Proceedings IRF2018: 6th International Conference Integrity-Reliability-Failure
Lisbon/Portugal 22-26 July 2018. Editors J.F. Silva Gomes and S.A. Meguid
Publ. INEGI/FEUP (2018); ISBN: 978-989-20-8313-1

PAPER REF: 7286

STABILITY EVALUATION OF MARBLE STONE CLADDING AFFECTED BY BOWING AND WIND PRESSURE- A CASE STUDY

Rui Sousa(*), Hipólito Sousa

Department of Civil Engineering (CONSTRUCT), University of Porto, Porto, Portugal
(*)*Email:* ruysousa@fe.up.pt

ABSTRACT

Bowing is an uncommon pathology that can affect marble stone cladding of building facades. It is characterized by a large and permanent deflexion and degradation of strength of the stone slabs that can cause them to fall from the facades. On the other hand, the wind pressure effects on the building facades may also cause stability problems. Therefore, stone cladding in these conditions presents a high risk of fracture and collapse that needs to be evaluated.

This work describes a case study regarding an evaluation of the resistance/stability of a marble stone cladding of a building façade affected by bowing and submitted to wind pressures. This evaluation was performed through numerical simulations and experimental tests to characterize the mechanical properties of the marble stone. The results obtained demonstrated stability problems in some stone slabs due its large dimensions and loss of resistance due to aging and bowing effects.

Keywords: stone cladding, marble, bowing, stability.

INTRODUCTION

a) Bowing phenomena

Following the use of marble stone cladding with reduced thickness on building facades, the bowing phenomena has been reported by scientific studies (e.g. Siegesmund, 2008), causing in some cases the fall of the slabs and/or their total removal from the façades. The bowing can be characterized by a permanent deflexion and decay of the mechanical strength of the stone slabs (some cases reported 20 to 30mm/m of permanent deflexion and 40% of strength decay).

The main causes of bowing are complex and may be associated to more than one cause. However, the most common cause is the use of “younger” calcite marbles (i.e. with low metamorphic degree) with high porosity, associated to a climate exposure characterized by fast drying and excessive humidity cycles, resulting in an irreversible expansion and fracture of the stone matrix.

This bowing/deflexion is irreversible, increases over time and causes the loss/degradation of the stone mechanical strength (Figure 1), usually faster in the beginning and slower over time (Logan, 2006).

On the other hand, the wind pressure effects on the building facades may cause stability problems on stone cladding, including their fixings/anchorage system. Therefore, stone cladding affected by bowing and wind pressure can present a high risk of fracture and collapse that needs to be evaluated.

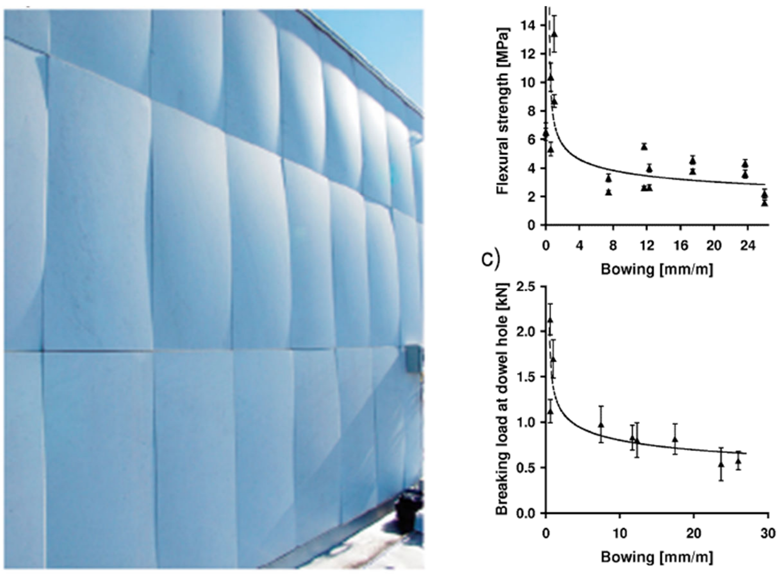


Fig. 1 - Examples of bowing occurring in stone marble façade (Loughran et al, 2007) and decay of resistance VS bowing of marble (Koch, 2004)

Since 1999 this phenomenon was studied in European projects on marble durability, which followed the publication of EN 16306 in 2013. This European standard defines an accelerated aging test method to characterize the behaviour of marbles subject to cycles of heat / humidity, establishing allowable limits for bowing (≤ 0,4mm/m). Moreover, the experimental characterization of the modulus of elasticity and the flexural strength after aging tests are defined for the design of marble panels, since it is recognized the rapid loss of strength and rigidity in the marbles affected by bowing.

b) Properties of calcite marbles

The marble is a metamorphic stone of granoblastic texture, consisting essentially of calcite crystals (94 to 99%), or more rarely by crystals of dolomite, being able to contain other minerals in smaller quantity (mica, quartz, dolomite, graphite, among others). The calcite marbles are white or approximately white, and may have veins provided by the presence of other minerals (see above). Some of the most famous marbles are “Carrara (Italy)”, “Estremoz (Portugal / Alentejo)”, “Dionysos (Greece)”, among others.

Since it is a natural material, its physical and mechanical properties can vary significantly (more than 20% of the average), even when extracted from the same quarry, therefore it is necessary to characterize their properties experimentally on a case-by-case basis.

However, some mean values for the properties of white calcite marbles under initial conditions of use, such as “Carrara”, “Évora / Estremoz”, among others, can be found in technical literature (Gennaro,2003; Papamichos, 2006; Siegesmund, 2011, Amaral, 2015; LNEG, 2018):

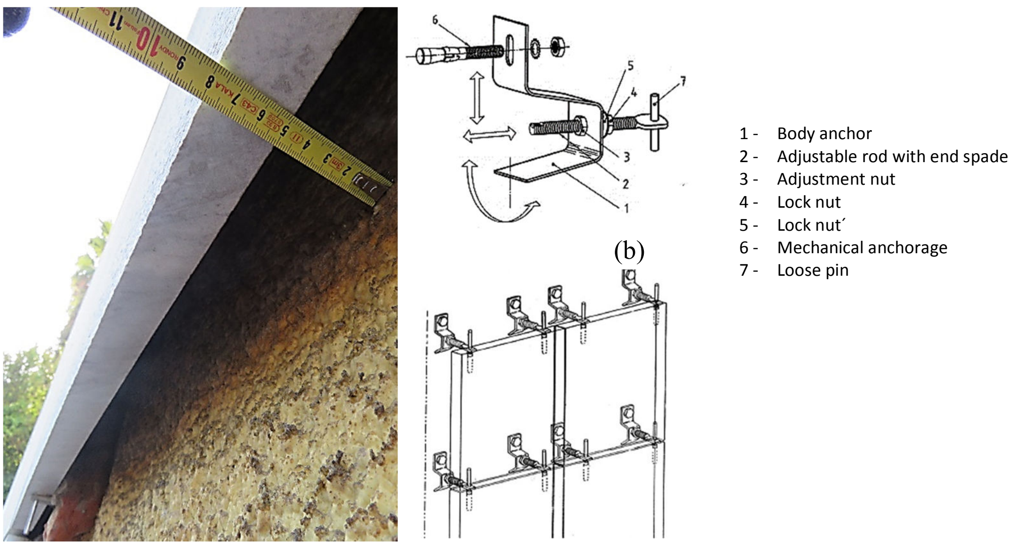
- Density: 2680 a 2710 kg/m^3;
- Compressive strength: 79 a 100 MPa;
- Flexural strength: 11 a 26 MPa;
- Elasticity modulus (dynamic/static): 40 to 50 / 16 to 25 GPa;
- Poisson coefficient: 0.25 a 0.41.

CASE STUDY

Using a case study of a 15years old building façade, made with marble stone cladding affected by bowing, an evaluation of the mechanical resistance of the stone slabs, including their fixings, submitted to wind pressure was performed through FEM simulations and laboratory tests.

The cladding system is made of marble stone slabs with open joints that are fixed to building façade with an air layer, forming a "ventilated façade". The most representative stone slabs have surface dimensions that vary from $1.5x1.3m^2$ to $1.5 \times 0.7m^2$, and a thickness of 3cm. These slabs are fixed to the building façade through stainless steel dowel anchorage system (body anchorage fixed on the walls, having pin dowels inserted in holes made on the slabs), and each slab has four fixing points (Figure 2 and Figure 3).

Fig. 2 - Partial view of the stone cladding applied on the north façade of the building



(a) (c)

Fig. 3 - Construction details of the cladding system: (a) detail view of cladding after removal of a stone slab (b) dowel anchorage system; (c) fixing points

According to an inspection performed on the building facade, the bowing was affecting more than 50% of the cladding system, and in some marble slabs there were measured permanent deflexions with 8 to 12mm (or 6 to 7 mm/m). No damage/fracture patterns were visually detected in the central part of the slabs with bowing, however, near some fixing points (dowel holes) of some slabs fracture patterns were found (Figure 4).

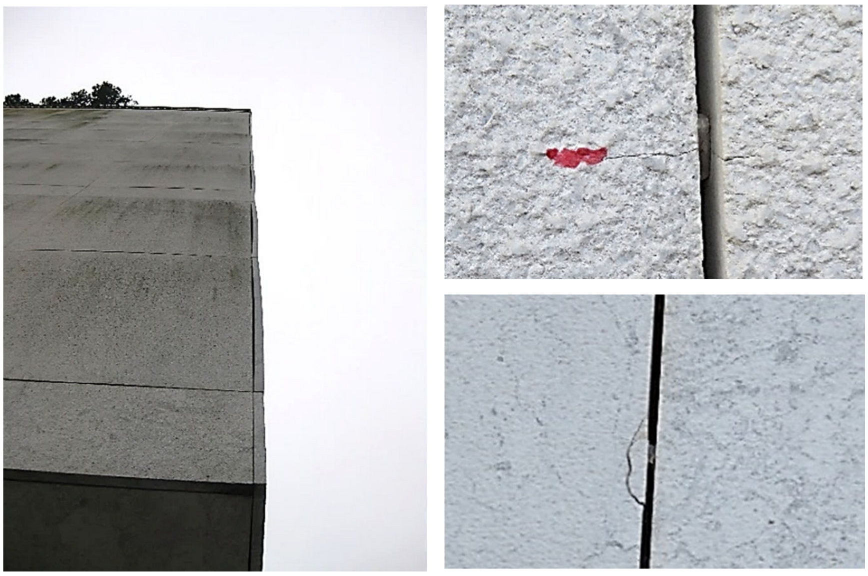


Fig. 4 - Examples of bowing and local damage/fracture detected on the marble slabs

EXPERIMENTAL TESTS AND NUMERICAL SIMULATIONS

To evaluate the mechanical resistance of the larger stone slabs and their fixing points, submitted to wind pressure, numerical simulations were performed by using the mechanical properties obtained from experimental tests.

a) Experimental tests

In order to characterize mechanical properties of the marble stone in its current/actual conditions, test specimens were obtained from 4 slabs removed from the building façade, 2 with and 2 without bowing. Therefore, the dimensions and number of test specimens were established according to the dimensions and available quantity of stone slabs. The lab tests performed according to European standards were (Figures 5 to 8):

- Flexural strength under constant moment (R_{tc}) and compressive strength (R) - EN 13161 and EN 1926;
- Static modulus of elasticity in the longitudinal direction (E_{sL}) and dynamic modulus of elasticity in the longitudinal and transversal directions ($E_{dL;}$ E_{dT}) - EN 13161 and EN 14146;
- Breaking load (F) at dowel hole - EN 13364;
- Apparent density (ρ_b) - EN 1936.

Moreover, a mineralogical/petrographic study was performed to identify/confirm the constitution of the marble. The results obtained from lab tests are presented in Table 1.

Fig. 5 - Examples of lab tests (flexural strength and static modulus of elasticity)

Fig. 6 - Examples of lab tests (compressive strength)

Fig. 7 - Examples of lab tests (breaking load at the dowel hole)

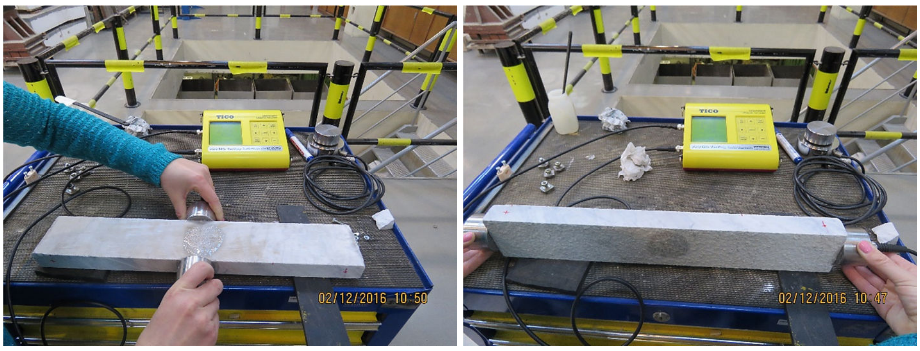


Fig. 8 - Examples of lab tests (measurement of dynamic modulus of elasticity in transversal and in longitudinal directions)

Table 1 - Test results obtained from marble stone specimens

Proprieties	Bowing effect	Nº specimens	Units	Mean value	Characteristic value (log-normal distribution **)	C.V. (%)
Apparent density(ρ_b)	With + Without	6	kg/m^3	2660	2473	3.0
Flexural strength (R_{tc})	Without	8	MPa	8.2	6.5	9.8
	With	14		7.8	5.3	17.8
	With + Without	22		7.9	5.8	15.1
Compressive strength (R)	Without	5	MPa	81.5	57.9	5.0
	With	5		72.5	63.8	8.6
	With + Without	10		77.0	62.2	9,2
Breaking load at dowel hole (F)	Without	5	kN	1.15	433	38,4
	With	4		1.19	671	18,7
	With + Without	9		1,17	596	29,2
Dynamic modulus of elasticity - E_{dL} / E_{dT} (ν = 0,25)*	With	4	GPa	38.8/40.9	33.8/28.0	4,8 / 11,8
Dynamic modulus of elasticity - E_{dL} / E_{dT} (ν = 0,40)*	With	4	GPa	21.7/22.9	18.9/15.7	
Static modulus of elasticity E_{sL}	With	4	GPa	18.8	10.6	16,3

* Poisson coefficient obtained from literature; ** 75% of confidence level and 5% fractile distribution

The mineralogical/petrographic study concluded that is a marble constituted mainly by calcite (calcite marble), although containing other minerals in smaller quantity (dolomite, quartz, biotite and chlorite), and generally possessing a granoblastic texture of fine equigranular grains (Figure 9).

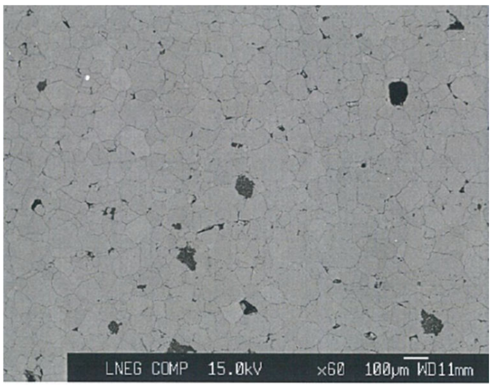


Fig. 9 - Observation with electronic microscope of calcite marble specimens

b) Numerical simulations

The FEM simulations was performed with a 3D model of a slab, supported by 4 nodes with translational restrains in orthogonal directions (x,y,z), submitted to a evenly distributed loads that simulate the wind pressure acting on the perpendicular direction of the slab surface (Figure 10).

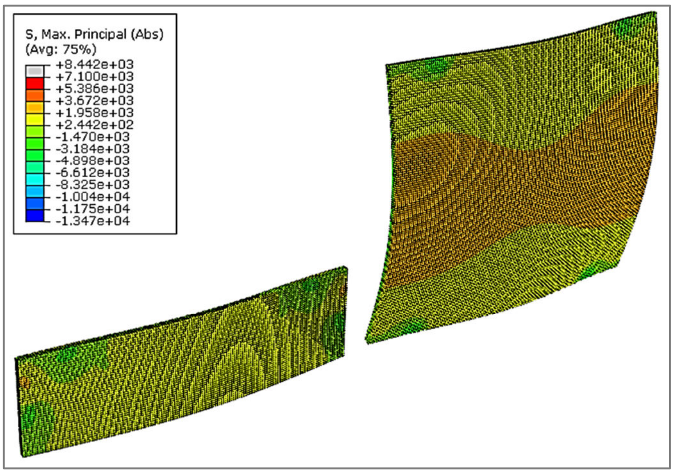


Fig. 10 - Examples of FEM simulations of marble stone slabs and stress distribution associated to wind pressure (SLS characteristic combination values in kPa)

In order to simulate the fragile behaviour of natural stone, the constitutive material model used was a linear elastic model with imposed limits for the compressive/tensile stresses. The strength and deformation properties of the stone obtained from the labs tests were used in numerical simulations (characteristic values of flexural and compressive strength, static modulus of elasticity and apparent density). However, since not all the slabs were affected by bowing, it was assumed the characteristic values obtained from slabs with and without bowing (see Table 1). The Poisson coefficient was assumed equal to 0.4.

Moreover, according to experimental results (see Table 1), the dynamic elastic modulus in the longitudinal and transversal directions presented small differences (near 6%). Therefore, for simplification purposes, the marble stone was considered an isotropic material in the simulations.

The wind pressure/loading was determined through Eurocode 1 standard calculation methodology (CEN, 2010), which takes into account the exposure conditions of the building facades (height, orientation, terrain roughness, surrounding constructions and obstacles, amongst others aspects) and the dynamic effects of wind speed on the building. The characteristic values for wind pressure (W_k) were obtained according to the position in height (h) of the stone slabs on the building façade:

- $h \leq 9m$ - $Wk = 1.3\ kN/m^2$;
- $9m < h \leq 18m$ - $Wk = 2.1\ kN/m^2$.

The stability/resistance was evaluated for serviceability limit sates (SLS), associated to the risk of permanent/irreversible damage impairing functionality, and ultimate limit states (ULS), associated to the risk of collapse/fracture due to loss of mechanical resistance, both defined in Eurocode 0 through verification of the basic security condition (CEN, 2010):

$$\frac{S_d}{R_d} \leq 1$$

S_d - Design load or stress determined from the combination of characteristic values of wind (W_k) and self-weigh of the slabs (G_k), acting simultaneously:

- Combination SLS: $S_d = G_k + 1{,}5\ W_k$;
- Combination ULS: $S_d = 1{,}35\ G_k + 1{,}5\ W_k$;

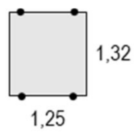
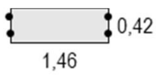
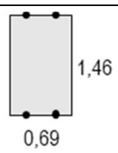
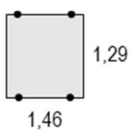
$R_d = \eta\ R_k / \gamma_m$ - Design resistance load or stress obtained from labs tests:

- R_k - Characteristic value obtained from statistical analysis of the lab tests results (minimum values obtained from a log-normal distribution - see Table 1);
- γm - Partial safety factor determined through a semi-probabilistic approach adapted for stone cladding (Camposinhos, 2014), by taking into account the coefficient of variation (C.V.) of the experimental results obtained from lab tests (ULS - $\gamma m = 2.4$; SLS - $\gamma m = 1$);
- η - Conversion factor to take into account the effects of temperature, humidity and other effects. However, since the stone in this case study was not in its initial conditions, i.e. it was submitted to 15 years of climate exposure, this factor was assumed equal to 1.

This verification was made in terms of satisfying (S) or not satisfying (NS) the basic condition for loads/reactions at the dowel holes/support nodes ($R_{sd}/F_{rd} \leq 1$), and for bending stresses at the cross section of the slab ($\sigma_{sd} / \sigma_{rd} \leq 1$).

The results obtained in the simulations, including the evaluation of stability/resistance according to basic security condition, are presented in Table 2.

Table 2 - Results obtained in FEM simulations and evaluation of stability

Stone slabs and surface dimensions (m)	**Security criteria**	**Bending stress (N/mm^2)**				**Load at dowel hole (kN)**			
		SLS		**ULS**		**SLS**		**ULS**	
		h≤9m	9<h≤18m	h≤9m	9<h≤18m	h≤9m	9<h≤18m	h≤9m	9<h≤18m
 1,32 1,25	Max.Value	1,7	2,7	2,5	4,0	0,54	0,87	0,80	1,3
	S_d/R_d	0,3	0,5	1,0	1,7	0,9	1,5	3,2	5,2
	Result	S	S	NS	NS	S	NS	NS	NS
 0,42 1,46	Max.Value	2,0	3,2	3,0	4,8	0,20	0,32	0,30	0,49
	S_d/R_d	0,3	0,6	1,2	2,0	0,3	0,5	1,2	2,0
	Result	S	S	NS	NS	S	S	NS	S
 1,46 0,69	Max.Value	3,1	4,3	4,46	6,25	0,53	0,73	0,76	1,0
	S_d/R_d	0,5	0,7	1,8	2,6	0,9	1,2	3,1	4,1
	Result	S	S	NS	NS	S	NS	NS	NS
 1,29 1,46	Max.Value	1,6	2,6	2,4	4,0	0,60	0,99	0,92	1,5
	S_d/R_d	0,3	0,5	1,0	1,6	1,0	1,7	3,7	6,0
	Result	S	S	NS	NS	S	NS	NS	NS

DISCUSSION

a) Test Results

The variation coefficient (C.V.) presents higher values for marble stone affected by bowing, being lower than 20% for most of the properties, except for the case of breaking load at dowel hole (without bowing, 38%).

In general, there is no significant difference between the mechanical properties of stone slabs with and without bowing, which can be related to the scarce number of samples available for testing. However, relatively small differences were found for the flexural strength (5% for the mean value and 20% for the characteristic value).

The mineralogical/petrographic study concluded that the stone is calcite marble.

b) Numerical Results

The bending resistance of all stone slabs is verified for serviceability conditions (SLS), therefore, there is a low risk of damage/fracture due to slab bending caused by moderate wind pressures (as observed in the inspections made).

However, the load capacity at the dowel hole is not verified for slabs located higher than 9m, therefore presenting a high risk of occurring damage/fracture in the stone at the dowel hole (as observed in the inspections made - see Figure 4).

The bending resistance and load capacity at the dowel hole are not verified for almost every cases analysed in ultimate conditions (ULS), meaning that the stone slabs have a high risk of collapsing at the presence of extreme wind pressures.

CONCLUSIONS

The test results were not entirely conclusive regarding the effect of bowing on the mechanical properties of the marble stone, since original stone slabs in initial use conditions and a large number of test samples were not possible to obtain from this case study. However, considering the obtained test results and similar calcite marbles properties found in literature, it was estimated, at least, a reduction of 30% on the flexural strength caused by the combined effects of aging degradation and bowing phenomenon.

The results obtained from simulations revealed stability problems on the stone slabs, especially for extreme wind conditions/pressures (ULS), therefore presenting a high risk of collapsing from the building. The main reasons for this security risk is the combination of high stresses induced by the wind pressure on slabs with high surface/dimensions, including their fixing points, with the bowing and ageing effects that decreased the stone mechanical strength.

Since the bowing causes irreversible damage on the marble slabs, the recommended and most usual intervention is to remove the affected slabs and replace them with marble less susceptible to bowing (satisfying the criteria of EN 16306), or using another type of natural or artificial stone.

REFERENCES

[1] A. Koch, S. Siegesmund. The combined effect of moisture and temperature on the anomalous expansion behaviour of marble. Environmental Geology (2004) 46; pp. 350-363.

[2] CEN. EN 1990 - Eurocode 0: Basis of structural design. Brussels, Belgium, 2010.

[3] CEN. EN 1991-1-4 - Eurocode 1: Actions on structures, Part 1-4: General actions - Wind actions. Brussels, Belgium, 2010.

[4] CEN. EN 1992-1-1- Eurocode 2: Design of concrete structures, Part 1-1: General rules and rules for buildings. Brussels, Belgium, 2014.

[5] Euripides Papamichos, Stefanos-Aldo Papanicolopulos and Idar Larsen. Mechanical properties and damage diagnosis of natural building stones. Chapter In: S.K. Kourkoulis (ed.), Fracture and Failure of Natural Building Stones, pp. 71-92, Springer, 2006.

[6] John M. Logan. On-site and laboratory studies of strength loss in marble on building exteriors. Chapter In: S.K. Kourkoulis (ed.), Fracture and Failure of Natural Building Stones, pp. 345-362, Springer, 2006.

[7] LNEG. Catálogo de Rochas Ornamentais Portuguesas. Laboratório Nacional de Energia e Geologia(consulted online at 23/1/2018: http://rop.lneg.pt/rop/).

[8] Patrick Loughran. Failed Stone: Problems and Solutions with Concrete and Masonry. Birkhäuser - Publishers for Architecture (Eds), Basel, Switzerland, 2007, p.159.

[9] Pedro Miguel Amaral, Jorge C. Fernandes, Vera Pires and Luis Guerra Rosa. Ornamental Stones, pp. 397-445. Chapter in: M.C. Gonçalves, F. Margarido (eds.), Materials for Construction and Civil Engineering, Springer International Publishing, Switzerland, 2015.

[10] Roberto de Gennaro, Domenico Calcaterra, Pio Di Girolamo, Alessio Langella, Maurizio de Gennaro, Discovering the stone heritage of southern Italy: technical properties of the Mondragone marble from Campania region. Environmental Geology (2003) 44; pp. 266-276.

[11] Rui S. Camposinhos. Stone Cladding Engineering. Springer Science, 2014, p.171.

[12] S. Siegesmund, J. Ruedrich, A. Koch. Marble bowing: comparative studies of three different public building façade. Environ Geol (2008) 56; pp. 473-494.

[13] Siegfried Siegesmund and Helmut Dürrast. Physical and Mechanical Properties of Rocks, pp. 97-225. Chapter In: S. Siegesmund, R. Snethlage (eds.), Stone in Architecture, 4th ed., Springer-Verlag Berlin Heidelberg, 2011(DOI: 10.1007/978-3-642-14475-2_3).