hall after 1 and 1.5 years on the test wall. The reference values were measured from the unused slabs.

The flexural strength of the marbles was determined according to the standard EN 12372:1999. Test specimens were prisms with a height of 30 mm, width of 70 mm and length of 180 mm. The distance between the supporting rollers during the tests was 150 mm. The load was increased uniformly at a rate of 70 N/s. Deviating from the clauses of the standard the specimens were dried at (40 ± 2)°C instead of (70 ± 5)°C. The flexural strength, R_{tf}, of each specimen was calculated by using the formula (1):

$$R_{tf} = 3Fl / 2bh^2 \qquad (1),$$

where F = breaking force, N
l = distance between the supporting rollers, 150 mm
b = width of the specimen, mm
h = height of the specimen, mm

The specimens were sawn from the slabs in such a way that the length of the prisms was either parallel (direction A) or perpendicular (direction B) to the longer side (1200 mm) of the original slabs, Fig. 1. Ten specimens were prepared in both directions for each test.

3.2.2 Water absorption, apparent porosity, bulk density

The water absorption, apparent (open) porosity and bulk density of the marbles were determined by using the slabs taken from Finlandia Hall after 1 and 1.5 years on the test wall. The reference values were measured from the unused slabs.

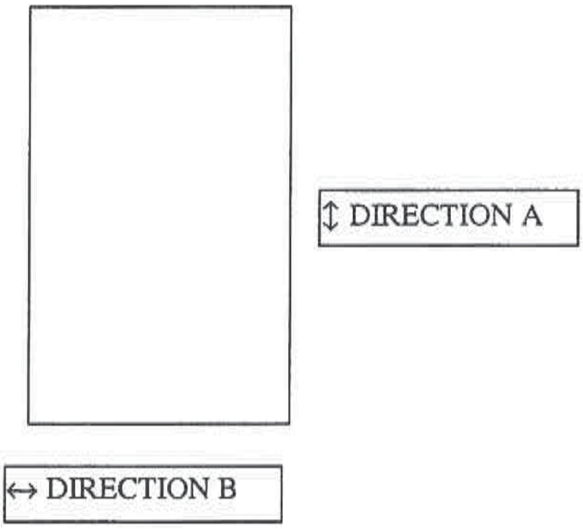


Figure 1. Flexural strength of marbles. Testing directions.

The water absorption properties of the marbles were determined according to the standard EN 1936:1999. Test specimens were prisms with a height of 30 mm, width of 70 mm and length of 180 mm. The surface area to volume ratio, A/V, of the specimens was 0.106. Deviating from the clauses of the standard the specimens were dried at (40 ± 2)°C instead of (70 ± 5)°C. Six specimens were prepared for each test. The water absorption, W, the apparent porosity, p_o, and the bulk density, ρ_b, of each specimen were calculated by using the formulae (2)-(4):

$$W = 100\% \times [(m_s - m_d) / m_d] \quad (2),$$

$$p_o = 100\% \times [(m_s - m_d) / (m_s - m_h)] \quad (3),$$

$$\rho_b = m_d / (m_s - m_h) \quad (4),$$

where
m_d = mass of the dry specimen, g
m_s = mass of the saturated specimen, g
m_h = mass of the specimen immersed in water, g

3.2.3 Mineral composition

3.2.3.1 X-ray diffraction

The mineral composition of the marbles was studied with a Philips PW 1710 X-ray diffractometer. The runs were made by using CuK_α -radiation, which was produced with a voltage of 50 kV and a current strength of 20 mA. Powder samples were used. Powders needed for the analyses were prepared by pulverizing pieces that were left over from the specimen prisms after their flexural strengths had been measured. In order to ascertain the homogeneity of the diffraction samples, the size of the batch that was pulverized was approximately 2 kg.

3.2.3.2 Thermal analysis

The mineral composition of the marbles was studied also with thermal analysis. The runs were made from the same powder samples that were prepared for X-ray diffraction by using a Netzsch STA 429 thermobalance. The run parameters were as follows:

atmosphere	flowing air, 6 cm^3/min	
heating rate	5°C/min	
end temperature	1000°C (sample)	
sample size	240-250 mg	
reference	Al_2O_3-powder, 195.2 mg	
crucibles	Al_2O_3	
thermocouples	Pt-Pt/Rh(10)	
scales	TG	125 mg
	DTG	500 µV
	DTA	200 µV

3.2.4 Microstructure

3.2.4.1 Thin section study

Thin sections of the marble specimens, 0.025x30x50 mm^3, were prepared at right angles to the surface of the slabs. Pieces were cut from the slabs with a diamond saw, impregnated with epoxy resin and ground first with a grinding machine and then by hand to final thickness (0.025 mm). The thin sections were studied with a Leica DM HC LP polarising light microscope and photographed with a Leica Q500IW image analysis equipment.

3.2.4.2 Elementary composition, distribution of elements

Similar pieces as for thin section studies were cut from the marble slabs. The surfaces of the sawn pieces were sequentially ground with a SiC paper of grit 320, 600, 800 and 1200. The ground surfaces were carbon coated and studied with a Jeol JSM 820 scanning electron microscope (SEM) in a backscattered electron mode (BSE). BSE-images were taken with an Imix image analysis system. Elementary analyses were made with an energy dispersive spectrometer (EDS) from areas that represented the materials just beneath the surfaces of the marble slabs. Elementary dot maps were collected over the same areas of elements Ca, Si, Al, Mg, Na, K, S, Cl, P, Fe and Mn. Ag-map was used to eliminate the effect of the background spectrum.

3.2.4.3 SEM-study

First part of the SEM-study was made by using polished marble sections. The surfaces of the sawn sections were sequentially ground with a SiC paper of grit 320, 600, 800 and 1200 and polished with diamond suspensions of grain sizes 6 and 0.25 µm. The sections were carbon coated and studied with a Jeol JSM 820 scanning electron microscope (SEM). The study was made in a backscattered electron mode (BSE) with a 50-fold magnification and in a secondary electron mode

(SE) with a 500-fold magnification. BSE and SE images were taken with an Imix image analysis equipment. BSE-images give information about the mean atomic weight of the compounds (the lighter the colour the higher the atomic weight of the compound). SE-images show the topography of the samples.

Second part of the SEM-study was made by using fractured surface samples of marbles. The samples were broken from the marble slabs, any loose material was wiped off and the fractured surfaces were carbon coated. The samples were studied with a Jeol JSM 820 scanning electron microscope (SEM) in a secondary electron mode (SE). SE-images were taken with an Imix image analysis equipment.

3.3 MARBLE CLAD ELEMENTS

3.3.1 Bond strength

The bond between the marble plate and the rest of the element structure was studied by measuring the force needed to loosen the marble from the base structure. In order to perform the measurement a cylinder-shaped drill core extending through the marble plate was first drilled on the surface of the slab. A metal plate with a drawhook was then glued on the marble inside the drill core. The plate was exactly the same size as the drilled core with a diameter of 50 mm. Finally, the drill core was pulled loose with a pulling machine which used the hook of the metal plate and which took its support from three points around the core. The tensile strength was calculated by dividing the required force with the area of the core. The place where the loosening had taken place was also recorded.

Six individual measurements were made from each slab. The measurement points formed a straight line which was parallel to the longer side of the element.

3.3.2 Microstructure

Microscopic study of the elements was made by using polished element sections. Pieces of the elements were cut at right angles to the surface of the slabs with a diamond saw and impregnated with epoxy resin containing fluorescent dye. Smaller samples (about 3x5 cm^2, thickness 3-5 mm) were sawn from the pieces, again perpendicular to the original slab surface, and glued on object glasses. The surfaces of the sawn samples were impregnated once again with epoxy and then sequentially ground with a SiC paper of grit 600, 800 and 1200. The sections were studied with a Leica DM HC LP polarising light microscope and photographed with a Leica Q500IW image analysis equipment. Both oblique illumination and fluorescent light from above were used.

3.4 COLOUR MEASUREMENTS AT FINLANDIA HALL

The behaviour of marble slabs on the walls of Finlandia Hall was studied also by measuring the colour of the slab surfaces at regular intervals. CIELAB system was used to define the colour. In this system any colour can be defined with the help of Lab co-ordinates L, a and b. The co-ordinate L describes the degree of lightness in such a way that the value L = 0 corresponds to totally black and the value L = 100 to totally white. The co-ordinates a and b describe the colour saturation, a in the axis of green...red (-60...+60) and b in the axis of blue...yellow (-60...+60).

The colour difference, ΔE, between two samples or between two measurements from the same sample is defined by using the formula (5).

$$\Delta E = (\Delta L^2 + \Delta a^2 + \Delta b^2)^{1/2} \tag{5}$$

The colour difference is clear if $\Delta E > 3$, but cannot be observed if $\Delta E < 1$.

The colour measurements were made by using an automatic Minolta CM-525i reflectance spectrometer. The light source was D_{65} corresponding to CIE standard.

Altogether nine slabs were chosen for the colour measurements, three representing marble A and two representing each of marbles D, E and K. All the slabs were placed on the roof walls directing either towards south (walls 24 and 202) or towards east (wall 23). Two of the slabs of marble A were directing towards south and one towards east. With the other marbles one of the slabs was directing towards south and the other one towards east. The colour of the slabs was measured from eight points, each including three spots. Thus, the colour of the slabs was presented as an average of total 24 individual measurement values.

3.5 FIELD SAMPLES

In order to get a little wider view of the material behaviour in real environmental conditions a few field samples were collected and studied. By the permission of the owners samples were taken from buildings with marble facades. All except one of these facades showed clear bowing and considerable loss of strength. All facades were 20-30 years old.

3.5.1 Mineral composition

The mineral composition of the field samples was studied with a Philips PW 1710 X-ray diffractometer and a Netzsch STA 429 thermobalance. The runs were made as described earlier in chapters 3.2.3.1 and 3.2.3.2. Powder samples were used. Powders needed for the analyses were prepared by pulverizing some of the sample pieces.

3.5.2 Thin section study

Thin sections of about 0.025x30x50 mm^3 were prepared from the marble specimens taken at right angles to the surfaces of the original slabs. Specimens were impregnated with epoxy resin and ground first with a grinding machine and then by hand to final thickness (0.025 mm). The thin sections were studied with a Leica DM HC LP polarising light microscope and photographed with a Leica Q500IW image analysis equipment.

3.5.3 SEM-study

SEM-study of the field samples was made by using fractured surface specimens. The specimens were broken from the marble pieces available, any loose material was wiped off and the fractured surfaces were carbon coated. The specimens were studied with a Jeol JSM 820 scanning electron microscope (SEM) in a secondary electron mode (SE). SE-images were taken with an Imix image analysis equipment.

4 RESULTS

4.1 MARBLES

4.1.1 Flexural strength

The flexural strength of marble A in initial stage and after 1 and 1.5 years on the test wall at Finlandia Hall is presented in Table 1. The corresponding values of marbles D, E and K are presented in Tables 2-4, respectively. The presented results are average values (av.) and standard deviations (s.d.) calculated from the testing data of individual specimens. The measurement results are shown in detail in Appendix 1.

Table 1. Flexural strength of marble A.

	flexural strength		
	direction A MPa	direction B MPa	A/B
unused			
av.	12.5	16.9	0.74
s.d.	1.2	0.6	
s.d. (%)	9.6	3.4	
test wall / 1 year			
av.	10.5	14.0	0.75
s.d.	1.0	1.1	
s.d. (%)	9.2	8.1	
test wall / 1.5 years			
av.	10.1	14.1	0.72
s.d.	1.1	1.0	
s.d. (%)	10.6	7.4	

Table 2. Flexural strength of marble D.

	flexural strength direction A MPa	 direction B MPa	A/B
unused			
av.	5.4	7.0	0.77
s.d.	0.7	0.7	
s.d. (%)	12.2	10.4	
test wall / 1 year			
av.	3.5	3.7	0.96
s.d.	0.2	0.6	
s.d. (%)	6.8	16.3	
test wall / 1.5 years			
av.	3.6	4.1	0.88
s.d.	0.4	0.4	
s.d. (%)	9.8	10.8	

Table 3. Flexural strength of marble E.

	flexural strength direction A MPa	 direction B MPa	A/B
unused			
av.	20.4	19.9	1.02
s.d.	1.3	1.8	
s.d. (%)	6.4	8.8	
test wall / 1 year			
av.	17.0	24.0	0.71
s.d.	4.0	1.0	
s.d. (%)	23.4	4.1	
test wall / 1.5 years			
av.	22.5	24.1	0.94
s.d.	2.7	1.3	
s.d. (%)	12.1	5.4	

Table 4. Flexural strength of marble K.

	flexural strength direction A MPa	 direction B MPa	A/B
unused			
av.	22.4	19.6	1.14
s.d.	0.9	1.4	
s.d. (%)	3.9	7.0	
test wall / 1 year			
av.	21.6	19.3	1.12
s.d.	0.7	1.4	
s.d. (%)	3.1	7.3	
test wall / 1.5 years			
av.	21.9	20.4	1.07
s.d.	1.6	0.9	
s.d. (%)	7.4	4.2	

For comparison the flexural strengths of the unused marbles are shown in Fig. 2.

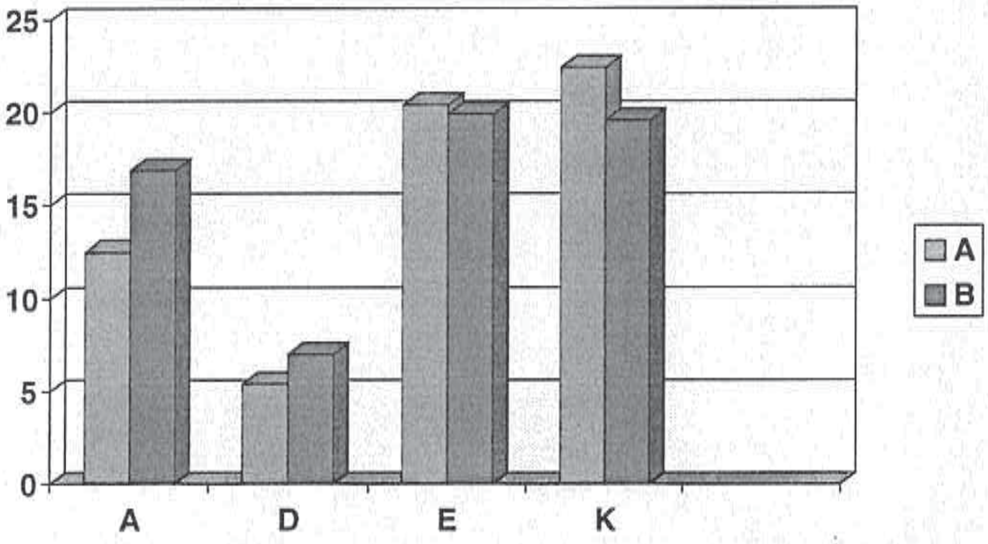


Figure 2. Flexural strengths of the unused marbles (MPa).

The relative changes of the flexural strengths, ΔR_{tf}, of the marbles that have taken place on the test wall are presented in Table 5. The basis of the comparison is in all cases the flexural strength of the unused marble.

Table 5. The relative changes of the flexural strengths of the marbles on the test wall.

marble	ΔR_{tf}	
	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

The loss of marble strength on the test wall is illustrated also in Figs. 3-6. In each case the flexural strength of unused marble has been given the value of 100.

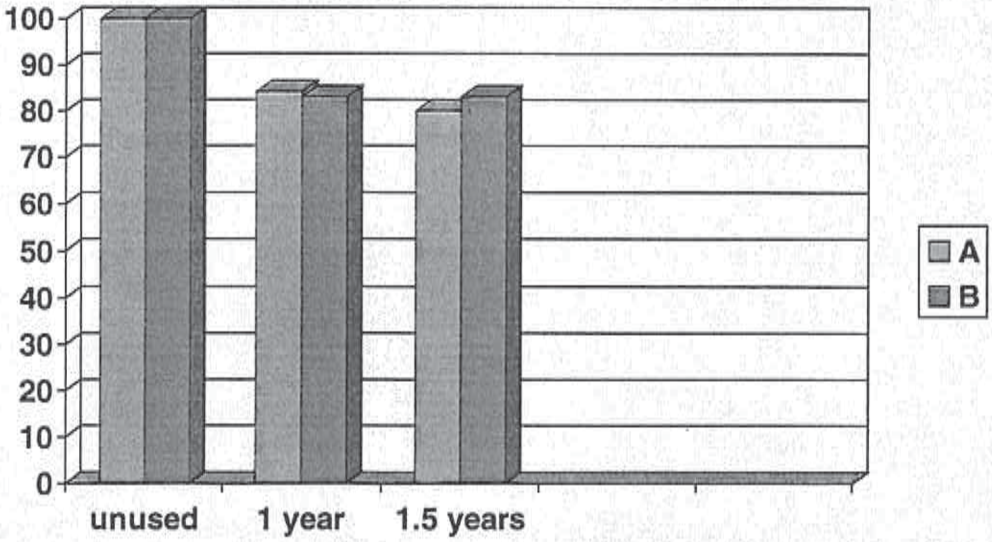


Figure 3. Flexural strength of marble A. A relative scale.

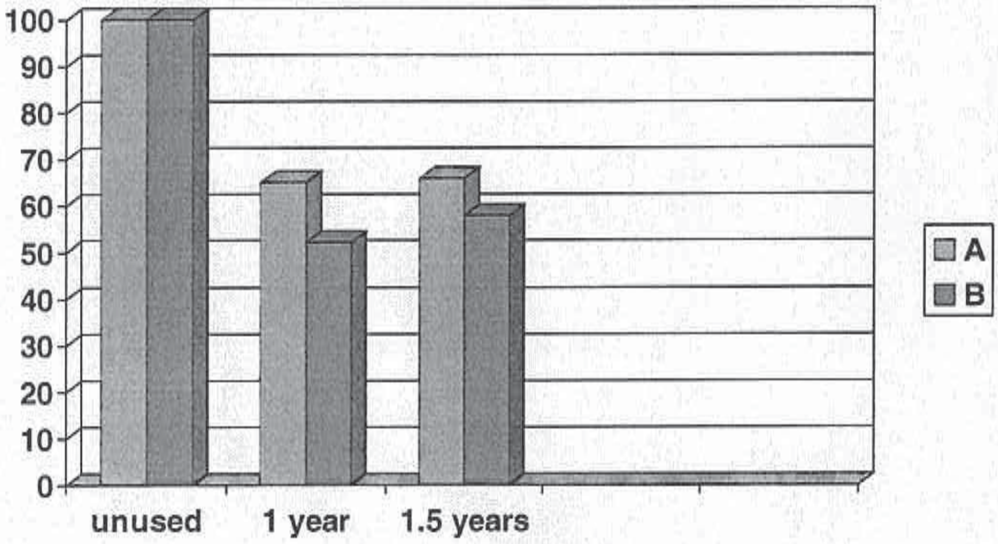


Figure 4. Flexural strength of marble D. A relative scale.

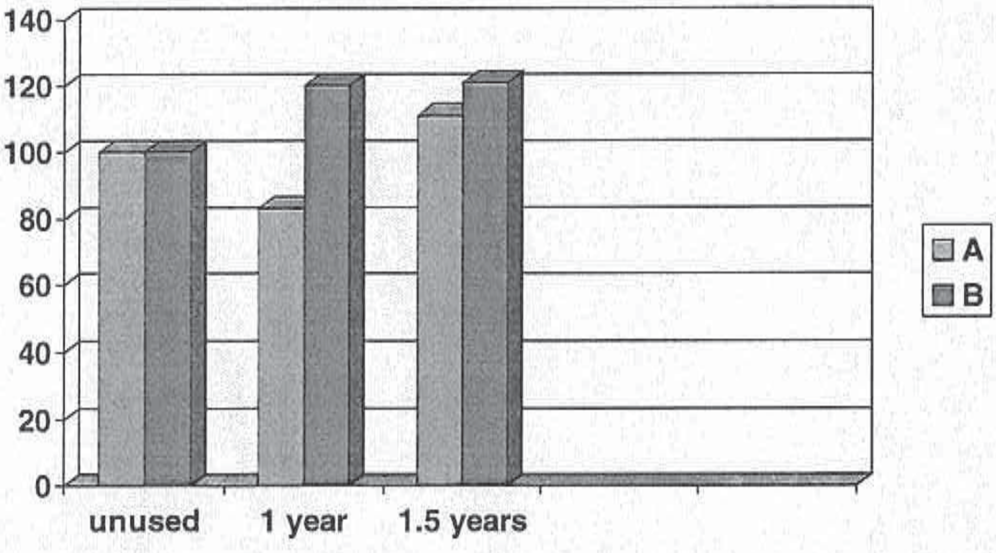


Figure 5. Flexural strength of marble E. A relative scale.

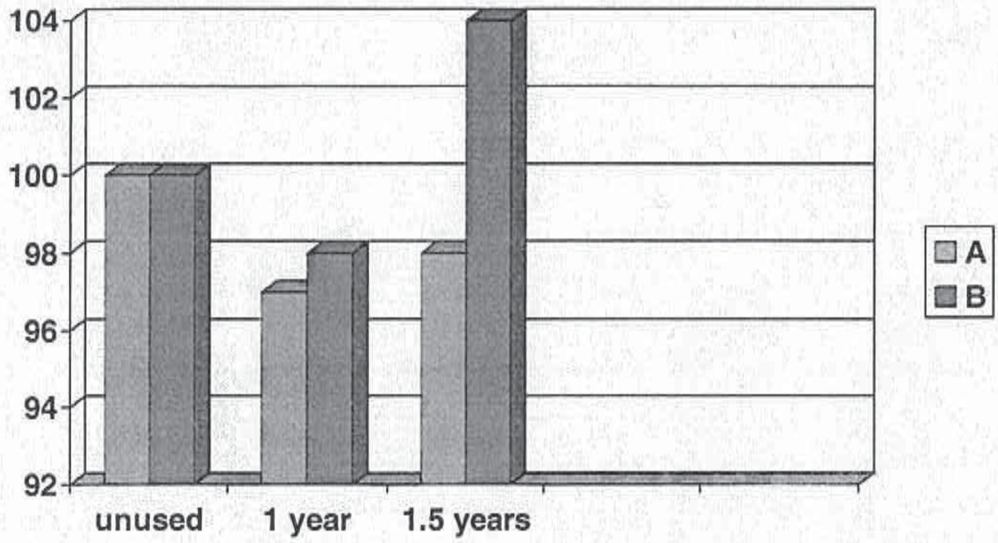


Figure 6. Flexural strength of marble K. A relative scale.

4.1.2 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 Finlandia Hall are presented in Table 6. The corresponding values of marbles D, E and K are presented in Tables 7-9, respectively. The presented results are average values (av.) and standard deviations (s.d.) calculated from the testing data of individual specimens. The measurement results are shown in detail in Appendix 2.

Table 6. Water absorption, apparent porosity and bulk density of marble A.

	water absorption w-%	apparent porosity 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

Table 7. Water absorption, apparent porosity and bulk density of marble D.

	water absorption w-%	apparent porosity vol-%	bulk density kg/m^3
unused			
av.	0.125	0.339	2718
s.d.	0.011	0.028	7
s.d. (%)	8.8	8.3	0.26
test wall / 1 year			
av.	0.240	0.650	2706
s.d.	0.009	0.023	1
s.d. (%)	3.8	3.5	0.04
test wall / 1.5 years			
av.	0.221	0.597	2705
s.d.	0.026	0.069	2
s.d. (%)	11.8	11.6	0.07

Table 8. Water absorption, apparent porosity and bulk density of marble E.

	water absorption w-%	apparent porosity vol-%	bulk density kg/m^3
unused			
av.	0.111	0.301	2715
s.d.	0.006	0.016	3
s.d. (%)	5.4	5.3	0.11
test wall / 1 year			
av.	0.124	0.339	2732
s.d.	0.006	0.018	23
s.d. (%)	4.8	5.3	0.84
test wall / 1.5 years			
av.	0.121	0.329	2713
s.d.	0.008	0.021	1
s.d. (%)	6.6	6.4	0.04

Table 9. Water absorption, apparent porosity and bulk density of marble K.

	water absorption w-%	apparent porosity vol-%	bulk density kg/m^3
unused			
av.	0.069	0.188	2716
s.d.	0.009	0.025	1
s.d. (%)	13.0	13.3	0.04
test wall / 1 year			
av.	0.108	0.294	2715
s.d.	0.013	0.036	1
s.d. (%)	12.0	12.2	0.04
test wall / 1.5 years			
av.	0.104	0.282	2713
s.d.	0.017	0.047	1
s.d. (%)	16.4	16.7	0.04

The water absorptions and apparent porosities of the marbles are shown in Figs. 7 and 8.

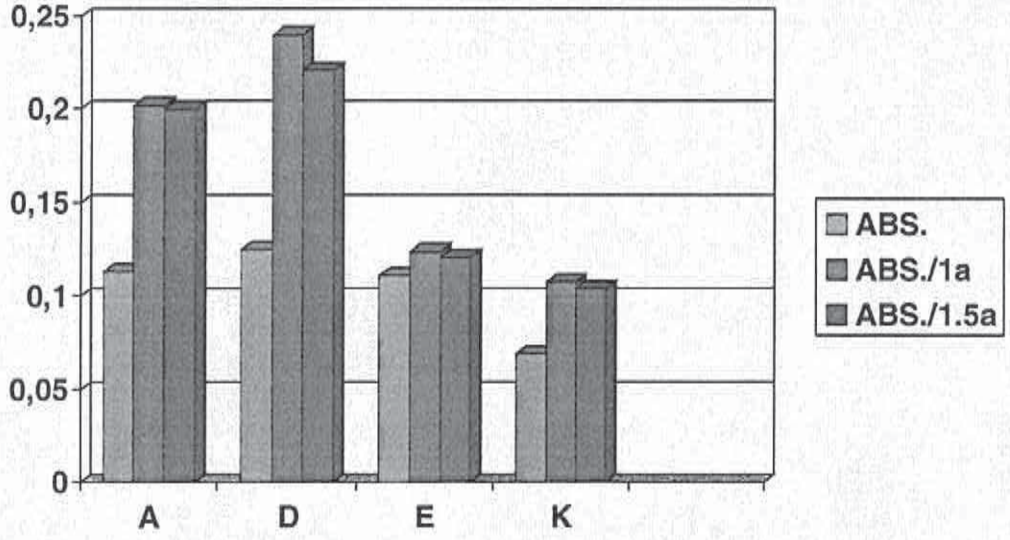


Figure 7. Water absorption of the marbles (w-%).

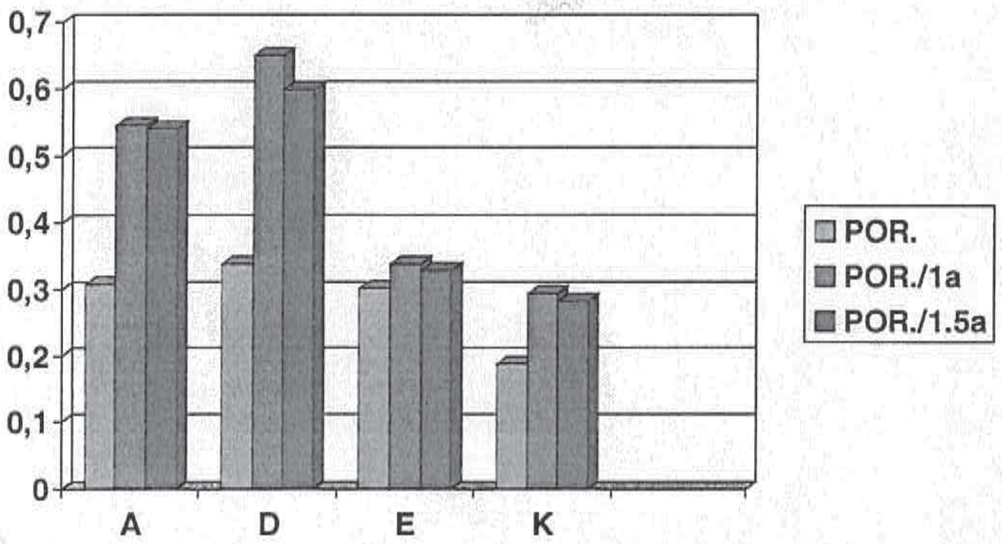


Figure 8. Apparent porosity of the marbles (vol-%).

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 10. The basis of the comparison is in all cases the value of the unused marble.

Table 10. The relative changes of the water absorption and apparent porosity of the marbles on the test wall.

marble	ΔW 1 year %	ΔW 1.5 years %	Δp_o 1 year %	Δp_o 1.5 years %
A	+79	+77	+78	+76
D	+92	+77	+92	+76
E	+12	+9	+13	+9
K	+57	+51	+56	+50

The increase of water absorption and porosity on the test wall is illustrated also in Figs. 9-12. In each case the water absorption (porosity) of unused marble has been given the value of 100.

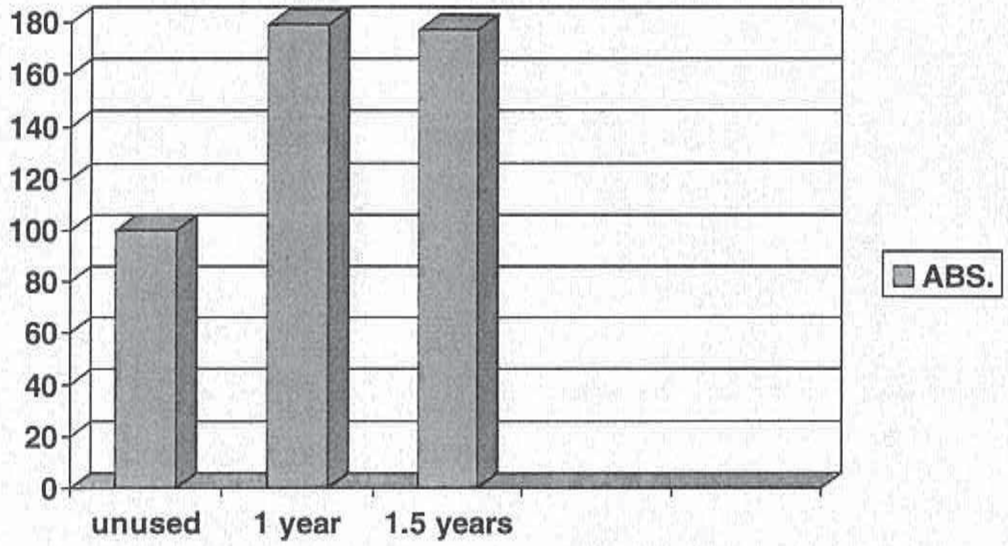


Figure 9. Water absorption (porosity) of marble A. A relative scale.

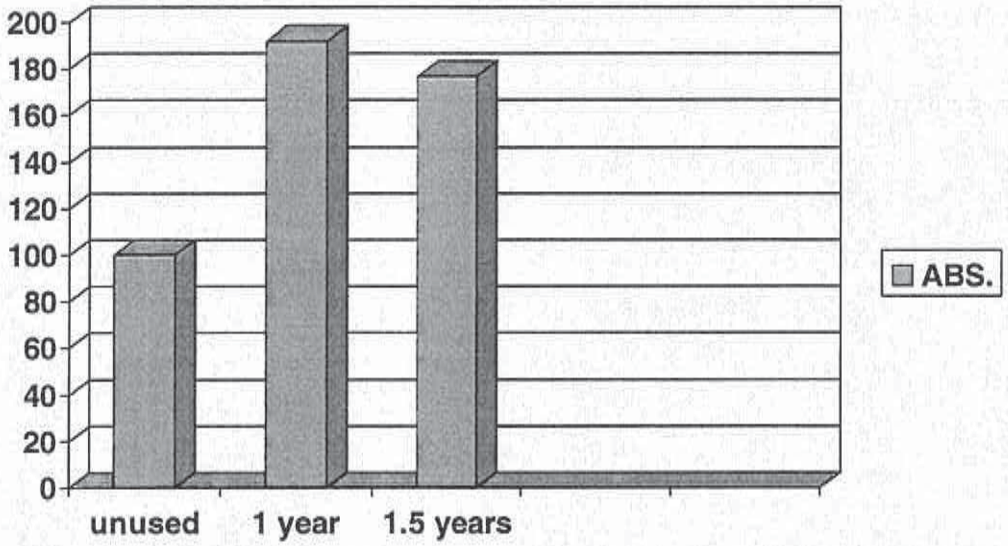


Figure 10. Water absorption (porosity) of marble D. A relative scale.

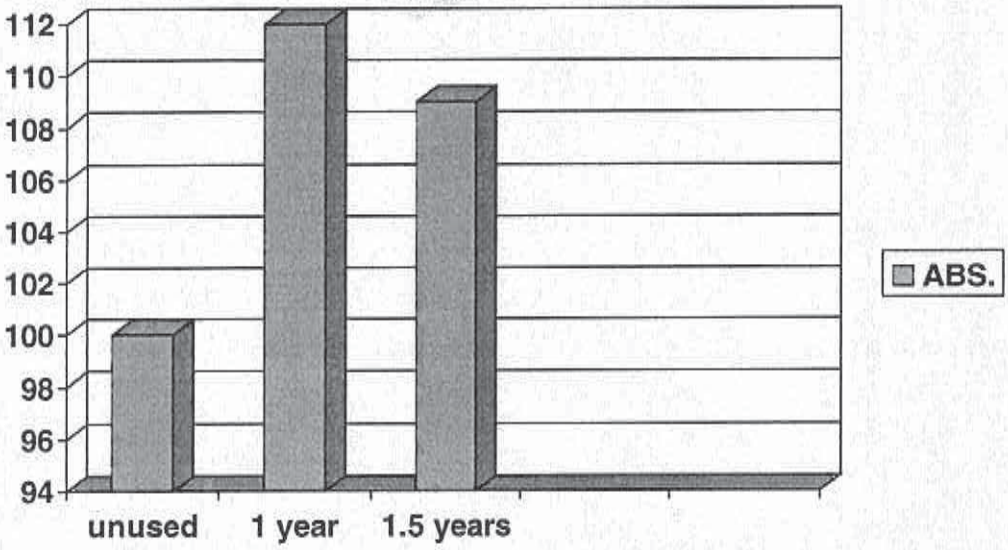


Figure 11. Water absorption (porosity) of marble E. A relative scale.

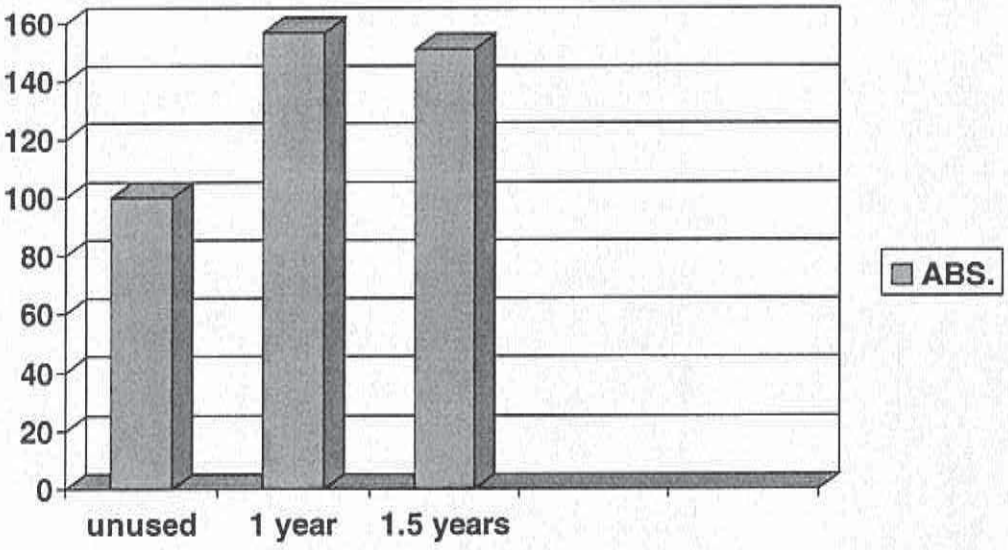


Figure 12. Water absorption (porosity) of marble K. A relative scale.

4.1.3 Mineral composition

4.1.3.1 X-ray diffraction

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. The diffraction diagram of marble A is shown in Fig. 13.

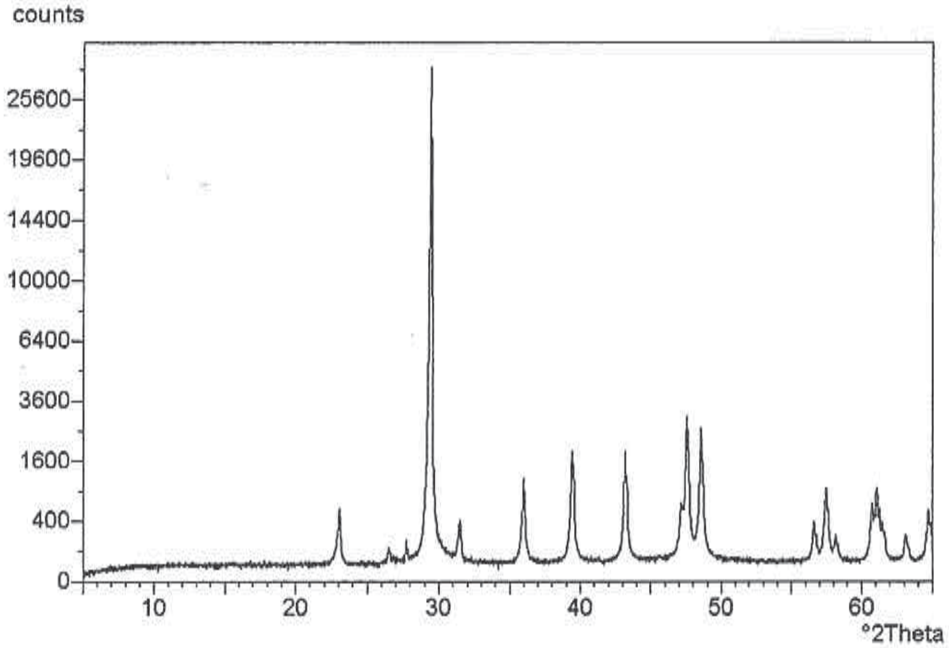


Figure 13. X-ray diffraction diagram of marble A.

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. The diffraction diagram of marble D is shown in Fig. 14.

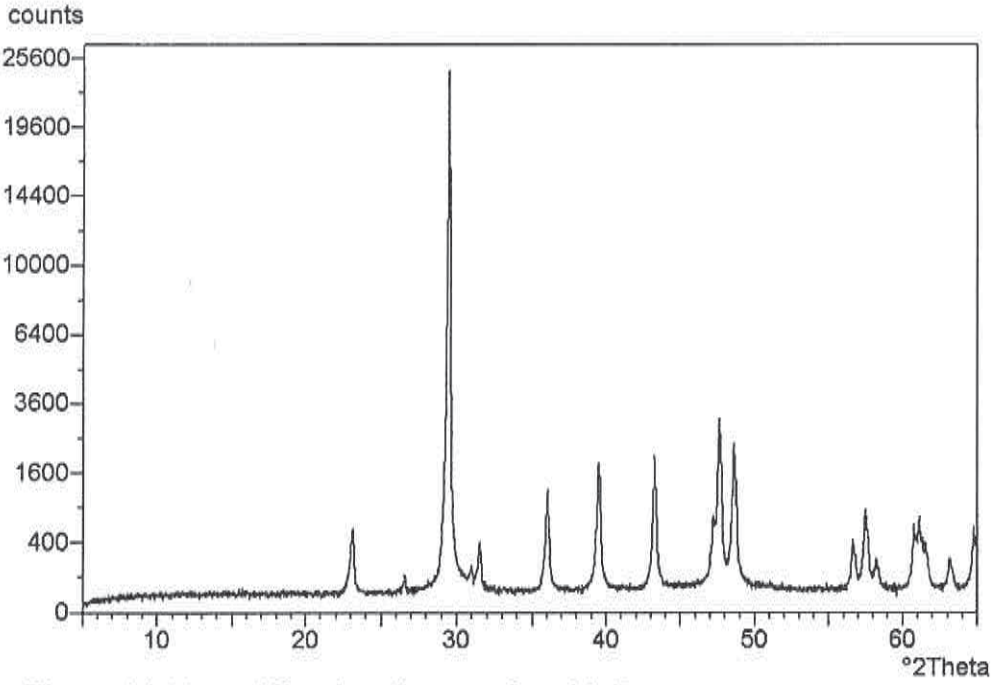


Figure 14. X-ray diffraction diagram of marble D.

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. The diffraction diagram of marble E is shown in Fig. 15.

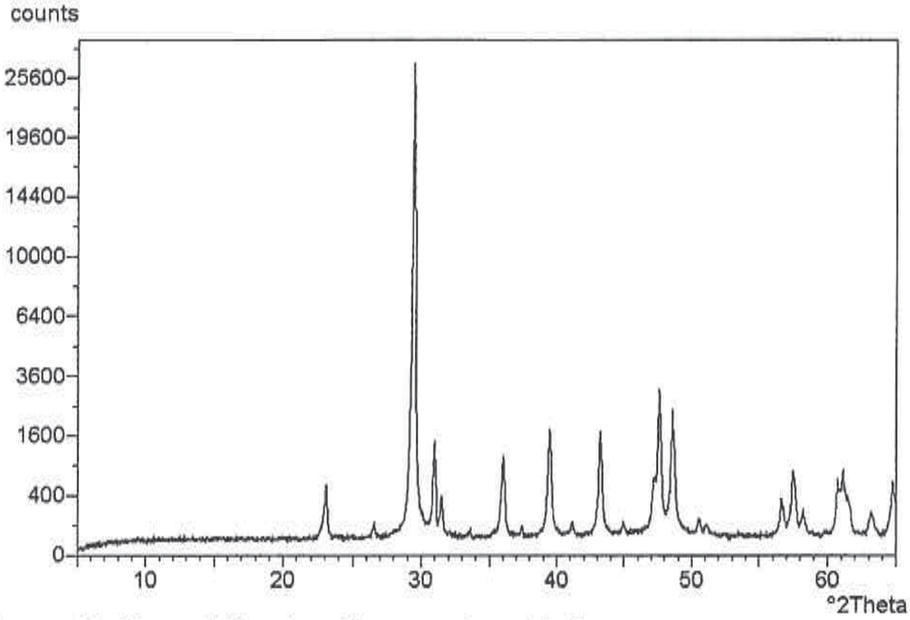


Figure 15. X-ray diffraction diagram of marble E.

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 diffraction diagram of marble K is shown in Fig. 16.

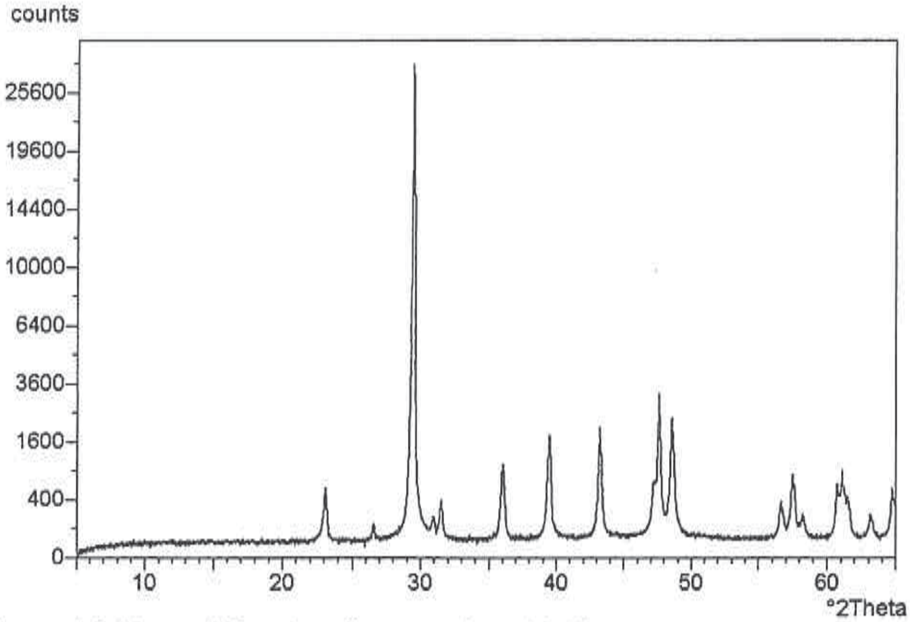


Figure 16. X-ray diffraction diagram of marble K.

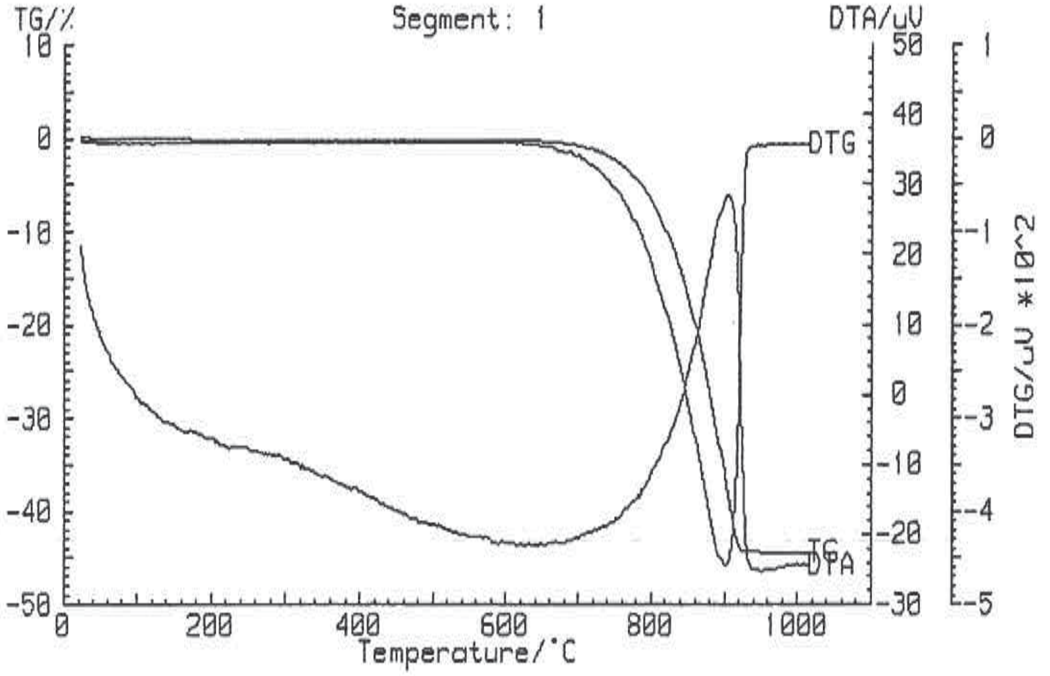


Figure 18. Thermal curves of marble D.

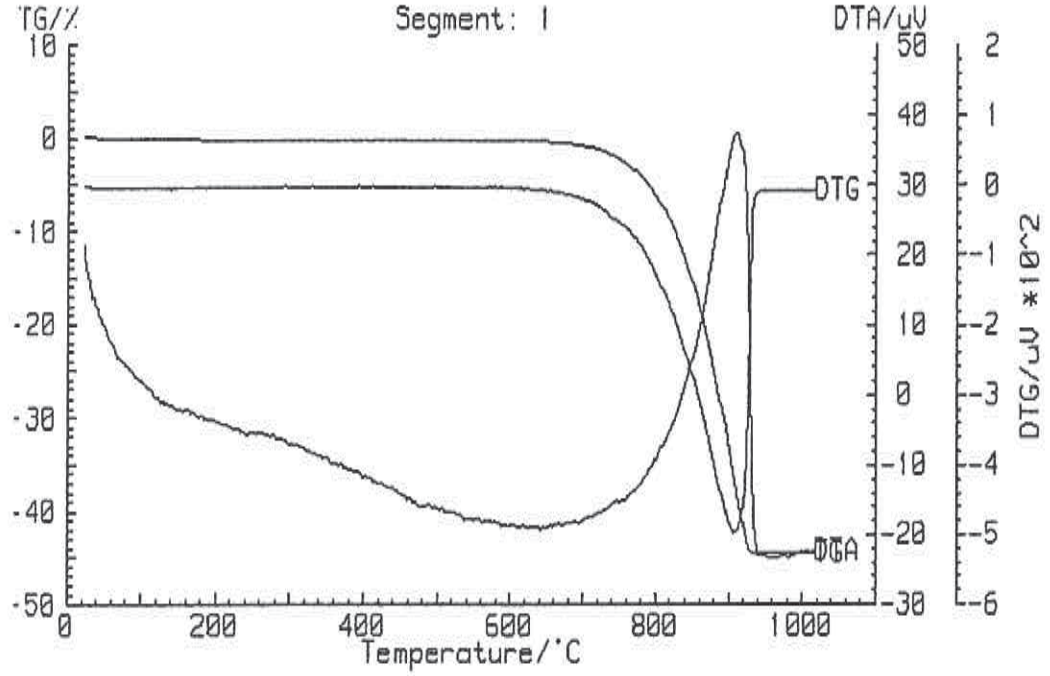


Figure 19. Thermal curves of marble E.

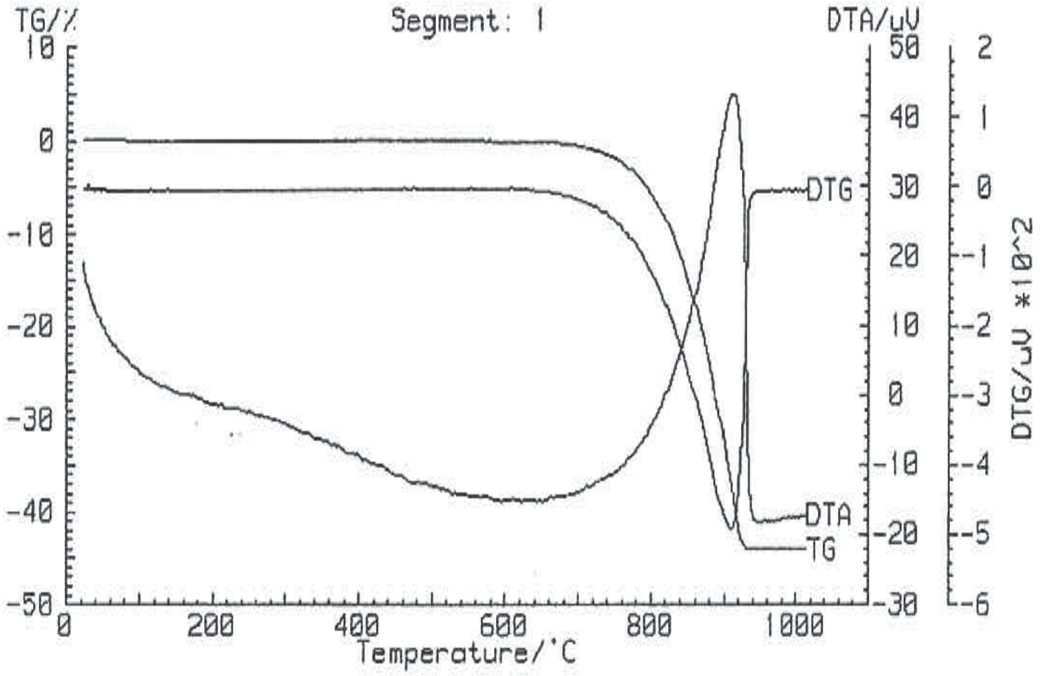


Figure 20. Thermal curves of marble K.

4.1.4 Microstructure

4.1.4.1 Thin section study

Photographs of the microstructure of marble A, unused and after 1 year on the test wall, are shown in Figs. 21-23. 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

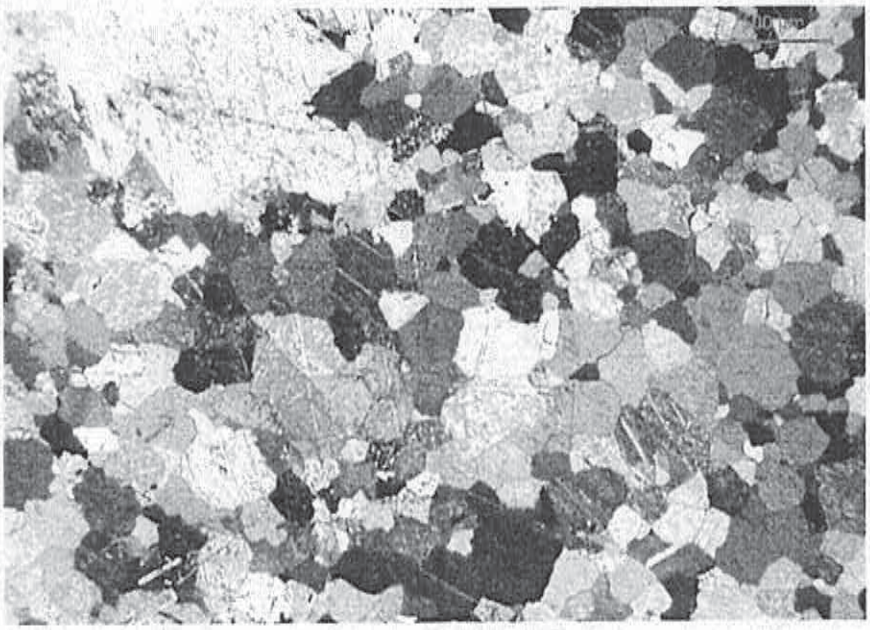


Figure 21. Microstructure of marble A. Unused. Cross-polarized light.

Figure 22. Microstructure of marble A. Unused. Plane-polarized light.

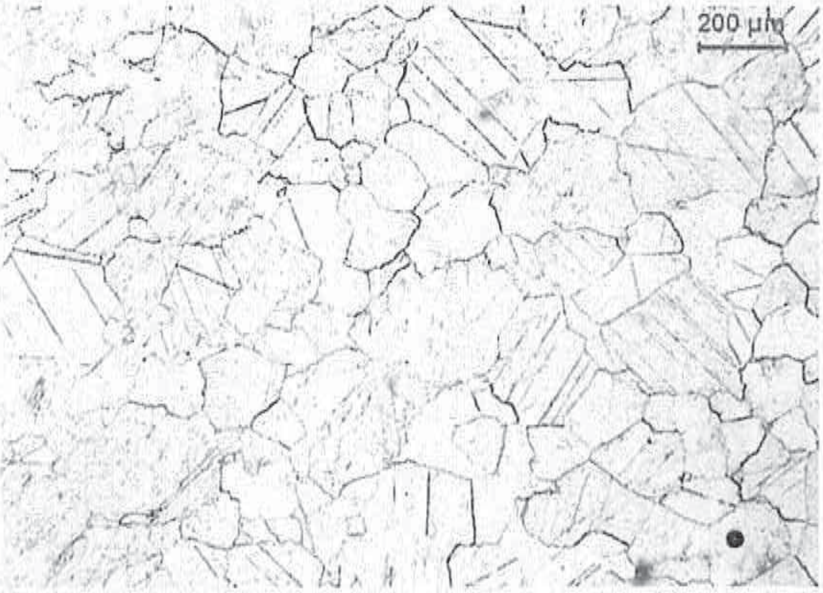


Figure 23. Microstructure of marble A. 1 year on the test wall. Plane-polarized light.

Photographs of the microstructure of marble D, unused and after 1 year on the test wall, are shown in Figs. 24-26. Following observations were made:

- fine-grained, fairly even-grained, not 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

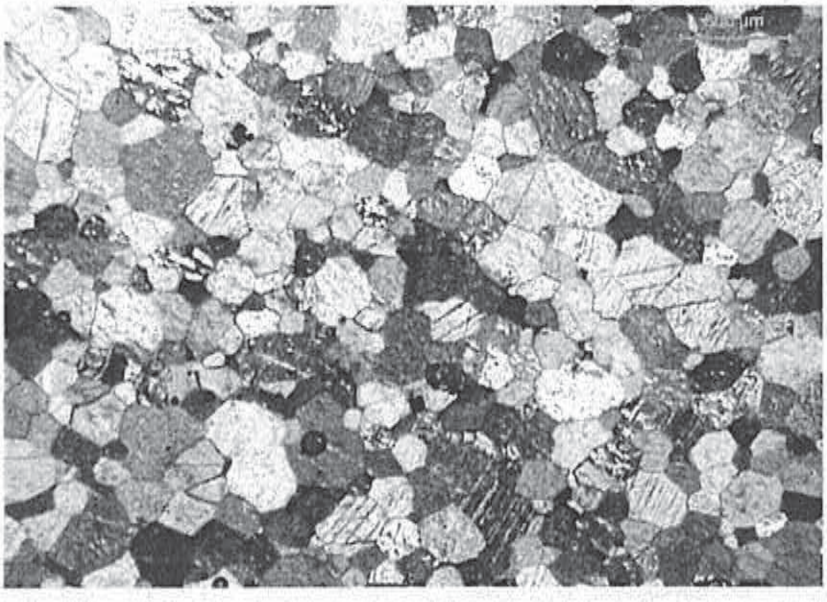


Figure 24. Microstructure of marble D. Unused. Cross-polarized light.

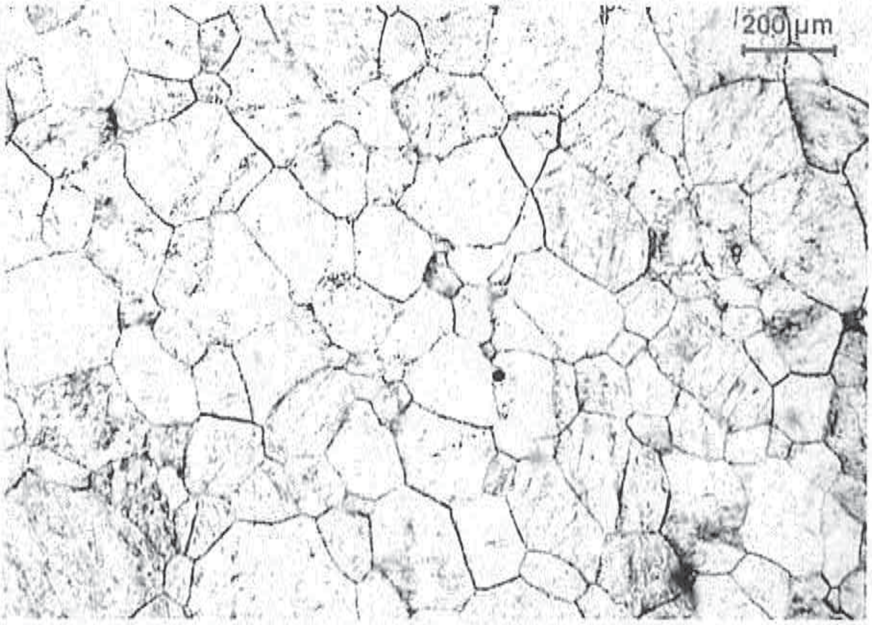


Figure 25. Microstructure of marble D. Unused. Plane-polarized light.

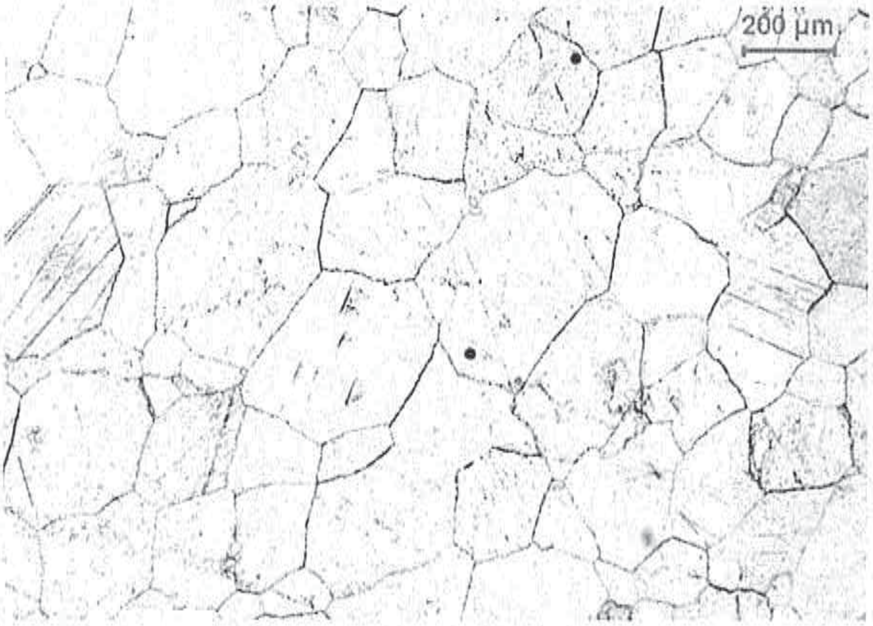


Figure 26. Microstructure of marble D. 1 year on the test wall. Plane-polarized light.

Photographs of the microstructure of marble E, unused and after 1 year on the test wall, are shown in Figs. 27-29. 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 rock, contains some opaque and mica type minerals
- some alteration of the grains
- no changes observable after 1 year on the test wall

Figure 27. Microstructure of marble E. Unused. Cross-polarized light.

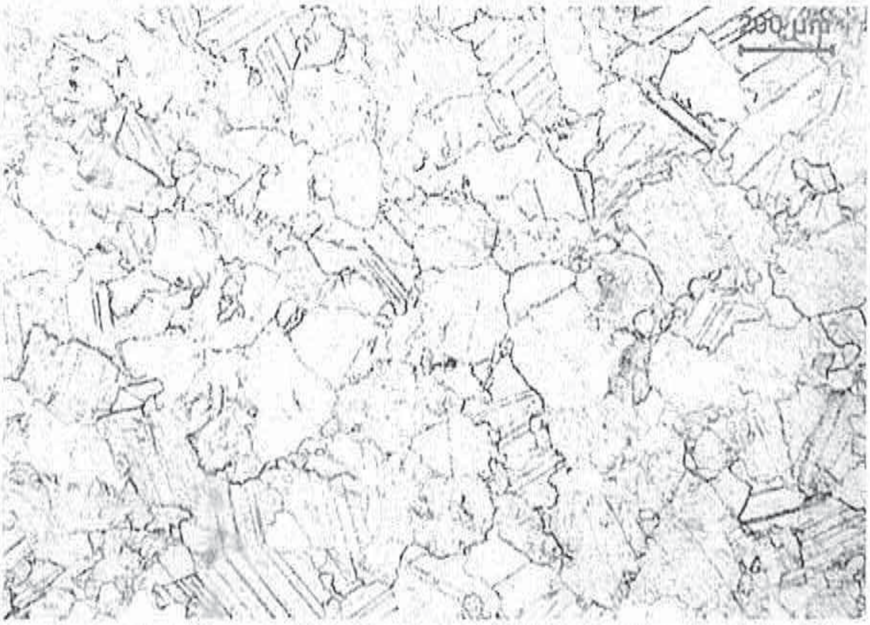


Figure 28. Microstructure of marble E. Unused. Plane-polarized light.

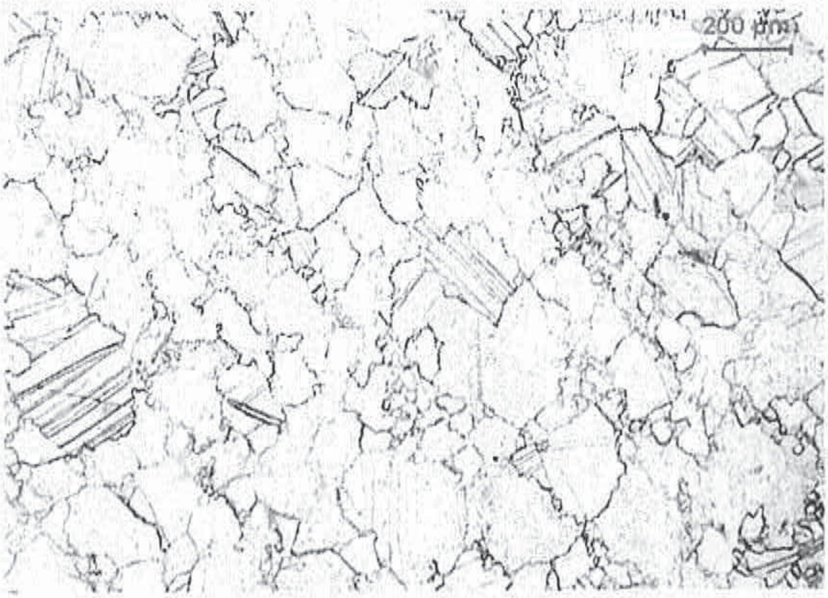


Figure 29. Microstructure of marble E. 1 year on the test wall. Plane-polarized light.

Photographs of the microstructure of marble K, unused and after 1 year on the test wall, are shown in Figs. 30-32. Following observations were made:

- fine-grained, not oriented
- average grain size about 200 µm
- very fine-grained (cryptocrystalline) lenses and veins among the groundmass, the lense boundaries are usually 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

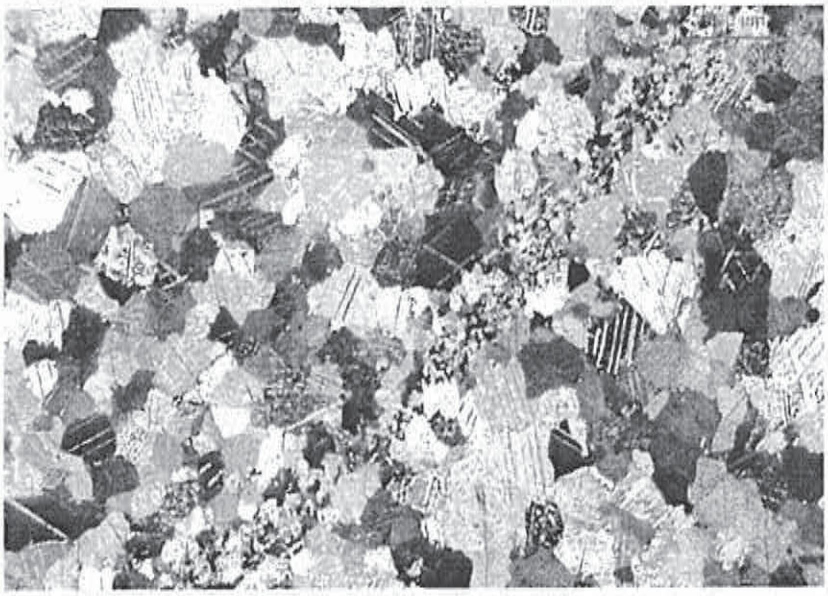


Figure 30. Microstructure of marble K. Unused. Cross-polarized light.

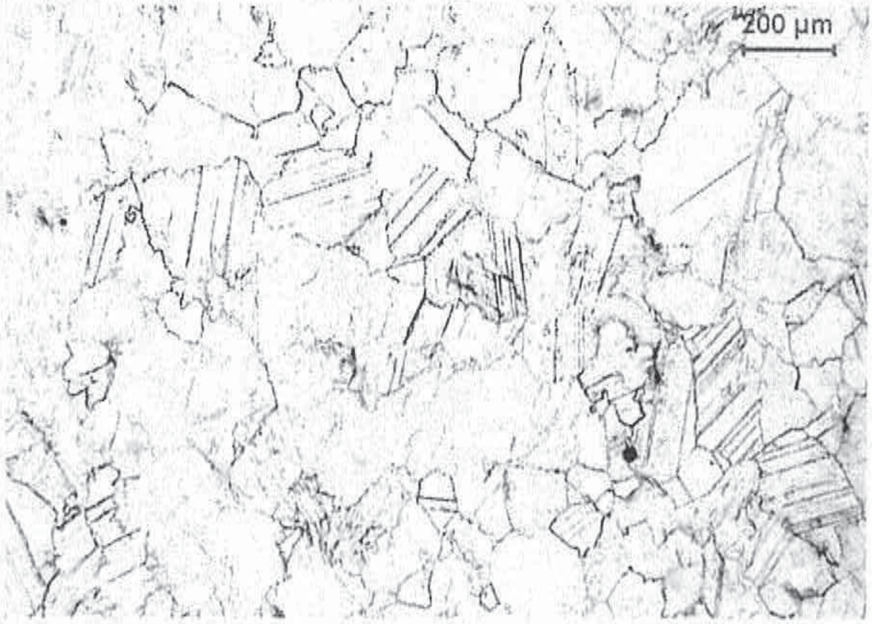


Figure 31. Microstructure of marble K. Unused. Plane-polarized light.

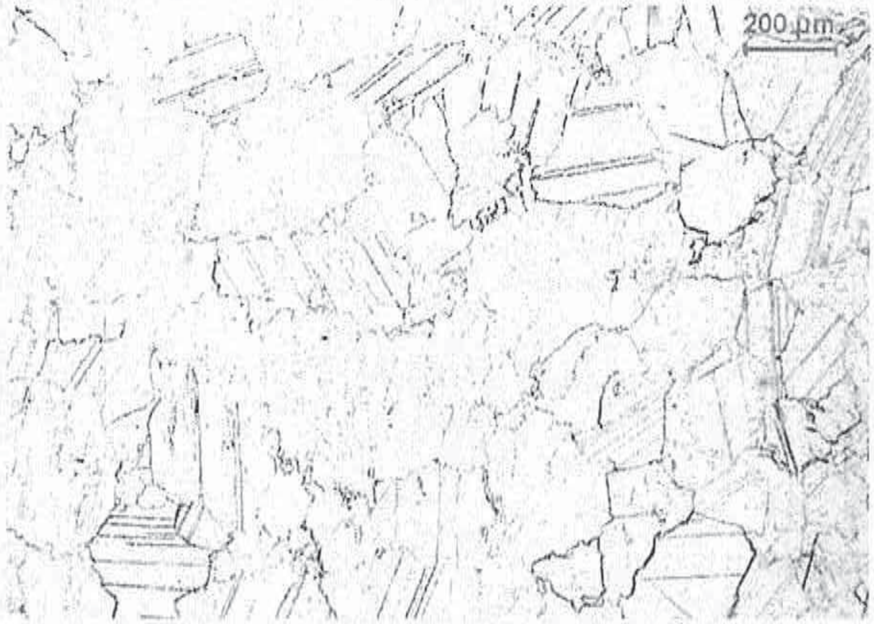


Figure 32. Microstructure of marble K. 1 year on the test wall. Plane-polarized light.

4.1.4.2 Elementary composition, distribution of elements

According to the EDS-analysis marble A consisted almost entirely of calcium, carbon and oxygen, i.e. calcium carbonate. Several small grains with high atomic weight were, however, observed. These grains contained iron and sulphur referring to iron sulphides. Elementary dot maps showed that there were also spots with a high content of silicon and spots with high contents of silicon, aluminium and potassium, Fig. 33. The former were probably due to quartz and the latter to feldspar. Other elements were very evenly distributed.

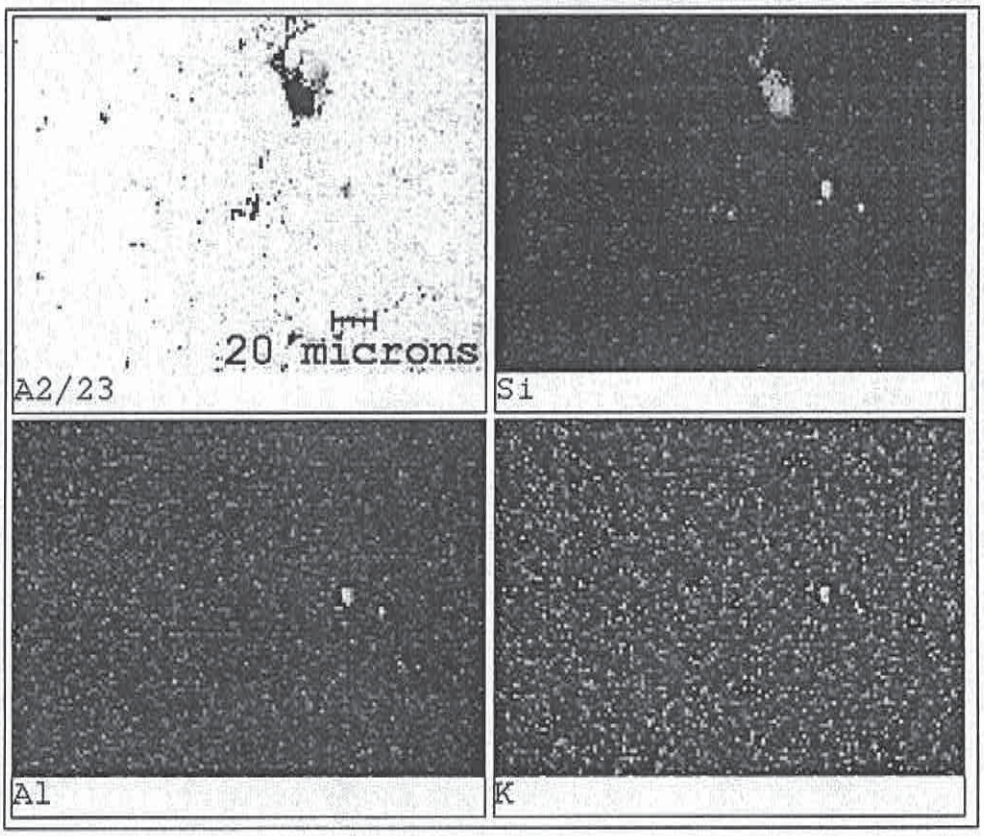


Figure 33. Marble A. Unused. BSE-image (500x, near the surface) and elementary dot maps of silicon (Si), aluminium (Al) and potassium (K).

According to the EDS-analysis marble D consisted almost entirely of calcium, carbon and oxygen, i.e. calcium carbonate. Some spots, a few mm in size, with low atomic weight were, however, observed. These grains contained magnesium and calcium. Thus, they were dolomite. Associated with these dolomitic spots some small grains with high atomic weight were also found. These contained iron, zinc and sulphur referring to sulphide minerals. Elementary dot maps showed that there were also spots with a high content of silicon, Fig. 34. These spots, which seemed to concentrate on the grain boundaries, were probably due to quartz. Other elements were very evenly distributed.

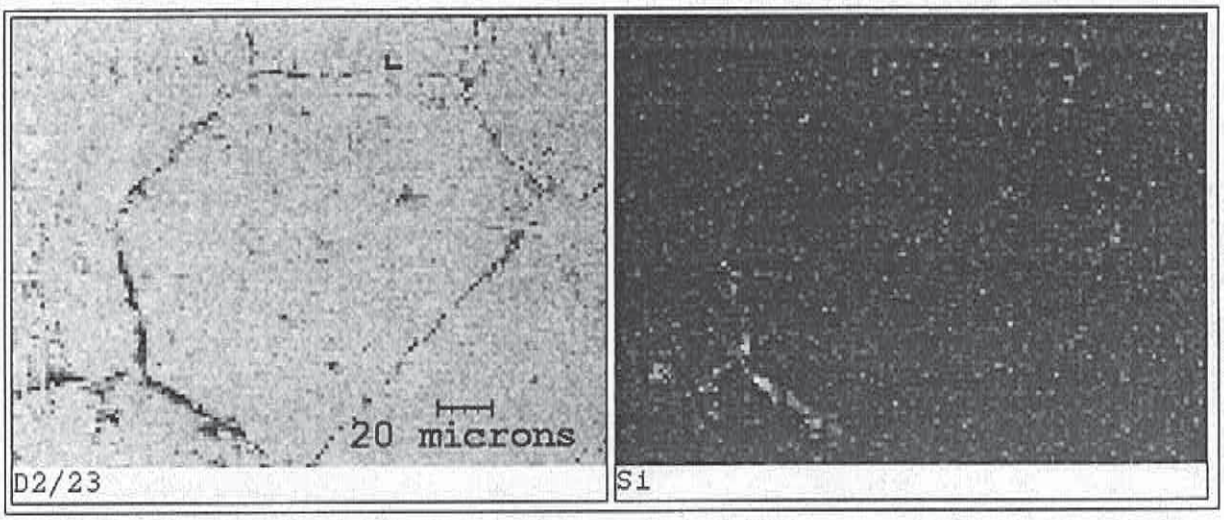


Figure 34. Marble D. Unused. BSE-image (500x, near the surface) and elementary dot map of silicon (Si).

According to the EDS-analysis marble E consisted almost entirely of calcium, carbon and oxygen, i.e. calcium carbonate. Some large spots, several mm in size, with low atomic weight were, however, observed. These grains contained magnesium and calcium. Thus, they were dolomite. Elementary dot maps showed that there were also spots with a high content of silicon, Fig. 35. These spots were probably due to quartz. Other elements were very evenly distributed.

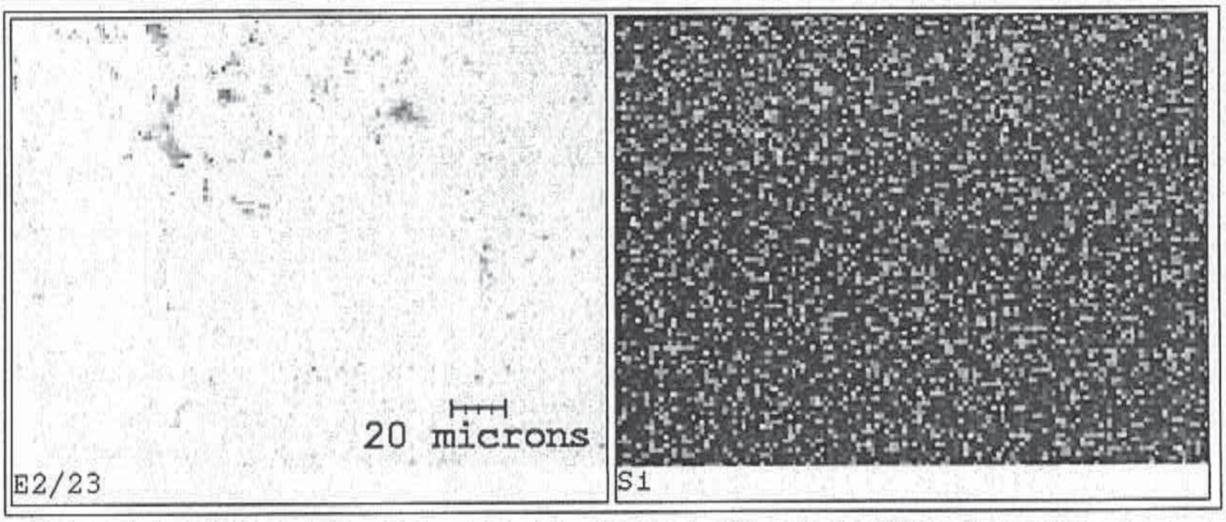


Figure 35. Marble E. Unused. BSE-image (500x, near the surface) and elementary dot map of silicon (Si).

According to the EDS-analysis marble K consisted almost entirely of calcium, carbon and oxygen, i.e. calcium carbonate. A couple of narrow veins with low atomic weight were, however, observed. These veins contained magnesium and calcium. Thus, they were dolomite. Elementary dot maps showed that there were also spots with a high content of silicon, Fig. 36. These spots, which seemed concentrate on the grain boundaries, were probably due to quartz. Other elements were very evenly distributed.

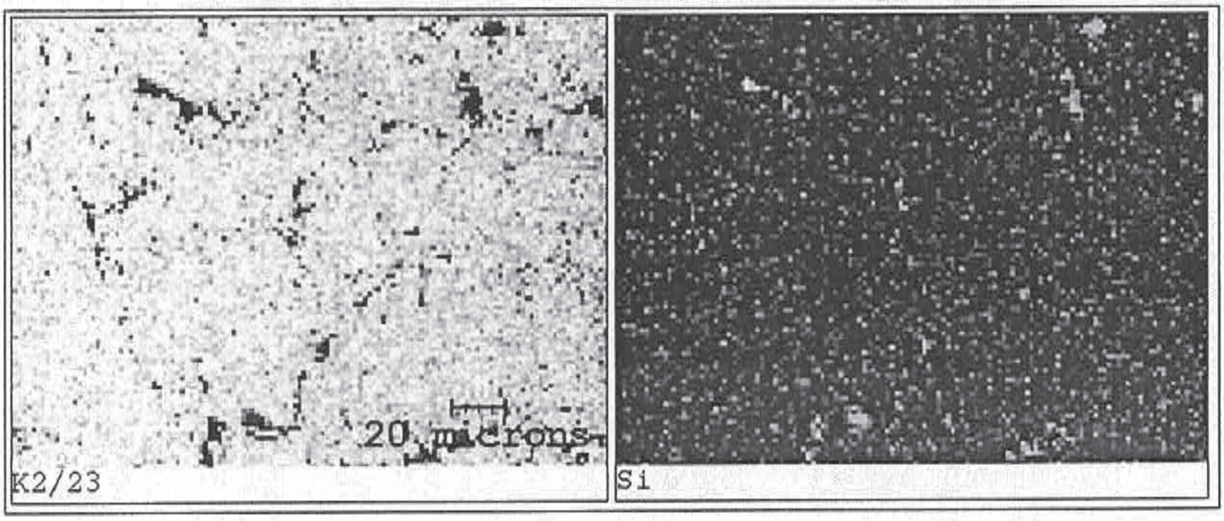


Figure 36. Marble K. Unused. BSE-image (500x, near the surface) and elementary dot map of silicon (Si).

No changes could be observed either in the general chemical composition or in the distribution of elements of any of the marbles after 1 and 1.5 years on the test wall.

4.1.4.3 SEM-study

BSE- and SE-images of marble A, both unused and after 1 year on the test wall, are shown in Figs. 37-40. Grain boundaries can partly be distinguished. No changes could be seen in the structure of the marble after 1 year on the test wall.

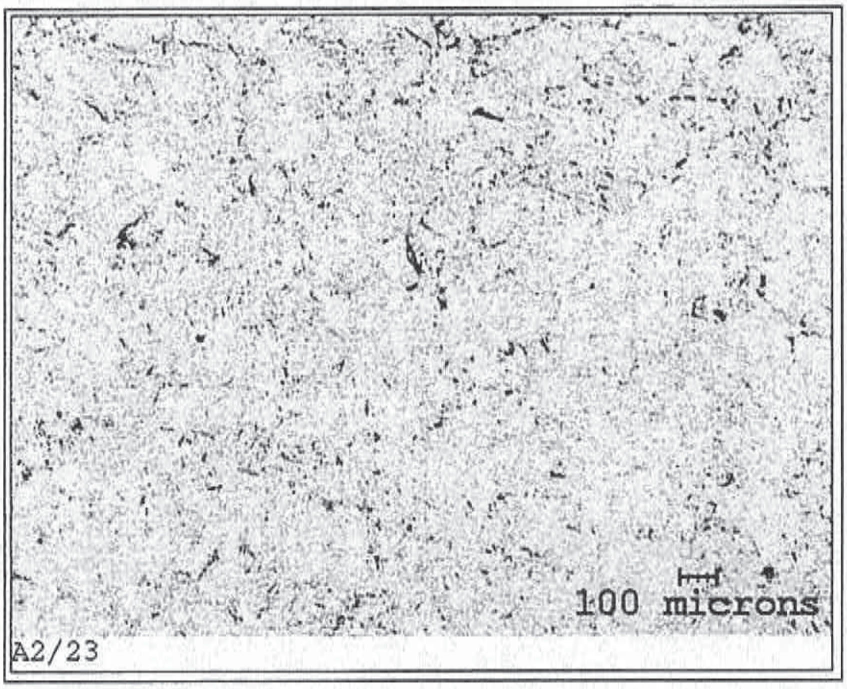


Figure 37. Marble A, unused. BSE-image, 50x.

Figure 38. Marble A, 1 year on the test wall. BSE-image, 50x.

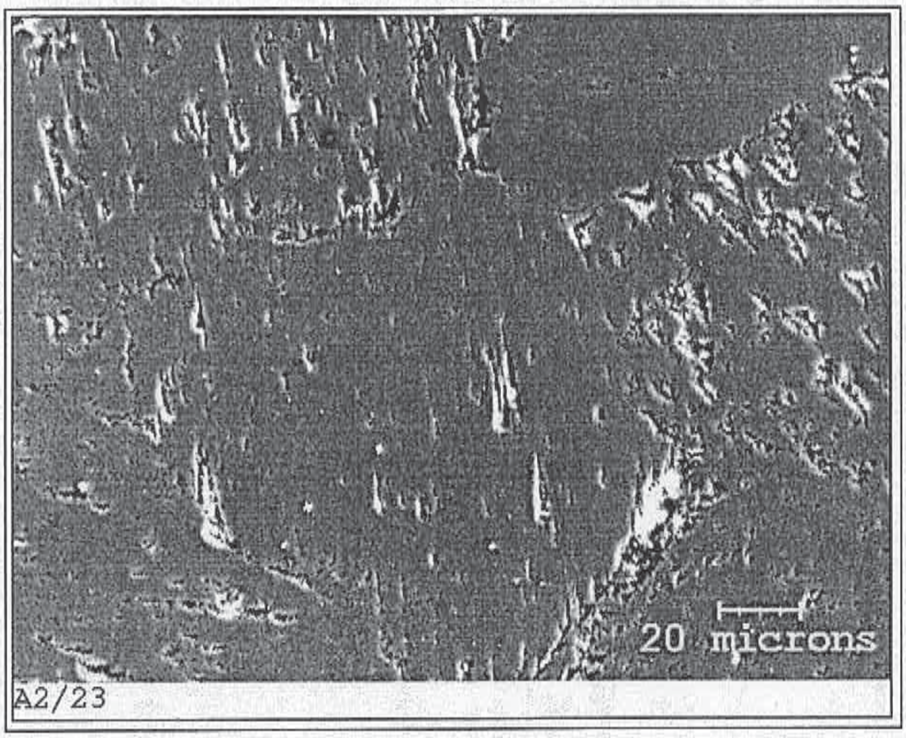


Figure 39. Marble A, unused. SE-image, 500x.

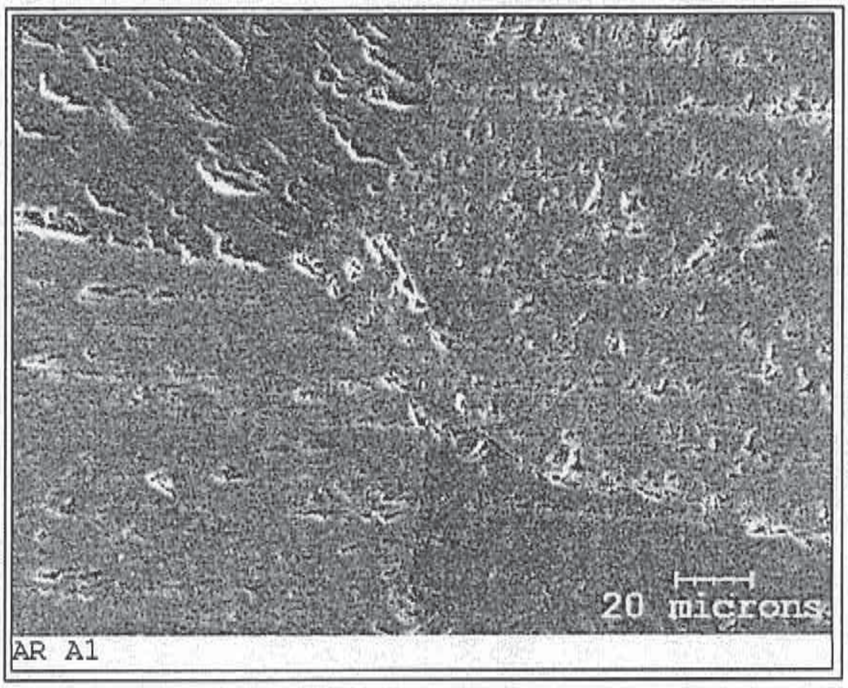


Figure 40. Marble A, 1 year on the test wall. SE-image, 500x.

BSE- and SE-images of marble D, both unused and after 1 year on the test wall, are shown in Figs. 41-44. Grain boundaries can clearly be distinguished. Stresses caused by 1 year on the test wall seemed to affect the structure of the marble in such a way that the grain boundaries could be distinguished even more easily.

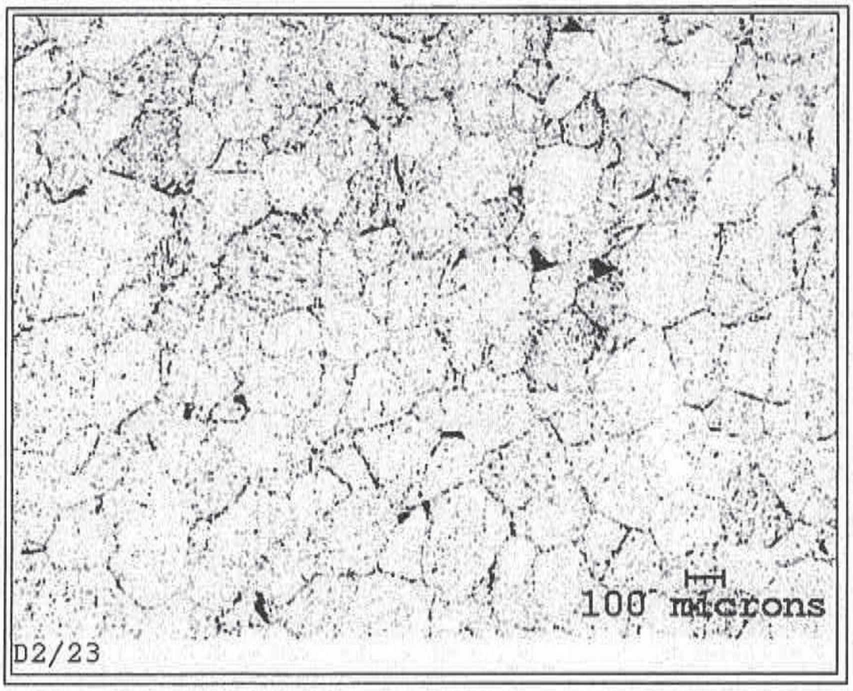


Figure 41. Marble D, unused. BSE-image, 50x.

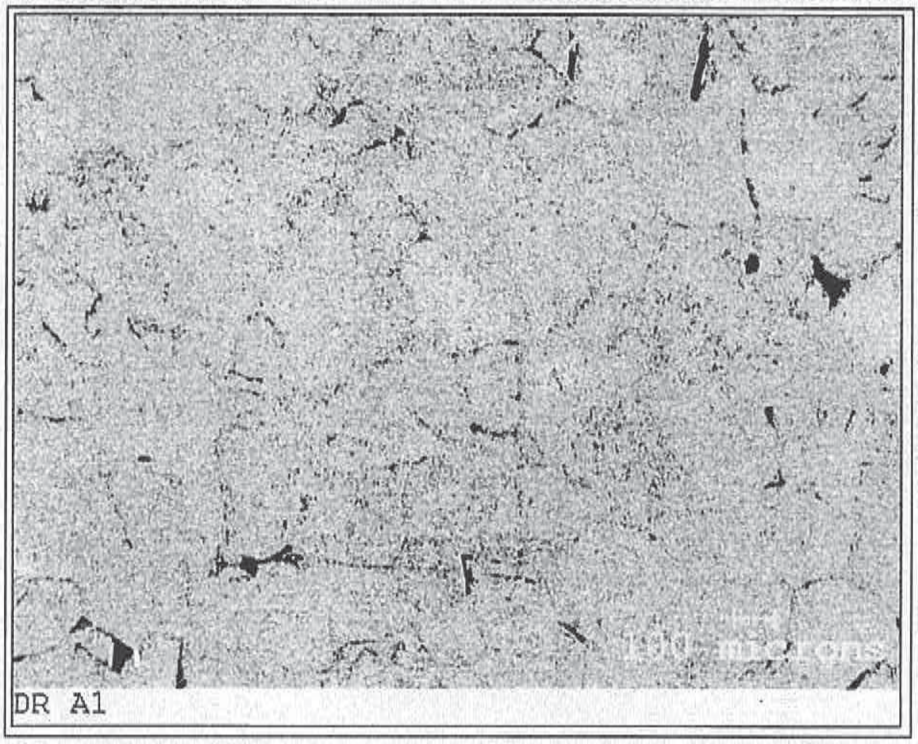


Figure 42. Marble D, 1 year on the test wall. BSE-image, 50x.

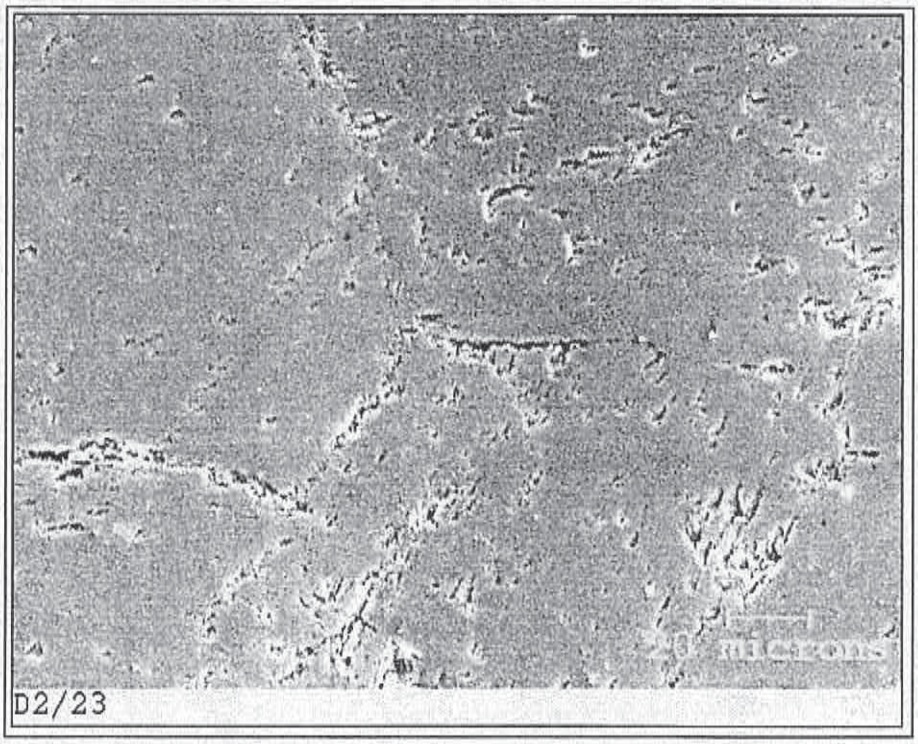


Figure 43. Marble D, unused. SE-image, 500x.

gure 44. Marble D, 1 year on the test wall on

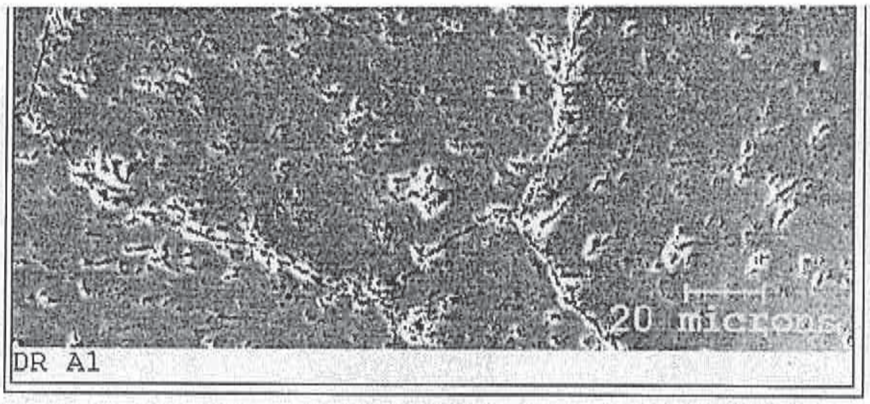


Figure 44. Marble D, 1 year on the test wall. SE-image, 500x.

BSE- and SE-images of marble E, both unused and after 1 year on the test wall, are shown in Figs. 45-48. Grain boundaries can only partly and even then very vaguely be distinguished. No changes could be seen in the structure of the marble after 1 year on the test wall.

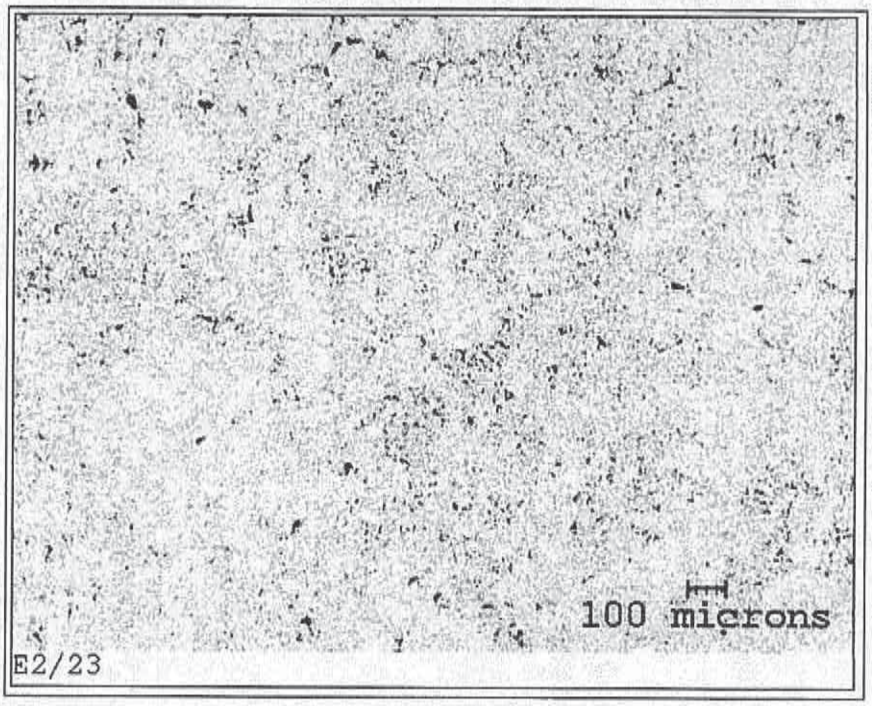


Figure 45. Marble E, unused. BSE-image, 50x.

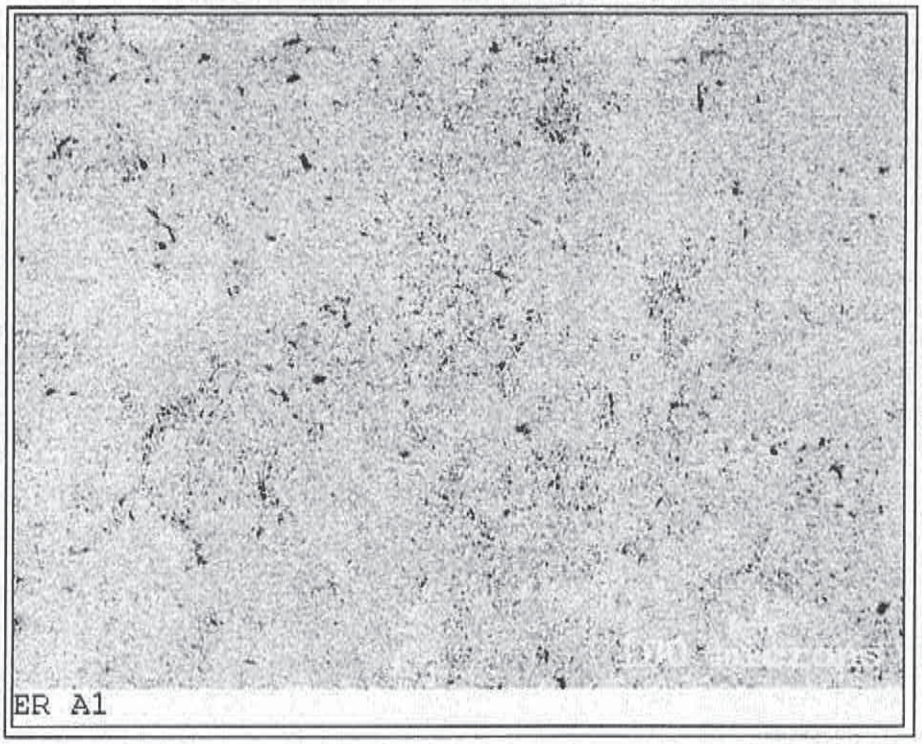


Figure 46. Marble E, 1 year on the test wall. BSE-image, 50x.

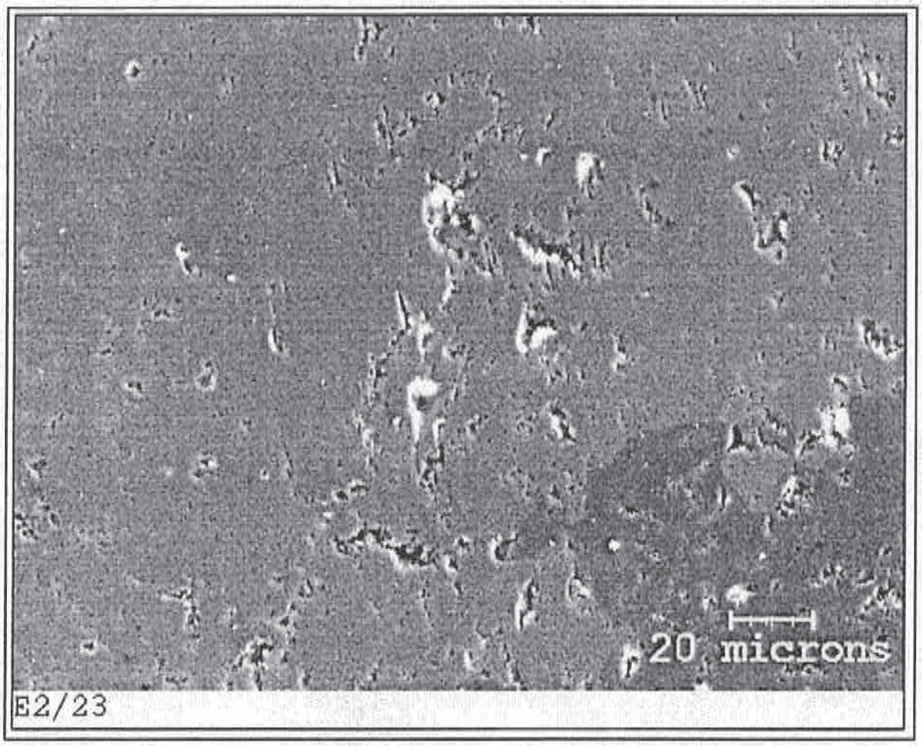


Figure 47. Marble E, unused. SE-image, 500x.

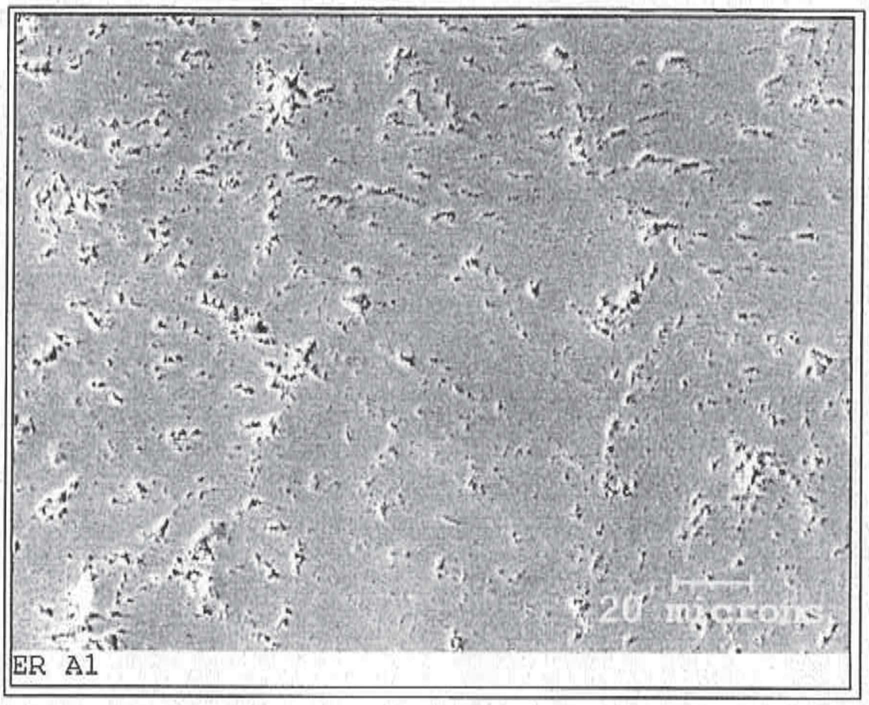


Figure 48. Marble E, 1 year on the test wall. SE-image, 500x.

BSE- and SE-images of marble K, both unused and after 1 year on the test wall, are shown in Figs. 49-52. Grain boundaries can only partly and even then very vaguely be distinguished. No changes could be seen in the structure of the marble after 1 year on the test wall.

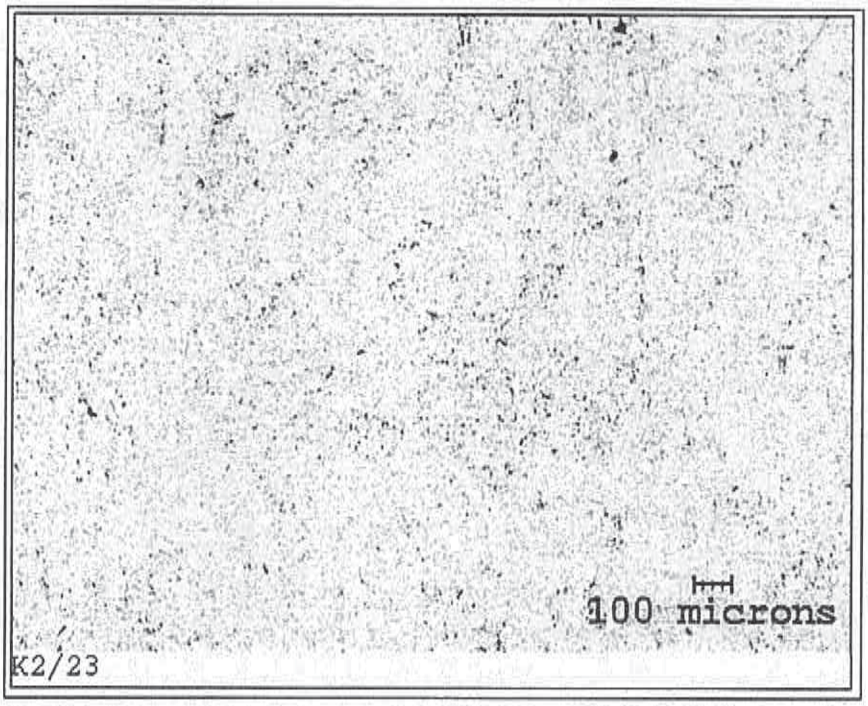


Figure 49. Marble K, unused. BSE-image, 50x.

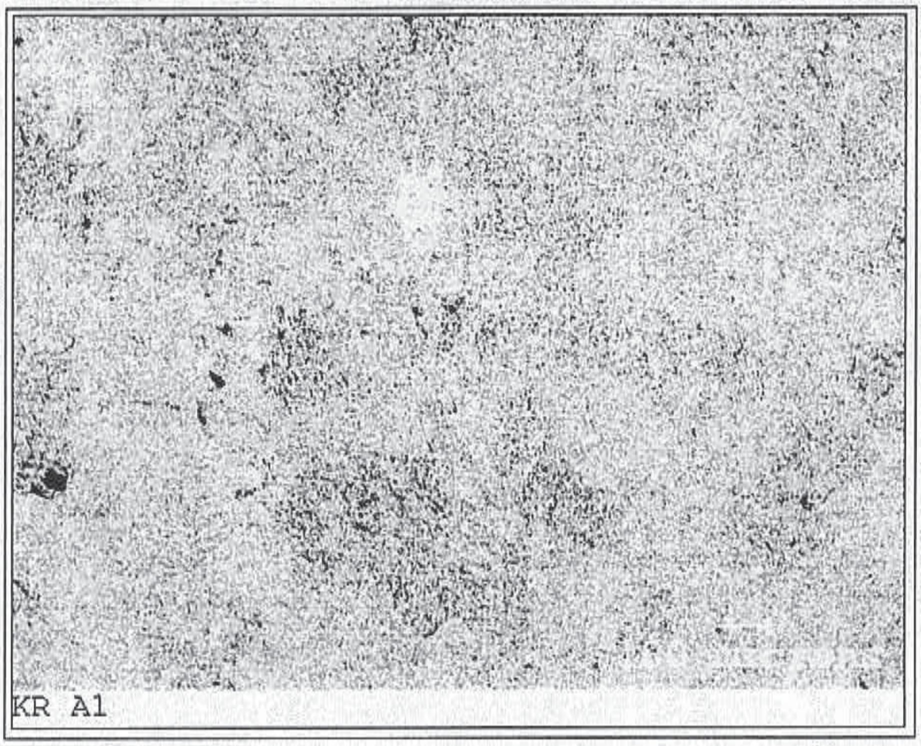


Figure 50. Marble K, 1 year on the test wall. BSE-image, 50x.

Figure 51. Marble K, unused. SE-image, 500x.

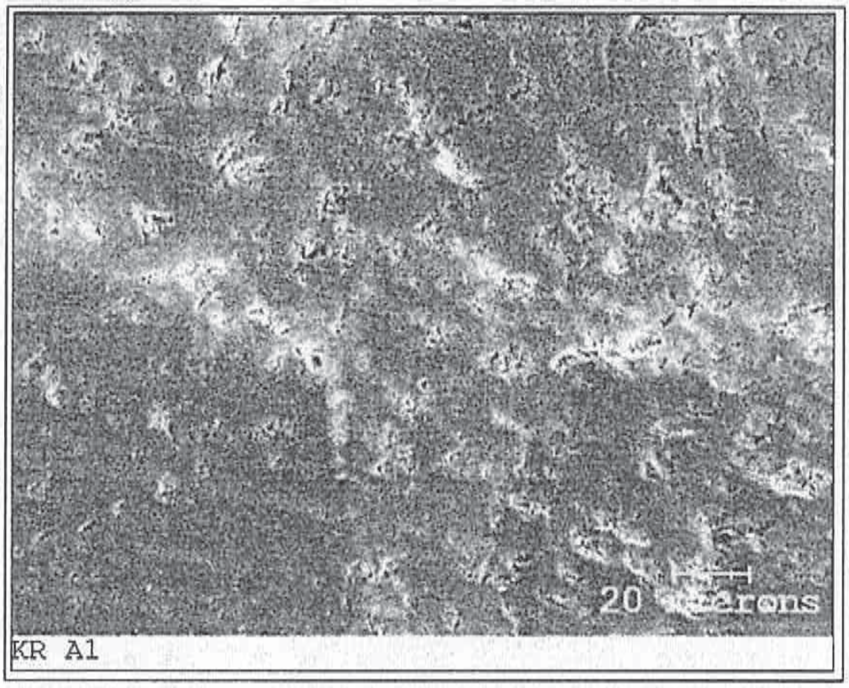


Figure 52. Marble K, 1 year on the test wall. SE-image, 500x.

SEM-pictures of fractured surfaces of marble A, both unused and after 1 and 1.5 years on the test wall, are shown in Figs. 53-58. The individual grains can at least partly be distinguished from each other. Narrow cracks can also be noticed between some of the grains. More and wider cracks were detected when the marble had been exposed to the environmental stresses on the test wall. The maximum crack width after 1.5 years on the test wall is around 0.6-0.7 µm.

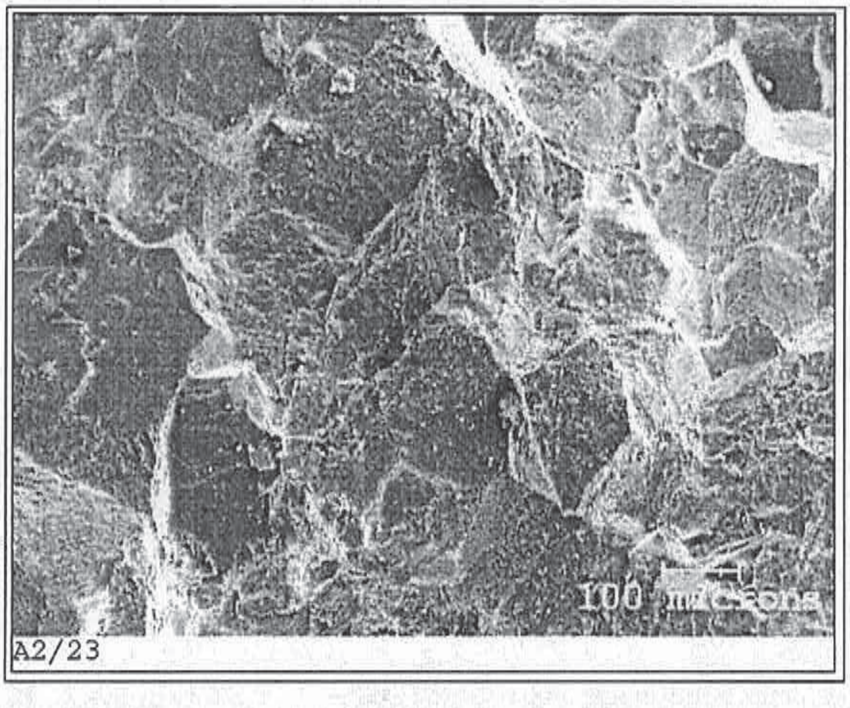


Figure 53. Marble A, unused. SE-image of fractured surface, 100x.

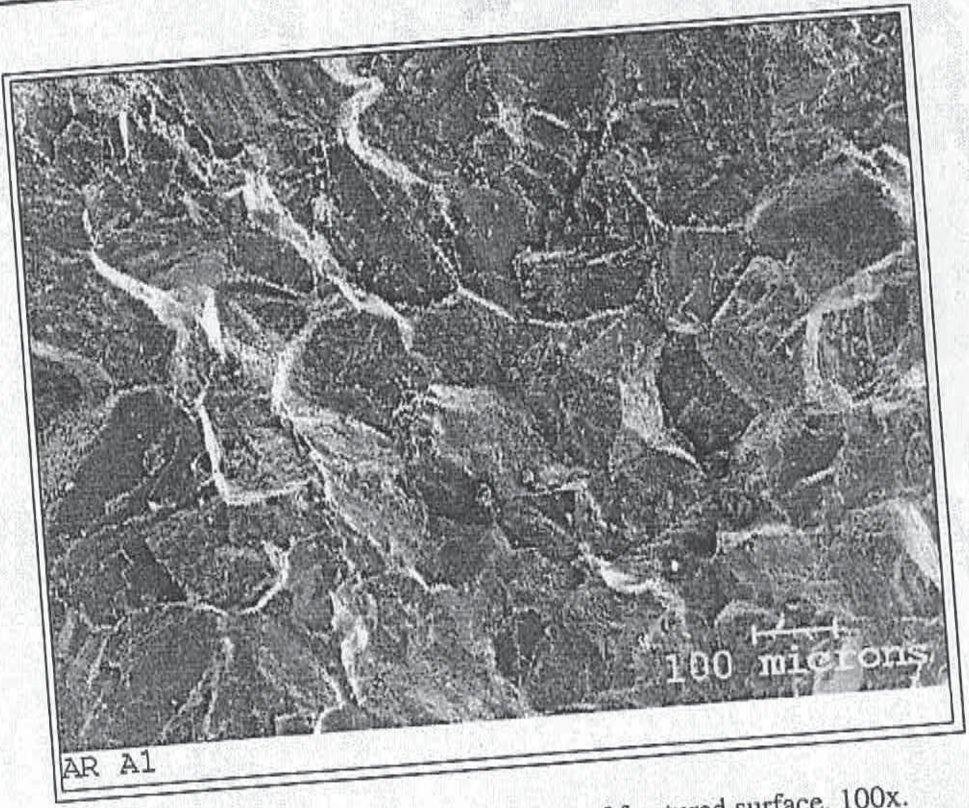


Figure 54. Marble A, 1 year on the test wall. SE-image of fractured surface, 100x.

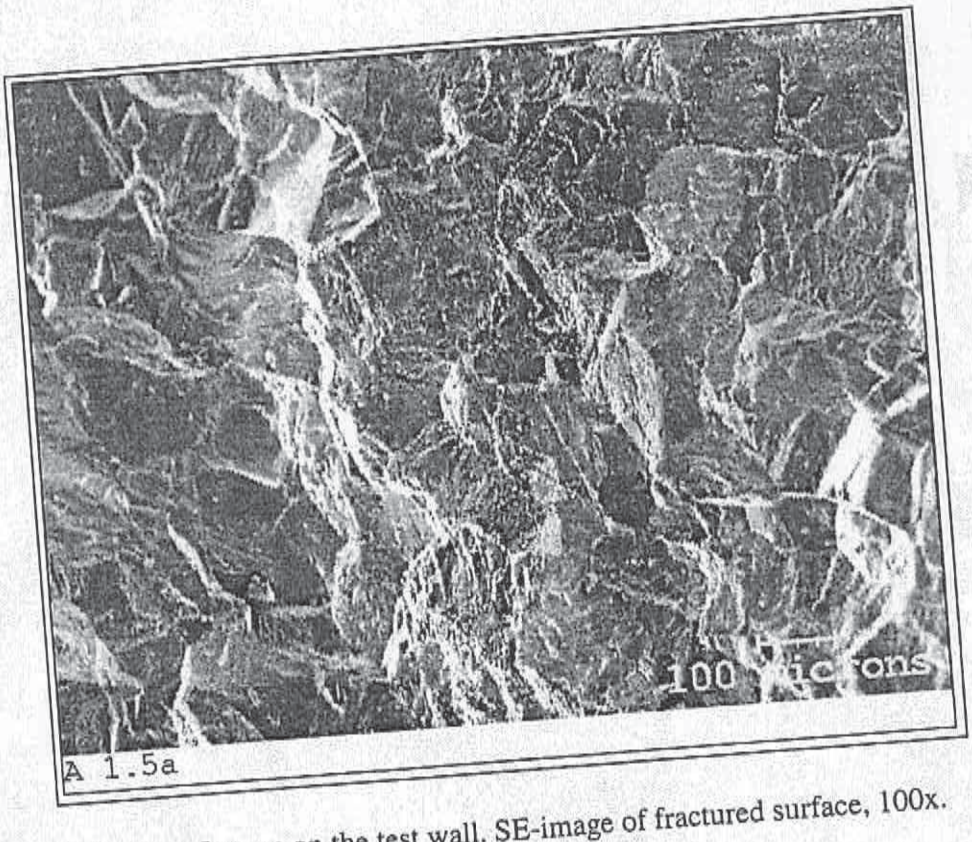
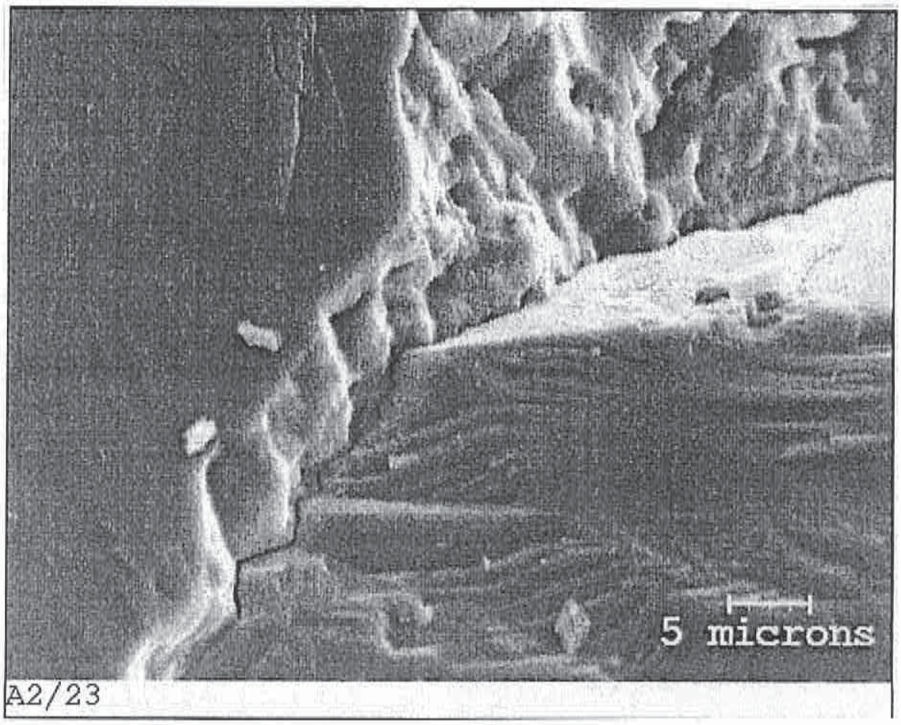


Figure 55. Marble A, 1.5 years on the test wall. SE-image of fractured surface, 100x.



A2/23

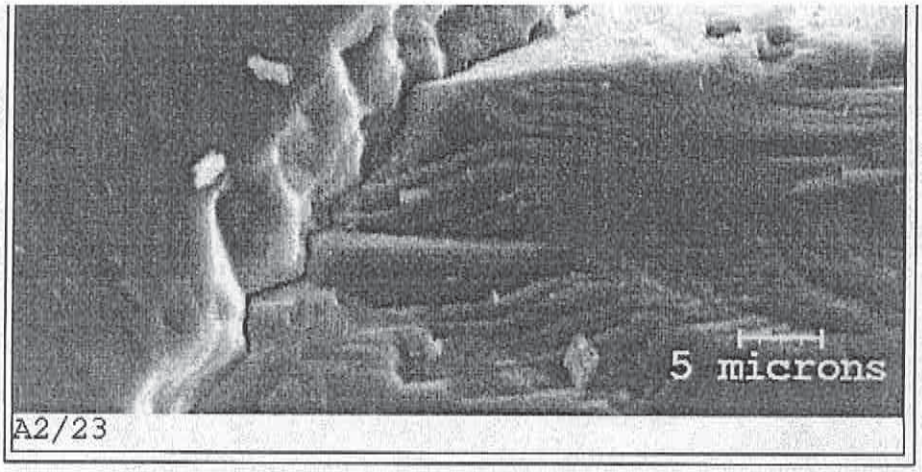


Figure 56. Marble A, unused. SE-image of fractured surface, 2500x.

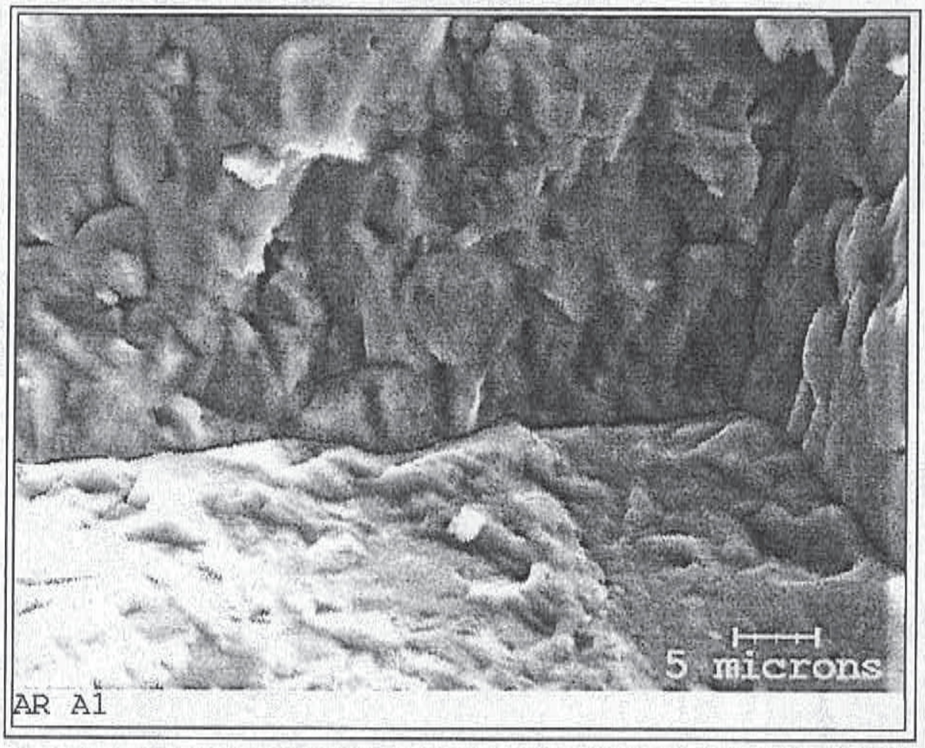


Figure 57. Marble A, 1 year on the test wall. SE-image of fractured surface, 2500x.

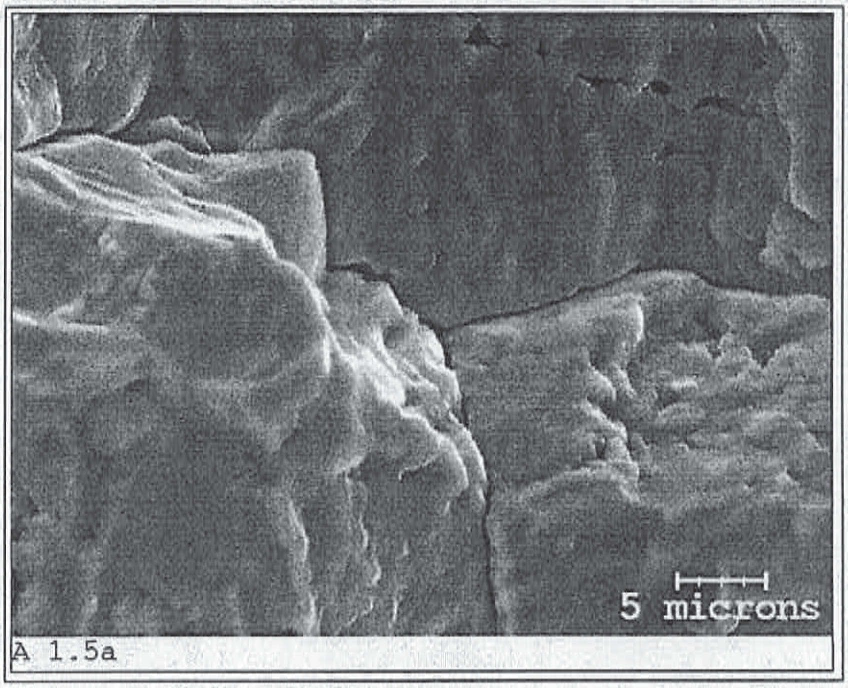


Figure 58. Marble A, 1.5 years on the test wall. SE-image of fractured surface, 2500x.

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. 59-64. The individual grains can easily be distinguished from each other. Clear cracks can also be noticed between all the grains. These cracks were wider when the marble had been exposed to the environmental stresses on the test wall. The maximum crack width after 1.5 years on the test wall is around 1 μm.

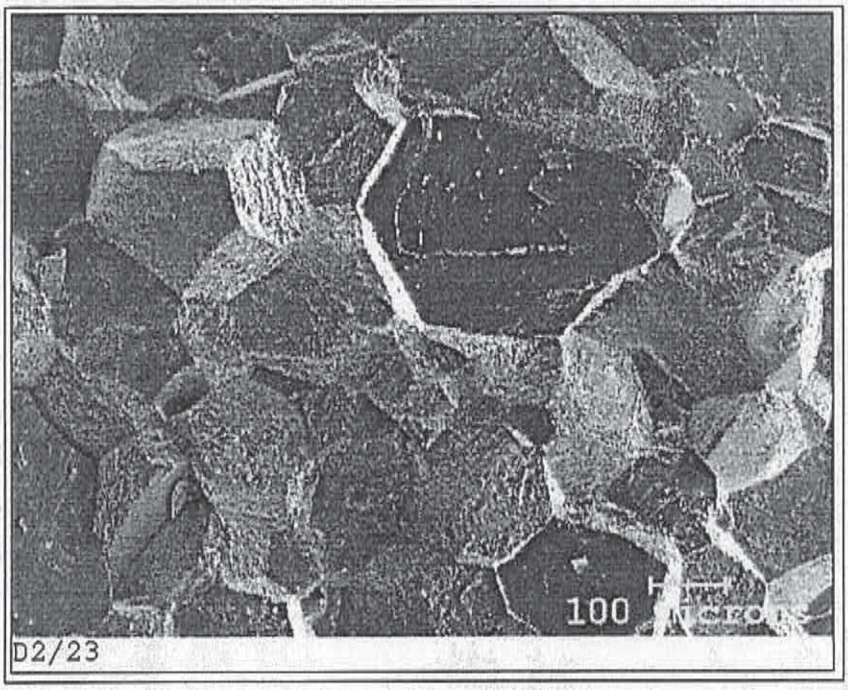


Figure 59. Marble D, unused. SE-image of fractured surface, 100x.

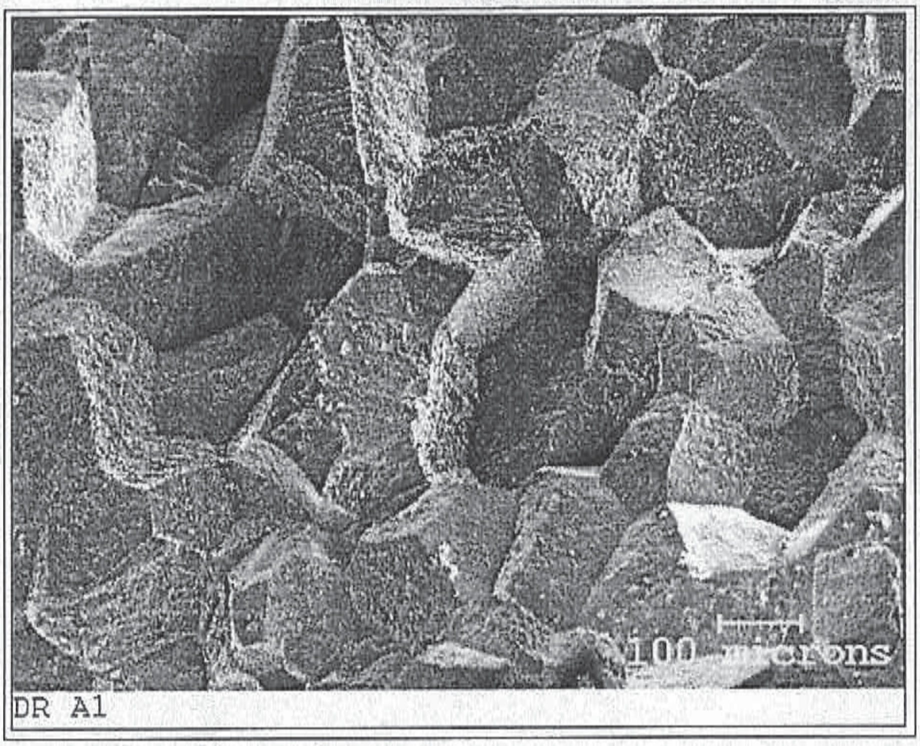


Figure 60. Marble D, 1 year on the test wall. SE-image of fractured surface, 100x.

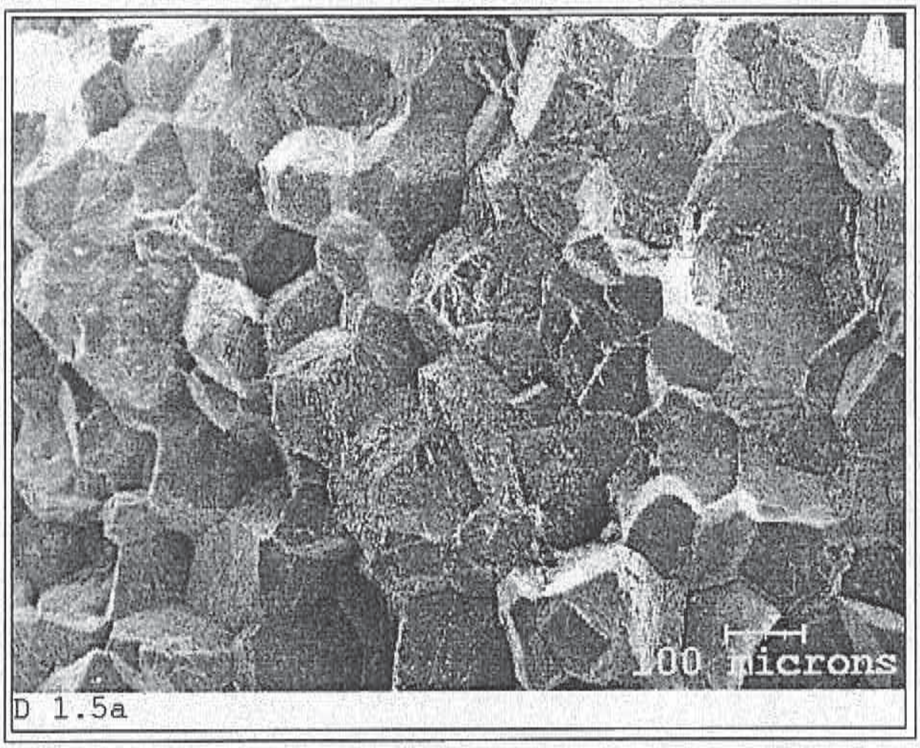
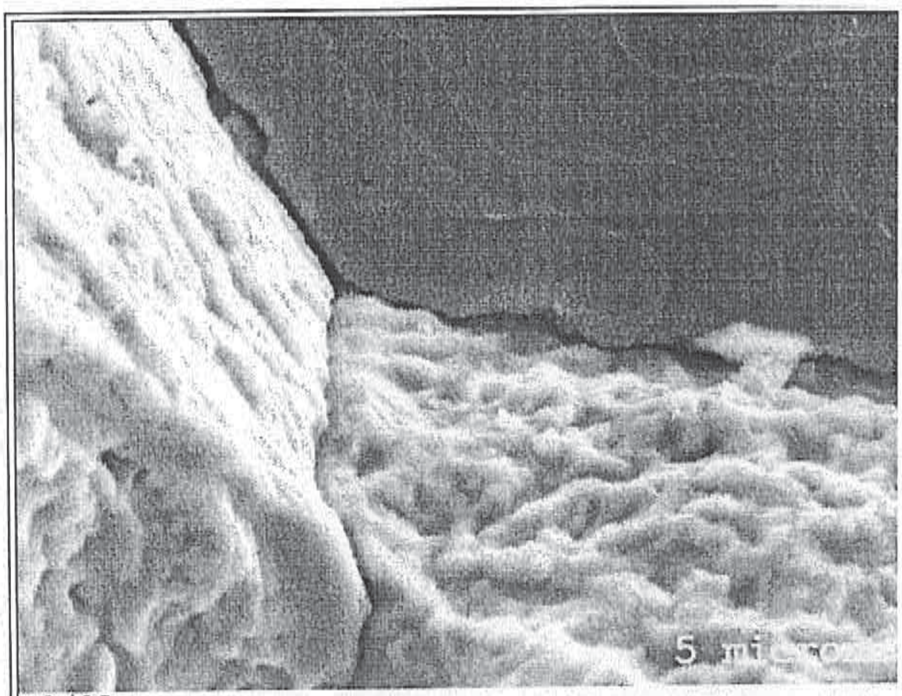


Figure 61. Marble D, 1.5 years on the test wall. SE-image of fractured surface, 100x.



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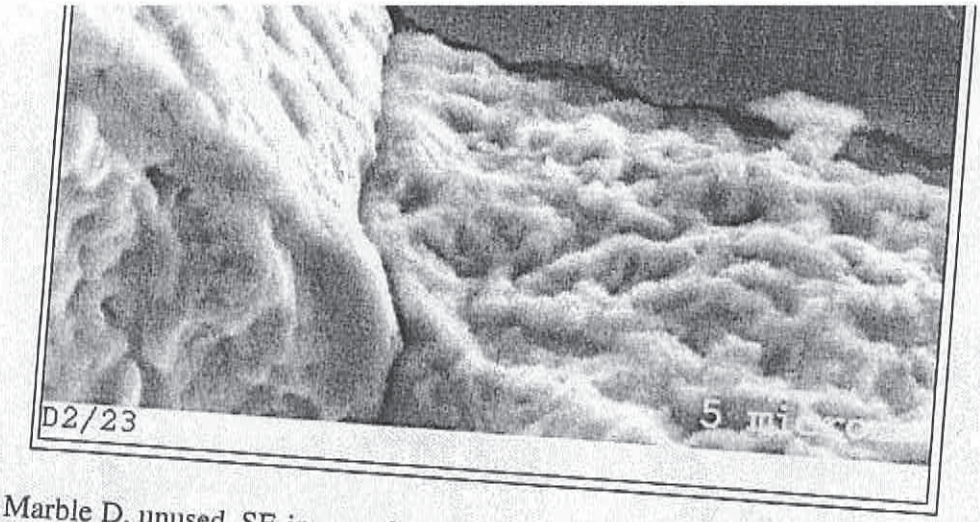


Figure 62. Marble D, unused. SE-image of fractured surface, 2500x.

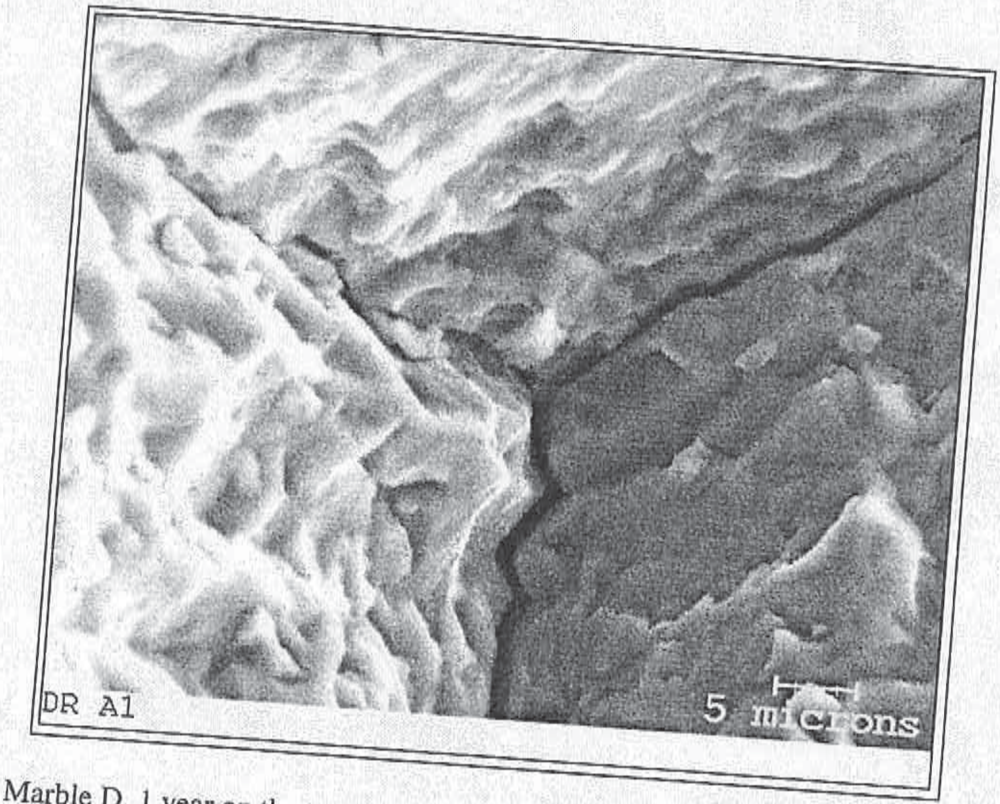


Figure 63. Marble D, 1 year on the test wall. SE-image of fractured surface, 2500x.

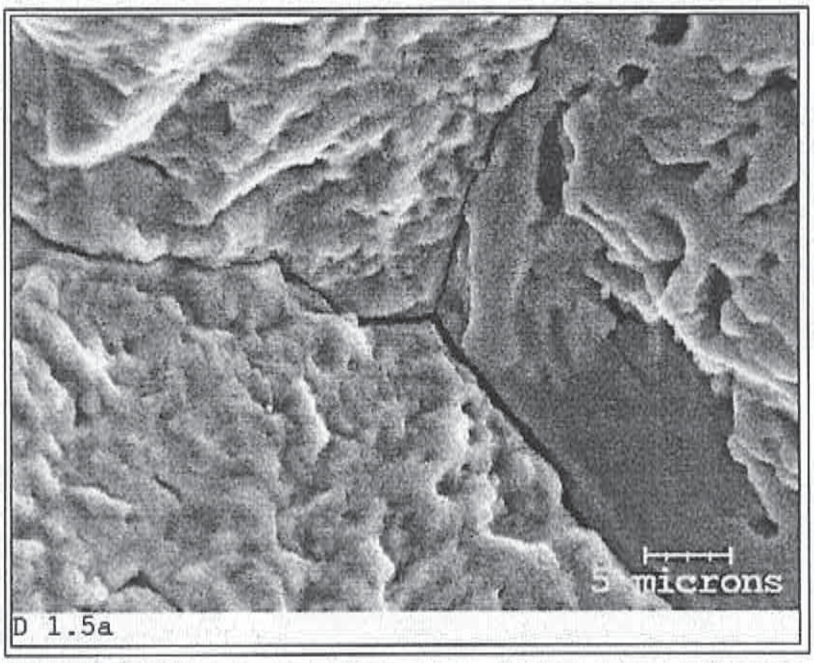


Figure 64. Marble D, 1.5 years on the test wall. SE-image of fractured surface, 2500x.

SEM-pictures of fractured surfaces of marble E, both unused and after 1 and 1.5 years on the test wall, are shown in Figs. 65-70. The grain boundaries can be seen only in some places. Thus, it is impossible to distinguish the grains from each other. Some very narrow cracks can be noticed between some of the grains. Some more and a little wider cracks were detected when the marble had been exposed to the environmental stresses on the test wall. The maximum crack width after 1.5 years on the test wall is around 0.3 µm.

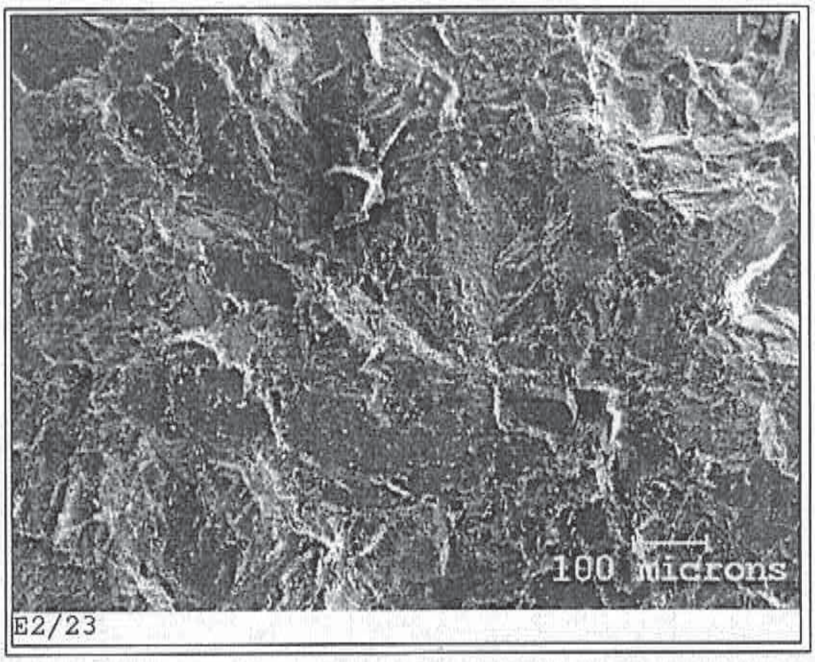


Figure 65. Marble E, unused. SE-image of fractured surface, 100x.

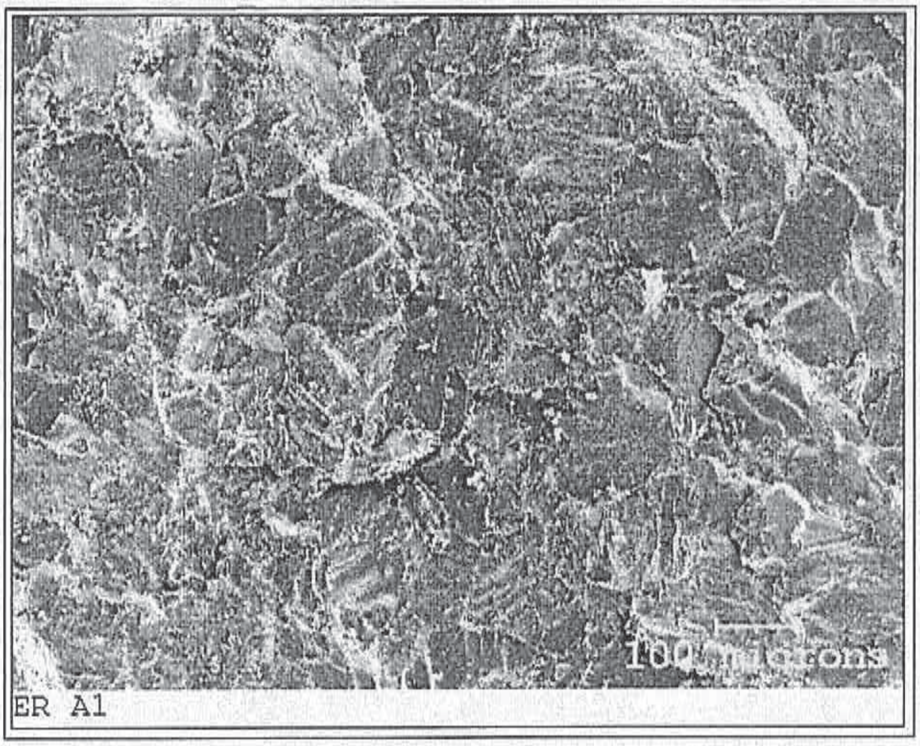


Figure 66. Marble E, 1 year on the test wall. SE-image of fractured surface, 100x.

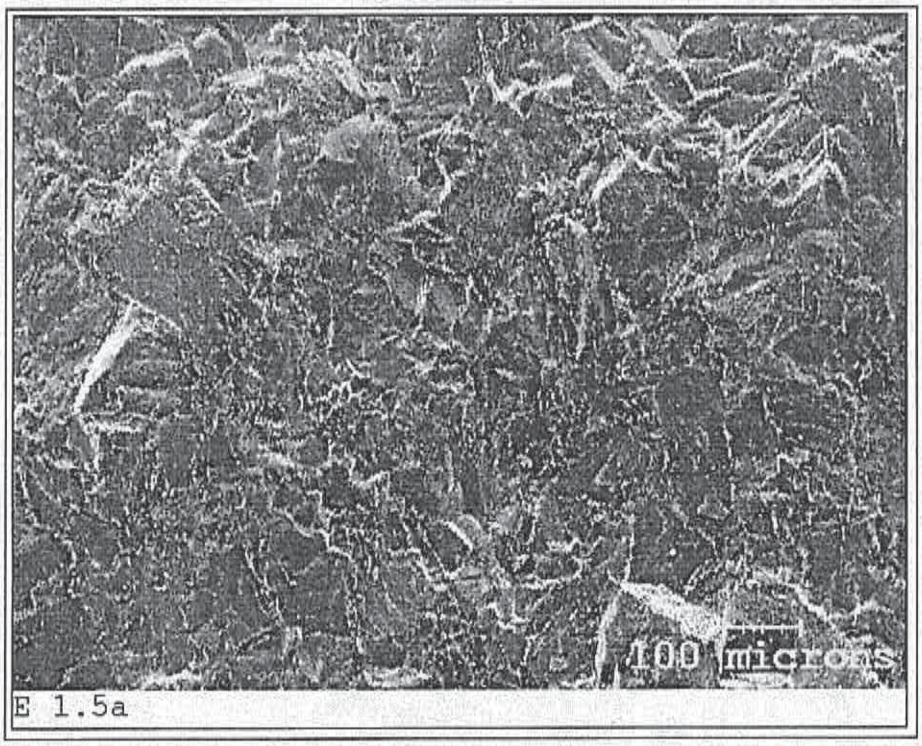
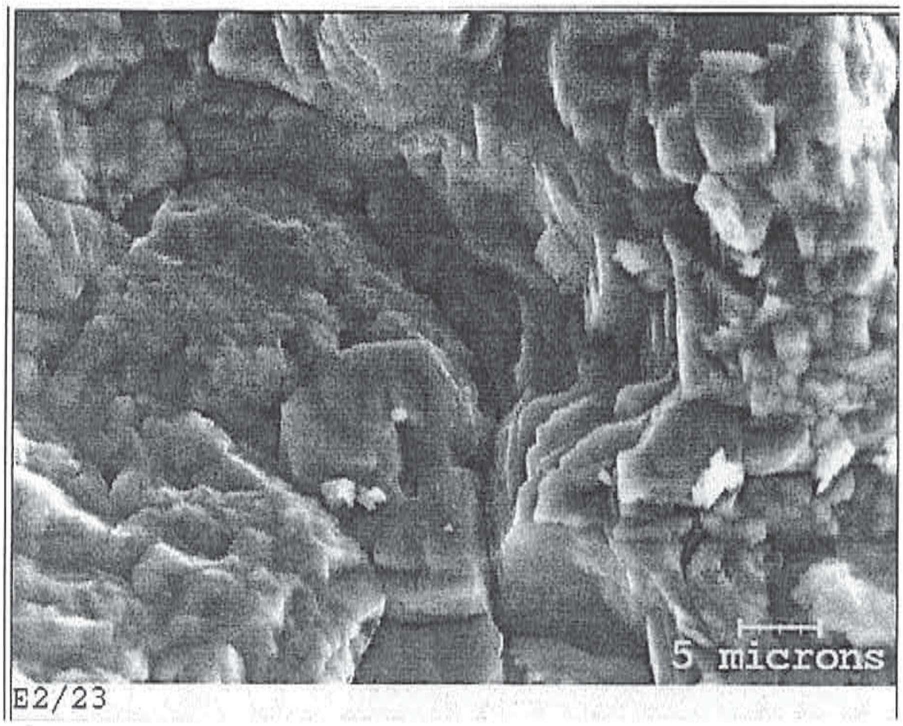


Figure 67. Marble E, 1.5 years on the test wall. SE-image of fractured surface, 100x.


5 microns
E2/23

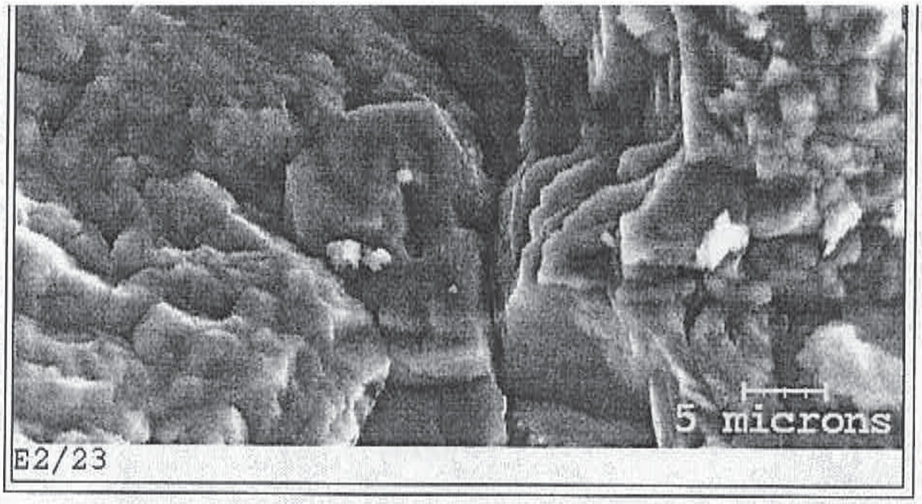


Figure 68. Marble E, unused. SE-image of fractured surface, 2500x.

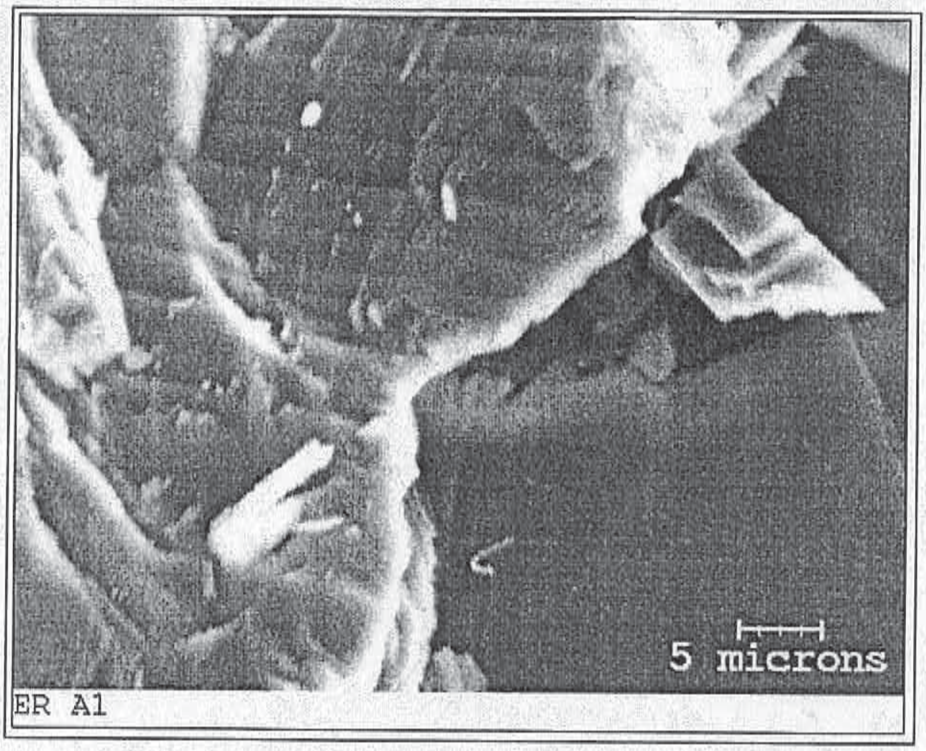


Figure 69. Marble E, 1 year on the test wall. SE-image of fractured surface, 2500x.

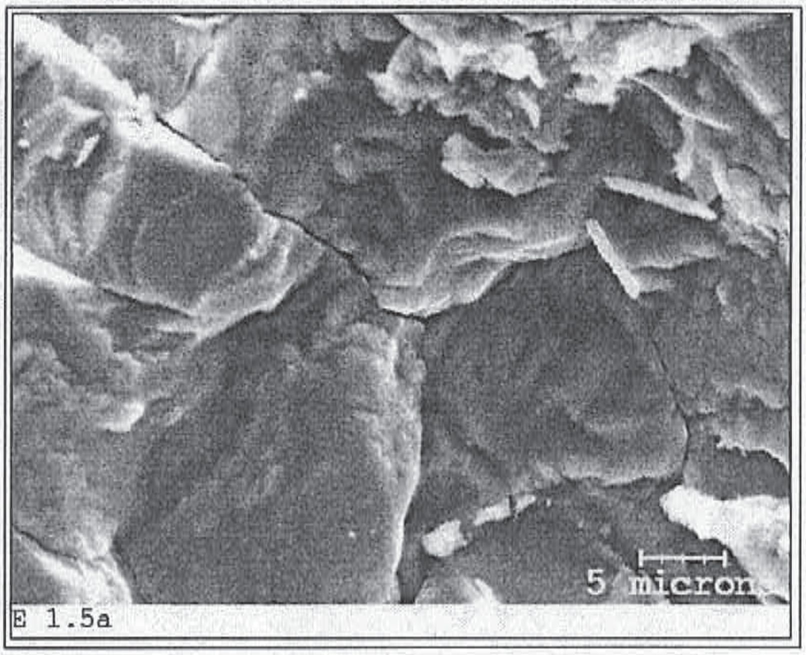


Figure 70. Marble E, 1.5 years on the test wall. SE-image of fractured surface, 2500x.

SEM-pictures of fractured surfaces of marble K, both unused and after 1 and 1.5 years on the test wall, are shown in Figs. 71-76. The grain boundaries can be seen only in some places. Thus, it is impossible to distinguish the grains from each other. Some very narrow cracks can be noticed between some of the grains. Some more and a little wider cracks were detected when the marble had been exposed to the environmental stresses on the test wall. The maximum crack width after 1.5 years on the test wall is around 0.3 µm.

Figure 71. Marble K, unused. SE-image of fractured surface, 100x.

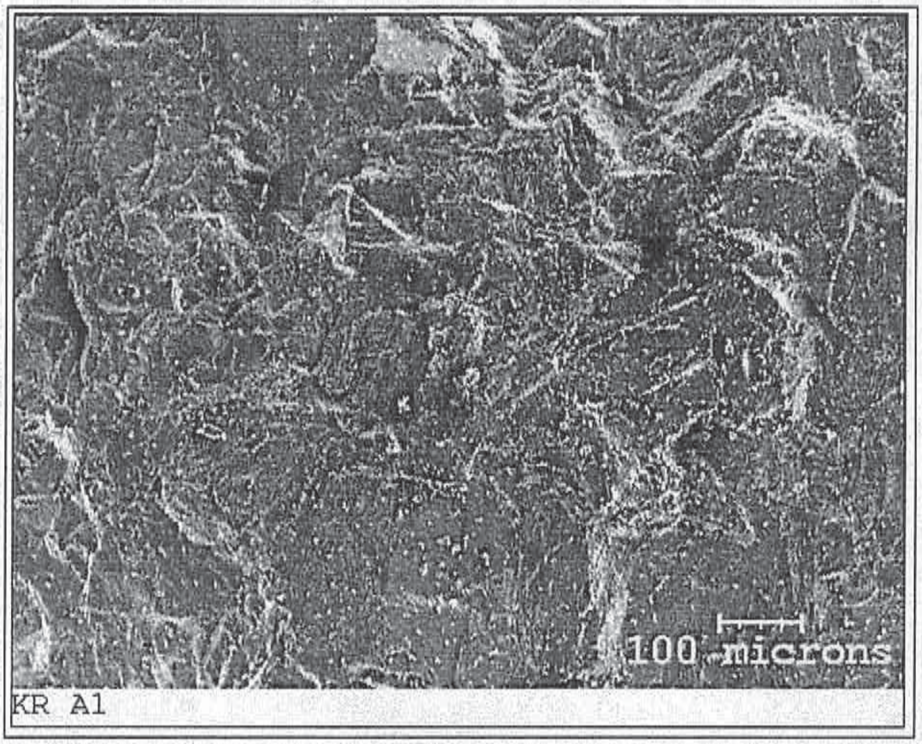


Figure 72. Marble K, 1 year on the test wall. SE-image of fractured surface, 100x.

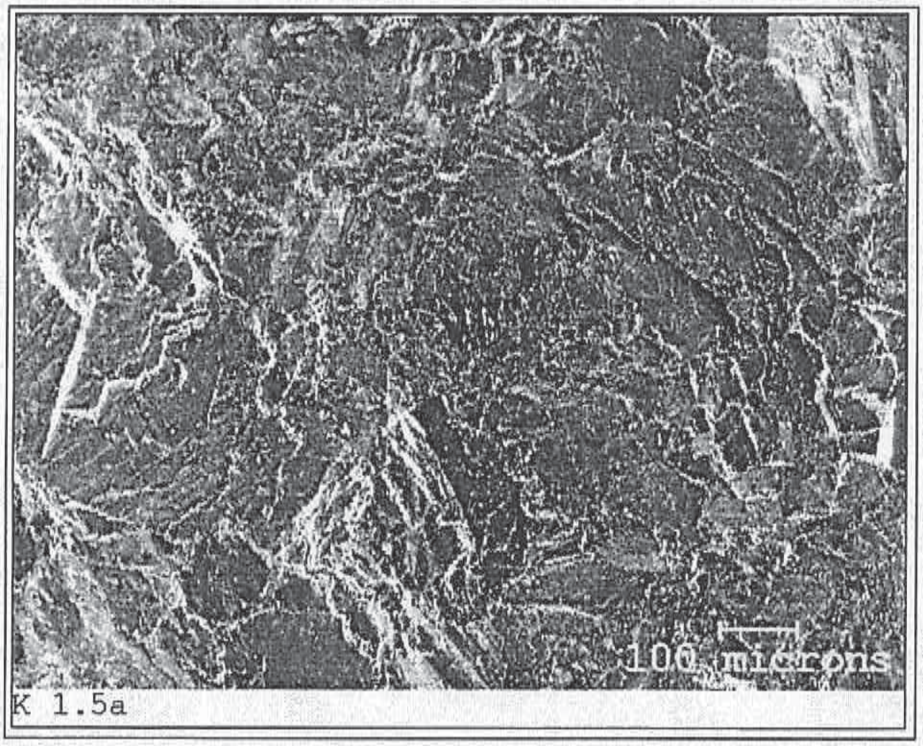


Figure 73. Marble K, 1.5 years on the test wall. SE-image of fractured surface, 100x.

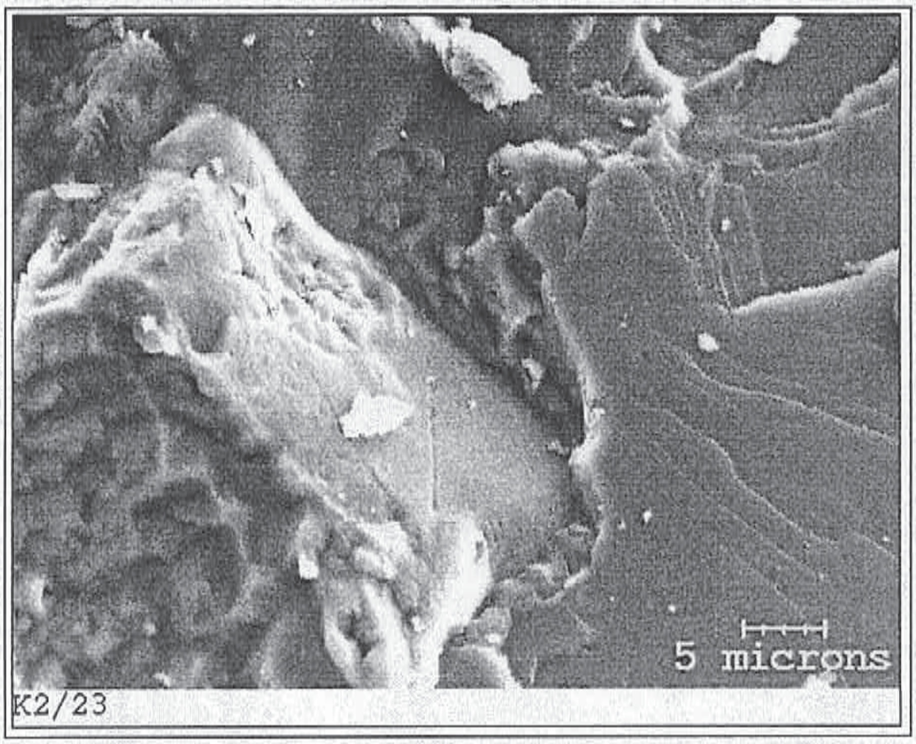


Figure 74. Marble K, unused. SE-image of fractured surface, 2500x.

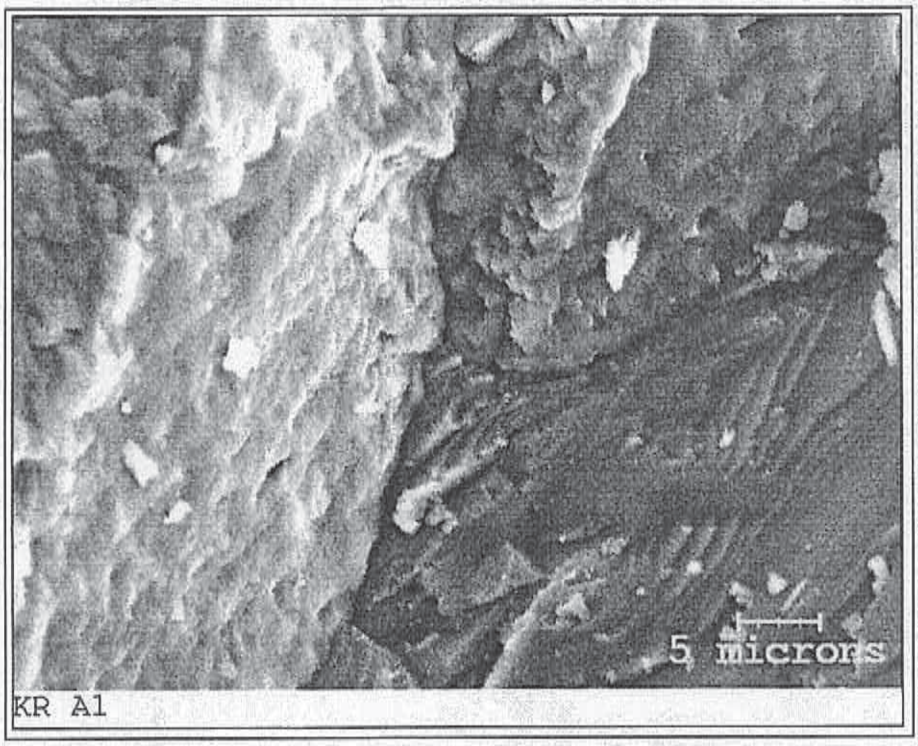


Figure 75. Marble K, 1 year on the test wall. SE-image of fractured surface, 2500x.

Figure 76. Marble K, 1.5 years on the test wall. SE-image of fractured surface, 2500x.

4.2 MARBLE CLAD ELEMENTS

4.2.1 Bond strength

The 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 Table 12 and in Fig. 77. The presented results are average values (av.) and standard deviations (s.d.) calculated from the testing data of individual specimens. The measurement results are shown in detail in Appendix 3.

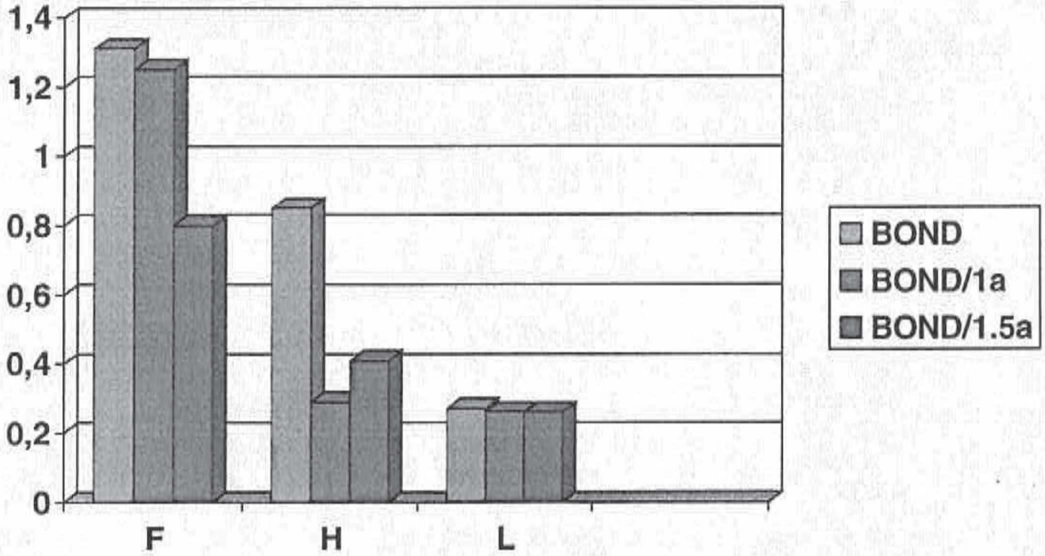


Figure 77. Bond strength of marble in marble clad elements (MPa).

Table 12. Bond strength of marble in marble clad elements.

	bond strength element F MPa	element H MPa	element L MPa
unused			
av.	1.31	0.85	0.27
s.d.	0.26	0.12	0.05
s.d. (%)	19.9	14.1	18.5
test wall / 1 year			
av.	1.25	0.29	0.26
s.d.	0.34	0.09	0.12
s.d. (%)	27.2	31.0	46.2
test wall / 1.5 years			
av.	0.80	0.41	0.26
s.d.	0.21	0.15	0.06
s.d. (%)	26.3	36.6	23.1

The relative changes of the bond strength that have taken place on the test wall are presented in Table 13. The basis of the comparison is in all cases the bond strength in the unused elements.

Table 13. 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.

4.2.2 Microstructure

Photographs of the microstructure of marble clad element F, unused and after 1.5 years on the test wall, are shown in Figs. 78-81. Following observations were made:

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

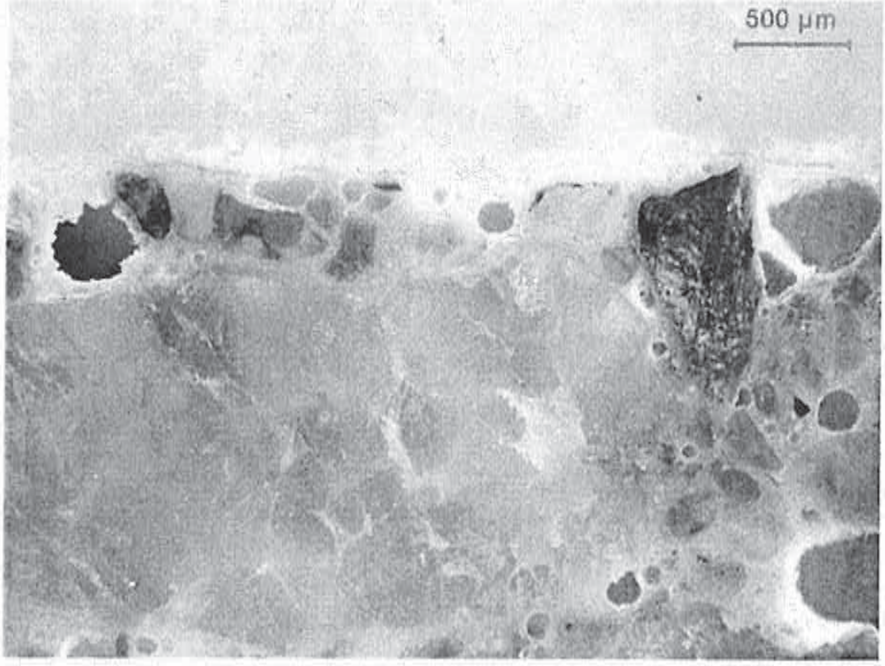


Figure 78. Microstructure of marble clad element F. Unused. Objective 2.5x, oblique illumination.

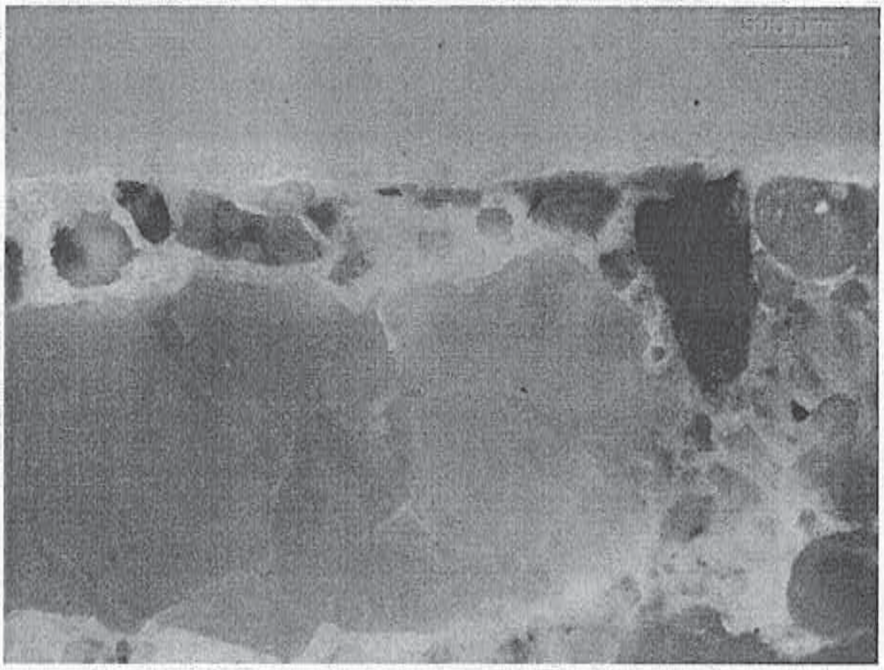


Figure 79. Microstructure of marble clad element F. Unused. Objective 2.5x, fluorescent light.

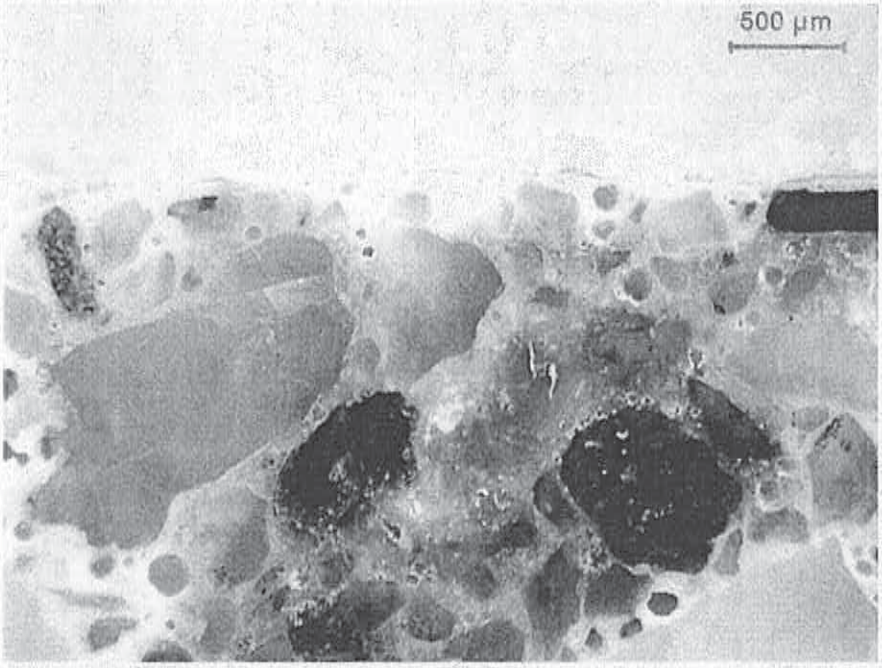


Figure 80. Microstructure of marble clad element F. 1.5 years on the test wall. Objective 2.5x, oblique illumination.

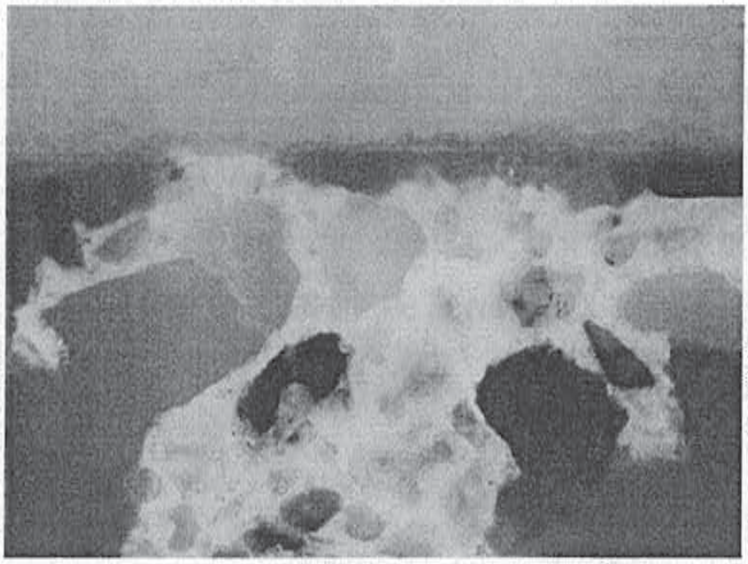


Figure 81. Microstructure of marble clad element F. 1.5 years on the test wall. Objective 2.5x, fluorescent light.

Photographs of the microstructure of marble clad element H, unused and after 1.5 years on the test wall, are shown in Figs. 82-85. 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 stressed for 1.5 years on the test wall the upper half of the glue layer tinted brownish
- in the element stressed for 1.5 years on the test wall open crack on about 60% of the contact zone marble/glue

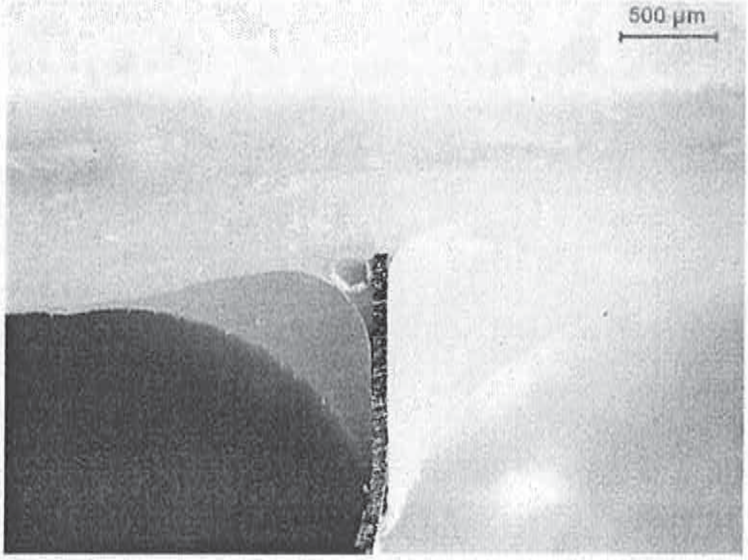


Figure 82. Microstructure of marble clad element H. Unused. Objective 2.5x, oblique illumination.

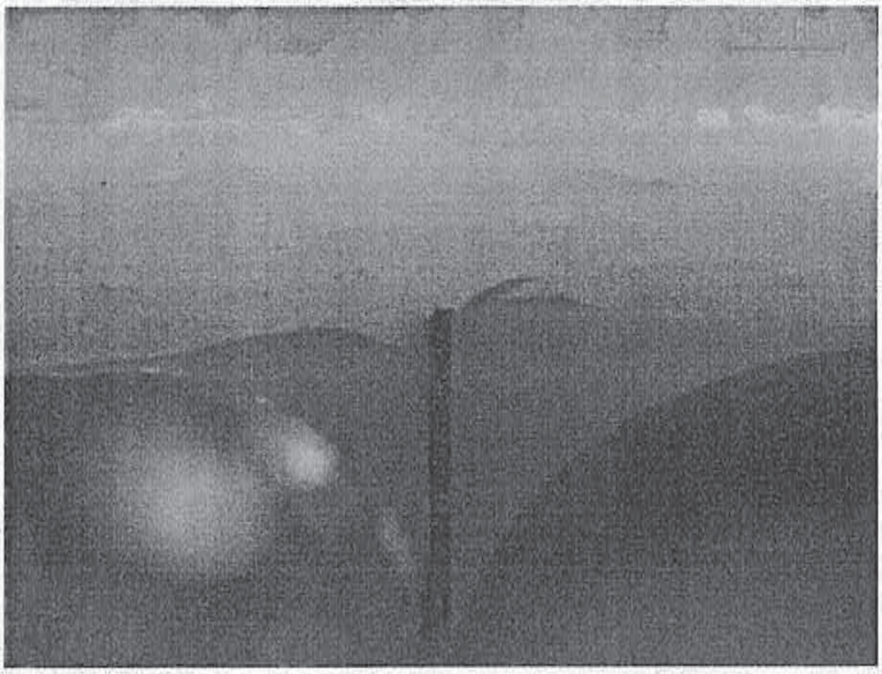


Figure 83. Microstructure of marble clad element H. Unused. Objective 2.5x, fluorescent light.

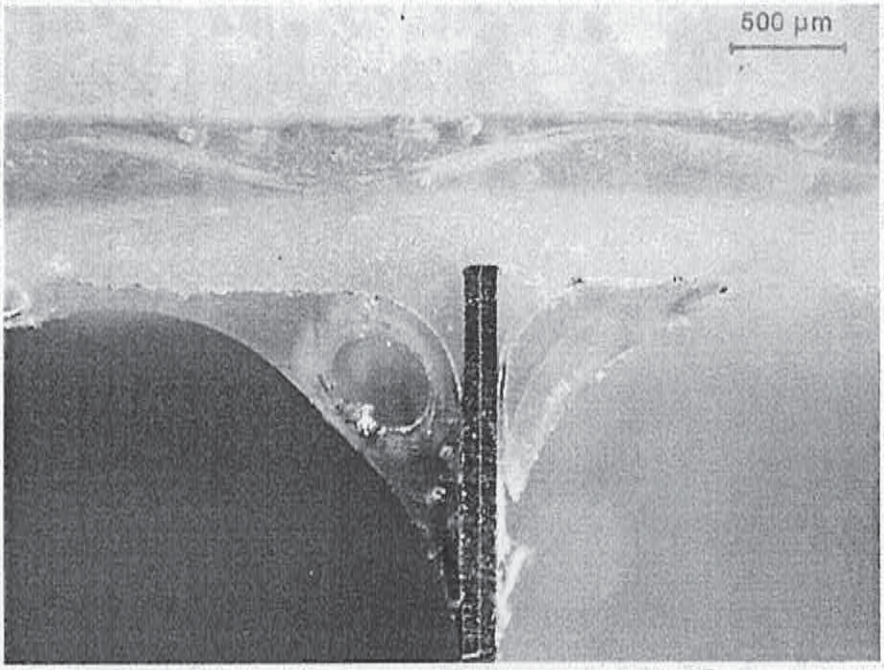


Figure 84. Microstructure of marble clad element H. 1.5 years on the test wall. Objective 2.5x, oblique illumination.

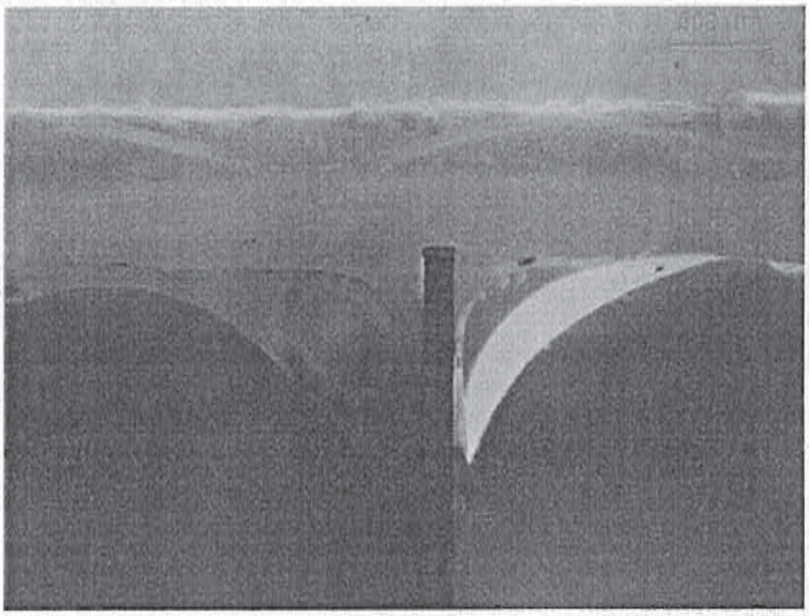


Figure 85. Microstructure of marble clad element H. 1.5 years on the test wall. Objective 2.5x, fluorescent light.

Photographs of the microstructure of marble clad element L, unused and after 1.5 years on the test wall, are shown in Figs. 86-89. 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 stressed 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

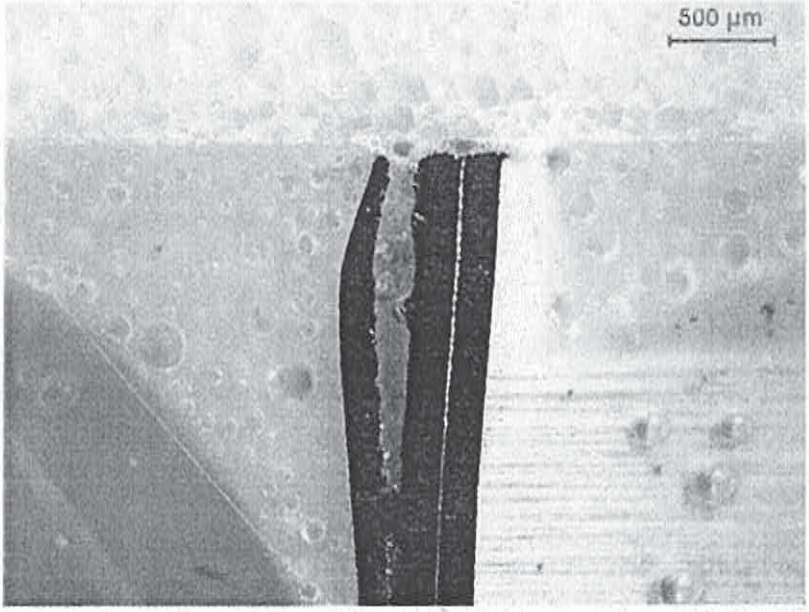


Figure 86. Microstructure of marble clad element L. Unused. Objective 2.5x, oblique illumination.

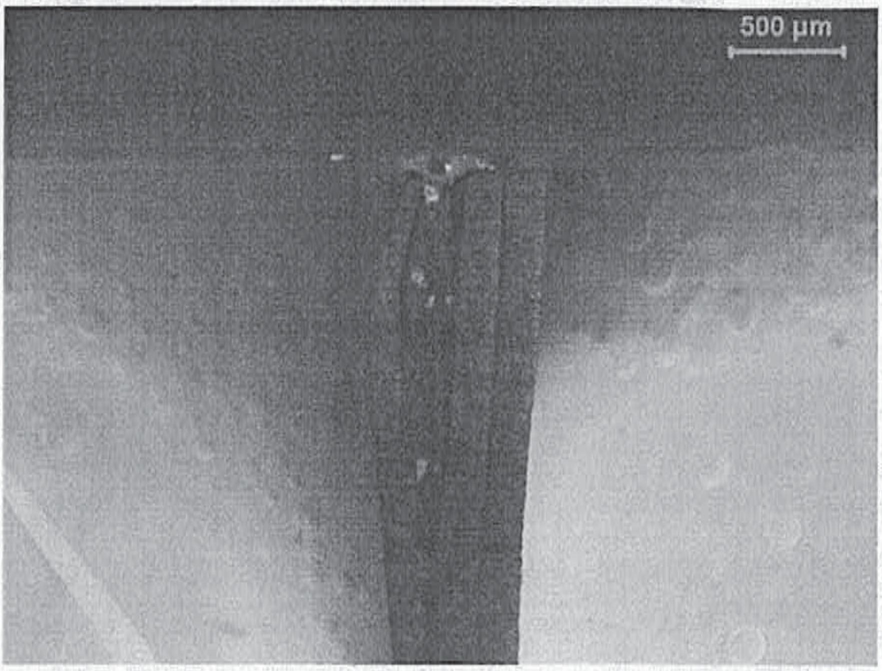


Figure 87. Microstructure of marble clad element L. Unused. Objective 2.5x, fluorescent light.

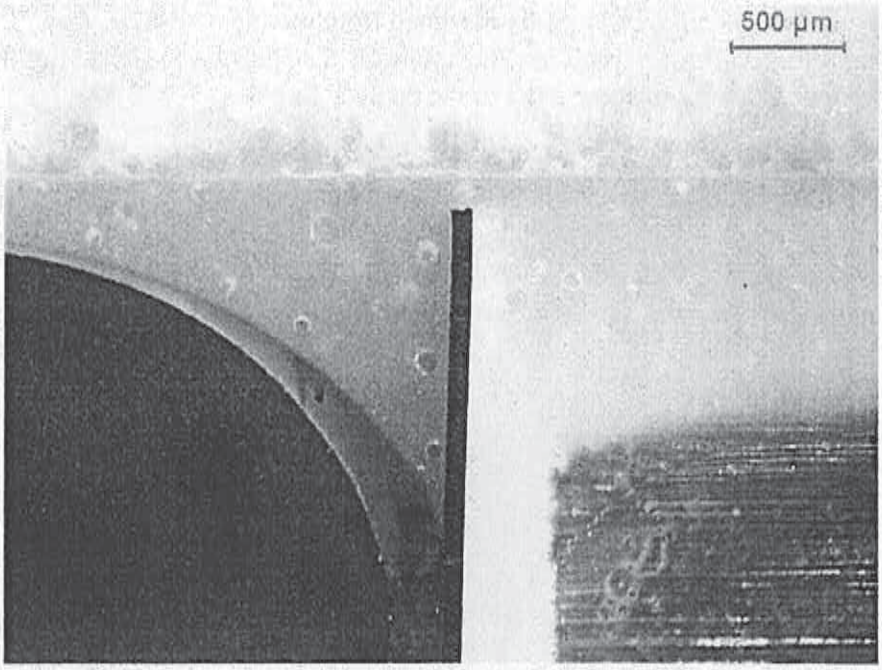


Figure 88. Microstructure of marble clad element L. 1.5 years on the test wall. Objective 2.5x, oblique illumination.

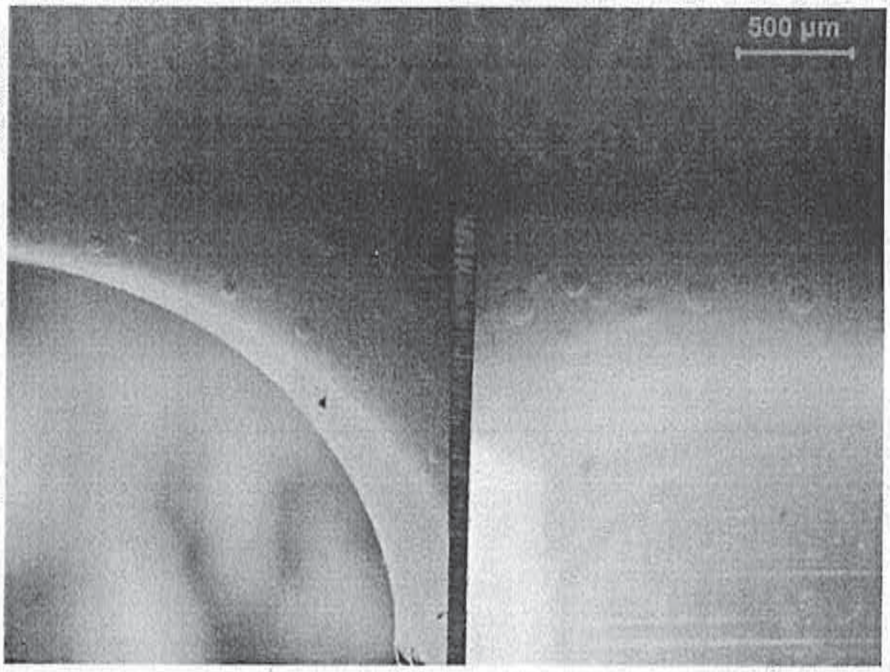


Figure 89. Microstructure of marble clad element L. 1.5 years on the test wall. Objective 2.5x, fluorescent light.

4.3 COLOUR MEASUREMENTS AT FINLANDIA HALL

The colour of the marble slabs chosen for this part of the study was measured 5 times during the project. The dates of the measurements were as follows:

code	date
1	23.06.1999
2	30.11.1999
3	17.05.2000
4	16.10.2000
5	08.03.2001

All the marble types were white, the L value of the unused slabs varying between 80 and 90. Marbles D and E had the highest L value and marble K the lowest. The values of the co-ordinates a and b were near zero, even though all the marble types had a slight greenish-blueish hue. The colour co-ordinates of the marble slabs placed on the eastern wall (23) in initial stage (measurement 1) are shown in Figs. 90-92.

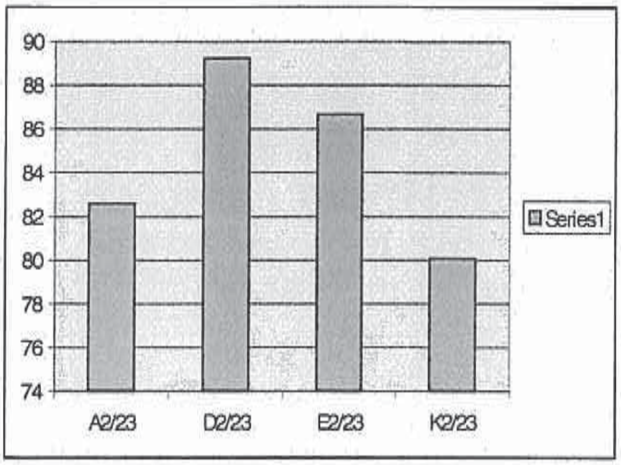


Figure 90. CIELAB colour co-ordinate L of the marbles. Eastern wall (23), first measurement 23.6.1999 (1).

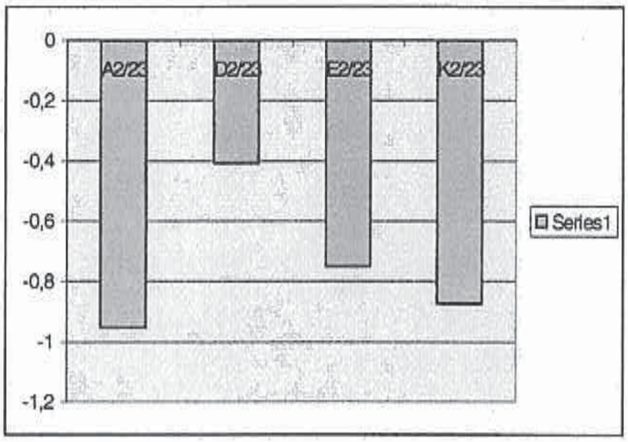


Figure 91. CIELAB colour co-ordinate a of the marbles. Eastern wall (23), first measurement 23.6.1999 (1).

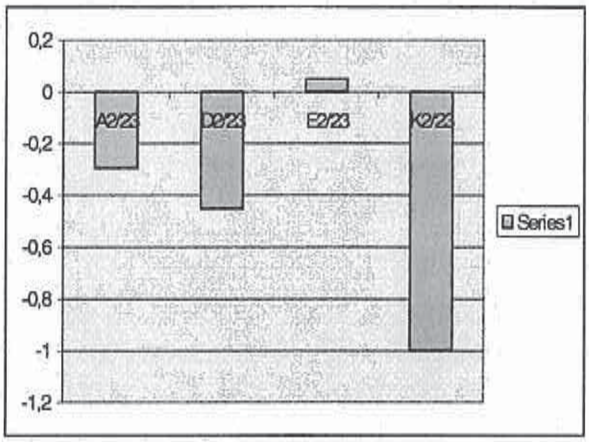


Figure 92. CIELAB colour co-ordinate b of the marbles. Eastern wall (23), first measurement 23.6.1999 (1).

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. Also, there has been a slight tendency for the co-ordinates a and b to move towards more positive values. This means that the marbles are getting more red and more yellow, which could refer to fouling of the marble surfaces. So far the changes have, however, been small. The results from the colour measurements are shown in Figs. 93-104. The detailed results are presented in Appendix 4.

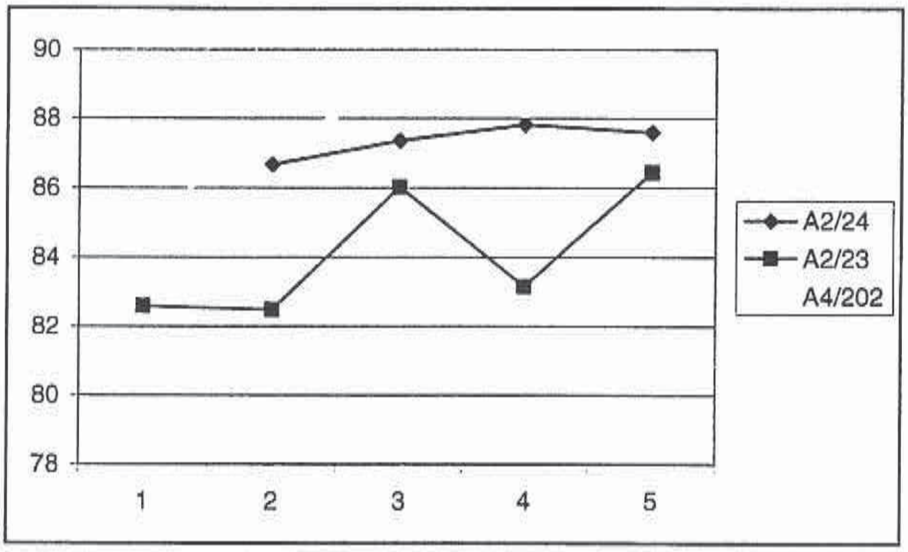


Figure 93. CIELAB colour co-ordinate L of marble A.

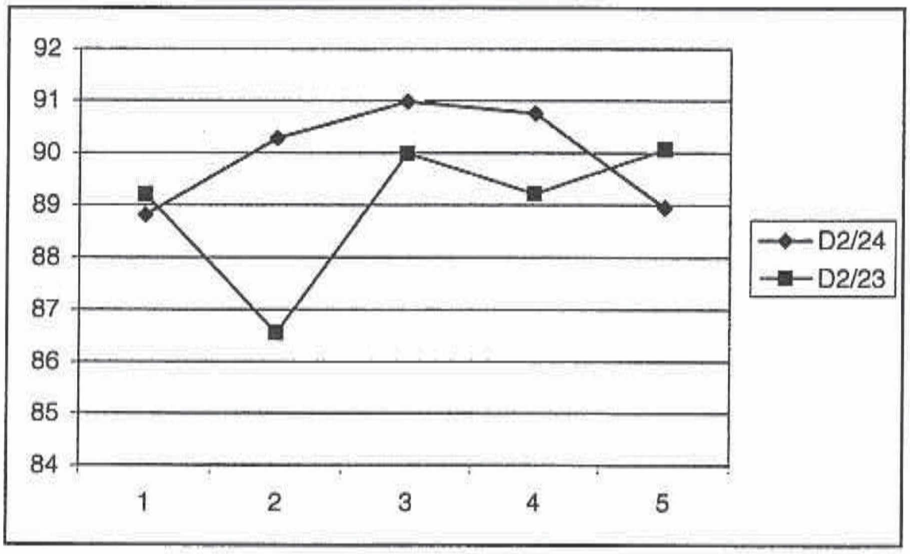


Figure 94. CIELAB colour co-ordinate L of marble D.

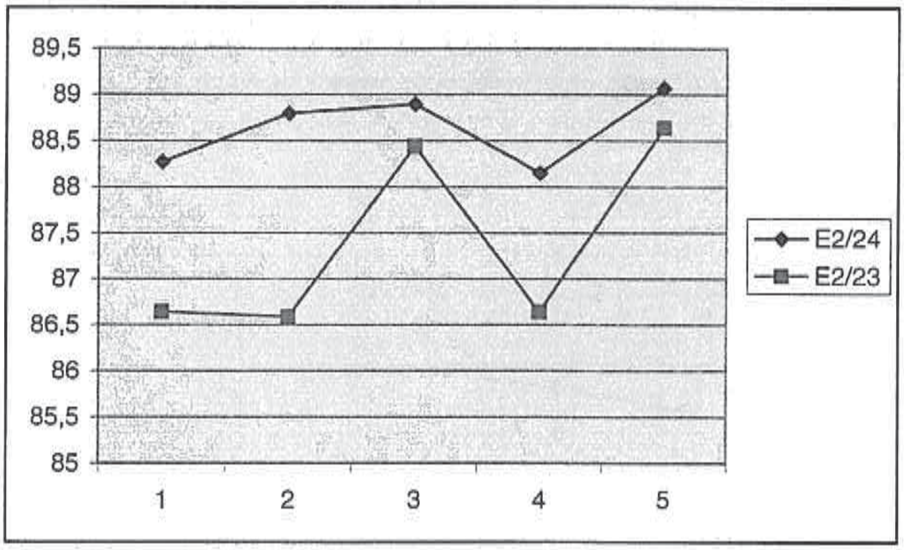


Figure 95. CIELAB colour co-ordinate L of marble E.

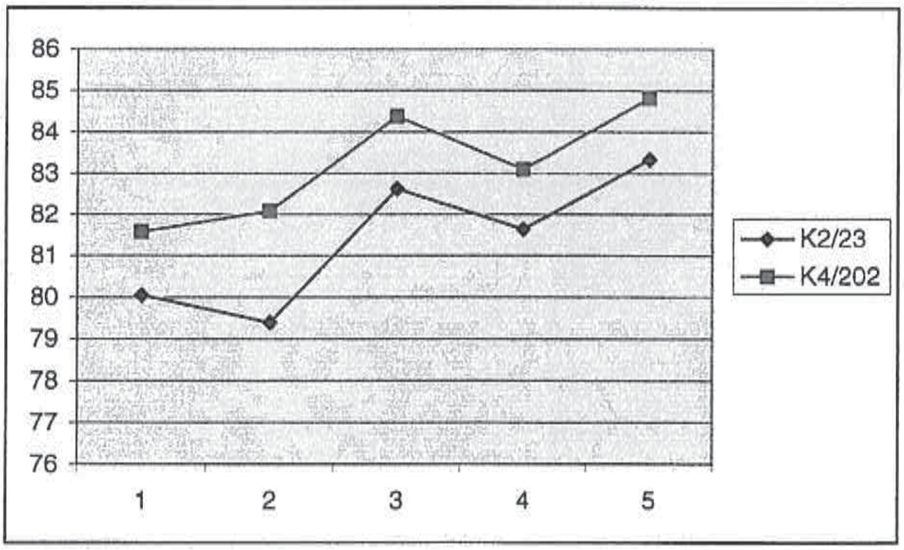


Figure 96. CIELAB colour co-ordinate L of marble K.

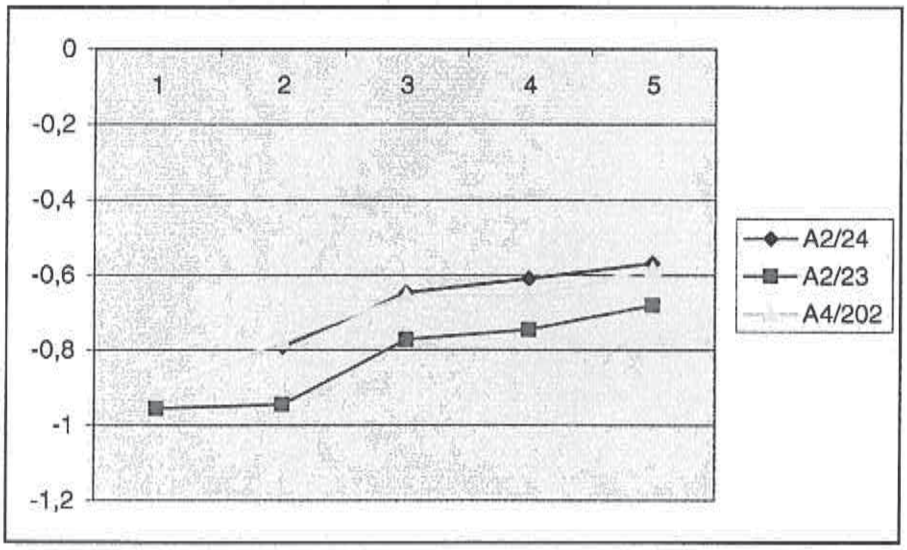


Figure 97. CIELAB colour co-ordinate a of marble A.

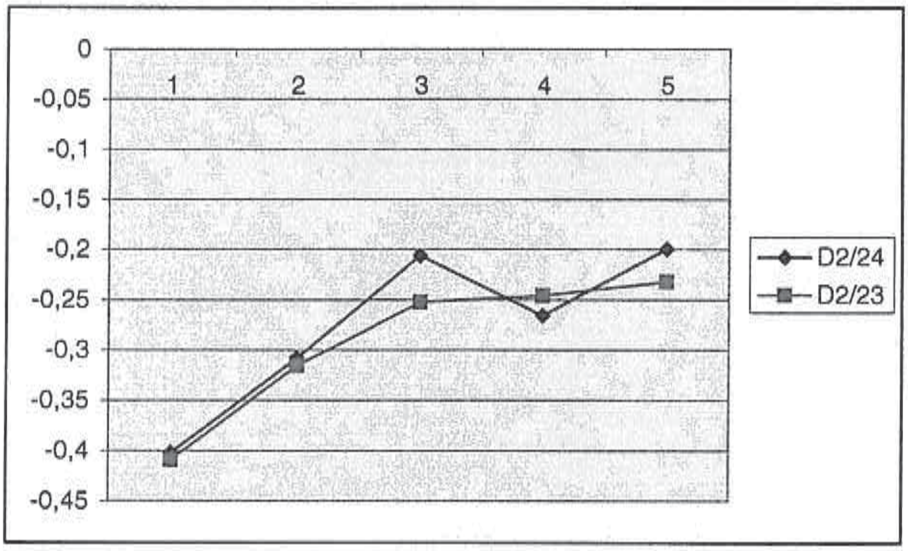


Figure 98. CIELAB colour co-ordinate a of marble D.

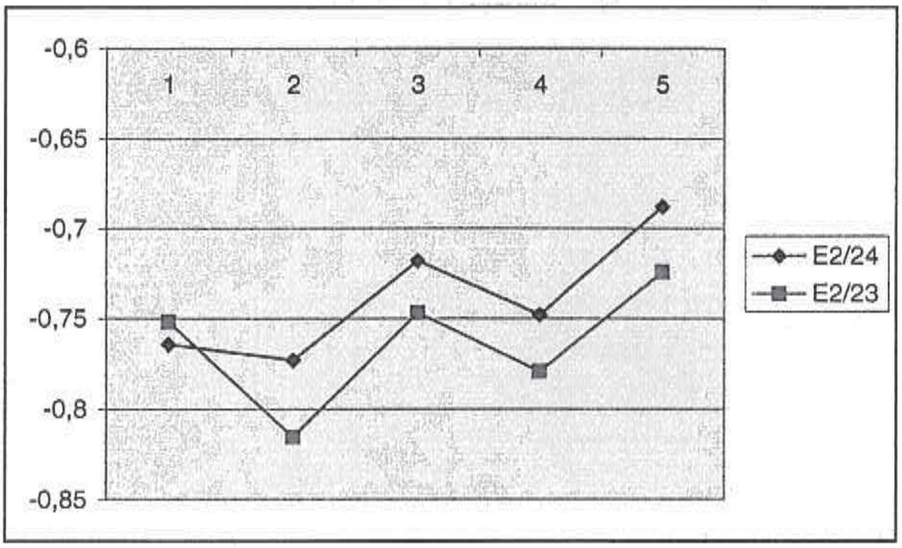


Figure 99. CIELAB colour co-ordinate a of marble E.

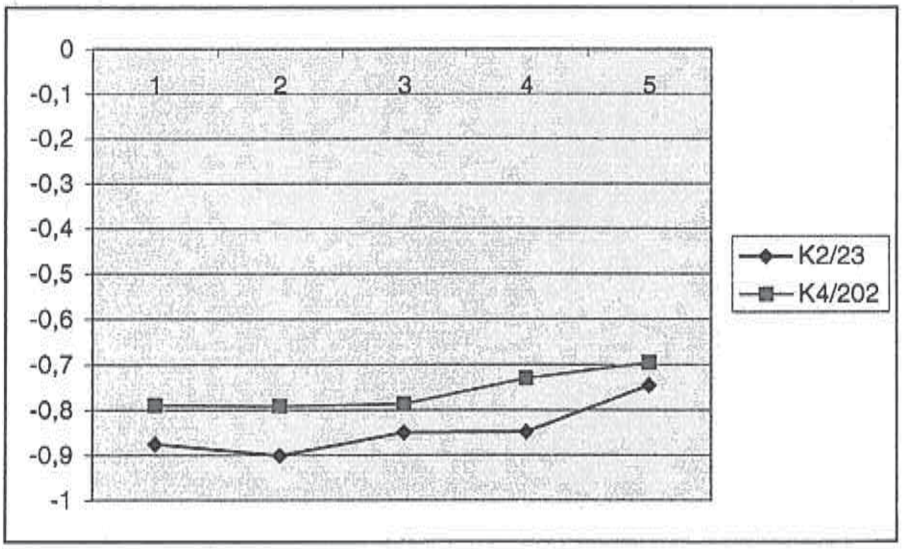


Figure 100. CIELAB colour co-ordinate a of marble K.

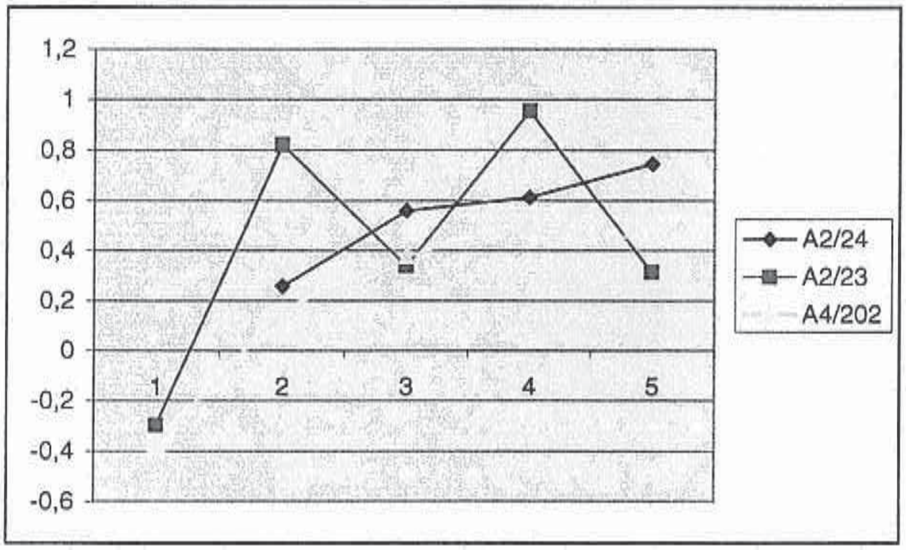


Figure 101. CIELAB colour co-ordinate b of marble A.

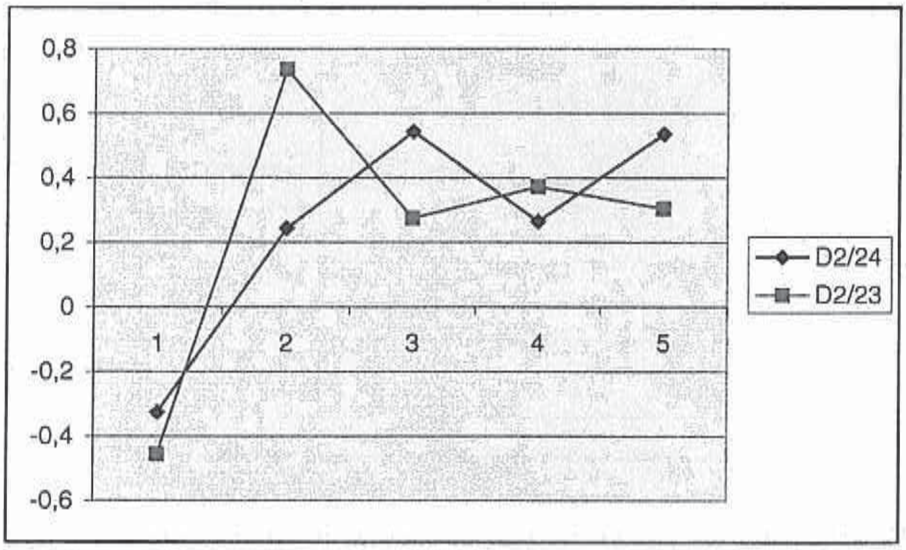


Figure 102. CIELAB colour co-ordinate b of marble D.

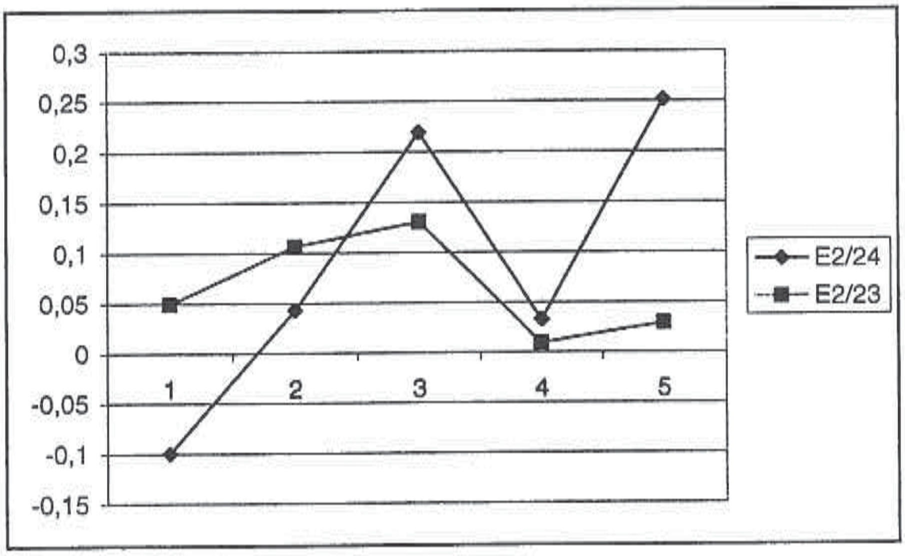


Figure 103. CIELAB colour co-ordinate b of marble E.

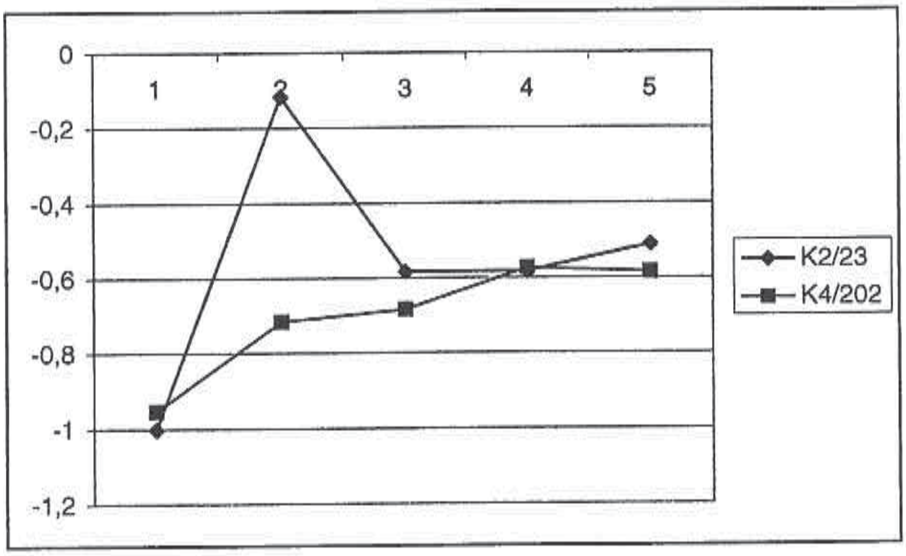


Figure 104. CIELAB colour co-ordinate b of marble K.

The colour differences, ΔE, of the marbles calculated from the values of the first (1) and the last (5) measurements are shown in Table 14. According to the results the colour change of marbles A and K, with the exception of slab A2/24, is evident. However, the colour change of marbles D and E is hardly noticeable so far.

Table 14. Colour change of the marbles during time period 6/99-3/01 (CIELAB).

marble	wall	ΔE
A	23	3.93
	24	1.08
	202	3.88
D	23	1.16
	24	0.90
E	23	1.99
	24	0.88
K	23	3.33
	202	3.24

4.4 FIELD SAMPLES

Marble samples from three different buildings were studied. Some background information dealing with the cases are presented as follows:

case 1

- private owned building situated in Helsinki
- part of the facades coated with marble, supporting structure from concrete elements, ventilation slot between marble and concrete, metal fixings
- built in 1965-1966
- severe deterioration: very notable warping and considerable loss of strength
- marble slabs taken off in 1999
- white marble from Carrara, exact type or origin unknown

case 2

- private owned building situated in Helsinki
- facades coated with marble, supporting structure from concrete elements, ventilation slot between marble and concrete, metal fixings
- built in two parts: older part is approximately 25 years and younger part approximately 15 years old
- severe deterioration: some warping and considerable loss of strength
- older part in much better condition
- white marble from Carrara, exact type or origin unknown

case 3

- public building situated in Oulu
- facades coated with marble, supporting structure from concrete elements, ventilation slot between marble and concrete, metal fixings
- built in 1979
- no warping, no loss of strength, breaking around the fixings
- slabs taken off in 2000
- white, heavily structured marble from finnish Lapland

In addition, the microstructure of a sample taken from the northern wall of the tower part of Finlandia Hall was studied. The cylindrical sample, Ø 30 mm, was taken in November 2000 by drilling through a 30 mm thick slab. The slabs on that wall had been installed during summer-autumn 1998.

4.4.1 Mineral composition

Marble from the building representing the case 1 was practically pure calcite, i.e. calcium carbonate. It contained only a few percents of quartz, feldspar and possibly mica as impurities. The weight loss of the marble in thermal analysis was 44.0 w-%. The X-ray diffraction diagram of the marble is shown in Fig.105 and its thermal curves in Fig. 106.

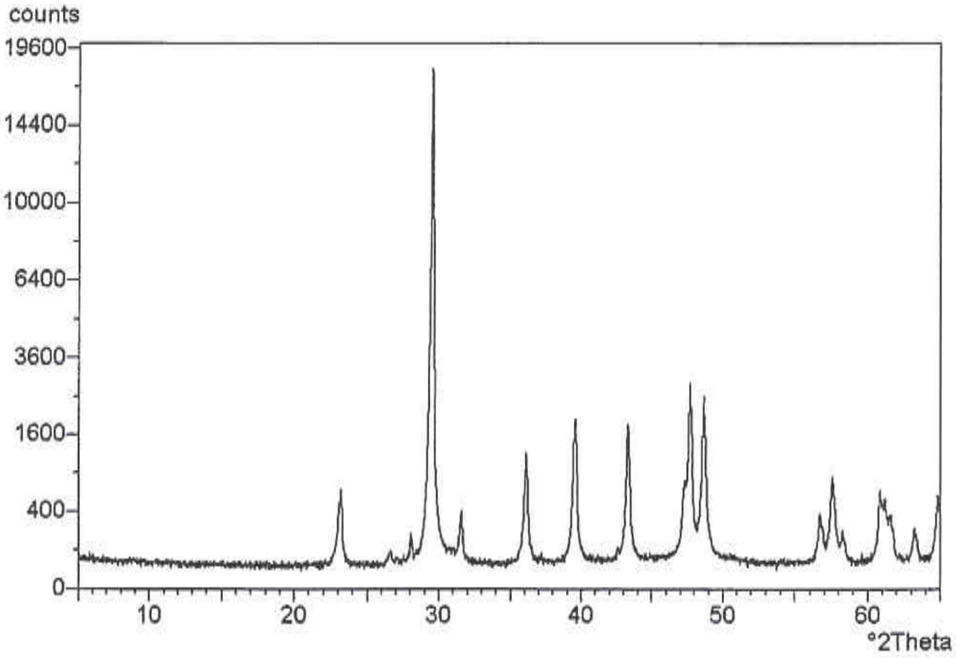


Figure 105. X-ray diffraction diagram of marble from case 1.

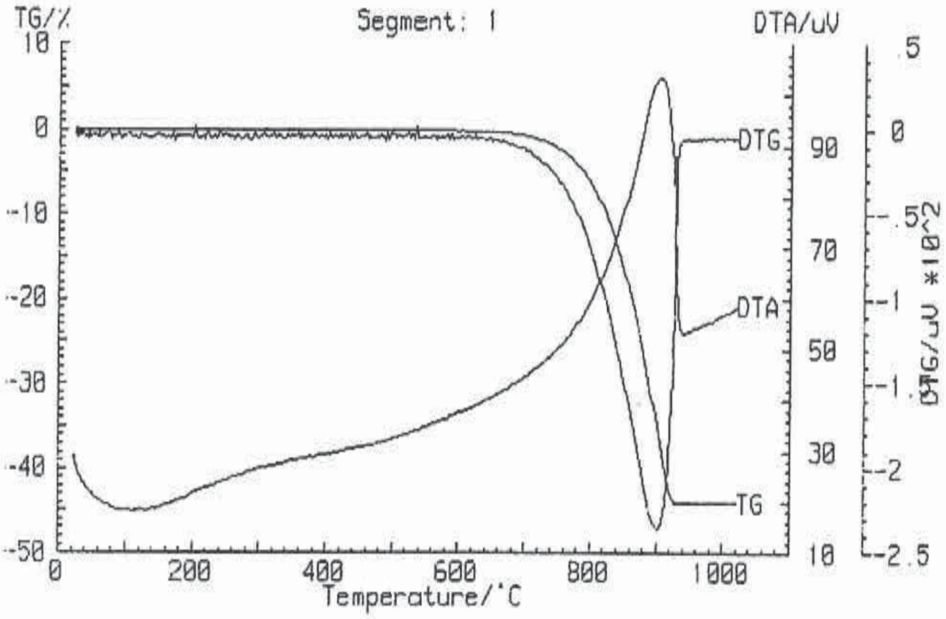


Figure 106. Thermal curves of marble from case 1.

Marbles from the building representing the case 2 were practically pure calcite, i.e. calcium carbonate. Marble from the older part contained only a few percents of quartz, marble from the younger part a few percents of quartz and feldspar as impurities. The weight loss of older marble in thermal analysis was 44.3 w-% and that of younger 44.2 w-%. The X-ray diffraction diagrams of marbles are shown in Figs. 107 and 108 and their thermal curves in Figs. 109 and 110.

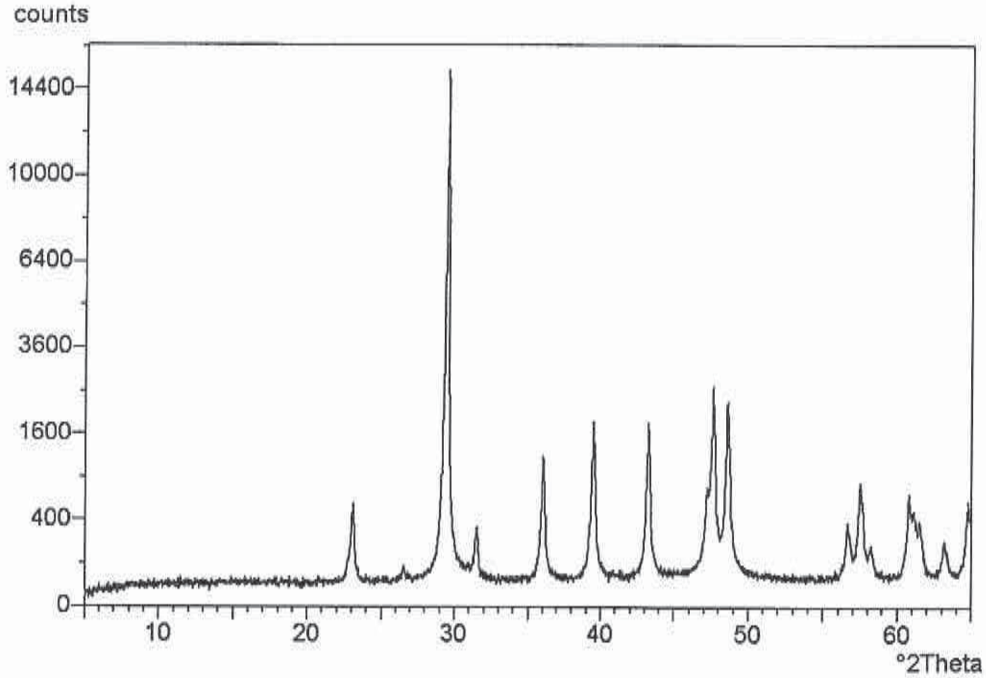


Figure 107. X-ray diffraction diagram of marble from case 2. Older part.

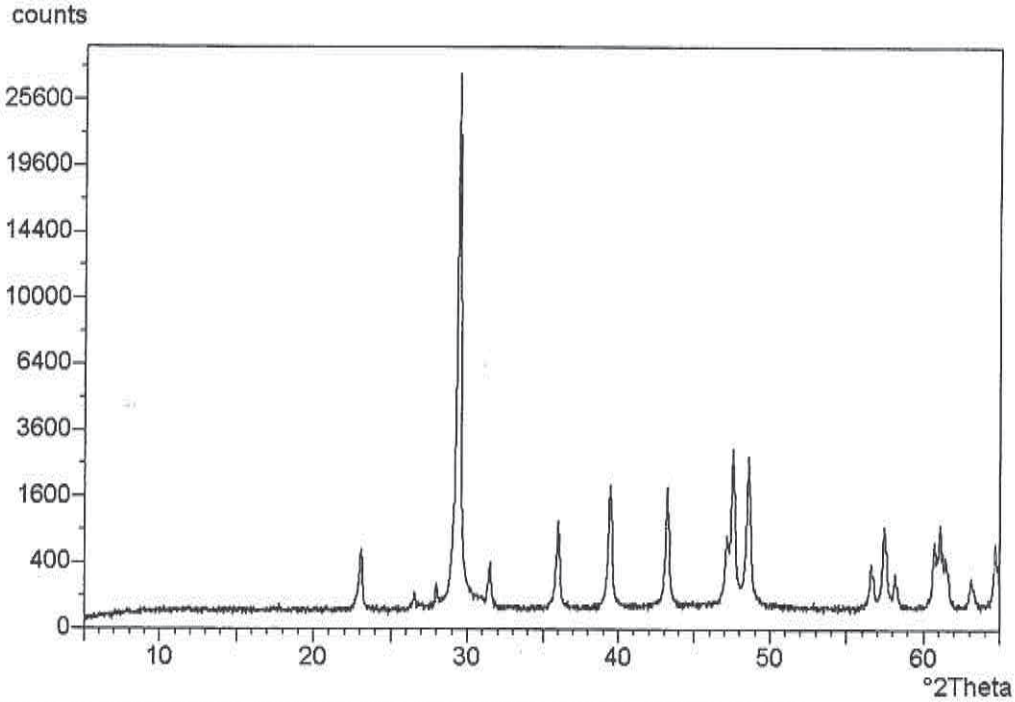


Figure 108. X-ray diffraction diagram of marble from case 2. Younger part.

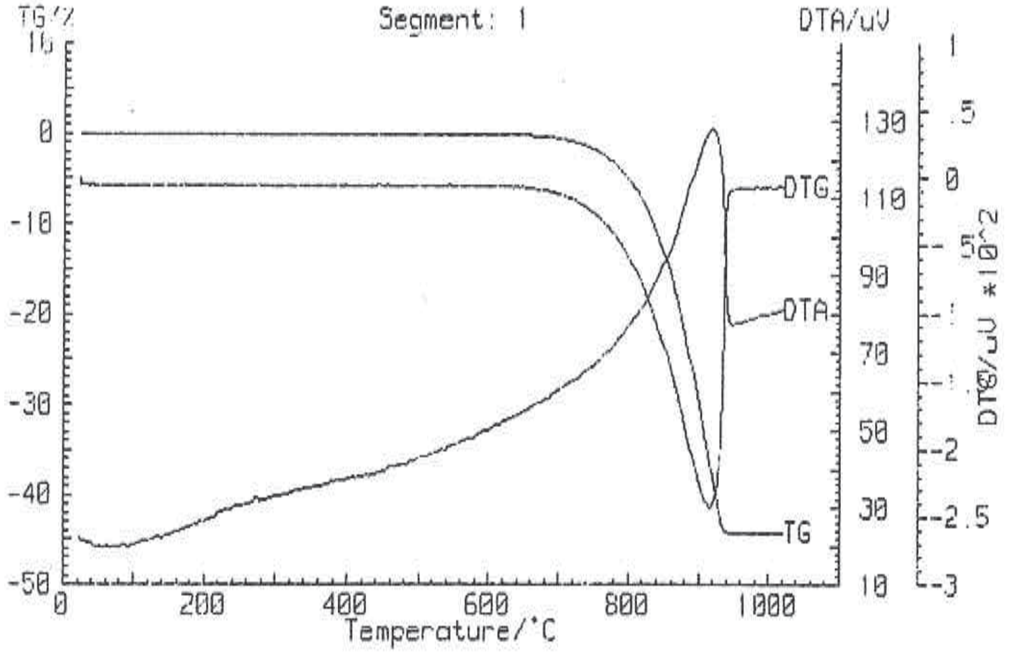


Figure 109. Thermal curves of marble from case 2. Older part.

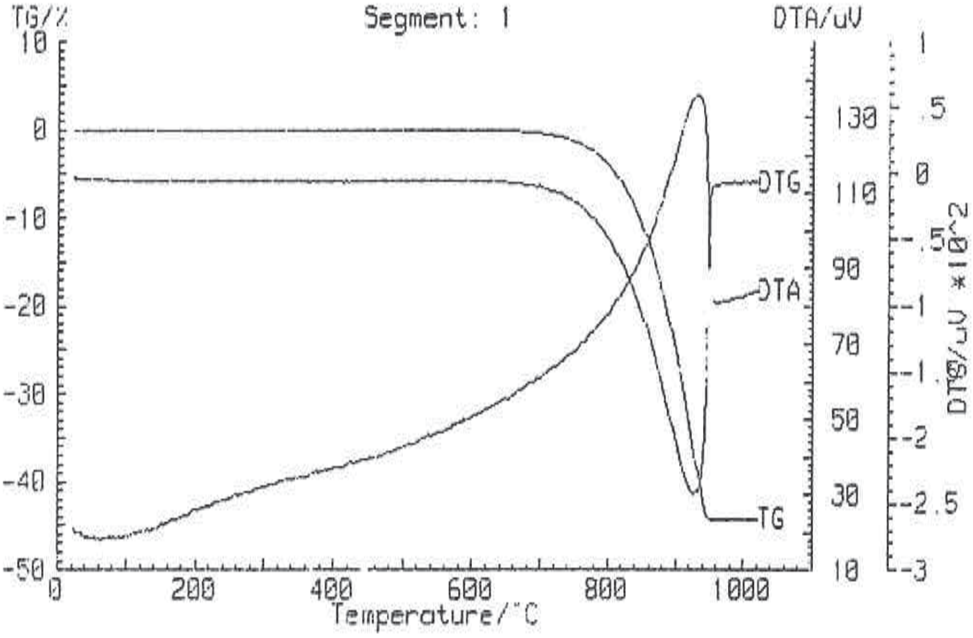


Figure 110. Thermal curves of marble from case 2. Younger part.

The main component of marble from the building representing the case 3 was dolomite, i.e. calcium magnesium carbonate. Thus, it was not question about marble. It contained also a notable amount of quartz and feldspar plus some mica and calcite as impurities. The weight loss of stone in thermal analysis was 43.3 w-%. The X-ray diffraction diagram of stone is shown in Fig.111 and its thermal curves in Fig. 112.

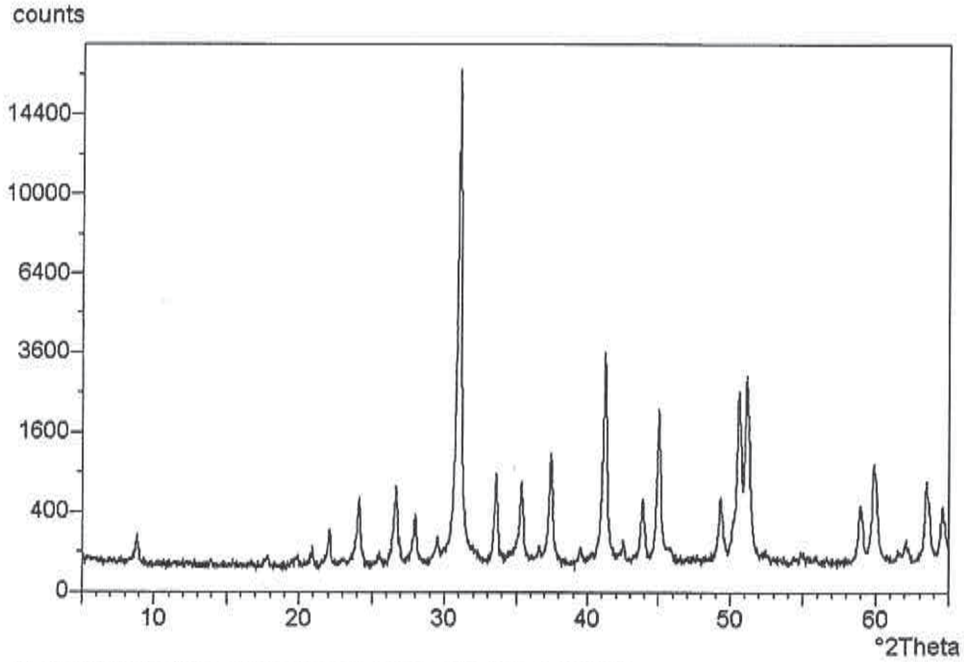


Figure 111. X-ray diffraction diagram of dolomite from case 3.

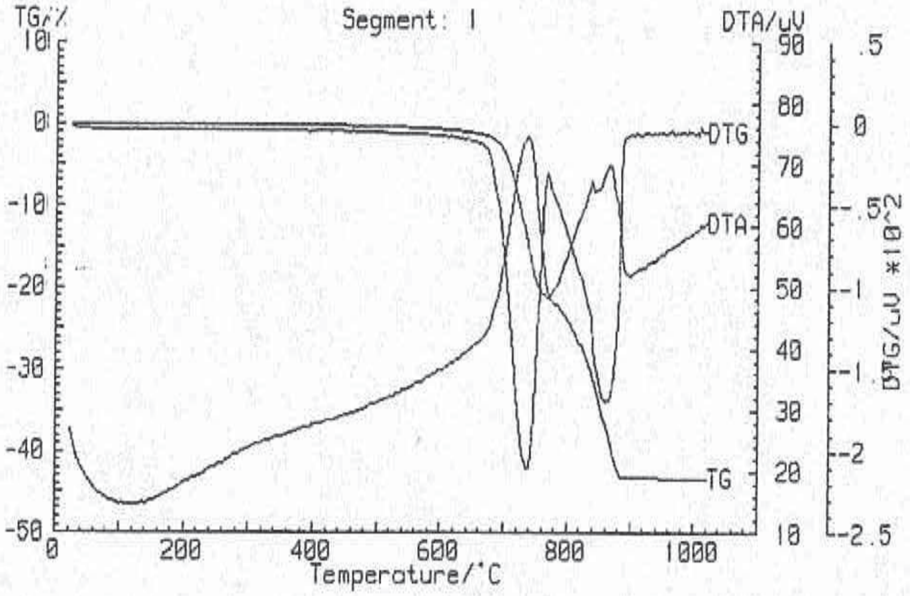


Figure 112. Thermal curves of dolomite from case 3.

4.4.2 Thin section study

A photograph of the microstructure of marble from the case 1 is shown in Fig. 113. Following observations were made:

- fine-grained ground mass, slightly oriented, average grain size 0.1-0.2 mm
- in places more coarse-grained veinlets with a thickness of about 1 mm, veinlets show the same orientation as the ground mass
- grain boundaries clear, often straight, grains easily distinguished
- nearly pure carbonate rock, only a little quartz and opaque minerals, possibly feldspar

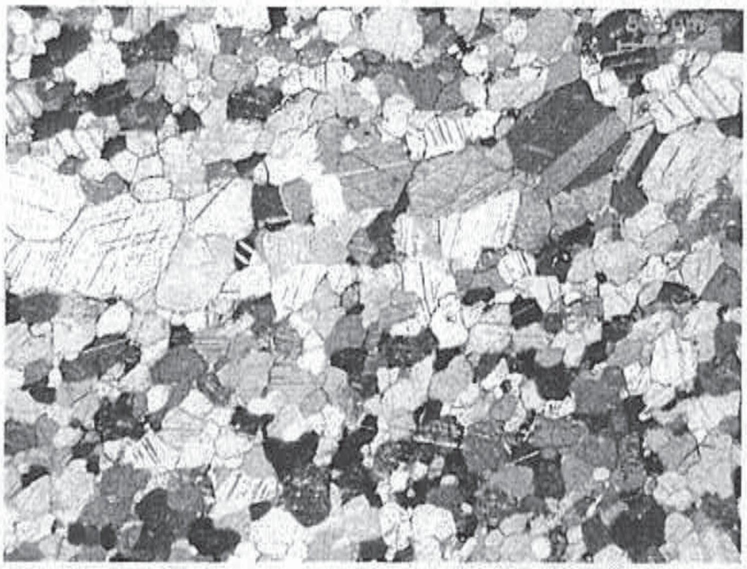


Figure 113. Microstructure of marble from case 1. Cross-polarized light.

Photographs of the microstructure of older marble from the case 2 are shown in Figs. 114 and 115. Following observations were made:

- ground mass fine-grained, even-grained, not oriented
- grain boundaries easily distinguished
- a few very fine-grained cryptocrystalline lenses, max. length about 10 mm, inside the ground mass
- no heavy cracking
- outer surface dirty and uneven

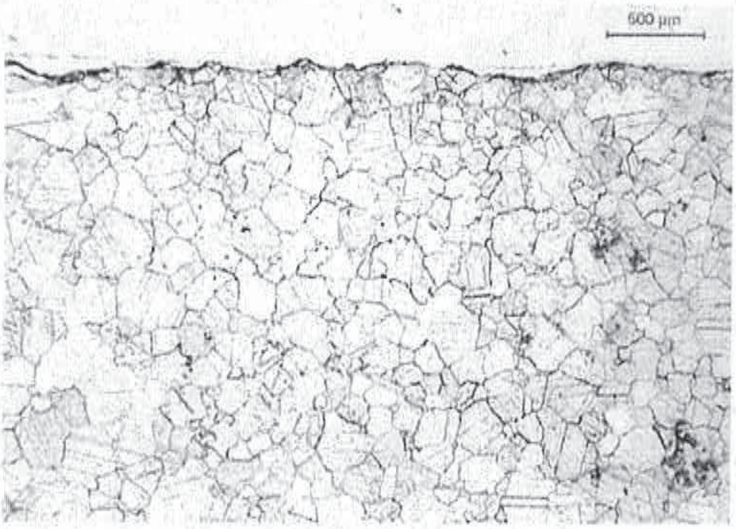


Figure 114. Microstructure of older marble from case 2. Plane-polarized light.

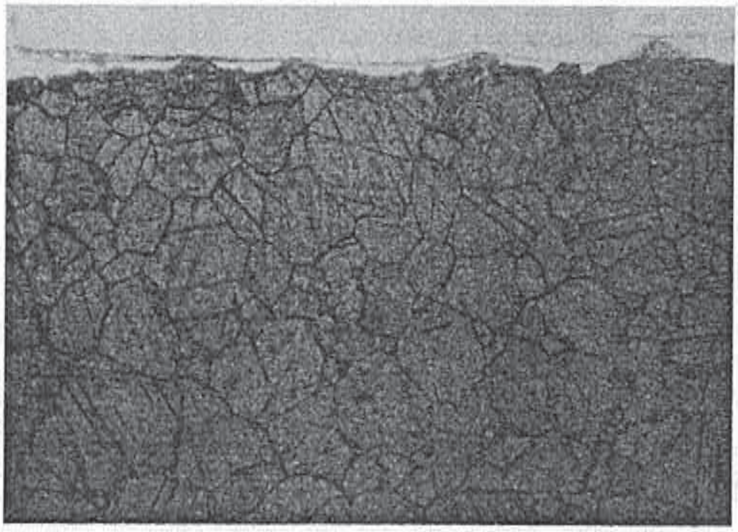


Figure 115. Microstructure of older marble from case 2. Fluorescent light.

Photographs of the microstructure of younger marble from the case 2 are shown in Figs. 116 and 117. Following observations were made:

- ground mass fine-grained, fairly even-grained, not oriented
- grain boundaries easily distinguished
- a few very fine-grained cryptocrystalline lenses, max. length about 2-3 mm, inside the ground mass
- cracks between the grains extending to a depth of about 2-3 mm from the outer surface and to a depth of about 1-2 mm from the inner surface, some cracks cut the surface
- outer surface dirty

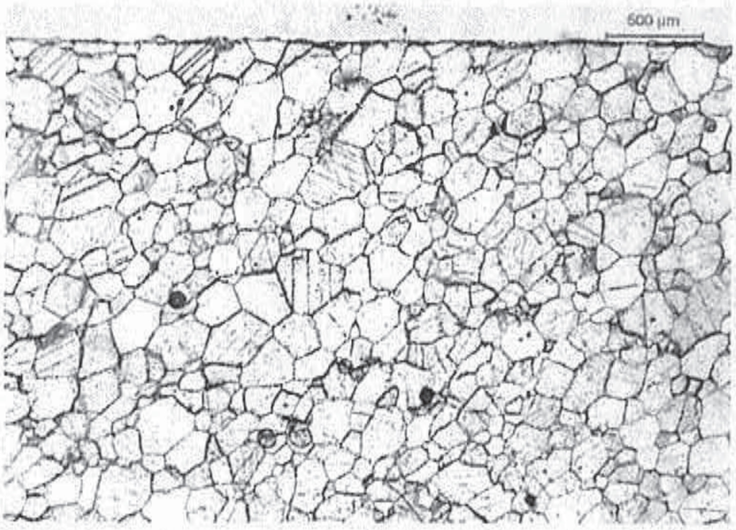


Figure 116. Microstructure of younger marble from case 2. Plane-polarized light.

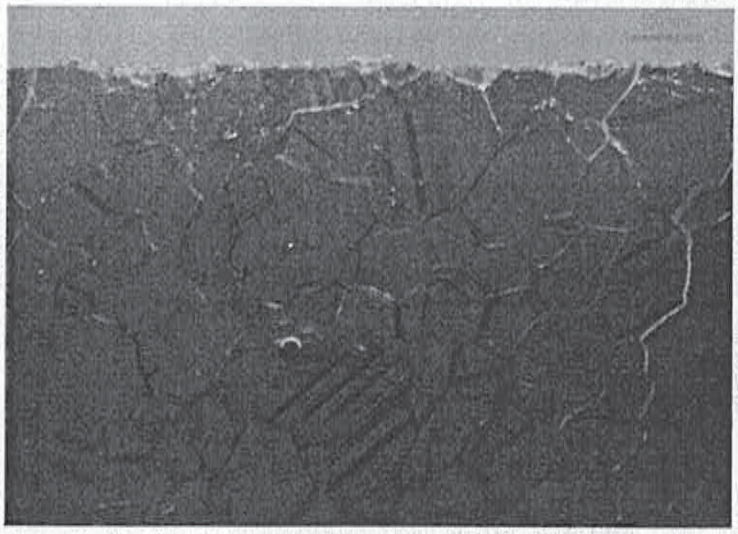


Figure 117. Microstructure of younger marble from case 2. Fluorescent light.

A photograph of the microstructure of dolomite from the case 3 is shown in Fig. 118. Following observations were made:

- ground mass very fine-grained, microcrystalline, dense
- clearly oriented, layered
- in places more coarse-grained veinlets with a thickness of about 1 mm, mostly oriented parallel to layering, a few also cross the layering
- some separate fine- to medium-grained quartz grains in rows, parallel to layering
- mainly carbonate rock, moderate content of quartz, other minerals include feldspar (probably plagioclase), mica (probably muscovite) and opaque minerals
- in places mica forms veinlets, partly with opaque minerals

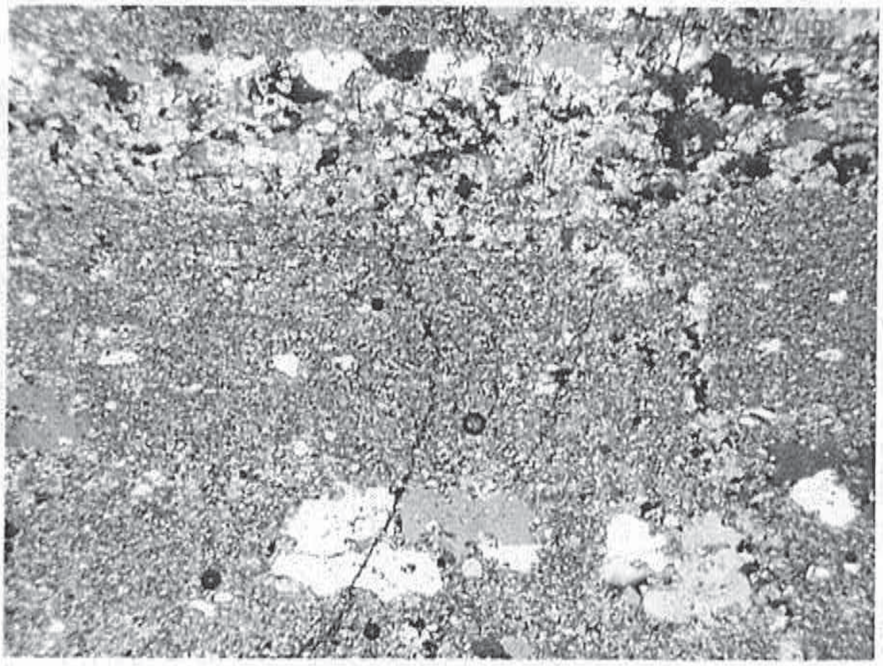


Figure 118. Microstructure of dolomite from case 3. Cross-polarized light.

A photograph of the microstructure of marble from Finlandia Hall is shown in Fig. 119. Following observations were made:

- fine-grained, fairly even-grained, slightly oriented
- average grain size 0.2-0.3 mm
- grain boundaries clear, straight, grains easily distinguished
- nearly pure carbonate rock, a little quartz and opaque minerals

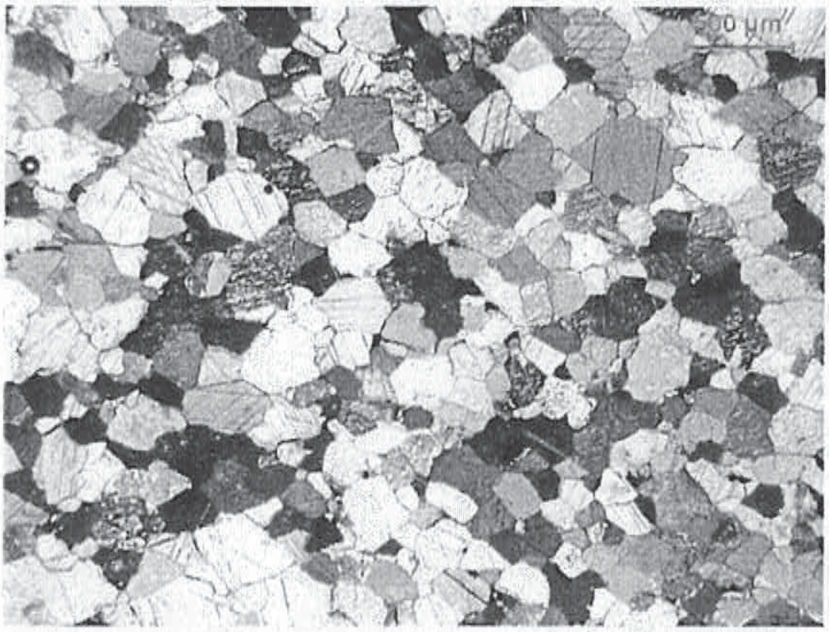


Figure 119. Microstructure of marble from Finlandia Hall. Cross-polarized light.

4.4.3 SEM-study

SEM-pictures of fractured surfaces of marble from the case 1 are shown in Figs. 120 and 121. The individual grains can at least for the most part be distinguished from each other. Cracks can be noticed practically between all the grains. The maximum crack width is around 2 µm. The average grain size of marble is about 200 µm.

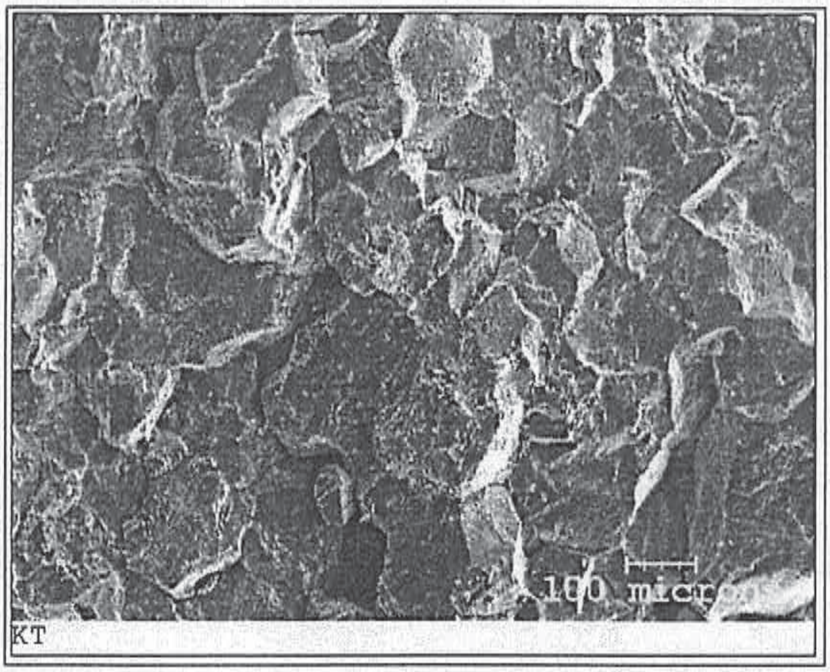


Figure 120. Marble from case 1. SE-image of fractured surface, 100x.

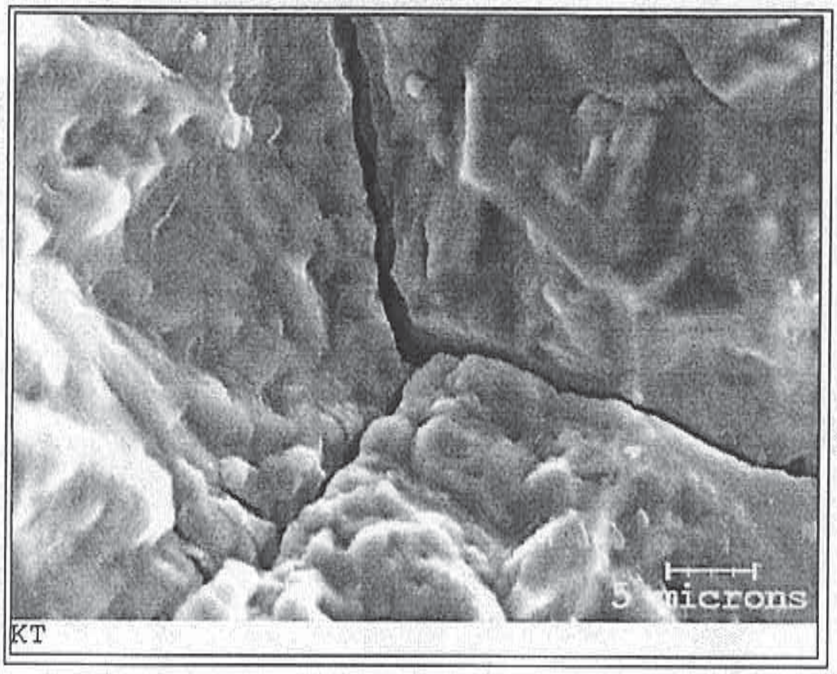


Figure 121. Marble from case 1. SE-image of fractured surface, 2500x.

SEM-pictures of fractured surfaces of marble from the case 2 are shown in Figs. 122 and 123. In marble of the older part the individual grains can at least for the most part be distinguished from each other. In marble of the younger part the grains are almost detached from each other. Wide cracks can be noticed between all the grains. The average grain size of older marble is about 200 µm, that of younger marble around 200-300 µm.

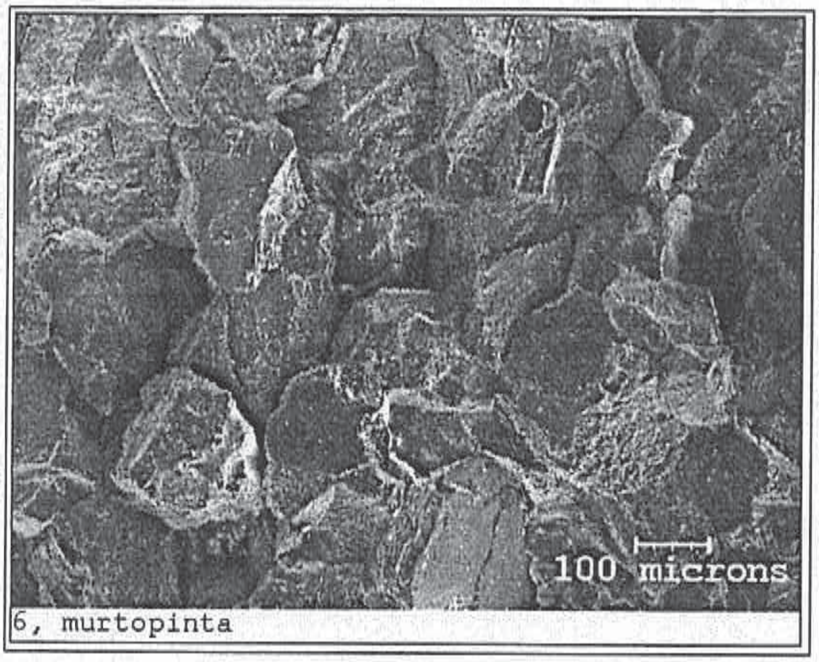
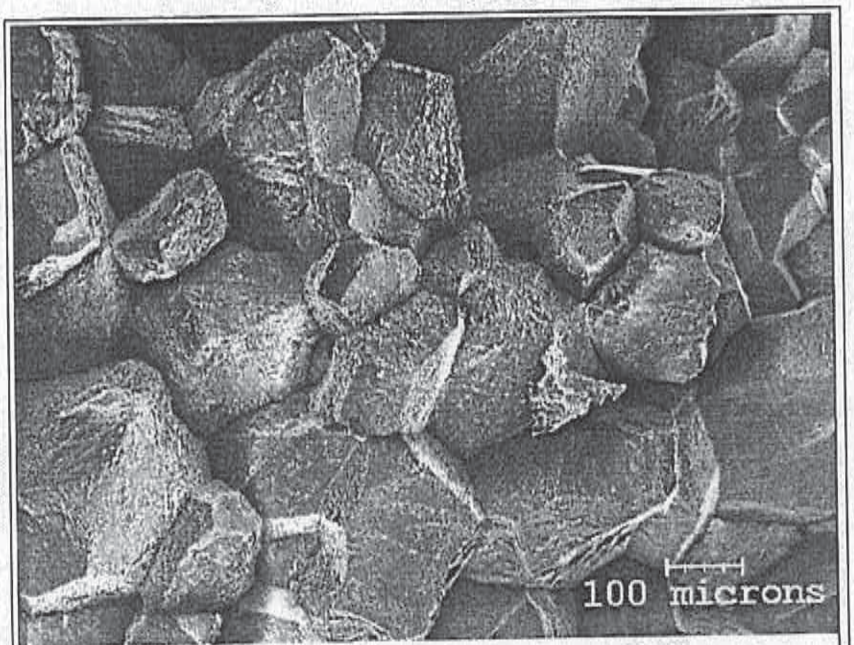


Figure 122. Marble from case 2, older part. SE-image of fractured surface, 100x.



3, murtopinta

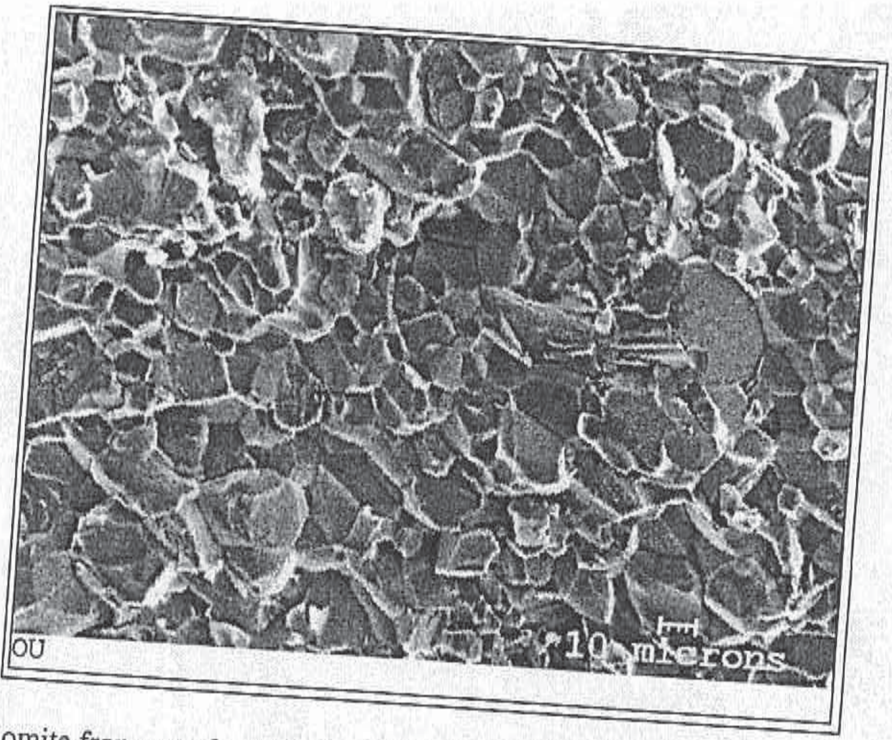


Figure 124. Dolomite from case 3. SE-image of fractured surface, 500x.

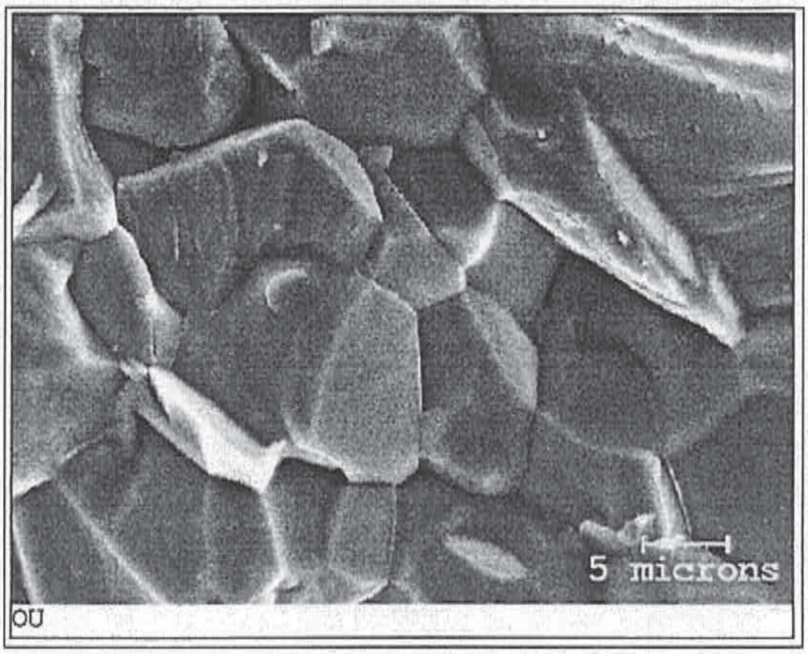


Figure 125. Dolomite from case 3. SE-image of fractured surface, 2500x.

SEM-pictures of fractured surfaces of marble from Finlandia Hall are shown in Figs. 126 and 127. The individual grains can at least partly be distinguished from each other. Cracks can be noticed between some of the grains. The maximum crack width is around 0.8-0.9 µm. The average grain size of marble is about 200 µm.

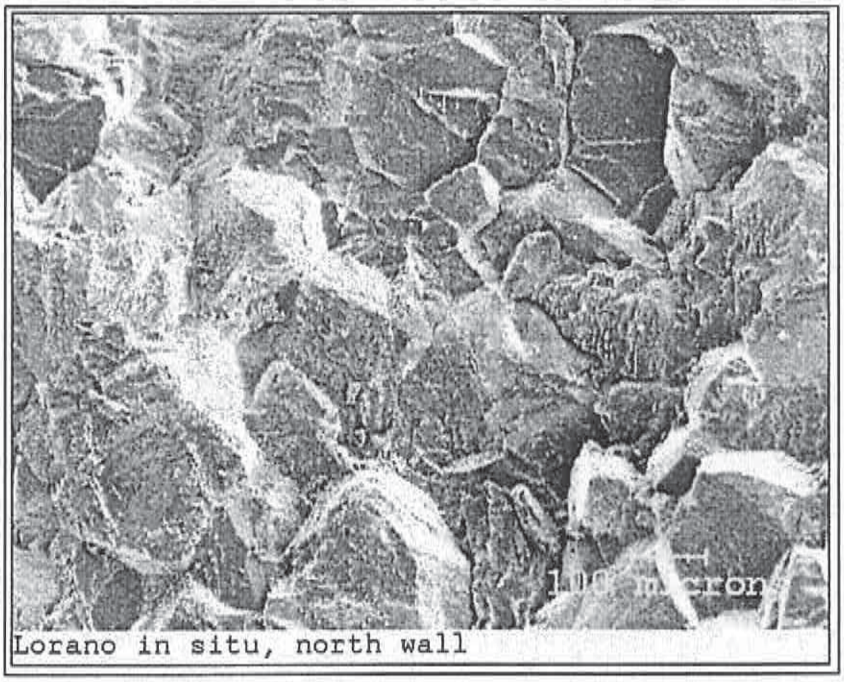


Figure 126. Marble from Finlandia Hall, north wall. SE-image of fractured surface, 100x.

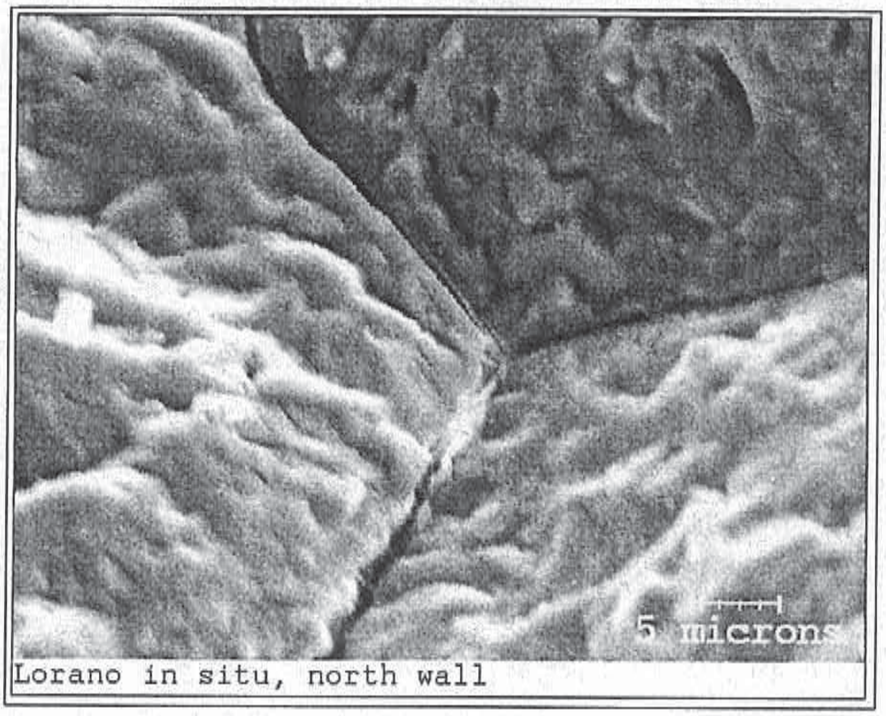


Figure 127. Marble from Finlandia Hall, north wall. SE-image of fractured surface, 2500x.

In connection with the SEM-study also the chemical composition of marble from the northern wall of Finlandia Hall was surveyed by using an energy dispersive PGT Imix spectrometer (EDS). The analysis was made from the fractured surface very close to the outer surface of the slab. The composition observed was practically that of the unused marble, only a little chlorine was detected. The EDS-spectra of marble are shown in Figs. 128 and 129.

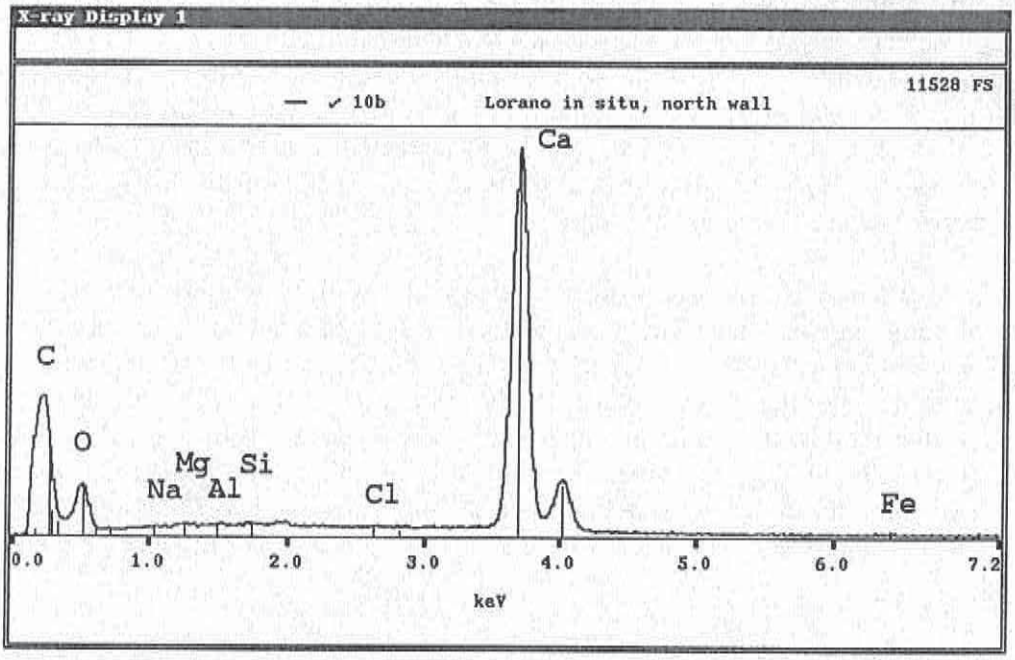


Figure 128. EDS-spectrum of marble from Finlandia Hall, north wall.

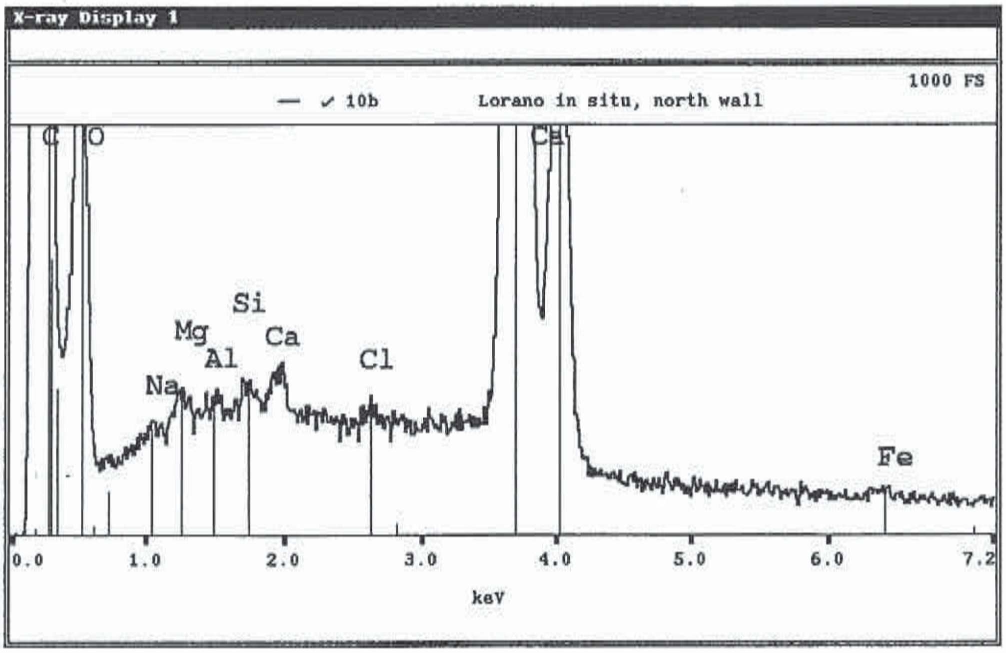


Figure 129. EDS-spectrum of marble from Finlandia Hall, north wall. Small peaks.

5 DISCUSSION

5.1 Strength properties

The flexural strengths of the marble types chosen for the study differed considerably from each other. Marbles E and K were very strong with an initial flexural strength of around 20 MPa or even higher. On the other hand marble D was weak with an initial flexural strength of 5-7 MPa. The initial flexural strength of marble A was between these two extremes varying in the area of 12-17 MPa. Marbles A and D seemed to be somewhat (20-30%) weaker in testing direction A than in direction B. This could refer to some kind of schistosity in stone structure. In this respect, the strength results of marbles E and K were more even.

The strengths of marbles A and D decreased noticeably on the test wall, which most probably is a sign of the effect of some sort of a deterioration process. The loss of strength of marble A was nearly 20%, and it was about the same in both directions. The loss of strength of marble D was even 35-40%, and it seemed to be more pronounced in the direction where the marble originally was stronger. The results for marble A in the subproject "Protective agent" were parallel to those discussed here. Correspondingly, the behaviour of marble D in the subproject "One-sided weather resistance test" was very similar to that observed on the test wall. 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.

The fact that the strengths were of the same order of magnitude after 1 and 1.5 years on the test wall was also a very noteworthy feature in the results of marbles A and D. 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 of marbles proceeded slowly if at all.

Deviating from the results of marbles A and D no significant loss of strength could be observed in marbles E and K. The results of marble E were, however, somewhat inconsistent. First of all the general strength level of the slab that was installed on the test wall seemed to have been clearly higher than that of the unused reference slab. Otherwise, it would be impossible to explain the high strength values measured from the test wall specimens. This explanation is supported by the results achieved in the Subproject "One-sided weather resistance test", as the strength level measured for marble E in those tests was around 25 MPa. Secondly, a fairly remarkable loss of strength, 17%, was measured in marble E in testing direction A after 1 year on the test wall. The standard deviation in that measurement was exceptionally high, and it was due to three specimens with very low strength level. It seems probable that those three specimens had been taken from an area that had suffered from some extra mechanical damage which had caused cracks to marble structure. If the results of those three specimens are excluded the average flexural strength of marble E in direction A after 1 year on the test wall is 19.3 MPa meaning a decrease of about 5% compared to the initial strength. This value is more in line with the other values of this subproject and with the values achieved in the weather resistance tests (5-10%).

5.2 Water absorption properties

All the marble types were very dense. The water absorption of marbles A, D and E was 0.11-0.13 w-% (apparent porosity 0.30-0.34 vol-%) and that of marble K only 0.07 w-% (apparent porosity 0.19 vol-%). The bulk density of every type was between 2713-2718 kg/m^3.

The water absorption and apparent porosity of marbles A and D increased considerably, approximately 80%, on the test wall. Also in marble K the relative increase of the water absorption and apparent porosity was fairly high, about 50%, but as its initial values were very low, the absolute increase can be considered to have been modest. The relative (also absolute) increase of the water absorption and apparent porosity of marble E was the lowest, only around 10%. 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 as well as in whole are in line with those from the strength determinations discussed above.

The fact that porosity of marbles increases when subjected to environmental stresses 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 stresses but then the process slows down and the degree of cracking stays more or less at the same level. Also, it is obvious that the various marble types show very different tendencies for cracking.