Figure 1
The new marble façade on Finlandia Town Hall – approximately 6 months after a recladding of the building.

Deterioration of Thin Marble Cladding
a major international study

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This intriguing article reveals that problems can and do occur, even with materials like Carrara marbles that have been used extensively for many years. The article also confirms that solutions can be found and improvements can be made. There is no sense in assuming that everything in the garden is rosy, when it patently is not. These images could be enough to deter any specifier from choosing thin marble as a cladding material. However, despite the cost of repairs and the apparent severity of the highlighted problem, the majority of marble façade installations perform adequately. This article serves to highlight the critical need for architects to be well informed about the materials they have at their disposal, and how and where they can be used effectively. This report was partially funded by the European Commission and conducted by TEAM (Testing and Assessment of Marble and Limestone).

Background

Natural stone has been used for facade applications since time immemorial. Originally, the stone employed was rather thick, when used as a construction element, and the strength and durability was very consistent . Scientific research on properties of marble began in the late 19th century. In the years following, the thickness of natural stones used on facades decreased from over 1000 mm (as in construction elements) to 20-50 mm (in cladding applications) as a result of new cutting technologies and equipment that was developed by industry.

The use of thin marble and limestone slabs as facade cladding has increased substantially during the last few decades.

Even though the vast majority of marble claddings perform satisfactorily, durability problems began to occur, following the advent of thin cladding materials. 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 and SCOR Tower in Paris and IBM Tower in Brussels have all experienced serious problems with their thin marble clad facades. The problems include expansion, bowing, loss of strength, and in the most serious cases complete detachment from the anchoring system.

The bowing of marble is not only restricted to buildings. Marble tombstones have also been known to bow. At the present time, most of the recorded cases of façade failures emanate from Europe or North America, because of the more widespread use of thin marble claddings in those parts of the world. However, failures have also been recorded in Lebanon, Australia, India and Cuba.

The problems regarding limestone facades are slightly different. Apparently, limestone does not bow, however it can expand causing serious problems if the joints are not sufficiently wide enough to tolerate the expansion.

The industry urgently needs to develop a repair system for existing facades that develop problems. Despite several European research projects, the prime solution relies on replacing the panels at a cost of approximately 600-900 AUD $/m^2$. The fairly recent example of the City Hall in Helsinki, where all panels were replaced in 1998, came in at a cost of 6.5 Million AUD$ (a figure that was not dissimilar to the entire cost of the TEAM project). This provides an economic perspective of the problem. The problem did not cease because it would appear that the new panels which were chosen incorrectly started to bow 6 months after installation! (**Figure 1**)

It is estimated that the known cost of repairs to damaged facades located in Europe will exceed AUD$400 million. This figure is based on current strategies used to effect repairs. Although the vast majority of reported durability problems with thin marble or limestone slabs relate to use of Italian Carrara marble, which is 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 satisfactorily. Note that there are about 200 different stone quarries in operation in Carrara, Italy! The direction of the observed bow may be either convex or concave relative the facade, this is probably determined by local climatic conditions.

Figure 2
A close-up of the bowed Carrara marble panels on Finlandia Town Hall few months before the panels were replaced by new Carrara marble panels.

Figure 3 The town hall in Malmo, Sweden features a 27 year old Carrara marble facade that is in perfect condition.

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 that will distinguish durable building stones from nondurable building stones.

Objectives

The main objectives in the TEAM 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 climatic terms.

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

Research, both in the laboratory and the field was performed on a large number of different natural stones from various countries utilised in varying climates. This provided an 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 in the 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.

Observation and results from the project

Inspection and investigation of buildings

During the project a total of 194 Building Projects have been identified and reported on, providing various levels of detail. This includes 26 Buildings that have been selected for further investigation.

- All of the 26 Buildings were considered as suitable for dismantling of the facade panels for laboratory testing purposes.
- Six buildings were selected for detailed field studies, measurements of bowing and supplementary investigations.
- Two buildings were selected for long term monitoring.

Based on the investigations we have concluded that the phenomenon of bowing of thin marble is actually rather common. Deformation by bowing is experienced in buildings of various ages, in buildings exposed to various weather conditions and for slabs of various

Figure 4

Figure 5

Figure 6

Figure 7

thickness and dimensions and with different anchoring methods. Finally, and what is most interesting, bowing is registered for marble of seemingly different composition and structure.

It is important to note that the problem of bowing is not restricted to one type of marble or one climatic zone. 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). 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 as having durability problems in terms of bowing.

It is also equally important to draw 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 specified.

The report also considered the possible effects of climate.It is reasonable to discuss the effects of different locations of the stone facade slabs on the building itself – height above the ground and directions of the compass. As for these parameters, our studies are in accordance with the literature:

- most pronounced bowing on the upper parts of the buildings and
- most pronounced bowing on the facades that face southeast and southwest. Pronounced bowing also occurs on facades that face south. The claddings facing to the north display less tendency to bow.

This implies that the facades which are subjected to the most sunlight

Figures 4-6 Examples from Croatia depict a building façade that exhibits severe bowing. Figure 7 Bowing measurement on a façade.

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exhibit the highest percentage of bowing panels and the largest amplitudes.

• 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 can occur on the same facade with the same marble.

• There is a clear correlation between bowing behaviour and deterioration leading to loss of strength.

• 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 various origins) that may bow. Marble selected from same region or even same quarry can demonstrate bowing as well as non-bowing behaviour.

• Problems other than bowing and deterioration have been registered and noted.

• Marble types with known or measured bowing problems and marked strength loss should be avoided in thin building claddings.

Based on the 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.

Investigations of selected buildings show large strength loss in the order of 80 % after 35 years for one calcitic marble and 40 % for one dolomitic marble. Laboratory studies 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.

It is surprising that, despite several reports of severe loss of strength, field investigations in relation to this topic are rare.

Main Conclusions

The TEAM project has significantly increased our knowledge of marble and limestone deterioration processes.

We hope that the findings will contribute to an increase in the use of marble and limestone for cladding and thus help restore some of the trust lost in these materials in particular countries and climatic conditions. 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 (see **www.sp.se/building/team**).

• 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 worldwide phenomenon not confined to one type of marble or one type of climate, e.g. frosty conditions are not necessary for this phenomenon to occur. Subsequent detailed case studies have provided the possibility of testing several deterioration hypotheses and yielded important information about the variables to be used in the test methods which were developed later in the project, and are especially relevant to variations in temperature.

• Sampling and testing of panels from the buildings have provided further information about the deterioration process and the rate of

Figure 8 Bowed marble panels on a building in Helsinki, Finland.

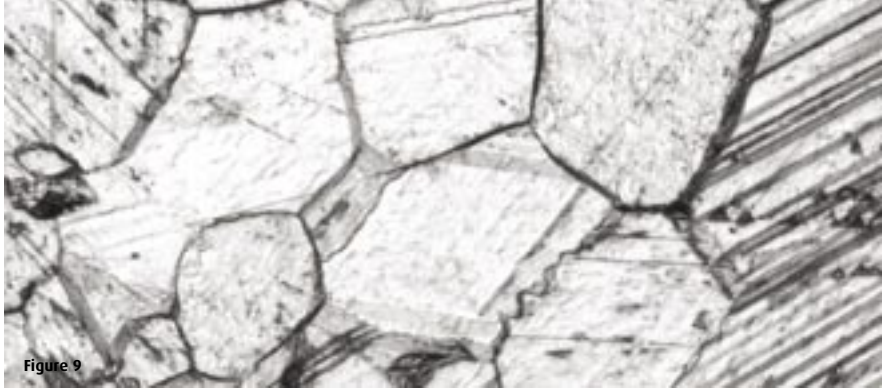

Figure 9

Figure 9 Microphoto (1.0x 1.5 mm) Carrara marble with granoblastic microstructure, marble with potential bowing behaviour.

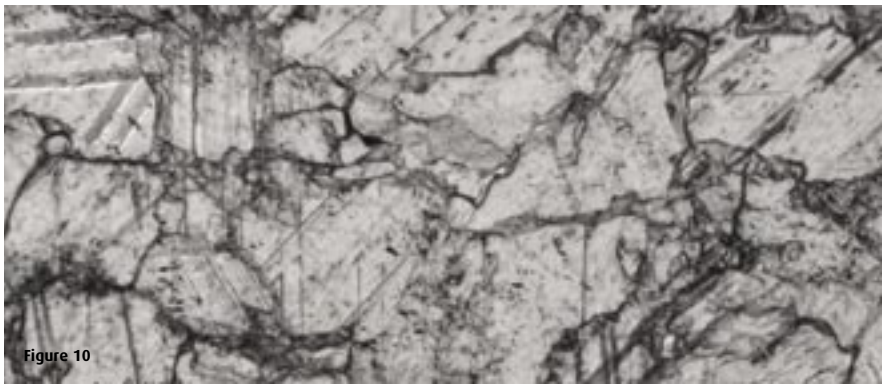

Figure 10

Figure 10 Microphoto (1.0x 1.5mm) Carrara marble with xenoblastic microstructure. A marble that does not bow.

change, together with the inspection methodology, this has provided a sound basis for building a model to predict the remaining service life, including analysis of the associated risk.

• 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 recrystallisation 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 that determines 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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