Assessment of the Durability of Marble Cladding by Laboratory Exposure compared to Natural Exposure

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ABSTRACT: Marble exposed to temperature cycles at high relative humidity (RH) under laboratory conditions loose strength similar to loss of strength for the same marble exposed to natural climate. Two marble types from three different building facades in Copenhagen are studied. From each building a marble cladding panel exposed for the south facing natural climate during 29, 60 and 61 years, respectively, and a cladding panel of each of the marble types only exposed for indoor climate are cut in bars of size 30x30x300 mm. The bars from indoor are exposed to temperature cycles between 10 °C and 60 °C at nearly 100% RH and at nearly 0% RH. The strength of the natural exposed marble as well as the laboratory-exposed marble are measured as flexural strength under concentrated load using four-point loading. Analysis of the strength test show that it is possible to transfer test results for laboratory exposed marble to results for natural exposed marble.

1 INTRODUCTION

Finlandia Hall, designed by Alvar Aalto as a concert and congress hall, was completed in 1971. The entire building is covered by a white marble façade made up of two different types of rectangular marble panels, small ones (approx. 450x1500 mm) and large ones (approx. 850x1500 mm), all approximately 30 mm thick. An intriguing phenomenon started just a few years after the conctruction was finalized: The marble slabs exhibited a tendency towards concave bowing, see figure 1. The bowing appears more or less homogenous within each side of the building, though it is more pronounced on some sides than others. Hardly any trace of convex bowing can be found. The rectangular panels are anchored by four pins.

The causes for bowing of the marble is not known very well, but among other factors moisture in combination with temperature cycling must be present (Lemvig et al. 2002). This also drastically reduce the macroscopic mechanical properties of the material. Figure 2, taken from Karhapää et al. (1994), summarises the results of a long series of experimental observations on Finlandia Hall's cladding from the year of its completion in 1971 up to 1991. The graph shows the development of bowing of one slab with advancing age and clearly correlates to the reduction of the material's flexural strength.

Several other building investigations of the problems with marble claddings have been carried out over the years. Some of the results are summarized in table 1 below. In the first column four different buildings with problems with their façades are listed. The first is Finlandia Hall. The next is an office building in Switzerland, followed by a hospital in Lünen, Germany, and the 80-storeyed Amoco building in Chicago. In the next column the year of construction for each building is seen. In the third column the type of natural stone used for cladding on each building is given. After a given period of years (seen in parenthesis in the last column) the absolute bowing of some selected panels has been measured. This result has been divided by the number of years the panels have been exposed on the building façade giving an expression for the average bowing in mm/year seen in the fourth column from the left. The flexural strength of the panels was measured after the same period of years, and measurements of the flexural strength of initial unexposed samples were also carried out to

Figure 1. Finlandia Hall in Helsinki, Finland. Concave bowing of marble panels.

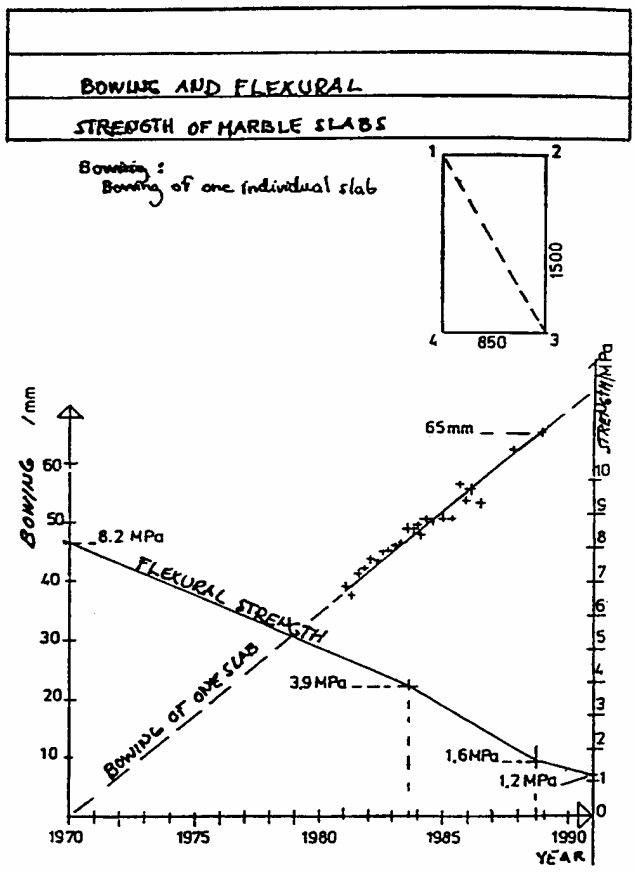


Figure 2. One slab from Finlandia Hall. Development in flexural strength and in bowing from 1970 to 1991. From Karhapää et al. (1994).

get an indication of the reduction in flexural strength given in the last column. The reduction in the flexural strength in MPa was divided by the number of years the panels have been exposed in order to achieve an indication for the average reduction in flexural strength per year as seen in the fifth column from the left.

1.1 *Tests on in-laboratory damaged materials reported in the literature*

In order to simulate the natural environment for natural stone panels used as building claddings, marble, limestone and granite specimens have earlier been subjected to different exposures (Lemvig et al. 2002). Test specimens have been exposed to 1, 10 or 20 temperature cycles between about 25 °C and 70 °C at 100% RH or 0% RH. Each temperature cycle consists of 2 hours of heating from 25 °C to 70 °C followed by a 10-hour period of slow cooling back to 25 °C. Each specimen series consist of 3, 6 or 12 homogeneous specimens of the same natural stone. The specimens have straight angles and size of 30x30x300 mm. The relative strength after exposure of the natural stone specimens was measured as loss in flexural strength.

Table 1. Examples of reported flexural strength loss of marble claddings from different buildings.

Building	Build year	Natural stone used for clad.	Bowing (mm/yr)	Reduction in flexural strength	
				(MPa/ year)	%
Finlandia[1] (Finland)	1970	B. Carrara (I)	~3-4	~0.4	~85% (21 yrs)
Switzerland[2]	1996	B. Cararra (I)	?	~1.3	~40% (3 yrs)
Lünen[3] (Germany)	1967-1982	Escamado/ Trigaches Ecsuro (P)	~1	?	~28-75% (14-28 yrs)
Amoco[4] (USA)	1973	B. Carrara (I)	~2-3	~0.15	~40% (15 yrs)

[1]Karhapää (1994), [2]Jornet & Rück (2000), [3]Stocksiefen (1996), [4]Logan (1993).

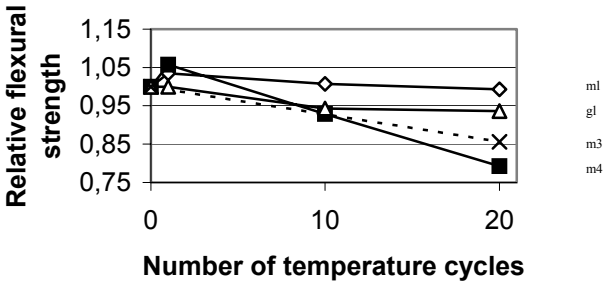


Figure 3. Relative flexural strength as a function of temperature cycles at 100% RH. m1 is limestone, m3 and m4 is marble, and g1 is granite. From Lemvig et al. (2002).

A four-point bending test is used to determine the flexural strength. The mean value of the flexural strength of the specimen series is defined as the flexural strength of the stone. The results are shown in figure 3.

All types of stone had their strength reduced almost linear after first cycle due to 20 temperature cycles at 100% RH. As it is seen in figure 3 the magnitude of the loss of strength of the stones varies from almost nothing (1%) to 21%. This indicates some variations in the durability of the tested stones. The strength of limestone and of one of the marble stones increases after the first temperature cycle. This is contrary to previous investigations (Chakrabarti et al. 1995), which showed the largest reduction after the first cycle. However, additional temperature cycles would be expected to reduce the strength further. This uniformity of loss of strength is not found in the stones exposed to 20 temperature cycles in 0% RH.

2 LABORATORY EXPOSURE COMPARED TO NATURAL EXPOSURE

The question is if marble exposed to temperature cycles at high RH under laboratory conditions loose strength similar to loss of strength for the same marble type exposed to natural climate. To answer the question two marble types from three different building facades in Copenhagen are studied. Type 1 is a marble from Greenland exposed for south facing natural climate including solar radiation during 60 years, while type 2 is a marble from Norway exposed for 29 years respective 61 years in south facing natural climate, also including solar radiation. From each building a marble cladding panel and a cladding panel of the same marble type only exposed for indoor climate are cut in bars of size 30x30x300 mm.

The bars from indoor are exposed to temperature cycles between 10 °C and 60 °C at nearly 100% RH and at nearly 0% RH in the laboratory. The specimens have been stored in sealed boxes in an oven. In this experiment the temperature cycles are exposed to all four sides of the sample, contrary to the one-sided cycles in nature. The specimens stored at 100% RH were kept in boxes with a small portion of water in the bottom (without direct contact to the water). One of the boxes with samples kept at 100% RH is seen in figure 4. The specimens stored in dry climate are ensured 0% RH by the presence of silica gel.

Figure 4. One of the sealed boxes with specimens kept at 100% RH. Notice the water in the bottom of the box.

Each temperature cycle consists of 12 hours of heating from 10 °C to 60 °C followed by a 3-hour period of cooling back to 10 °C. The specimens were exposed for 29 and 58 temperature cycles.

2.1 *Flexural strength*

Facade stone panels most often break due to bending, for which reason flexural strength testing is used. The flexural strength is one of the quantities used when dimensioning facade stone panel. A four-point bending test is used to determine the flexural strength. The principle of this method is to place a specimen on two supports and progressively to supply load at two points of force attack at a rate of (0.25±0.05) MPa/s until the stone breaks, refer figure 5. From the breaking load the flexural strength can be calculated.

2.2 *Results*

The type 1 and 2 specimens exposed for 100% RH

Figure 5. Flexural strength test.

in laboratory show a loss in strength nearly linear proportional to the number of temperature cycles. Also the natural climate exposed specimens show a decrease in strength. The type 1 specimens decrease in strength from 12 MPa for specimens only exposed for indoor climate to 7 MPa for specimens cut from a cladding panel natural climate exposed for 60 years. The type 2 specimens decrease nearly linear in strength from 16 MPa for specimens only exposed for indoor climate to 9 MPa after 29 years of natural climate exposure and to 4 MPa after 61 years of natural climate exposure. These results are shown in figure 6 and in figure 7. In the figures the graph to the left is strength as function of temperature cycles for specimens exposed for 100% RH in laboratory, while the graph to the right is strength as function of years for natural climate exposed specimens.

2.3 *Discussion of results*

In this case two methods are used to evaluate if marble exposed to temperature cycles at high RH under laboratory conditions loose strength similar to loss of strength for the same marble type exposed to natural climate. In both methods the flexural strength results from the accelerated temperature cycles exposure are used against the flexural strength results from the natural climate exposure.

In method 1 is calculated how many years of exposure in natural climate for a slab are equal to 10 temperature cycles at 100% RH in laboratory.
The result of the calculation is that 10 temperature

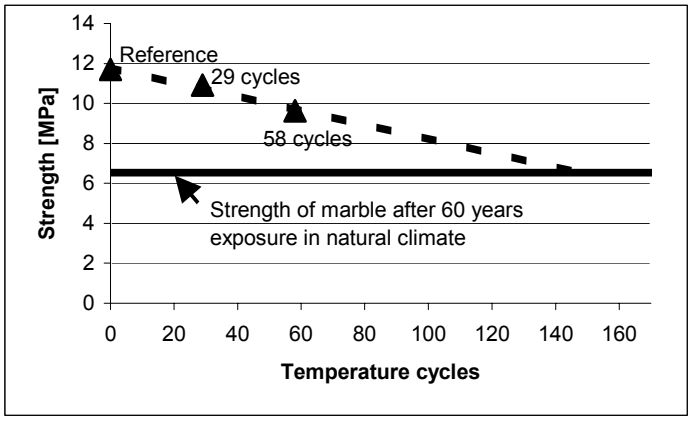


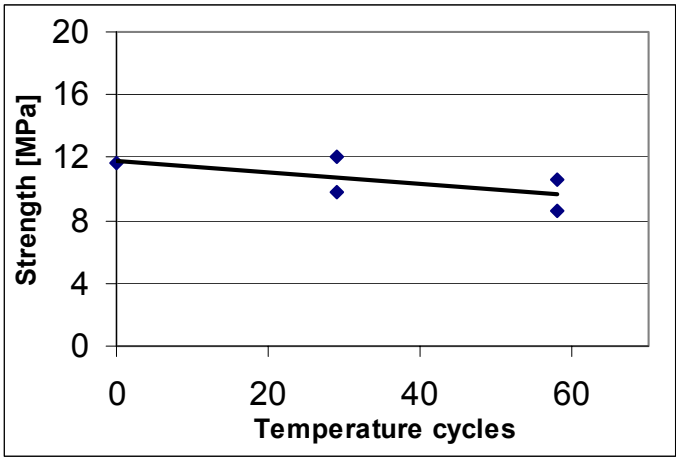
Figure 8. Method 2. Flexural strength as function of temperature cycles. The regression line is based on three measurements points, i.e. Reference point, 29 cycles point and 58 cycles point.

cycles from 10 ºC to 60 ºC in laboratory are equal to 4 years of exposure for both marble types.

In method 2 three measurement points, i.e. Reference point, 29 cycles point and 58 cycles point give a straight line by use of a linear regression. This line are continued up to 140 cycles where the regression line hits the horizontal line for strength for type 1 after 60 years exposure in natural climate, refer figure 8. Also by this method the result is 10 temperature cycles in laboratory equalizes 4 years of exposure in natural climate.

Based on these results 100 temperature cycles from 10 ºC to 60 ºC at 100% RH in laboratory will decrease the strength of a marble type equivalent to 30 – 50 years of exposure for south facing natural climate including solar radiation in Denmark.

The results for exposure at 0 %RH in laboratory are different for the two types: measured loss of strength for type 1 after 58 temperature cycles from 10 ºC to 60 ºC at 0% RH is only one third of the measured loss of strength at 100% RH, while no difference is seen for type 2. Based on this observation it can be concluded that moisture in combination with temperature must be present to give large decrease in flexural strength of marble.



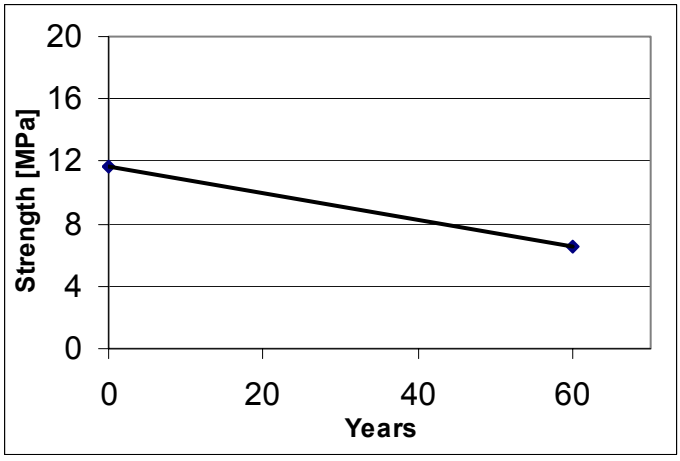
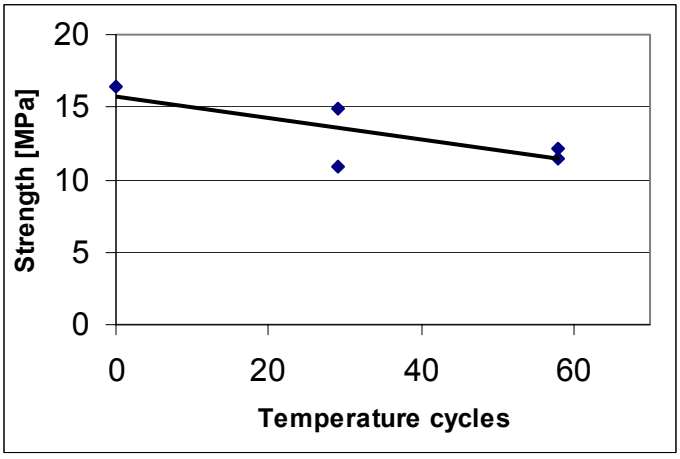


Figure 6. Marble type 1. Left: Flexural strength as function of temperature cycles for specimens exposed for 100% RH in laboratory. Right: Flexural strength as function of years for natural climate exposed specimens.



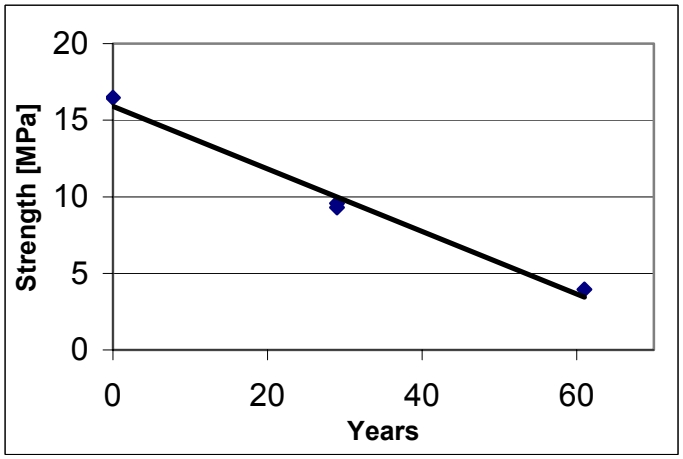


Figure 7. Marble type 2. Left: Flexural strength as function of temperature cycles for specimens exposed for 100% RH in laboratory. Right: Flexural strength as function of years for natural climate exposed specimens.

For marble type 2 also a cladding panel exposed for 29 years in south facing natural climate in the same wall as mentioned above but hidden of a tree was investigated. Bars from this panel and from the other panel exposed for solar radiation have been used for measurements of density, strength, porosity, water absorption and ultra sound propagation. Results from the measurements show that specimens from the panel exposed for solar radiation have higher porosity, higher water absorption and higher ultra sound propagation time and lower density and lower strength than specimens from the panel exposed for shadow. As the conditions for the two panels otherwise are the same it can be concluded that the temperature span does influence the decrease in the marble properties.

3 CONCLUSION

Marble exposed to temperature cycles at high RH under laboratory conditions loose strength similar to loss of strength for the same marble type exposed to natural climate. The strength loss is *apparently* linear regarding number of temperature cycles in laboratory as well as linear regarding number of years for marble exposed to natural climate. Exposure of 10 temperature cycles from 10 ºC to 60 ºC at 100% RH in laboratory will decrease the strength of the *two tested marble* types equivalent to 4 years of exposure for south facing natural climate including solar radiation in Denmark. As the same clear results in decrease of strength are not observed for temperature cycles in the same temperature interval at 0% RH it can be concluded, that moisture in combination with temperature must be present to give large decrease in flexural strength of marble.

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