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Environmental influences on damage and destruction of the structure of marble

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ABSTRACT

The Acoustic Emission Testing (AET) makes it possible to detect, analyze and evaluate graphically and numerically structural damage in rock (crack elongation, friction on interfaces, evaporation of water from interfaces and transformation of water into ice in pores, etc.) in dependence on the actual time of testing and actual temperature in the sample. Exemplary new and weathered Carrara marble is tested using the AE technique in a temperature range from frost to higher temperatures (−20 °C to 60 °C) for four to twenty-five thermal cycles (cooling/heating), thus expecting scientific results and new modeling for structural damage and destruction of rock.

1. Introduction

Marble objects show more or less damage after extended outdoor exposure. Antique buildings and historical landmarks often show signs of destruction of their outer marble paneling (bowing, cracking). All these damages are closely connected to the climate conditions, like temperature and humidity, of the exposed area. In the long-term range the multitude of alternating stress (warm/cold, wet/dry, frost/dew,…) essentially influences the progression of damages.

Damage and shape durability depend on the quality of the marble. It is common knowledge that certain varieties of Carrara marble when used outdoors are sensitive regarding their potential of damage and shape resistance [e.g. [1–4,42,48]]. Well known examples of damages of Carrara-marble statues and buildings are the Potsdam-Sanssouci castle,[5] the Finlandia Hall in Helsinki,[6] the Amoco building in Chicago,[7] the Grande Arche de la Défense in Paris[8] and the church of St. Leopold, an Otto Wagner building in Vienna.[22] These kinds of damages are dangerous to humans and the environment, therefore the bowed marble claddings have to be exchanged as well as the sculptures restored, which usually is rather expensive.

The phenomenon of outdoor damage and shape stability of marble sculptures and marble-cladded buildings has been repeatedly discussed and described in international literature as well as in practical research, e.g. the early studies of Winkler,[1] Grimm [e.g. [3]], Köhler,[5] Poschlod[10] and Grelk et al.[42]. At the end of the last century the damages to sculptures and buildings seemingly climaxed, and the EU funded international research projects to deal with this phenomenon increased. The CRAFT-Project (1995–1997)[12] and the TEAM-Project (2000–2005)[13] are examples for cooperation between universities and European masonry businesses, which lead to a large number of research programs integrating universities, research facilities and marble producers. Further papers are to be found in Refs. 11,20,22,23,25,28,29,35,37,42,43,48.

The cited literature shows that there is a lot of experience and knowledge about structural damage and degradation of rock due to weathering. These phenomena were described clearly by Köhler[5] distinguishing three phases of structural damage and destruction. In **Phase I** the damage process originates by varying outside temperature and stress redirection within the structure which lead to a first intergranular decohesion between the crystallites. A slightly changed pore structure in the marble develops where the water molecules only slowly may enter the submicropore system (< 4 nm). The damage is very small and can be neglected in practice.

Due to frequent temperature variations, whose amplitudes depend on the changes of day and night (daily) and summer and winter (seasons) changes, a slow expansion of the grain boundaries is caused (Fig. 1).[21] This stadium is characterized by the enlargement of the pore system and leads to **Phase II**. First water and ice crystals are built within the pores due to the enlargement of the micro-pores (4–100 nm). In the first instance only a frost blasting of the structure takes place..

Phase I and Phase II (without and with frost) proceed very similar in all climate zones and set the first basic damage to the marble. If the trend (velocity) of the damaging (large temperature differences, enlargement of pores) increases, primarily the location and orientation of the building or sculpture is decisive whether strain of frost will take place or not (e.g. Helsinki or Athens).[21]

Phase III, as described by Köhler,[5] may pass under different climatic conditions with varying temperature changes and local humidity. Pores can absorb water, which leads to damage of the structure. Damages due to freezing are higher in colder than in warmer climates. If the temperature in the marble oscillates around the freezing point,

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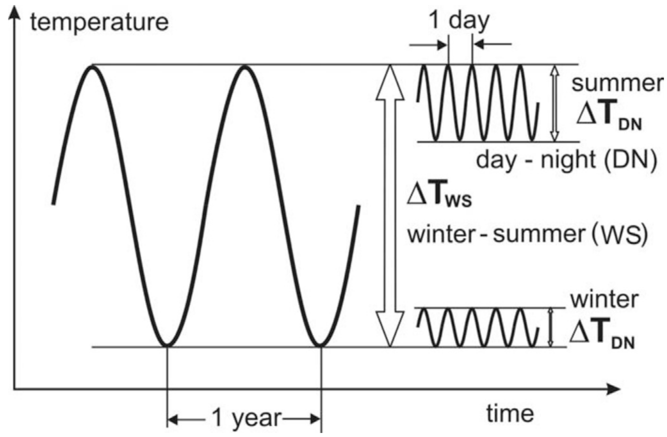

Fig. 1. Schematic variation of the temperature amplitude as a function of time in winter – summer (WS) ΔT_{WS} and day – night (DN) ΔT_{DN} on the outside of the wall.[21]

the damaging process is repeated at each freezing, which leads to a rapid destruction of the rock structure. All works[1–3,10,12,13,20,21,37,40,42,43] point out this damage and destruction mechanism of marble.

Despite the importance of the structural destruction of marble only a few experimental studies have contributed in the past to an identification of the timing of phenomenon I, II and III. Was it the shortcoming of the current measuring methods or the lack of financial support for application of novel methods?

2. Present measuring methods for examination of the damage processes in marble

The current most important measuring methods for investigating the damage process of marble due to weather influences are stated and shortly described in the following.

2.1. Dilatation method

If a marble sample is heated and cooled to its original temperature, the thermal expansion coefficient and residual strain (after the treatment the sample is longer) can be determined resp. the damage assessed. Several dilatometers had been applied in[2,13,16,17,20,23,25–27] at room and raised temperature, which lead to numerous outcome with different marbles. There are only rare applications of dilatometers at low temperatures on marble.[12] Several problems arise in connection with path receptors (linear measure) as occasional freezing so that no justifiable data could be determined.

Dilatometric measuring cannot determine the moment and temperature of the structural damage. This knowledge – location, time, and temperature of the structural damage – is from the scientific point of view crucial for a better understanding of the damage processes. This lacking is a great disadvantage of the dilatation method.

2.2. Runtime-method

Ultrasonic Runtime-Measurement is a longtime practice of diagnosis of the degree of damage of rock [e.g. [5,15,16,50,51]]. Mostly longitudinal waves are used in measuring, determining E-modulus and porosity (deducted from raw density). The sample is mounted between the tactile heads (sender and receiver) and treated with ultrasound of certain frequencies, mostly 40–60 kHz. Runtime values of dry, saturated and damaged marble samples, tested at low temperatures ($<$ 0 °C), were similar, as shown in Ref. 15 It is therefore not possible to identify varying damages.

Disadvantageously it cannot be determined, at what time and temperature the damage of the marble (e.g. transition of water into ice in the marble) had taken place. Usually the damage of the marble is determined at room temperature with this method.

2.3. Mercury-porosimeter

The mercury-porosimetric method is frequently used for examination of macro- and micro-porous systems in civil engineering and geosciences.[9,44,45] Mercury is forced by rising pressure into the pores of the material. The pressure can range from 0.13 bar to 2000 bar, and pore diameters down to 7.5 nm can be determined. Beside the distribution of the pores' radius, the pore volume, porosity and specific surface of the sample can be estimated.[9]

Structural damage and destruction of marble can only be determined by the count of pores and changed pore volumes. A disadvantage of this method is that the time of damage at given temperature cannot be determined. Conclusions of the change in volume of the pores are only possible after (laboratory) measurements.

2.4. Fluorescence-micro-method

This method is used with microscopic examination to determine the width of micro-and macro- cracks as well as the size of the pores and pore systems in cuts.[19,46]

Disadvantageously the amount of damage can only be determined after the damage process microscopically in the laboratory. The exact time of damage at a certain temperature cannot be determined, which is essentially for a scientific investigation.

2.5. Strain-Gauge-Method

A strain gauge is fixed on the sample. Upon a temperature change of the sample the dimension of the strain gauge and therefore the signal on the sensor bridge change too. At the end of the process and determination of the residual strain the strain gauge cannot be removed and is lost.

The Strain-Gauge-Method is applicable for examination of marble of E-modulus and residual strain at low to higher temperatures,[12] further quotes in literature point out, that fixing and handling is not trouble-free and seldom used in practice. Although this method is applicable in the complete temperature range, but the disadvantages are similar to the dilatation-method.[47]

The above stated methods in the field of geosciences and historical preservation show that the time of structural damage and destruction of marble in the temperature range of −20 °C to 60 °C cannot be determined and that the Acoustic Emission Testing (AET) method could be a new expedient analytical method.

3. Acoustic emission method for examination of the damage processes in marble

The Acoustic Emission Method is based on the consideration that micro-seismic and micro-acoustic measurement methods are means of documentation of structural damages of rock. They can be applied in material testing (e.g. concrete, natural stone), material sciences, restoration, mining and tunneling, and therefore assess potential dangers. Like studies in the field of mineralogy, petrology and structural science have already been presented [e.g. [2,14,18,20,24,28,30–32,36]]. AET has not been used for examination of the timing of the damage in dependence of the testing temperature. Elimination of these drawbacks has been tried in Ref. 41.

3.1. Acoustic emission of marble

Application of mechanical stress on marble leads to accumulation of elastic energy. Increasing the stress can damage the structure (e.g. micro-cracks). Local changes of stress can induce short time move-