MARA -PROJECT

DEVELOPING LONG-TERM DURABILITY
OF MARBLE FACADES

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DEVELOPING LONG-TERM DURABILITY OF MARBLE FACADES

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ABSTRACT

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 economical problem without forgetting the disappearance of our cultural heritage. Deteriorated stone façades may in some cases even present a considerable safety risk.

The badly damaged marble façade of Finlandia Hall in Helsinki, Finland was renewed during the autumn 1998 and spring 1999. In connection with that project the Public Works Department of the City of Helsinki launched with a support from European Commission (Raphael program) a research project "Developing long-term durability of marble façades" known as "MARA –project". This was done, because it was noted that the behaviour of thin stone veneers and stone protection treatments on a long-term basis was not known well enough. Also the deterioration mechanism and the reasons for deterioration were unknown. The connection with the renovation project gave an unique opportunity to reserve a part of the actual façade for scientific purposes. The main goals of the project were to find out the reasons for characteristic behaviour of marble panels in outdoor uses; to find out the means to extend the service life of a marble façade; to find out new information on the material behaviour and to disseminate the results as widely as possible.

The project management has been on the responsibility of Public Works Department of Helsinki City. Other participants of the project have been in Finland the National Board of Antiquities, Stonecon Oy, Technical Research Centre of Finland (VTT) and Helsinki University of Technology (HUT); in Italy Parma University, Internazionale Marmi e Macchine (IMM), Henraux S.p.A and Savema S.p.A; in Portugal Cevalor. A number of other companies producing marble products have also taken part in the project.

The research program was divided in two entities: field tests and laboratory research. In field tests the behaviour of marble structures consisting of thin stone panels was followed in actual circumstances in the façade of Finlandia Hall. Studied matters were the impact of marble panel thickness, stone panel size and initial stone strength on the durability of marble and coating structure. Also the bowing and changes in colour were measured. Different types of marble-coated structures were selected for the research, as well as different qualities of Carrara Bianco. The laboratory tests aimed at determining the reasons for marble weathering and curving. Variables under survey were the qualities of marble, external straining factors and optional structural solutions. Applied research methods were microscope tests, spectrophotometric measurements, weather resistance tests, compression tests, bending and tension stress tests and other tests for physical properties.

According to the studies made the deterioration of marble structure in environmental stresses is caused by granular decohesion of calcite grains marble consists of. This decohesion forms cracks along the grain boundaries and is a consequence of the anisotropic thermal expansion behaviour of calcite crystals. Calcite grains have a tendency of

breaking away from each other when thermal variations affect the material. Freezing and thawing may have an accelerating effect on the process after it has started. Bowing of the panels is caused by gradient of the granular decohesion level through the panel.

According to the studies the damaging of a marble structure takes place very soon after it has been subjected to environmental stresses. The very first cycles seem to be the most damaging, afterwards the deterioration process slows down. The microstructure of marble influences its resistance against environmental stresses; homoblastic structures seem to be degradated very easily, whereas xenoblastic structures are much more resistant.

The effect of the chemical attack from impurities in atmosphere was also studied. In this study samples from the both old and new façades were studied and they both confirmed similar results; traces of chemical attack can be noticed only in the surface of the panels, not inside.

Also the effect of protective agents was studied. Because of the nature of the deterioration it can not be influenced by the use of these products. Still, according to the 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, however the agents themselves seem to be affected by UV –radiation and thermal strains thus limiting their service life.

For studied structural products deterioration seems to be two-folded; on the other hand granular decohesion is weakening the marble as in massive panels, but on the other hand the bond strengths between marble and background is decreasing remarkably.

Environmental conditions by the Finlandia Hall were monitored extensively during the project. Temperature and humidity was measured in several points by the façade by VTT. According to the recorded data the prevailing conditions include several factors that cause strain to the building's marble façades. These factors are annual and daily variation of temperature, freeze-thaw cycling and variation of humidity on different sides of a panel. Annual variation during the monitoring period was from -25°C to +50°C, daily variation was during summertime 15-20°C. The amount of annual freeze-thaw cycles was much bigger than expected; the results showed 60-70 annual cycles. To summarise, the outer surface of panels are suffering from higher environmental stresses (daily variation of temperature, the number of freeze-thaw cycles and relative humidity). These stresses are all affecting to the same direction and thus contributing to the bowing of the panels. The sum of factors was highest on southern walls and lowest on northern walls.

Using the parameters from different studies a theoretical model for interpreting the marble degradation was developed. Microstructural FEM –model, considering an assemblage of calcite grains connected by an interface cementing layer, provided a wealth of evidence that granular decohesion can be produced by thermal variations, even when uniformly distributed.

CONTENTS

1 INTRODUCTION

1.1 Background

Marble has been used successfully for centuries in buildings and monuments all over the world. The use of marble and other calcareous stones has been extensive especially in historic cities of Europe, but marble has also been used in modern architecture. Previously, when only massive marble was used, marble was like any other building material with no specific problems. But as marble is in modern architecture most commonly used in thin panels some serious problems have occurred during the last decades.

Special problems of ventilated Carrara White Marble façades are the deterioration of the structural strength of marble and the curving of marble panels. One of the main reasons for the deterioration and fouling of natural stones is the climatical stresses induced to the panels. Also the rising amount of acid compounds and impurities coming mainly from industrial and traffic sources cannot be neglected. Stone structures are today exposed to harsher environmental conditions than ever before. Nowadays commonly used thin stone veneers are even more sensible for weathering than the traditional, massive structures.

The reasons for durability problems in Carrara White Marble façades, and possible means to solve them, have been studied to some degree by estate owners and research institutes in different countries. So far the universal solution for these problems has not been found.

The need for conserving, restoring and protecting stone buildings and monuments in cities throughout the world has been accepted unanimously. The decay of old stone structures is in many areas becoming a remarkable technical and economic problem. Deteriorated stone façades 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.

A famous and well known object with remarkable façade is Finlandia Hall in Helsinki, Finland. Architect Alvar Aalto designed the Finlandia Hall as a part of his Helsinki Centre Master Plan in 1962 to serve as a concert and congress hall. The first construction phase of the Finlandia Hall was completed in 1971 and the additional conference wing in 1975. Since completion the hall has been used for congresses, conferences, meetings, galas and concerts of music from light to classical. During the concert season it is the main venue of the Helsinki Philharmonic Orchestra and the Finnish Radio Symphony Orchestra. Several important international and national meetings and events have been organised in the house, the most important of them are perhaps the European Security and Co-operation summit in 1975 and the European Council meeting in 1999.

Besides the Finlandia Hall, there are several well-known buildings with deteriorated stone façades, for example Sydsvenska Dagbladet, Malmö, Sweden, Byggnadsförbundet, Stockholm, Sweden, Stadshuset i Nyköping, Sweden, Konstmuseum, Ålborg, Denmark, La Grande Arche de la Défense, Paris, France, Amoco Building, Chicago, USA, Hotel Hesperia, Helsinki, Finland, Enso-Gutzeit Oy, commercial building, Helsinki, Finland, Savings Bank premises in Oulu and Tammisaari, Finland, as well as Tapiola Insurance Company premises in Turku, Finland.

Marble and other calcareous stones have in all times played an essential role in the European architecture. Today there is a significant need for developing new technically and economically suitable methods for marble in order to be able to cope with the huge maintenance task of the existing marble buildings and monuments and to secure the future position of the European marble industry.

1.2 Finlandia Hall

In the Finlandia Hall the marble façades are white for a definite reason. The shapes of the building are separating themselves from their surroundings with sharp-cut features so emphasising the sculptural nature of the building. Whiteness is a feature, which continues through the large entrée hall inside the building adding to the impression of spaciousness. Whiteness is an essential feature to be preserved, and that is why marble coating is considered absolutely necessary. The surface of marble is pervious to light and has a soft gloss. The seams of the stone make the building lighter. These characteristics have been essential in the architect's point of view. Alvar Aalto's own personal style and artistic ideas are presented in the final results. To him marble was an important link with the Mediterranean culture which he wanted to introduce into Finland.

1.3 Contents of the project

1.3.1 Starting point

The façade of Finlandia Hall showed very soon after completion the tendency for bowing. The condition of the façade was monitored carefully and after certain time it became obvious that the panels should be changed for safety and esthetical reasons. The discussion on the material was alive for several years and finally decision was made to use marble panels also in the renovation. Renovation project was completed in May 1999.

In the preparation of the renovation works it was noted that the behaviour of thin stone veneers and stone protection treatments on a long-term basis was not known well enough. Also the deterioration mechanism and the reasons for deterioration were unknown. There were many different, partly confrontational theories, but none of which could explain the phenomena comprehensively. MARA –project was established to answer to these questions. The connection with the renovation project gave us an unique opportunity to reserve a part of the actual façade for scientific purposes; by this way we were able to study different products under actual weathering conditions.

1.3.2 Objectives of the project

The main goal of the project is to find out the reasons for the characteristic behaviour of marble panels in outdoor uses. This information can be used in finding better solutions for building a more durable marble façade or in restoring the existing façades and monuments comprising the European cultural heritage.

One of the main goals is to create an active network between European stone companies, experts and research institutes and a model plan for continuous development work between them. The project contributes also to transferring technologies developed outside Europe, dealing with research and use of marble in Europe.

1.3.3 Limitations, outlines

We decided to concentrate only to Italian marbles quarried in Carrara, Massa and Lucca areas. This is because the bowing phenomena is the best known in Italian marbles and also because this project was supposed to explain the behaviour of Carrara Bianco. In those marbles we decided to concentrate in light coloured "white" marbles suitable for use in the façade of Finlandia Hall. Three granite qualities were added for comparison.

The behaviour of marble is strongly defined by its microstructure. In Apunian marbles the range is from pure homoblastic to pure xenoblastic textures, in addition to which there is of course a wide variety of different intermediate textures. Due to the vast amount of different qualities it was necessary to choose some typical qualities to represent the different microstructures; one of homoblastic texture, one xenoblastic and two intermediate. By this way we could cover the whole range of different varieties. The behaviour of other qualities can later be predicted by their microstructure, when behaviour of these representatives is known completely.

1.3.4 Research areas

1.3.4.1 Field tests

The behaviour of marble structures consisting of thin stone panels was followed in actual circumstances in the façade of Finlandia Hall. Studied matters are the impact of marble panel thickness, stone panel size and initial stone strength on the durability of marble and coating structure. Also the bowing and changes in colour are measured. Different types of marble-coated structures are selected for the research, as well as different qualities of Carrara Bianco.

Each product has about 10 m^2 share of the research wall, the total area of which is about 140 m^2. In addition to this research wall, a certain rack was constructed on the roof of the house in order to carry the specimen for destructive tests. The actual weather conditions i.e. humidity, temperature and the composition of the air by the wall were followed very closely.

The character and degree of damage in a deteriorated marble, which was damaged in real conditions, was studied in laboratory. In the facade research samples were tested and measured in laboratory during the survey in order to determine the change in the stone qualities.

1.3.4.2 Laboratory tests

The laboratory tests aim at determining the reasons for marble weathering and curving. Variables under survey are the qualities of marble, external straining factors and optional structural solutions. Research methods to be used are microscope tests, spectrophotometric measurements, weather resistance test, bending and tension stress test and other tests for physical qualities.

1.3.4.3 Development of new solutions

With the help of information obtained from facade research and laboratory tests, a summary is drawn dealing with the reasons for marble deterioration. Recommended methods for the improvement of marble durability and for prolonging the service life of marble facade coating carried out with the help of modern technology are be developed. Studied factors are the qualities of the original marble, dimensioning of stone construction components, chemical protection treatments on stone panels and constructional solutions of the panels. Also a test method for marble selection in terms of durability is presented.

1.4 Organisation

1.4.1 Management, co-ordination

The project management has been on the responsibility of Public Works Department of Helsinki City. PWD Construction Management Unit has taken the practical actions in the project co-ordination and management. PWD Construction Management Unit has used Stonecon Oy as a consultant both in project management and scientific work.

1.4.2 Participants

Participants of the project are in Finland Stonecon Oy, Technical Research Centre of Finland (VTT) and Helsinki University of Technology (HUT); in

Italy Parma University, Internazionale Marmi e Macchine (IMM), Henraux S.p.A and Savema S.p.A; in Portugal Cevalor. A number of other companies producing marble products have also taken part in the project by providing us material to be studied and a valuable link to stone industry.

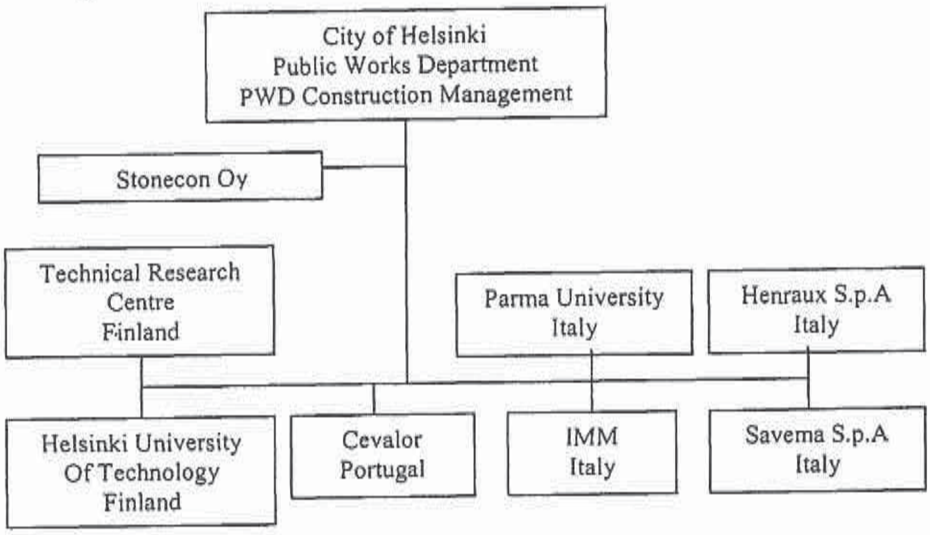


Figure 1. Organisation of MARA Project

1.5 Course of the project

Project started with defining the scope of work in a more detailed way. The entity was divided in smaller subprojects which could then be delivered further to other partners of the project according to their resources. After this we could start the discussions with our collaborators in order to define each subproject more precisely.

Partner agreements were signed in the end of March 1999 after which the actual work could start. First research meeting was held as a project start-up in May 1999 in Finland, in Finlandia Hall to be exact. Since then there has been four other research meetings (in Helsinki, Finland Nov. 1999, Carrara, Italy, May 2000, Helsinki, Finland Nov. 2000, Borba, Portugal, Feb. 2001) and other meetings with laboratories and project management. The laboratories have worked independently between the meetings, having active correspondence through e-mail.

MARA Project has been of wide public interest from the very beginning of the project. Several press conferences have been held following the proceeding of the project, both in Finland and in Italy. The conferences in Italy have been held during the annually organised Carrara Fair. A final seminar where all the results and this report will be published, will be held in May 2001 in Finlandia Hall, Helsinki and in the beginning of June 2001 in Carrara.

Discussions with other projects and experts concentrating on stone research and use have been active during the project. Several meetings have been held for example with MARC 1999 (Course on Modern Architecture Conservation), TEAM (Testing and Assessment of Marble) and CEN –committee.

2 RESEARCH PROGRAM

2.1 General outline

2.1.1 Objectives and tasks

Main objective of Mara research was to develop more durable solutions for a facade cladding of white Carrara marble (Carrara Bianco) in order to achieve a longer service-life. Practical research was focused primarily on the durability properties of marbles.

In order to achieve the main objective Mara project was divided into the following sub-objectives and tasks:

- main causes for marble deterioration in facade claddings
- main influencing factors and the failure mechanism
- method for testing the suitability of a given marble
- technical specifications for a stone cladding
- recommendations for maintenance of a marble facade

Apart from the material research emphasis was given to solving the structural principals to be used for a thin facade cladding in order to ensure a durable solution. In the research Finlandia Hall was used as the main reference object. Previous experiences obtained from Finlandia Hall as well as the ongoing tests at the actual facade gave valuable contribution to the research activities.

The aim was to develop solutions that can be used for new buildings as well as for maintaining and restoring of the existing façades and monuments comprising the European cultural heritage. Results of the project are in many ways useful for design and implementation of natural stone facade claddings. In order to achieve good understanding of the specific problems main emphasis was given to research of Carrara Bianco marble. However, the results can easily be applied for any marble cladding as well as for any stone cladding.

One of the goals was to create an active network between European experts, research institutes and stone producers. The project contributes also to transferring technologies developed outside Europe, dealing with research and use of natural stone in Europe.

2.1.2 Research areas

Main research areas of Mara project were the field test located at Finlandia Hall and the laboratory tests carried out in four European laboratories. In addition structural development and collaboration within an expert network was included. Figure 2 represents the division of main tasks in Mara project.

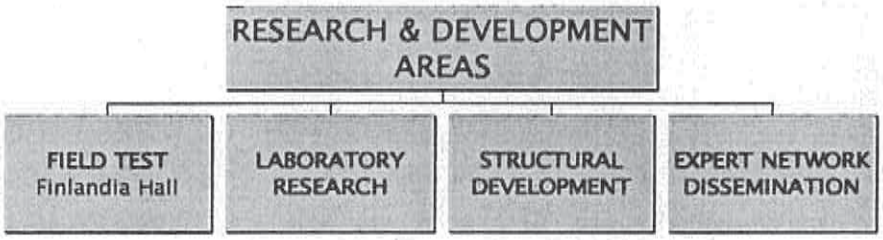


Figure 2. Division of research areas in Mara project

2.1.3 Scope of marble type selection

The aim was to select a range of marbles representing typical types of Carrara Bianco marble. The selection of materials was based mainly on the facts available on the appearance, physical and durability properties as well as the microstructural characterisation of the marbles (see also1.3.3). Previous use and experience of suitability were used as additional criteria when applicable. After several considerations four marble types were selected to be used as samples in the research. In table 1 is given the basic description of the chosen marble types. Marble type A was used as the reference material.

Table 1. Basic properties of Carrara Bianco marbles A, D, E and K used in Mara research project.

	A	D	E	K
microstructural characterisation	homo-/xenoblastic	homoblastic	xenoblastic	homo-/xenoblastic
appearance	white, veined	white, veined, clear contours	white, slightly veined	light grey, slightly veined
strength	medium or high	Low	high	High
porosity	low	Low	low	Low
typical uses	all purposes	mainly interior purposes	all purposes	all purposes
earlier experience about suitability	considered to be one of the best qualities in the region	known to have durability problems when used outdoor	known to be durable	known to be durable
rough geografic location	Carrara	Carrara	Lucca	Massa

Same marble types were used in all tests throughout the project in order to obtain comparable results at the field test and laboratory tests carried out during same time in the participating laboratories.

2.2 Sampling

2.2.1 Sampling procedure

Sampling for all Carrara Bianco marble types was arranged in collaboration with IMM being responsible for the local co-ordination and quality control during the sampling process. Samples were produced by Savema Spa and Henraux Spa as follows:

- all massive marble panels for field test were delivered by Savema Spa
- all samples for laboratory research of marble types A and K were delivered by Savema SPa
- all samples for laboratory research of marble types D and E were delivered by Henraux SPa

Field test panel samples were delivered in connection with the completion of the facade renovation in April 1999. Laboratory samples were then processed of the same raw materials and delivered directly from Italy to each laboratory as explained in Table 2. Carrara Bianco for structural panel coatings were chosen by the suppliers according to the instructions given by the coordinator.

2.2.2 Control of cutting direction

Directions in stone were defined and marked to the blocks at the quarry according to the principal presented in figure 3. Cutting directions chosen for the samples were respectively the following:

- parallel to the rift = along the rift plane (verso; $\gamma = 0$)
- perpendicular to the rift = along the head-grain plane (contro; $\beta = 0$)

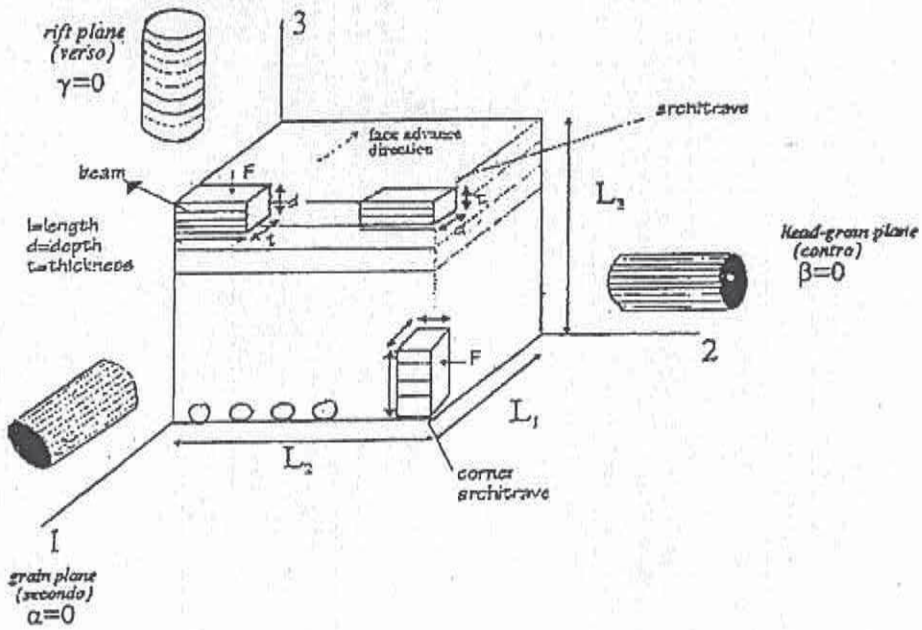


Figure 3. Rift plane, grain plane and head-grain plaine

Table 2. Summary of laboratory samples delivered to each laboratory.

		Research Institute											
		VTT Building and Transport			Helsinki University of Technology			University of Parma			Cevalor		
Marble type	Cutting direction	Size [mm]	Thickness [mm]	Number of samples	Size [mm]	Thickness [mm]	Number of samples	Size [mm]	Thickness [mm]	Number of samples	Size [mm]	Thickness [mm]	Number of samples
A	parallel to rift	800x1200	30	9	800x1200	30	1	800x600	40	1	800x1200	50	1
A	perpendicular to rift	800x1200	30	3	800x1200	30	1	800x600	40	1	800x1200	50	1
D	parallel to rift	800x1200	30	5	800x1200	30	1	800x600	40	1	800x1200	50	1
D	perpendicular to rift	800x1200	30	3				800x600	40	1	800x1200	50	1
E	parallel to rift	800x1200	30	5	800x1200	30	1	800x600	40	1	800x1200	50	1
E	perpendicular to rift	800x1200	30	3				800x600	40	1	800x1200	50	1
K	parallel to rift	800x1200	30	3				800x600	40	1	800x1200	50	1
K	perpendicular to rift	800x1200	30	3				800x600	40	1	800x1200	50	1

Each panel was clearly marked with water resistant colour using the specific code related to the stone type and cutting direction. Marking codes were written both at the edge and at the back of each panel. Rift direction/sawing direction was to be clearly marked on the panel surfaces by using for example dense striping. Test specimens were cut from the panels by respective testing laboratories.

For all Carrara Bianco marble samples IMM stone specialists were responsible for controlling and marking of the cutting directions at quarry and during processing of the test panels. Individual laboratories were responsible for controlling the given directions during preparation of samples and during various testing activities.

2.3 Field test

2.3.1 General scope of the research

Main objective of the field test was to find out the behaviour of different stone types and stone covered structural products in real conditions. The aim of the research 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 was to examine the behaviour of various structural solutions.

Field test was put into practice using test walls, which were part of the renovated Finlandia Hall facade. In addition to the test walls separate stone samples for destructive laboratory tests were placed on the roof on a supporting structure. By this way the actual test walls remained available for a long-term follow-up research after the Mara project.

Temperature and humidity conditions in the facade cladding as well as the general weather conditions were observed and measured according to a detailed program during the project (see 2.4).

2.3.2 Organisation

Field test was carried out in collaboration with several companies, which took responsibility for delivering the stone samples, structural products and protective agents for the test walls. VTT Building and Transport was responsible for laboratory testing and measurements at site together with HKR Rakennuttaja. Figure 4 shows the organisation structure and the distribution of tasks applied in the field test.

Carrara Bianco samples were delivered by leading Italian stone producing companies Savema Spa and Henraux Spa. Selection of the samples according to the requirements set for the research was controlled by IMM in Carrara. Granite samples were delivered by Erikstone Oy in Finland.

Structural products with stone facing were delivered by:
Joptek Oy, Finland
Aleksin Kivi Oy, Finland
Skanska Prefab AB, Sweden
Stone Panels Inc, USA

Protective chemical agents were delivered by Finnish companies Dyny Clean Kiinteistö Oy and Leni Vesiviljely Oy.

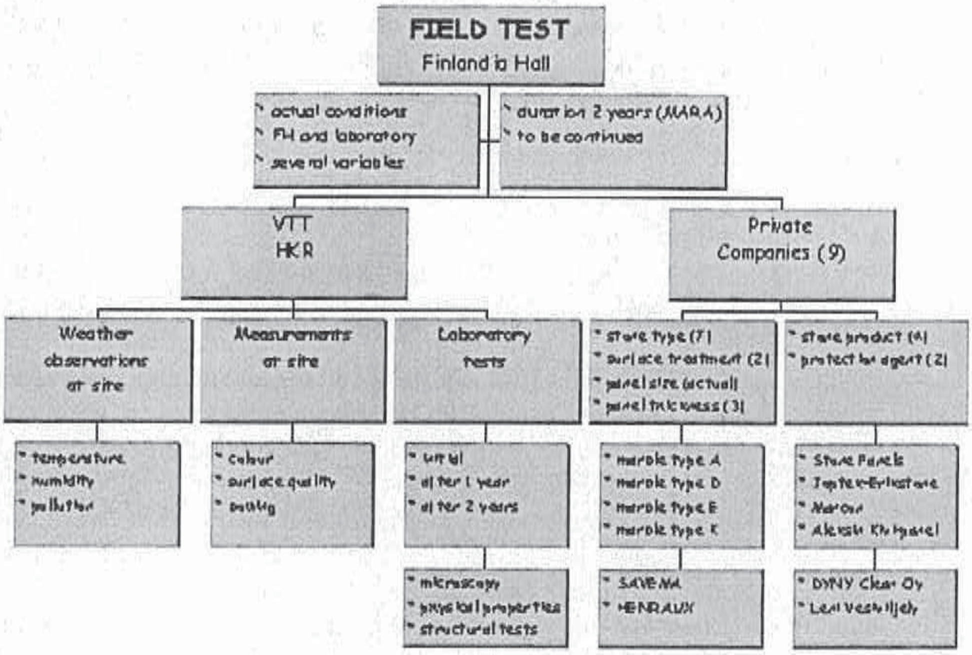


Figure 4. Organisation and task chart of the field test.

2.3.3 Research variables

Parameters included in the field test can be divided in the following groups:

- Carrara Bianco marbles
- granites
- panel size
- panel thickness
- surface finishing
- protective agents
- structural products

Carrara Bianco marbles

Four representative types of white marble from Carrara region were chosen as stone samples. Marble type A was used as reference material. See more detailed at 2.1.3.

Granites
Three types of light coloured granites were included in the research. During the long preparation period for the recent renovation all of these granites have been submitted a permission to be used in the Finlandia Hall façade.
- Tolga White granite from Norway
- Mt Airy granite from USA
- Bethel White granite from USA

Panel size and thickness
Importance of panel size and thickness has often been mentioned as one of the important factors with respect to bowing of the panels. Panel sizes and thicknesses used at the test wall were following:
- sizes according to the architectural design
- panel thicknesses 30, 40, 50 mm

Surface finishing
Honing at 600 was used as the finishing for the actual Finlandia Hall facade cladding panels. It gives Carrara Bianco marble a smoothly shining appearance. Back side of the marble panel is normally with the surface created in the diamond cutting. The surface finishing of the individual panels is for this reason unsymmetric. One of the tested products at the test wall was finished symmetrically at 600 on both sides of the panel.

Surface finishings included in the research were thus:
- unsymmetric finishing
    - front side 600 / back side diamond-sawn
- symmetric finishing
    - front side 600 / back side 600

Protective agents
Chemical impregnating products fill the outer pores of the marble and prevent water and other soluble weathering agents from penetrating in the material. Protection was applied on the outer surface of the tested panels.
Protective surface treatment agents had the following commercial brands:
- Dyny
- Prolapit

Structural products
Basic idea with the structural products is to attach the stone panel into a secondary structural frame. In three of the tested panels marble was glued in the backing material and in one of the panels, marble was fixed mechanically. In the panels where stone is fixed with glue, the thickness of marble coating is only 5-10 mm. Some of the panels are much lighter than massive stone panel due to the low density of the backing material.

Structural products included in the field test were
- Stone Panels
- Joptek-Erikstone
- Marcon
- Aleksin Kivi-panel

2.3.4 Realisation of the field test

Three test walls were placed on the lower roof level of Finlandia Hall as actual parts of the new facade. The walls were built in April and May 1999 during the actual facade renovation of Finlandia Hall. The walls included in the research were view 24, view 23 and view 202. In addition a separate frame was built for the panels intended for destructive laboratory testing during the project.

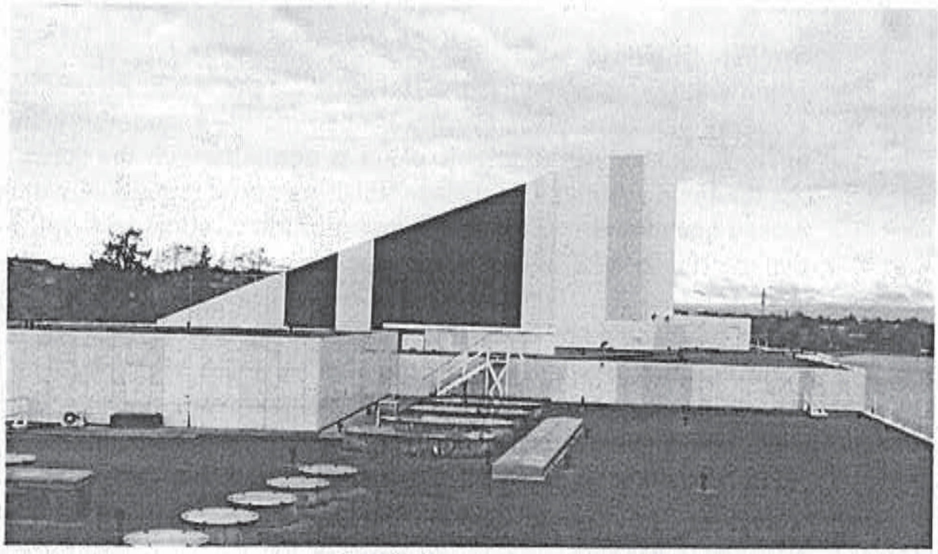


Figure 5. General view of the field test area

Sizes of the panels in the three test walls are according to the architectural plans for the façade. Stone panels were fixed to the load-bearing concrete structure by the same anchors used for the actual façade. Some of the structural products were, however, fixed using special anchors for the product. All test walls are thermally insulated with hard mineral wool with thickness of 150 mm. Panels on the separate frame are supported by the wooden frame structure. Total area of the test wall was 106 m^2 and the total number of full-size test panels was 188 pieces. For each product to be tested the area was between 8 – 13 m^2. Distribution of the test area and the cardinal points are given in table 3.

Table 3. Dimensions of the test walls by views and the separate frame.

	View 24	View 23	View 202	Frame
Cardinal point	south	east	South	South
Height (m)	3,0	3,0	2,0	1
Width (m)	10,5	16,5 + 1,0*1,6	20,8	6
Number of test panels	48	80	60	9

View 24:

This wall is directed towards south, which can in Finnish circumstances, be considered to be a direction with hardest weathering effect due to temperature changes and diagonal rain. Total area used for testing is at this wall about 30m^2. Products tested at this wall are the following:

- Carrara Bianco type A, thicknesses 30, 40 (type B) and 50 (type C) mm
- Carrara Bianco type D, thickness 30 mm
- Carrara Bianco type E, thickness 30 mm
- Structural panel, type F
- Structural panel, type G
- Structural panel, type H

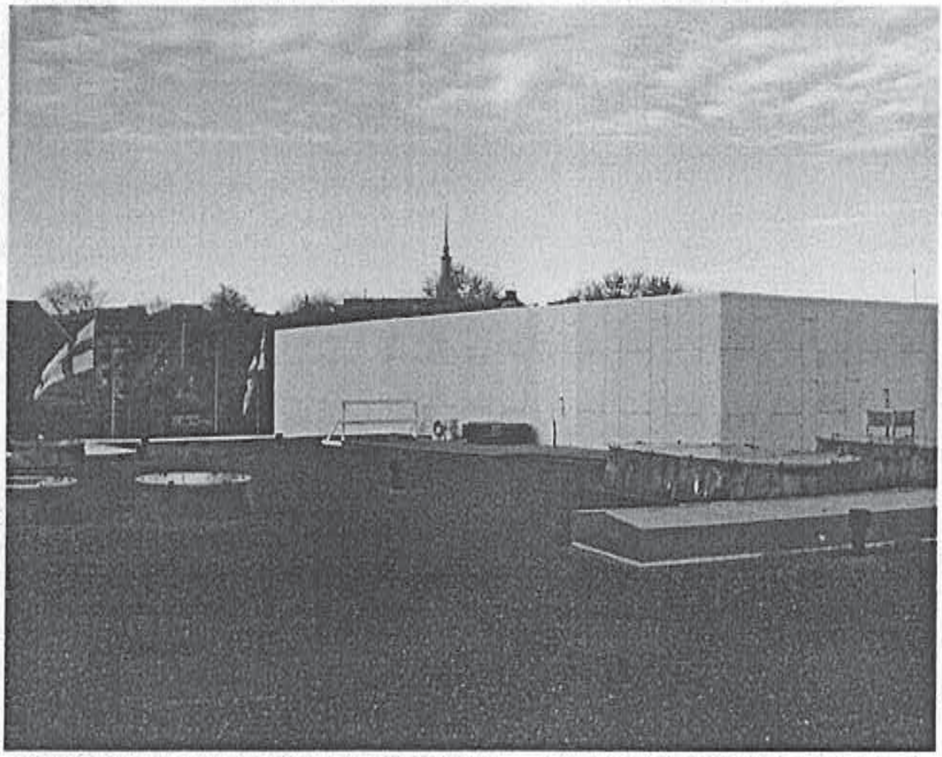


Figure 6. Test wall, view 24

View 23:
This wall is directed towards east with slightly less strenuous weathering conditions than at wall 24. Total area used for testing is at this wall about $51m^2$. Products tested at this wall are the following:
- Carrara Bianco type A, thickness 30
- Carrara Bianco type A, thickness 40 (coded as B)
- Carrara Bianco type A, thickness 50 (coded as C)
- Carrara Bianco type D, thickness 30 mm
- Carrara Bianco type E, thickness 30 mm
- Carrara Bianco type K, thickness 30 mm
- Structural panel, type F
- Structural panel, type G
- Structural panel, type H
- Structural panel, type L
- Protective agent type M
- Protective agent type O

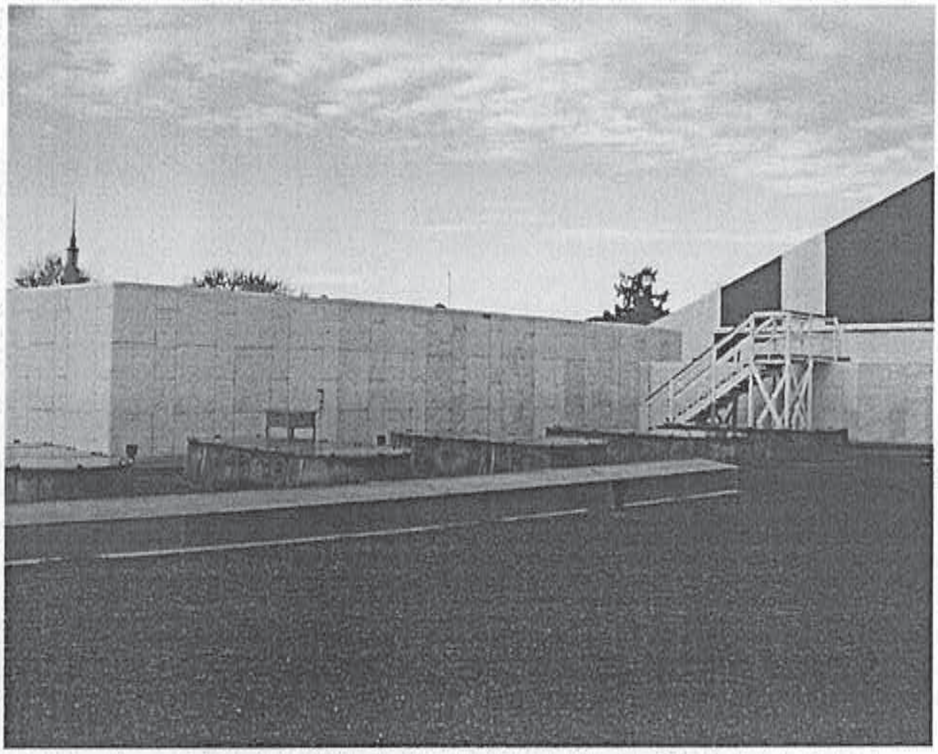


Figure 7. Test wall view 24

View 202:

This wall is directed towards south and is comparable with view 24 with reference to the weather conditions. Total area used for testing is at this wall about 41m^2. Products tested at this wall are the following:

- Carrara Bianco type A, thickness 30
- Carrara Bianco type A, thickness 40 (coded as B)
- Carrara Bianco type A, thickness 50 (coded as C)
- Carrara Bianco type K, thickness 30 mm
- Structural panel, type L
- Protective agent type M
- Protective agent type M
- Protective agent type O
- Granite type P
- Granite type R
- Granite type S
- Surface finishing 600/600

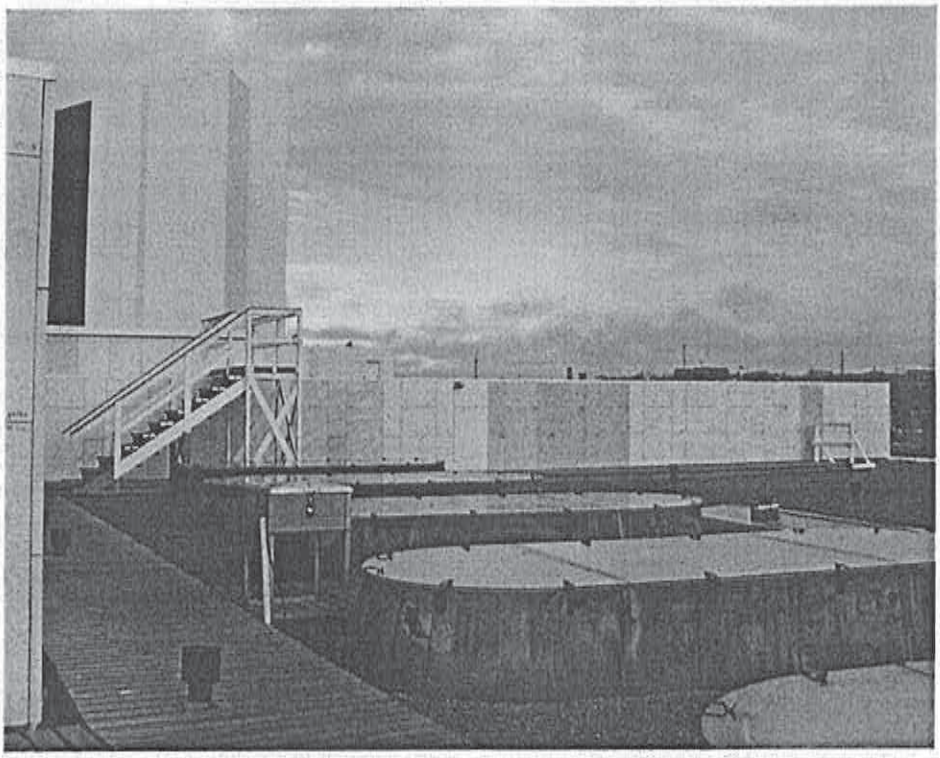


Figure 8. Test wall, view 202

Frame:

Apart from the test walls additional stone samples of some products were placed on the roof on a separate supporting frame. Point of the compass for these panels was south. Idea was to create comparable conditions with the panels in the actual test walls. These samples were used for laboratory tests in two intervals during Mara project. Total area of the test panels on the frame structure was about $7m^2$. Products on the frame were the following:

- Carrara Bianco type A, thickness 30 mm
- Carrara Bianco type D, thickness 30 mm
- Carrara Bianco type K, thickness 30 mm
- Structural panel, type F
- Structural panel, type G
- Structural panel, type H
- Structural panel, type L
- Protective agent type M
- Protective agent type O

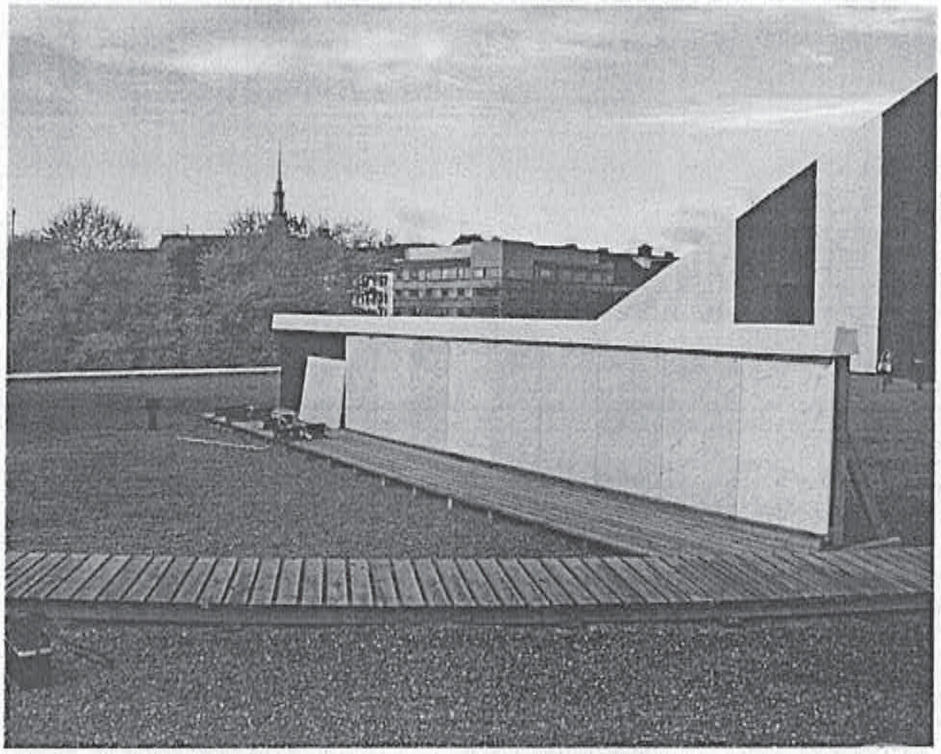


Figure 9. Laboratory test samples on the roof of Finlandia Hall

2.3.5 Research program for field test

2.3.5.1 Objective

The aim of the field test was to identify measurable changes in the functional properties of different marble products during the two-year period of Mara project. It is quite evident that significant changes in stone properties due to weathering normally appear only after several years of service-life. However, using accurate measuring methods, even smaller changes can be registered. On the other hand it is appropriate to continue with the field test during a longer period of time in order to be able to establish more clearly the changes due to ageing. Main tasks included in the field test were observations and measurements done at site and laboratory tests.

2.3.5.2 Observations at site

Observations and measurements made at site were non-destructive of nature and can be divided in two categories:

- marble surface (colour, roughness)
- bowing of the panels

Changes in the appearance of marble surfaces were measured at site by VTT Building and Transport using a CIELAB system, which is described in detail in *Appendix 1*. Measurements with this device are based on three separate axis: white-black, green-red and blue-yellow. Very small changes in colour of the stone surface could be measured and documented. Based on the measurements the effect of the environmental strain at Finlandia Hall on the colour and the appearance of marbles was determined. In addition visual inspection was performed on more or less continuous basis.

Bowing of stone panels was measured by HKR using special equipment designed for this purpose (see figure 10). This device was used also previously when monitoring the bowing of the old façade of Finlandia Hall. Two panels of each product on each test façade were measured and the changes in straightness were documented. Bowing measurements were repeated five times during the project using each time exactly the same measuring points. Principals applied in bowing measurements are shown in figure 11.

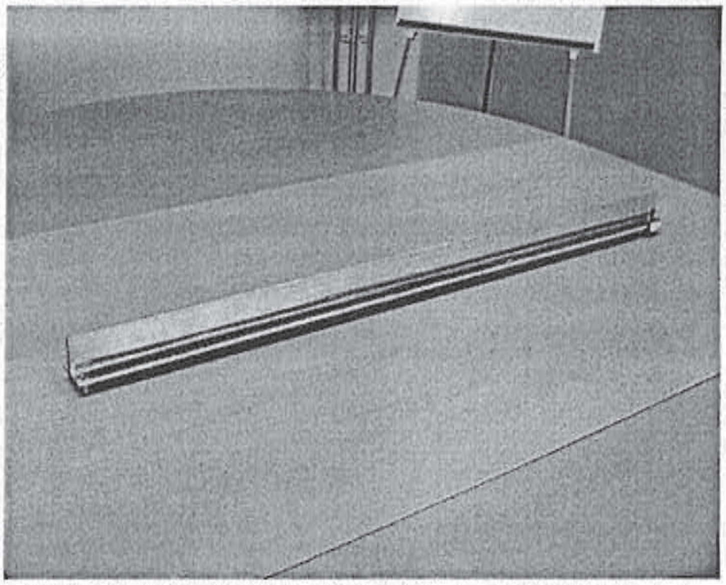


Figure 10. Measuring device for straightness of stone panels.

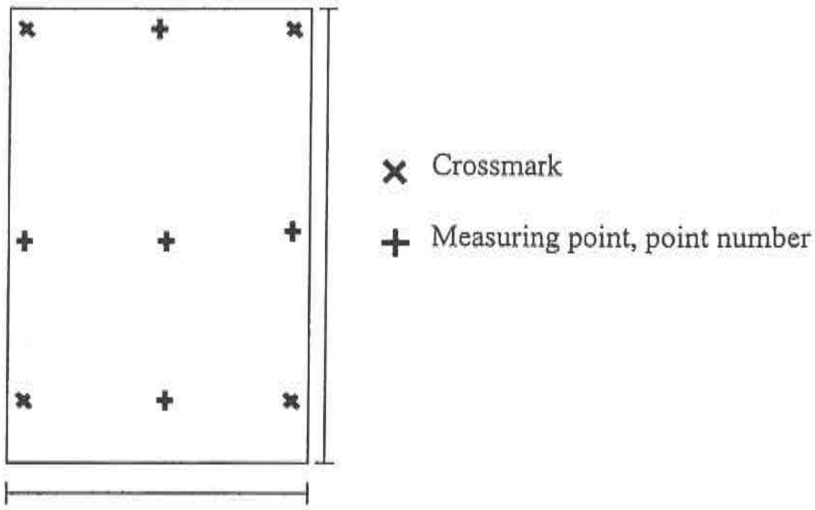


Figure 11. Principals used for the bowing measurements.

2.3.5.3 Laboratory tests

Laboratory tests were destructive of nature and they were repeated three times during the project: in the beginning, after 1 year and after 2 years. For the initial testing unused samples were used. For tests done after 1 and respectively 1,5 years separate stone samples apart from the test walls were used. These samples were placed on a frame structure placed close to the test walls. Half of the samples was cut for tests made after one year and the other half of the samples was put back on the frame to be tested after two years.

Tested properties for massive stone panels were
- flexural strength
- density, water absorption
- microscopic research

Based on the measurements and test results the effect of the environmental strain prevailing at Finlandia Hall on the strength properties as well as on the microstructure and the composition of different marble qualities was determined.

For structural products the following evaluations were made
- adhesion of the glued stones in structural panels
- structural examinations
- microscopic research

Based on the measurements and test results the effect of the environmental strain prevailing at Finlandia Hall on the strength properties of marble clad panels was determined.

2.4 Observation of weather conditions

2.4.1 Scope of the research

The aim was to determine the straining factors that affect the marble and the structures of the facades. This was done by recording the real environmental conditions (temperature, humidity) and their annual variations at Finlandia Hall façade cladding. VTT Building and Transport was responsible for this part of the reseach (Appendix 1).

Four tasks were included in this part of the research:
- designing and installing of the necessary measuring and recording devices
- regular recording of the environmental factors and processing of the data
- acquiring of other necessary information (pH, general weather conditions) and processing of the data
- conclusions and reporting of the results

2.4.2 Measuring and recording arrangements

Prevailing temperatures were recorded from five different marble panels, all of which were placed on roof walls of Finlandia Hall. Four of the panels were chosen in such a way that each one of them was heading to a different cardinal point. The fifth panel was chosen to represent extreme values, and thus it was taken from top of the tower part of the building (point A). The measuring points were as given in table 4.

Table 4. Measuring points for temperature measurements at Finlandia Hall.

Measuring point	Wall number	Cardinal point	Remarks
A	2	South	At the top of the building
B	38	West	
C	13	North	
D	24	South	Field test wall
E	23	East	Field test wall

In each panel specified above there were four thermocouples, which were measuring temperature
- in outdoor air,
- in ventilation gap,
- on outer surface and
- on inner surfaces of the marble panel.

In the measuring point A there was also a fifth thermocouple, which was recording the outer surface temperature of a black granite panel beside the marble panel with the four other thermocouples. Temperature was recorded once an hour in each point, and the values were saved into a data logger.

Recording of temperatures was started in May 1999, and latest measurements were made in the end of February 2001. After Mara project recording of temperatures and humidity is continued for the time being. The data loggers were emptied at regular intervals, and the data collected was downloaded to a transportable computer. Due to power failures or logger malfunction some of the data was, however, lost during the measurement period.

Prevailing relative humidities were recorded from two marble panels, which were panels with the temperature measuring points D and E. In both panels there were three sensors, which were measuring relative humidity in outdoor air, in ventilation slot and in the middle of the marble panel. In order to measure humidity in the middle of the panels, a hole was drilled through the lower edge of the panels before installing them on the roof wall. The sensor was put into the drilled hole, and the hole was sealed. The recording was done as that of temperatures described above. The same data logger as for temperatures was used to save the humidity data.

2.4.3 Other information about weather conditions

The data concerning general weather conditions was acquired from the Finnish Meteorological Institute. Research results from the measurements of acidity of rain water were delivered by the Finnish Environment Institute.

2.5 Laboratory research organisation

Four laboratories from three different countries were involved in the Mara research project. Finnish contribution was given by Building and transport laboratory of Technical research centre of Finland (VTT Building and Transport) and Helsinki University of technology (HUT). Both are located in Espoo.

From Italy University of Parma was chosen because of the previous experience of the key persons available for the research. Cevalor from Portugal was chosen as the leading development and training centre for stone in the country. Figure 12 represents the organisation and task distribution of laboratory research in the Mara project.

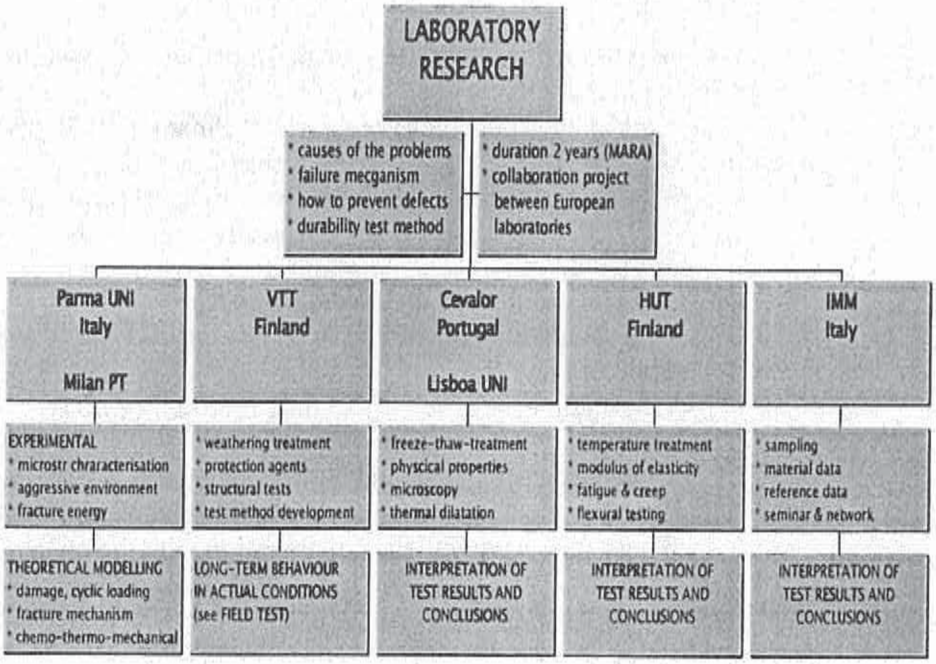


Figure 12. Organisation and task chart of the laboratory research.

Many laboratories involved contributed in the research by bringing a wide range of professional skills and experience to the project. This was very important during the research meetings held during the project. In addition to that the professional contact network behind each laboratory gave a further support to the scientific basis of the research.

On the other hand it was considered as a challenge to manage a multi-laboratory research. This was especially important because of the demanding nature of the objectives in Mara research. Already at the initial stage when the partners where chosen emphasis was given to the consideration of building up a good professional team with ability to collaborate with each other. During the project the effort given to this concern proved to be beneficial.

2.6 VTT Building and Transport research

2.6.1 Scope of the research

Primary goals for the research done at VTT Building and Transport were the following:

- determine the deterioration mechanism of marble,
- set requirements for a durable marble facade structure and
- development of test method for marble suitability.

Research at VTT Building and Transport was also directed to the following studies:
- the environmental conditions at Finlandia Hall (see 2.4)
- the durability of different types of marble,
- the performance of alternative structural solutions and
- the possibilities of using protective treatments.

All parts of the research were done in co-operation with Helsinki University of Technology, University of Parma in Italy and Cevalor in Portugal. VTT Building and Transport was also responsible for all the laboratory tests carried out in connection to the field test (see 2.3).

In addition VTT Building and Transport has also completed a series of tests for Carrara Bianco marble taken from other building objects in Finland. These tests were done in collaboration with the owners of the buildings.

2.6.2 Effect of protective agent

2.6.2.1 Objective

The aim of the subproject was to study the effect of a chemical protective agent on the properties of marble and to determine the quality of the protection mechanism. In addition, the aim of the work was to preliminary evaluate the usefulness of protective agents in marble facades.

In order to achieve the goals set the subproject was divided into three tasks:
- the effect of a protective agent on the durability properties of marble
- the effect of a protective agent on the behaviour of marble exposed to the environmental strains prevailing at Finlandia Hall
- analysis of the results including the evaluation of the usefulness of protective measures

Research was carried out partly at the test wall and partly at the laboratory (Appendix 4).

2.6.2.2 Test wall samples

a) Flexural strength

The flexural strength of the marbles was determined by using the panels taken from Finlandia Hall after 1 and 1.5 years on the test wall. The reference values were measured from the unused panels. The flexural strength of the marbles was determined according to the standard EN 12372:1999.

b) Water absorption, apparent porosity, bulk density

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

The water absorption properties of the marbles were determined according to the standard EN 1936:1999.

c) Microstructure

Thin sections of the marble specimens, 0.025x30x50 mm, were prepared at right angles to the surface of the panels. Pieces were cut from the test specimens 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 Leica DM HC LP polarising light microscope and photographed with Leica Q500IW image analysis equipment.

First part of the SEM-study was made by using polished marble sections. Second part of the SEM-study was made by using fracture surface samples of marbles. The samples were broken from the test specimens, any loose material was wiped off and the fractured surfaces were carbon coated.

d) Colour measurement

The behaviour of marble panels on the walls of Finlandia Hall was studied also by measuring the colour of the panel surfaces at regular intervals by CIELAB system. The colour of the panels was measured from eight points, each including three spots. Thus, the colour of the panels was presented as an average of total 24 individual measurement values.

2.6.2.3 Laboratory tests

a) Resistance to UV-radiation

The resistance of the protective agent to UV-radiation was studied according to the standard ISO 4892-2. The effect of radiation was evaluated by using colour measurements using the CIELAB system. The colour co-ordinates of the specimens were measured after the radiation treatment and they were compared with the reference values measured from the treated and untreated panels from which the specimens were prepared.

b) Heat resistance

The heat resistance of the protective agent was studied by treating protected marble specimens in a heat chamber. Three treating temperatures were used: 50°C, 70°C and 110°C. All the specimens were treated in a heat chamber for 100 h. The effect of heat was evaluated by using colour measurements using the CIELAB system. The colour co-ordinates of the specimens were measured after the heat treatment and they were compared with the reference values measured from the treated and untreated panels from which the specimens were prepared.

c) Chemical resistance

The chemical resistance of the protective agent was studied according to the standard ISO 10545-13:1995. In the test the specimens were immersed vertically to a depth of 25 mm in the vessel containing the test solution maintained there for 12 d. After that the specimens were subjected to running water for 5 d and then boiled for 30 min while completely immersed in water. Finally, the specimens were dried and the effect of chemicals was evaluated visually according to the instructions described in the standard.

d) Resistance to stains

The resistance to stains of the protective agent was studied according to the standard ISO 10545-14:1995. In the test a few drops of staining agents were spread on the surface of the specimens and were left in place for 24 h. After that the specimens were subjected to successively to cleaning procedures described in the standard. After each cleaning procedure the result was evaluated visually and this repeated using more and more effective methods until the stain was removed. The cleanibility class was recorded accordingly as represented in the standard.

2.6.3 One-side weather resistance test

2.6.3.1 Objective

The aim of the research was to study the behaviour of various marbles in one-side weather resistance test and to compare the results with those of the other laboratory weather resistance tests and with the observations made from the marbles that were strained on a test wall in real conditions.

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

- planning of the tests and constructing of the experimental arrangements
- the effect of one-sided weather resistance test on the physical properties
- and on the microstructure of marbles
- analysis of the results and comparisons with other observations
- conclusions concerning especially the practicability of the one-sided test

2.6.3.2 Weather resistance test

a) General arrangements

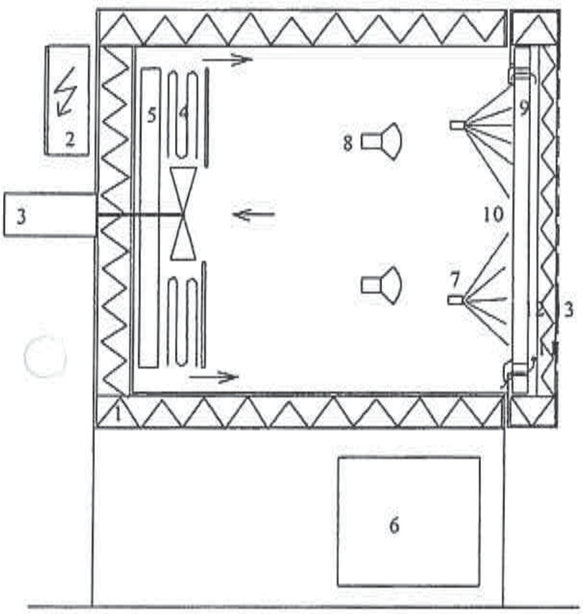
Two different types of marbles were used in the studies, and they were coded with letters D and E. According to a general assumption formed from practical experiences the marble type E shows a relatively good durability in outdoor applications. Correspondingly, the marble type D was thought to be not durable and thus unsuitable for facades.

One panel of both marbles were chosen for the weather resistance test. The panel of marble D was cut perpendicular to the rift and that of marble E parallel to the rift. The marbles were tested simultaneously.

b) Climate chamber

The tests were basically performed according to the principles presented in the standard DIN 52252/3. A climate chamber that was built to fulfil the requirements set in the standard was used. Except cooling and heating systems the chamber included a fan, water nozzles (4) and lamps (4) producing UV-light (Appendix 3).

CLIMATE CHAMBER



1 Frame
2 Control unit
3 Fan
4 Heater
5 Cooler
6 Water container
7 Water nozzle
8 UV-light
9 Marble slab
10 Temperature measurement points
11 Thermal insulation
12 Ventilation gap
13 Plastic sheet

Temperature measurement points

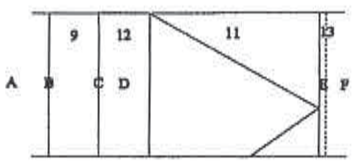


Figure 13. Schematic diagram of the climate chamber and the testing arrangements.

c) Testing program

The cycling procedure was constructed from two separate cycling programs, which were used sequentially. The details of the freeze/thaw cycles of the program 1 are shown in Table 5 and those of the program 2 in Table 5.

Table 5. Freeze/thaw cycle of program 1.

Program phase	Temperature at chamber air	Time (hours:minutes)
Wind	+25 °C	0:10
UV-light, 2400 W/m^2	+25 °C climate chamber air +45...+50 °C marble surface	1:00
Wind	+25 °C	0:10
Water spraying	+25 °C	0:10
Cooling	+25...-25 °C	1:00
Freezing	-25 °C	4:30
Thawing	-25...+25 °C	0:30
Water spraying	+25 °C	0:30
Total time		8:00

Table 6. Freeze/thaw cycle of program 2.

Program phase	Temperature at chamber air	Time (hours:minutes)
Wind	+25 °C	0:10
UV-light, 2400 W/m^2	+25 °C climate chamber air +45...+50 °C marble surface	1:00
Wind	+25 °C	0:20
Cooling	+25...-25 °C	1:00
Freezing	-25 °C	4:30
Thawing	-25...+25 °C	0:30
Wind	+25 °C	0:30
Total time		

2.6.3.3 Properties of marble

a) Flexural strength

The flexural strength of the marbles was determined by using the test specimens taken from the climate chamber after 100 and 200 cycles. The reference values were measured from the pieces of the panels that were left over after sawing the test specimens.

The flexural strength of the marbles was determined according to the standard EN 12372:1999. The samples were sawn from the specimens 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 panels, Figure 14. Six samples were prepared in both directions for each test.

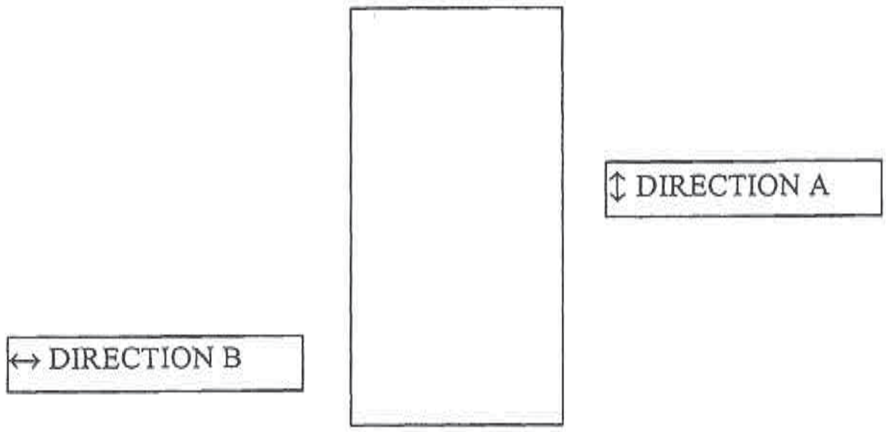


Figure 14. Flexural strength of marbles. Testing directions.

b) Water absorption, apparent porosity, bulk density

The water absorption, apparent (open) porosity and bulk density of the marbles were determined by using the test specimens taken from the climate chamber after 100 and 200 cycles. The reference values were measured from the pieces of the panels that were left over after sawing the test specimens. The water absorption properties of the marbles were determined according to the standard EN 1936:1999.

c) Mineral composition

The mineral composition of the marbles was studied with a Philips PW 1710 X-ray diffractometer. The mineral composition of the marbles was studied also with thermal analysis.

d) Microstructure

Thin sections of the marble specimens, 0.025x30x50 mm, were prepared at right angles to the surface of the panels. Pieces were cut from the test specimens 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 Leica DM HC LP polarising light microscope and photographed with Leica Q500IW image analysis equipment.

First part of the SEM-study was made by using polished marble sections. Second part of the SEM-study was made by using fracture surface samples of marbles. The samples were broken from the test specimens, any loose material was wiped off and the fractured surfaces were carbon coated.

e) Colour measurement, gloss

The behaviour of test specimens during the weather resistance tests was studied also by measuring the colour of the specimen surfaces at regular intervals using the CIELAB system.

The gloss of the surfaces of the marble panels was measured at regular intervals according to the standard ASTM D 523 by using specular angles of 60° and 85°.

f) Warping

Warping of the marble panels was studied by measuring the distance from a measuring rod to the surface of the panel. For the purpose two small metal plates with a hole in the middle were glued on the surface of each marble panel to function as fixed points of the measurements. The distance between the fixed points, L, was 493 mm, and they were installed on the mid-line, parallel to the longer side of the panels. The measuring rod was equipped with supporting feet that could be fitted into holes of the metal plates forming the fixed points. The distance between the lower edge of the measuring rod and the surface of the marble panel was measured in the middle point of the rod by using a dial gauge. The results were compared with the calibration values which were achieved using a straight granite panel. The scale of the dial gauge was adjusted in such a way that a positive value would mean convex bowing of the panel. Correspondingly, a negative value would mean concave bowing of the panel.

2.6.4 Evaluation of marble samples from other facade objects

Marble samples from three different buildings were studied. The buildings were chosen as examples of objects where Carrara Bianco is used as facade material. Common to all buildings were the varying durability problems with the marble facade cladding. The chosen objects were:

- case 1: private owned building situated in Helsinki, built 1965-1966
- case 2: private owned building situated in Helsinki, built 1971, 1985
- case 3: public building situated in Oulu, built in 1979

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

2.7 Helsinki University of Technology Research

2.7.1 Scope of the research

The objective of this study was to reveal the changes in the particular physical and structural properties of the three Italian marble types exposed to thermal cycling simulating the natural thermal behaviour of the stone façades in Nordic climates. The research was divided in two parts

- material research and
- mechanical research.

Material tests were done at Laboratory of Engineering Geology and Geophysics (Appendix 5). Mechanical studies were carried out by Laboratory of Rock Engineering (Appendix 6).

Material research covers the following marble properties before and after cycling:

- physical properties
- microstructural properties

The physical properties studied were bulk and grain densities, porosity, water absorption, and coefficient of capillary water absorption. The structural properties included mineralogy, and the quantity and quality of resin filled cracks.

Mechanical research can be divided in the following tasks:

- elastic stress-strain behaviour,
- critical stress states in compression,
- bending strength,
- modulus of elasticity in bending and
- measuring of the acoustic emission (AE)

2.7.2 Test program

Three of the marble types were included in the program: A, D and E. For all marble types test samples were cut parallel to the original rift plane. In addition to that another series of samples of type A was prepared cutting perpendicular to the rift.

After sawing all samples were measured and weighed before the cycling and testing phase by Laboratory of Engineering Geology and Geophysics. Before cycling the samples were divided equally into two groups according to the porosity. One group was chosen for thermal cycling and the other for reference samples. In this way the possible deviation caused by the porosity is represented in both groups and the results can be interpreted together.

The temperature and the moisture of the samples were not measured. The samples were always kept at least one day in the same room at the normal room temperature and humidity before the testing.

Half of the samples were thermally cycled. The temperature range in the thermal cycling was -20 to +60 °C degrees. It was chosen to represent the normal average temperature range the marble facade may undergo in actual conditions in Finland. The maximum amount of the cycles were 500 cycles. The tests and treatments in this study refer to dry specimens. Investigation of the effect of freezing or expanding pore water was not included in this study.

The elastic stress-strain behaviour and critical stress states were studied with uniaxial and triaxial compression tests. The modulus of elasticity in bending and bending strength were studied using the three point bending tests. The measuring of the acoustic emission (AE) was used in the uniaxial tests.

Originally it was intended to study the long term strength using creep tests in bending. Due to practical problems in defining the right creep load the creep test was later replaced with a test, where the effect of cycling was studied in bending using 1, 5, 10, 50 and 100 temperature cycles. Only two marble types, APA and LPE were tested. The total number of samples became thus 102 (Table 7, Figure 15).

Table 7. Final test program

Test configuration	*Uncycled tests*	*Cycled tests*
Uniaxial compression test 0.75 MPa/s	12	12
Triaxial compression test, 5 MPa confined	12	12
Bending test	12	12
"Cycling test"		30
Total	36	66
Total of marble samples	**102**	

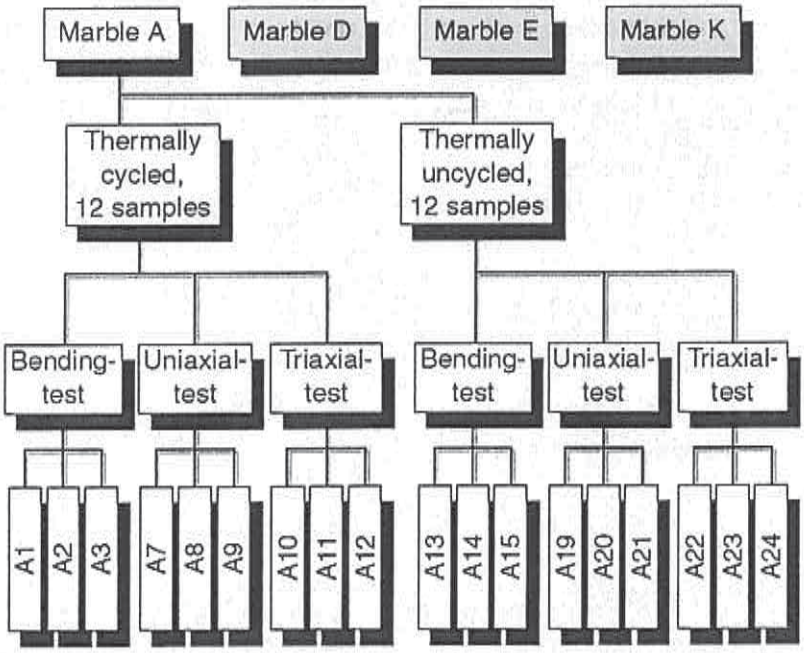


Figure 15. Final test program for one marble type excluding the "cycling" test.

2.8 Parma University research

2.8.1 Scope of the research

Main scope of the experimental activity in University of Parma was to evaluate the leading characteristics of the connection between the constituent calcite grains. Granular decohesion damage occurs when the granular connection is overcome. Standard tests cannot be considered to give quite reliable indications about the durability properties of marble. In order to find a more reliable criteria the experimental procedures were divided in two main categories:

- direct tensile tests with close-loop control of the specimen-head rotations, in order to establishing the strength of the bonding
- bending tests with pre-cracked beam technique, usually employed for ceramic materials, to define the fracture energy.

Apart from these, the University of Parma has given consideration to another series of tests, performed with a high precision dilatometric apparatus. The main goal in these tests, carried out in collaboration with VTT Building and Transport, was to demonstrate that thermally-induced granular decohesion produces, at the macroscopic level, permanent dilatation of marble specimens. This observation is fundamental because it allows to correlate the observed bowing in marble panels, produced by different elongation of material fibres, with damage occurring at the microstructural level.

The aim was to develop, based on the results obtained in the experimental research, reliable theoretical models for explaining the deterioration phenomena at microstructural level such as

- modelling of damage due to cyclic loading,
- modelling of fracture mechanism and microstructure and
- numeric computation and modelling of damage due to chemo-thermo-mechanical actions
- suggestion for a test method to defining the properties and suitability of a given marble for use as a facade caldding material

As a conclusion, the aim was to develop a model for explaining the connection between microstructural behaviour and bowing as a macroscopic consequence of granular decohesion. Finally suggestions of reliable criteria to be applied in the future for restoration activities for Finlandia Hall, was to be given (Appendix 7).

2.8.2 Research program

2.8.2.1 Direct tensile strength

In order to establish the strength of the bonding a direct tensile tests with close-loop control of the specimen-head rotations were carried out. The testing system consisted of a closed-loop electromechnical Instron testing machince with a maximum capacity of 100KN, for which the main characteristics are:

- electromechanical controls with a minimum speed of 2μm h^{-1},
- three control channels, one of which can be external (giving possibility to choose feedback signal that allows a stable tests control),
- closed-loop control with integral and derivative gain (in order to remove the effect of the finite stiffness of the machine).

For the uniaxial tensile test, the specimens were carefully glued to the plates clamped to the testing machine, making the geometrical tolerance between specimens and plates very small. Two cylindrical heads with four micrometers located at right angle one to the other allowed precise positioning of the grips. Attachment of specimens to plates was done directly on the testing machine.

A total number of 23 specimens of the four selected materials, either virgin or conditioned, carved with different orientation with respect to the marble rift plane, were tested under tensile load. The specimen characteristics, with an indication of the reference monograms, are summarised in Table 8.

Table 8. Summary matrix for direct tensile tests.

Direct tensile tests							
Nr	Spec. name	Marble-type	test nr.	termal conditioning	Dim (cm)	Angle to rift	comment
1	E1-PA-TT	E	N1	NO	6x12x4	0	-
2	E2-PA-TT	E	N2	NO	6x12x4	0	-
3	E1-PE-TT	E	N1	NO	6x12x4	90	-
4	E2-PE-TT	E	N2	NO	6x12x4	90	-
5	E3-PE-TT/C	E	N3	20 cyc. -20°C to+ 80°C	6x12x4	90	-
6	E4-PE-TT/C	E	N4	20 cyc. -20°C to+ 80°C	6x12x4	90	-
7	K1-PA-TT	K	N1	NO	6x12x4	0	-
8	K2-PA-TT	K	N2	NO	6x12x4	0	-
9	K1-PE-TT	K	N1	NO	6x12x4	90	-
10	K2-PE-TT	K	N2	NO	6x12x4	90	-
11	K3-PE-TT/C	K	N3	20 cyc. -20°C to+ 80°C	6x12x4	90	failed
12	K4-PE-TT/C	K	N4	20 cyc. -20°C to+ 80°C	6x12x4	90	-
13	A1-PA-TT	A	N1	NO	6x12x4	0	-
14	A1-PE-TT	A	N1	NO	6x12x4	90	-
15	A2-PE-TT	A	N2	NO	6x12x4	90	-
16	A3-PE-TT/C	A	N3	20 cyc. -20°C to+ 80°C	6x12x4	90	-
17	A4-PE-TT/C	A	N4	20 cyc. -20°C to+ 80°C	6x12x4	90	-
18	D1-PA-TT	D	N1	NO	6x12x4	0	-
19	D2-PA-TT	D	N2	NO	6x12x4	0	-
20	D1-PE-TT	D	N1	NO	6x12x4	90	-
21	D2-PE-TT	D	N2	NO	4x6x3	90	-
22	D3-PE-TT/C	D	N3	20 cyc. -20°C to+ 80°C	6x12x4	90	-
23	D4-PE-TT/C	D	N4	20 cyc. -20°C to+ 80°C	6x12x4	90	-

2.8.2.2 Pre-cracked bending test

This technique is usually employed for ceramic materials for defining the fracture energy. The fracture toughness, K_c, is considered the main material property qualifying the reliability of brittle materials. The applicability to Carrara marbles of a two-step procedure for fracture toughness determination has been examined.

The testing method used consists of a two-step procedure applied to prismatic bars:

- a starter notch is propagated to a through-thickness configuration using a pre-cracking technique and
- the bar containing a natural crack is fractured under three-point bending loading.

Here special attention is given to the identification of a suitable pre-cracking technique to insert natural flaws in two marbles.

The standard procedure for plane-strain fracture toughness determination requires the introduction of a natural crack of controlled geometry into the specimen. However, the inherent brittleness of marbles, similarly to ceramics, complicates this pre-cracking step. Various experimental techniques have been advanced including diamond saw–through notches or chevron-notches in different specimen geometry, but size effects and actual crack behavior during the test, respectively, complicate the interpretation. Natural cracks of complex shape can be readily inserted in ceramics by Vickers indentation, but it may not apply to rock-like materials.

A conventional linear elastic fracture mechanics (LEFM) interpretation of these methods resorts to the stress intensity factor (SIF) evolution as controlled by the pre-cracking apparatus. SIF evolutions for the two pre-cracking techniques here considered were determined using a combination of the weight function (WF) method (Bueckner, 1970) and the finite element (FE) method. Accordingly, we assume for SIF or K the value

$$K(a) = \int_0^a \sigma(y) h(y,a) dy \qquad (1)$$

where σ(y) is the normal stress acting on the perspective crack plane in the uncracked bar and $h(y,a)$ is the weight function for the single-edge-bar geometry (Bueckner, 1970). Three types of specimens were examined:

- specimens artificially indented with a diamond saw,
- natural pre-cracking method B – Bridge method and
- natural pre-cracking method SB – Sandwich Beam method,

Unfortunately, just a few preliminary tests showed that the B-method cannot be directly applied to marbles as micro-cracks are not produced by the indentation method: a starter notch has to be machined instead as shown in the scheme of Figure 16.

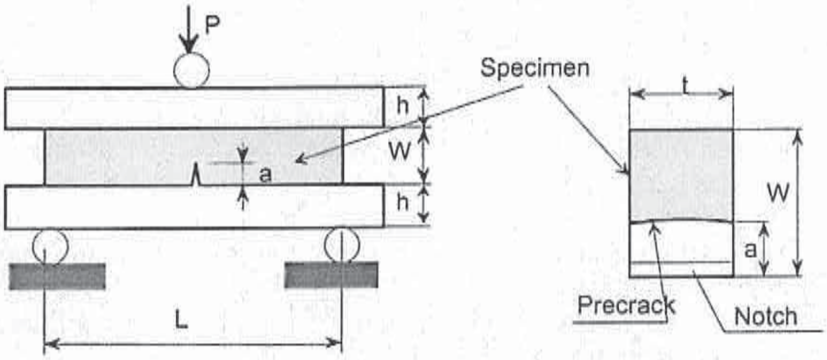


Figure 16. Scheme of the Sandwich-Beam (SB)-method.

The main depth-controlling parameter of the SB-method is the relative bending stiffness of the specimen, $(EI)_s$, and of the sandwich beams, $(EI)_b$, (i.e. $(EI)_b/(EI)_s$ ratio). Two values were examined, namely 1.43 and 4.83. The normal stress distributions in the plane of perspective crack propagation were used in Equation (1) to determine SIF evolution. Subsequent normalization used the bending stress in the specimen defined as $\sigma = 3PL/(2tW^2)$ and the crack length a, as shown in Figure 17.

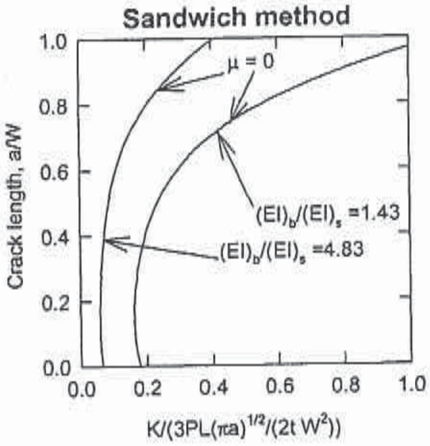


Figure 17. Normalized SIF for the precracking phase of the SB method

In order to investigate the influence of material texture on fracture toughness, approx. thirty prismatic bars (t=10mm, W=20mm, L=100 mm, refer to Figs. 16 and 17) were cut parallel and perpendicular to the material plane of natural schistosity, i.e. the rift plane. The surfaces were polished and a short lateral through notch was inserted using a thin diamond saw. As different marbles reacted differently to the pre-cracking technique, specimens with a sharp 150-μm-wide machined notch were also used to provide a reference value and an alternative experimental route for marbles

The total number of tests performed was thus 50. The natural precracking bridge-method was abandoned after a few preliminary tests. Thus, evaluation of the material fracture toughness was limited to sandwich-beam pre-cracked specimens and to specimens containing natural pre-cracks 150-μm-wide, obtained though a precision diamond saw.

2.8.2.3 Dilatometric tests

In order to assess whether the measured difference in temperature and moisture might be sufficient to provoke bowing, a series of tests was performed using a high-sensitivity dilatometer, able to monitor the expansion of marble while varying its temperature. Since granular decohesion implies volume increase, the permanent dilatation may represent an index of the amount of damage produced. Different qualities of marbles were considered. Dilatometric tests were made in close collaboration with VTT Building and Transport.

Since granular decohesion is always accompanied by opening of intergranular cracks, volume increase and a consequent permanent dilatation should be its counterparts at the macroscopic level. Marble bowing could thus be explained assuming a gradient of the decohesion level through the panel thickness. The reasons why the granular decohesion level should vary through the panel thickness may be numerous and different in type. For example, as confirmed by careful measurements, temperature may vary between the inner and outer surface of the façade due to the building internal heating; differences in the humidity level, also confirmed by measurements, might as well play an important role.

2.8.2.4 Modelling of granular decohesion

Experimental observations have provided evidence for that just a few degrees temperature increase, even when uniformly distributed in the specimen, may be sufficient to provoke a progressive detachment of the calcite granules. The characteristic feature of this phenomenon is that the grains remain integral, hardly showing any traces of transgranular cleavage fracture, but rather look as if their cementing material had been gradually destroying.

We recall that possible explanations of the decohesion phenomenon essentially involve three different possible causes:

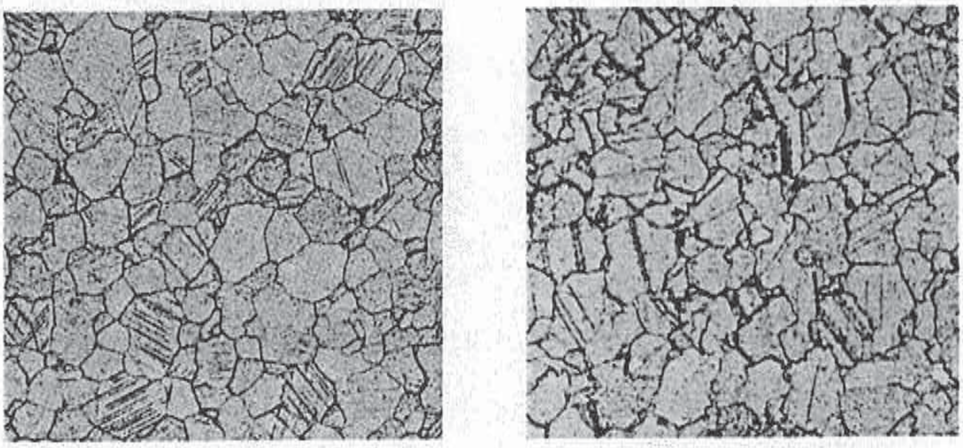
- the chemical-physical attack of sulfates and chlorides (Winkler 1994);
- the mechanical action of soluble salts which, penetrating in a solution, increase their volume when the solvent evaporates and may expand existing cracks (Franzini, 1995);
- thermal variations, which may cause a self-equilibrated state of stress inside the material (Royer,-Carfagni 1999). Particular hygrometic conditions may, of course, have a synergetic effect with the other causes.

Despite the fact that an universal agreement has not been found yet, our personal experience seems to suggest tentatively that the first two mentioned agents have only a side importance. Examination of the bowing phenomenon in a number of other monuments, show that chemical attack is confined to the superficial crust and hardly any trace of soluble salt can be found inside the slab, despite an evident signs of granular decohesion.

2.8.2.5 Microstructural characterisation

Materials that in nature appear to be composed of aggregates of granules more or less cemented together are usually referred to as natural conglomerates. Despite the generality of our considerations, here we refer to the specific case of Carrara Bianco marble. The various qualities of marble, rather than by appreciable difference in the mineral composition, are distinguished by the dimension, and even more so, by the shape of the constituent grains. These are arranged in microstructural textures which may range between the two extreme cases usually referred to as *homoblastic*, when the grains present gently curved boundaries, and *xenoblastic*, characterized by the close interlacing of weavy contours.

The various qualities of marbles, despite presenting practically the same chemical composition, show considerable differences in their mechanical properties and the experimental evidence suggests relating such differences with the material underlying microstructure. In the present paper we propose a simple method to describe the microstructural textures, based on the *quantitative* classification of the geometric shape of the grains by means of indicators, likewise the grain area A, the perimeter p or the skeleton s, primarily used in the field of computer vision.



a) b)

Figure 18. Thin sections of typical homoblastic (a) and xenoblastic (b) marbles.

Besides the material classification a possible correlation between the microstructural parameters and mechanical macroscopic properties shall be examined, likewise bending strength or porosity. Recent studies have in fact evidenced that many material properties may be influenced by the underlying microstructure. For example, in (Royer-Carfagni, 1999a) the resulting state of stress in grains subjected to uniform thermal variations has been considered. This stress is originated by the springing apart of contiguous grains due to the anistropic thermal expansion of calcite, since the grains are randomly oriented. In (Royer-Carfagni 1999a) it has been shown that the most dangerous stress at the grain borders, in particular at the texture nodes, where more than two grains converge at one point.

More in particular, the sharper the grain corners are, the less dangerous is the resulting stress, a finding which might suggests that xenoblastic marbles are more resistant than the homoblastic qualities. The experimental investigation (Franzini, 1995) seem to confirm this trend. Another example is given by the fatigue response of marbles subject to cyclic uniaxial (Royer-Carfagni e Salvatore, 1998, 2000). Also in this latter case, tests have confirmed that xenoblastic marbles are, as a rule, more resistant than the homoblastic ones. In conclusion, a quantitative microstructural characterization can allow a prediction of macroscopic mechanical properties and, what is more important as evidenced in (Royer-Carfagni 1999b), an indication of the material natural attitude to granular decohesion thermal damage.

2.9 Cevalor research

2.9.1 Scope of the research

The aim of the work carried out by Cevalor was to give added value to the research of the effect of freezing-thawing treatment on marble properties. Work was completed as a comprehensive series of laboratory tests. In practice the study was divided in six workpackages:

- Workpackage 1 (WP1) - Selection of sites with "old carrara" marble,
- Workpackage 2 (WP2) - Characterisation of the sites.
- Workpackage 3 (WP3) - Collection of samples from sites,
- Workpackage 4 (WP4) - Collection of samples from other stone types,
- Workpackage 5 (WP5) - Testing Campaign,
- Workpackage 6 (WP6) – Comparison of results

Workpackage 5 (WP5) - Testing Campaign, was divided in three tasks:
- initial characterisation,
- testing campaign each 25 cycles of the freeze/thaw;
- Interpretation of results

The chemical characterisation included in the research was done by IGM, Geologic Institute and the microscopic observation by FCT/UNL, Lisbon Univers. All the above referred tests were done for five types of marbles, four Italian and one Portuguese. The testing procedure is given in figure 19 (Appendix 8).

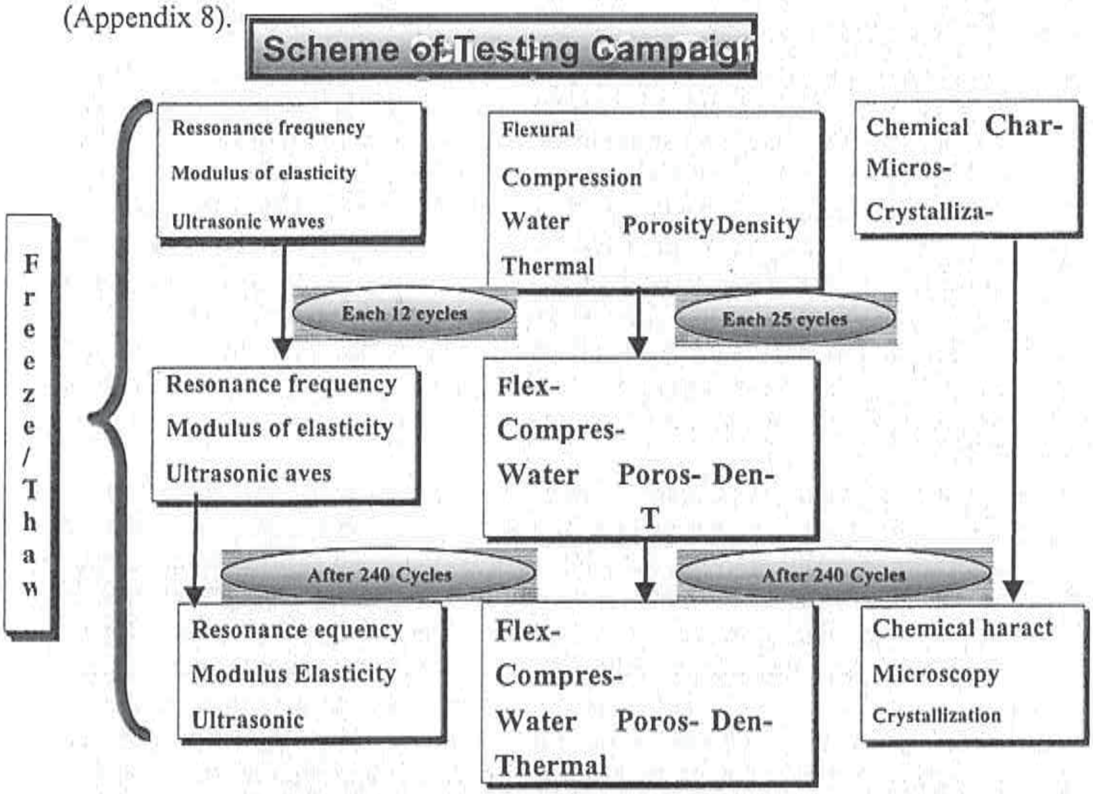


Figure 19. Testing procedure of Cevalor studies

2.9.2 Technical testing program

2.9.2.1 Workpackages

Workpackage 1 - Selection of Sites With "Old Carrara" Marble
Samples of old Carrara Bianco were taken from the Finlandia Hall original façade. In this case the stone has been submitted to several climates variations prevailing in Finland. It's aspect is already characterised by the appearance of decay phenomenas.

Workpackage 2 - Characterisation of The Sites
The Northern countries are characterised by cold winters, with temperatures usually below zero (the annual temperature variations in Finland is from – 30°C to 30°C, leading to situations where stone facade temperatures vary from – 30°C to + 50°C). In southern countries with a more mild climate and hot summers (average temperature around 22°C-35°C) white stone facades can reach up to 60°C.

Workpackage 3 - Collection of Old Carrara Sample From Sites
The Old Carrara sample was provided by the project management.

Workpackage 4 - Collection of Samples From Other Stone Varieties
Several Carrara marble varieties were selected, for testing. In addition a variety of Portuguese marbles was selected by Cevalor initiative, in order to compare obtained values. Portuguese marble with code V was chosen because of its physical/mechanical similarity with the Italian marbles.

Workpackage 5 - Testing Campaign
In order to study the behaviour of the chosen materials, when subjected to climate variations, several tests were done. The following tests were agreed (done according to European Standards defined by CEN/TC 246):
- Freeze/Thaw (prEN 12371),
- Resonance Frequency and Dynamic Modulus of Elasticity (prEN WI00246035),
- Ultrasonic propagation Speed (prEN WI00246012),
- Resistance to Flexural Strength Under Concentrated Load (EN 12372),
- Resistance to Compression (EN 1926),
- Water Absorption at P.t.N, Open and Total Porosity, Volumetric Mass (prEN WI036 and EN 1936),
- Thermal Shock (prEN WI00246016),
- Chemical Characterisation,
- Microscopic Observation,
- Crystallisation Test (prEN 12370).

2.9.2.2 Laboratory tests for WP 5

Freeze/Thaw (prEN 12371)

This European standard specifies a method to assess the effect of freeze/thaw cycles on natural stones. According to the climatic variation and the oscillation between high and low temperatures, were made for each sample about 240 cycles, each cycle consists of a 6 hour freezing period in air until –20°C, followed by 6 hour thawing period until + 20°C during which the specimens are immersed in water.

In order to control the behaviour of the stones, three criteria were used to assess the action of freezing and thawing cycles on the specimens:
visual inspection
measurement of the apparent volume
measurement of the dynamic elastic modulus
measurement of ultrasonic speed
measurement of resonance frequency

For each stone 7 specimens with (300x50x50) mm were used. One specimen was used to monitor the core temperature. In the beginning of the test all samples were dried at 70°C in the oven until constant mass, after dried the specimens were immersed to constant mass was attained.

Resonance Frequency and Dynamic Modulus of Elasticity (prEN WI00246035)

This standard defines methods to determine the fundamental resonance frequency and the calculation of the dynamic modulus of elasticity. The used method was based on continuos longitudinal excitation, with a frequency generator range of 2,8 kHZ.

The calculation of the longitudinal dynamic modulus of elasticity was calculated by the longitudinal resonance frequency and the real density of the stone.

Ultrasonic propagation Speed (prEN WI00246012)

The European standard specifies a method for the determination of the velocity of propagation of pulses of ultrasonic longitudinal waves in natural stone.

A pulse of longitudinal vibrations is produced by an electro-acoustical transducer held in contact with one surface of the stone under test. After traversing a known path length in the stone, the pulse of vibrations is converted into an electrical signal by a second transducer and electronic timing circuits enable the transit time of the pulse to be measured.

Resistance to Flexural Strength Under Concentrated Load (EN 12372)

This European standard specifies a method for the determination of flexural strength under a concentrated load. The load on the specimens was increased uniformly at a rate of 0,25 Mpa/s.

For each stone 6 specimens with (300x50x50) mm were used for initial characterisation, and 2 specimens each 25 cycles during the freeze/thaw campaign. In the beginning all of the test samples were dried at 70°C in the oven until constant mass was attained.

Resistance to Compression (EN 1926).

This European standard specifies a method for determining the compressive strength of natural stones. The load on the specimens was applied at a constant stress rate of 1 Mpa/s.

For each stone 6 specimens with (50x50x50) mm were used for initial characterisation, and 2 specimens each 25 cycles during the freeze/thaw campaign. In the beginning all of the test samples were dried at 70°C in the oven until constant mass was attained.

Water Absorption at P.t.N, Open and Total Porosity, Volumetric Mass (prEN WI036 and EN 1936)

These European standards specifies methods for determining the water absorption, the real density, the apparent density, and the open and total porosity of natural stones.

After drying the specimens at 70 °C in oven until constant mass, the apparent density and the open porosity were determined by vacuum assisted water absorption and submerged weighing of specimens.

Definitions:
Apparent density = the ratio between the mass of the dry specimen and its apparent volume
Apparent volume = the volume limited by the external surface of the specimen, including any voids
Open porosity = the ratio (as percentage) between the volume of the open pores and the apparent volume of the specimen

For each stone 6 specimens with (50x50x50) mm were used for initial characterisation, and 2 specimens each 25 cycles during the freeze/thaw campaign.

Thermal Shock (prEN WI00246016)

This European standard specifies a method to assess possible modifications, of natural stones under the effect of sudden changes in temperature (thermal shocks)

After drying at 70° C until constant mass was attained, the specimens were submited to successive cycles, each formed by drying at 70° C followed by immediate immersion in water at 20±5°C

For each stone 6 specimens with (200x200x2) mm were used for initial characterisation, and 2 specimens each 25 cycles during the freeze/thaw campaign.

Chemical Characterisation

The chemical analyse consist in determination of major elements by ray X florescence. This test was made in the beginning and after the end of the freeze/thaw.

Microscopic Observation

The microscopic observation consisted in two types of observation, the petrography and the SEM, Scanning Electron Microscope. The tested samples were observed, at different stages of freeze/thaw.

Crystallisation Test (prEN 12370).

This European standard specifies a test method to assess the relative resistance of natural stones with an open porosity greater than 5%, the objective is to evaluate the damage caused by the crystallisation of salts.

For each stone 6 specimens with (40x40x40) mm were used for the initial characterisation and 2 specimens after the end of freeze/thaw campaign. In the beginning of the test all samples were dried at 70°C in the oven to constant mass. The Crystallisation tests were made

2.9.3 Case studies

In addition to the technical testing program a study was made to collect data about experiences on use of marble in Portugal. The aim of this work was to find objects in Portugal with facades of Carrara Bianco or Portuguese marbles. This was done in the first place by contacting the following groups:

- Stone Companies
- Architects Offices
- Building Companies

Information was then collected by interviews of parties involved in the specific object and other technical experts available. Main objects were documented by photographing.

2.10 Collaboration with IMM

2.10.1 Internationale Marmi e Macchine

Internationale Marmi e macchine (IMM) is an organisation representing the Italian stone industry in Carrara region. General purpose of IMM activities is to promote the use of building stone for building purposes and monuments. For this purpose IMM provides versatile development, expert and marketing services. One of IMM activities is to participate in the European standardisation and international development work. Main even organised by IMM is the annual international stone fair in Carrara, which has been organised since late 1970´s. Carrara stone fair is directed in the first place to stone material production and stone processing equipment. In addition a professional seminar is organised each year for real estate owners, designers and other professionals in the stone field.

2.10.2 Main objectives and tasks

In Mara project IMM had several roles. Main objective was to provide the project with information and better understanding of Carrara Bianco, its production and use in the buildings worldwide. On the other hand IMM gave support to collaboration with the local marble producers and played an active role as an organiser of the dissemination seminars in connection to the stone fairs in Carrara in 1999, 2000 and in 2001 for the presentation of the final results of the project.

In the beginning of the project IMM gave professional assistance to choice of the stone types and took responsibility for the local quality control during the sampling process. This is very important in a multi-laboratory project like Mara in order to guarantee equal quality of stone material used in individual laboratories. For comparability of the research results it is essential to be able to provide all laboratories with similar samples.

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