The laboratory testing of potential bowing and expansion of marble

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ABSTRACT: The use of thin marble and limestone panels for facade cladding has increased substantially during the last five decades. The durability of such thin slabs (often only 30 mm thick) has been assumed to be satisfactory based on centuries of successful use as a structural building stone. Nevertheless, all over the world, the long-term deformation and strength loss of some cladding panels have led to concerns about its safe and durable use. The detailed assessment of marble and limestone within the TEAM-project (see also www.sp.se/building/team), is used to develop a hypothesis for the observed deterioration and to develop remedial actions. This paper presents test methods for the bowing and expansion potential of marble. The method is discussed and the relevance of the test exposures is demonstrated by comparisons with on-site observations on marble cladding. A number of results are presented, illustrating the influence of the temperature cycles, the humidity and the stonetype on the bowing and expansion.

1 INTRODUCTION

Marble and other natural stone have been used for cladding in many structures and have usually performed very well. There are also cases throughout the world, where the panels have developed severe bowing (Fig 1.) or expansion (Fig. 2), leading to severe loss of strength, failure of joints, fixings (Fig.3) or collapse of the panel itself. Such cases will usually lead to an expensive replacement of the cladding and the fixing system.

The research, inspection (see Yates et al, 2004) and testing show that a great many factors may influence the risk of bowing and expansion as e.g. stone type, panels thickness, joint design, fixing methods as well as the environment. The inspections showed, that an environment with temperature cycles and moisture as in Northern and Central Europe increased the risk of bowing and expansion.

The problem has become increasingly important as the international trade has lead to an increased use of new stone types in new environments, without the proper testing. The problem can be solved or reduced substantially by screening the selected stone types with e.g. a realistic, accelerated testing of the bowing and expansion potentials. The partners in the TEAM project decided therefore to develop test methods for bowing and expansion and to correlate these to conditions and performance in practise.

This paper presents the developed test methods for bowing and expansion potentials, a few typical results and a correlation to observations from practice.

Figure 1. Bowing panels on a facade in Copenhagen.

Figure 2. Expansion of panels leads to contact stresses and compaction of joint material, which can be squeezed out.

2 TESTING OF BOWING POTENTIAL

The test method NT Build 499, developed by Schouenborg et al. (1997), 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 conditioned by drying at 40 ^{o}C until a stable weight is achieved (usually within 7 days), followed by cooling to 20 ^{o}C and a partial submerging in water for 24 hours at this temperature.

The specimen is placed in an insulated container, where it is placed on a tray, filled with a layer of filter cloth or sand (Fig. 3). 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 ^{o}C over a period of 1-3 hours. The surface temperature is maintained at 80 ^{o}C for 2-3 hours, after which the infrared heating is turned off and the specimen allowed to cool to ambient room temperature, (20 ^{o}C) until at least 24 hours has passed from the start of the exposure cycle. The surface temperature on the upper side shall therefore follow the ideal curve shown in Figure 4 with a tolerance of $\pm$5 ^{o}C. The Figure 4 shows also the actual temperatures measured on the top and the bottom of a test specimen, which shows that the temperature is almost identically the same through the specimens at any given time.

Temperature measurements on panels on buildings by Perrier & Boineau (1997) have revealed that the daily magnitude of the temperature cycles can be up to 60 ^{o}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. This is carried out by placing the specimen in the bow-test rig (Fig. 5), where the specimen is supported in fixed positions with a distance (L = 350 mm), which ensures that all measurements of the deformation (Δh) are carried out in the same position on the specimen. The bowing is then defined as the ratio Δh / L.

The test method has been applied on a large number of different stone types during the TEAM-project and has yielded very important results.

The bowing will usually grow unlimited in an environment with temperature cycles and moisture (Fig. 6). 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. The Figure 6 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.

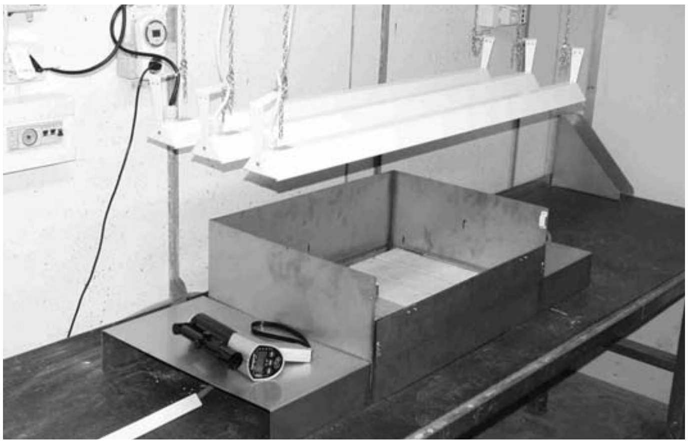

Figure 3. Illustration of test set-up, NT Build 499.

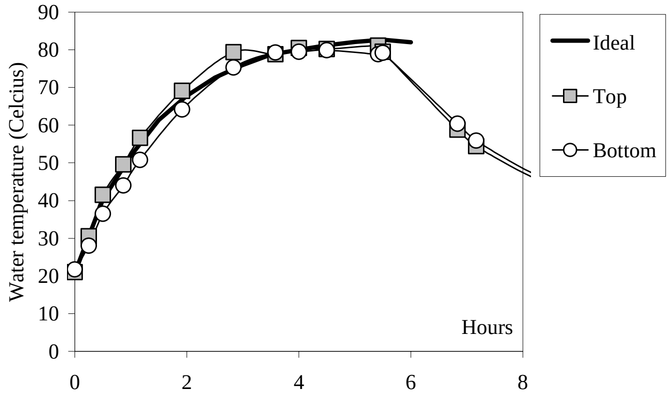

Figure 4. Ideal temperature variation in bowing test and monitored temperatures on the upper and lower side of a test specimen.

Figure 5. Measuring bowing in the laboratory.

The bowing potential differs significantly between different stone types, as it can be seen in Figure 7, where samples have been cut from exposed panels from the buildings facades and some samples from unexposed panels, stored inside the buildings. The unexposed panels came from the same delivery as the exposed panels, but have been kept in storage or at indoor positions, where they are not exposed to temperature cycles or moisture.

The thickness of the panel will also have an effect on the development of bowing as shown in Figure 8.

The testing has so far not been able to identify a "pessimum", defined as a critical thickness, where the bowing would be largest, but have shown that a larger thickness leads to a slower development of the bowing.

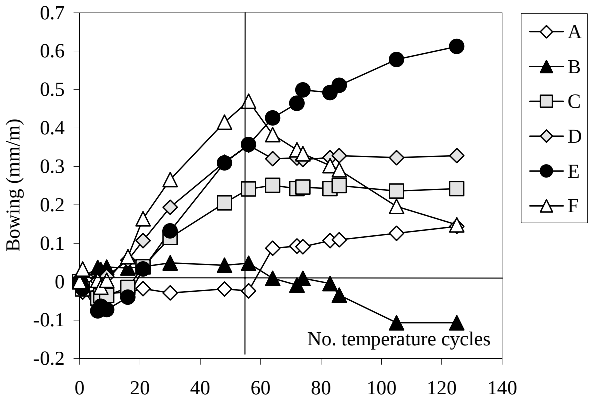

Figure 6. Bowing on Norwegian marble versus cycles; wet and dry exposure.
A: Dry exposure until 56 cycles, then wet.
B: As A, but with wetting of upper surface.
C: Wet exposure for the first 56 cycles, then dry.
D: Wet exposure for the first 56 cycles, then constant temperature in dry environment.
E: Wet exposure.
F: Wet exposure, but sample is turned after 56 cycles.

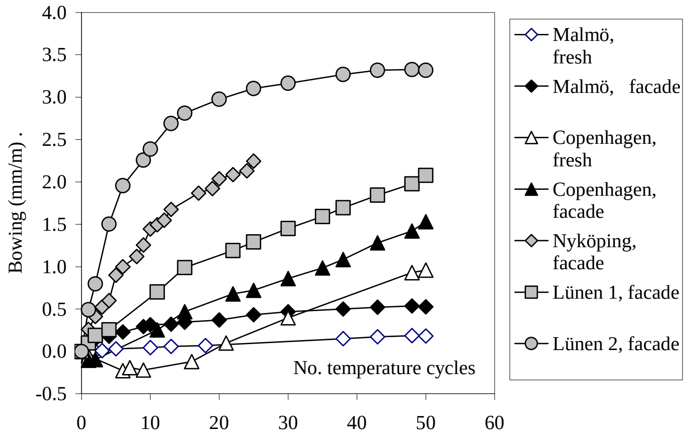

Figure 7. Bowing of marble versus cycles; wet exposure of samples from exposed panels from the buildings facades and unexposed (fresh) panels.

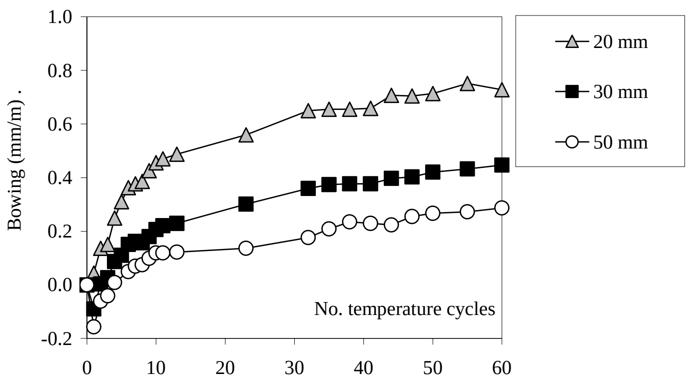

Figure 8. Bowing of samples of Norwegian marble with different thickness versus cycles; wet exposure.

Parallel petrographic studies showed that the microstructure influences the bowing potential significantly. It has been shown from the above tests and from the numerous other tests on other marble samples, that the calcitic marbles with interlobale grain shapes have low bowing potentials and that the marbles with granoblastic-polygonal grain shapes have a much higher bowing potential. The influence of the mineral properties on the bowing and expansion potentials is described in details by Alnæs et al. (2004)

The microstructure of a marble with typical interlobale grain shapes is shown in Figure 9, top (taken from the Malmö panels) and the microstructure of a marble with typical granoblastic-polygonal grain shapes is shown in Figure 9, bottom (taken from the Nyköbing panels). The terms granoblastic-polyygonal and interlobale grain shapes in this paper are used in accordance with Passchier et al. (1996) and Spry (1983).

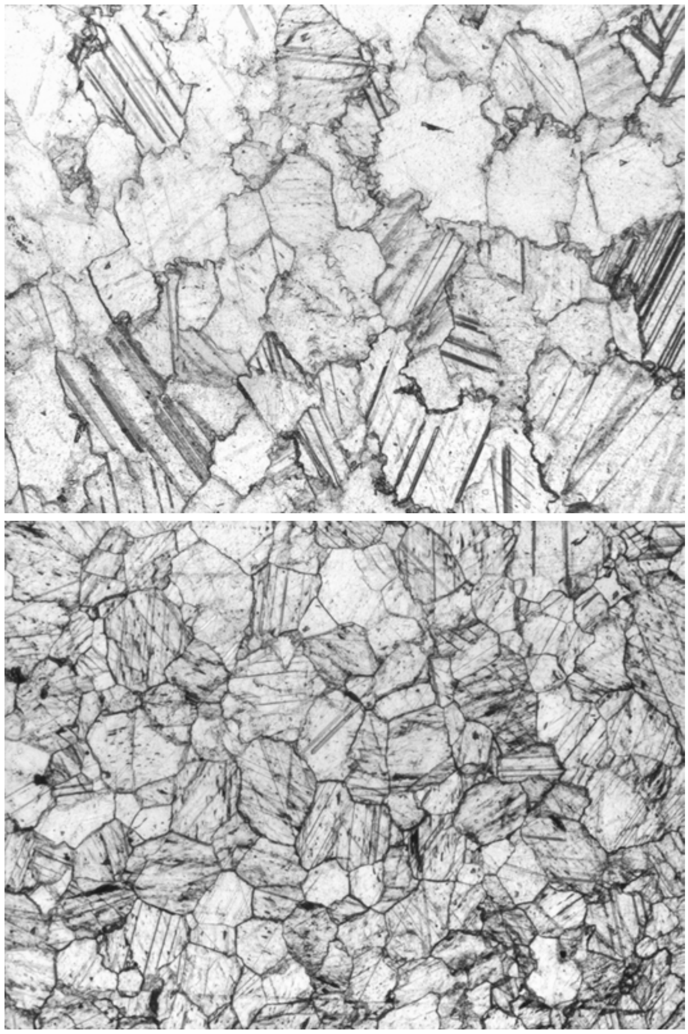

Figure 9. Microstructure of tested marbles; top is Malmö (interlobale) and bottom is Nyköping (granoblastic-polygonal). Each image is 2 x 2.8 mm.

Bowing and loss of strength have been reported by Yates et al (2004) to correlate in samples from building claddings. Flexural strength 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.

3 TESTING OF EXPANSION POTENTIAL

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 specimen is conditioned as the bow test specimens. The specimens are then placed in a tank, filled with distilled or demineralised water with an ambient temperature of 20±5 °C and left until constant mass is reached, at which stage the length and mass is measured again.

The temperature of the water in the tank follows the same variation as the surface temperature in the bowing test (Fig. 4) 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 (Fig. 10). 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 11, 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. The Figure 11 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 (Fig. 12).

Figure 10. Expansion test-setup (right) and measurement of the length of the specimen (left).

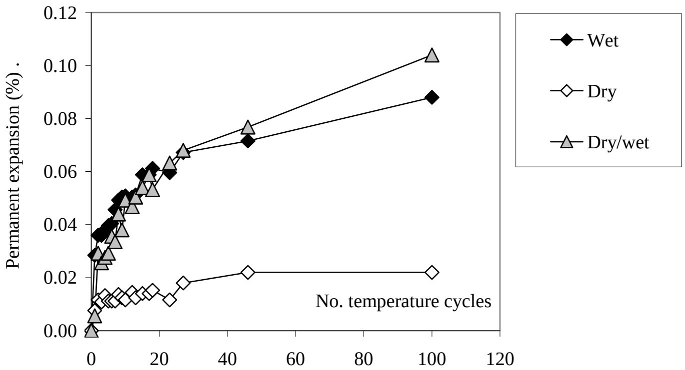

Figure 11. Expansion versus cycles; wet and dry exposure of Norwegian marble.

Figure 12. Failure over anchoring fixing (dowels), due to permanent expansion of the panels.

4 EFFECT OF DIRECTION

The samples normally tested in the expansion or bowing testing are cut in a direction, determined by the panels direction, which again were determined by the producer.

This may have an effect, since the extremely anisotropic coefficient of thermal dilatation of calcite (26 x 10^{-6} / °K parallel to the crystallographic c-axis and -6 x 10^{-6} / °K perpendicular to it according to Kleber (1990)) is well known from literature to be responsible for the development of thermal micro cracks in marble due to diurnal atmospheric heating-cooling-cycles (Fig. 13).If the bulk marble shows a preferred orientation of the c-axes its thermal dilatation anisotropy should approximate that of calcite.

Moreover, the orientation of newly formed microcracks is controlled by the lattice preferred orientation as well leading to a directional dependence of the permanent length change.

As a consequence, the cut direction may have an effect on the bowing and expansion potentials if the microfabric of a calcitic marble is anisotropic.

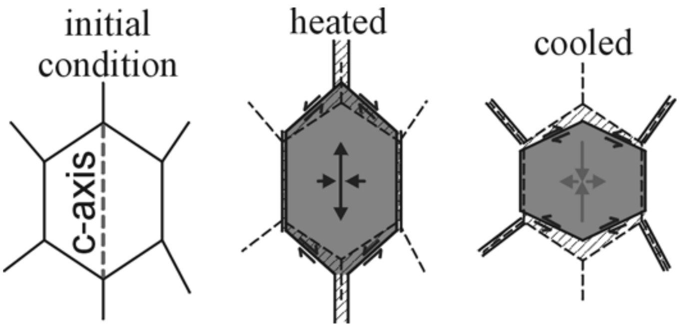

Figure 13. Anisotropic thermal behaviour of a single calcite crystal (after Ruedrich et al. 2001).

The TEAM project has therefore looked into the directional dependence on bowing and expansion as reported in Koch & Siegesmund (2004). It was found that some calcitic marbles with a strong lattice and grain shape preferred orientation display an anisotropic bowing and expansion behaviour. A calcitic marble with an average grain size of 0.2 mm and a broad grain size distribution from 0.1 mm up to 1.5 mm and mostly curved or irregular, rarely straight grain boundaries was used for the testing. Thin sections of different orthogonal orientations revealed a distinct grain shape preferred orientation, which is perpendicular to the c-axis maximum of the calcite crystals. To detect the anisotropy test specimens were cut in two different orientations (Fig. 14).

The detection of thermal expansion anisotropy was tested under modified conditions. Cylindrical specimens of 50 mm length and 15 mm diameter were measured in a pushrod dilatometer in two orthogonal directions coinciding with the directions of maximum and minimum thermal expansion. The specimens were exposed to eight dry and ten wet temperature cycles at the same time. Each cycle started at 20 °C followed by a heating phase by 0.5 °C / min, an equilibration phase of two hours under dry conditions or eight hours under wet conditions at 90 °C, a cooling phase by 0.5 °C / min and a final equilibration phase of two hours at 20 °C. One hour before the heating-up of each wet cycle the climate chamber of the dilatometer was filled with demineralised water, which evaporated during the heating period.

The specimens cut in orientation “B” (Fig. 14) showed a three times higher bowing than those in the “A”-orientation after 40 cycles in the laboratory bowing test (Fig. 15). A similar observation was made in the modified expansion test (Fig. 16). As described above the expansion reached a constant level after a few cycles under dry conditions and increases continuously under wet exposure. The expansion parallel to the c-axes (orientation “B”) was found to be three times as high as the expansion perpendicular to the c-axes (orientation “A”).

This shows that the preferred crystallographic direction may have a marked influence on the bowing and expansion.

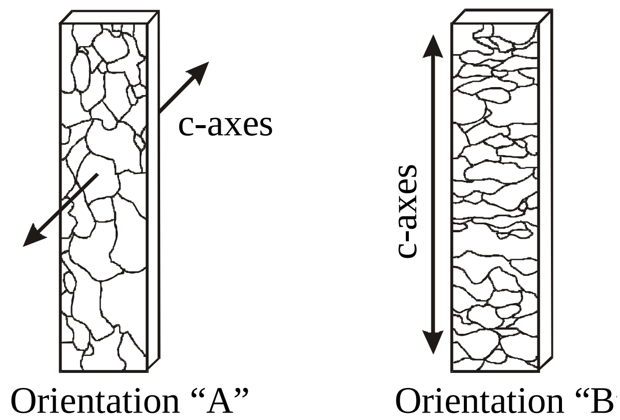

Figure 14. Scheme of bowing test specimens cut in two different orientations in relation to c-axes and grain shape preferred orientation of calcite.

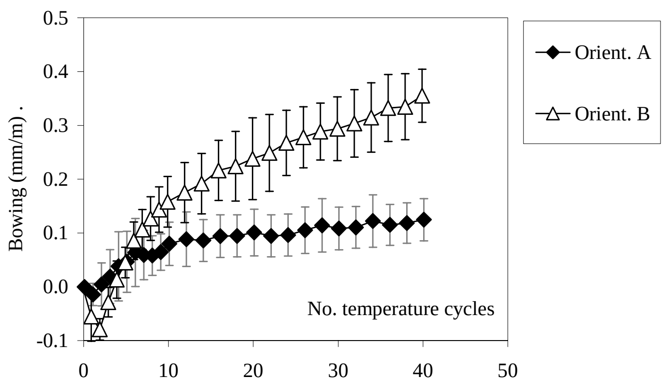

Figure 15. Bowing of marble slabs versus number of heating cycles in Koch & Siegesmund (2004). Each curve represents the mean bowing trend of three specimens.

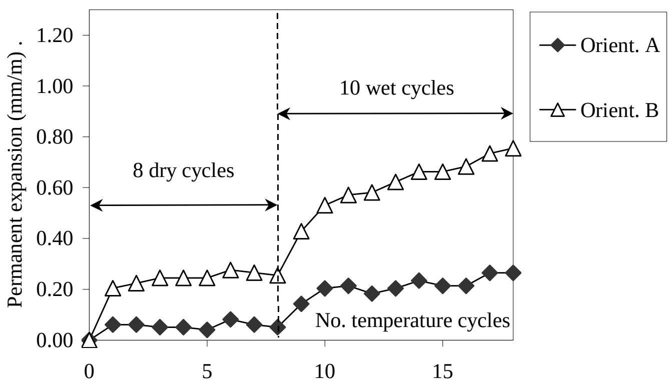

Figure 16. Irreversible expansion of marble versus number of heating cycles (20-90 °C) under dry (cycle 1 to 8) and wet (cycle 8 to 18) conditions in Koch & Siegesmund (2004).

5 LAB TESTING VERSUS FIELD CONDITIONS

The purpose of the laboratory testing is to 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, which have been carried out during the TEAM-project.

The TEAM has obtained both exposed and non-exposed panels from a number of the inspected buildings. Samples from both groups of panels have been tested.

A number of other buildings were inspected, but non-exposed panels were not available and it was therefore necessary to identify the quarry, producing the original panels. A number of test panel were obtained from these quarries and used for the laboratory testing.

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.

6 CONCLUSION

The two test methods have 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. The results of the test methods correspond to the observed behaviour in buildings with marble cladding. The results of the test methods provide also a necessary link to other material data and to the microstructure of the marble and will thus facilitate the understanding of the deterioration mechanism.

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 methods are being discussed as potential CEN-test methods and could form a part of the later, mandatory product control.

7 ACKNOWLEDGEMENT

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8 REFERENCES

Alnæs, L., Koch, A. ,Schouenborg, B., Åkesson, U., Lindborg, U. & Moen, K. 2004., Influence of rock and mineral properties on the durability of marble panels. Proc. Dimension Stone 2004.

Kessler, D.W. 1919. Physical and chemical tests on the commercial marbles of the United States. Technological papers of the Bureau of Standards No. 123.

Kleber, W. 1990. Einführung in die Kristallographie. Berlin: VEB Verlag Technik.

Koch, A. & Siegesmund, S. 2004. The combined effect of moisture and temperature on the anomalous expansion behav-iour of marble. In: S. Siegesmund, H. Viles & T. Weiss (eds), Stone decay hazards, Environmental Geology, in press.

Malaga, K., Scouenburg, B.,Alnæs, L, Bellopede, R. & Brundin, J.-A. 2004. Field exposure sites and accelerated laboratory test of marble panels, Proc. Dimension Stone 2004.

Passchier, C.W. & Trouw, R.A:J. 1996. Microdefects. Springer verlag.

Perrier, R & Bouineau, A. 1997, La descohesión Térmica en mármoles y calizas marmóreas, Roc Maquina.

NT Build 499 2002, Cladding panels. Test for Bowing.

Ruedrich, Weiss, J.T. & Siegesmund, S. 2001. Deterioration characteristics of marbles from the Marmorpalais Potsdam. Zeitschrift der Deutschen Geologischen Gesellschaft 152: 637-664.

Schouenburg, B., Grelk, B., Brundin, J.-A. & Alnæs, L. 2000., Bow test for facade panels of marble, Nordtest project 1443-99.

Spry, A. 1983. Metamorphic textures, Pergamon Press.

Yates, T., Brundin, J.-A., Goltermann, P. & Grelk, B. 2004., Observations from inspection of marble cladding in Europe. Proc. Dimension Stone 2004.