AGA- THE METHOD TO DEMONSTRATE THE RELATIONSHIP BETWEEN MICROSTRUCTURE AND BOWING PROPERTIES OF CALCITE MARBLE CLADDINGS

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Abstract The use of thin (20-40 mm) marble for facade cladding has increased substantially during the last few decades. Many of the marble facades perform well with this thickness. However, some durability problems have occurred, especially with calcite marble, because the cladding started to bow indicating the strength had decreased considerably. This study considers the influence of the microstructure on the bowing of the calcite marble. In order to quantify the microstructure, Adjacent Grain Analysis (AGA) was applied.
Calcite crystal belongs to the hexagonal crystal system. In an ideal even-grained granoblastic texture, all calcite crystals share grain boundaries with six grains, which are referred to as *adjacent grains* AG. An increasingly irregular grain boundary or a more heterogeneous grain-size distribution will result in an increase of 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. A larger number of AG occurs also in calcite marble with complex grain boundaries. 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 microstructure.
The results showed that the samples with a granoblastic microstructure all had six adjacent grains. The samples with a greater complexity of the microstructure (seriate interlobate microstructure) had up to 13 adjacent grains. Additionally, samples showing granoblastic microstructure all had the greatest degree of bowing. This indicates that the microstructure is a crucial parameter for the durability of marble and that AGA could be a fast and easy method to make a numerical description of the transition from granoblastic to seriate interlobate microstructure.

Keywords: Calcite marble; Microstructure; Adjacent Grain Analysis

1. Introduction

Marble has been used for thousands of years as a construction material. Traditionally, natural stones were 100 mm or more in thickness. In the last four decades, there has been a considerable increase in the use of marble panels as cladding material for facades, but their thickness are typically 20-40 mm. Many of the marble slabs perform well with this thickness. However, some stability problems have occurred, especially with the calcite marbles, where the cladding started to bow and where the strength had decreased considerably. This phenomenon has been observed on several famous buildings such as La grande Arch de la Defénse in Paris, the Lincoln First Tower in Rochester (Cohen and Montiero, 1991) and Alvar Aalto's Finlandia Hall in Helsinki (Royer-Carfagni, 1999).

Several studies have tried to explain this phenomenon (e.g. Sir Raiyleigh, 1934; Bain 1940; Widhalm et al., 1994;Winkler, 1996), and the most relevant environmental factors seems to be temperature fluctuations in combination with moisture. 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)

However, it is important to state that not all calcite marble claddings bow, and there are also cases were dolomite marble claddings displays a weak bowing (Malaga et al., 2004). In this study we investigate how the microstructure of the marble influence the degree of bowing. The microstructure of the marble is dependent on the deformation and metamorphic history of the rock and the recrystallisation 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 This is termed granoblastic texture. When a dynamic recrystallisation occurs, grain boundary migration and recovery of the material is possible (Passchier and Trouw, 1996). A microstructure 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) state 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 stable marble (Royer Carfagni, 1999). The grain size is considered to be a less important factor for the deterioration of the marble (Zeisig et al., 2002).

The objective of this study was to find a characteristic of the microstructure that can be quantified in an easy way and related to the bowing property of marble. This includes also formulating a reliable and easily applied method that marble 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.

The present study was a part of an EC funded project: Testing and Assessment of Marble and Limestone - TEAM (EC project no. TEAM G5RD-CT 2000-00233). The main objective of the project can shortly be summarized as: Solving the problem of how to choose, produce and use marble and limestone cladding panels without the risk of degradation due to bowing or expansion.

2. Materials and method

2.1 Tested materials

Approximately 50 different types of calcite marbles have been tested in the TEAM project, for their bowing properties (Grelk et al., in prep.). Among the 50 tested marbles these five were chosen for the microstructure analysis described in this paper (Fig. 2).

The magnitude of bowing for these marbles is between 0.017 mm/m and 1.4 mm/m after 25 temperature cycles (Fig. 1).

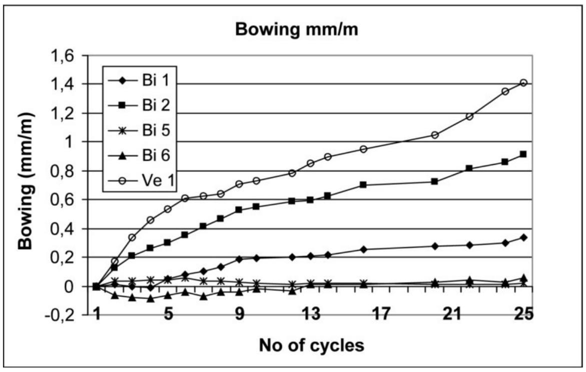

Fig. 1. Diagram showing the magnitude of bowing of selected samples (From Grelk et al., in prep). The test was performed according to NT BUILD 499 and one cycle lasted 24h with a temperature interval between 20 and 80°C.

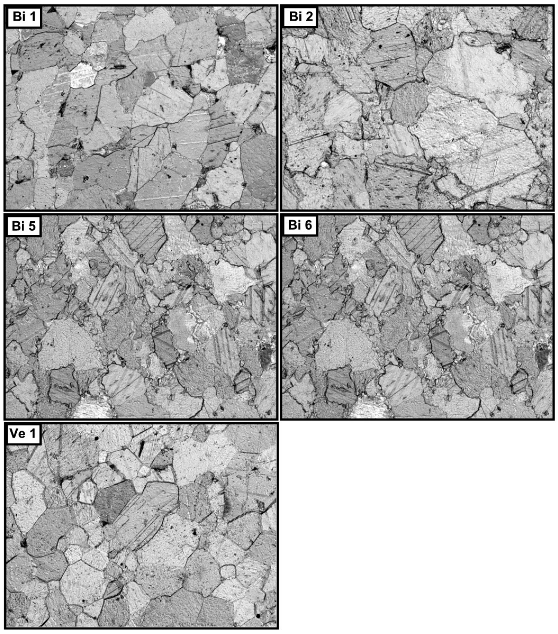

Fig. 2. Microphotograph of the microstructure of the investigated samples (plan polarised light). One image corresponds to 1326 x 996 micron.

The reason for the selection of these marbles is that they give a representative spread among different magnitudes of bowing. The microstructure of the selected samples (Fig. 2) range from a granoblastic microstructure (Ve1) with euhedral hexagonal calcite crystal to what could be described as a seriate interlobate microstructure (Bi5 and Bi6).

2.2 Microstructure analyses

The samples were cut and vacuum impregnated with epoxy resin containing fluorescent dye. Thin sections, with an area of approximately 1200 mm^2 were made from each sample. The petrographic images in figure 2 show that there are clear differences in the microstructure for the investigated samples.

Grain-size distribution

Traverses were randomly drawn on microscopic images. The maximum ferret diameter was then measured on each mineral cutting a traverse. From these measurements could the grain size distribution be determined for the investigated samples (Fig. 4).

Adjacent grain analysis – AGA

Calcite crystal belongs to the hexagonal crystal system. In an ideal even-grained granoblastic microstructure, all calcite crystals share grain boundaries with six grains, which are referred to as *adjacent grains* AG. An increasingly irregular grain boundary or a more heterogeneous grain-size distribution will result in an increase of 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. A larger number of AG occurs also in calcite marble with complex grain boundaries. 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 (Fig. 2)). In order to quantify the increasing complexity of the microstructure we counted the number of adjacent grains but only around the measured mean-sized grains in each sample (Fig. 3). The reason for using only mean-sized grains is that if the AG are counted around the smallest or the largest mineral grains, the results would not be comparable. The selection of analysed grains was determined from the grain-size measurements. The AGA was performed on images taken with a polarising microscope using a digital camera. The images were enlarged on a computer screen to easily count the number of adjacent grains. The AG were counted for one hundred grains on each sample.

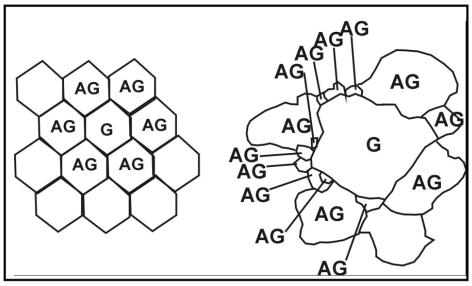

Fig. 3. Schematic image of an ideal granoblastic polygonal microstructure (left), and a seriate interlobate microstructure (right). The image also shows how the adjacent grains AG are counted.

3. Results

The results from the grain-size analyses show that the five samples form two groups. Three samples that have between 30-40 % of their counted grains less than 63 µm. The other two samples have only approximately 10 % counted grains less than 63 µm (Fig. 4).

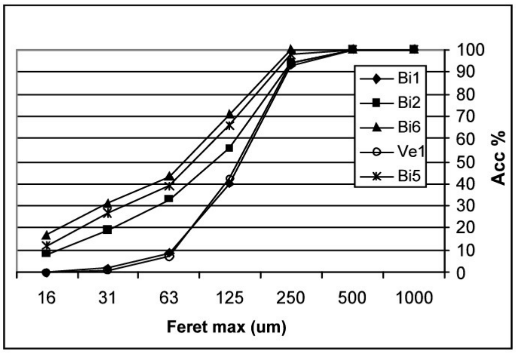

Fig. 4. Grain size distribution of the investigated samples.

The results of the AGA show that the number of AG in the five samples ranges from four to 13 and the mean ranges from six to nine (Table 1). 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. 4).

Table 1. 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

5. Discussion

The results from the quantitative analyses of the microstructure showed that there is a good correlation between the 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 (Fig. 2). In low magnification under the microscope, the grain boundaries look 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 microstructure (Fig. 5). The apparently “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 microstructure.

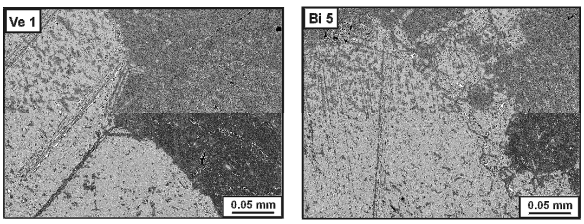

Fig. 5. Microphotograph of sample Ve 1 (left) and Bi 5 (right). The images show that the grain boundaries of Bi 5 only, are rather sutured and the “irregular grain boundaries” observed in lower magnification and shown in figure 2 are actually represented by several small grains. In sample Ve 1, no fine-grained matrix is observed.

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. One of the buildings shows no bowing whereas the three other show bowing up to several centimetres per meter. Figure 6 shows the typical petrographic microstructure from these marble claddings. It also shows that the three buildings with bowing panels all have granoblastic microstructured marble, whereas the non-bowing facade cladding have a similar seriate interlobate microstructure as sample Bi5 and Bi6. The results from the AGA were comparable with those obtained on the laboratory samples (Table 2).

Table 2. 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)
Nyk (Sweden)	6	20-30
Sydsv (Sweden)	6	30-40
Mch (Sweden)	9	1-2
RK (Denmark)	7	10-20

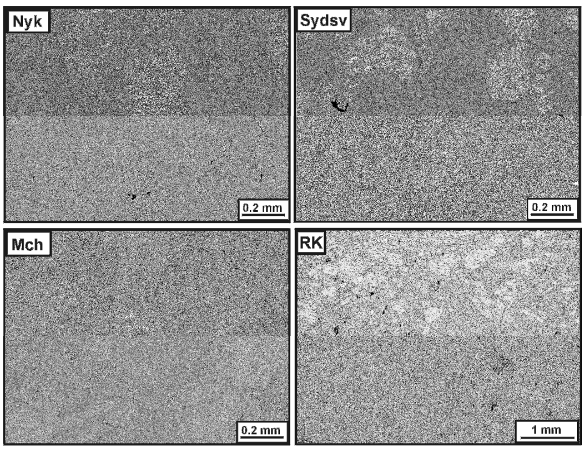

Fig. 6. The microstructure of the marble claddings from the four buildings. Three of the images show a granoblastic microstructure, whereas sample Mch have a seriate interlobate microstructure. The image of building RK also shows that this marble have a very heterogeneous grain size distribution.

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.

4. Conclusion

The microstructural properties have been quantified using adjacent grain analysis (AGA). This technique is a fast and easy method to quantify the microstructural transition from granoblastic to seriate interlobate marble. The results show that marbles with granoblastic texture all have six adjacent grains (the median value). They also show that marble with a greater amount of fine-grained matrix and, to some extent a more heterogenous grain-size distribution, have a greater number of adjacent grains. 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 fewest adjacent grains showed the greatest degree of bowing.

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

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