FINAL TECHNICAL REPORT

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ACRONYM : **TEAM**

TITLE : **Testing and Assessment of Marble and Limestone**

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1 Executive publishable summary

Background: The use of natural stone as facade cladding has been shown to have much lower life cycle costs, i.e. they are more environmentally friendly than comparable products of concrete, glass and steel. Promoting the use of natural stone has therefore a great positive impact on the environment. However, the number of occurrences of bowing and expansion of marble and limestone panels has lead to increased maintenance costs besides the significant safety risk and has given negative publicity. The lack of knowledge of a solution to the problem of bowing marble has a large negative effect on the entire stone trade. In response, short-sighted and less durable construction solutions are used as alternative, adding to the decreasing export figures and numbers of employees within the stone sector. The TEAM project addresses a problem with marble types, from several European countries, that display bowing on facades in both cold and warm climates. There is, therefore a need to develop harmonised European standards for differentiating between marble that is susceptible to bowing and marble that is not. Resolution no. 013, in May 1999 taken by CEN TC 246 Natural Stone states the urgent needs "to develop a direct test method of the bowing risk for marble cladding products". Thus, the project addresses the mandate for external wall coverings and the safety of panels.

Objectives: The main objectives were:

- To understand and explain the mechanisms of the expansion and loss of strength, probably the most important phenomena leading to degradation of marble and limestone clad facades.
- To prevent the use of deleterious marble and limestone by introducing drafts for European standards.
- The project also aimed to develop a concept for assessment of facades, including a monitoring system in order to predict strength development and improve safety and reliability.
- To analyse if surface coating and impregnation could prevent or diminish the degradation.
- The project has also addressed quality control aspects in order to optimise the production conditions.

Work carried out: The TEAM project consortium, representing 9 EU countries, comprised 16 partners representing stone producers and trade associations, testing laboratories, standardisation and certification bodies, consultants, building owners and care-takers and producers of fixing and repair systems.

A state-of-the-art report has been written and is based on an extensive compilation of more than 300 papers on marble and limestone deterioration dating from late 1800s to 2005.
A survey of about 200 buildings has given a clear picture of the extent of the problem in geographical, geological and climatological terms.

Detailed case studies of 6 buildings have resulted in a methodology for assessment of facades including monitoring system and risk assessment.

Research both in the laboratory and the field were performed on a large number of different stone types from different countries and used in different climates. This gave the explanation of degradation mechanisms and lead to the determination of the critical influencing factors.

Two tests methods, including precision statements: one for bowing and one for thermal and moisture irreversible expansion have been prepared for submission to CEN TC 246.
Repair techniques based on the use of surface coating and impregnation systems has been tested at laboratory and in field. Positive side effects including increased durability and easier cleaning have been observed.

Guidelines for production and product control have been proposed.
An instruction for stone sampling and description has been developed.

Dissemination: The findings have been and will be disseminated mainly through technical papers, workshops, conferences and the introduction of EN-standards.

2 Objectives of the project

The use of thin marble and limestone slabs as facade cladding has increased substantially during the last few decades. However, during recent years reports of facade failures have increased dramatically. Prominent buildings such as the Amoco building in Chicago, the Finlandia City Hall in Helsinki, La Grande Arch in Paris and IBM Tower in Brussels have all experienced serious durability problems with their marble clad facades. The problem is expressed by expansion, bowing, loss of strength, and in most serious cases the detachment from the anchoring system (Amoco building, USA, Sydsvenska Dagblad, Malmö, Sweden). The problems regarding limestone facades are slightly different. Apparently, limestone does not bow, but it expands causing serious problems if the joints are not sufficiently wide to account for the expansion.

There is a large need of repair systems for existing facades. Despite several European research projects, the only solution for repair is replacing the panels at large costs of about 400 Euro/m^2. The recent example of the City Hall in Helsinki, where all panels have been exchanged in 1998-1999 at a cost of 3.8 Million Euro (the same order of magnitude as the entire TEAM project) gives an economic perspective of the problem. The problem did not stop as the new panels were chosen on incorrect grounds. The new panels on the City Hall started to bow already 6 months after the installation! The today known damaged buildings in Europe are expected to necessitate repair for well over 240 Million Euro unless other solutions can be foreseen! Although the vast majority of reported durability problems with thin marble or limestone slabs refer to the Italian Carrara marble, which is also by far the most widely used marble in the world. Other marbles e.g. American, Norwegian and Portuguese have also been reported to bow on facades. However, the reports on performance of Carrara marble are inconsistent, since in some cases Carrara marble apparently performs satisfactory. Note that there are about 200 different stone quarries in operation in this area! The direction of the observed bow may be either convex outward or concave inward relative the facade, probably mostly depending on environmental (climatic) conditions. However, despite considerable effort the exact physico-chemical processes responsible for the degradation of thin marble and limestone slabs exposed to outdoor conditions have not been established by the research community. As a consequence of the reported durability problems and the lack of fundamental understanding of the problem, both producers and users (architects and building owners) of marble and limestone are almost desperate for more knowledge and in particular they are eager to find a test method able to distinguish durable building stones from non-durable building stones.
Therefore the project is addressing three clear-cut objectives being:

- *To establish a sound understanding based on natural sciences of the phenomena leading to poor field performance of marble clad facades.*
- *To develop a laboratory test method for determination of potential bowing of thin slabs of natural stone.*
- *To develop a field monitoring, evaluation and repair guide for facade cladding, which will include risk assessment and service life prediction.*

To fulfil the objectives the work aimed:

- to update the state of the art.

- to establish the service record of a number of marbles and limestones from case studies of existing buildings in different climatic conditions both of good and poor performance
- to select at least 5 buildings for detailed testing and monitoring in order to develop a monitoring and evaluation program enabling the prediction of the service life of existing facade claddings
- to conduct research studies on vast number of different marbles and limestones in different environmental conditions leading to comprehensive material characterisation of the materials including determination of all intrinsic and extrinsic parameters described previously believed to influence durability as well as a number of other critical parameters
- to test different anchoring system and their influence on bowing
- to test the repair techniques based on the use of surface coating and impregnation systems

3 Scientific and technical description of the results

Introduction

Natural stone has been used for facade applications for centuries. Originally, the stone was rather thick, when used as construction elements, and the durability was apparently good. Scientific research on properties of marble began in the late 19th century. In the years following, the thickness of natural facade stones decreased from over 1000 mm (as in construction elements) to typically 20-50 mm (in cladding applications) as a result of new cutting technologies and equipment being developed by the industry. Even though most marble claddings perform satisfactory, durability problems have begun to appear at an increasing rate after some 50 years of using thin cladding. Well-known buildings such as the Amoco Building in Chicago, SCOR tower in Paris and the Finlandia Hall in Helsinki (figure A) have had their marble cladding replaced after less than 30 years at a cost of many millions of Euros. The deterioration gives a very conspicuous change in the appearance of the panels, they bow, warp or dish.
Most cases of bowing involve marble from the Carrara area, simply because it is the most widespread and used marble type. It is, however, vital to emphasize that many building facades with Carrara marble perform well, and furthermore that marble from other areas all over the world also exhibits durability problems.

Figure A. Examples of some famous buildings clad with marble or limestone with durability problems.

The bowing of marble is not only restricted to buildings, but gravestones of marble are also known to bow as is seen in e.g. Montmartre Cemetery (figure B). At present time, most of the recorded cases are from Europe or North America, most likely because of the much more widespread use of thin marble claddings in these parts of the world. However, single recordings have also been made in India (Grabmal des Humayun, Bouineau & Perrier 1995) and Cuba (Cementary at Havana, Kessler 1919).
Despite more than 100 years of research and being a worldwide problem, the solution to the problems with bowing marble has not yet been found. Numerous methods have been employed to investigate possible factors responsible for deterioration of marble. However, no systematic investigation based upon inspections of building facades with marble cladding have been carried out before now.

Figure B: Bowing of marble on the Finlandia Hall, Helsinki, Finland (left) and on a gravestone in the Montmartre cemetery, Paris, France (right).

Methodology

The holistic approach of the TEAM project takes into consideration the fact that the problem of bowing and expanding marble and limestone is of interdisciplinary character. This is illustrated in the work flow scheme below (figure C). The project has therefore engaged experts from all disciplines concerned, such as stone producers, traders and trade associations, testing laboratories, authorities/standardisation and certification bodies, consultants, building owners and care-takers and producers of fixing and repair systems, from 9 European countries (figure D). The leaders of the different work packages are listed in table A.

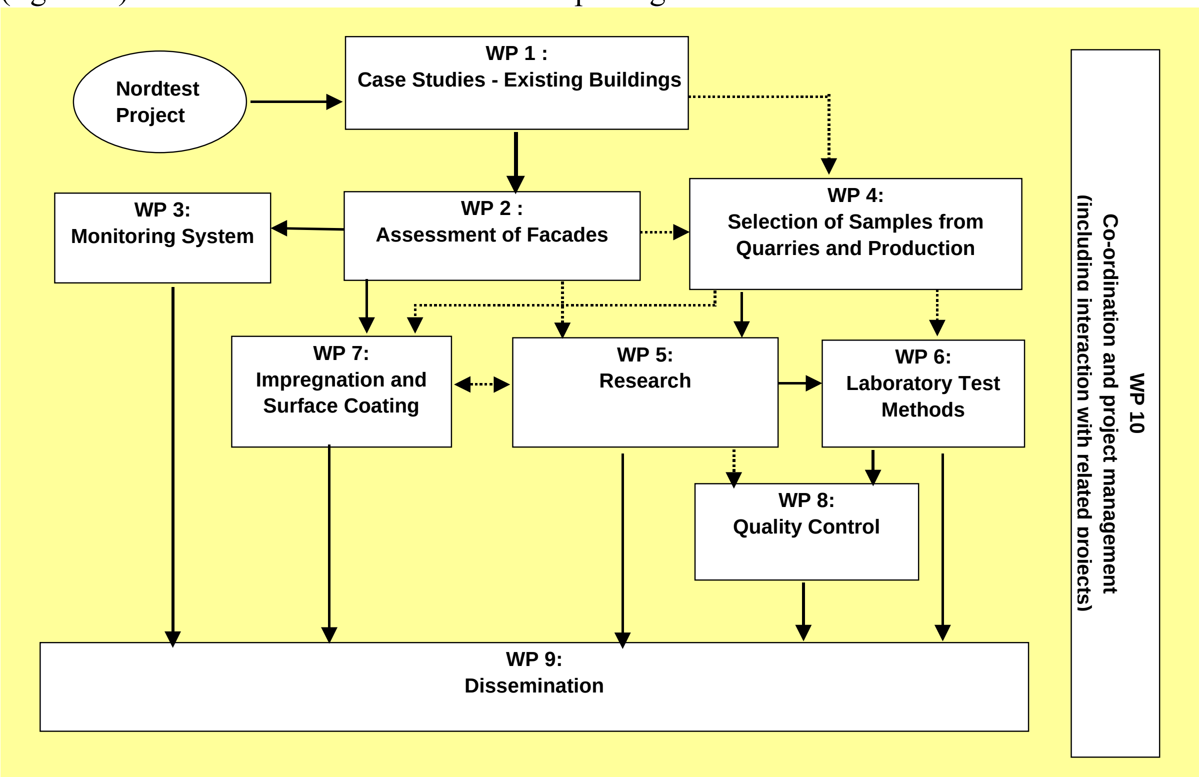


Figure C. Flow chart of activities work packages (WP) and their relationships in TEAM.

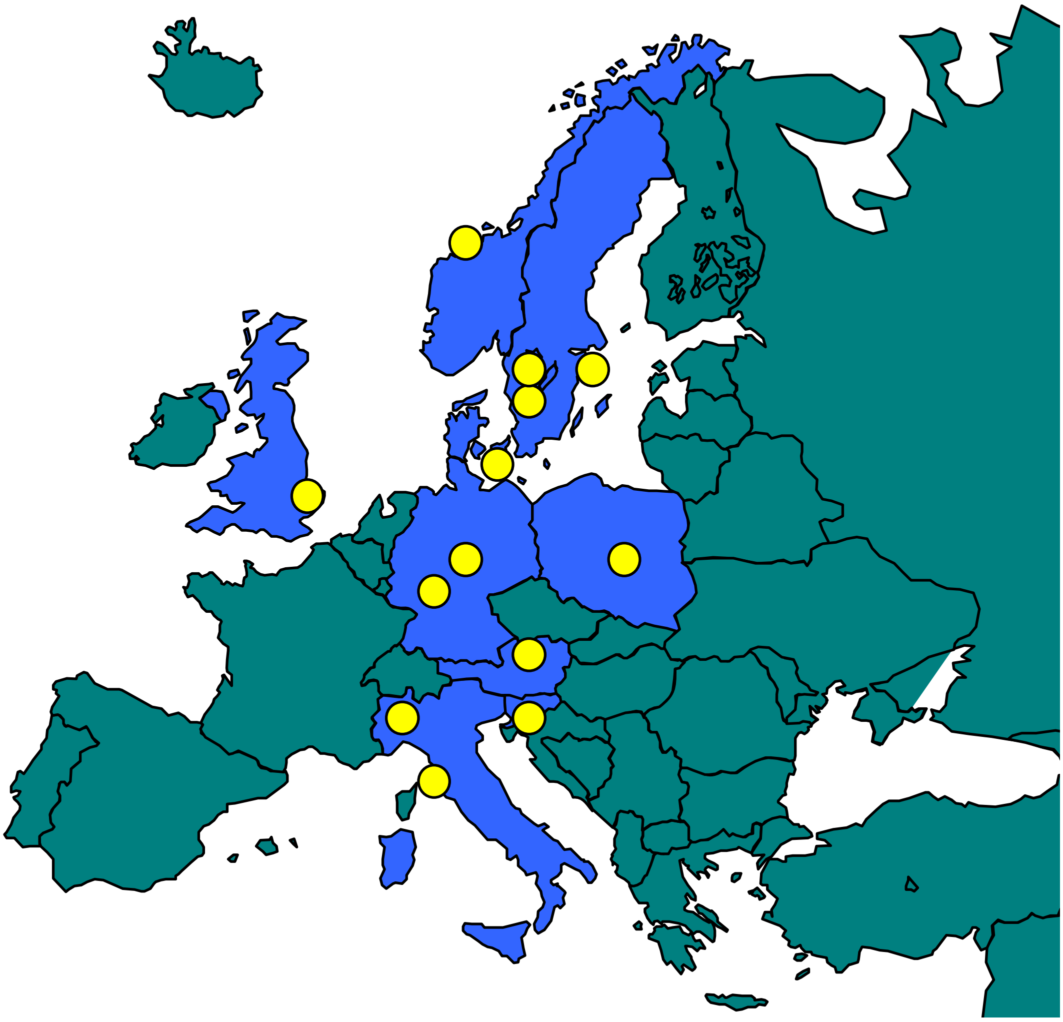


Figure D. Representation of partners in TEAM.

Table A. Overall responsibilities for the work packages.

WP	Activity	Leader	Country
1	Review of literature and buildings	Janaders Consulting	SE
2	Detailed investigation of selected buildings	Rambøll	DK
3	Long-term monitoring of 3 buildings	Building Research Establishment, BRE	UK
4	Sampling of materials	UGE & IMM	DE & IT
5	Quarry and laboratory testing	SINTEF	NO
6	Develop of test methods, precision trials	SP	SE
7	Field exposure sites, remedial activities	BRE	UK
8	Quality control of products and production	SINTEF	NO
9	Dissemination	IMM	IT
10	Administrative and scientific management and co-ordination	SP	SE

The findings in the Nordtest project "Testing of bowing of marble facade" were of vital importance for the definition of the workplan in the TEAM project as input, e.g.
for the facade assessment system and the bowing and expansion tests. The general approach was therefore to start with updating the necessary information from past and present related projects into a state-of-the-art report of the deterioration mechanisms. In addition, to perform general case studies in order to gather information about geographically, meteorologically and geologically differences.
Based on this first step input was mainly given to WP 2 and 3, for the selection of suitable buildings to be studied in more detail, including the design and installation of long-term monitoring systems. Monitoring the microclimate in relation to the strain and bowing give information needed to be able to give recommendations on the possible use in different climates. It also gives the necessary information to be able to perform a risk assessment, i.e. to predict further bowing development and decrease in strength (WP 3). Safety criteria can subsequently be drawn up depending on the type of building, anchoring, locality etc. The outcome of this second step has been a concept for Assessment of facades. Whether the anchoring system plays an important role to prevent bowing will be assessed in WP 2.

Additional input to other WP's is the selection of marble and limestone types (WP 4) for laboratory research of the deterioration mechanisms. In order to get relevant information about the material properties and performance, a large selection of different marble and limestone varieties are therefore needed. Among other things, different production orientations in relation to rock structures in the quarry have been represented among the samples, and different surface finishing such as grinding and polishing.

The next step, WP 5, was to try to understand the degradation mechanisms by laboratory research on samples from buildings, quarries and production. Material characterisation was performed in relation to the findings from WP 1, 2 and 3. Critical levels of temperature and moisture were determined for the development of test methods. Stress measurements were carried out in the quarry for the characterisation of the rock mass properties. Critical variables were then mainly given to WP 6 and 8. As a result of this, one single test method for bowing and one for irreversible thermal and hydric expansion were chosen within WP 6. The test procedures have been fixed and the precision established by an inter-comparison test. The methods and data have been presented to CEN TC 246 Natural Stone.

Previous research has shown that one condition that has to be present for the panels to bow is moisture. In order to decrease the moisture content and decrease or inhibit further bowing, different surface coatings and impregnation systems have been tried in-situ and in a field site, WP 7.

In order to promote a sustainable materials production, WP 8 dealt with the quality control and how to prevent the production and use of deleterious marble and limestone material.

One of the most important factors for a successful outcome of a project like this is the possibility to implement the results among the producers, users and authorities. A detailed dissemination workpackage (WP 9) was therefore described. This WP has included exhibitions and seminars at annual fairs, Web sites, workshops and a very close co-operation with the European standardisation of natural stone, CEN TC 246.

Description of research and results in each WP

3.1 WP 1 Case studies – Existing buildings

The work package is divided into the following two tasks:

1. Case studies
2. Deterioration mechanisms hypothesis

3.1.1 Task 1.1 Case Studies

In the *TEAM Project Contract Annex A*, the following milestones and deliverables were defined for Work Package (WP) 1 - Task 1.1:

- A procedure for inspection of Buildings.
- Summary report from Case Studies / Buildings, including selection of potential Buildings for WP 2 and WP 3.
- Selection of potential Buildings for WP 2 and WP 3.
- Summary Report on Case Studies.

The following forms and guidelines have been developed

- Field Method for Investigation of Bowing of Natural Stone Slabs for Cladding [1]
- Form 1.1.1 - Pre Investigation Report [2]
- Method Statement – How to approach Building Projects with damaged facades [3]

In addition a database (ORACLE 7.3) has been developed and used for compilation of all data from investigated buildings.

A total of 194 Building Projects have been identified and reported on various detailing levels (table 1.1). Among them, 26 Buildings have been selected for further investigation (table 1.2).

- All of the 26 Buildings were considered as suitable for dismounting of facade panels for laboratory testing purposes. Involved partners have tried to get samples dismounted from the buildings for laboratory testing purposes.
- 6 Buildings were selected for detailed field studies, measurements of bowing and supplementary investigations and reports under WP 2 (table 1.2).
- 2 Buildings were selected for long term monitoring under WP 3 (table 1.3).

We have concluded that the phenomenon of bowing of marble is actually rather common (figure 1.1). Deformation by bowing is experienced in buildings of various ages, in buildings exposed to various weather conditions and for slabs of various thickness and dimensions and with different anchoring methods. Finally, and what is most interesting, bowing is registered for marble of seemingly very various composition and structure.

Based on our studies we can state that bowing has developed in many more stone varieties than previously reported in the literature. This has given us an important clue for the further investigations in the TEAM project.

We have not – as far as investigations in WP 1 is concerned - identified any "artificial means", used on the market, for preventing, stopping, hindering or delaying the effects of long term deformation through bowing and subsequent loss of strength. When saying "artificial means" we refer to choice of stone slabs thickness or dimensions, choice of method for application (open/closed joints, type of anchoring system, ventilated air slot etc), differences in climatic regions, applications height over the ground or to various directions of the compass.

Figure 1.1. Yellow boxes mark cities with observations of marble clad buildings (good and poor). The figure also shows the geographical spread of the problem.

Related to the climate regions/zones it is reasonable also to discuss the effects of different locations of stone facade slabs on the building itself – height over the ground and directions of the compass. As for these parameters, our studies are in accordance with the literature:

- most pronounced bowing at the upper parts of the buildings and
- most pronounced bowing on the building sides facing southeast and southwest. Pronounced bowing also at facades facing south. The claddings facing to the north show less bowing tendencies.

This implies that it is the facades receiving the most sunlight that exhibit the highest percentage of bowing panels and the largest amplitudes.

- Further conclusions from WP 1 observations are:
- The bowing seems to be related to some types of marble and marble/limestone while other stone types (travertine, slate, granite, sandstone etc) do not demonstrate this problem.
- Both concave and convex bowing ca occur on the same facade with the same marble (figure 1.2)

- There is a clear correlation between bowing behaviour and deterioration leading to loss of strength (figure 1.3).
- It cannot be stated that non-bowing stone slabs are not deteriorating and loosing strength (e.g. mortised facade slabs seem to be hindered from bowing but might still deteriorate)
- There are quite a few different types of marble (with different origin related to quarry areas) that demonstrate the bowing behaviour.
- Marble types or selections from same quarry area or even same quarry can demonstrate bowing as well as non-bowing behaviour.
- Damages and problems of other kind than bowing and deterioration have been registered and noted but not further discussed within the TEAM programme.
- Marble types with known or measured bowing problems and marked strength loss should be avoided in thin building claddings.

Based on the WP1 observations it is also possible to conclude that revisions in e.g.:

- Application system (fixing methods)
- Thickness of stone slabs
- Panel face dimensions
- Placement on the building

may not totally hinder or reduce the deterioration in such marbles.

Table 1.1. Registered Buildings (REGBU) grouped by country location and divided in "With Bowing Slabs" and “With Non-Bowing Slabs.

Country	**TOTAL REGBU**		**Bowing registration acc WP 1 table**					
			Bowing		**Non-Bowing**		**No Record**	
	Quant	**%**	**Quant**	**%**	**Quant**	**%**	**Quant**	**%**
Denmark	37	19	4	11	28	76	5	
Sweden	31	16	13	42	18	58	0	
Austria	13	7	4	31	8	62	1	
Germany	18	9	9	50	8	44	1	
Norway	17	9	1		16		0	
Portugal	9	5	0		9		0	
Slovenia	11	6	5		6		0	
Greece	7	<4	0		6		1	
Italy	8	<4	3		4		1	
Belgium	6	<4	0		0		6	
Finland	5	<4	4		0		1	
France	5	<4	3		1		1	
Spain	6	<4	4		2		0	
Croatia	3	<4	1		2		0	
Poland	7	<4	2		5		0	
UK	3	<4	1		2		0	
Switzerland	2	<4	0		0		2	
Estonia	1	<4	0		1		0	
USA	4	<4	3		1		0	
Holland	1	<4	1		0		0	
Total Sum	**194**		**58**		**117**		**19**	

Table 1.2. Overview of buildings where a more detailed investigation has been performed within WP 1.1.

	NO	Building	Resp. Partner	Bow	Rock type / Responsible Partner for Collecting Samples
1	SE 02	Malmö, City Hall	JAC	No	Carrara Marble (IT) / JAC
2	SE 03	Gothenburg, School of commerce	JAC	No	Vratza Limestone (BG) / JAC
3	SE 06A	Stockholm, Polstjärnan	JAC	Yes	Bianco Carrara (IT) / JAC
4	SE 07	Västervik, Folkets Hus	JAC	Yes	Bianco Carrara (IT) / JAC
5	SE 14	Borås, City Hall	SP	No	Biacno Carrara (IT)/ SP
6	DK 01	Copenhagen, Realkredit	RMB	Yes	Hove / Porsgrunn (NO) / RMB
7	DK 03	Lyngby, Town Hall	RMB	No	Marmorilik (Greenland) / RMB
8	DK 07	Århus, City Hall	RMB	No	Hove / Porsgrunn (NO) / STF
9	NO 01	Oslo, Dokk-bygget	STF	No	Vencac Beli (YU) / IMM
10	NO 03	Trondheim, Televerket	STF	No	Hove / Porsgrunn (NO) / STF
11	NO 05C	Bergen, Berstadbygget	STF	No	Tjøtta (NO) / STF + IMM
12	NO 06	Stavanger, Svanapoteket	STF	No	Porsgrunn (NO) / STF
13	NO 07	Tromsø, Unibygget	STF	No	Norwegian Rose (NO) / STF
14	NO 09	Oslo, Sparebank-1-group	STF	No	Porsgrunn (NO) / STF
15	NO 15	Trondheim, Gamle Skillingsbank	STF	Yes	Bianco Carrara (IT) / STF
16	SF 02	Kouvola Town Hall	SP	Yes	Bianco Carrara (IT) / SP
17	DE 05	Kiel, Bordesholmer Spk	UGE	Yes	Verde Viana (PT) / UGE, JAC
18	IT 01	Torino, Telecom Building	PTO	No	Lasa, Ornovasso (IT) / PTO
19	IT 02	Milano, Gemini Centre	PTO	Yes	Bianco Carrara (IT) / IMM
20	IT 06	Verona, Mazzi Tower	PTO	No	Bianco Carrara (IT) / IMM

Table 1.3. Overview of buildings selected for detailed assessment within WP 2.

	No	Building	Resp. Partner	Bow	Rock type	WP
1	SE 01	Nyköping, City Hall	JAC	Yes	Bianco Carrara (IT)	2 + 3
2	DK 02	Copenhagen, Danish Nat. Bank	RMB	Yes	Porsgrunn (NO)	2
3	DE 01	Lünen, Hospital	UGE	Yes	Trigaches (PT)	2
4	DE 03	Göttingen, University Library	UGE	Yes	Bianco Carrara (IT)	2 + 3
5	DE 04	Göttingen, University Juridicum	UGE	Yes	Peccia (CH)	2
6	IT 07	Magenta Hospital	PTO	Yes	Bianco Carrara (IT)	2

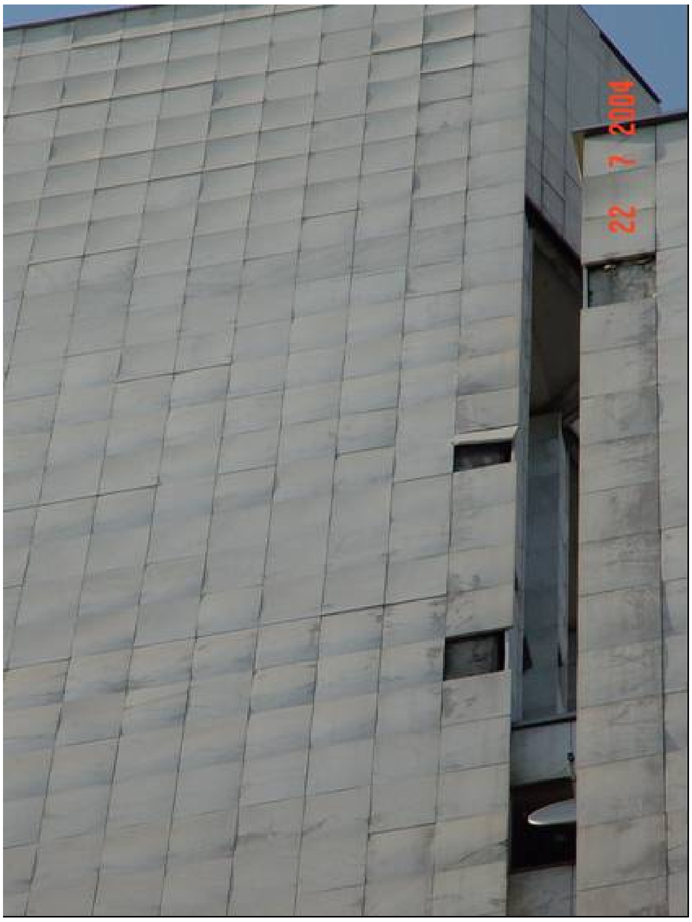


Figure 1.2. A building in Zagreb, Croatia have concave bowing at higher levels of the building and convex at lower levels at same facade elevations.

Figure 1.3. Severe strength loss associated with bowing.

3.1.2 Task 1.2 Deterioration mechanisms hypothesis

3.1.2.1 Objectives

Preparing a state-of-the-art report based on the latest documentation available and new interpretations and including the identification of:

1. Marble and limestone types with potential risk of bowing.
2. Deterioration mechanisms.
3. Critical environmental conditions.

The different deterioration mechanism hypothesis shall be listed. The parameters relevant for performing an adequate inspection shall be pointed out. Based on the results from task 1.1, previous inspections reports and other relevant literature marble and/or limestone types with potential risk of bowing shall be identified. Critical environmental conditions for the deterioration mechanism shall be described and updated State-of-the-art Report shall be produced.

3.1.2.2 Introduction

Durability of natural stone can be regarded as a measure of its ability to resist decay, i.e. to maintain its essential and distinctive characteristics of strength and appearance. Durability may be viewed as the period of time that a stone can maintain its innate characteristics in use. This period varies with the environment and use, and with the properties of the stone itself. Durability and deterioration are functions of the intrinsic properties of the rock and the external environment that are active throughout the lifetime of the natural stone. In order to understand why some marble types bow and loose their strength when used as thin claddings in buildings, what reactions that occur between the material and the exterior and how the decay starts and proceeds, it is necessary to extract information from the literature related to the different influencing factors. The factors identified include:

- Features of the raw material (mineralogy, fabric/texture, pore properties, hydric and thermal behaviour etc.).
- Weather and microclimate.
- Construction specific factors.

3.1.2.3 Findings and discussion

It is surprising that, despite several laboratory reports of severe loss of strength, not more field investigations have been made on this topic. However, investigations have been reported by Garzonio et al. (1995), Stocksiefen (1996), Jornet (2000), Hook (1994), Wonneberger (1999) and Mustonen (1993).

Case studies made by TEAM also show large strength loss as shown in figure 1.4; in the order of 80 % after 35 years for one calcitic marble and 40 % for one dolomitic marble. Laboratory studies performed by the authors (Schouenborg et al. 2000 and TEAM, 2001b) clearly indicate that there is no correlation between the amount of bowing and the loss of strength. This is especially worrying since there is a potential risk of severe strength loss without any evident bowing of claddings.

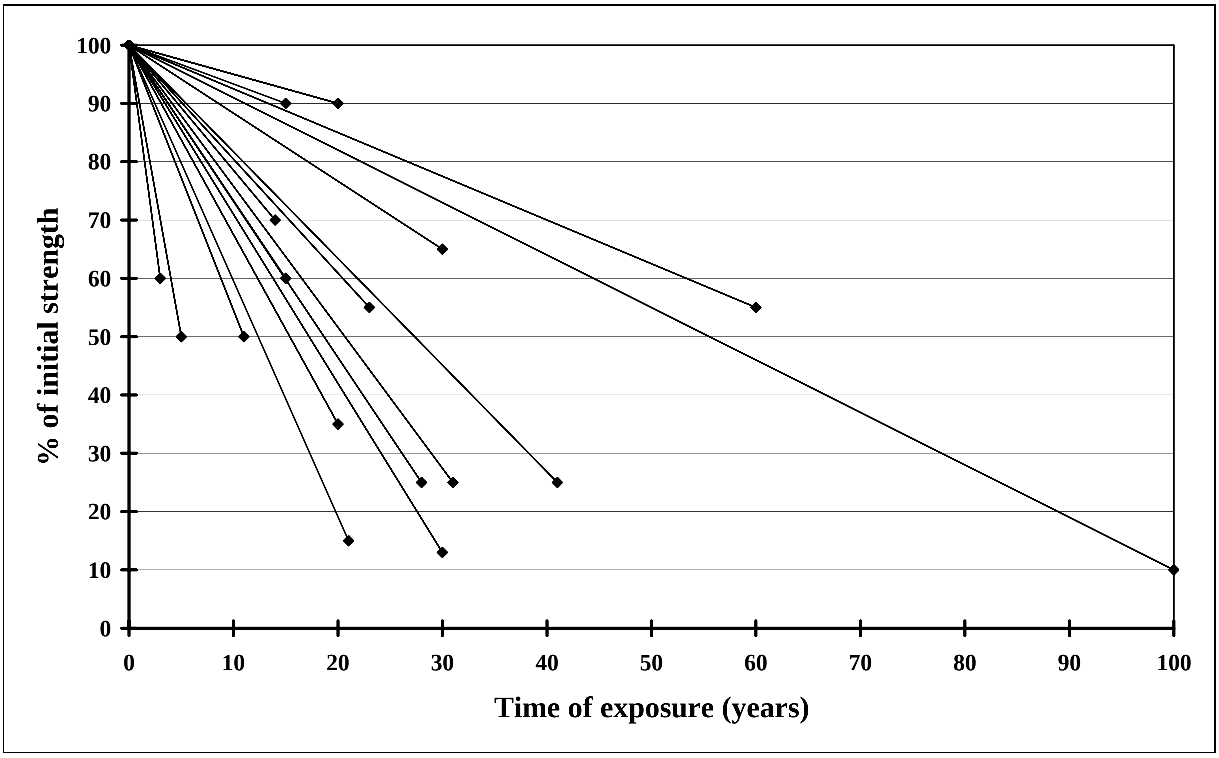


Figure 1.4. The relative loss of flexural strength of marble panels exposed to outside climates.

Several hypotheses have been proposed for the observed bowing of marble. Many of them are contradictory and none fully explains all the different observations and investigations made by the authors sited in this literature review. Nevertheless, three different directions may be pointed out:

- Anisotropic thermal expansion of calcite and dolomite.
- Influence of moisture (and possibly free water) and temperature variations.
- Release of locked-in rock stresses.

Erlin (1989, 1999) presents the following 8 steps, which leads to the problems with bowing of marble panels:

- *"Thermal expansion of the surface region occurs during high local temperatures.*
- *Individual calcite crystals expand in direction of the "c" axis and shorten in the direction of the "a" axes.*
- *Calcite crystals, orientated at non-parallel angles to adjacent calcite crystals, "butt" into the "side" of adjacent.*
- *The contact created forces the dislocation (a phenomenon known as twinning) of the crystals so that the displaced portion extends into the "space" created by the "a" axis shortening.*
- *Shortening of the surface region occurs because of a temperature drop.*
- *The disturbed calcite crystals restrict full return of crystals to their exact original positions.*
- *A volume increase (expansion) occurs in the affected surface region.*

- *Cyclic heating is more dominant on the exposed surface regions than toward the backs of the panels. Thus there is a volume increase of the face and restraint to that increase by the rest of the stone. The result is a dished surface.*

This hypothesis is however not in agreement with the observation on original cladding of the Finlandia Hall where the non-exposed surfaces were found to be expanding.

Another hypothesis has been put forward by Winkler (1994). According to Winkler (1994) the reason for the bowing of marble slabs appears to be a combination of processes that occur in the following sequence:

- *"Dissolution triggers micro cracking, followed by dilation from the relief of internal stresses. Without dissolution the processes of dilation and decay would probably not occur.*
- *Diurnal thermal expansion-contraction cycles continue to dilate the stone, leading to expansion, bowing, and loss of strength.*
- *Moisture from rain and relative humidity quickly fills pore spaces. Moisture expansion in heating-cooling cycles dilates the stone further. Bowing of stone panels is normally not observed in desert areas."*

Taking Winkler's last point one step further it appears that all porous materials have the potential for "moisture expansion" in heating/cooling cycles. If sufficient pressure is generated due to thermal expansion of water during heating, all materials will dilate. If wet marble/limestone is heated it will dilate unless water can escape quickly enough to avoid pressure generation due to thermal expansion. This theory is in agreement with Svenson (1942).

A third hypothesis has been proposed by Garzonio (1995), which includes the following parameters:

- *Built-in strain.*
- *Chemical and physical weathering.*
- *Relaxation and creep stress caused by the weight of material itself.*
- *How the material was laid.*
- *Stress history (applied over a long period of time).*
- *Tectonic-metamorphic processes release of locked-in residual stresses.*

However none of the above mentioned hypothesis could explain all the observations. For example none of the proposed hypotheses explain the apparently beneficial effect of dolomite content. The "stress history" can be similar for a dolomitic and a calcitic marble but the tendency for bowing totally different. The problem is that there is no systematic investigation of rock's stress magnitude and directions related to the problem of bowing and loss of strength.

3.1.2.4 Conclusions

Despite the amount of literature available, neither the key influencing factors nor the mechanisms of the observed deterioration are clear. Several explanations and hypotheses have been proposed but as yet none explains all the observations in practice. Concerning the loss of strength it can be concluded that most previous studies have been made on laboratory samples. However these and observations from buildings (including TEAM) confirm the seriousness of the situation in that many claddings panels can loose much of their strength during exposure, regardless of whether they show bowing or not.

As for **intrinsic material parameters**, most authors suggest that fine grained, calcitic marble with straight grain boundaries are the carbonate rocks most sensitive to this type of durability problem. The most important parameters as regards the type of marble appear then to be composition, grain size and grain interlocking. However, the number of different marble types investigated by each author is generally very limited and therefore the conclusions concerning the influence of composition can be incoherent. There is also a lack of agreement concerning the optimum grain size. A related problem is that the description of grain size is generally done with one figure, which gives a poor picture of the grain size distribution of the stone. The inconsistency of micro-structure description also makes it very difficult to interpret the influence of that parameter. Thus, there is a great need to quantify the micro-structure parameters and to investigate a larger number of marble varieties.

As for **environmental parameters**, both temperature variations and moisture are clearly involved. Moisture has only recently been acknowledged as a key factor. The interaction of temperature and moisture is believed to be a crucial external factor for the bowing and strength loss of certain marble types. This is in accordance with both laboratory and field investigations performed so far within the TEAM project. However, while the moisture in laboratory specimens can be controlled and define, the moisture contents and gradients in the construction have not been given much attention in the literature.

As for **processing and construction specific parameters**, the investigated literature does not make it possible to conclude about the potential relevance of anchoring system, joint widths, panel dimension etc.

The risk and rate of degradation of marble cladding increases with:

- Increasing temperature and moisture variations and gradients
- Increasing idioblastic microstructure

Since it is nearly impossible to restrict the temperature and moisture variations for claddings, the proper choice of marble type becomes very important. In this respect it appears to be highly desirable to develop a reliable and conclusive laboratory test method for investigation of bowing and strength loss sensitivity of carbonate rocks. The need for a reliable test method can best be illustrated by the fact, that the new marble cladding on Finlandia City Hall started to bow significantly (figure 1.5) less than one year after replacement in 1999.

Figure 1.5. Finlandia City Hall, Helsinki. The new marble cladding clearly bowed in less than 1 year after the old marble cladding had been replaced. The photo was taken in spring 2001. NB: Almost all of the old panels were bowing concave, however the new panels bow convex! In both cases the marble type was a Carrara marble (Bianco Carrara).

Monitoring especially focusing on the influence of the microclimate has been performed (see WP 3). Studies will also be made on building physics, i.e. ventilation and insulation, in order to investigate whether it is possible to control the microclimate around the cladding.

It is important to note that the problem of bowing is not restricted to one type of marble or one climatic zone. The excerpt given below from the published summary of the first years result in TEAM on this topic states: "In order to gather information and to map the extent of the problem, about 140 buildings have been selected for classification and/or investigations. The buildings are situated in Northern, Central and Southern Europe, and there are buildings with bowed slabs in all countries (Austria, Belgium, Denmark, Finland, France, Germany, Greece, Italy, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and United Kingdom) (figure 1.6). Many of the buildings with problems have been visited and a preliminary investigation has been conducted. During these investigations several different marble types from Greece, Italy, Portugal, Spain, Norway and USA have been identified showing durability problems in terms of bowing."

It is also equally important to draw the attention to the fact that many marble and limestone claddings and pavements tend to be durable and robust, provided that the correct quality has been use (e.g. as seen in figure 1.7).

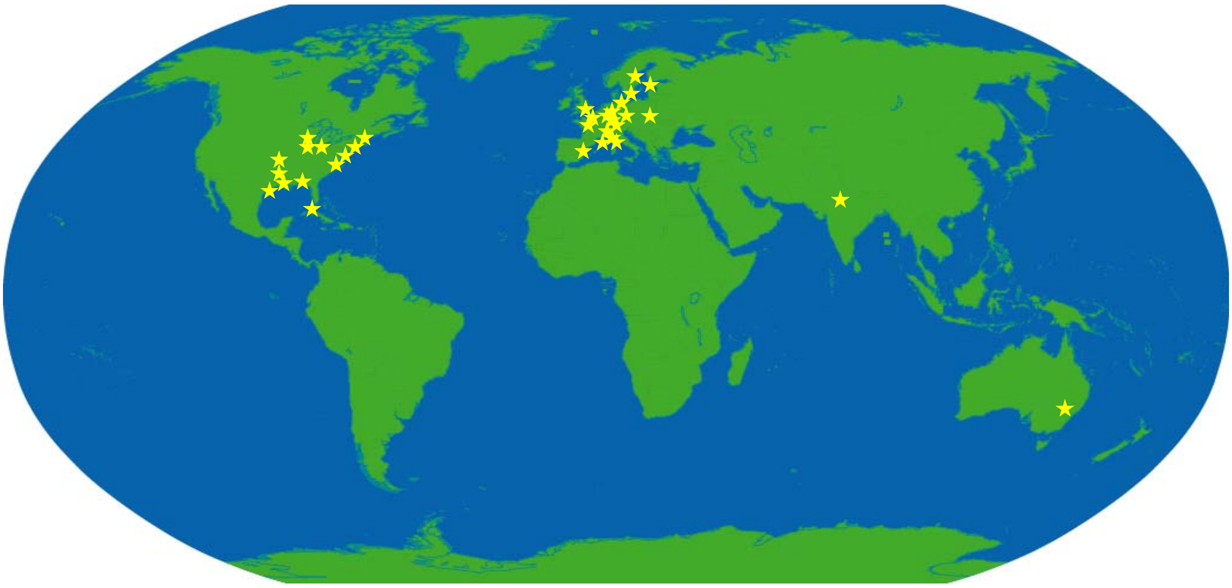


Figure 1.6. Geographical distribution of marble bowing registered by TEAM partners.

Figure 1.7. The Malmö Stadshuset (City hall), S. Sweden; An example of a 30 year old marble facade with no signs of deterioration or damages.

3.2 WP 2 Assessment of facades

The work package is divided into the following six tasks:

1. Equipment for field measurement of bowing
2. Inspection of selected Buildings from WP 1
3. Strength Tests
4. Risk Analysis
5. Preparation of Samples
6. Anchoring System

The main objectives are to: Develop a method and equipment for measuring in-situ bowing and expansion of building facades with marble and limestone claddings. Define an inspection procedure and model for calculation of the safety risk for a facade with marble and limestone cladding in relation to bowing, reduced strength and anchoring system. Give specific input to all the involved building owners.

3.2.1 Task 2.1 Equipment for field measurement of bowing

3.2.1.1 Objectives

The objective was to establish a technique and develop a suitable field instrument, a measuring bridge with a measuring accuracy adequate to measure small continuous changes from year to year, for in-situ measurement of bowing of building facades.

A bow-meter was developed and tested for precision (mainly reproducibility). The equipment includes a digital vernier calliper (figure 2.1), readable to 0,01 mm and that can be connected to a computer for more efficient recording of measurements on building with very high number of panels.

The reproducibility was measured to better than 0,2 mm. The coefficient of variation is better than 0,8 %. The equipment is included in the method for in situ investigation of facades [4].

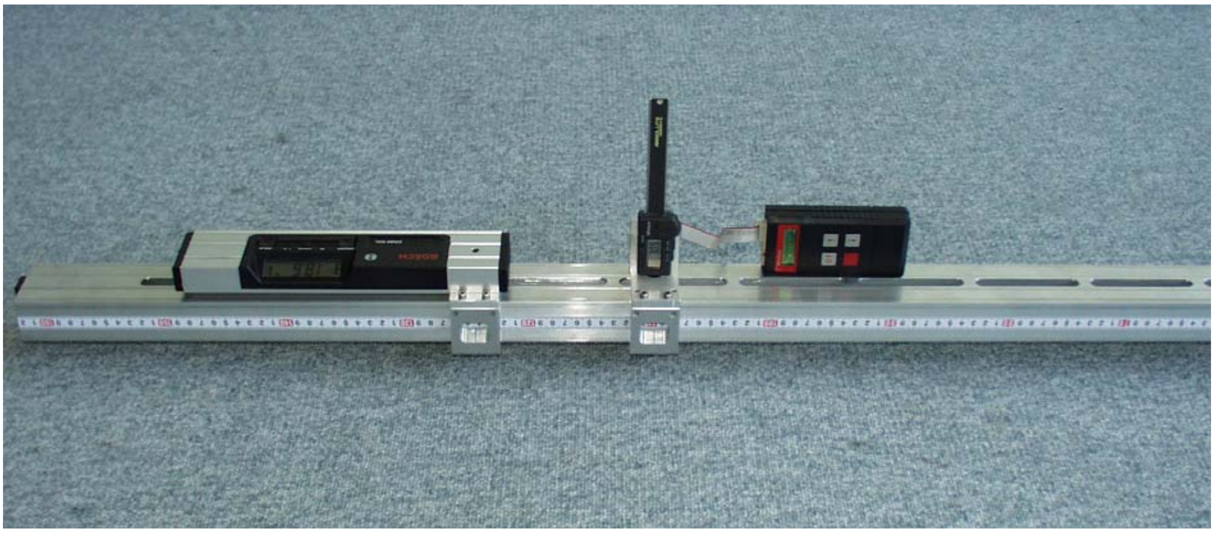


Figure 2.1. The "Bow-meter" has been produced by gluing 3 aluminium profiles together to increase the strength and decrease the weight.

It is always crucial to measure the magnitude of the bow versus a flat reference surface. Since is not always possible to find a flat surface, a zero-set device was developed (figure 2.2).

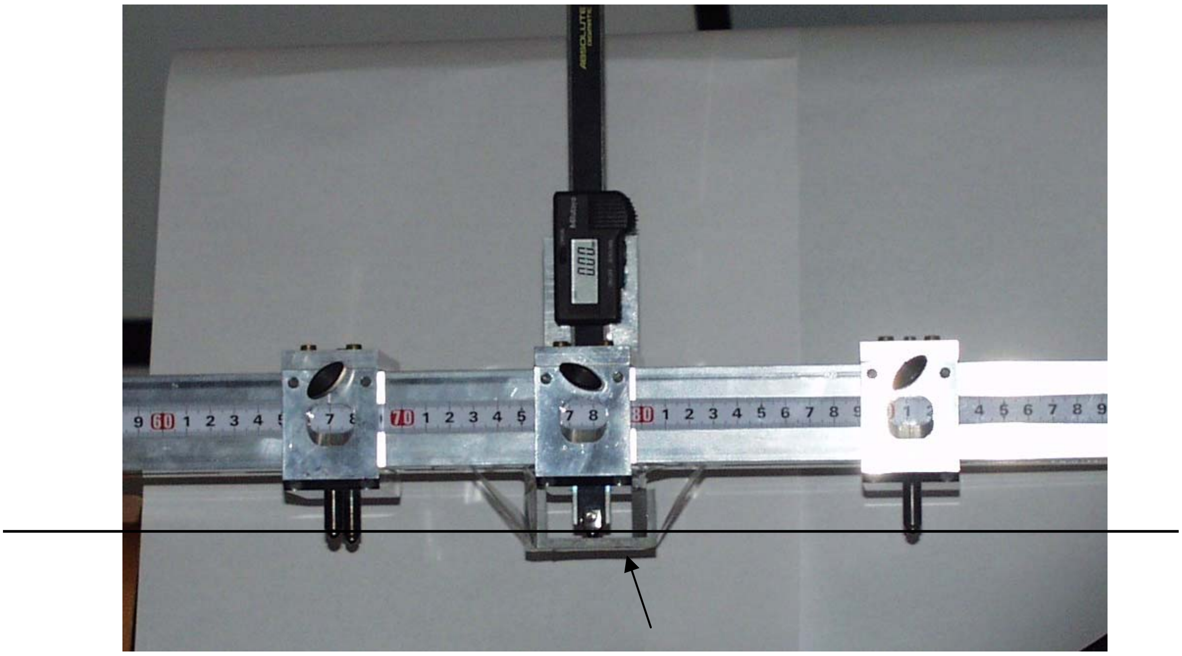


Figure 2.2. Precision gauge block for zero-setting of the Bow-meter, equivalent to a reference plane.

3.2.2 Task 2.2 Inspection of selected Buildings from WP 1

3.2.2.1 Objectives

A detailed inspection of 6 selected buildings from WP 1 has been planned to be carried out. The task includes documentation of the amount of bowing using the measuring device from Task 2.1, selection of samples of slabs, reports on the anchoring systems, and a more detailed description of any damage effects and signs of deterioration. An increased number of cladding panels has been measured in detail, compared to WP 1, to ensure a statistically sound basis for assessment of the risk analysis.

3.2.2.2 Introduction

A number of buildings with marble cladding has been reported to have deterioration problems with bowing and expansion of the panels, leading to loss of strength, cracking and break-outs of fixing systems and thus to potential safety problems with a risk of panels falling from the facade.

A part of the TEAM project has therefore dealt with the detailed inspection and assessment of the buildings. A total of 6 buildings with bowing facades have therefore been subjected to a detailed inspection and assessment as test cases in order to design suitable inspection and assessment procedures.

Based on the investigations on the 6 selected buildings it is possible to point out some valuable inspection methods and results for each of the objectives. The observations (table 2.1) and the conclusions which are relevant for the inspection and assessment of the bowing and expansion phenomena are presented in the following sections. The inspection results are in this report not compared to the later results of the laboratory testing of the sampled panels, but are discussed in other reports.

3.2.2.3 Age of the panels

Bowing and expansion will increase with the age of the panels, and it is preliminarily assumed that these will develop, proportionally to the exposure time. The inspected buildings and the literature show that already after a few years of exposure (< 5-10 years), bowing and deterioration may occur in panels.

Knowledge gathered from the buildings outside the TEAM project supports actually the assumptions that bowing (and strength loss) is linear correlated with the age and time of exposure. However, the observed rate of development varies from one panel to another, even in the same building. This rate can to some extend be determined by measuring bowing and joint width for a larger number of panels.

Repeated measurements of e.g. joint width or bowing will over a longer time provide documentation for the expansion rate in the actual building. This may be obtained by permanent, long-term monitoring or by repeated inspection with 2-5 years intervals using bow meter. The concept of measuring the joint widths for a range of panels with 2-5 years interval was tried at the Danish National Bank in 2001 and 2004 where the additional 3 years exposure corresponded to 10-15 % increase of the exposure time, but this indicated no decrease of the joint width over this period.

3.2.2.4 Panel dimensions

Bowing is observed for all panel dimensions (largest dimension ranges from 900 to 2000 mm) and all thickness ranging from 30 to 60 mm. In the literature some scientist mentioned an optimal thickness due to bowing but so far it has not been possible to verify this during the inspections.

The inspections and the literature shows clearly that larger panel dimension (width and height) will increase the bowing, since the bowing amplitude (U) is correlated with the length (width) (l) and the thickness (t) of a panel. The physical equation should be obtained:
$U = \Delta\varepsilon\ l^2 / 8\ t$, where $\Delta\varepsilon$ is the difference in strain from the front to the rear side of the panel.

The loss of strength of smaller panels may therefore be equally severe, even if the smaller panels show smaller visible bowing amplitude, just as expanding panel with no visible bowing may loose strength.

The bowing and expansion ultimately lead to increased forces at the fixing points or lines and the dimensions can therefore often influence the resulting forces, which need to be transferred and thus to the increased risk of failures.

Table 2.1. Summary of information on assessed buildings.

Objective	DE 01 St. Marien Hospital Lünen	DE 03 University Library Göttingen	DE 04 University Theologicum Göttingen	DK 02 Danish National Bank	SE 01 Nyköping City Hall	SE 03 Malmö Stadshus
Construction year Age of panels	(A) 1967/70 - 35 years (B) 1980/83 - 22 years	1991 11 years	1966 36 years	1972/1978 30 / 24 years	1968-69 34 years	1974 - 19 years
Stone type	(A) Ruivina (Calcitic) (B) Trigaches (Dolomitic)	Bianco Carrara (Calcitic)	Peccia Virgino (Calcitic)	Porsgrunn (Calcitic-silisic)	Bianco Carrara (Calcitic)	Bianco Carrara (Calcitic)
Façade Orientation - Points of the Compass	W (A) / W (B) / S (B) / E (B)	N / E / S / W	N / E / S / W	W / NNW / S / ENE	NNW / ENE / SSE / WSW	
Panel Dimensions l x h x t (mm)	450 x 925 x 30 (A) 450 x 925 x 30 (B) 600 x 925 x 30 (B)	1045 x 740 x 40 1520 x 740 x50 (roof level)	670 x 1280 x 30	1393 x 833 x 30	930 x 910 x 30 120 x 1150 x 60 400-900 x 1100 x 30 900 x 300 x 30	976 x 652 x 30
Height above Ground	16 – 32 m (A) 9.3 – 38 m (B).	0.6 – 14.2 m.	0.6 – 12.8 m.	1.4 - 3.1 m.	4-15 m	
Fixing Systems	Dowel anchors in the vertical and the horizontal joints	Dowel anchors in the vertical and the horizontal joints	Continuous rail in a notch in the bottom and a ledge in the top	Dowel anchors in the vertical joints	Dowel anchors in the vertical and the horizontal joints	Dowel anchors in vertical joints and rails at the bottom
Cladding Design	20 mm gap on the rear side, not ventilated. Sealed joints.	Ventilated on the rear side (50 mm gap). Open joints.	Ventilated on the rear side (10-20 mm gap). Open joints.	Ventilated on the rear side (20 mm gap). Sealed joints.	10-20 mm gap on the rear side, not ventilated. Sealed joints	Ventilated on the rear side. Sealed joints.
Climate	Max. average in July: 19 °C. Min. average in Jan: 0 °C. Average rainfall: 750 mm per year	Max. average in July: 17 °C Min. average in Jan: 0 °C Average rainfall: 700 mm per year	Max. average in July: 17 °C Min. average in Jan: 0 °C Average rainfall: 700 mm per year	Max. average in July: 20.4 °C Min. average in Feb: -7.1 °C Average rainfall: 613 mm per year	Max. average in July: 30 °C Min. average in Jan: -20 °C	
Designed Width of Joints	8 mm	8 mm	5 mm	7 mm	8 mm	8 mm
Extent of the Problem	Bowing on all facades, mostly concave. Amplitudes up to 2.5 mm/m (A) and 10 mm/m (B). Cracks and breakouts on S- and W-facades. Joint width has decreased down to 4-6mm	Convex bowing up to 8 mm/m observed. Joint width has decreased.	Bowing on all facades, amplitudes up to 12 mm/m. Both concave and convex bowing are observed. Cracks and breakouts are observed. Joint width has decreased down to 0-4 mm	Bowing on all facades, amplitudes up to 8 mm/m on the south façade. Both concave and convex bowing are observed. Joint width has decreased down to 4-6 mm. Cracks are observed on the south facade	Bowing on all facades, amplitudes up to 23 mm/m on the WSW-façade. Both concave and convex bowing are observed. Joint width has decreased down to 4-6 mm.	Maximum observed bowing is 3.5 mm/m
Fabric / Orientation of Foliation	Not observed	Not observed	It is observed that this has influence on the bowing amplitudes.	Not observed	Not observed	Not observed

3.2.2.5 Facade orientation

The bowing observations indicated significant differences in the bowing amplitudes depending on the facade orientation (figure 2.3). It appears from the investigations that the bowing phenomenon is less significant to facades not or less exposed to temperature differences during a day.

It is experienced that the largest bowing amplitudes are usually not found on the north facades, because these are not exposed to large temperature cycles during a day.

For several buildings or part of these more pronounced bowing was observed on the east or west facades than on the south facades. A reason for that could be that a low sun angle might course larger temperature variations during a day than a high continuous sun angle. That might have influence on the bowing behaviour between different facade orientations on a certain building. Besides this, it is a fact that the sun angle varies from north / south to the equatorial zone, and that might give some explanation why bowing behaviour differs between different zones.

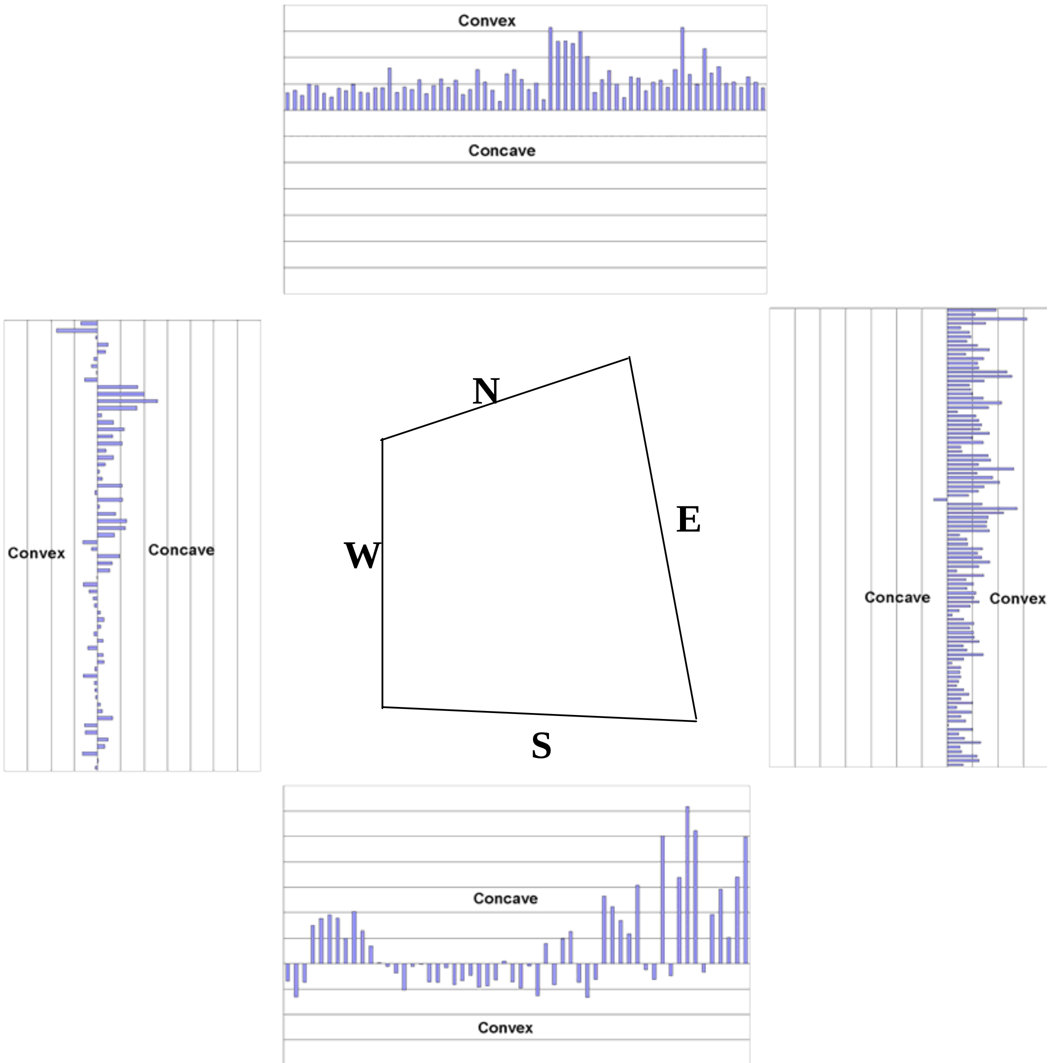


Figure 2.3. Bow measurements at Danish National Bank in 2001, 2nd row from the ground. Scale for bowing is in steps of 1 mm/m.

3.2.2.6 Height above the ground

For the buildings in Göttingen (see figure 2.4) and the building in Nyköping it is observed that the bowing phenomenon increases with the height above ground. This may be explained as the exposure and the variation of the climate (wind, humidity, temperature) increases with the height above ground.

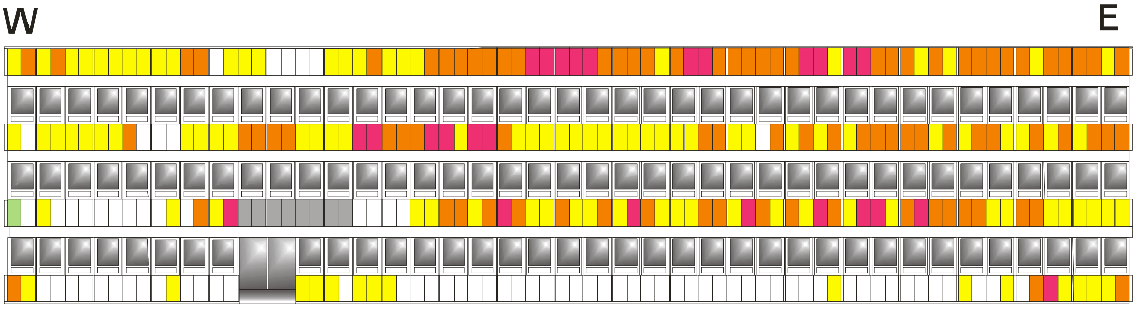


Figure 2.4. Building map of the southern facade of the Theologicum Building (true to scale). Different colours represent panels with different bowing amplitudes (colour code see figure 2.5)

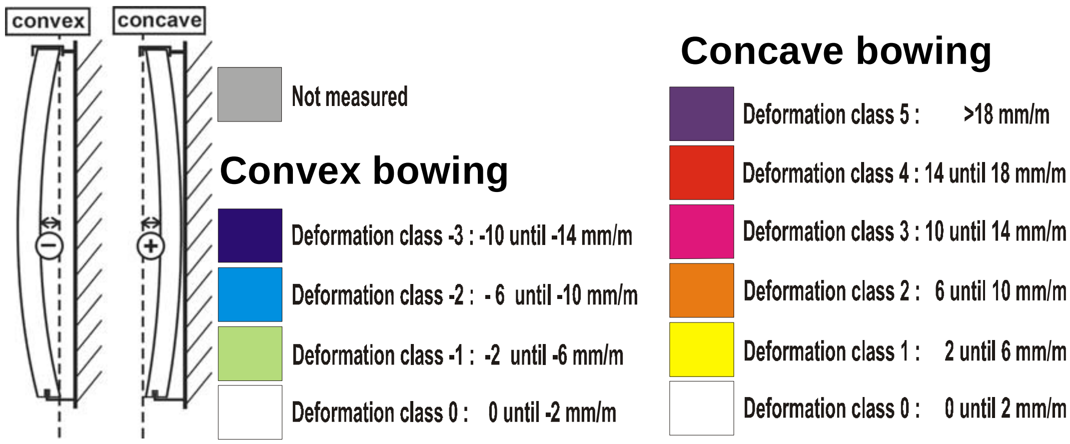


Figure 2.5. Definition of bowing value, deformation classes and colour codes.

3.2.2.7 Climatic conditions

From most of the investigated buildings it is observed that the absolute temperature and the temperature variations seem to be very important factors for bowing to occur. The higher the temperature variations the higher the degree of bowing will be. Varying temperature gradients through the panel thickness may have an influence on bowing, but this has not been verified by the inspections.

On the Danish National Bank and other structures larger temperature variations were measured on the front side than on the rear side, since the back side is sheltered from direct rain and sun exposure. This may have influence on the degree of bowing and also the bowing direction, but the influence can not be verified by the observations so far. The humidity might also be an important factor due to bowing, but based on the building investigations it is not possible to draw any conclusion. However, it is observed in the laboratory that bowing only occurs when free water is available. A dry screening test results in expansion only and no bowing.

3.2.2.8 Fixing/anchoring systems

Bowing, concave and convex as well, is observed for all fixing systems represented in the investigated buildings. Based on the investigations no specific fixing system can be pointed out as being more (or less) suitable to prevent bowing, expansion or the development of damages.

The type of fixing system, influences the bowing shape at a late stage of the bowing (sever bowing) and the type influences significantly the type of cracking and spalling observed in the buildings.

3.2.2.9 Cracks and breakouts

Cracks and stone damages are observed near the supporting dowel anchors or kerfs. An increase in bowing is correlated with an increase in the relative frequency of damages e.g. cracks and breakouts (figures 2.6, 2.7 and 2.8).

Figure 2.6. Typical crack out of fixing pins at Göttingen university library.

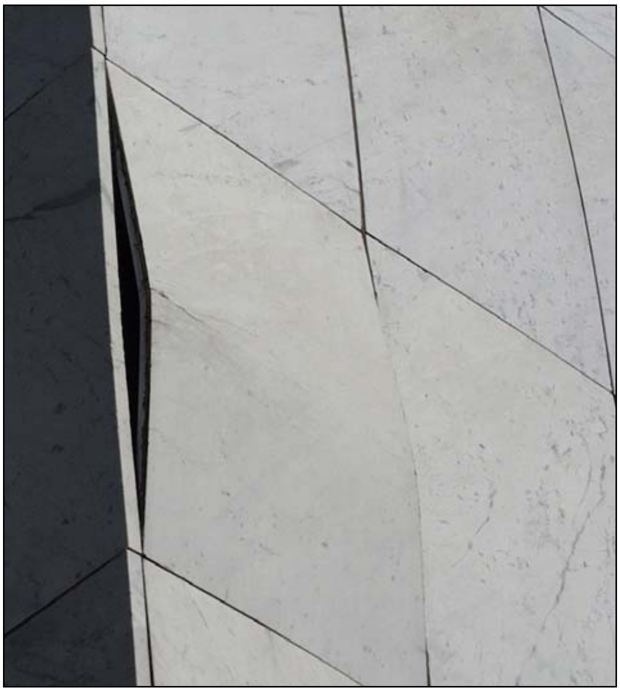


Figure 2.7. Panel fixed by fixing pins at top and bottom, cracked by bowing.

Figure 2.8. Cracking at corner, typical for panel anchored by rail at Theologicum.

3.2.2.10 Cladding design

Bowing, concave and convex as well, is observed for all cladding design represented in the investigated buildings. Based on the investigations no specific conclusion can be drawn.

3.2.2.11 Open or closed joints

The use of open joints may lead to larger variation in the environment behind the panel, in contact to the design with closed joint, where the air behind the panels may be sealed in and isolated from the outdoors. No effect of this has been verified by the inspections, however, facade claddings with elastic sealant in the joint will often reveal if an expansion has taken place (see figure 2.9).

3.2.2.12 Width of the joints

For most of the buildings it is observed that the average widths of joints are below the design width. If a panel is strained when free movement in the joints is not allowed, normal forces will occur in the panel or it may lead to a pushing aside of the neighbouring panels. The restraining may cause the shape of the bowing panel to change, e.g. to bowing predominantly in one direction and with damages typical near the fixings.

On Danish National Bank the investigations indicate a linear correlation between the absolute bowing amplitude and the mean value of the joint width. The smallest joint width is found where the bowing is strongest. It is assumed that this is a fact for all investigated buildings.

Figure 2.9. Elastic joint between expanded panels. Notice the squeezed out elastic sealant.

3.2.2.13 Fabric/orientation of foliation

On most of the investigated buildings the orientation of foliation could not be observed but on one building (Oeconomicum in Göttingen) it was possible to investigate that the cutting direction, with respect to the metamorphic layering, foliation or macroscopic folds had influence on the bowing amplitudes and shapes.

3.2.2.14 Convex or concave bowing

It has not been possible to explain why panels are bowing in the concave or convex shape on a building.

One theory was that panels exposed in the same way for example on a part of certain facade would bow in the same direction, but it has repeatedly been observed that some few panels bow opposite than the rest. It has in addition to this been observed that new fresh panels mounted instead of demounted panels are bowing opposite the demounted panels.

3.2.2.15 Surface finishing and treatment

After the assessments it has been discussed whether the surface finishing and/or the cutting processes may influence the bowing and the start conditions in the beginning of a panel's lifetime. Possible surface finishing could be mechanical (rough, smooth or honed) or treatments like chemical (impregnation, soap etc.) and the cutting process could be more or less "rough".

No conclusion concerning finishing could be reached based on the results from the 6 building inspections.

3.2.2.16 Sampling and strength tests

The visual inspection and the measurements of bowing and joint widths provided a good overview of the conditions. However, the detailed assessments clearly showed that the effects of the bowing and expansion could only be determined by taking samples form the exposed and deformed panels in combination with "fresh panels". This should normally include:

- One panel, from the most exposed part of the structure, where most bowing has been observed.
- One panel, from a moderately exposed are, where the panels bow moderately.
- One panel, from the least exposed part of the structure, where no or almost no bowing has been observed. This panel shall preferably be taken from the reserve panels (a building owner will often have a reserve of panels intended for replacement of cracked panels and such panels have never been exposed to the environment).

These panels are normally used for determining the actual loss of strength and for carrying out laboratory testing for bowing and expansion and additional strength test, so the observed bowing can be roughly correlated to strength loss.

3.2.2.17 Short conclusion

The 6 detailed assessments have provided a lot of general knowledge of the deterioration. Most important is the establishment of a basis for the development of inspection guidelines and procedures for inspection, assessment and sampling for the later risk based assessment of the facade cladding. The guidelines are provided as a separate report.

3.2.3 Task 2.3 Strength Tests

3.2.3.1 Objective

The objective was to analyse the relation between the bowing, expansion and ageing of marble and limestone slabs received from Task 2.5 and a reduced strength if any of the same slabs. Strength testing includes as a minimum following tests: flexural strength and break load of dowel holes.

This task was later integrated in WP 5 laboratory testing, including materials from quarries, production and buildings. No further comments will therefore be given here.

3.2.4 Task 2.4 Risk Analysis

3.2.4.1 Objectives

Set up an evaluation and prediction model for risk analysis of marble and limestone cladding failure and carry out the risk analysis for the buildings inspected in Task 2.2. The model is not foreseen to be computer based. The model shall be submitted after 24 months to WP 3.

3.2.4.2 Introduction

Although a considerable amount of information about the performance of marbles has been collected from previous investigations and research projects the data is still far from complete and so it is not possible at present to build a general predictive model to calculate the safety risk for all kinds of marble and limestone cladding. The reason for this is that the data tends to be very specific to particular sites, environments, and stone types. Not enough data has been collected yet to establish any correlation of the factors that influence the risk of failure between the sites reported on.

The key factors in determining the propensity to bowing, loss of strength and facade performance are:

Marble type
Panel size and thickness
Material Strength
Fixings
Prevailing weather – wind loading, temperature & moisture

Assuming the observed and predicted decay rates to be reasonably correct it is possible to calculate the time for the strengths to fall below the design wind loading and the time for the strengths to fall below the limit where the factors of are unity.

The point at which the design strength and panel strength match in merely informative as at this point the factors of safety are at 8 and 6 respectively for flexure and shear. These factors are present to accommodate such issues as variability in the stone, workmanship, material decay and other uncertainties.

Obviously there is cause for concern where these factors of safety have been substantially eroded – hence giving an estimate of the possible time scale is important.

Applying all of this data allows an estimate of risk to be made where risk is the product of the probability for "failure" and the consequences of that failure. For many facades the consequences of a panel falling into the street are very great and so even a very small probability of this occurring gives rise to an unacceptable risk.

3.2.4.3 Description of a risk analysis model for marble

Although a considerable amount of information about the performance of marbles has been collected from previous investigations and research projects the data is still far from complete. It is not possible at present to build a general predictive model to calculate the safety risk for all kinds of marble and limestone cladding. The reason for this is that the data tends to be very specific to particular sites, environments, and stone types. Not enough data has been collected yet to establish any correlation of the factors that influence the risk of failure between the sites reported on.

There is no single theoretical basis for the various modes of failure reported on. However, there a few common factors linking some of the failures that can be used as a starting point for a risk analysis. These are:- temperature cycling caused by sunshine, mineral "fabric", fixing method, and cladding design. As more data becomes available from case studies a much better correlation among the modes of failure and deleterious effects should emerge. Ultimately, failure mechanisms and theories should enable quantitative predictions to be made.

The approach that has been taken is to establish a framework that will be populated as data is collected during the project. An active document scheme has been started that puts current knowledge into a structured form that can be easily browsed in a similar way to Internet web browsers. The user is guided through the document to the information relevant to their task. The information in the document is in the form of text, tables and graphics but other media and methods can be added such as sound and calculations or any other suitable for Internet browsers. The document can have forms that can be filled in to direct the user to the appropriate parts of the document. As more data becomes available from other parts of the TEAM-project, external commissions etc, sections of the hypertext document can be made more specific. Where formulae and test methods are available it will be possible to perform calculations and make specific recommendations.

3.2.4.4 The proposed model

In its present form the model can be viewed with the current Windows™ help system. This is based on compiled HTML (an Internet web page format) documents. Requirements for using the system are Windows 9x or later with the Internet Explorer version 4 or later also installed. The Windows™ help system displays the information in a similar way to a web browser (such as the Microsoft Internet Explorer) but with some automatic features that provide in-built indexing and search capabilities. These features can be made accessible for expert users wishing to access specific areas of information. Non-expert users will not necessarily have an index available but will be guided through the documents depending on choices they make as they progress.

The textual basis of the HTML documents is compiled from a Microsoft Word™ document that has been extracted from the State-of-the-art report. The extraction is not yet complete. Information from the case studies will be included as it becomes available.

The document is structured under the headings as outlined below:

Introduction

Environmental Factors
- Temperature
- Moisture
- Air pollution, acid gasses etc.,
- Freezing and thawing cycles
- Orientation to the sun and prevailing weather

Construction Specific parameters
- Anchoring system
- Surface treatment
- Age of facade
- Production and processing techniques

Mineralogy

Geological framework
Mineralogy – primarily calcite/dolomite
Anisotropy
Grain size, grain interlocking, grain boundaries
Preferred orientation of crystals
Porosity, pore size distribution, permeability, water absorption

Physical (mechanical) Properties

Strength
Distortion

When viewed from within the Windows™ help system the user can select the next topic by "clicking" and appropriate button. A screen shot of the introductory page is shown below (figure 2.10).

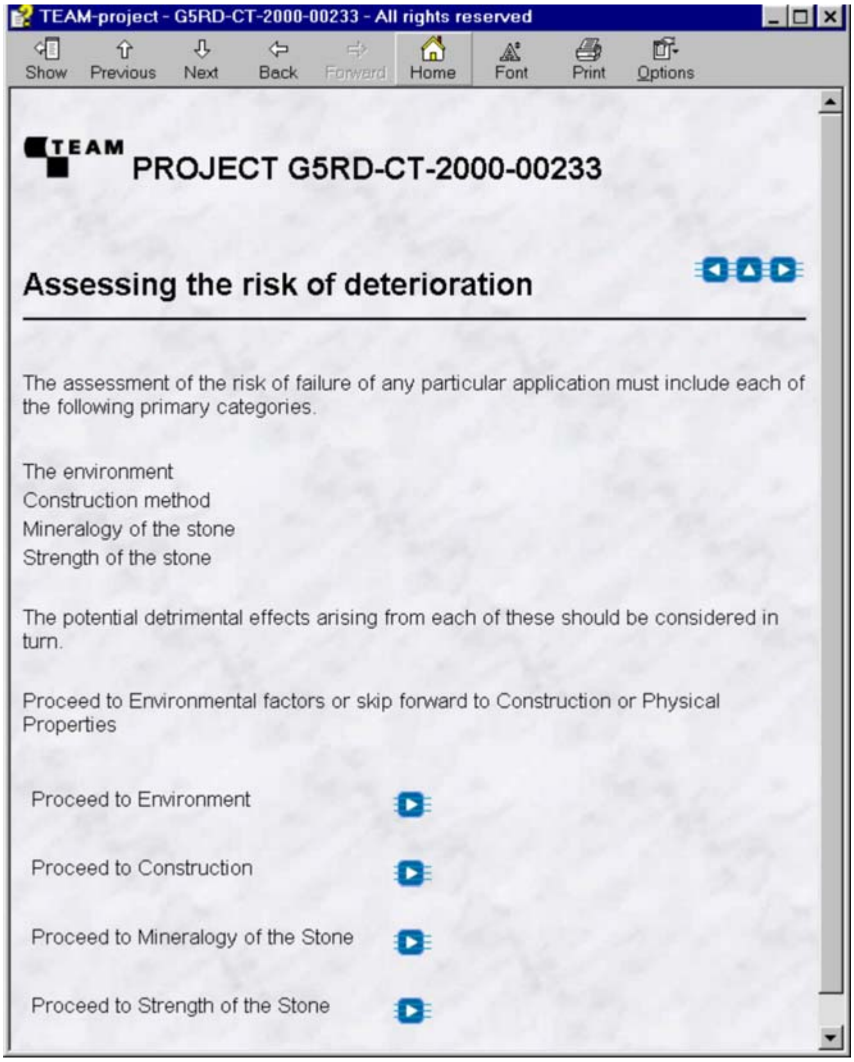


Figure 2.10. Example of an active document format.

As the scheme is developed the user will arrive at guidance relevant to their task. Where possible at least some "boundary conditions" will set, using current data from the case studies, to establish the high/low, best/worst states.

A more specific evaluation of service life and risk will be gained as the findings and ideas from the case studies are linked with loss of strength and the fixing and wind loads.

3.2.5 Task 2.5 Preparation of Samples

3.2.5.1 Objective

Development of an instruction for sampling and preparation of samples received from Task 2.2 for laboratory testing of strength, bowing and petrography.

The document WP 2.5-SP-TD-020621-Samples from buildings-rev 4 gives guidance of how to sample and prepare samples for testing in order to be able to evaluate the material properties and get a general idea about the present strength and strength development over time for the actual building.

Three principally different types of panels shall be sampled whenever possible:

Fresh material from spare material or inside mounted
Strongly/clearly bowed slab from a very exposed placed
Slab from the outside but taken from a sheltered place

Normally five to six panels will be sufficient to get enough specimens for every test and get a spread in the strength properties represented among the samples.

Test specimens shall be cut in order to represent any directional dependency, inner and outer (the frame) parts of the panel. One example of cutting pattern is illustrated in figure 2.11 below.

In addition to traditional testing of physical properties, it is also proposed to test bowing tendencies and to use non-destructive (NDT) testing like ultrasonic pulse velocity (UPV). If a relationship can be established between strength and UPV, it is also possible to monitor the changes of the facade at repeated visits without demounting any more panels.

Figure 2.11. The photo illustrates where test specimens will be cut.

3.2.6 Task 2.6 Anchoring System

3.2.6.1 Objective

Investigation of the influence of the anchoring system on the bowing and expansion of marble and limestone panels based on input from Task 2.2. The taskleader (Fischerwerke), together with Jananders Consulting, carried out the investigation and make a report on the use of various anchoring systems and describe if possible whether they have been designed to account for any anticipated bowing.

3.2.6.2 Summary of the survey

The TEAM inspections of buildings (about 200 projects in Europe) related to different Anchoring Systems used for thin Stone veneers– combined with knowledge from previous experience - have resulted in a listing of Application types as follows:

1. Mortised with or without tying back fixings at edges or back faces.
2. "Traditional" anchors with dowels at stone edge dowel holes.
3. Brackets or rails at horizontal Stone edge kerfs.
4. Full floor level high facade sections resting on the bottom Stone edge.
5. Back face fixings on special sub-frame systems.
6. Prefabricated concrete units with Stone panels tightly attached to a concrete layer.
7. Simple sandwich units composed of a Stone panel attached to a thin concrete layer.
8. Honeycomb supported Stone panels installed by special sub-frame systems.

Type 1) installations have been observed at a limited number of building projects. It has been noted that marble types that deform on other types of installation have not been observed to do so when mortised.
Type 2) is the most frequently used version of application principles of the inspected buildings. The positioning of anchors defines a reference plane. In cases where the marble panels have deformed by curving or dishing the anchors do not have any influence on this phenomenon, other than the shape of the bowing. The anchor location defines a permanent reference plane and the Stone panel deforms related to this plane.
Type 3) is registered at two projects (Göttingen Theologicum and Magenta Hospital, Torino) with a deforming type of marble. The rails define a reference plane around which the marble panels deform. This type of anchoring is the most common one in the USA.
Type 4) was not registered among inspected buildings within TEAM.
Type 5) is frequently used but there is no knowledge of projects with marble or limestone. Opposing to the other types of installation this type is characterised by the fact the Stone panels are hanging from the fixing points while the Stone panels installed by the other types of application are resting on the fixings – or in some few cases carried over the whole surface.
Type 6) have a similar principle structure as Type 1) but the building projects with this type of built up were not covered with marble. They were covered with other types of Stone known for having no tendencies for bowing or degradation.
Type 7) was not registered among inspected buildings within TEAM.
Type 8) was not registered among inspected buildings within TEAM.

3.2.6.3 The Fischerwerke test wall

The partner Fischerwerke has installed a test wall (figure 2.12) and performed measurements continuously once a month starting in July 2003. Readings have been reported in a formula prepared for its purpose. Selected parameters have been collected and summarised in diagrams.

Figure 2.12. Image of test wall for anchoring systems completed with marble panels slab numbers and type of fixing system applied at each set of columns.

3.2.6.4 Conclusions

Three main conclusions can be drawn from this study:

1. Panels installed mortised are bowing significantly less then the other types. Panels installed on continuous rails have the most significant bowing and the three remaining types show roughly identical bowing behaviour (figure 2.13).
2. All slabs located in bottom row bow less then all slabs in top row. Slabs in middle row in most cases have shown amplitudes between those of the top row and the bottom row. See curve diagrams figure 2.14 below.
3. The type of application has an obvious impact on the extent of bowing but is not a method to avoid bowing. Pending on the "rigidity" of the application, the bowing will be more or less significant.

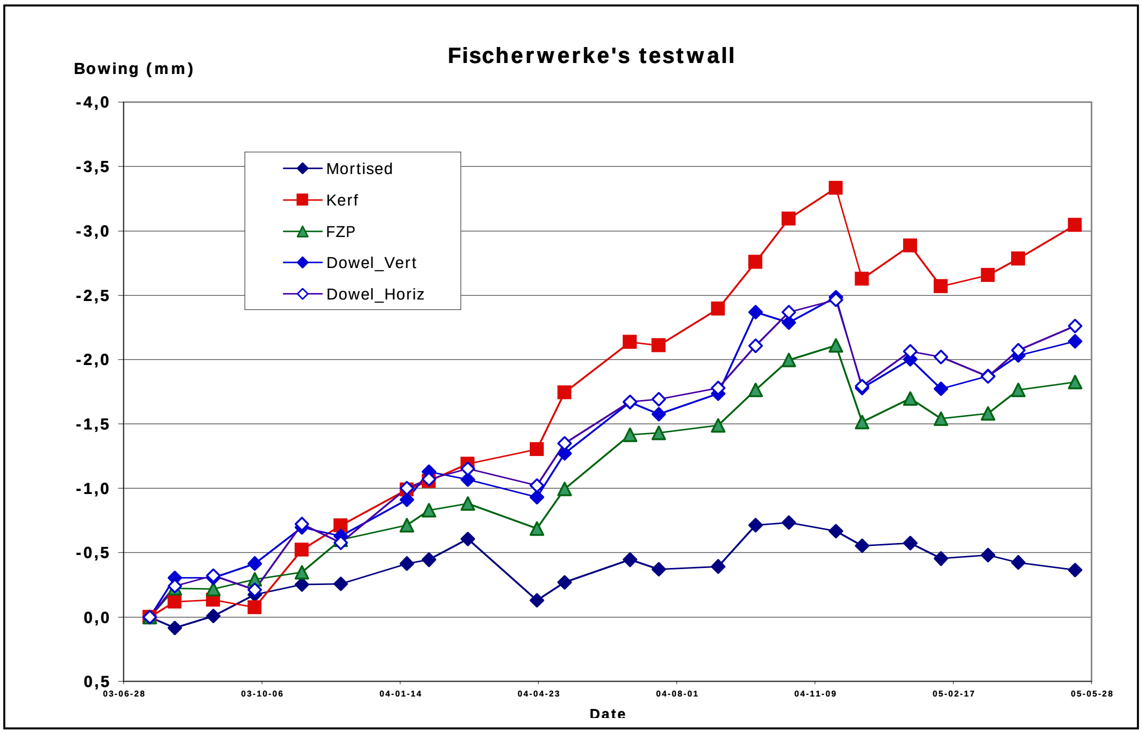


Figure 2.13. Mean values for bowing (always convex, i.e. bowing outwards) for each type of application.

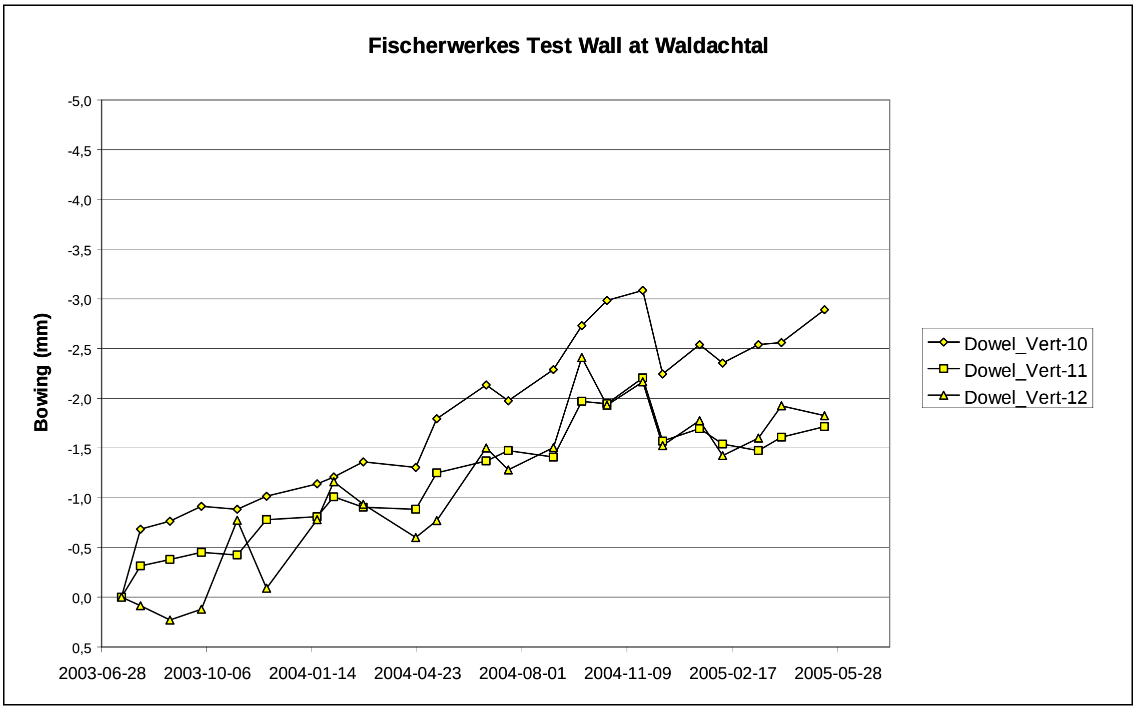


Figure 2.14. Bowing amplitudes – Dowel vertically. Wall slabs bowing development for top, middle and bottom rows.

3.3 WP 3 Long term monitoring system

3.3.1 Objective

The principle objective of this Work Package was to develop and evaluate a system to continuously monitor deformation/movements for panels and to monitor environmental conditions in order to determine if bowing is occurring and the changes induced with time. The task within the WP included developing a procedure and requirements for long term monitoring and to provide input to the calibration of the risk model in WP2.4.

3.3.2 Introduction

This work package has two main monitoring parts, to monitor deformation/movement for panels and to monitor environmental conditions. The aim was that all tests and measurements performed would be non-destructive.

The task necessitated the development of equipment for long term monitoring, installation of equipment at three locations and processing of the results. The data has been used to calibrate a model of the risks of failure associated with the changes in the properties of the panels over long periods of time in order that these risks can be better understood and managed.

3.3.3 Task 3.1: System installation requirements

This task was used to choose suitable equipment and monitoring systems - temperature/ humidity sensors, strain gauges, data logging – and to select suitable buildings – with access to front and rear of panels. This task, together with Task 3.2, were used to determine the necessary data logging frequency and protocol for collection and analysis of data. It was decided that we would start with an easily accessible location to check that the system works satisfactory

The selection of parameters to be measured, selection of equipment and selection of suitable buildings were all given careful consideration before being agreed. It was agreed that ideally at each location monitoring would include:

- surface temperature on the external surface of the stone
- strain in two directions on the external surface of the stone
- surface temperature on the internal surface of the stone
- air temperature in the gap behind the panel
- relative humidity in the gap behind the panel
- strain in two directions on the internal surface of the stone
- shade air temperature
- shade relative humidity

There were problems with finding ideal sites and so there was a need to ‘compromise’. The final list of sites is:

- Danish National Bank, Denmark
- University Library Göttingen, Germany
- Nyköping City Hall, Sweden

It was planned that additional monitoring may be undertaken at some of the other buildings in the project but that this monitoring would be short term and focussed on specific questions.

3.3.4 Task 3.2: On-site monitoring, installation and data collection

The first two sets of equipment were installed in Copenhagen at the beginning of September 2001, two sets of equipment were installed in Göttingen in November 2001, and three sets at Nyköping in October 2002 (figures 3.1 and 3.2). The ‘sophistication’ of the equipment has progressed as the team has gained further experience of the sites and has overcome the initial problems relating, for example, to the fixing of the strain gauges. The three sites are described below.

Figure 3.1. Photo of the three panels monitored at Nyköping City Hall.

Danish National Bank

Amongst the most interesting results from the Danish National Bank in Copenhagen is the fact that there is very little difference between the temperatures on the front and back of the panels – only a few minutes ‘lag’ (figure 3.3). On the eastern side the front can be 4 ºC warmer when the sun first shines on this face. The full temperature rise can take 6 hours but in more extreme cases the rate is around 0,3 °C per minute and this information has been used in the development of the bowing test.

Figure 3.2. Solar cell charged logging equipment at Nyköping City Hall

Göttingen University Library

The equipment has been in place since November 2001. The aim of the logging at this site was to evaluate a new type of temperature and humidity logger and to evaluate the first strain gauges for their thermal stability and the magnitude of movement.

Most of the equipment seemed to work well but there were concerns about the strain gauges as the data shows sudden changes in strain. Despite some problems with the downloading of data interesting results have been found with diurnal cycles clearly visible against a background of longer term changes with reliable stable data being obtained over short periods – for example 7- 8 days.

However, over longer periods the 'drift' and background strain readings still seem to show sudden changes.

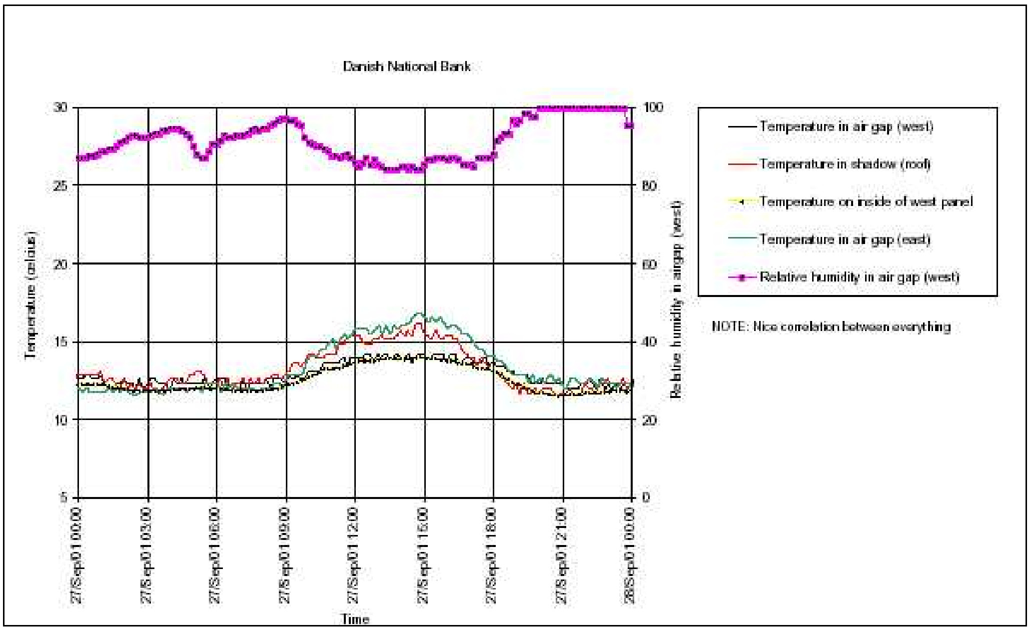


Figure 3.3. Temperature and humidity data, Copenhagen

Nyköping City Hall
The equipment was installed on the City Hall at Nyköping in October 2002 – this was timed to coincide with the setting up of the field exposure site. The aims at this site are to evaluate the re-designed strain gauges, in particular to look at the magnitude of movement, expansion vs bowing and the effects of surface treatments.

The strain gauges are a new design using 'Invar' to reduce the thermal expansion of the gauges and provide more stability in the results. There are three monitoring locations – one location is on an existing Carrara panel (that has been demounted and replaced), the second is on a new panel of Carrara with similar dimensions to the existing panel. The third location is on a panel that has been treated with a microcrystalline wax from Trion Tensid. In all three cases, strain gauges have been fixed to the rear and front faces to allow determination of movement in three dimensions. Further analysis allows this to be converted to a 'bowing' figure which can be compared directly to the 'bow meter' measurements being made on site. All of the data is collected by a single data logger. Only one set of temperature and humidity measurements is being made behind the panels and in the air as experience from Göttingen has shown that there is very little variation between adjacent panels.

3.3.5 Data Analysis and Interpretation

The diurnal movement in the strain gauges can be clearly registered with this equipment and it is also clear that this daily movement is likely to 'mask' any longer term residual movement in the panels from the early expansion and/or bowing of the marble. As a result a considerable effort has gone into the development of methods to 'process' the data. Three approaches have been used:

- Selecting and examining strain gauge data recorded over a narrow range of temperatures.
- Selecting strain gauge data recorded at the same time each day
- Correcting the entire dataset (14,000 points) for thermal movement of the strain gauges.

Figures 3.4 -3.6 show the results from applying the first method. The residual bowing of the panels can be seen over the 15 months of the monitoring.

Figure 3.4 shows Panel 1 which was removed from the building in November 2002 and replaced on new fixings. The pattern of movement seems to show a fairly rapid bowing immediately after the panel was replaced – possibly as it moved back against the fixings- followed by a long period with very little movement.

Figure 3.5 shows Panel 3 which was a panel of new Carrara marble. Note that the panel is bowing in the opposite direction to Panel 1 and that the magnitude of the bowing is also much greater.

Figure 3.6 shows Panel 2 at Nyköping which was a panel of new Carrara marble that was treated with a hydrophobic coating. The treatment was intended to reduce the bowing. Initial the rate seemed to be reduced but it is not clear now quite what is happening except the panel seems to be move far more on the horizontal axis than on the vertical axis.

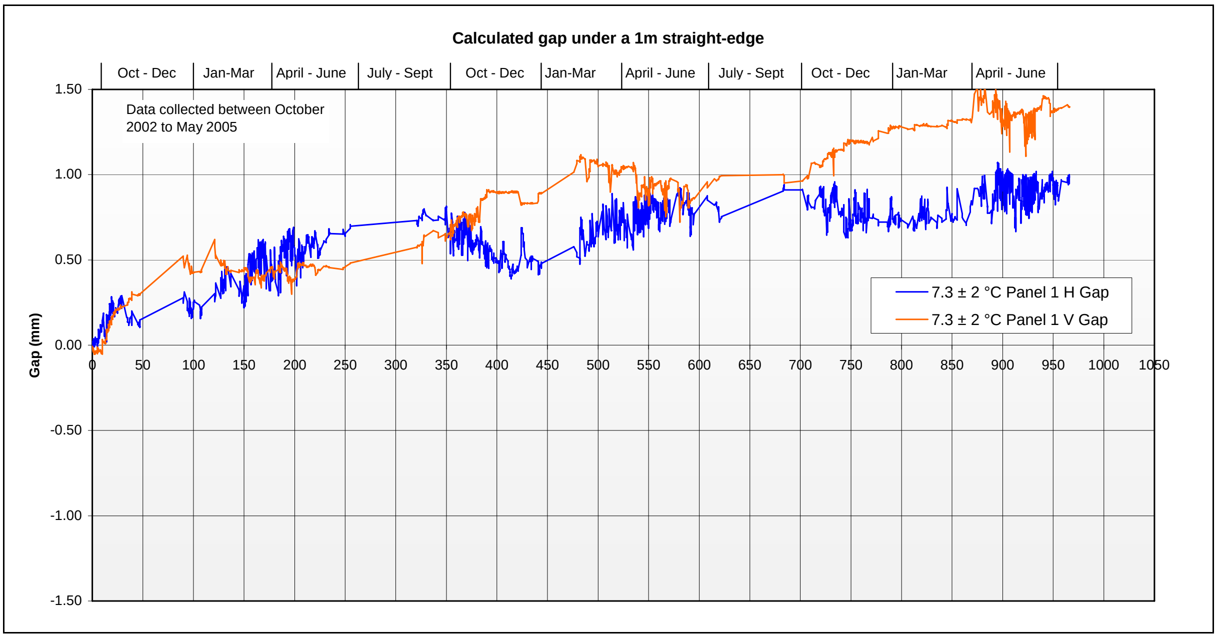


Figure 3.4. Panel 1 at Nyköping – an existing panel of Carrara Marble removed and refixed.

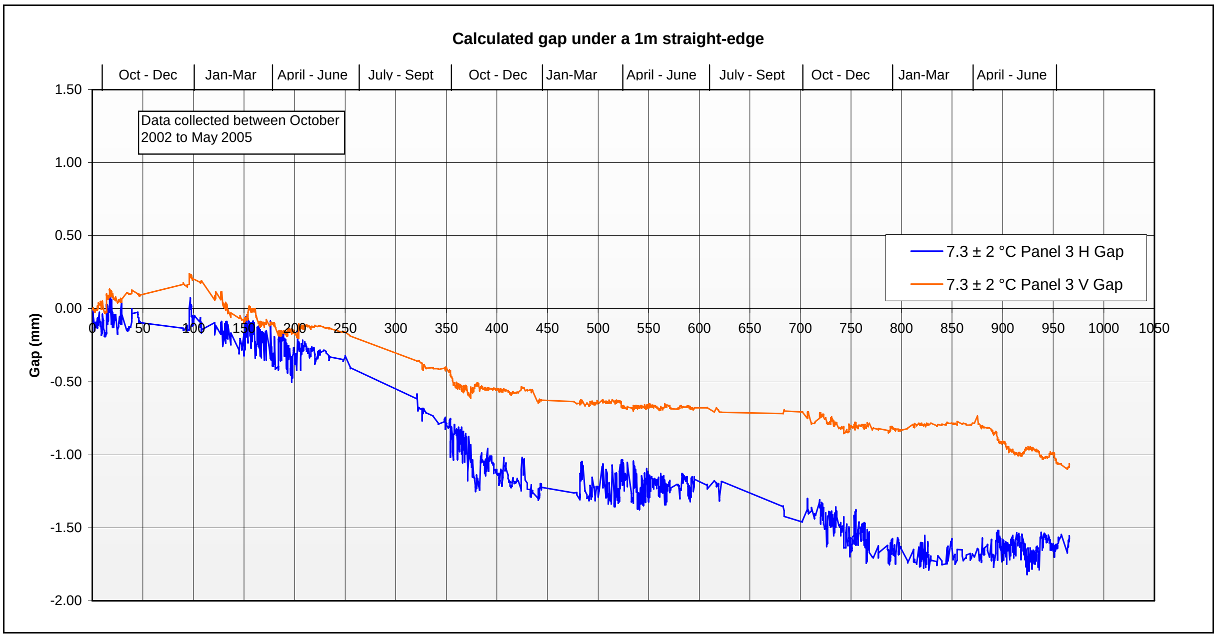


Figure 3.5. Panel 3 at Nyköping – a new panel of Carrara Marble

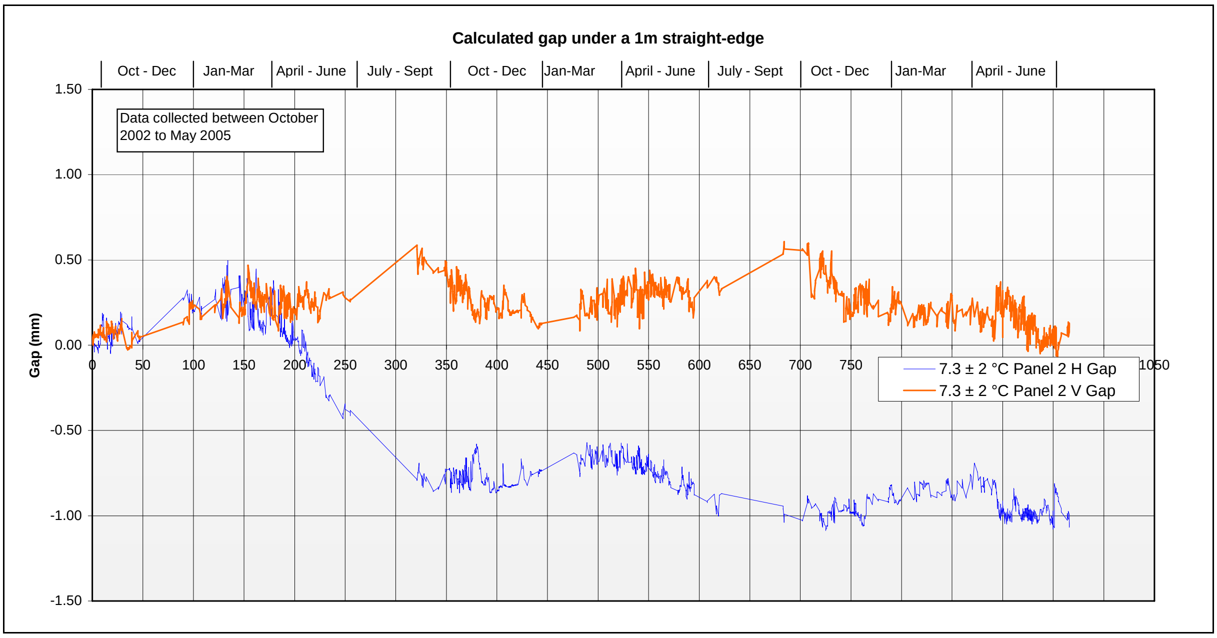


Figure 3.6. Panel 2 at Nyköping – a new panel of Carrara Marble treated with a hydrophobic coating.

3.3.6 Discussion and findings

The key finding since the initial installation requirements were determined is that there are no "off the shelf" systems available for this type of monitoring. In particular, all the strain gauge systems required installation conditions which cannot be achieved on existing marble panels - for example a polished and clean surface or heating to 70 °C to set the adhesive for the gauges. As a result considerable effort has been put into the development of a system which is suitable for measurement on an existing building. Evaluation of the initial observations from Copenhagen and Göttingen have been used to design more stable equipment for the measurements at Nyköping and this new equipment seems to be working successfully. The earlier work at the Danish National Bank has shown that it is possible to reduce the data logging frequency with no loss of precision in the results and the analysis of the data from Nyköping has show that it is possible to determine the bowing of the panels by filtering the data to specific temperatures and so removing the need to correct all the data points for thermal movement of the gauges.

Comparison of the strain gauge monitor and the bow meter measurements shows the results to be very similar which indicates that the "real time" strain gauge measurements can be used to supplement and strengthen the findings from the bow meter measurements.

The methods to "filter" diurnal changes have provided important input to the interpretation of data from field exposure on Nyköping City Hall and at the various field sites established at the TEAM partners.

3.4 WP 4 Selection of samples from quarries and production

3.4.1 Objective

The purpose of the task has been to select different marble and limestone types mainly on the basis of the results from WP 1, 2 and 5 (screening test), taking into account how they are quarried and further processed in respect of different tectonic directions in the rock mass. By this is meant that e.g. important anisotropy planes, cleavage directions etc. shall follow the rock material into the final specimen preparation. The work has implied the following activities:

- Decide about rock types and varieties that shall be selected
- Describe the stone types and the quarries using the forms from Task 4.1
- Agree with other WPs about number, cutting directions and sizes of samples and specimens needed for laboratory tests in WP 5, 6, and 7
- Perform the sampling and provide samples for other WPs
- Use and update the data compilation system from Task 4.1

3.4.1 Introduction

The main work has focussed on trying to link observations made in WP 1 and 2 to the selection of samples from quarries, to define crucial parameters of the stone, discuss rock mass properties, incl. rock stresses and the quarrying and processing that may influence the sampling strategy. (WP4.2-UGE-TD-010425-Selection of samples from quarries and production-State-of-the-art and WP4.2-STF-TD-050930-State-of-the-art-Part-Rock Stresses). Finally, to define detailed instructions for the sampling and sample identification to assure traceability throughout the project [5].

3.4.2 Choice of samples

The information about the marble used for any building is very poor. In general, the type of marble is known. The quarry is not known. Considering the many individual quarries in a quarry district it is easy to understand that the possibility to select the exact same material that is represented on a building is close to zero. The decision was therefore taken to try to trace the material as far as possible and then choose the most similar marble to the ones present on the buildings investigated in WP 2.

In total, 16 quarries have been sampled, giving 17 varieties of carbonate rocks (table 4.1). The sampled rock types represent 3 pure dolomite marbles, 11 pure calcite marbles, 1 ophicalcitic marble (containing serpentine), 1 limestone and 1 silicate rich, contact methamorphic limestone. In addition a large number of marble types were chosen for test screening for later selection of additional stone types to include in the comprehensive testing scheme of WP 5 (table 4.2).

3.4.3 Sampling instruction and sampling

A "Rock Assessment form" [6] has been developed and used (included in the report WP4.1-STF-IMM-UGE-TD-011128-Sampling method statement Quarries) for the description of the sampled stone types as well as the quarries from where the specimens were selected. For the purpose of TEAM, it has not been a goal to map or to be in full control of quality variations in each quarry, but to select one variety (one block) and assure that all laboratories and partners perform the analyses on the same block material and on specimens cut in the same way.

The importance of traceability and to be present and supervise the sampling has been emphasised during sampling in WP 4. Therefore, most of the blocks were sampled and marked under control of at least one geologist and member of the TEAM research group.

In general, one block of sufficient size was selected from an existing quarry face, or alternatively, a block was selected from a block storage or processing plant. The sampling in Slovenia and Poland was done in 2003, the rest in 2001-2002. The blocks chosen for cutting into test specimens were oriented in case of visually present fabric (figure 4.1). Drill cores were also taken in order to try to detect the presence of any preferred orientation of minerals (figure 4.2).

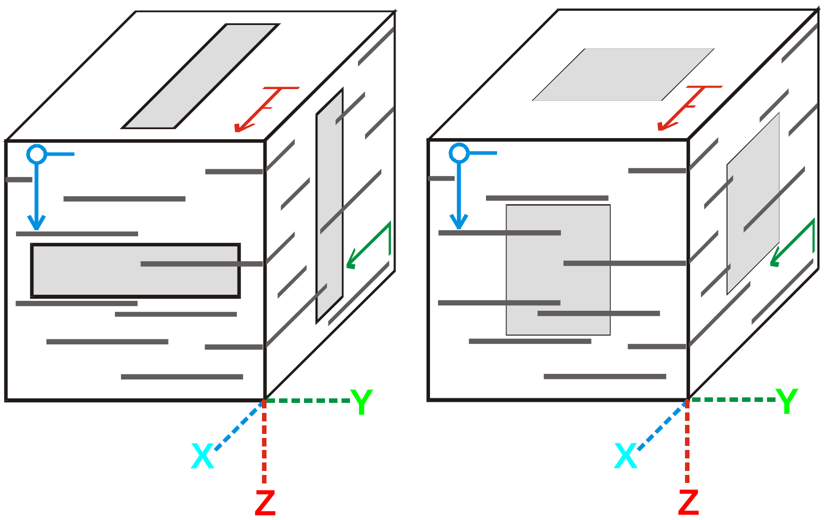


Figure 4.1. Principal sketch of cutting orientation in relation to the fabric of one of the stone types.

In order to secure confidence, a coding system was established during sampling and marking (table 4.1). The first two letters design country of the origin, "q" stands for quarry (in order to separate these samples from samples from buildings) and numbers from 1 to 4 for the number of the quarry or the variety, respectively (e.g. chq1 and chq2 are from the same quarry, but two different varieties).

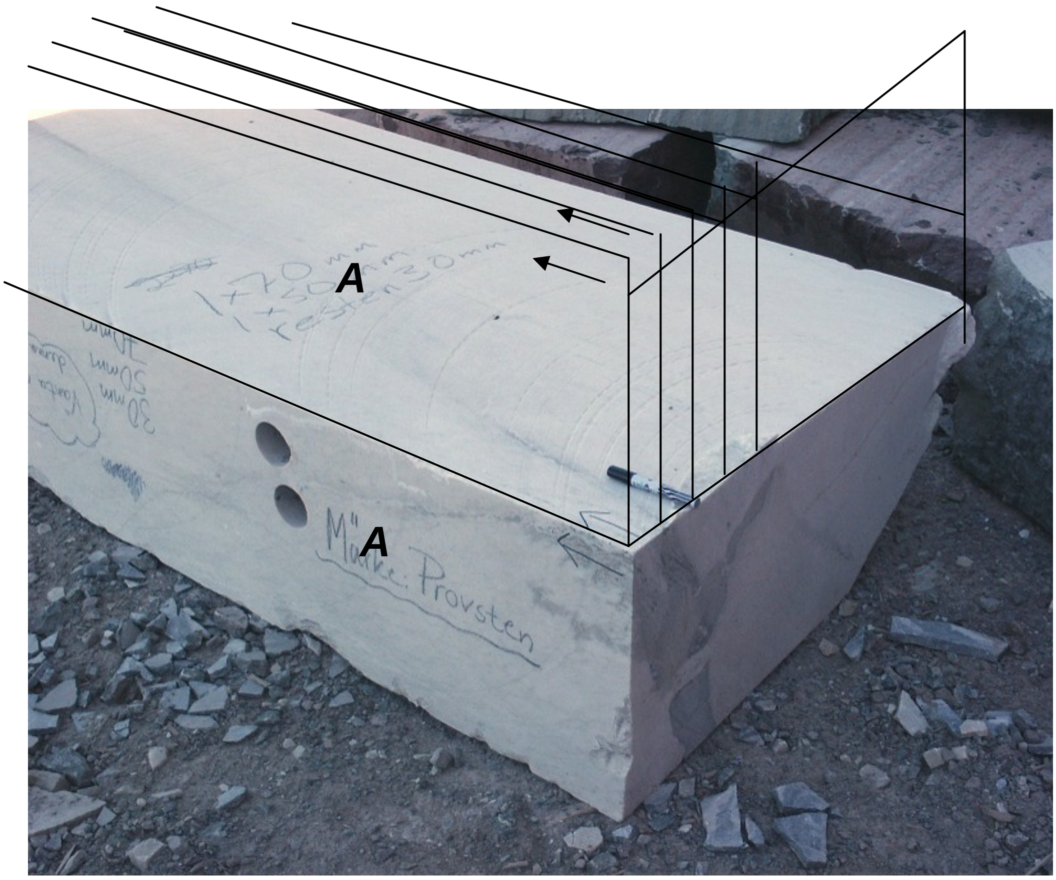


Figure 4.2. Half of the block with holes from the oriented samples. Arrows are oriented the same way as on the sawn slabs below.

Table 4.1. The table shows the stone types sampled for the major laboratory testing programme in WP 5, 6 and 7.

Stone code	**Country of extraction**	**Rock Type**	**Represented in building No. (Task 1.1)**	**Bowing problems known?**
Chq1	Switzerland	Calcitic marble	DE04	Yes
Chq2		Calcitic marble		
Grq1	Greece	Dolomittic marble	GR07	No
Itq1	Italy	Calcitic marble	?	?
Itq2		Calcitic marble		
Itq3		Calcitic marble		
Itq4		Calcitic marble		
Noq1	Norway	Calcitic limestone-marble (contact methamorphic)	DE07, DE08, DE09, DK01, DK02, DK07, DK24, NO03, NO06, NO09, NO10, NO13	Yes
Plq1	Poland	Calcitic marble	PL03	No
Plq2		Calcitic marble	PL01	No
Poq1	Portugal	Ophicalcitic marble	DE 05, PT05, PT07	Yes
Poq2		Calcitic marble	DE01, PT02, PT03, PT09	Yes
Poq3		Calcitic marble	PT01PT04, PT06, PT08	Yes
Poq4		Calcitic marble		No
Seq1	Sweden	Dolomitic marble	SE04, SE06, SE08, SE15, SE16, SE17, SE18, SE23, SE24, SE26, SE27	Yes
Slq1	Slovenia	Limestone (calcitic)	SL 02	No
Slq2		Dolomitic marble	SL 01, SL 03, SL 04, SL 05, SL 07, SL 09	Yes

Table 4.2. The table shows the number of samples for screening with the bow test, from different countries. Each sample consists of several test specimens.

Country	No. of samples
Italy	36
Greece	10
Portugal	13
Sweden	8
Norway	7
Greenland	4
Turkey	1
Bulgaria	1
France	1
USA	5
Total:	**86**

3.5 WP 5 Research – Finding the mechanism of bowing

3.5.1 Objective

Through field and laboratory investigations, combined with discussions with experts from industry and research, find the driving force behind and main factors influencing deterioration due to bowing and/or thermal expansion. Give input to stone companies regarding production and processing optimising, further developed within WP 8.

The work package is divided into the following four different tasks:

1. Geological framework
2. Production conditions
3. Rock and mineral properties
4. Other properties (moisture gradient etc.)

3.5.2 Task 5.1 Geological Framework (In-Situ Stresses)

3.5.2.1 Objective

To investigate the potential influence of in-situ rock stresses on bowing of marble, three dimensional rock stress measurements have been carried out in three quarries in the Carrara area, Italy. Based on the results, laboratory bow tests on specimens cut in various directions to the major principal stress have been performed on specimens from two of the quarries.

3.5.2.2 Introduction

The original hypothesis for the rock stress measurements was that we would expect high stresses or high anisotropic stress pattern in areas where strong bowing material is extracted and low stresses in localities where the marble has not shown problems with bowing. If this was not achieved, we could conclude that rock stresses were not a major reason for bowing of marble. In addition, we could expect different responses if the marble is cut in various directions in relation to the measured principal stress directions, see figure 5.1. The measuring programme therefore comprised both rock stress measurements and bow tests of specimens sawn out in different directions according to the main rock stresses.

3.5.2.3 Method

The rock stress measurements have been carried out with a so-called three-dimensional (3D) overcoring system (figure 5.2). Principally, this is stress relief method, where the rock stresses are relieved by drilling out a diamond drill core, and where the corresponding rock strains are recorded by resistance strain gauges. The Young's modulus and Poisson's ratio are determined on the recovered rock core material, and the principal stresses and their directions are computed using elastic theory.

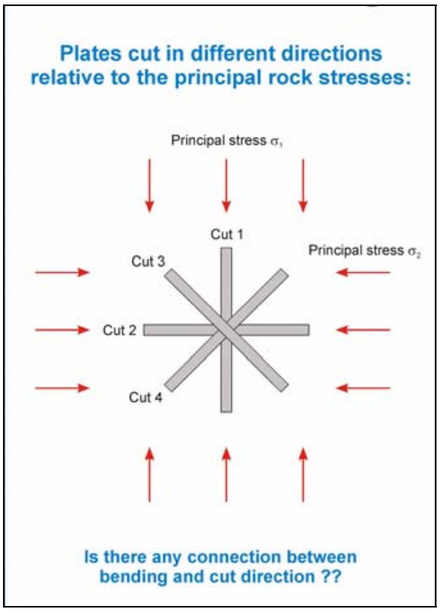


Figure 5.1. Illustration of potential relation between bowing and direction of rock stresses.

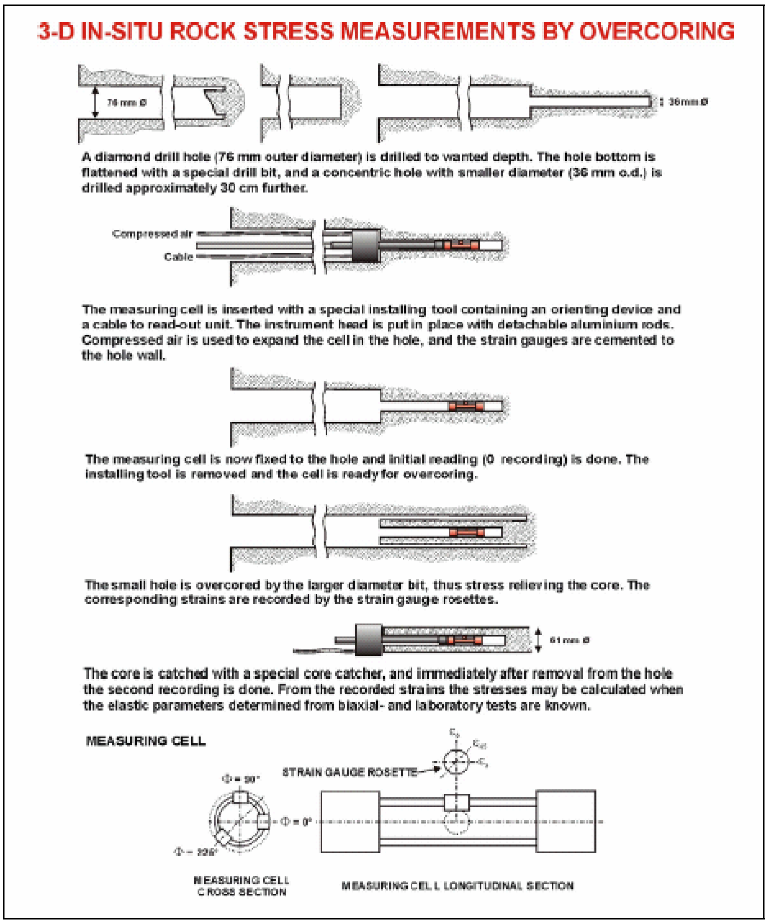


Figure 5.2. Principle of rock stress measurements by 3D overcoring (CSIR overcoring cells).


Figure 5.3. Rock stress measurements in one of the Carrara quarries.

3.5.2.4 Results and conclusions

The in-situ stress measurements at the three quarries clearly indicate that the marble at all sites is subject to quite high, non-gravitational stresses, and that the major principal stress is sub-horizontal. Horizontal stresses up to 18 MPa have been measured. The theoretical gravity stresses are either low or virtually zero (at least at the Gioia and Buca locations).

The stresses are probably a combination of locked-in residual stresses and tectonic stresses. In the Canaloni quarry, the stresses seems to be relieved the first couple of metres from the rock face, even if the marble otherwise is seemingly strong and free from fractures. This is also supported by the fact that no stress indicators like spalling surfaces may be observed. This may mean that marble blocks taken out probably to a large extent are stress relieved. The marble has high Young’s modulus (Elastic modulus) and sonic velocity, and has a nearly perfect linear elastic behaviour, and would under otherwise equal conditions be less prone to deform.

In the Gioia quarry, the stresses are quite high even close to the rock face. This supports observation of spalling surfaces, and also reports on diamond wire jamming during release of marble blocks in the quarry. This may mean that relieved blocks still have locked-in stresses after release from the solid rock. The marble has significantly lower Young’s modulus and sonic velocity than the marbles from Canaloni and Buca, and also has a more curvilinear elastic behaviour with hysteresis. This marble would under otherwise equal conditions deform easier than the two others.

In the Buca quarry, the stresses are quite high close to the rock face, which supports the observation of spalling surfaces at the measuring site.

The marble has quite high Young’s modulus and sonic velocity, and also shows a linear elastic behaviour. This marble could be less prone to deform than the Gioia marble.

The results of the actual rock stress measurements show that our original hypothesis is somewhat simplified. High stresses are measured in all marbles, even in those where no bowing has been experienced. Nevertheless, for these two quarries, it seems that the stresses are released during block extraction, in opposite to the quarry where they have experience with bowing marble. In addition, the rock mechanical properties (Young's modulus and sonic velocity) of this marble is much lower than the other two.

As a follow up of the rock stress measurements, bow tests on test specimens cut out parallel with and normal to the major principal stress direction, and also 45° to these directions were performed (Figure 5.4 and 5.5). There is a tendency that the highest bowing occur in specimens cut parallel or 45o to $\sigma 1$. These findings support a hypothesis that the most pronounced bowing will occur in directions where the effective shear stresses are highest, due to the internal friction of the rock.

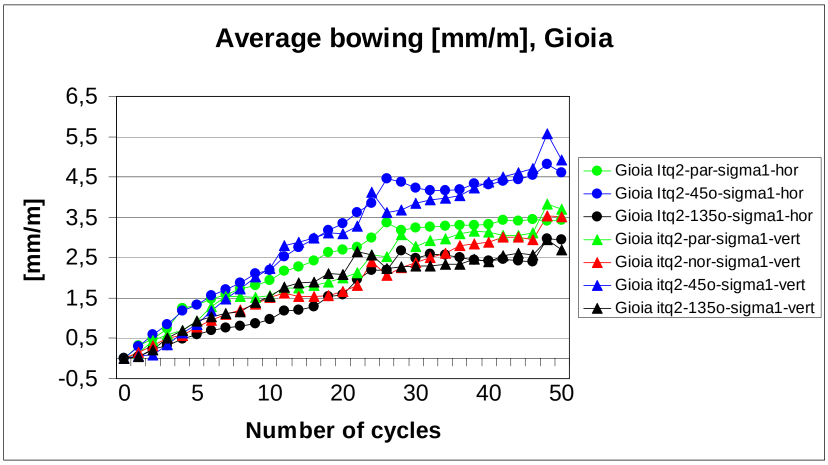


Figure 5.4. Average bowing values (mm/m) for specimens of Gioia marble cut in various directions according to the major principal stress .

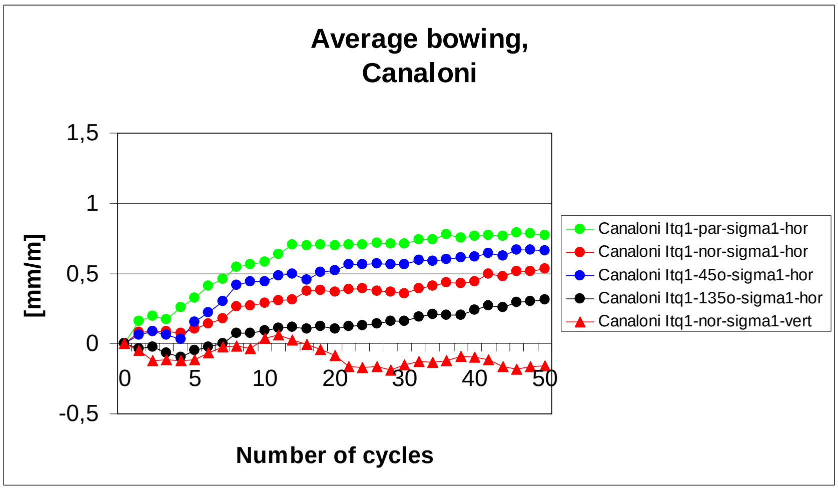


Figure 5.5. Average bowing values (mm/m) for specimens of Canaloni marble cut in various directions according to the major principal stress.

Even though the work has identified a relationship between in situ rock stresses and bowing magnitude for two marble types, it is difficult to separate this from especially the influence of rock fabric, i.e. the lattice preferred orientation of the calcite crystals.
In practice it will be very difficult to make use of this information between the rock stress situation and bowing. Nevertheless, it is important for general block production (yield) to take

the in situ rock stresses present in the rock mass itself into consideration during quarrying. In order to avoid or reduce the risk of damages to humans, to blocks and to the quarry face itself, knowledge about the magnitude and direction of in situ rock stresses is important to take into account.

3.5.3 Task 5.2 Production Conditions

3.5.3.1 Objective and methods

The purpose of Task 5.2 – Production Conditions - has been to find out whether production and processing practices have any influence on bowing. Establishing practices and conditions for transformation of raw blocks into finished marble products by site observations and collecting information from companies has played a major role within this task. Of value has also been to discuss the path from the selection of a stone material for a specific building project to the production and processing of the actual stone. Thus, the various parameters, procedures and practices that can be included in the terms "production and processing" have been discussed (quarrying and processing methods, influence of cutting directions, panel size and thickness). In addition, findings from building studies (WP 1 and 2) and other WPs and Tasks have been brought into this discussion. Laboratory bowing tests on oriented samples, as well as on specimens with various thicknesses and surface processing (honed, polished, dolly pointed) have been performed.

3.5.3.2 Results and conclusions

The literature is often vague and insufficient in describing the processes of block extraction and further processing with respect to bowing and strength loss of marbles. A finding from the comprehensive literature review performed within the project is that production and processing parameters are often brought into the discussion when observations are difficult to explain otherwise.

As an introductory conclusion to the work of Task 5.2 it can be stated that some production and processing factors influence the bowing and deterioration pattern of marble claddings. The various factors depend to a large degree on the intrinsic properties of the marble itself. Thus, one main goal for further use of marble in thin facade claddings should be to seek for marble varieties with the most favourable intrinsic properties to prevent such changes to happen. Since various production and processing factors may influence the behaviour of various marbles to various degree, a second goal is to try to optimise the quality of the final product, considering e.g. the effect of cutting directions, slab thickness and slab thickness with respect to surface processing.

<u>Quarrying methods – diamond wire sawing</u>

Several authors have suggested that modern production and processing techniques may introduce special stresses within the rock material that may enhance the rock bowing susceptibility. Especially the introduction of diamond wire saws has been suggested as important in this respect.

There has been a remarkable development in block extraction methods through the last e.g. 50 years. Drilling and blasting has been the traditional method for centuries within the stone industry. Today, most of the marble quarries in Europe and elsewhere make use of various sawing techniques, but with drilling with pre-splitting and/or soft blasting as important for several of the operations in the quarry (final block production etc.).

The age of investigated claddings (concentrated on marble claddings with bowing problems) ranges from 1 - 270 years. This time interval indicates that several quarrying techniques may have been used for production of the slabs. From this one could suggest that the extraction methods can not explain bowing occurring after installation. Another finding from the building investigations, are that bowing of marble slabs starts "immediately" or at least shortly after slab installation, and that the deformation reaches a maximum through time. Since one must assume that the slabs were planar at the time of installation, the bowing experienced in many marble claddings is thus a result of the material's response to the prevailing conditions on the building, and by such very difficult to explain as due to the extraction method used.

It has been found that various quarrying methods may give various impacts on rocks to be extracted, but it is very difficult to explain the behaviour in marble claddings as a result of the quarrying method itself. It is reasonable to assume that drilling and blasting will "cut off" possible in situ rock stresses in the material, so that it will take a longer time for locked in stresses to disappear during block extraction in comparison to diamond wire sawing. One main finding from investigations during diamond wire sawing is that in total a release of rock stresses in the extracted block is actually happening during this type of block extraction. Based on this study there is no indication that diamond wire sawing introduces stresses within the rock material that may enhance rock bowing susceptibility.

Cutting directions

In general one could suggest that the direction of the final building slab is a combination of (or sometimes a compromise between) the designers request and the producers need for taking advantage of rock cleavage properties. After the quarrying stage, the blocks to be used for the building are cut into slabs. The cutting direction may be controlled by the requested visual appearance, but also by the producers wish to optimise the block yield, selecting a cutting direction that gives the largest slabs. Thus, in general terms, various cutting directions are most likely represented in all buildings.

Each material generally shows an optimum cutting direction, in terms of pattern and physical-mechanical properties. However, this does not mean that it can not be cut in different ways to obtain special aesthetical features. For marbles with clear, visual foliation this feature is easy to detect or to gain if requested. Nevertheless, for more homogenous marbles, the cutting direction may give much of the same visual appearance. However, this does not automatically mean that the technical properties of slabs cut in various directions are the same.

Both building inspections (figure 5.6) and laboratory bow tests (figure 5.7-5.8) have revealed that the cutting direction may have an effect on the bowing and expansion potentials if the fabric of the marble is anisotropic.

Figure 5.6. Interrelation between bowing and cutting direction at part of the Oeconomicum Building in Göttingen, Germany.

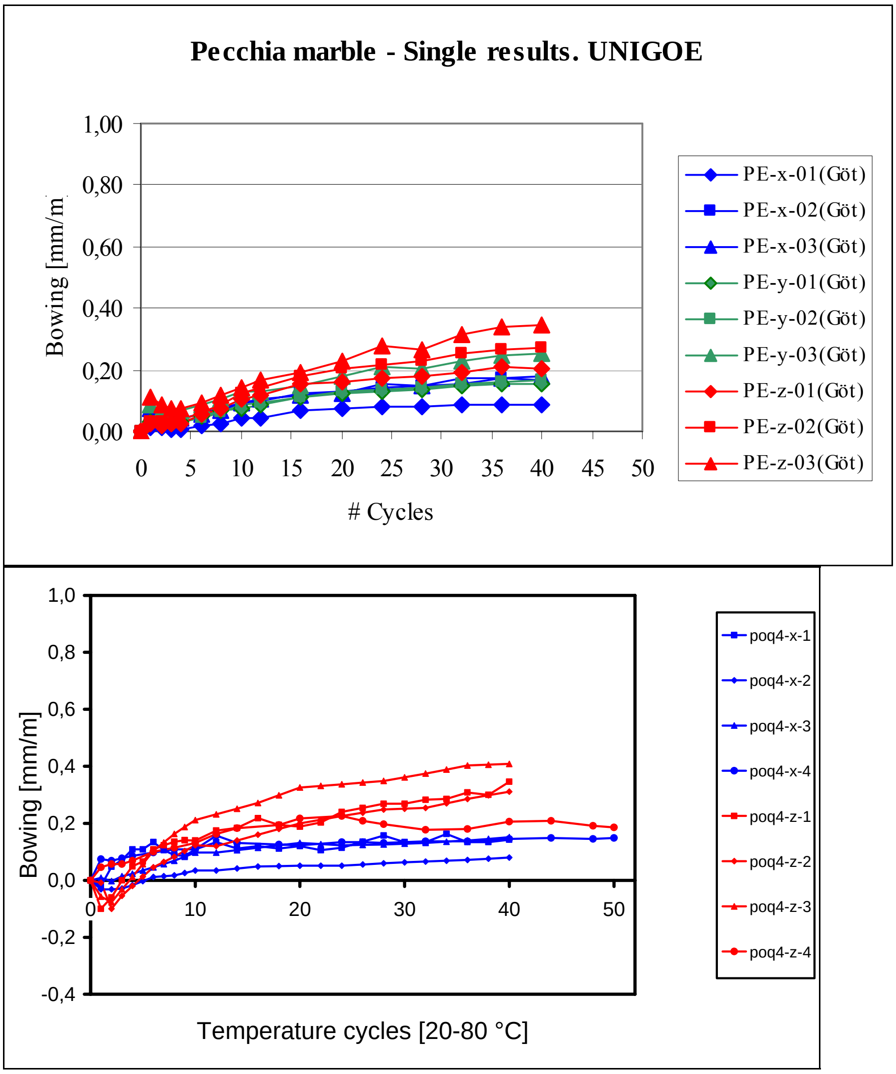
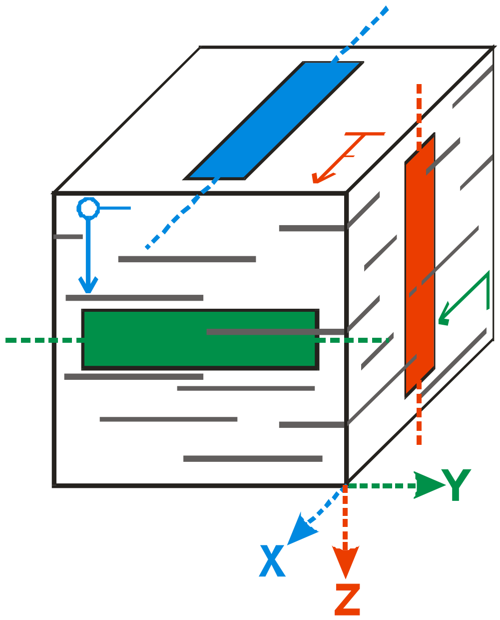


Figure 5.7. Results of bow tests from UNIGOE. Upper diagram – Peccia (Chq1), lower diagram – Ruivina (Poq4).



The various cutting directions are as follows:

Specimens designed "x":
Represent specimens cut parallel to the foliation, i.e. parallel to the xy-plane (blue curves)
Specimens designed "z":
Represent specimens cut normal to the foliation, i.e. parallel to the xz-plane (red curves)
Specimens designed "y":
Represent specimens cut normal to the foliation, i.e. parallel to the yz-plane (green curves).

Figure 5.8. Cutting of specimens for bow tests.

Even though the influence of cutting directions on bowing has been studied on marbles with relative low bowing susceptibilities, there is a tendency that the various cutting directions give different bowing amplitudes. What has been found from studies within Task 5.3 (see next chapter), is that both for the Peccia, Ruivina and Rosa Estremoz marbles, which all have a clear foliation, the grain shape preferred orientation, and thus also the grain boundary preferred orientation is oriented parallel to the foliation plane and the LPO (texture), i.e. the preferred orientation of the c-axes of the calcite crystals, is oriented perpendicular to the foliation plane. Both fabric elements; the grain boundary preferred orientation and the LPO are the real influencing parameters on the anisotropy of the bowing of marble slabs.

Measurements on building slabs and on slabs cut from fresh quarry blocks have also revealed high anisotropy of flexural strength for several marbles cut in various directions (figure 5.9).

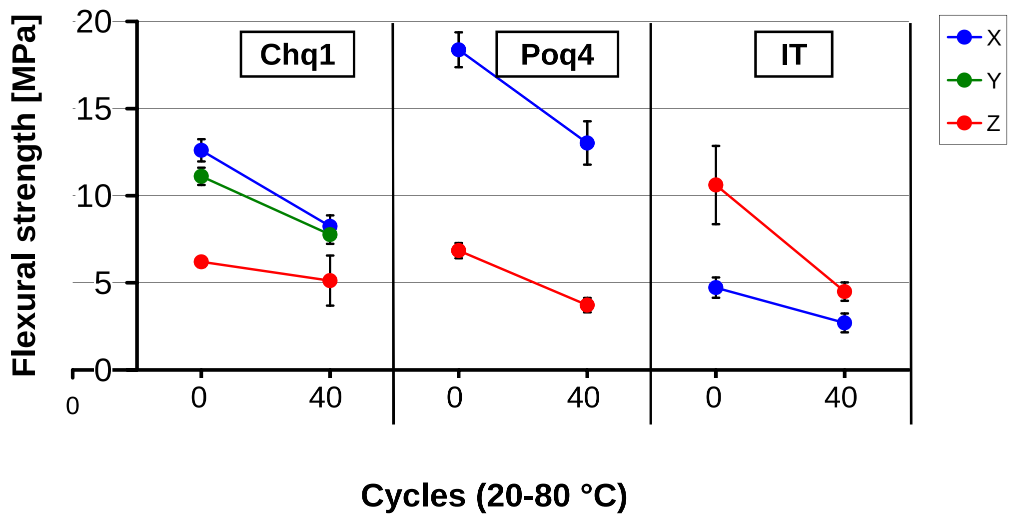


Figure 5.9. Diagram illustrating the flexural strength as a function of cutting direction for various marbles (Chq1 – Peccia, Poq4, Ruivina and a Carrara marble). Reference measurements (0) and specimens after 40 bow test cycles (40). Results from UNIGOE.

Slab dimensions and thickness:
No conclusive answer can be given to the degree and speed of deterioration as a function of panel sizes, but thickness has been found to influence the bowing and deterioration of marble. However, there is no "safe thicknesses" of slabs above which bowing will not occur. For a marble with favourable rock and mineral properties, the behaviour is less dependent on thickness.

Surface processing:
Various processing methods give various impacts on stone materials and may change the microstructure/micro porosity both in and beneath the slab surface. For some techniques this may influence the capillary properties of the product's surface and also its strength. It has been demonstrated that several natural stone varieties, including many marbles and granites may bow as a response to the processing itself. Both sawing, honing, and bush-hammering may cause slabs to bow, typically towards the worked face. It is verified that different marbles respond differently and that there are a relationship between the behaviour during processing and the mechanical properties of the marble. The measurements indicates that marbles with high Young's modulus (stiff) and elastic behaviour will better resist the forces active during various kinds of processing than less stiff marbles with hysteretic behaviour in the stress/strain curve during loading/unloading. It should be expected that the thickness of the slabs are of importance here, the thicker the slabs, the less influenced the material will be by the processing itself. There also seem to be a tendency that less stiff marbles are more prone to bow as a result of stresses induced into the material from temperature and humidity gradients.

3.5.4 Task 5.3 Rock and mineral properties

3.5.4.1 Introduction

Many studies have tried to explain this phenomenon (e.g. Sir Raiyleigh, 1934; Bain 1940; Widhalm et al., 1994;Winkler, 1996), and the main environmental factor seems to be temperature fluctuations in combination with moisture and water that causes the bowing of the marble claddings. This could be due to the anisotropic thermal expansion of the calcite crystal (Kessler, 1919) causing an intergranular decohesion of the material (Perrier and Bouineau, 1997; Malaga 2003).

However, it is important to state that is not all calcite marble claddings that bow, and there are also cases were dolomite marble claddings displays a weak bowing (Malaga et al., 2004). In this study we wanted to investigate how the microstructure of the marble influences the degree of bowing. The microstructure of the marble is dependent of the deformation and metamorphic history and the recrystallisation process related to these events. A static recrystallisation causes a grain boundary area reduction, resulting in the presence of even sized crystals with straight or smoothly curved grain boundaries, forming a granoblastic texture. When a dynamic recrystallisation occurs, grain boundary migration and recovery of the material is possible (Passchier and Trouw, 1996). A fabric of dynamic recrystallised marble is composed of old anhedral grains surrounded by subgrains, forming a seriate interlobate grain aggregate. This has also been called xenoblastic texture (Royer Carfagni, 1999).

Previous studies have shown that there are several microstructural parameters that could influence the bowing tendencies of marble. Siegesmund et al., 2000 stated that the lattice preferred orientation as well as the grain fabric control the deterioration of the marble. The irregularity of the grain boundaries is considered to be another parameter that influences the deterioration, where an increasing irregularity of the grain boundaries gives a more sustainable marble (Barsottelli et al, 1998, Royer Carfagni, 1999). The grain size is considered to be a less important factor for the deterioration of the marble (Zeisig et al., 2002).

Within the scope of the TEAM project, a comprehensive laboratory research programme has been carried out among the partners. Exposed building samples and samples from quarries have given a very good spread in types and varieties of carbonatic rocks for the research. The laboratory analyses have included both standard European tests for general material characterization and analyses directed towards specific problems. The purposes of the analyses can be summarized as follows:

1. Characterize and describe investigated rocks
2. Investigate which, how and how much various intrinsic and extrinsic factors influence deterioration
3. Define rock properties and test results that indicate durable/vulnerable marbles and seek threshold values for performance characteristics
4. Study and understand mechanisms for the deterioration
5. Find correlations between test results and real life performance
6. Define which parameters should be tested, i.e. test methods and procedures for
    - Stone selection for claddings
    - Product and production control for regular FPC and towards specific building projects.

All rock types from sampled quarries (see chapter 3.4) have been tested and investigated. Mineralogy has been determined on samples, and sections from all samples have been quantified by distinct microstructure parameters describing crystal growth, grain boundaries, grain shapes, grain size, cleavage, twinning, grain size distribution, grain shape factors and number of neighbours. Lattice preferred orientation of calcite in several marbles has also been studied. Image analysis has been performed to quantify some of the important microstructure elements such as grain size distribution and grain shape factors. Adjacent grain analysis has also performed.

The entire work package contains numerous of marble and limestone types. A summary of all petrographic analysis is given in table 5.1. Detailed descriptions are given in the technical report [7].

Table 5.1. Summary of petrographic properties of the main rock types.

Marble	Comp	Grain boundaries	Shape of grain aggregates	Crystal growth	Subgrain growth	Twinning	D10	D50	D90	(Perim /circ) Cum80%	AGA
Chq1	cc	Lobate (straight)	Interlobe(polyg)	Hypidiobl	None(weak)	Medium	228	508	648	1.70	9
Grq-1	dol	Sutured	Interlob	Xenobl	Strong	Medium	83	369	591	1.55	10
Itq1	cc	Lobate / caries	Interlob	Hypidiobl	Weak	Weak	55	119	200	1.70	8
Itq2	cc	Straight	Polyg	Idiobl	None	Weak(no)	86	173	371	1.50	7
Itq3	cc	Sutured	Interlob	Xenobl	Strong	Medium	45	127	231	1.70	8
Itq4-1	cc	Straight(lobate)	Interlob	Idiobl	None	Weak	47	97	174	1.70	8
Itq4-2	cc	Straight(lobate)	Interlob	Idiobl	Weak	Weak	35	71	123	1.70	
Noq-1a	cc	Lobate / caries	Interlob	Xenobl	Weak	Weak	57	159	547	1.50	9
Noq-1b	cc	Lobate / caries	Interlob	Xenobl	Weak	Weak					
Poq1x	other	Lobate(straight)	Polyg(interlob	Hypidiobl	None	No	109	387	652	1.70	13
Poq1y	other	Lobate(straight)	Polyg(interlob)	Hypidiobl	None	No	105	416	652	1.60	
Poq1z	other	Lobate / caries	Polyg(interlob)	Hypidiobl	None	No(weak)	155	462	647	1.65	
Poq2x	cc	Lobate / caries	Polyg	Hypidiobl	Weak		236	439	629	1.70	8
Poq2y	cc	Lobate(straight)	Polyg	Hypidiobl	None	Weak	275	489	639	1.60	
|Poq2z	cc	Lobate / caries	Polyg(interlob)	Hypidiobl	None	No(weak)	265	502	641	1.60	
Poq3-1	cc	Straight	Polyg	Hypidiobl	Weak	No	176	375	555	1.65	7
Poq3-2	cc	Sutured	Polyg	Hypidiobl	Medium	No	171	401	647	1.65	8
Poq4	cc	Lobate (Straight)	Interlob (polyg)	Hypidiobl	None	No	104	219	377	1.60	8
Siq2	dol	Straight	Polyg	Idiobl	None	No	68	126	181	1.60	8
Seq1	dol	Lobate / caries	Interlob	Xenobl	None	No	133	289	451	1.70	8
M4-1-1	cc	Straight(lobate)	Polyg	Hypidiobl	None	Weak	97	189	283	1.60	8
M4-1-2	cc	Lobate(straight)	Polyg	Hypidiobl	Medium	No	82	155	227	1.50	8
M4-2-1	cc	Lobate(straight)	Polyg	Hypidiobl(Idiobl)	Weak	Weak	101	184	293	1.60	7
M4-2-2	cc	Straight	Polyg	Idiobl(Hypidiobl)	None(weak)	Weak	87	152	230	1.55	7
M4-3-1	cc	Straight(lobate)	Interlob	Hypidiobl	Weak	Weak	89	163	249	1.60	8
M4-3-2	cc	Straight	Polyg	Hypidiobl	None		81	142	219	1.50	7

The objective of this study was to find a correlation between a microstructural characteristic that can be quantified in an easy way and the bowing property of marble. This includes also formulating a reliable and easily applied method that the producers can use as a tool for quarry planning and the buyers can use as a rapid tool for ensuring a purchase of a suitable marble for cladding. In order to validate our findings the results obtained on laboratory tested samples were compared with marble samples taken from buildings.

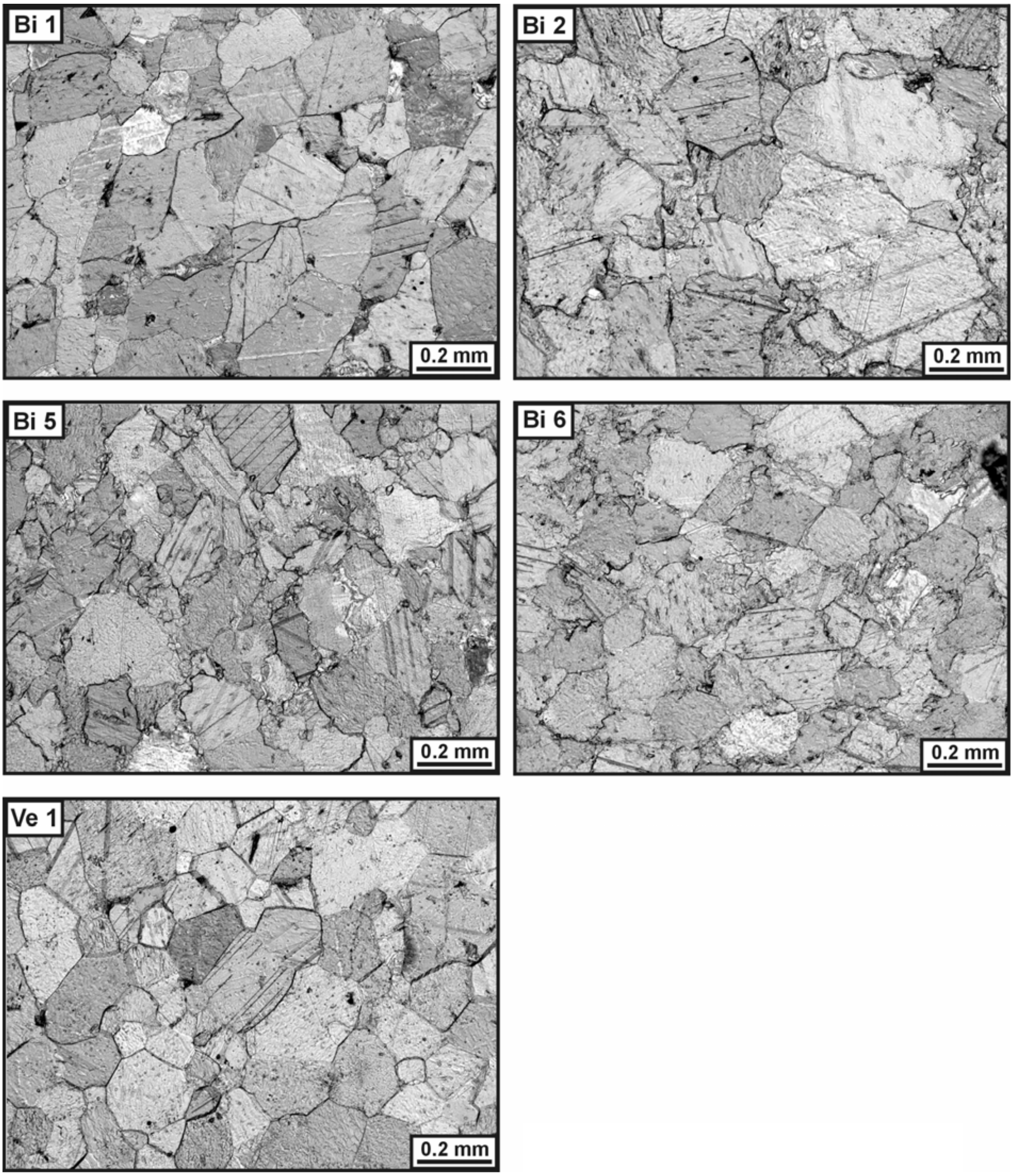


Figure 5.10. Microscopic images of the samples used for AGA-analysis.

3.5.4.2 Microstructure analysis

After the bow tests samples were cut and vacuum impregnated with epoxy resin containing fluorescent dye. One thin section, with an area of approximately 1200 mm^2, was made from each sample. The microscopic images in figure 2 show that there are clear differences in the microstructure for the investigated samples. The microstructure was quantified as follows: The 2-dimensional grain size distribution was measured and the 3-dimensional grain size distribution was calculated. In addition, an adjacent grain analysis was applied, see section 3.5.4.4 below.

3.5.4.3 Grain size distribution

Traverses were randomly drawn on microscopic images. The maximum ferret diameter was then measured on each mineral cutting a traverse. The measurements of the ferret maxima only express the 2- dimensional grain size distributions of the samples. The NT Build 486 method (Sandström, 1995) was used in order to calculate the 3 dimensional grain-size distributions. For natural sand this method reproduces the results obtained through sieving (Lindqvist & Sandström 1999).

3.5.4.4 Adjacent grain analysis - AGA

A calcite crystal belongs to the hexagonal crystal system. In an ideal even grained granoblastic texture, all calcite crystals share grain boundaries with six grains. These are in the following referred to as adjacent grains AG. An increasing complexity of the grain boundary and a more heterogeneous grain size distribution, changes the relationship and increase the number of adjacent grains. In a calcite marble with a heterogeneous grain size distribution, the largest crystals have the highest number of adjacent grains whereas the smallest crystals can have less than six adjacent grains. The same features occur in a calcite marble with complex grain boundaries of the crystals. Both of these microstructures increase the ratio between the total grain perimeter and the square root of the number of analysed grains in comparison with a granoblastic texture. This relation was observed by Bain (1941) in an investigation on grain-border measurements on several types of marbles.

The marbles used in this study range from almost perfectly granoblastic (Ve1) to seriate interlobate (Bi5 and Bi6). In order to quantify the increasing complexity of the microstructure were the number of adjacent grains counted around the measured mean sized grains in the rock. The reason for using only medium sized grains is that if the adjacent grains are counted around the smallest or the largest mineral grains would the results not be representative. The selection of analysed grains was determined from the grain size measurements. The AGA was performed on images taken with a polarisation microscope using a digital camera and enlarged on the computer screen to easily count the number of adjacent grains. The AG was counted around one hundred grains on each sample and the results are shown in figure 5.10.

3.5.4.5 Results

The results from the grain-size analyses show that the samples form two groups. One group that have between 70-80 % of counted grains less than 63 µm according to the 3D-grain size calculations. The two other samples have no counted grains less than 63 µm (figure 5.12). The same groups are observed in the ferret max plot in figure 5.11.

The results from the AGA (table 5.2) show median values from 6 to 9 for the number of adjacent grains, and the distribution of AG are plotted in figures 5.11 and 5.12. Samples Bi5 and Bi6 that showed the lowest bowing tendencies have 9 AG, whereas sample Ve1, showing a bowing of 1,4 mm/m have 6 AG. The samples with 7 to 8 adjacent grains (sample Bi1 and Bi2) have a more irregular grain shape than Ve1, showing a granoblastic texture and they have also a more heterogeneous grain size distribution (Fig 5.10).

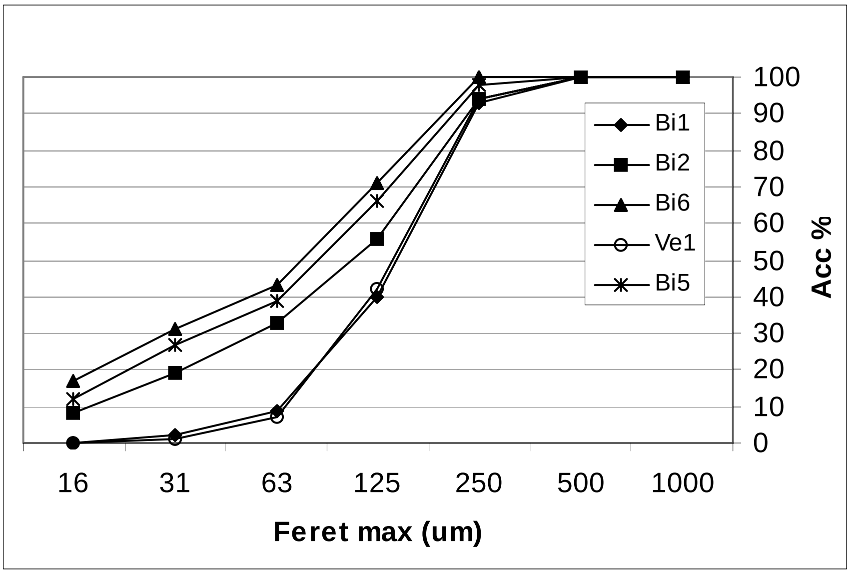


Figure 5.11. 2D-grain size distribution of the investigated samples.

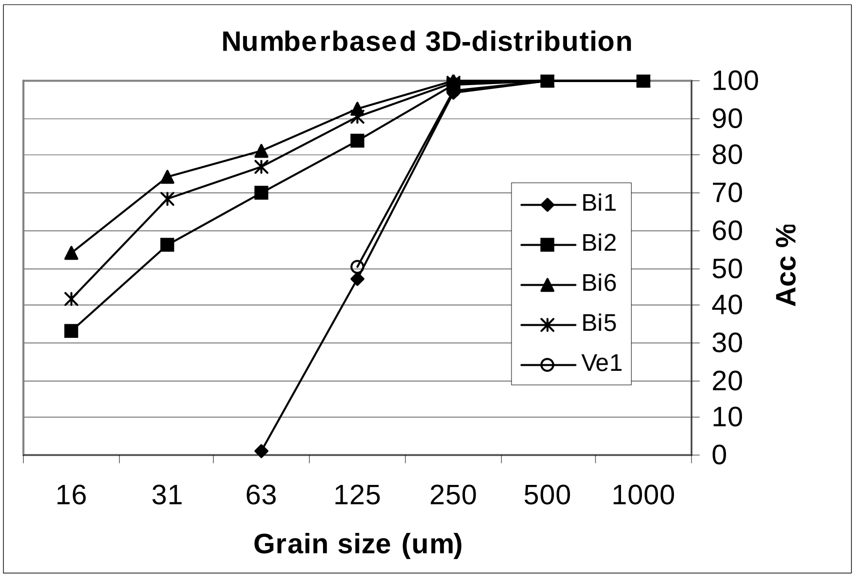


Figure 5.12. 3D-grain size distribution of the investigated samples.

Table 5.2. Adjacent grain analysis for the investigated samples

Sample	No of AG (median values)
Bi 1	7
Bi 2	8
Bi 5	9
Bi 6	9
Ve 1	6

The results from the quantitative analyses of the microstructure showed that there is a good correlation between the type of texture, grain-size distribution and the number of AG. Additionally, the microstructure seems to have an important influence of the magnitude of bowing. Those samples that have 9 AG show a microstructure referred to as seriate interlobate texture (figure 5.10). In low magnification under the microscope, the grain boundaries look rather complex and very irregular. However, in high magnification it is possible to see that these boundaries only show a slight suturation, which is almost the same feature as grain boundaries in a granoblastic texture (figure 5.13). The "irregular grain boundaries" are instead represented by several small, 5-20 µm euhedral to subhedral grains. These observations indicate that the shape of the grain boundaries is not the crucial parameter. What seems more important for a durable marble is the amount of fine-grained matrix around the larger mineral grains. This is in agreement with Zeisig et al., (2002) who showed that marbles with irregular grain boundaries could show the same residual strain as marbles with a granoblastic texture.

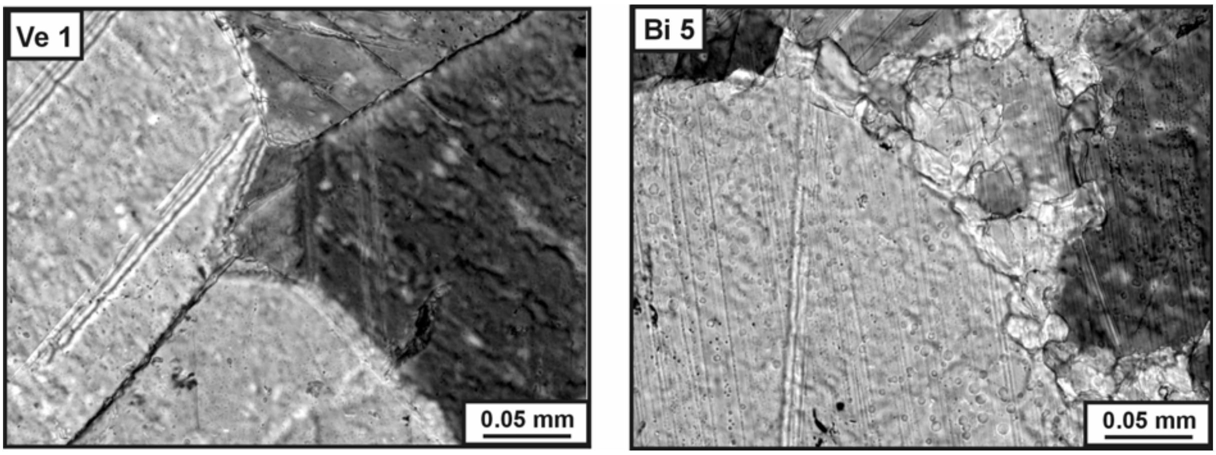


Figure 5.13. Microphotograph of sample Ve 1 (left) and Bi 5 (right). The images show that the grain boundaries of Bi 5 only, are rather sutured and the "irregular grain boundaries" observed in lower magnification and shown in figure 5.10 is instead represented by several small grains. In sample Ve 1 is no fine-grained matrix observed. The image surface corresponds to 333x250 microns.

To evaluate the relevance of the results from the laboratory tests, the AGA technique was applied on samples from four different buildings, which are included in the TEAM project. One building is situated in Denmark and three in Sweden (Fig 8). One of the buildings shows no bowing whereas the three other show bowing up to several centimetres per meter. Figure 9 shows the typical microstructure from these marble claddings. It also shows that the three buildings with bowing panels all have granoblastic textured marble whereas the non-bowing façade cladding have a similar microstructure as sample Bi5 and Bi6. The results from the AGA were comparable with those obtained on the laboratory samples (table 5.3).

Table 5.3. Adjacent grain analyses and bowing from the four buildings.
(Measurements from Yates et.al., 2004, except Sydsv, Alnaes et al., 2004).

Building	No of AG	Bowing (mm/m) Site/laboratory
Nyk (Sweden)	6	20-30/strong
Sydsv (Sweden)	6	30-40/very strong
Mch (Sweden)	9	1-2/none
RK (Denmark)	7	10-20/medium

The sample from Denmark differs from all other investigated samples. The grain size distribution of this marble is very heterogeneous with grains of a few microns up to several mm, (actually cm size in some places) but these grains are not mixed together, they rather form clusters of fine and coarse-grained areas. A determination of the grain-size distribution alone is therefore not a sound basis for assessing the bowing properties of a calcitic marble.

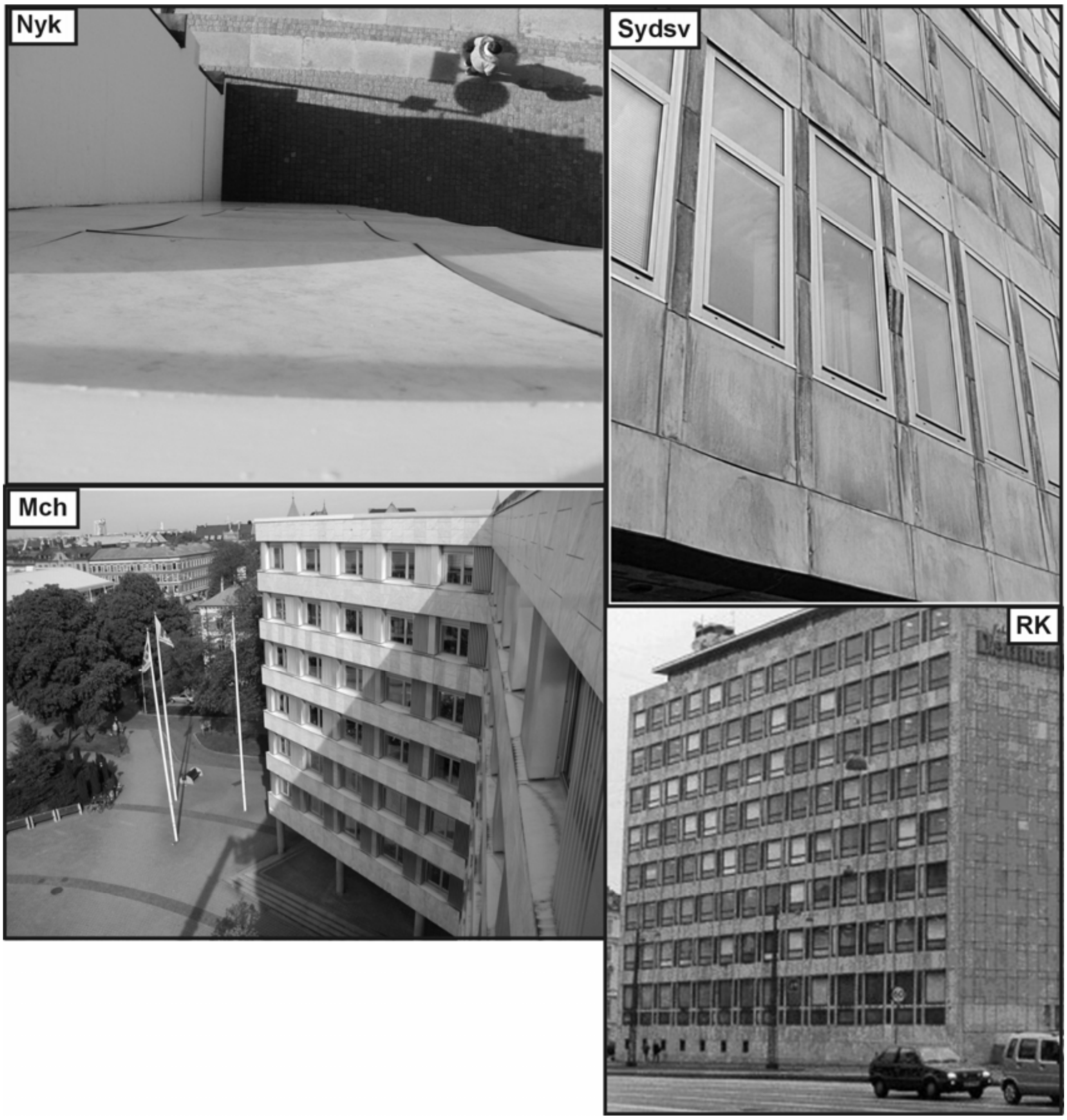


Figure 5.14. The four investigated buildings. Nyk show a bowing of 20-30 mm/m; Sydsv; 30-40 mm/m; Mch 1-2 mm/m; RK, 10-20 mm/m.

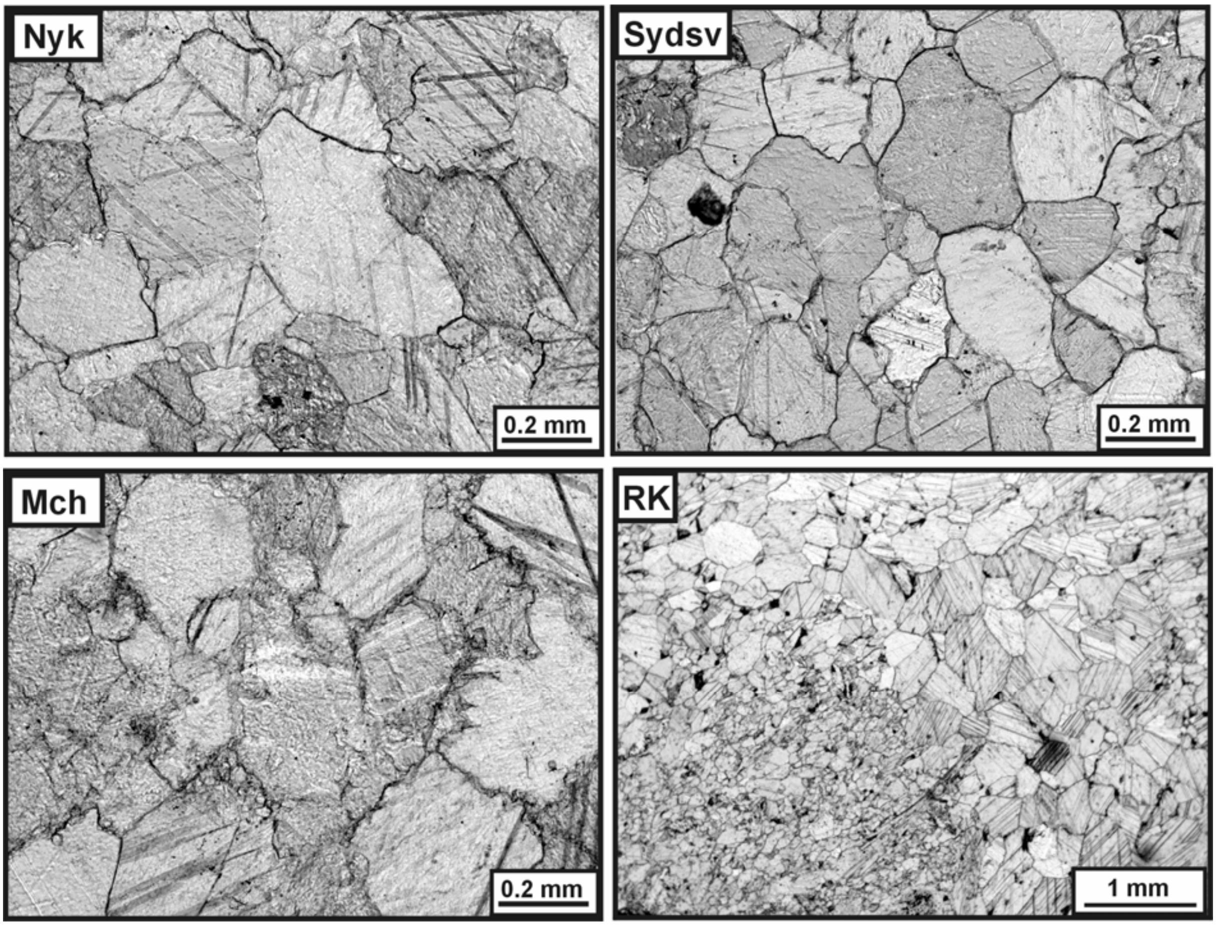


Figure 5.15. The microstructure of the marble claddings from the four buildings. Three of the images show an almost granoblastic texture similar to Ve 1, whereas sample Mch has a microstructure similar to Bi5 and Bi6. The image of building RK also shows that this marble has a very heterogeneous grain size distribution.

3.5.4.6 Conclusions

The microstructural properties have been quantified using several techniques, including adjacent grain analyses, AGA. This technique is a fast and easy method to make a numerical description of the microstructural transition from granoblastic to seriate interlobate marble. The results show that the marbles with granoblastic texture all have six adjacent grains (the median value). They also show that with increasing amount of fine-grained matrix and, to some extent a more heterogenous grain size distribution, the number of adjacent grains increased. Additionally, the results also show that there is a good correlation between the number of adjacent grains and the degree of bowing. The samples with six adjacent grains showed the greatest degree of bowing.

The present investigation only deals with pure calcite marbles. There are known cases where dolomitic façade claddings display weak bowing. Dolomite does not have the same anisotropic characteristics concerning e.g thermal expansion as the calcite crystal, and should therefore be treated as an individual group.

3.5.5 Task 5.4 Other Properties (moisture gradient etc.)

3.5.5.1 Objective

The purpose of this section of the report is to demonstrate the research that underpins the two tests methods developed and evaluated in WP 6. In particular, it shows the processes by which the parameters and their values were established.

Before

3.5.5.2 Introduction and background

The main purpose of this task was to find out which external environmental and use factors influence bowing and/or expansion of marble and limestone; how they influence the bowing and/or expansion; and by how much. Based on the findings from WP 1 and 2, preliminary laboratory analyses (direct bowing tests and test methods for irreversible thermal and hydric properties) were performed in order to determine critical levels of moisture and moisture gradients; sample conditioning properties; and temperature intervals. The findings from these screening tests were used to develop and refine the "bow test" and the "expansion test" that were evaluated in the inter-laboratory comparison in WP 6, task 6.1.

In addition, the implications of anchoring systems (WP 2.6) on bowing/expansion were considered but at the time that the tests were being developed there was no evidence for any direct relationship and so this was not included in the test methods evaluated in WP 6.

There have been many studies of the bowing and deterioration of marble and these are reviewed in the State-of-the-Art Report produced as part of WP 1. Deterioration of marble panels involves several parameters and properties. Bowing is the most obvious phenomenon, but bowing is often followed by a volume change, i.e. the marble expands. However, for obvious reasons the most serious deterioration feature is the loss of strength which may progress so far to total loss of cohesion (decohesion) between the grains. The above three features may cause cracking of panels, spalling in connection with anchor points and in the worst cases ultimately failure of the panel.

Even though no conclusive explanation for the bowing of marble had been found prior to the TEAM project, two parameters were agreed on: temperature variations and moisture, in combination. The project has developed from this point, and other key factors like the internal microstructure of marble has now been recognised (Alnæs et al 2004). Grelk et al. (2004) pointed out that, in theory, laboratory testing for bowing, expansion and flexural strength is a very good method to establish the durability and like future behaviour of a given marble. Successive in-situ measurements and inspections of field exposure sites (Malaga et al. 2004) and of building facades (Yates et al. 2004) have contributed to the knowledge on the bowing mechanisms in relation to environmental conditions and construction specific parameters. These findings have been used to underpin the development of two laboratory tests – one for bowing of marble and the other for the permanent expansion of marble.

Table 5.4. Selected stone types from quarries- Material data.

Stone code	Country of extraction	Rock type	**Commercial name**	Porosity (Hg) (%)	Open Porosity (%)	Apparent density (kg/m3)	Water absorption (weight %)	Capillarity ($g/m^2 \cdot S^{0,5}$)	Flexural strength (MPa)	Break out load at dowel holes (MPa)			
										Different orientation versus the foliation			
Chq1	Switzerland	Calcitic marble	Peccia Virginio Normal	0,33	-	-	-	-	10,4		1,51	1,55	1,53
Chq2			Peccia Colombo	-	-	-	-	-	15,0	1,78			
Grq1	Greece	Dolomitic marble	Snow White of Thassos	0,30	0,67	2824	0,22	0,72	13,2	2,61			
Itq1		Calcitic marble	Venato	0,07	0,30	2708	0,10	0,59	21,1	2,06			
Itq2		Calcitic marble	Bianco Ordinario	0,63	0,57	2703	0,20	0,50	7,7	1,26			
Itq3		Calcitic marble	Bianco Ordinario	0,23	0,38	2704	0,13	0,64	22,9	2,29			
Itq4	Italy	Calcitic marble (Breccia)	Arabescato	0,42	0,60	2704	0,21	1,50	15,5	1,86			
Noq1	Norway	Calcitic-silicic limestone (contact methamorphic)	Porsgrunn	0,21	0,46	2708	0,18	0,60	13,0		1,91	2,42	2,33
Plq1	Poland	Calcitic marble	Biala Mariana	-	-	-	-	-	17,5				
Plq2		Calcitic marble	Slawn-iowice (“white”)	-	-	-	-	-	-				
Poq1		OphiCalcitic marble	Verde Viana	0,35	-	-	-	-	-		1,58	1,57	1,69
Poq2		Calcitic marble	Trigaches	0,18	-	-	-	-	-		1,78	1,86	1,81
Poq3		Calcitic marble	Rosa Estremoz	0,12	0,39	2703	0,15	0,54	9,9-22,5		2,09	2,16	2,57
Poq4	Portugal	Calcitic marble	Ruivina	0,18	0,54	2696	0,16	0,79	11,4		1,75	1,95	1,99
Seq1	Sweden	Dolomitic marble	Ekeberg	0,15	0,31	2859	0,15	0,36	21,0	2,47			
Slq1	Slovenia	Limestone (Calcitic)	Hotavlje Grey	-	-	-	-	-	-				
Slq2		Dolomitic marble	Sivec	-	-	-	-	-	-				

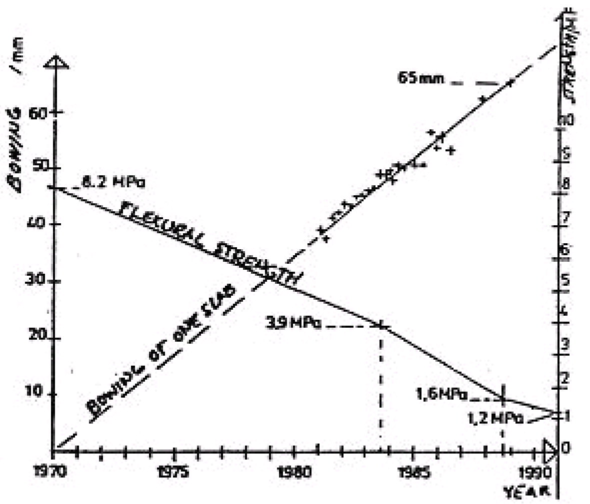


Figure 5.15. Correlation between strength parameters and bowing of marble slabs (from Royer Carfagni 1999).

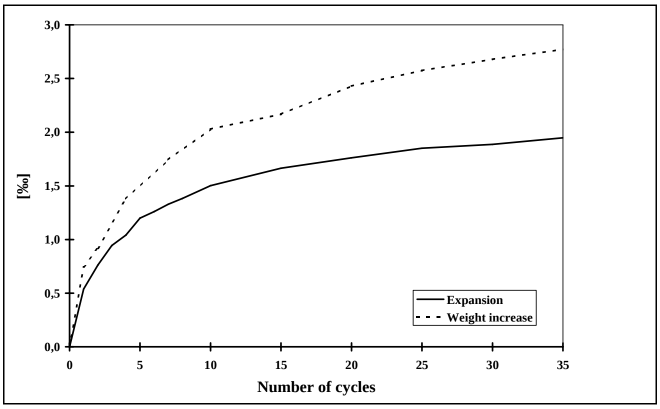


Figure 5.16. Expansion and weight increase of marble prisms exposed to a number of heating cycles (20-80 ^{o}C) in wet conditions. The weight increase is measured in "wet" condition and corresponds to an increase of porosity in the marble.

3.5.5.3 Observations from visual surveys of buildings

One of the first tasks of the project was to collect data examples of bowed marble cladding from Europe. This data collection has continued throughout the project and has been expanded to include examples from the USA. A total of 194 buildings have been identified and described at various levels. 26 of these buildings have been selected for more detailed investigation, of which 6 of them have been selected and investigated both with detailed field study and some measurements of bowing. All of the 26 buildings are considered as suitable for dismounting of facade panels for laboratory testing purposes. Involved partners have tried to get samples dismounted from the buildings for laboratory testing purposes. The selection of buildings for WP 2 (6 buildings) and WP 3 (3 buildings) was also chosen among these 26 buildings. To date examples have been recorded from around 50 different locations in Europe but it is likely that many more examples remain un-noticed.

There is, for natural reasons, a concentration of buildings affected by bowing reported from countries facing on the Baltic Sea – particularly northern Germany, Denmark, Finland and Sweden, but there are also examples from the rest of Europe including Slovenia, Switzerland, Austria, France, UK, Belgium, Italy and Poland. This is merely the reflection of the partner's initial knowledge, and ease of access to sites and information. The most well known example in Europe is the Finlandia Hall in Helsinki, Finland. There is no evidence that any particular climate is typical of the conditions that can result in long term bowing and expansion. Cases of bowing have been reported from the most different climates, from Libya in the south to northern Sweden/Norway in the north but a temperature range and a source of moisture are common to all locations.

A wide range of buildings were visited and the condition recorded along with details of the type of stone used, the panel dimensions, the fixing system and the local environment. The main findings from this stage of the work were:

Facade compass direction and height over ground
Bowing is observed to all facade directions as well as on all heights over ground. On same facade section there is a tendency that bowing amplitudes are more significant higher up on the facade. There is also a tendency that facades facing south and west have higher bowing amplitudes then is the case for facades facing north and east.

Colour of marble
Among reported projects different colour marble types with bowing problems are included such as light types from Italy, Switzerland, Russia, Macedonia and Sweden, green type from Portugal, dark grey types from Portugal and Norway. It shall be stressed that same types of marble on other reported projects does not show any bowing. Thus there is no clear indication as to the effect of colour range of the marble related to deformation by bowing or not bowing.

Panel face dimensions and thickness
Very large marble panels (> $2m^2$) have been recorded with perfectly plane and unaffected surfaces while on other buildings small (< 0,1 m^2) have deformed, deteriorated and fall from the facade. No correlation has been observed between bowing tendencies and stone panel thickness. It might however be noted that marble panels on Nyköping City Hall (Sweden) which are 30 mm thick have deformed in concave direction while adjacent smaller panels which are 60 mm thick on the same facade elevation have deformed in convex direction.

Convex or concave bowing
It has not been possible to relate the options of convex or concave to any other influencing factor. Panels on one side or one location of the same building might deform in concave direction while on an other side or location the bowing is convex, for example at Lünen Hospital (Germany), Nyköping City Hall .

It has also been noted that the original marble facade panels on Finlandia Hall in Helsinki (Finland) were mainly concave with extremely high amplitudes after 30 years of exposure. However, the panels installed some 3-4 years ago of same white Italian marble type (however not from same quarry) have started to deform in a convex direction.
Another striking example is Torsviks Torg in Lidingö (Sweden) – here three tower buildings which are covered on all sides with marble panels (600 x 900 x 30mm) show convex and concave bowing on alternate rows of panels.

Anchoring system
Most of the inspected facades have 30 or 40 mm thick marble panels on various types of anchors and with a ventilated air cavity 20 – 40 mm wide between the stone panel back face and layers of insulation. Some facades are, however, installed on mortar beds with or without restraint anchors – this means that there is no ventilated cavity. Some projects have part of the installation done on freely standing railing systems allowing both the front and rear panel faces to be "exposed" to the surroundings. To date no link has been observed between the type of anchoring system and the bowing of marble panels with the exception panels which are bedded on mortar which do not seem to be susceptible to bowing.

Building measurements
Some preliminary measurements were made at a number of these buildings using a modified version of the "bow meter" that had been developed in the earlier Nordtest project (see NT Build 500). The "bow meter" is basically a 1200 mm straight edge with a digital dial gauge that allows the distance from the edge to the panel surface to be measured very accurately. Detailed site investigations, measurements, sampling etc, have, so far, been performed at 8 buildings (seven are recorded in table 5.5, the eighth is the University Library at Göttingen, Germany). In addition, panels were removed from 10 buildings for further investigations in the laboratory, seven of these have been completed to date. Petrographic thin sections have been produced and described from all these samples and they have been subjected to a laboratory bowing test and the flexural strength determined. A summary of the results of the site measurements and laboratory bowing is given in table 5.3.

Table 5.5. Summary of the results from site measurements and laboratory tests on seven buildings in Europe.

Building name	Country	Marble type	Bowing Site/laboratory
Nyköping City Hall	Sweden	Italian Calcitic	20-30mm / strong
Lünen Hospital	Germany	Portuguese Calcitic	30-50mm / very strong
Bank Building, Copenhagen	Denmark	Norwegian	10-20mm / medium
Office Building, Copenhagen	Denmark	Norwegian	10–20mm / medium
Malmö City Hall	Sweden	Italian Calcitic	1-2mm / none
Hotel Terazza	Sweden	Swedish Dolomitic	5-15mm / medium
Lyngby City Hall	Denmark	Greenland Calcitic	0-2mm / weak

Probably the most important physical change observed is the loss of flexural strength. The results of changes in strength recorded during the literature review and the testing of samples from buildings are summarised in table 5.5. In addition to the bowing and loss of strength there are also examples of spalling of stone around the fixing points (often associated with the movement of the panel against the fixing) and erosion of the surface as the marble becomes less durable.

The survey confirmed that although buildings are found in a wide range of climates they are linked by having significant temperature ranges and wetting and drying cycles. This helped to confirm the basic parameters for the laboratory tests – temperature and moisture cycling. The survey also showed that panels could respond to these parameters by expanding and that in cases where the faces expanded at different rates that this resulted in bowing. It was also clear that the samples used in the laboratory tests need to be of suitable dimensions for flexural strength testing since this would provide a key part of the data required to establish likely service life.

Table 5.6. Summary of recorded losses of flexural strength.

Building	Country	Marble type	Age (Year)	Loss of flexural strength (from literature)	Reference
Finlandia Hall	Finland	Bianco Carrara (Italy)	21	~ 85%	Mustonen (1993)
Amoco	USA	Bianco Carrara (Italy)	15	~ 40%	Hook (1994)
Office building in Nyköping	Sweden	Bianco Carrara (Italy)	31	~ 75%	TEAM (2001 b)
Hospital, Lünen	Germany	Trigaches E./ Escamado (Portugal)	14 28	~30% ~75%	Stocksiefen (1996)
Office building	Switzerland	Bianco Venato Gioia (Italy)	3	~ 40%	Jornet (2000)
Collegiata di Sant'Andrea	Italy	Bianco Carrara (Italy)	~ 100	~ 90%	Garzonio (1995)
Bank building in Copenhagen (Danish National Bank)	Denmark	Porsgrunn (Norway)	23	~ 45%	Leksø (2002)
Office building in Copenhagen	Denmark	Porsgrunn (Norway)	41	~ 75%	Leksø (2002)
Office building in Copenhagen	Denmark	Marmorilik, (Greenland)	60	~ 45%	Leksø (2002)
Office building in Suresnes	France	Bianco Carrara (Italy)	5	~ 50%	pers.com. (2002)
Office building in Paris	France	Bianco Carrara (Italy)	11	~ 50%	pers.com. (2002)
Office building in Paris	France	Bianco Carrara (Italy) Bardiglio (Italy)	~ 10 -15	~ 35% ~ 10%	pers.com. (2002)
Office building in Malmö	Sweden	Bianco Carrara (Italy)	20	~ 10%	Internal report

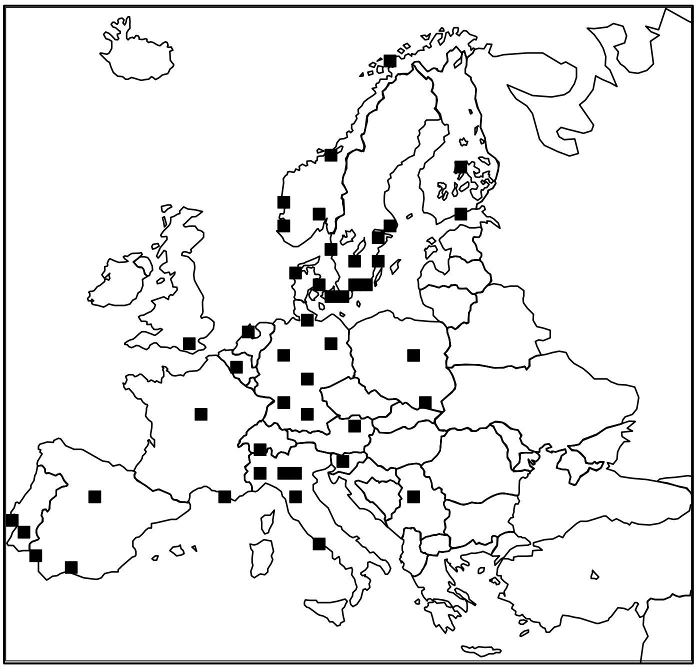


Figure 5.17. Distribution of buildings where bowing or distortion of the marble cladding has been recorded by the TEAM partners.

3.5.5.4 Development of Laboratory Screening Tests

Bowing

The development work was designed to build on the test method NT Build 499, developed prior to the TEAM project (see Nordtest NT Build 499). This uses a standard test specimen of 400 mm length, typically 100 mm width and a thickness, similar to the panel's thickness (or 30 mm in standard tests). The specimen is placed in an insulated container, where it is placed on a tray, filled with a layer of filter cloth or sand. The tray is filled with distilled or demineralised water up to approx. 10 mm below the upper surface of the test specimen.

The specimens are exposed to a number of cycles. Each cycle begins with an exposure to infrared heating from above, which lead to an increase of the surface temperature from the ambient room temperature to 80 °C over a period of 1-3 hours. The surface temperature is maintained at 80 °C for 2-3 hours, after which and the specimen allowed to cool to ambient room temperature, (20 °C) until at least 24 hours has passed from the start of the exposure cycle. Temperature measurements on panels on buildings by Perrier & Boineau (1997) and as part of this project have revealed that the daily magnitude of the temperature cycles can be up to 60 °C and that most of this temperature increase happens in within 3 hours. The bowing of the specimen is measured after a number of cycles.

The test method has been applied on a large number of different stone types during the TEAM project and has yielded very important results. In addition, the maximum temperature, the rate of heating, and the amount of moisture present were all varied during the development work in the TEAM project. The bowing will usually grow unlimited in an environment where there are temperature and moisture cycles. The same tests have been carried out on test specimens from the same sample, but without any water in the tray, corresponding to a dry exposure. Figure 5.13 shows that the bowing after a few cycles reaches a stable level in a dry environment, after which the bowing does not increase. This illustrates that bowing only becomes critical in environments, where moisture is also present.

The bowing potential differs significantly between different stone types, and the thickness of the panel will also have an effect on the development of bowing.

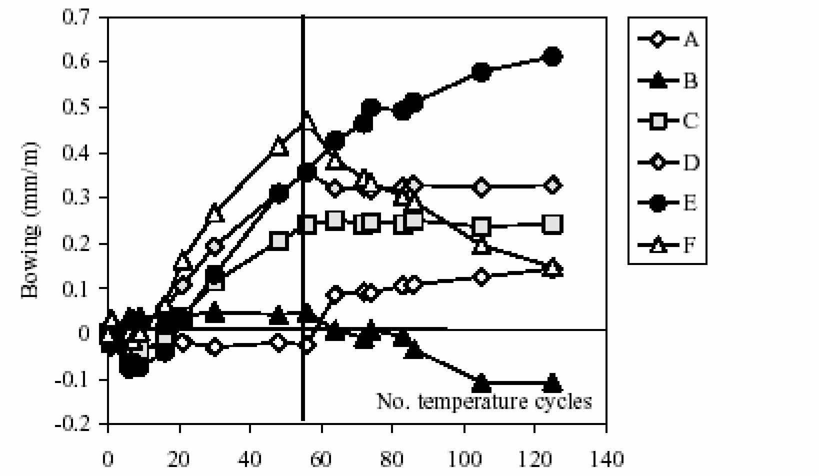


Figure 5.18. Bowing on Norwegian marble versus cycles; wet and dry exposure.

A: Dry exposure until 56 cycles, then wet.
B: As A, but with wetting of upper surface.
C: Wet exposure for the first 56 cycles, then dried.
D: Wet exposure for the first 56 cycles, then constant temperature in dry environment.
E: Wet exposure.
F: Wet exposure, but sample is turned after 56 cycles.

Bowing and loss of strength have been reported by Yates et al (2004) to correlate in samples from building claddings. Flexural strengths have therefore also been measured on a number of bowing laboratory specimens. A correlation of loss of flexural strength and bowing has been observed on the laboratory specimens.

Expansion

One of the first to report irreversible thermal expansion of different marble types was Kessler (1919), but many researchers have later shown, that repeated heating cycles lead to permanent expansion of marble. The TEAM-project has therefore developed a test method for permanent expansion of marble, exposed to temperature cycles.

This test method uses a standard test specimen of 30 x 30 x 300 mm. The temperature of the water in the tank follows the same variation as the surface temperature in the bowing test with a tolerance of +5 °C. The length of each specimen is measured 2 hours after 80+5 °C in the water has been reached. The temperature is then decreased to the ambient temperature and the length is measured again at least 2 hours after 20+5 °C in the water has been reached.

The expansion can be mapped as a function of the number of exposure cycles as shown in Figure 5.19, where it can be seen that the expansion seems to grow continually with the number of exposure cycles. The similar exposure can also be carried out in a dry environment and will lead to an expansion, which after a few cycles reach a permanent level. This difference between the wet and the dry exposure corresponds to the differences observed in the bowing testing. The expansion testing can also be carried out with every second cycle dry and every second one wet, simulating an environment, where moisture is only available in some periods. Figure 5.19 shows that this exposure (wet/dry) will lead to approx. the same expansion as a constantly wet environment.

The permanent expansion may lead to large forces in the panels and joints and may lead to failure of the panels or the fixings and so it is important that the magnitude of the likely expansion can be established in the laboratory.

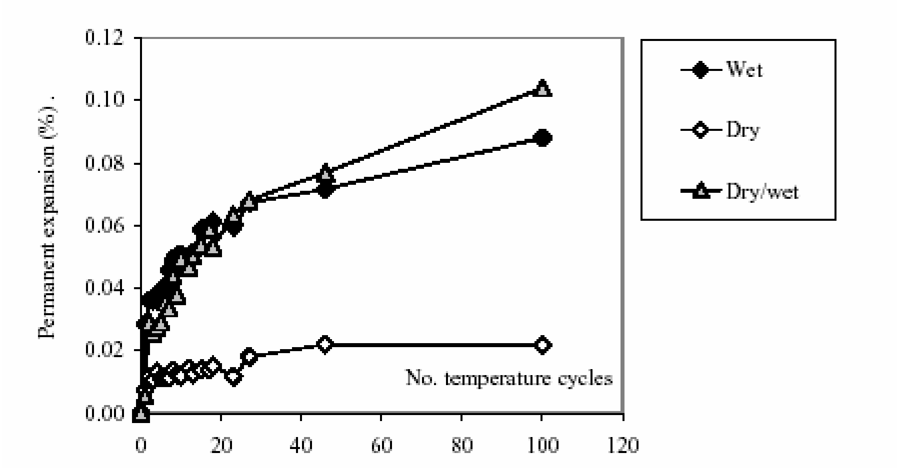


Figure 5.19. Permanent expansion versus cycles; for wet and dry exposure of Norwegian marble.

3.5.5.5 In-situ site monitoring observations

Selection of monitoring parameters and sites

Based on the wide range of geographical locations, materials and buildings identified and recorded in WP 1, three sites were selected for continuous monitoring of deformation/ movements for panels and monitoring of environmental conditions in order to determine under which conditions bowing is occurring and how the changes vary with time. This necessitated the development of equipment for long term monitoring, installation of equipment at three locations and processing of the results. The data is being used to calibrate model of the risks of failure associated with the changes in the properties of the panels over long periods of time in order that these risks can be better understood and managed.

The selection of parameters to be measured, selection of equipment and selection of suitable buildings were all given careful consideration before being agreed. It was agreed that ideally at each location monitoring would include:

- surface temperature on the external surface of the stone
- time-of-wetness/condensation on external surface of the stone
- strain in two directions on the external surface of the stone
- surface temperature on the internal surface of the stone
- air temperature in the gap behind the panel

- relative humidity in the gap behind the panel
- time-of-wetness/condensation on internal surface of the stone
- strain in two directions on the internal surface of the stone
- shade air temperature
- shade relative humidity

There were problems with finding ideal sites and so there was a need to "compromise". The final list of sites was:

- Danish National Bank, Denmark
- University Library Göttingen, Germany
- Nyköping City Hall, Sweden

Installation of equipment
The first two sets of equipment were installed in Copenhagen at the beginning of September 2001, two sets of equipment were installed in Göttingen in November 2001, and three sets at Nyköping in October 2002. The "sophistication" of the equipment has progressed as the team has gained further experience of the sites and have overcome the initial problems relating, for example, to the fixing of the strain gauges.

Danish National Bank
Amongst the most interesting results from the Danish National Bank in Copenhagen is the fact that there is very little difference between the temperatures on the front and back of the panels – only a few minutes "lag". On the eastern side the front can be 4 ºC warmer when the sun first shines on this face. The full temperature rise can take 6 hours but in more extreme cases the rate is around 0,3 °C per minute and this information has been used in the development of the bowing test.

Göttingen University Library
The equipment has been in place since November 2001. The initial aim of the logging at this site was to evaluate a new type of temperature and humidity logger and to evaluate the first strain gauges for their thermal stability and the magnitude of movement. Most of the equipment seems to be working well but there are concerns about the strain gauges as the data shows sudden changes in strain. One set of covers have been added but it does not seem to have solved the problem. Despite some problems with the downloading of data interesting results have been found with diurnal cycles clearly visible against a background of longer term changes with reliable stable data being obtained over short periods – for example 7- 8 days.
However, over longer periods the "drift" and background strain readings still seem to show sudden changes.

Nyköping City Hall
The equipment was installed on the City Hall at Nyköping in October 2002 – this was timed to coincide with the setting up of the field exposure site. The aims at this site are to evaluate the re-designed strain gauges, in particular to look at the magnitude of movement, expansion vs bowing and the effects of surface treatments.

The results show that the panel which was removed from the building in November 2002 and replaced on new fixings shows a fairly rapid bowing immediately after the panel was replaced – possibly as it moved back against the fixings- followed by a long period with very little movement.

One panel was of new Carrara marble and this has bowed in the opposite direction to "old" panel and the magnitude of the bowing is also much greater.

The third panel at Nyköping was new Carrara marble that had been treated with a hydrophobic coating. The treatment was intended to reduce the bowing. Initially the rate seemed to be reduced but this became less clear after a longer exposure period.

The in-situ monitoring provided important information for the development of the tests – particularly data on the likely temperature ranges (both diurnally and annually) and the temperature gradient through the thickness of the panel.

3.5.5.6 Summary and conclusions

The purpose of this Task was to consider and quantify a wide range of data from earlier research, observations on buildings, in-situ monitoring, and laboratory tests in order to verify that the two laboratory tests evaluated in WP 6 provide a relevant and realistic prediction of what would happen to the panels under the field conditions in a structure. The results of the testing of the bowing potential and the expansion potential must therefore be correlated to the observations on structures.

- The work has confirmed the importance of external factors – particularly temperature variations in combination with humidity are the external factors required for bowing to occur.

- A very good correlation was observed between the observed bowing problems and the laboratory bow tests; all stone types, which had been observed or reported to bow on the facade did also bow in the laboratory.

- Stone types, which did not bow in the laboratory, has not been observed or reported to bow on any facade.

- The correlation between bowing and loss of strength, observed in exposed building panels has also been observed in laboratory test specimens. The bowing test method therefore provides a good assessment of the risk of bowing potentials in real structures.

- The test methods are able to distinguish between stone types with low, medium and high bowing and expansion potentials, thus providing a very much needed tool in the selection of suitable marbles.

The two test methods have now been tested over more than 5 years and on 75 different stone types, which cover marble, sandstone, granite, chalkstone, etc. and originate from over 15 countries. The test methods have been found to work very well in the laboratories involved. The results of the test methods correspond to the observed behaviour in buildings with marble cladding. The results of the test methods also provide a necessary link to other material data and to the microstructure of the marble and will thus facilitate the understanding of the deterioration mechanism.

3.6 WP 6 Laboratory test methods

3.6.1 Objectives

There are two main objectives in this work package:

- To develop a test method for assessment of the potential risk of bowing.
- To develop a test method for assessment of the potential risk of irreversible thermal and hydric expansion. (Existing EN-standards are not suitable for natural stones to be used as outdoor cladding).

These two objectives also formed the two first tasks of the WP. The third task aims at drafting the methods in the CEN format and provide them with precision data according to the results of an inter-comparison trial.

The two tasks are a direct continuation of the work done in WP 5.4. The specific purpose of WP 6 was to define the final versions of the test methods to be used in the precision trial and to recommend to CEN TC 246 Natural stones.

3.6.2 Test method for bowing properties

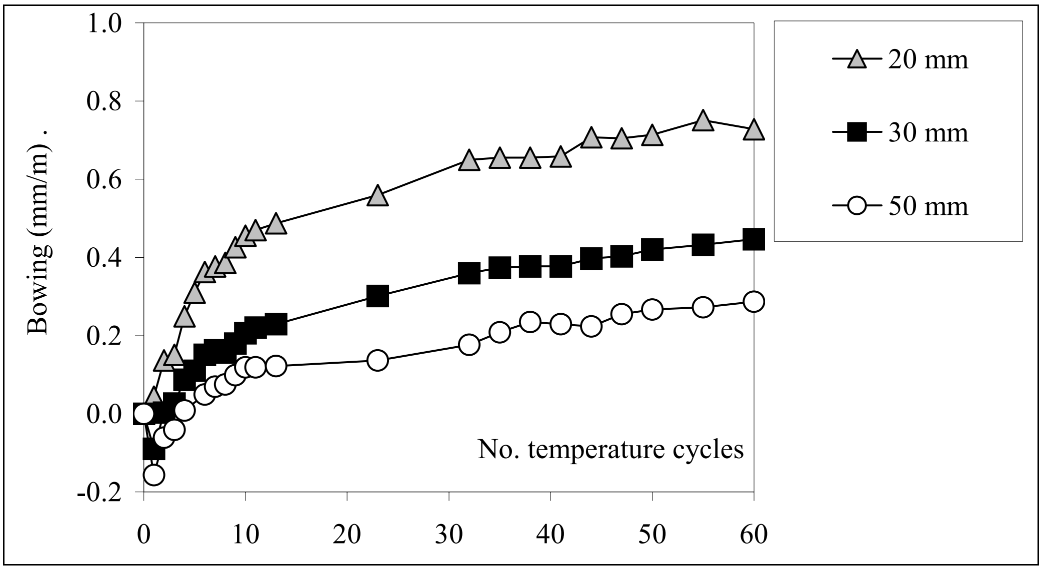
3.6.2.1 Background

A standard test method was developed and published in NT Build 499 (common Nordic test methods) in the late 1990ies. It was imperative that the test method simulated the environmental conditions for a facade panels, and that the results of the test could be correlated with observations from actual weathering. Tests were carried out on marble, limestone and granite, and all results proved to be in agreement with building observations. However, only a limited number of marble types were tested, and still there was no obvious explanation for the mechanism behind the bowing phenomena of marble.

3.6.2.2 Development of the test procedure

Through numerous experiments in TEAM (in WP 5 and 6), the key parameters were identified and subsequently restrained. The variation in results was mostly due to un-precise exposure to heat, and a controlled heating curve was included in a new test description. The black reference according to ISO 4892-1 was introduced to ensure the same external climate (heating) for any test specimen. This will actually result in different surface temperatures on marble of different colour. Very dark marble will reach a maximum temperature near to 80 °C and a white marble will reach a surface temperature around 50 to 60 °C. This is in agreement with measurements on many buildings around Europe.

Testing showed that the thickness is influencing the test results (figure 6.1) and had to be specified. Standard test specimens are used with dimensions of 400 mm length, typically 100 mm width and a thickness, similar to the panel’s thickness (or 30 mm in standard tests). The specimen is conditioned by drying at 40 °C until a stable weight is achieved (usually within 7 days), followed by cooling to 20 °C and then partially submerged into water for 24 hours at this temperature.



Figur 6.1. Bowing of samples of Norwegian marble with different thickness versus cycles; wet exposure.

The detailed case studies in WP 2 provided the specification of the temperature curve.

After conditioning, the specimen is placed on top of the filter cloth in the insulated container (figure 6.2). The tray is filled with distilled or demineralised water up to approx. 10 mm below the upper surface of the test specimen. The specimens are exposed to a number of heating-cooling cycles. Each cycle begins with an exposure to heating from above, which lead to an increase of the surface temperature from the ambient room temperature to a maximum 80°C, depending the colour of the marble, over a period of 1-3 hours. The surface temperature of the black reference is maintained at 80°C for 2-3 hours, after which the heating is turned off and the specimen allowed to cool to ambient room temperature, (20°C) until at least 24 hours has passed from the start of the exposure cycle. The surface temperature of the black reference must follow a defined T-curve with a tolerance of ± 2°C at the maximum temperature.

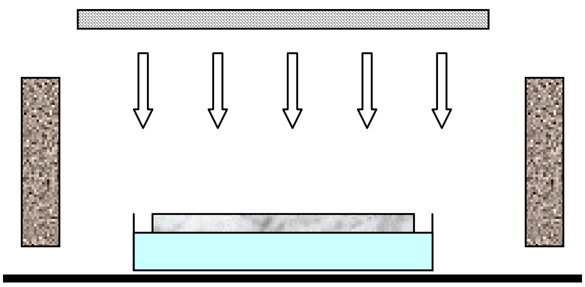


Figure 6.2. Principle sketch of equipment for testing the potential bowing properties of marble. The test specimens are placed in container which is partly filled with water and heat is distributed from above. The walls are preferably insulated.

The bowing of the specimen is measured at 20 °C at regular intervals after a defined number of cycles. A minimum of 25 cycles are used. Depending on the bowing magnitude and the shape of the bow-curve another 25 cycles may be necessary to carry out.

The results from the investigations showed that the test itself is quite sensitive to a range of parameters, ranging from how careful the test specimens is handled by the operator during the test period, to the heating rate of the temperature cycle. A number of factors therefore have to be controlled to enhance the reproducibility of the data. Controlling a number of these factors constituted the main improvements of the Nordtest 499 method, and was the basis for performing the precision trials in task 6.3.

The improvements comprised e.g.:
- Uniform maximal temperatures by using a black reference plate (according to ISO 4892-1) as thermometer.
- Controlled heating rates by using the automatic Eurotherm 2604 system
- Improved formula for calculation of the actual bowing

Conclusions

- The test method has now been tested over more than 5 years and on 75 different stone types, which covers marble, sandstone, granite, chalkstone, etc. and originate from over 15 countries.
- The test methods have been found to work very well in the laboratories involved. However, it is clear that the test has to be used and skill has to be developed to be able to handle the more complicated parts of the testing procedure.
- The results of the test methods correspond perfectly to the observed behaviour in buildings with marble cladding. No observations from the laboratory and from building inspections "contradict" the correlation between the two. In addition, the AGA-analysis is another important test that can be used for assessing the bowing potential and which correlates well with the results of the bow-test.
- The test method are able to distinguish between stone types with low, medium and high bowing potentials, thus providing a very much needed tool in the selection of suitable marbles. The methods are being discussed as potential CEN-test methods and could form a part of the later, mandatory product control.
- The results of the test methods also provide a necessary link to other material data and to the microstructure of the marble and thus facilitate the understanding of the deterioration mechanism. A clear correlation between microstructure and bowing potential have been established: Marbles with a granoblastic texture have high bowing potentials, while marbles with xenoblastic texture have low bowing potentials.

3.6.3 Test Method for Irreversible Thermal and Hydric Properties

3.6.3.1 Objective

The purpose of Task 6.2 – Test Method for Irreversible Thermal and Hydric Properties – has been to develop a test method for permanent expansion of natural stone exposed to temperature cycles and humidity on a facade. The test method shall be used to determine the appropriate joint width of marble panels and its suitability for cladding purposes.

3.6.3.2 Introduction and background

Thermal treatment leads to permanent irreversible expansion in every stone type. The magnitude of permanent expansion is considered as the accumulated amount of the widening of micro-cracks that causes the granular de-cohesion of the material and thus accompanied by a significant loss of strength. The permanent expansion may therefore lead to failure of the panels at the location of anchoring (figure 6.3). Thus, it is important that the magnitude of the likely expansion can be pre-established in the laboratory before use on a facade.

Figure 6.3. Expansion of panels leads to contact stresses which can provoke spalling at the fixing points.

Repeated heating cycles under dry conditions reaches a constant level after a few cycles. In contrast, permanent expansion, under wet conditions, seems to grow continually with the number of exposure cycles. The TEAM-project has therefore developed a test method for thermally and moisture induced permanent expansion of marble.

The aim of this task was to optimize the test procedure and equipment for the assessment of permanent expansion as a function of varying temperature and humitidy conditions. For this purpose, key variables had to be identified and constrained in order to establish stable and reproducible environmental conditions in the experimental set-up.

3.6.3.3 Development of the test procedure

In the following, important parameters which can have an impact on the magnitude of permanent thermal expansion are identified.

3.6.3.4 Moisture

Moisture is one of the critical parameters. Under cyclical heating all stone types will show a permanent expansion, however, in a dry condition there will be only a limited permanent expansion. In a humid condition the expansion is larger but still much smaller than in a wet condition. Expansion tests performed on specimens conditioned in a moisture chamber show slightly higher expansion than under dry specimens. In addition it is often difficult to achieve reproducible conditions when a certain level of moisture shall be achieved at several laboratories. The expansion test carried out with changing dry and wet conditions leads to the same or even slightly higher permanent expansion (figure 6.4). The capillary forces also act during the drying phase.

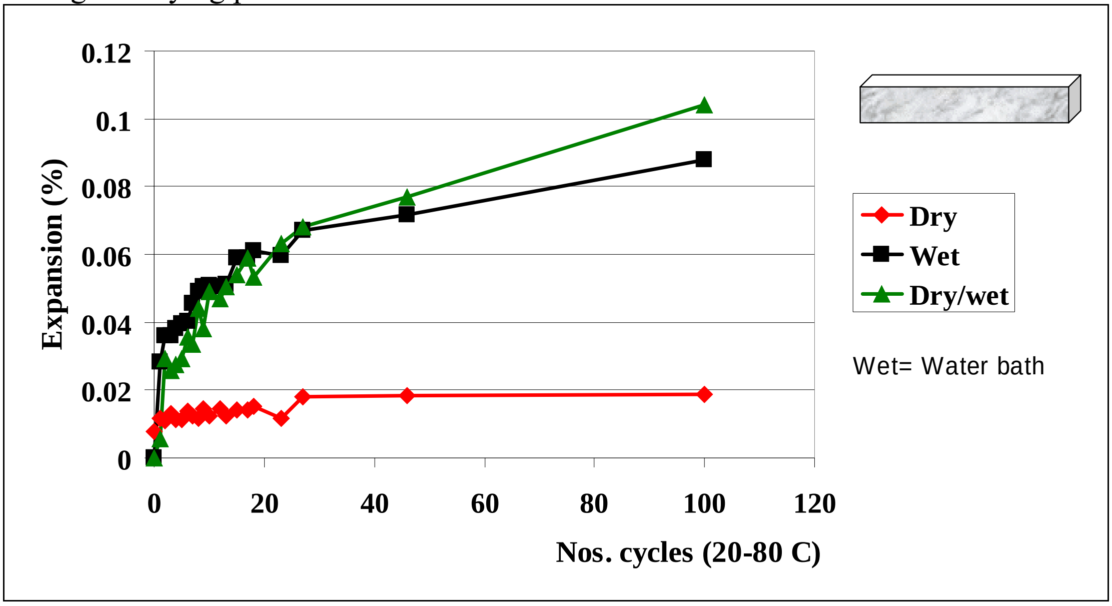


Figure 6.4. Permanent expansion of a Norwegian marble in different moist conditions.

Therefore, the most reproducible test conditions are gained when the specimens are constantly submerged. This also simulates the worst case on a facade.

3.6.3.5 Temperature

Temperature variations are absolutely essential for permanent expansion. The maximum temperature during cyclical heating has a significant impact on the magnitude of permanent expansion (figure 6.5). Examples on maximum temperatures on building facades are given from Copenhagen (~53 °C in August, South facade, light to dark grey marble) and from Paris (~77 °C in July, South facade, dark limestone) so that a destination temperature of 80 °C in the standardized expansion test appears reasonable.

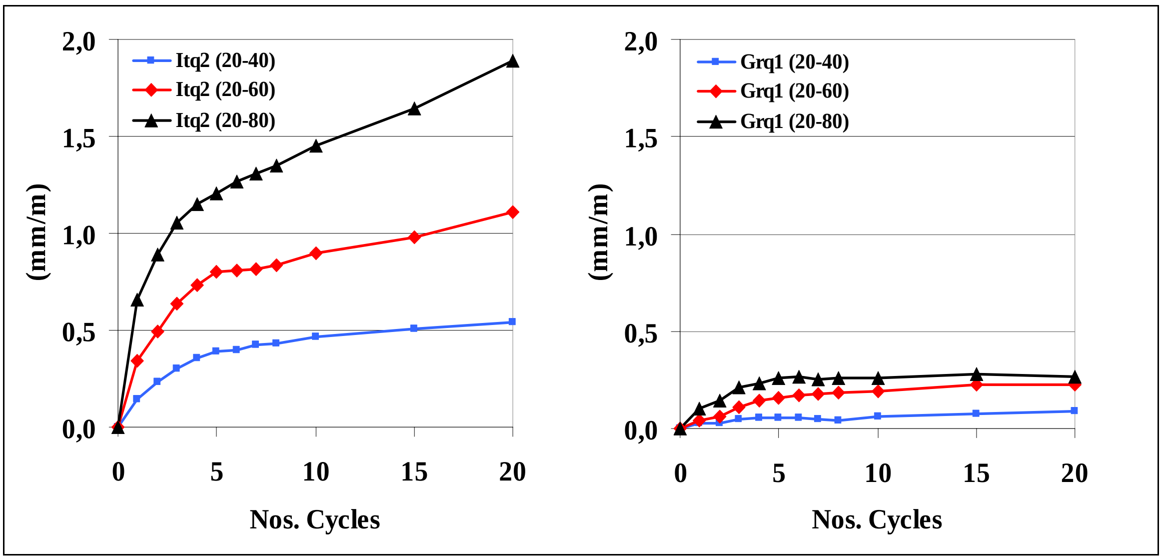


Figure 6.5. Permanent expansion of a strongly expanding (left) and a weekly expanding marble (right). Expansion curves are shown at different temperature intervals with different maximum temperatures (40, 60 and 80 °C).

The temperature regime, i.e. the rate of temperature increase and decrease during a temperature cycle also influences the magnitude of thermal expansion (figure 6.6 and 6.7). The highest permanent expansion can be observed when the temperature changes happen rapidly.
The detailed case studies in WP 2 provided the specification of the temperature curve. Examples from different facades reveal temperature increase rates of up to 20 °C/hour. Additionally, the temperature curve follows very closely the one in the test method for assessment of the potential risk of bowing since both permanent expansion and bowing are subject of the same conditions. This also allows for a correlation between the permanent expansion and the bowing.

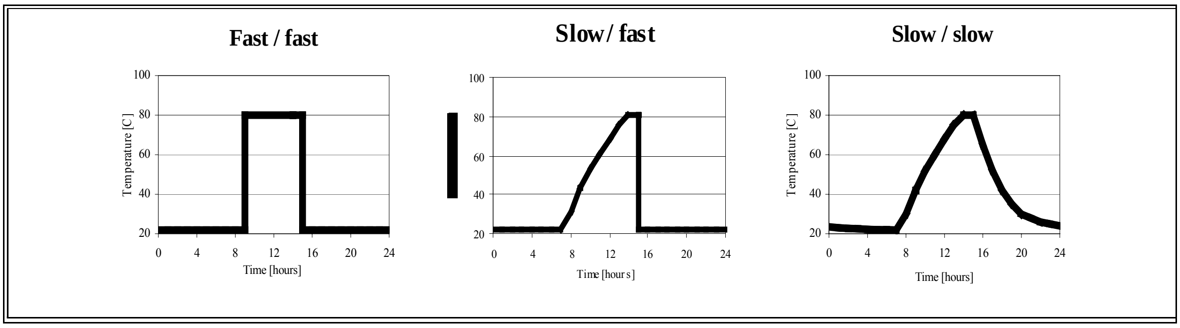


Figure 6.6. Principle sketch of different heating and cooling situations.

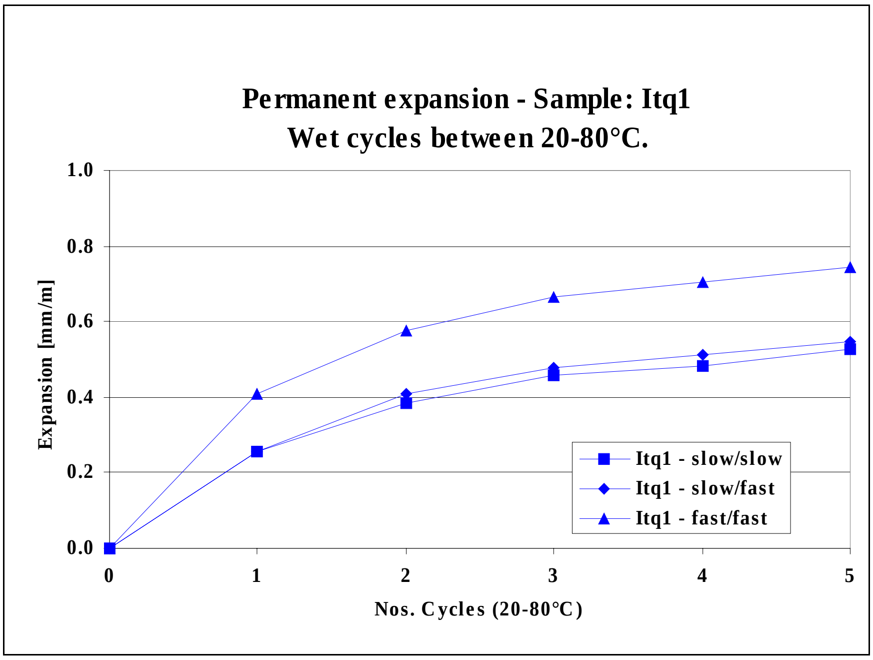


Figure 6.7. Permanent expansion as a function of the heating-cooling regime.

3.6.5.4 Orientation in relation to the rock fabric

Anisotropic fabric properties can have a significant impact on the magnitude of thermal expansion. Therefore, the orientation has to be considered when the expansion potential is assessed. The highest amount of permanent expansion can normally be observed parallel to the preferred orientation of the crystallographic c-axes of calcite which normally coincides with the perpendicular of the foliation plane of dynamically recrystallised marbles ("Orientation A" in figure 6.8). In addition to the lattice preferred orientation (LPO), the grain boundary orientation has an effect on the anisotropy of thermal expansion. This fabric parameter used to support the effect of LPO in most cases.

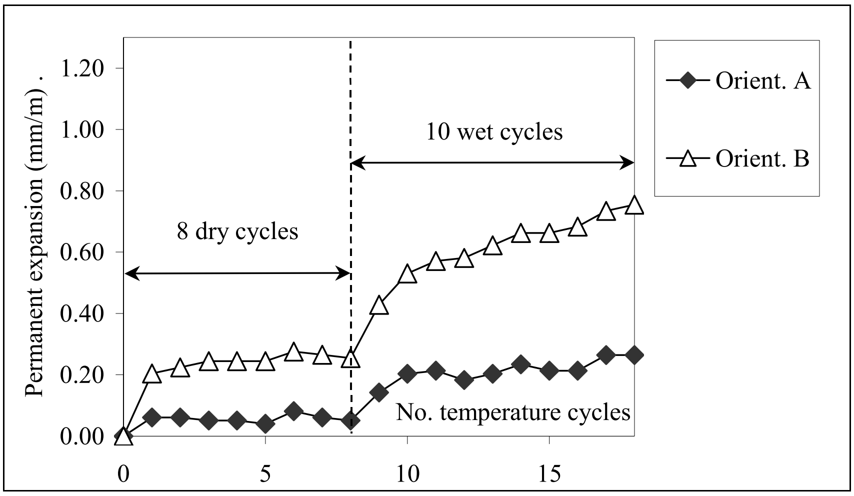


Figure 6.8. Permanent expansion in two different directions of the same marble type. "Orientation A" is perpendicular to the foliation plane (=preferred orientation of grain boundaries) and parallel to the preferred orientation of the crystallographic c-axes of calcite. "Orientation B" is perpendicular to "Orientation A".

3.6.5.5 Specimen size

The width of test specimen has no unambiguous influence on the permanent expansion (figure 6.9). It seems that a larger width produces a lower expansion result (in the test!), but for one exception, the 20 mm wide prisms. This is mot likely due to the combination of grain size and too small a sample dimension, the so called "corner effect". To avoid such effects it is of recommended that the smallest dimension shall be at least 3 times the grain size. Similarly, due to the heterogeneity and the large grain size of some marble types a sample length of less than 200 mm is not justifiable.

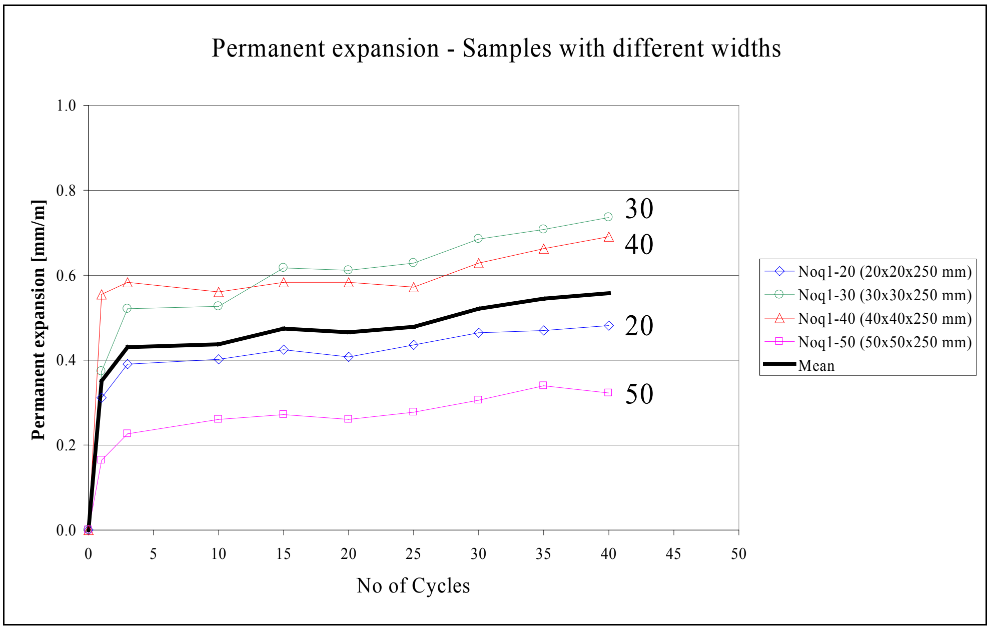


Figure 6.9. Expansion curves of a Norwegian marble as a function of the sample width.

3.6.5.6 Number of specimens

Heterogeneous marble types require a higher number of specimens than homogeneous marble types in order to get a reliable result (figure 6.10). In addition, the risk of loosening measuring knobs is high. For this purpose, a number of six specimens per marble type and orientation was found to be the required minimum.

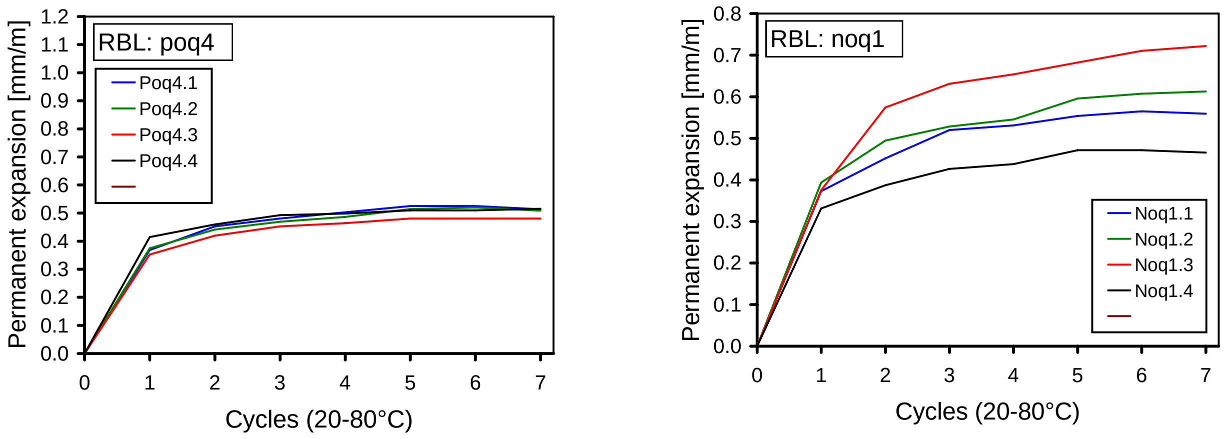


Figure 6.10. Variability of expansion curves of a homogeneous marble from Portugal (left) and a heterogeneous marble from Norway (right).

3.6.5.7 Number of temperature cycles

The test results showed that the increase rate of permanent expansion does not significantly change after 10 cycles, thus, a number of 10 temperature cycles is sufficient to assess the expansion behaviour.

3.6.5.8 Conclusions

- The test method has been found to correlate very well with the results from the laboratory bowing test.
- In the test method, the influence of moisture and temperature has been identified and constrained to ensure a stable and reproducible environmental conditions in the experimental set-up.
- For the test method, the minimum number of specimens and temperature cycles as well as the proper size of specimens have been identified.
- The test method is able to distinguish between stone types with low, medium and high potentials of permanent expansion. The method is being discussed as potential CEN-test method and could form a part of the later, mandatory product control.
- A clear correlation between microstructure and permanent expansion has been established. Marbles with a granoblastic grain fabric have a high magnitude of permanent expansion, while marbles with an irregular grain fabric have a low magnitude of permanent expansion. It was found that the directional dependence of permanent expansion is controlled by the lattice preferred orientation and the grain boundary preferred orientation of the calcite (dolomite) crystals.
- The test method takes into consideration both the permanent expansion and the loss of strength of the natural stone, something that facilitates a better understanding of the degradation process and the extent of it.

3.6.4 Inter-Comparison trials

The inter-comparison trial aimed at determining the repeatability (r) and the reproducibility (R) of the test methods. In addition it aimed at finding any remaining critical variables that needed further detailing.

3.6.4.1 The bow test

Based on the initial tests of bowing potential in WP 5, three different marble types were chosen to be included in the precision trial. One with no expected bowing potential (seq1), one with a low-mean bowing potential (plq2) and one with high bowing potential (itq2).

Four test specimens and the final draft of the method was distributed to all laboratories. In addition a test protocol was developed to use for compilation and calculation of the results in an equal manner for all participants.

It turned out that there were still several differences in the test equipment and means to monitor and control the temperature between the different participants. These differences greatly influenced the results that scatter more than expected (figure 6.11). A few of the more critical deviations are:

- Measuring all cycles, which will induce higher stresses on the test specimens than measuring them every 5th cycle
- No black reference or no way to use it for controlling and monitoring the temperature.
- Measuring the temperature on the surface of the black reference with an infrared device. This has proven to give a different temperature than to use the built-in thermocouple.
- Measuring the temperature on the surface of the stone instead of on the black reference

By trying to improve the writing and clarifying some of these aspects it should be possible to avoid these errors and achieve an acceptable precision.

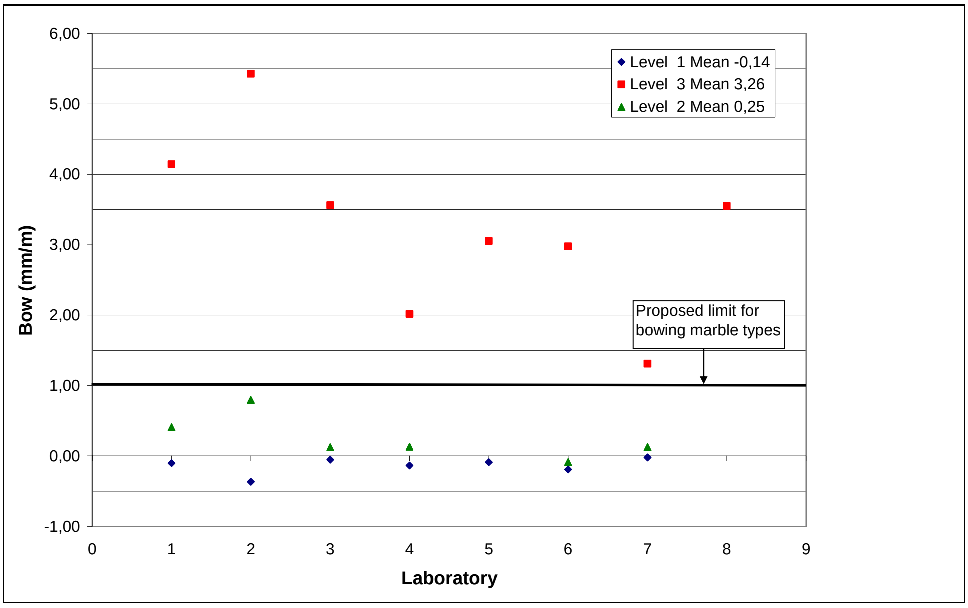


Figure 6.11. Diagram showing the mean values of the laboratories bow-test results. Outliers have been deleted.

The test results (table 1 and figure 6.11) indicate the bowing of the second level to be quite lower that expected and only slightly higher than level 1. However, the statistical evaluation indicates that the difference between level 1 and 2 is not significant. This, together with the heterogeneous nature of itq2, contributes to a significant part of the spread in the results and the possibility to define outliers. The identification of outliers can also be aided by comparing the results from the precision trial with those obtained in WP 5.

Table 6.1. Individual results (mm/m) for all laboratories and test specimens.

Decimal:	3	3	3
Laboratory	Ekeberg	Gioia	Slavnivice
SP, test 1	0,163	4,653	0,408
test 2	-0,082	3,020	0,245
test 3	-0,327	4,571	0,327
test 4	-0,163	4,327	0,653
BRE, test 1	-0,490	5,469	0,816
test 2	-0,245	5,224	1,061
test 3	-0,327	5,469	0,571
test 4	-0,408	5,551	0,735
PTO, test 1	-0,122	3,176	-0,016
test 2	-0,008	4,163	0,238
test 3	-0,176	2,931	0,090
test 4	0,098	3,976	0,189
STF, test 1	-0,155	3,167	0,180
test 2	-0,327	2,082	0,073
test 3	0,049	1,110	0,122
test 4	-0,106	1,706	0,147
UGE, test 1	-0,302	4,776	
test 2	-0,024	2,694	
test 3	0,000	1,363	
test 4	-0,024	3,380	
ZAG, test 1	-0,302	4,482	-0,122
test 2	-0,220	1,967	-0,147
test 3	-0,139	2,767	-0,090
test 4	-0,106	2,694	0,016
RMB, test 1	0,016	0,898	0,106
test 2	0,000	0,204	0,098
test 3	0,000	1,878	0,196
test 4	-0,106	2,261	0,106
IMB, test 1	0,604	3,192	1,192
test 2	0,351	4,114	1,241
test 3	0,327	3,347	1,061
test 4			1,331

The statistical calculation of precision data in accordance with ISO 5725:94 produces several different ways to treat and interpret the results. Two of the more commonly used ones are k- and h-statistics (figure 6.12 and 6.13). They provide a measure of the repeatability of each laboratory and the deviation from the general mean.

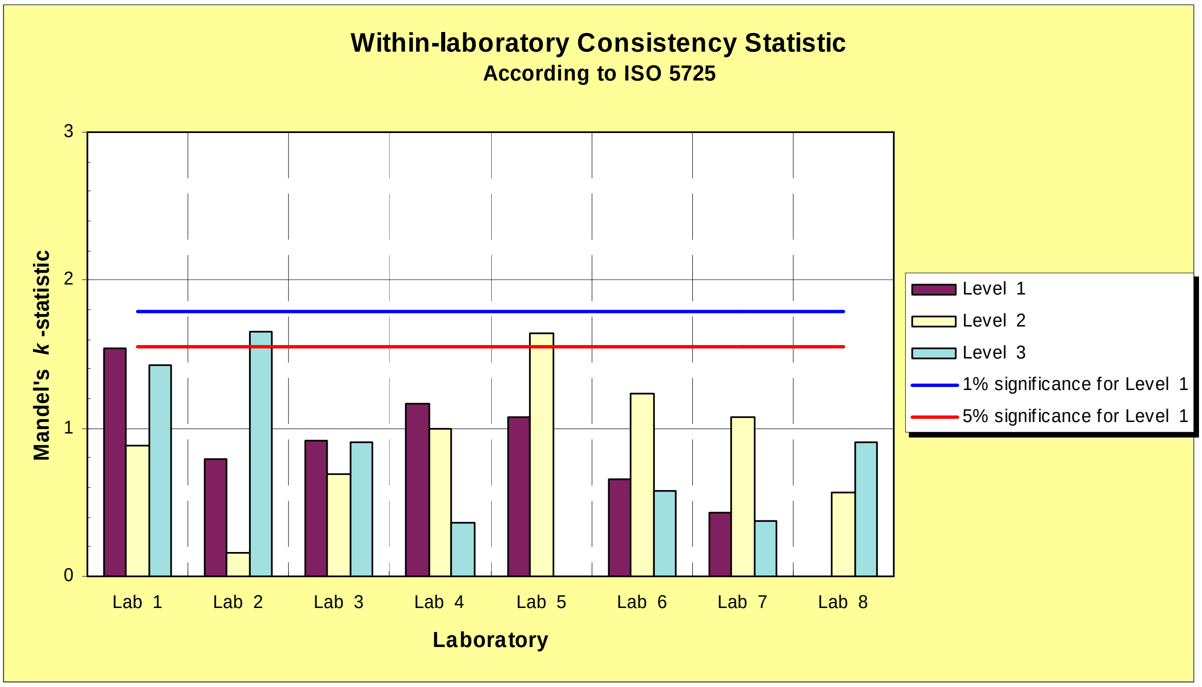


Figure 6.12. K-statistics a measure of the repeatability. The diagram shows the number of standard deviations from the laboratory mean value.

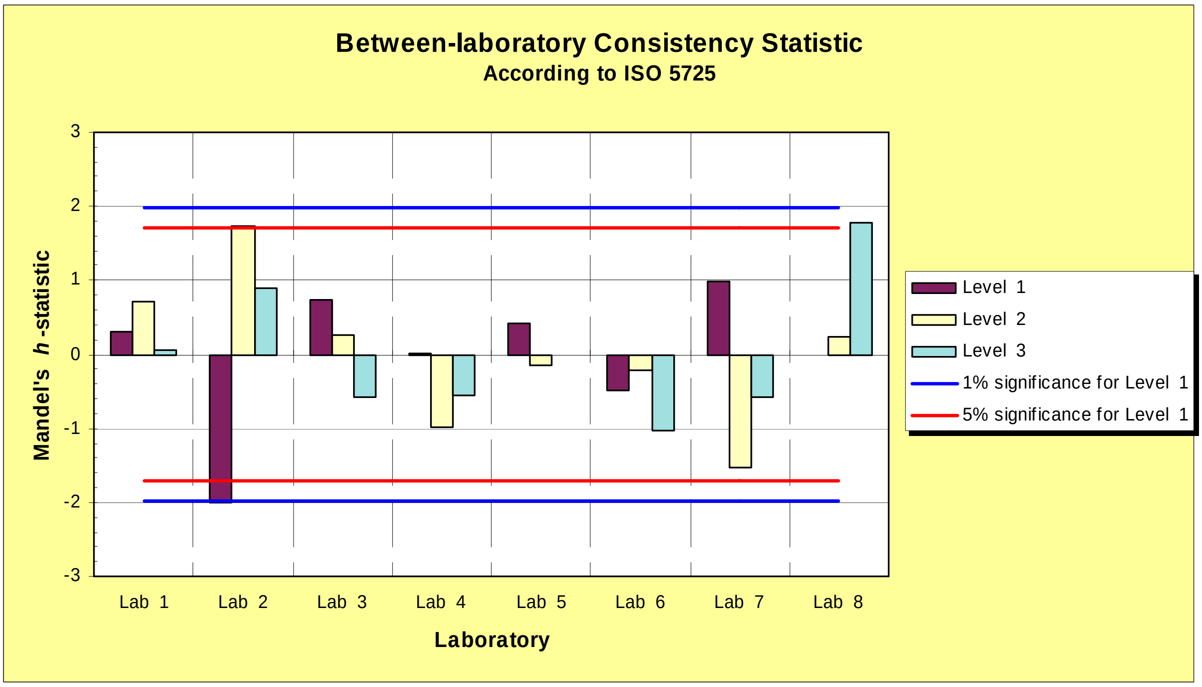


Figure 6.13. H-statistics, a measure of the reproducibility. The diagram shows the deviation from the general mean value.

Discussion and conclusion

Preliminary results for 8 laboratories, 3 different marble types and 4 replicates indicate that the number of test specimens (replicates) shall be increased to 6 and that the method is very sensitive to any deviation from the defined test procedure. All participating laboratories did not have access to the black reference and the temperature control is the single most important factor in this test. The results therefore scatter more than wanted. Especially the rate of achieving the maximum temperature is crucial and the possibility of maintaining the maximum temperature with very small variations (± 2 °C) in all parts of the test "chamber". However, it is clear that the method can discriminate between bowing and non-bowing marble. This is also the main purpose of the method. The proposed threshold is 1,0 ± 0,1 mm/m and all laboratories were able to discriminate between marble above and below this limit.

The test method has been amended accordingly to include a more detailed definition of the test procedure for improved precision. A follow-up precision trial is recommended when all laboratories have installed the necessary equipment and been accustomed to the test. It is not recommended to use the test for any major building project until the laboratory has proven able to achieve accurate test conditions and results.

3.6.4.2 The expansion test

The project also deals with marble cladding where the problem is not bowing but expansion. One limestone was also included in the precision trial for the expansion test in addition to the same three marble types included in the bow test.

The same organisation system as for the bow-test was used and a template for reporting of the test results was developed and submitted to the partners together with the last version of the test method.

Information about the equipment at the participating laboratories was collected before the trial. The range of different equipment is very wide. The differences in the equipment and techniques to measure length changes are clearly reflected in the differences in the test results (figure 6.14 and table 6.2). In addition, some laboratories lacked the possibility to stir the water to ensure a homogeneous temperature in all parts of the container. See also figures 6.15 and 6.16 for a statistical assessment of the laboratories' performance as repeatability and deviation from the general mean.

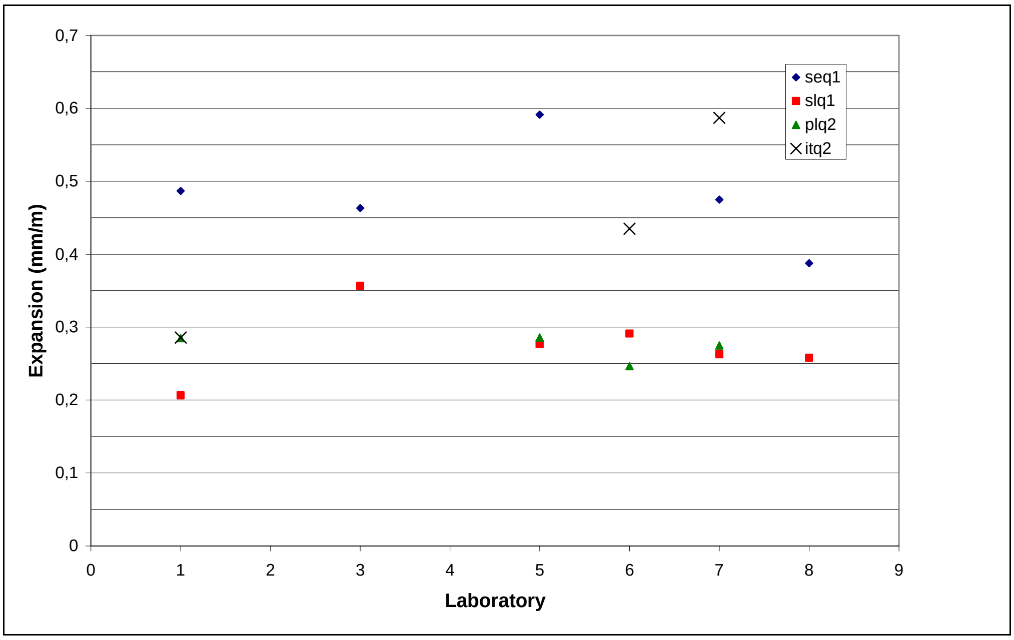


Figure 6.14. Summary of the mean values for all laboratories, outliers excluded.

Table 6.2. Individual results (mm/m) for all laboratories and test specimens.

Collection of the Original Data y_{ij}

Decimal:	3	3	3	3
Laboratory	Ekeberg	Hotavlje	Slavnivice	Gioia
1 SP, test 1	0,520			0,335
test 2	0,528	0,264	0,336	0,246
test 3	0,448	0,224	0,200	0,309
test 4	0,416	0,224	0,320	0,254
test 5	0,440	0,016	0,272	0,305
test 6	0,568	0,304	0,296	0,265
2 BRE, test 1	0,720	1,740	0,373	0,707
test 2	0,120	1,113	0,453	0,673
test 3	0,633	1,023	0,987	0,757
test 4	0,047	0,980	0,400	0,640
test 5	0,693		0,313	1,293
test 6	0,687			0,640
3 PTO, test 1	0,5	0,345	0,35	0,47
test 2	0,495	0,235	0,275	0,53
test 3	0,48	0,34	0,355	0,62
test 4	0,46	0,37	0,32	1,615
test 5	0,41	0,3	0,195	0,52
test 6	0,435	0,55	0,345	0,545
4 STF, test 1	5,332	2,824	0,619	0,299
test 2	4,266	2,982	0,734	0,769
test 3	4,779	2,761	0,367	0,612
test 4	4,801		1,073	0,414
test 5	4,376			0,670
test 6	4,801			0,435
5 UGE, test 1	0,550	0,177	0,335	
test 2	0,632	0,330	0,246	
test 3	0,592	0,324	0,309	
test 4			0,254	
test 5			0,305	
test 6			0,265	
6 ZAG, test 1	0,488	0,247	0,192	0,370
test 2	0,566	0,179	0,257	0,479
test 3	0,533	0,452	0,213	0,443
test 4	0,344	0,287	0,325	0,448
test 5				
test 6				
7 RMB, test 1	0,457	0,293	0,280	0,574
test 2	0,476	0,277	0,297	0,576
test 3	0,480	0,244	0,275	0,586
test 4	0,491	0,267	0,242	0,585
test 5	0,465	0,267	0,281	0,598
test 6	0,480	0,228	0,275	0,603
8 IMB, test 1	0,366	0,303		0,426
test 2	0,377	0,253		0,403
test 3	0,42	0,223		0,767
test 4		0,253		

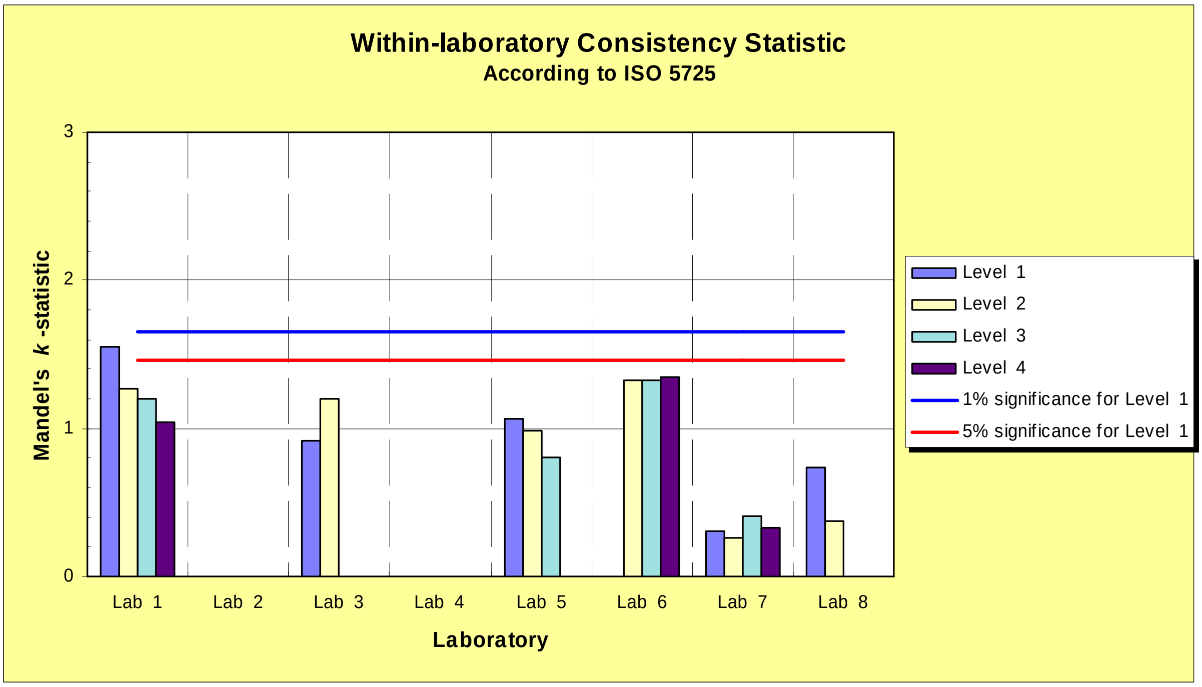


Figure 6.15. K-statistics a measure of the repeatability. The diagram shows the number of standard deviations from the laboratory mean value.

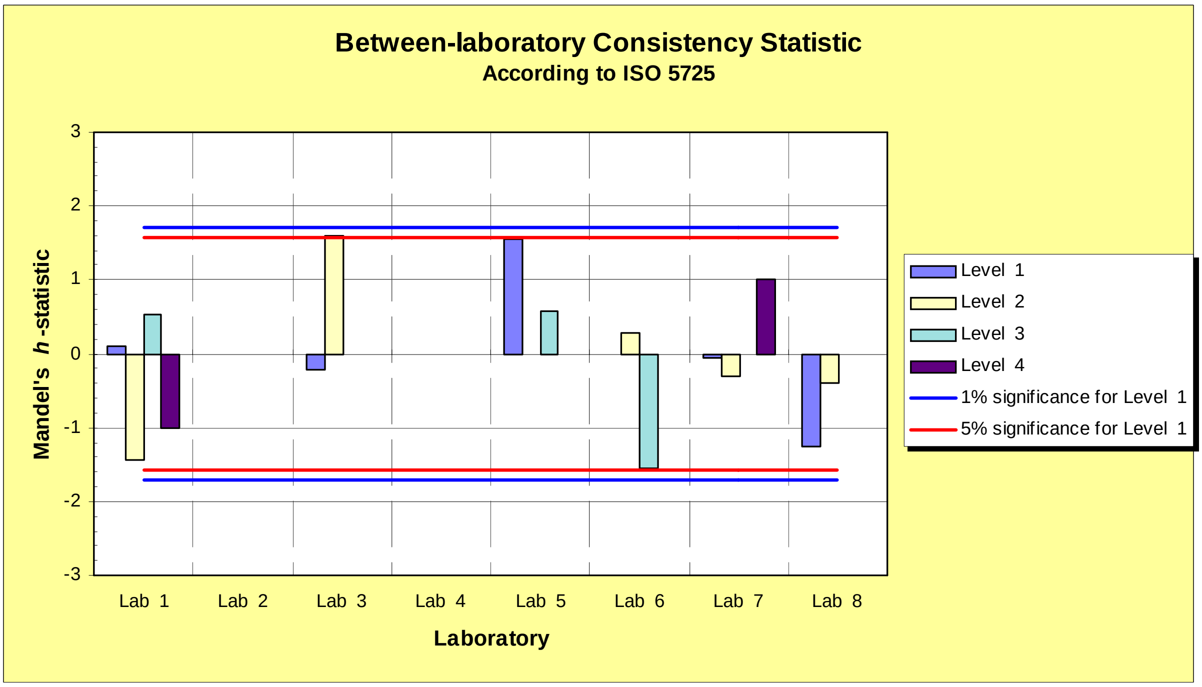


Figure 6.16. H-statistics, a measure of the reproducibility. The diagram shows the deviation from the general mean value.

Discussion and conclusion

Preliminary results for 8 laboratories, 3 different marble types, 1 limestone and 4 replicates indicate that the number of test specimens shall be increased from 4 to 6 and that the method is very sensitive to any deviation from the defined test procedure. The reproducibility coefficient of variation (S_R) is about 15 % for two of the materials and twice as high compared to the other two materials.

It is worth noting that by use of more homogeneous test materials it would most certainly be possible to get a better precision data. Especially the limestone and itq2 are quite heterogeneous, also indicated by tests in WP 5. However, natural stones are not always that homogeneous and the results will scatter more than for many other materials.

The test method has been amended accordingly to include a more detailed definition of the measurement procedure for improved precision. Especially the techniques of measuring length changes and to ensure a homogeneous temperature in the water bath have been restrained. A follow-up precision trial is recommended when all laboratories have been accustomed to the test.

3.7 WP 7 Impregnation and surface coating

3.7.1 Objective

The main objective of this WP was to evaluate if surface impregnating/surface coating treatments can reduce bowing and deterioration in cladding panels and if so, under which circumstances they can be applied. In addition, the WP was designed to evaluate whether the physical properties can be improved – particularly strengthen stone and reduce water absorption.

3.7.2 Introduction

The central part of this Work Package was the establishment of a series of field exposure sites where a wide range of parameters could be monitored and evaluated under controlled conditions. The sites were established at five locations; in Sweden, Poland, Slovenia, Italy and the UK. The materials exposed included a range of marble types and a more limited range of stone types which were exposed at different panel sizes, thicknesses, and different exposure directions (north, south, etc.). At the two sites in Sweden two treatments were applied to some of the panels – an "impregnation" and surface coating- to assess whether it is possible to reduce the bowing of some marble types. The exposure work was supported by laboratory tests carried out as part of Task 7.1 and Task 7.4.

The work was divided into four Tasks:

Task 7.1 Laboratory test for bowing
Task 7.2 In situ testing on existing panels
Task 7.3 Test field for bowing
Task 7.4 Positive side effects

3.7.3 Task 7.1 Development of a laboratory test for bowing

Different surface treatments and impregnation chemicals were reviewed and those that seemed suitable will be assessed. Initially it was envisaged that the test samples would include:

- Bowed marble from buildings
- New samples bowed artificially in laboratory tests
- New samples before artificial bowing

Following preliminary trials, using the bow-meter, this task was placed "on hold" until the partners involved had a better understanding of how the laboratory bow test worked and how water affects the deterioration of marble panels. However, the conclusion from a review of the task and the initial results from SP and Rambøll indicated that the bow test developed under WP 5 would not be appropriate unless the samples were treated on all surfaces as otherwise the moisture still effected the specimen. At some point in the future it will be necessary to decide whether the current bowing test can be adapted or if a new test is needed.

3.7.4 Task 7.2 In-situ testing on existing panels

The purpose of this Task was to perform in situ tests by applying treatments on existing panels at one or more localities representing various climatic/weather conditions. The main location for the test was combined with the monitoring being undertaken in WP 3. The treated panels and the effect on strain (dimensional changes) and water absorption was determined as part of WP 3.

This task took place in Nyköping on the main field exposure site in conjunction with the City Authorities (Municipality of Nyköping) who are partners in the project. After discussion with the project partners it was agreed that the following treatments would be applied on the Nyköping site:

- Trion Tensid (TT) microcrystalline wax, known as AGS (which should reduce water uptake as well as acting as an anti-graffiti barrier and a system for reducing weathering).
- EKA Colloidal silica.
- EKA and TT treatments (applied sequentially).

The treatments and coatings were applied to marble itq2 which is known from both laboratory tests and observations on buildings to be at risk of bowing.

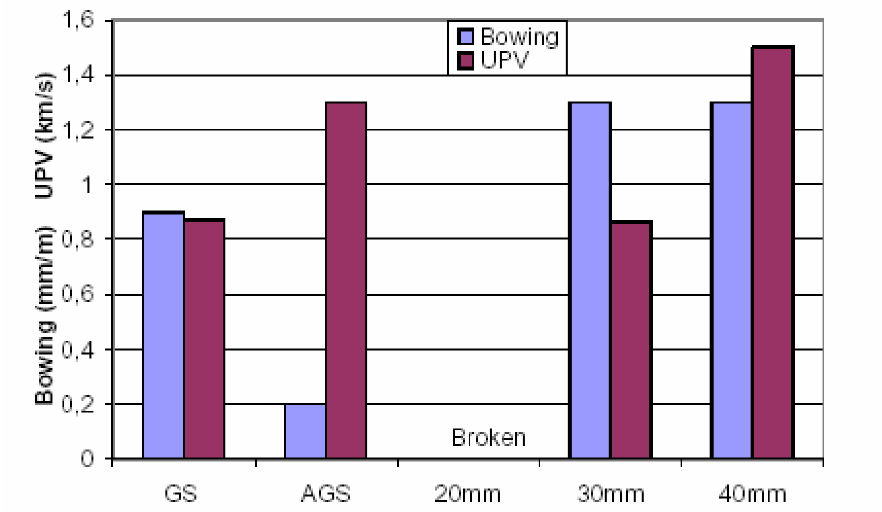


Figure 7.1. Absolute and permanent bowing for itq2 after three years exposure at Nyköping City Hall.

The panels were measured regularly to determine the permanent bowing using both strain gauges and the bow-meter. In addition, changes in UPV were also measured at regular intervals. Figure 7.1 (above) shows the results for the bow-meter and UPV measurements after three years of exposure. The AGS treatment appears to have inhibited the bowing of the panels with the same observations on both new and old panels. There is no apparent difference in the UPV values suggesting that the stones may still undergo some internal changes influencing the gradual disintegration.

3.7.5 Task 7.3 Test field for bowing

The test field for bowing was seen as an important and long term part of the project. Initially three locations were selected in addition to the "in situ" panels at Nyköping – these were SP (to give a colder continental climate), BRE (to give an Atlantic/humid climate), and Polito (to give a southern European climate). The extension of the project to include NAS countries (Newly Associated States) allowed two more sites to be established – in Slovenia and Poland. It was hoped to expose at least 20 different stone materials with and without surface coatings and impregnation systems and this was achieved – though not all the stones are on the Nyköping site. It is anticipated that the test fields will continue to be used after the end of the project. New chemicals and stone types have thus the possibility to be assessed and compared with reference data from those used in the project.

The main test field site is at the City Hall Nyköping. At this site full scale samples of 15 different marbles were installed in October 2002. There are also additional samples of Gioia Carrara marble of different thicknesses. Measurements are made at this site at regular intervals.

Figure 7.2. The test field site at Nyköping City Hall.

This was followed up by the installation of test field sites at SP, BRE and Polito with the racks in place in December 2002 at SP and at BRE and Polito in June 2003. Additional samples from the new partners have since then been added at these sites.

The key findings are that all marble type will bow, though for many it can not be considered significant within the monitored time span. Two types show significant variations with respect to bowing and Itq2 showed differences in bowing in relation to panel thickness and plan area.

One additional site, specifically to look the effect of different fixing systems, was set up at Fisherwerke, near Stuttgart, Germany, in conjunction with WP 2. The results of two years of exposure were compiled and assessed in August 2005. It showed that there is an influence by the fixing system. In particular it was confirmed that panels fixed in mortar resist bowing better than other types of fixing. The results are described in more detail in the WP 2.6 report.

Figure 7.3. The test field site at BRE, UK.

3.7.6 Task 7.4 Positive side effects

Surface treatments may have other positive effects besides reducing the bowing tendency. Parameters that were considered are the effect of different surface coatings and impregnation chemicals on surface finish behaviour (esthetical aspects including graffiti removal), frost resistance and effectiveness of cleaning and graffiti removal and effects on staining caused by sealant migration ("picture framing").

The positive effects on cleaning and graffiti removal were studied in collaboration with the chemical industry partner (EKA) and the stone cleaning partner (Trion Tensid). This included the partners assessing practical testing of the effectiveness and durability of different treatments in the laboratory and at the test site.

The work carried out at Nyköping on treatments was supported by a comprehensive accelerated test programme by NBI (Norwegian Building Research Institute) in collaboration with SINTEF using a large scale chamber which provides a number of different conditions in each cycle. This programme included the evaluation of a wider range of coatings and treatments and was also linked to Task 5.4. In total, 28 slabs were exposed to artificial ageing covering continuous cycling of the slab surface to UV- radiation, heat, water and frost (figure 7.4).

In addition to the EKA colloidal silica and the Trion Tensid AGS a hydrophobic treatment composed of acrylic-copolymer with various fluorinated, silane, non-ionic and ionized chains called Faceal Oleo HD and a Dow Corning MH-1109, a hydrofobic siloxane were included in the accelerated test.

The monitoring included both the effect of the cycles on the panels and on the treatments.

Figure 7.4. One of the series of panels in the NBI accelerated exposure chamber.

The accelerated test results indicated that:

- The fresh panels did show a very low bowing, while the old panels from Nyköping showed significant bowing.
- All panels showed strength loss and loss of sound velocity, independently of the impregnation.
- The impregnation did not prevented the strength loss of marbles exposed for freeze/thaw cycling. No significant differences between various chemicals were detected.
- The impregnation did not change the colour and visual appearance of the slabs.
- The microclimate in the surroundings of the slabs is one of the factors governing the direction of bowing.

3.8 WP 8 Production quality control

3.8.1 Objectives

Find methods, techniques and procedures for product and production control in order to minimise the risk for final stone products to give bowing/expansion problems. Through this also contribute to sustainable and economical materials productions and uses and by such also secure European environmental and safety aspects. Provide input to European Standardisation work regarding product requirements and Factory Production Control.

The work package is divided into two tasks:

1. Product Control (Screening Test)
2. Product control

3.8.2 Introduction

The main purpose of this "WP 8 – Production quality control" is to find methods and procedures for product and production control in order to minimise the risk for final stone products to give bowing/expansion problems.

The final report includes recommendations of value both for (1) producers/suppliers and for (2) planners and users of marble for cladding purposes. The recommendations within WP 8 are restricted to marbles and the topic of bowing, expansion and strength loss when used as thin exterior building claddings. Also input to European Standardisation work regarding product requirements and FPC – “Factory Production Control” is presented.

Lack of technical specifications and guidelines related to the bowing problem is a disadvantage at a time where such problems have turned up in several famous buildings, world-wide. The wishes to use marble as cladding materials for buildings are jeopardized. Many producers are aware of the potential durability problems of some marbles, however in general terms they lack detailed knowledge about their own materials in this respect.

Consultants, architects, building owners and investors must have confidence in the final product quality to secure that marble and limestone of sufficient technical quality are used. The material must be tested to ensure that it meets to required standards for the proposed design. Project specifications and tender documents must include requirements to achieve that proper testing and control is done.

Producers and suppliers of marble for exterior cladding purposes must have sufficient knowledge of the technical quality of their stone material, in order to give guidance for and deliver the right material to the appropriate application. FPC system that satisfies the requirements in relevant European product standards and codes of practices in various countries should be used. Such FPC system must manage to intercept quality variations of importance for the material usage.

The European FPC system defined for natural stone materials is not yet well known neither among producers nor among designers and architects. This situation is about to change, since many European product standards have become mandatory. FPC systems will soon be implemented by many producers and processing companies. They will benefit from better knowledge and control of the technical quality and quality variations of their own materials. However, the FPC as it looks today is not suitable for many of the applications or stone types. It has to be complemented with specific test methods, e.g. for bowing and wet-expansion. In addition, testing frequencies have to be adapted to each producer and quarry and not as today a standard frequency depending on the property.

The deterioration pattern of marble claddings may include bowing, strength loss and expansion. Frequently there are also examples of fractures and spalling of stone around the fixing points, erosion of the surface and sometimes detachments of panels from the facade. The changes are due to a successive, granular de-cohesion of the marble. This means that the grain structure of the material is opening up, with fissures developing along grain boundaries (not the spalling). The material weakens, the porosity increases and over time it may finally lead to a full disintegration, through the process often called "sugaring".

3.8.3 Selection and testing of marbles – Recommendations towards specifiers and suppliers

Even though problems of durability of thin marble claddings have been experienced, the TEAM project has shown that marble also may behave as a durable material in this kind of application.

The optimum marble for thin cladding purposes, according to the TEAM findings, is a marble with the following properties:

- Favourable micro structure, i.e. the marble should be dominated by irregular grain boundaries and the presence of many sub grains, meaning a wide grain size distribution
- Low bowing figures in the TEAM bow test
- Low wet thermal permanent expansion
- Low strength loss during bow test/thermal expansion

Giving the "right" marble type; i.e. a resistant micro structure, the bowing and strength loss will be much smaller regardless of the severity of external factors. Even though deterioration will take place even in these, the weathering rate will be much slower and the service life time correspondingly longer.

For prescription, selection and delivery of marbles for cladding purposes with the focus of avoiding the particular deterioration pattern of bowing, expansion, strength loss and granular de-cohesion, the following tests must be performed:

- TEAM Laboratory bow test, coupled with flexural strength measurements
- TEAM Wet expansion test
- Petrographic analysis

Bowing of marbles could be considered the visible effect of a deeper degradation occurred in slabs. The material has been affected in its structure and the mechanical properties are usually weakened. i.e. loss of strength. It is a fact that all natural stone looses strength over time under real exposure conditions. It is also an experience that some marbles typically reveal higher strength loss in real applications than e.g. granites. It is also shown that marbles not revealing bowing may loose strength in real applications. This should be taken into consideration when evaluation of the applicability of marbles for claddings. Thus, it is crucial that all three tests are performed in order to have a sound evaluation basis.

Results from the TEAM bow-test clearly indicate that bowing figures less than 1 mm/m after 50 cycles are characteristic for marble types of the "non-bowing", i.e. resistant type.

Rather big differences in strength loss for various marbles subjected to the bow test have clearly been demonstrated within the project. The strength loss in the test range from below 10 % to above 60 % after 50 bow cycles. Marbles with a strength loss of 10-15 % are characteristic for resistant marbles. Marble types with a higher strength loss can also be recommended depending on the intended service life of the facade.

It has been indicated from the TEAM bow test that bowing figures less than 0.4 mm/m after 50 cycles (Test results according to the Nordtest method NT Build 499) / i.e 1,1 mm/m (Test results according to the revised TEAM Bow Test (TEAM 12)) may be suggested as being characteristic of "non-bowing", i.e. resistant marbles.

Rather big differences in strength loss for various marbles subjected to the bow test have clearly been demonstrated within the project. The strength loss in the test range from below 10 % to above 60 % after 50 bow cycles. It has been indicated that marbles with a strength loss less than 15 % may be suggested as being characteristic for resistant marbles.

These potential threshold values with respect to bowing and strength loss should be the subject of more testing and evaluation between more testing laboratories during the time schedule for revision of the product standard for claddings (EN 1469), which is within 5 years from the publication, i.e.2010.

These potential threshold values with respect to bowing and strength loss are relevant only when a laboratory with experience of the test method carries out the test. Several of the variables specified in the test method are very sensitive to changes! It is therefore absolutely crucial to follow the method in every detail!

3.8.4 Recommendations to designers

Marble - being a material which properties normally varies throughout the quarry – must be tested to ensure that it meets to required standard for the proposed design. Good design is required to make the most out of the material. The marble type and design have to be appropriate for the geographical location, elevation and intended method of application.

All stone materials expand and contract on a building due to thermal effects. Some suffer a permanent change of dimension. This process is greatly enhanced by the presence of moisture due to condensation as well as rainfall. The combination of elevated temperatures, moisture and material properties cause decrease in the material strength and may also cause bowing of the panels.

During the evaluation and qualification procedure for selecting a marble, the following aspects should be considered:

- Denomination and origin

- Visual appearance and evaluation of reference samples from aesthetical and technical/durability points of view
- Assessment of performance on other buildings in similar climates and applications
- Technical properties – verified and relevant test results
- Visits to quarry and production plant in order to agree on and verify
  - FPC documentation
  - Quarry variations
  - Defining a testing programme
  - Defining selection criteria

Selection criteria are most often divided into visual appearance of the material, total costs, availability of production and processing possibilities and technical properties of the material. The technical quality should be given high score during the evaluation procedure for material selection. Without a sufficient technical quality the intended service life will be significantly shortened.

When a marble is selected, a FPC programme divided in Block control and Delivery control must be established to secure quality of the finished stone product. Such FPC programme shall include a specification of which properties (esthetical and technical) that shall be controlled. In addition to inspection routines and acceptance criteria, the frequency/amount of testing shall be defined.

3.8.5 Recommendations to suppliers (producers)

Compliance with the requirements of the standards and the voluntary (rough blocks and rough slabs) and mandatory (finished slabs) attestation of conformity must be demonstrated by the supplier. This means the producer is responsible for carrying out initial type testing, and additionally he shall exercise a permanent FPC. Continuous testing and documentation of quarried stone material is recommended whereby a historic record can be attached to the stone in connection with new applications. For documentation of technical quality of own materials directed towards new building projects, test results older than for 2 years (rough blocks and slabs) or ten years (for some properties specified for cladding products) should not be referred to. The product standards specify either system 3 or 4 for attestation of conformity. For a majority of the tests specified, the producer may perform the testing "in-house".

3.8.6 Elements of importance for FPC

FPC elements to be used involve the following levels and actions:

Selection of stone

- Identification of the deposit/quarry.
  - Geological and Petrographic mapping of the deposit/quarry. Identify new/existing deposits/quarries
  - Technical property testing depending on the intended application. For cladding purposes we recommend the mandatory tests given in the product standard (EN 1469 Slabs for cladding - Requirements) complemented with the tests developed in TEAM, laboratory bow test, wet-thermal expansion test and petrographic analysis including AGA. Establish a correlation between AGA and lab-bow test!
  - Production plan including critical parameters; stone/areas for various applications

Quarrying

- General block control
- Cutting directions according to directional variations – general yield optimizing if possible
- Effect of cutting directions on technical quality (often not feasible but should be considered whenever possible)
- Follow the EN standard specifications (EN 1467 Rough block - Requirements)
- Higher focus on sampling and sampling marking for reliable traceability and feed-back to the production. Unique block marking or coding has to be used
- Testing in relevant directions towards use
- Non destructive tests (e.g. ultrasonic pulse velocity) to evaluate any major change in the general quality
- Petrographic analysis including AGA to ensure that no significant change in the micro-structure occurs

Processing and product control

The processing and product control have to follow the FPC requirements stated in the relevant product standard. We recommend that special attention shall be placed on properties directly related to the bowing and expansion. It is not always possible for the producers to do this themselves. It may therefore prove useful to develop indirect tests that can produce quick results. The relationship between quantified microstructure (AGA) and laboratory bow test shall be established. Most producers have, or contract, a geologist for the geological quality control. This geologist can easily implement and use the AGA. It is also crucial that every producer understands the importance of developing relevant testing frequencies for their own quarry and production situation.

- Effect of processing on technical quality shall be evaluated and used whenever relevant
- Simple destructive tests can be used for assessing the strength
- Determination of water absorption and density are also simple and useful tests for this purpose, and tests that the producers can implement themselves
- Specific application test such as bowing and wet-expansion test shall be used at regular intervals

General

- Implement own testing facilities
- Record and document building references for traceability
- Towards specific building projects both block control and control in processing plants

3.9 WP 9 Dissemination and exploitation

3.9.1 Objectives

To spread and implement the project findings (reports, guidelines etc.) to all parties concerned within and outside the project. To secure awareness of and knowledge about problems and solutions connected to marble and limestone claddings among stone companies, architects, building owners etc.

The WP is divided in 2 different tasks:

- Guide-lines and other publications
- Fairs, workshops, seminars etc.

3.9.2 Activities and results

The work package has been led by IMM and many of the tasks were carried out under the responsibility of the Exploitation Board. The main tasks of the Exploitation Board are to evaluate the economic potential of the results of the project and to define a market policy.

The patent/licensing policy has been discussed by the members in the Exploitation Board, but has not yet been concluded. A number of the results of the project have, however, already been identified as potential candidates for patent protections in the table below.

Table 9.1. Protection of Intellectual Properties.

Partner	Part developed	Protection of Intellectual Property
RAMBOLL, SP, SINTEF, JAC	BOW-meter	Possible patent
RAMBOLL, SP, SINTEF	Bowing Test method (Simple screening test method)	Possible patent / secret knowledge
All	Procedure for inspection of buildings	Secret knowledge
Fischer	New, improved anchoring system	Possible patent
EKA + TTA (on their own products)	Surface treatment	Possible patent / secret knowledge
EKA + TTA	Surface treatment procedure	Possible patent / secret knowledge

Publication

The rules of publication are given in the Consortium Agreement and detailed in the minutes of the meeting at Wik.

Abstracts and papers are sent to the Project Coordinator, which will distribute them to all the partners and forward a copy to the Commission. *It is however a requirement that all papers, (both technical papers and papers with a general description of the project), must be approved by the Scientific Officer, prior to publication.*

The needs to publish results as a part of the exploitation have been discussed at the Exploitation Board meetings, (latest at the meeting on the 22 November 2003), where:

- It was decided that the results should be presented to a broad audience.
- It was pointed out that dissemination of the results should contain both general presentations and scientific papers.

- A list with the information about conferences shall be prepared and distributed to all partners.
- It was discussed what kind of book or handbook TEAM should produce. One of the early ideas was to write an "easy to read" handbook in form of guidelines for end-users that can be used as a manual. The EB has discussed this idea and has discussed to write a general and extended TEAM project report, combined with shorter, independent leaflets, each covering a specific topic.

A general presentation of the TEAM project has been prepared in Powerpoint and has been placed on the website. All partners can copy from this presentation and use the results in other presentations.

A special TEAM session was established at Dimension Stone 2004 in Prague in 14-16 June 2004, where four papers were presented and later published in the proceedings:

- T. Yates, J.-A. Brundin, P. Goltermann and B. Grelk: "Observations from inspection of marble cladding in Europe".
- K. Malaga, B. Schouenborg, L. Alnæs, R. Bellopede and J.-A. Brundin: "Field exposure sites and accelerated laboratory testing of marble panels".
- B. Grelk, P. Goltermann, B. Schouenborg, A. Koch and L. Alnæs: "The laboratory testing of potential bowing and expansion in marble".
- L. Alnæs, A. Koch, B. Schouenborg, U. Åkesson and K. Moen: "Influence of the macro- and microstructure on the durability of facade material".

Three other conference presentations have been carried out:

- B. Grelk and J.-A. Brundin: "How to choose, produce and use marble and limestone cladding panels without the risk of deterioration due to bowing or expansion" is expected for the conference “Building with stone: Granite & Marble for architectural exteriors & Monuments”, May 8-9 2004 in Cambridge, Massachusetts.
- B. Grelk, C.C. Christiansen, B. Schouenborg, J-A. Brundin and L. Alnæs: "Deterioration of thin marble cladding - Observations from the inspections of buildings with marble cladding in Europe", VIIIth International Docomomo Conference, 2004. (Notice: No TEAM funding required).
- L. Alnæs and some of her co-workers have submitted an extended abstract "Texture measurements of marbles with different use behaviors by EBSD" for poster to "International Congress on Applied Mineralogy", ICAM 2004 in Brazil September 2004. (Notice: No TEAM funding required).

The following other papers have been submitted for publication or have already been published:

- A. Koch and S. Siegesmund: "The combined effect of moisture and temperature on the anomalous expansion of marble". Environmental Geology 46, 350-363.
- T. Yates: "The bowing of marble cladding – The EU TEAM Project", Natural Stone Expert 2004.
- J.A. Brundin, B. Schouenborg, B. Grelk and L. Alnæs "Problemfacader", STEN 1/2004.

just as an abstract has been submitted:

- Koch, A., Grelk, B., Siegesmund, S. 2005. Correlation between rock properties and the in situ behaviour of marble used as cladding material at buildings. EGU General Assembly 2005, Vienna, Austria: Geophysical Research Abstracts connected with a poster presentation which is still in preparation

and six theses have been produced, including TEAM results:

- Katarina Malaga (2003) "Microscopic and macroscopic studies of initial weathering of natural stones used as building materials", Göteborg University, Dept. of Chemistry. Thesis for Doctoral degree
- Urban Åkesson (2004) "Microstructures in granites and marbles in relation to their durability as a construction material". Göteborg University, Earth science Centre, Thesis for Doctoral degree, A 95.
- Nike Ferraris (2004) "The bowing of marble – Approach through case histories and laboratory test". Politecnico di Torino, Engineering faculty. Thesis for Doctoral degree
- Alenka Mauko (2004)" Ukrivljanje Fasadnih Plosc iz Slovenskega Naravnega Kamna", Licentiate Thesis from Ljubljana.
- Koch, A. (2005). Deformation von Fassadenplatten aus Marmor: Schadenskartierungen und gesteinstechnische Untersuchungen zur Verwitterungsdynamik von Marmorfassaden. Dissertation, University of Göttingen, Thesis for Doctoral degree
- Bellopede Rossana (to be published 2006) The ultrasonic pulse velocity test: the methodology reliability in the detection of stones properties. Politecnico di Torino, Engineering faculty. Thesis for Doctoral degree

General presentation of projects current results "Testing and Assessment of Marble and limestone" have been carried out at fairs and conferences:

- 25th International Fair for Marble, Machinery and Services, 26-29 May 2004 by P. Blasi, T. Yates and L. Alnæs

The projects results have also contributed as a minor part of the general description of durability concerns in natural stones in post-graduate training of engineers and architects at The Danish Institute for Constructions and Concrete on "Natural Stones in Construction" ("Natursten i Byggeriet") by B. Grelk and J. Brandt.

The partners are members and/or chairmen of the following committees:

- CEN TC 246 – Natural stone (chairman and members)
- CEN TC 178 – Paving units and kerbs (chairman and members)
- CEN TC 128 – Slates for roof covering (members)

Small scale workshops/seminars have been organised. The workshops were mainly held locally (e.g. Denmark, Sweden and Italy) and focussed on 1-2 main groups of costumers, where key persons were invited directly.

A project web at http://www.sp.se/building/team/ is set up as described under the Management and Co-ordination Aspects. The project web contains public information about the TEAM project as well as electronic copies of published reports reachable only for the partners and scientific officer.

4 List of deliverables

4.1 Document numbering system

The document numbering system used in the project is described with the example below:

WP1.1-JAC-TD-000321-Case studies-p
A document from WP1, task 1. Jananders Consulting has produced the document. It is a technical document issued 21 March 2000 and describes the subject Case studies. p = the document is a preliminary issue (i.e. a working document open for comments/discussion). Administrative documents were denoted AD.

Table 4.1. List of deliverables.

Deliverable No.	Output from WP. No.	Nature of Deliverable File name
1	1	**Updated State-of-the-art report regarding deterioration mechanisms and influencing factors** *WP1.2-RBL-TD-001128-State-of-the-art-report*
2	1	**Summary report from case studies/buildings, including selection of potential buildings for WP 2** *WP1.1-JAC-TD-050830-Case studies-Final* *WP1.1-JAC-STF-TD-010427-Summary report-1*
3	2	**Field Equipment with use instruction** *WP2.1-SP-TD-010123-Gauge block for zero setting*
4	2	**Concept for inspection and assessment of facades (Enclosures to the reports are not mentioned in this list)** *WP2.2-RMB-TD-021014-Concept for inspection and assessment of facades-pr1* *WP2.2-SP-TD-001212-Instruction for site inspection* *WP2.2-BRE-TD-020725-Detailed assessment-Library-DE* *WP2.2-JAC-TD-020925-Detailed assessment-Nyköping-SE* *WP2.2-JAC-TD-020925-Detailed assessment-Lünen-DE* *WP2.2-PTO-TD-021022-Detailed assessment-Magenta Hospital-IT* *WP2.2-RMB-TD-010527-Detailed inspection-pr1-report1-DNB-DK* *WP2.2-JAC-TD-030915-Detailed inspection-Malmö stadshus-SE* *WP2.2-UGE-TD-020514-Detailed assessment-pr1-report2-Theologicum-DE*
5	2	**Reports from inspection of facades** *WP2.6-FS-TD-020223-Anchoring*
6	2	**Building/facade specific prediction of lifetime including recommendations regarding measures and actions** *WP2.4-BRE-TD-020212-Predicting service life-risk analysis*
7	3	**Specification for system and protocol for use** *WP 3-BRE-TD-010219-Deliverable 7 system and protocol*
8	3	**Preliminary report after initial site trial** *WP3 .2-BRE-TD-030304-Deliverable 8- Preliminary Report after initial site trials*

9	3	**Final report** *Complete.*
10	4	**Method statement regarding sampling and description of sampling procedure** *WP4.1-STF-IMM-UGE-TD-011128-Sampling method statement Quarries* *WP2.5-SP-TD-020205-Instructions for sampling from buildings* *WP4.2-UGE-TD-010425-Selection of samples from quarries and production-State-of-the-art* *WP4.2-STF-TD-050930-State-of-the-art- Part- Rock stresses* *WP4.2-STF-TD-050614-Quarry sampling and samples*
11	5	**Separate reports from each tasks** *WP5.1-STF-TD-020430-Rock-stress-report. Part 1* *WP5.1-STF-TD-030619-Rock-stress-report. Part 2* *WP 5.3 Has been combined with output from WP 6.1 and 6.2* *WP 5.4-BRE-TD-050815-Summary report of lab test development for bowing and expansion tests*
12	5	**Workshop for producers and processing companies** *See chapter 3.3.9 Dissemination and exploitation*
13	6	**Draft Proposal for European test methods to CEN TC 246. Precision statements** *WP6.1-RMB-TD-050831-Lab bow-method-precision trial-final* *WP6.2-UGE-050228-expansion test method-precision trial final*
14	7	**Report with results and recommendation about impregnation and surface coating** *WP7.4+5.4-STF-TD-050815-Accelerated-test-report-p3* *WP7-SP-TD-051024-Field exposure sites*
15	8	**Draft Proposal for a screening test for product control** *Included in the report below (deliverable 16)*
16	8	**Report with conclusions regarding production and product control** *WP 8-STF-TD-050831-Report WP 8-Task8.1+8.2*
17	9	**Oral and written presentation at annual fair** *See chapter 3.3.9 Dissemination and exploitation*
18	9	**Guidelines, instructions, recommendations** *Included in deliverable 16*
19	9	**Web site** *http://www.sp.se/building/TEAM*
20	9	**Input to European Standardisation** *Two test methods including precision data, see deliverable 6*
21	9	**Papers, articles** *See chapter 3.3.9 Dissemination and exploitation*
22	9	**Seminars, workshops, fairs etc.** *See chapter 3.3.9 Dissemination and exploitation*

5 Comparison of initially planned activities and work actually accomplished

The initially planned activities taken from the work packages description and work actually accomplished are listed the Table 5.1 and main delays and deviations are discussed below.

WP 1 Planned activities:
All planned tasks were completed. The deliverables as well as the Project Work under WP 1 were planned for and done during Y1 and Y2. As the results of the building inspections as well as the continuous input to the State-of-the-Art Report gave valuable new and completing information it was decided that WP 1 work should continue through the whole project and end in February 2005.

WP 2 Planned activities:
All planned tasks were completed. The plans to set up a site at NTUA Greece had to be abandoned but one additional site specifically to look the effect of different fixing systems was set up at Fisherwerke, near Stuttgart, Germany, in conjunction with WP 2. The results of two years of exposure were produced in August 2005 and showed that there is some effect from the fixing system in particular it confirmed that panels on mortar resist bowing. The results are described in more detail in the WP 2 report.

WP 3 Planned activities:
Monitoring was planned to be finished in August 2004 but it has been agreed to continue until beyond the end of the programme (to the end of 2005) to maximise the data collected.

WP 4 Planned activities:
The description of rock types and quarries in the "“Rock Assessment Form" has been completed, compiled and put forward to WP 5. The part of the "State-of-the-art report" connected to "In-situ rock stresses and their potential influence on quarrying" as it concerns WP 4 was discussed in the report from task 5.1 which contains a description and discussion about in situ rock stresses and their influence on quarrying in general (underground/open pit) and how the rock mechanical properties and rock stress situation in quarries should be taken into consideration during production planning.

WP 5 Planned activities:
All planned tasks were completed however with a significant delay. The delay influenced the work in the WP 6. The planned workshop for the dissemination of the results has been postponed after the end of the project. This workshop is thus not considered to be solely connected toWP 5 activity, but a main output from the whole project.

WP 6 Planned activities:
All planned tasks were completed though the work was delayed due to the closer interaction with WP 5 and also inclusion of additional marble types. The WP 6.1 Test Method for Bowing Properties was ready by November 2004. Two partners have ordered a computer controlled system for the heating in order to have the same equipment as the one at SP. In order to achieve comparable results Bianco Carrara Savema marble that was used in the previous Nordtest project is also used as a reference in The TEAM project. Marble from

Poland and Slovenia have been added to the test scheme. During this period the Task 6.2 Thermal and hygric expansion have been finalised. The Task 6.3 Inter-Comparison Tests started in April 2005 and was finalised by June 2005. The draft methods: "Development of expansion test" and "Development of laboratory bow test" have been prepared and will be proposed to the CEN TC 246 after the end of the project.

WP 7 Planned activities:
All planned tasks were completed. Two exposure sites in Poland and Slovenia were added due to extension of the project members.
It has been agreed to continue the in situ monitoring and the collection of the "bowing" measurements from the field sites beyond the end of the project.

WP 8 Planned activities:
The work and recommendations from WP 8 are gathered in a joint report (Deliverable D1-8). This deliverable goes further than what was originally planned (to draft a proposal for screening test for product control, see table below). Several test methods developed or used within the project can be used both for analysing marble in various quarries (prospecting phase), differences within the same quarry/deposit (mapping/production phase, e.g. whenever a separate quarry unit/face etc. shall be opened) and also for assessing the quality of marble for specific building projects. Various approaches and recommendations for quality control have been put forward, and guidelines directed both towards stone producers and users are included in the report.

Table 5.1. List of deliverables.

WP	Description	Date of delivery	
		Scheduled	**Actual**
1.1	A procedure for inspection of buildings	June 2000	January 2001
1.1	Summary report on case studies	January 2001	March 2001
1.1	A selection of potential buildings for WP 2 and 3	January 2001	January 2001
1.2	Updated State-of-the-art report regarding deterioration mechanisms and influencing factors	March 2001	March 2001
2.1	Field equipment with instructions (D1-2)	May 2000	June 2000
	Documentation of accuracy (M1-1)	May 2000	March 2001
2.2	Concept for inspection and assessment of facades (D2-2)	May 2001	October 2002
	An inspection report for each selected building (D3-2)	May 2001	October 2002
	Summary report of observations from inspection of buildings combined with results from strength test (M2-2)	May 2001	October 2002
2.4	A model for prediction of lifetime and durability for building facades including a risk assessment (D4-2)	Feb 2002	1st draft July 2002
2.5	Collection of samples for laboratory tests (WP2.3+WP5) from buildings	April 2002	December 2002
2.6	An evaluation report concerning anchoring systems (D5-2)	Feb 2002	2nd draft June 2002
3	The WP started on time and is progressing according	January	January 2001

	to plan. Milestone 7 was completed in September 2001 Milestone 9 was completed in November 2001 Deliverable 2-3 Report on initial results Updated hardcopy of D2-3 Input to the Revision of M10 – June 2005 A final version of D9 will be produced in October 2005. A paper summarising the findings of WP3 was submitted for the Dimension Stone 2004 conference.		2001 July 2002	 May 2002 Feb 2003
3.1	According to plan		January 2001	January 2001
3.2	This was due to start in September 2001 but in order to have all the equipment selected, tested and installed before winter it was agreed to bring the start forward to May 2001. Monitoring was due to end in August 2004 but it has been agreed to continue until beyond the end of the programme (probably to the end of 2005) to maximise the data collected. As a result D9 will now be drafted in June 2005 and finalised in October 2005.		September 2001	May 2001
3.3	This was due to start in September 2001 but the first set of data from the National Bank in Copenhagen was not available until October 2001		September 2001	October 2001
4.2	Sampling of blocks for work in WP5, 6, 7 and 8		Dec 2003	May 2003
4.1	D1-4/ M1-4 "State of the Art Report"		March 2001	Apr. 2001 (Part I) June 2003 (Part II) May 2004: Compilation
4.1	D2-4/ M2-4 "Sampling Method Statement"		July 2001	April 2002
4.1	M3-4 "Sampling Method Statement" – final version		Nov. 2001	May 2002
4.1	D3-4: A quarry and a rock type description form	1st draft version	n/a	Nov. 2000
		final version	n/a	April 2002
4.2		filled in	Dec 2003	August 2004
WP5 5.1	D1-5	Initial workshop for producers and processing companies	August 2001	September 2001
	D2-5	Report task 5.1	February 2002	March-02 (Part 1) April-03 (Part 2)
5.2	D3-5	Report Task 5.2	March 2002	August 2005
	M1-5	Specific input regarding stone and sample types for WP6	February 2002	February 2002

5.3	M2-5	From the main influencing factors and causes give “stop or go” for WPs or planned tasks within other WPs. Direct input and specifications for planned activities within WP6, 7, 8 and 9	February 2003	February 2003
	D4-5	Report Task 5.3	February 2003	August 2005
5.4	D5-5	Report Task 5.4	February 2003	August 2005
	D6-5	Special workshop at the end of WP5 for the European Stone industry	February 2003	February 2005 1)
6.1		Test Method for Bowing Properties		February 2004
6				August 2005
7		The WP started on time and is progressing according to plan.	December 2001	December 2001
7.1		According to plan	December 2001	December 2001
7.2		Due to start May 2002	May 2002	March 2002
7.3		According to plan Milestone M7 Establishment of the test field	December 2001 August 2002	December 2001 October 2002
7.4		Due to start May 2002 D14 Report delayed to accommodate extra data and the late start of 7.4	May 2002 August 2004	January 2004 October 2005
8.1		Delays in final discussion and reporting	May-04	August 2005
8		Draft proposal for screening test for product control with description of testing equipment and procedures	August – 04	August 2005

6 Management and co-ordination aspects

The TEAM was an important project from a scientific, technical and social point of view. The mixture of different cultures, not only between the countries, but especially between the universities, industrial companies and research institute resulted in many fruitful discussions, but sometimes also in disputes. We think that it is worthwhile pointing out the two "major obstacles" to help minimise the risk of repeating them in future projects.

The importance of a complete consortium agreement has to be stressed, in which all details concerning e.g. publication policy and dissemination of the results during the project should be agreed and accepted by all partners before the project start. There were a few conflicts due to this aspect. However, they could be solved by clarification of the project publication policy.

Another important aspect that may cause problems is the external costs, especially for the SMEs involved in the project. In many cases they struggle with the time and economy. This also proved to be an obstacle for the TEAM project, leading to time delays, unnecessary discussions and, in cases, changes of the work content.

The objectives of the project were straightforward and clear, which made it possible to organise the project in a logical way, and to clearly define partners' responsibilities. The administrative procedures and planned meeting schedule have worked well. The Steering Committee (SC) and the Project Management Group (PMG) meetings have been combined with the working meetings.

It has been accepted by the Commission to prolong the TEAM project with six months. The project has been closed by the 31st of August 2005.
The project Homepage http://www.sp.se/building/team/ contains general information about partners and project objectives directed to the public. It has been updated to contain confidential information for the partners and scientific officer, accessible by a password. Example of such confidential information is the Project management handbook containing information such as working procedures, templates and contracts and results.
The results from the building inspections on different levels have provided very important input to other WPs mainly WP 3, 5, 6 and 7. WP 1 has therefore been prolonged through the entire project however at a low level of activity.
The technical progress for the whole project and the planned versus actual date for deliverables and milestones have been in phase with the project plan except for the precision trials that has been finished during the extended months. However, the following can be commented on:

- The monitoring of the facades is planned to continue through 2005 at all places.
- The earlier starting time for Task 3.2 led to differences between scheduled and actual manpower used by BRE and Rambøll for the first year. The earlier starting date had no influence on the total effort in WP3 but BRE's additional effort to collect the data at Nyköping (rather than using a sub-contractor) had increased BRE's total man-months but not the total cost.
- The delayed WP 6 the precision trial was finished by June 2005.
- It was important that WP 7 was co-ordinated with Task 2.5 (Evaluation of the effect of fixing systems), WP 3 (Monitoring) and WP 5 (Laboratory testing).

Concerning collaboration with other projects and organisations: Contact has been established with other projects such as HERMES, MARA and Nordtest. Both the HERMES

and Nordtest projects are finalised. The contact with MARA has mainly given useful personal contacts with some of the partners for technical input to the laboratory tests. Contacts have been taken with the Thematical Network OSNET and with McDUR. The latter has given rise to collaboration concerning laboratory tests and field tests. Some of the partners of TEAM are also partners of McDUR. The collaboration with OSNET generated more contacts and also the possibility to market TEAM on the OSNET homepage. Several TEAM partners are involved in the I-STONE project that gives possibilities to disseminate results from the TEAM project.
Information has been continuously given about the project at CEN TC 246 meetings. The main input to the European standardisation will however come from WP 6 after the end of the project. A decision was taken at the Midterm meeting to avoid presentation of partial information that may harm the industry. The dissemination of the results has been done at several international conferences and meetings as well as part of several PhD dissertations and Master of Sciences theses.

Actual and planned manpower allocation: More man months than foreseen have been used on WP 2, 3 and WP10. The main reason for this has been the need for development of equipment suitable for monitoring on the facades; installation of the field test site at fisherwerke and extended work with Polish and Slovenian partners as well as the management and co-ordination aspects. This was due to work with the new NAS partners, which was not foreseen in the original budget. Several reallocations within one and the same partner without interfering with other partners' budget or work plan were approved. Further changes to the planned manpower allocation have been discussed at the Ljubljana meeting in April 2005 and agreed by all partners. The proposition was send to the scientific officer and the new budget with small corrections was accepted.

Workplan: The main difference compared to the initial project plan was inclusion of a test site for different anchoring systems. WP1 and WP 2 investigations have shown there might be an influence on deformation related to the type of anchoring system used for a project. The TEAM Work Programme did not include any planned test site for different anchoring systems. However the result from inspections was discussed and it has been concluded that a test site should be installed for this purpose. Partner fischerwerke (supplier of anchoring systems) offered to use there facilities for such test wall and the SC agreed on an allocation of funds.
Two new partners were included in the project which resulted in two additional field exposure test, additional building inspections and new materials.
Further WP6 activities were slightly prolonged in order to finish precision trials at laboratory by June 2005 and evaluate the results. The on-line monitoring at the field exposure sites has been prolonged to the end of August 2005. No destructive testing on the samples from the field exposure has been performed. The field exposure sites are planned to be controlled even after the end of the project.
An outline for a book for professionals involved in work with natural dimensional stone has been discussed and agreed on. The preparation of it is planned after the end of the project.
The final meeting took place the 1st of July in Copenhagen.

7 Results and conclusions

7.1 *Introduction/Background*

The TEAM project is by far the largest R&D project ever directed towards natural stones used for building applications. It has focused on the problem of expanding and bowing marble and expanding limestone cladding for outdoor uses. The main problem with unsuitable stone types is the decrease of strength that is always associated with the bowing and/or expansion.

The basis for our results are, in addition to personal knowledge, the literature review of more than 300 articles, a survey of about 200 buildings and a comprehensive programme of laboratory and field work. The project has rendered numerous findings that are useful for stakeholders such as the stone industry, European standardisation, testing and research organisations, building owners, consultants and architects. The most important ones are discussed below.

The project started in March 2000 and ended in August 2005 and has had 16 partners from 9 different countries and a budget of about 4,2 M EURO partly financed by the European Commission.

7.2 *Discussion of the main results*

7.2.1 Literature study

The starting point of the project was a literature study aiming at collecting and evaluating the more than 100 years of research relating to this specific problem. The existing hypotheses were compiled and evaluated and many of them tested in the laboratory phase of the project.

Some of the most common hypotheses/statements were:

- Fine-grained marble is good or bad (both proposals occur)
- Carrara marble is bad
- Acid rain and pollution are the reasons for the problems
- Frost action is the cause and marble should not be used in the ‘far north’ e.g. in Finland
- Marble with a specific range strength is suitable
- Anisotropic thermal expansion of calcite and dolomite causes granular de-cohesion.
- The influence of moisture (and possibly free water) and temperature variations are crucial
- The release of locked-in rock stresses is important
- A complex microstructure is favourable

It has become very clear, through the findings of the project, that the major influencing parameters are the thermal expansion in a wet condition and the microstructure of the marble. See more under 7.2.5 below.

7.2.2 Survey of stone projects

In parallel to the literature survey, about 200 buildings using natural stone were identified, mostly in Europe, but also in other parts of the world. Most of these buildings were clad with marble (both ‘good’ and ‘bad’ performing) and limestone. It gave us the opportunity to study and test many of the hypotheses on real buildings and not just in the laboratory. This has given us knowledge of the extent of the problem, both geographically and geologically. Suitable marble types can survive for many years in any climate. It is equally clear that unsuitable marble comes from many countries all over the world. The buildings also provided TEAM with the possibility to investigate further with detailed studies of a few of them. The geographical, geological and climatic spread of the 200 buildings is believed to be representative for all of Europe!

7.2.3 Detailed cases studies

Six of the two hundred buildings were chosen for detailed study. A special piece of equipment (the bow-meter) which can be used for high precision and repeatable measurements of the bowing magnitude of the panels has been developed. IN addition to those parameters listed below, the influence on the bowing of the design, the anchoring system, the building physics (like ventilation and insulation), façade orientation, etc were studied. Studied parameters included:

- Height above the ground
- Climatic conditions
- Cracks and breakouts in panels
- Cladding design
- Open or closed joints
- Width of the joints
- Fabric/orientation of foliation of the stone
- Convex or concave bowing
- Surface finishing and surface treatment

The study of the 6 buildings led to the selection of many of the marble types for the major laboratory research work. A methodology for site investigations and also for sampling was developed, together with a methodology for risk assessment. The latter can also be used for prediction of remaining service life. By including the results of WP 5 and WP 7 it has been possible also to give recommendations for remedial actions. One of them is to minimise the influence of water by applying a surface treatment. The development of the laboratory bow-test (described in 7.2.7 below) has clearly shown that each marble and building is unique. Every marble has its unique degradation curve. Any prediction of the remaining service life for a specific building has, therefore, to be developed individually and depends on the specific marble type in combination with the micro-climate (especially surface temperature variations).

7.2.4 Long term monitoring

Monitoring equipment was installed on three of the six buildings. The following parameters were monitored:

- surface temperature on the external surface of the stone
- time-of-wetness/condensation on external surface of the stone
- strain in two directions on the external surface of the stone
- surface temperature on the internal surface of the stone
- air temperature in the gap behind the panel
- relative humidity in the gap behind the panel
- time-of-wetness/condensation on internal surface of the stone
- strain in two directions on the internal surface of the stone
- shade air temperature
- shade relative humidity

- The bowing magnitude was measured four times a year, with the bow-meter and correlated with the strain measurements. The monitoring has mainly generated input to the definition of the laboratory bow-test and the wet-expansion test and a greater understanding of the diurnal variations in temperature of the panels. By filtering these small scale changes it has been possible to establish a very good correlation between measurements of long term residual strain and the manual measurements of the bowing magnitude with the bow-meter. One very important finding is that manual measurement on one occasion by use of the bow-meter will provide almost random values due to the diurnal changes that can be up to 2 mm/m. Measurements of the bowing magnitude has therefore to be done on repeated occasions under similar conditions!

At one location the monitoring has been combined with an *in situ* test wall of different marble types, thicknesses, treatments etc. See part 7.2.7 below.

7.2.5 Sampling and influencing parameters

The case studies of buildings with suitable and unsuitable marble provided most of the input for the selection of marble types to include in the major laboratory research programme. It was impossible to be completely sure of the exact quarry location for the marble on every building due to incomplete documentation. In total, 16 quarries have been sampled, giving 17 varieties of carbonate rock types. The samples represent 3 pure dolomite marbles, 11 pure calcite marbles, 1 ophicalcitic marble (containing serpentine), 1 limestone and 1 silicate rich, contact metamorphic limestone. In addition, 86 marble types were sampled on different occasions at exhibitions, fairs etc. See table 7.1 below. These samples were used in the laboratory bow-test for evaluating the bowing potential and provided the additional necessary samples in order to ensure a broad geological spread of marble types in the laboratory test programme.

Table 7.1. Screening test samples

Country	No. of samples
Italy	36
Greece	10
Portugal	13
Sweden	8
Norway	7
Greenland	4
Turkey	1
Bulgaria	1
France	1
USA	5
Total:	**86**

The possible influence of quarrying and productions processes, together with geological aspects, was assessed in order to include such variables in the samples and at the same time increase the possibilities of explaining the test results. Detailed sampling and sample marking instructions were developed in order to ensure full traceability of all laboratory samples. A very few of the marble types had a visually observable foliation and these were sampled with respect to that in order to enable the assessment of this parameter's influence on the test results.

7.2.6 Full scale laboratory testing, including quarry and processing variables

Rock stress measurements were carried out in three quarries in the Carrara area. The original hypothesis for the rock stress measurements was that we would expect high stresses or high anisotropic stress pattern in areas where strong bowing material is extracted and low stresses in localities where the marble has not shown problems with bowing. The *in-situ* stress measurements clearly indicate that the marble at all sites is subject to quite high, non-gravitational stresses. The stresses are probably a combination of locked-in residual stresses and tectonic stresses. The results of the actual rock stress measurements show that our original hypothesis was somewhat simplified. High stresses are measured in all marbles, even in the two marbles where no bowing have been experienced. For these two quarries, it seems that the stresses are released during block extraction, which is not the case in the quarry where they have experience bowing marble. In addition, the rock mechanical properties (Young's modulus and sonic velocity) of the bowing marble are much lower than the other two.

A summary of the findings related to quarrying and processing are:

- Some production and processing factors influence the bowing and deterioration pattern of marble cladding. The various factors depend to a large degree on the intrinsic properties of the marble itself.
- Even though various quarrying methods may give various impacts on rocks being extracted, it is very difficult to explain the very different behaviour in marble cladding as a result of the quarrying methods.
- There is no indication of that diamond wire sawing introduces stresses within the rock material that may enhance rock bowing susceptibility. A marked stress relief may be experienced during diamond wire sawing, and not an introduction of stresses (or stress concentrations) as suggested in the literature.
- A relationship between the rock fabric and bowing and expansion (and strength) of marbles has been found. The cutting direction may therefore have an effect on the bowing and expansion potentials if the fabric of the marble is anisotropic. However, it is most important to point out that marble types that have been found unsuitable for outdoor cladding should not be recommended regardless of extraction and processing directions. The decrease in strength may be equally high in such panels although in another direction and therefore of equally high risk. In most cases it is not economically justifiable to experiment with different blocks in the natural stone industry.
- No conclusive answer can be given as regards the degree and speed of deterioration as a function of panel sizes. But thickness has been found to be important for bowing and deterioration of marble. There are no safe thicknesses of slabs above which bowing will not occur. For a marble with favourable rock and mineral properties, the behaviour is less dependent on thickness.
- Sawing, honing, and bush-hammering may cause slabs to bow during processing, typically towards the worked face. It has been verified that different marbles respond differently and that there is a relationship between the behaviour during processing and the mechanical properties of the marble. Less stiff marbles with hysteresis in the stress/strain curve during unloading seem to be the most vulnerable. There is also a tendency for such marbles to be more prone to bowing as a result of stresses induced into the material from external factors like temperature and humidity gradients.

One of the most important findings in the project is the development of the possibility to quantify the microstructure of suitable calcitic marble types for cladding purposes.

Adjacent grain analysis (AGA) is a quick and simple way of assessing whether a marble is likely to be suitable or not. AGA is a combination of grain size analysis and grain shape analysis. It will not quantify the magnitude of bowing or the strength loss that will occur over the years. But it will give a reliable basis for the decision whether it is justifiable to make more analyses, e.g. the laboratory bow-test, the wet-expansion test strength tests. Thus far, we have only been able to validate the method for calcitic marbles.

A lot of tests have been carried out trying to find out the potential relationship between lattice preferred orientation and bowing and a clear correlation has been established. However, the influence on the magnitude of bowing is quite low for the marble types with a clear orientation. The difference is actually lower than the precision of the test method, but as it is systematic it cannot be ignored.

A huge number of other tests have been carried out, such as water absorption, capillary suction, flexural strength, breaking load energy, frost resistance, ultrasonic pulse velocity, long-term bending, heat capacity, heat conductivity and specific heat. One of the first important findings was the absolute necessity to dry marble and limestone samples at lower temperatures than those normally specified. Most standards specify the conditioning of stone samples to be done in 70 °C. TEAM has observed a significant reduction in strength at considerably lower temperatures. In order to minimise the damage of the test specimens before testing we therefore recommends drying in only 40 °C for one week. This procedure has been used throughout the project.

Many of the results from these tests have contributed to the verification or refuting of the numerous pre-existing hypotheses. The possibility to compare a result obtained in the laboratory with that observed on a building or at the field exposure sites has been extremely valuable. Many results and relationships obtained in the laboratory cannot be proved to be consistent with observations in the field simply because of the complex nature of the problem, with several influencing factors acting at the same time. The same marble has been observed to bow in both convex and concave directions on the same façade and in very nearby position (figure 7.1). In places where the temperature variations are less extreme, parameters such as fabric may play a more pronounced role. On the south and west facades of a building, where the temperature generally is the highest, temperature is by far the single most important influencing factor.

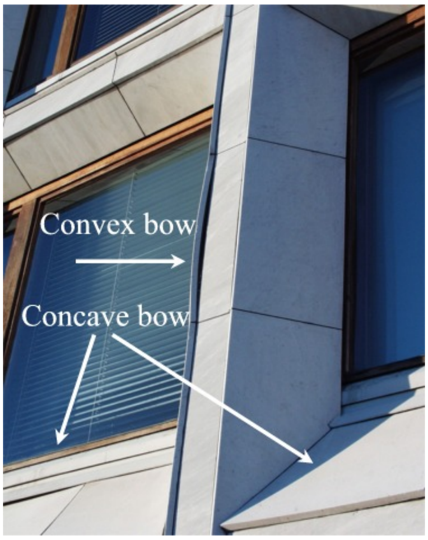


Figure 7.1. The same marble can display different bowing patterns on the same building.

One of the main objectives of the project was to try to determine the mechanism for the bowing. However, even though a lot of progress has been made we feel that there is still some work left before we can give a full explanation of the mechanism. However, this additional work maybe not economically justifiable from an industrial point of view, particularly since TEAM has developed a test method that correlates very well with the performance of marble cladding. It is easy to say that granular de-cohesion is causing the expansion and the bowing. However, we are still unsure as to why this phenomena does not take place in all marble types and why it is more often found in calcitic than dolomitic marble. The differential expansion in different crystal lattice orientation is a property that marble shares with many other rock types and can not explain the phenomena by itself, although it is seen as an important contributing factor.

A crucial parameter is the complexity of the grain boundaries and the grain size distribution of mineral grains in the rock. This provides different bonding strength between the mineral grains due to the complexity of the arrangement of the grain boundaries in combination with the crystal structure. The irregular grain structure that all marble types suitable for outdoor cladding have in common is the product of the metamorphism that turned limestone into a marble, combined with a dynamic re-crystallisation event. This type of event or metamorphism will create a more or less irregular micro-structure with complex grain boundaries and a wide span of grain sizes and a crystal lattice that may include defects.

This structure gives a stronger grain boundary bonding through a mechanically stronger contact (complex grain boundaries) and a larger contact area, with more bonds between individual grains, through a larger surface area compared to the "ideal" regular hexagonal crystals. The type of mineral grain/crystal with complex shapes and lattice defects, mentioned above, is more prone to a change through redistributing individual atoms than a defect free ideally shaped hexagonal grains/crystal. This is due to the fact that such crystals have a higher inner energy, due to the strain energy, compared to ideally shaped ones. We may look on these defects as internal stresses built up during a dynamic re-crystallisation. Stresses that want to be released can do so without primarily affecting the grain boundaries. The triggering event can be exposure to the elevated temperature and moisture cycling on a façade. The ideally shaped crystals don't have the same ability (or willingness) to rearrange atoms within the lattice and are therefore primarily reduced to movements along the grain boundaries causing granular de-cohesion. Furthermore, crack propagation as well as expansion and coalescence of voids can take place more easily in a structure with straight grain boundaries.

The influence of the water is also not totally clear but we know that stresses are built up both during wetting and drying processes and we know that most marble types with a bowing potential have more open grain boundary compared to the non-bowing types (figure 7.2). This enhances the ingress of water and larger capillary forces to act on the micro-scale for the unsuitable marble types. Furthermore, the energy needed for crack initiation and propagation is lower in a wet rock when compared to a dry one. The reason for this is that the energy increase is higher when a solid-solid contact is replaced with a solid-air contact compared to a solid water contact.

Once the micro-structure is open it is also easier for more water to enter the stone, water that may cause frost damage during winter time. In addition, the weathering through acid solutions from polluted rain is enhanced in an open structure.

The great complexity of the problem is the most likely reason for many of the misconceptions in previous projects. Too few marble types, in combination with the lack of opportunities for validating the results in the field, have often resulted in erroneous or unsubstantiated conclusions.

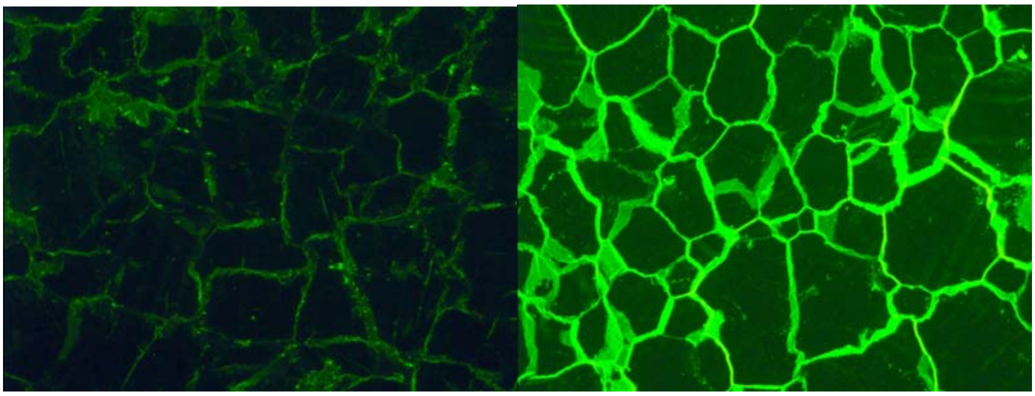


Figure 7.2. Fluorescent micro-photo of non-bowing marble to the left and a bowing one to the right. The marble to the right has a high proportion of cracks between the individual grains.

7.2.7 Development of the bow-test and the wet-expansion test

The work to develop test methods to determine the bowing potential and the temperature expansion in wet condition crossed two work packages (WP 5 and 6). It was clear from an early stage of the project that a moisture gradient is needed to obtain bowing. This phenomenon had previously been observed on many flooring installations where marble tiles have bowed soon after the placement in a grout. However, this bowing is not permanent. The bowing we can observe on the buildings is largely permanent and caused by elevated temperatures in combination with the moisture gradient. A laboratory test method was therefore developed to try to simulate these conditions. It is necessary in order to reproduce bowing in the laboratory to create the same conditions as on a façade. The detailed building inspections, together with the long-term monitoring and the literature study, have given the necessary information about the maximum temperature of a stone surface on a façade (at least in Europe). It has also given information about the 'ramp time', that is how fast the maximum temperature is reached and the time for the cooling of the panels. The resulting test method for bowing has produced results that correlate very well with the observations in the field. One important finding during the design of the method was the need to be able to repeat the temperature (T)-cycle in every test and to ensure equal "climatic" conditions for any test specimen regardless of marble type, colour etc. The only way to achieve this was by using a black reference in accordance with ISO 4892-1 (Plastics – Methods of exposure to laboratory light sources.).

The second test method developed, is an expansion test that correlates better with the observed performance in the field than currently available standard methods. Those responsible for designing a building generally favour a very small joint between stone panels. This joint is called a 'dilatation' joint and is used to allow for some movement between the individual panels without causing any breakage. The usual input to the design of such a joint has previously been the "thermal coefficient of expansion" in dry condition. The problem is that building facades are not always dry and the expansion in wet condition is generally significantly higher than in a dry condition. Thus we frequently see damage like that in figure 7.3. Bowing is also a differential expansion and the causes of the two phenomena are, therefore, directly related. The information input for the expansion test and the bowing test from other parts of the project is thus similar. It has proved insufficient to merely condition test specimens in different relative humidity. The test is, therefore, based on water saturated samples.

Figure 7.3. Cracking at anchoring points due to excessive expansion in relation to the dimensions of 'dilatation' joints.

Both test methods were used in an inter-comparison trial in accordance with the requirements stated in ISO 5725:1994. The repeatability (r) and reproducibility (R) were calculated accordingly.

Bowing test
It should be noted that the conditions were not identical in all laboratories and the test results therefore vary more than expected. Both the stones and the bowing method are very sensitive to differences in temperature and not all the laboratories had the possibility to install the black reference the during the project time. Slightly different lay-outs of the equipment was also reflected in different test results. However, it is clear that all laboratories have been successful in discriminating between bowing and non-bowing marble through this test.

Expansion
One major problem with the expansion test relates to the practicalities of carrying out the test. For example, despite many trials with different types of glue, some of the installed measuring points tend to detach from the stone surface during the expansion in hot water. It is therefore important to start with a large number of test specimens. This is a common problem shared with many other expansion methods, e.g. expansion of concrete. Similar to the bow-test, the expansion test can be further refined but it has already proved to be able to give clear guidance on the suitability of a marble (and limestone) type for cladding. In addition, it provides an important input to the dimensioning of the 'dilatation' joints.

Both test methods are complemented by the determination of flexural strength after the temperature cycling. This provides a clear indication of the potential strength decrease over time and so provides an important input to the prediction of the service life. However, it should be noted that if a more precise estimate of the service life is needed, it is necessary to know the temperature and temperature variations of the stone surface on the actual locality of the building. If a bowing marble has been chosen it may also be necessary to determine the frost resistance of that stone before and after temperature cycling.

7.2.8 Field exposure and possibilities to prevent the bowing or decrease the speed of the ageing

Five field exposure sites have been installed (Sweden, Poland, Slovenia, Italy and the U.K.) and one *in situ* on the City Hall in Nyköping. The test sites have provided essential information about the behaviour of different marble types, and the influence of thickness and treatments, for example surface coatings and impregnation.

It has been concluded that all marbles, both calcitic and dolomitic, showed bowing that can be measured in the field condition, however the magnitudes differ greatly. Comparable bowing was observed in all climatic zones of the participating countries with Itq2 panels displaying the highest bowing and deterioration potential after one year's exposure at every field exposure sites. Itq2 was the most sensitive marble but other types such Thassos marble showed bowing and especially cracking independently of the climate. It is essential to point out the substantial difference between bowing magnitude of the same samples measured at field conditions and after drying indoors. All results from *in situ* measurements gave higher bowing compared to measurements on dried samples. In some cases, marble panels showing bowing when measured on the field exposure sites showed no signs of bowing after drying in indoors conditions. This indicates that no permanent bowing could be observed for these panels. Therefore, it is recommended that bowing measurements taken outdoors should be taken when the temperature variations are as small as possible (summer and winter) and that the measurements are repeated on a number of occasions.

Analyses of how thickness and impregnation influence bowing were performed on one type of fresh marble, Itq2, and on the old panels on the façade in Nyköping. The analysis of variance indicates that bowing depends on the thickness and impregnation. The highest bowing was observed for the 20 mm thick panels and lowest for the 30 mm impregnated thick panels. Both impregnation agents were shown to have an inhibiting effect on bowing process after one year of exposure. However, after three years of exposure it was clear that only the microcrystalline wax (AGS) was preventing bowing. Impregnation with a hydrophobic treatment decreased the bowing for the fresh panels. The results from the field exposure were comparable to results from the laboratory experiment on the old panels from the Nyköping. The AGS impregnated samples showed small or no bowing at all. This effect could not be observed for the GS impregnated samples. No aesthetic change could be observed as a result of the impregnation process. Hydrophobic treatments had an inhibiting effect on the bowing and could be recommended as a remedial action for damaged panels, thought not as a final solution. It is important that each case is investigated independently.

7.2.9 Guidelines for production and product control

Guidelines for production of panels and product control have been drafted. They are primarily directed towards the producers and suppliers but also to designers. The importance of choosing a technically suitable marble for outdoor claddings is strongly emphasised. If a bowing marble is chosen or one that rapidly will loose strength the consequences are considerably – for example in terms of increased maintenance costs due to the fact that such a marble will quickly get an open micro-structure that is more susceptible for soiling. Removal of graffiti will be more difficult and, of course, the risk of failure due to loss of strength will make it necessary to monitor the changes and finally change part, or all, of the facade before as the risks of panel failure become unacceptable. Technically acceptable properties should therefore have very high priority when choosing a marble type for a building project, whereas today aesthetical properties are often considered as being of greatest importance even though the aesthetic properties will change rapidly for a non-suitable marble as it deteriorates.

The recommendations to the producers are to provide a geological map of their quarry and request a petrographical analysis including the AGA for all areas identified as significantly different. They should then carry out the laboratory bow-test and the wet-expansion test to establish a correlation between those parameters and the petrography. By using non-destructive tests it should be possible to identify major changes at the rough block stage of production and so avoid unsuitable material entering the processing stage. A detailed instruction for marking and identification of material at all stages is also strongly recommended for sake of traceability and feed back to the production company.

7.2.10 Dissemination activities

TEAM has produced numerous internal technical reports (chapter 9 references), many peer reviewed scientific articles and has been represented at several international conferences. Small scale national workshops for producers and architects have also been made, and many presentations for European standardisation at CEN TC 246 meeting. One of the results that we are most proud of is that the project has contributed to 6 doctoral theses!

Dissemination activities will also continue after the project is completed:

- CER 2005: Communicating European Research 2005 a major event in November at the Heyzel Expo in Brussels (http://europa.eu.int/comm/research/conferences/index_en.cfm)
- The TEAM homepage will be updated shortly after the finalisation of the project.
- The TEAM book that is planned for publication in 2006 and will contain all our main work and findings.

7.3 Conclusions

The TEAM project has given our knowledge of marble and limestone deterioration processes a significant push forward and we hope that our findings will contribute to an increase in the use of marble and limestone for cladding and thus help regaining some of the trust lost in these materials in particular climates and countries.

The main conclusions are given below:

- A deeper understanding of the properties influencing the durability of marble and limestone as an outdoor cladding material has been gained, not the least through compiling and reviewing most of the literature (over 300 articles) in this field and making it available to anybody through the homepage.
- A comprehensive building survey, of about 200 buildings, has given a very good picture of the extent of the problem both geographically and geologically. Bowing is a world-wide phenomenon not confined to one type of marble or one type of climate, e.g. frost action is not necessary for this phenomenon to occur. Subsequent detailed case studies have provided a possibility to test several deterioration hypotheses and given important information about the variables to be used in the test methods developed later in the project, especially relevant temperature ranges.
- Sampling and testing of panels from the buildings have given further information about the deterioration process and its rate and , together with the inspection methodology, provided a sound basis for building a model to predict the remaining service life, including analysis of the associated risk.

- The long-term monitoring underlined the importance of repeated measurements in order to enable reliable conclusions to be made. One time measurements are of little use due to large diurnal and seasonal variations.
- The sampling of test materials is very critical for any project. Detailed sampling and sample marking instructions have to be used for any sampling. Our findings have been reported to CEN TC 246 Natural Stone.
- Laboratory testing of almost 100 different types of marble has taken us much further in our search for the mechanism and allowed us to refute many “old” hypotheses. The main extrinsic influencing factor is elevated temperature in the presence of a moisture gradient. This creates the external stresses that different marbles will then respond to in different ways. The most crucial intrinsic parameter is the complexity of the grain boundaries and the grain size distribution of mineral grains in the rock. This provides different bonding strength between the mineral grains due to the complexity of the arrangement of the grain boundary and in combination with the crystal structure. The irregular grain structure that all marble considered suitable for outdoor cladding have in common is the product of the metamorphism that turned limestone into a marble combined with a dynamic re-crystallisation event. Weaker bonds will cause granular de-cohesion, ’sugaring’, of the marble and significant strength losses.
- The work in developing the test methods has proved that every marble is unique and has a unique response to climatic stresses with its own degradation curve. The acceleration factor of the laboratory bow-test is therefore different for different marble types. The test methods developed enable a relevant evaluation of whether a marble is suitable for outdoor cladding or not. The bow-test can be adapted and used for predicting the remaining service life of a specific marble on a particular building.
- Field exposures have shown that it is possible to inhibit or decrease the degradation of marble by coating the surface with a hydrophobic treatment. The effect is most pronounced on marble already exposed and it should not be used to support the selection of an unsuitable marble for a new building project.
- Guidelines for designers and producers/suppliers have been given to ensure a proper selection of suitable marble and limestone for outdoor cladding and to insure production with a homogeneous and acceptable quality respectively.

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10 List of reports

References, in the main text, to internal TEAM reports, e.g. technical reports are given in numbers within brackets [1].

Ref nr	Technical report
[1]	NT Build 499. Cladding panels - Test for bowing
[2]	WP1.1-JAC-TD-050830-Case studies-Final
[3]	WP2.2-SP-TD-001212-Instruction for site inspection
[4]	NT Build 500. Cladding panels- Field method for measurement of bowing
[5]	WP 4.1-STF-IMM-TD-011128-Sampling statement
[6]	WP4.2-STF-TD-050615-Rock Assessment Forms_Appendix 4
[7]	WP5.3-STF-TD-050614-Petrographic description-Quarry samples

	Other technical reports
	WP1.1-JAC-STF-TD-010427-summaryreport-1
	WP1.1-TD-JAC-050830-Case studies-Final
	WP1.2-RMB-TD-050816-State-of-the-art-report Review of literature
	WP1.2-RBL-TD-050105-Literature list
	WP2.2.-BRE-TD-020725-Detailed Assessment-Library-DE
	WP2.2-BRE-TD-020725-Detailed assessment-Library-DE-app A
	WP2.2-BRE-TD-020725-Detailed assessment-Library-DE-app B
	WP2.2-BRE-TD-020725-Detailed assessment-Library-DE-app C
	WP2.2-BRE-TD-020725-Detailed assessment-Library-DE-app D
	WP2.2-BRE-TD-020725-Detailed assessment-Library-DE-app E
	WP2.2-BRE-TD-020725-Detailed assessment-report-Library-DE
	WP2.2-JAC-TD-020925-Detailed assessment-Nyköping-SE
	WP2.2-JAC-TD-020925-Detailed assessment-Nyköping-SE-app A
	WP2.2-JAC-TD-020925-Detailed assessment-Nyköping-SE-app B
	WP2.2-JAC-TD-020925-Detailed assessment-Nyköping-SE-app C1
	WP2.2-JAC-TD-020925-Detailed assessment-Nyköping-SE-app C2
	WP2.2-JAC-TD-020925-Detailed assessment-Nyköping-SE-app C3
	WP2.2-JAC-TD-020925-Detailed assessment-Nyköping-SE-app D
	WP2.2-JAC-TD-020925-Detailed assessment-Nyköping-SE-app E
	WP2.2-JAC-TD-021006-Detailed assessment-Lunen-DE
	WP2.2-JAC-TD-021006-Detailed assessment-Lunen-DE-app A
	WP2.2-JAC-TD-021006-Detailed assessment-Lunen-DE-app B
	WP2.2-JAC-TD-021006-Detailed assessment-Lunen-DE-app C
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	WP2.2-JAC-TD-021006-Detailed assessment-Lunen-DE-app E
	WP2.2-JAC-TD-030915-Detailed assessment-Malmo city hall-SE
	WP2.2-PTO-021022-Detailed assessment-Magenta-IT
	WP2.2-PTO-021022-Detailed assessment-Magenta-IT-app A
	WP2.2-PTO-021022-Detailed assessment-Magenta-IT-app B
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	WP2.2-PTO-021022-Detailed assessment-Magenta-IT-app E
	WP2.2-RMB-TD-010527-Detailed assessment-DNB-DK
	WP2.2-RMB-TD-010527-Detailed assessment-DNB-DK-app A
	WP2.2-RMB-TD-010527-Detailed assessment-DNB-DK-app B

	WP2.2-RMB-TD-010527-Detailed assessment-DNB-DK-app C
	WP2.2-RMB-TD-010527-Detailed assessment-DNB-DK-app D
	WP2.2-RMB-TD-010527-Detailed assessment-DNB-DK-app E
	WP2.2-RMB-TD-010527-Detailed assessment-DNB-DK-app F
	WP2.2-UGE-TD-020514-Detailed assessment-Theol-DE
	WP2.2-UGE-TD-020514-Detailed assessment-Theol-DE-app A
	WP2.2-UGE-TD-020514-Detailed assessment-Theol-DE-app B
	WP2.2-UGE-TD-020514-Detailed assessment-Theol-DE-app C
	WP2.2-UGE-TD-020514-Detailed assessment-Theol-DE-app D
	WP2.2-RBL-TD-050620-Summary Report Building inspections
	WP2.2-RMB-TD-021014-Concept for assessment-pr1
	WP2.2-SP-TD-001212-Site inspection
	WP2.4-BRE-020212-Predicting service life-risk analysis
	WP2.5-SP-TD-020205-Samples from buildings
	WP2.6-JAC-TD-050830-AnchorRep-Final
	WP3 .2-BRE-TD-030304-Deliverable 8- Preliminary Report after initial site trials
	WP3-BRE-TD-050715-Final report of WP 3
	WP3-BRE-TD-010219-Deliverable 7 system and protocol
	WP4.2-STF-TD-020826-Sampling of oriented cores in Porsgrunn 2002 March
	WP4.2-STF-TD-050614-Quarry Sampling and samples
	WP4.2-STF-TD-020826-Sampling SINTEF_Annex 1-4
	WP4.2-UGE-TD-021107-Sample Cutting UNIGOE_b
	WP4.2-UGE-TD-021107-Sample Cutting UNIGOE_b_annex1-1
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	WP4.1-SP-Form411-050616-Seq1-Ekeberg
	WP4.1-ImBigs-Form411-050620-Plq1-Biala Mariana
	WP4.1-ImBigs-Form411-050620-Plq2-Slawniowice
	WP4.1-IMM-Form411-011113-Grq1-Thassos
	WP4.1-IMM-Form411-040802-Itq1-Canaloni
	WP4.1-IMM-Form411-040802-Itq2-Gioia
	WP4.1-IMM-Form411-040802-Itq3-Buca
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	WP4.1-STF-Form411-050615-Noq1-Porsgrunn
	WP4.1-STF-Form411-050620-Porsgrunn_Annex A
	WP4.1-STF-IMM-UGE-TD-011128-Sampling method statement Quarries
	WP4.1-UGE-Form411-020516-Chq1-Peccia
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	WP4.2-SP-TD-021127-Sample Cutting Ekebrg
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	WP5.1-STF-TD-020430-D2-5Report-Appendix7
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	WP5.1-STF-TD-030619-D2-5.Report-Part2-Appendix 2
	WP5.1-STF-TD-030619-D2-5.Report-Part2-Appendix 3
	WP5.2-STF-TD-050815-Production and processing conditions-Report
	WP5.3-STF-TD-050614-Petrographic description-Quarry samples
	WP5.4+7.5-STF-TD-050815-Accelerated test report (+ 8 annexes)
	Annex 1: product data sheets are not included here
	WP5.4+7.4-STF-TD-050815-Acc test-Annex 2 - Installation scheme
	WP5.4+7.5-STF-TD-050815-Acc test-Annex 3-bow readings during exposure
	WP5.4+7.5-STF-TD-050815-Acc test-Annex 4-Bow diagrams exposure
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	WP5.4-BRE-TD-050815-Summary report of lab tests for Other properties
	WP6.1-RMB-TD-050831-Lab bow-test method EN draft
	WP6.2-UGE-TD-050816-Lab expansion-test method EN draft
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	WP8-STF-TD-050930-Report WP8-Task 8.1+8.2
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