Deterioration of the granodiorite façade – case example Maximarket, Ljubljana

Propadanje granodioritne fasade – študijski primer Maximarket, Ljubljana

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Abstract: Problems related to natural stone panels bowing have been often reported in the past decades. Most of the reported examples are related to marble and limestone panels, rarely to other natural stones. In the following article deterioration features of granodiorite façade of Maximarket in Ljubljana are described. Special attention is given to the bowing of panels, since this is the first reported case of bowing granodiorite facade panels so far. The causes of bowing are discussed, especially thermal and hydric expansion of quartz and other minerals in granodiorite. Some other deterioration features are discussed like different type of stains, cracks and break-downs of the panels.

Izvleček: Problemi, povezani z ukrivljanjem fasadnih plošč iz naravnega kamna, so v preteklih desetletjih v nekaterih primerih imeli velik negativen vpliv na kamnarsko industrijo in na sloves naravnega kamna kot trajnega gradbenega materiala. Poročila o problemih zaradi ukrivljanja so vezana predvsem na nekatere marmorje in apnence, v redkih primerih je ukrivljanje bilo opaženo na granitnih nagrobnikih. Konkavno ukrivljanje granodioritnih plošč na fasadi objekta Maximarket v Ljubljani je tako prvi tovrsten pojav, opažen na nekarbonatnih fasadah. Avtorji v članku na podlagi laboratorijskih in terenskih opažanj podajajo posamezne značilnosti pojava. Poleg ukrivljanja so podane še nekatere druge karakteristične oblike staranja granodioritne fasade na objektu Maximarketa.

Key words: bowing, granodiorite, “pohorje tonalite”, stone façade cladding, weathering
Ključne besede: ukrivljanje, granodiorit, “pohorski tonalit”, ventilirana fasada, preperevanje

Introduction

Natural stone façade cladding has been used extensively in Slovenia in the past century. A number of prestigious buildings were clad with natural stones that originated mostly from localities in Slovenia, but also from other parts of the former Yugoslavia. Although bowing of natural stone panels has been known among scientists for almost a century (Kessler, 1919, Bain, 1940, Grimšičar, 1974), public interest of this

Scientific paper

phenomena has increased substantially over the last couples of decades, because of deterioration of some marble claddings on buildings such as Lincoln tower in Rochester - USA, the Amoco building in Chicago – USA (COHEN & MOINTEIRO, 1991), the Finlandia hall in Helsinki – Finlandia (ROYER-CARFAGNI, 1999), and others. Since bowing was accompanied by substantial strength loss (LOGAN ET AL, 1993) questions on the claddings' safety become more frequent. Many hypotheses about bowing development have been drawn (e.g. WINKLER, 1994, ERLIN, 1999, TSCHEGG 1999), most of them explain bowing of marble panels as effect of anisotropic expansion of calcite grains. Importance of moisture present is also recognized by many authors (KOCH & SIEGESMUND, 2004).

Since most of the reported bowing problems are related to marble cladding and because a good correlation between observed problems and laboratory examinations of the respective marble types has been established (ROYER-CARFAGNI, 1999, GRELK ET AL, 2004), a general feeling among scientists has prevailed that bowing is prone only to marbles. Furthermore, some authors conclude that other minerals such as quartz and feldspars do not posses the unique thermal characteristics of calcite, and rocks consisting of such minerals are thus not prone to such strength loss. In contrary, WINKLER (1994) reports about bowing granite tombstones at the Greenwood cemetery in subtropical humid climate of New Orleans. WINKLER (1996) also reports of tent-like spalling of thin slabs of granite on urban buildings. It is in his opinion that the bowing of granite panels shares some of the complex factors with marble panels such as the action of moisture dilatation, stress relief and temperature action causing microcracking by excessive contraction of the quartz grains during cooling.

This article features a case study of a 34 years old building at the Maximarket in Ljubljana, Slovenia, which is covered by façade panels of granodiorite exhibiting severe bowing. Field studies were supplemented with laboratory test of bowing potential of the rock type, flexural strength measurements and microscopic analyses in order to clarify some of the reasons for the bowing granodiorite panels.

Thermal-Hydric Deformation Of Granitoid Stones

Stone as all other solid materials changes the dimension due to cooling and heating. The change in dimension of the stone depends on mineral composition (the amount and type of minerals), porosity and fabric - the grain size and the orientation of grains (BILBIJA, 1984). The maximum temperature on the surface of the panels and in the stone due to solar radiation are indirectly related to the colour of stone surface. WINKLER (1994) showed that the surface temperature of some granodiorites could be more than ten degrees higher than the air temperature. It was reported by MAUKO (2004) that some natural stones in the climate of central Slovenia can exhibit temperatures higher than 55 ^{o}C. In such circumstances the stone panel can suffer from severe damage due to the cyclic thermal expansion in the range of 60 ^{o}C and more. The linear dilatation coefficient of the most common minerals in granodiorite (e.c. quartz: linear dilatation in interval of 20-100 ^{o}C is 0.14 % perpendicular to c axis and 0.08 % parallel to c axis, K-feldspar: 0.049 % parallel to a-axis (Clark, 1966)) show the importance of mineral composition on the expansion caused by the temperature changing. An average linear dilatation coefficient of granite type of stone is 37 x 10^{-7}/ ^{o}C up to 60 x 10^{-7}/ ^{o}C (Bilbija, 1984), which means an average of 0.296 % up to 0.48 % of linear dilatation in interval of 20-100 ^{o}C. That means that granite is the rock of the highest dilatation coefficient and is as high as the quartz sandstones and quartzite. By other words granite stone of 1 meter length can expand during sunny winter day up to 0.36 mm/m in the temperature interval of 60 degrees. Repeated cooling and heating cause about 20 % of irreversible deformation and is finally expresses as mechanical damage of stone.

The porosity and presence of microcracks also influence on the amount of water absorbed after the raining. Porosity is one of the main controlling factors of the expansion of the stone slabs (see also Malaga-Starzec et al, 2002; Koch & Siegesmund, 2004). Although the hydric dilatation of granite is only 0.004 up to 0.009 % after the repeated wetting and drying the presence of water is also important for thermal degradation of granitoid panels. For the example, the expansion of granite at the temperature of 60 ^{o}C is 0.15 % and water has the expansion of 1.5 % at the same temperature. The difference results as the stress on pore walls of about 39.5 MPa (Bilbija,1984). If stone slabs are anchoraged the strain would be promoted and it would lead to bowing of slabs.

Building Characteristics

“Maximarket”, which is situated at Trg republike 1, is one of the first department stores built in Ljubljana. It was designed by the architect Edo Ravnikar and his associates in the 1960s. The building was completed in November 1971.

The building’s facades of approximately 1000 m^2 are covered by one of Slovenia’s most widely used types of architectural stone: “tonalite” or “pohorje granite” from the quarry Cezlake I. The quarry is situated on the southern part of this magmatic massive of Miocene age (Dolenec, 1995), which borders on the south to the metamorphic complex. Petrographic name of stone is granodiorite (Zupančič, 1994). It consists mostly of white feldspars (55-70 %) with 50-60 % plagioclase and 5-10 % orthoclase, light grey quartz (20-30 %) and almost black biotite in amount of 10 – 15 % and 1 % of hornblende. Other minerals are: apatite, zircon, pyrite, chlorite, titanite, calcite and epidote (Mirtič et al, 1999). The rock is fine to medium grained, grey in colour with a hypidiomorphic texture.

The preferred grain boundary orientation of quartz and biotite defines the foliation, which is intersected by veins of pegmatite and aplite, up to 10 and more centimetres thick. Cohesion between the veins and ground mass is very good. Mafic minerals (mostly biotite and chlorite) are sometimes condensed in mafic nests or in lenses having a size measured in centimetres. The basic mechanical and physical properties of granodiorite from Cezlak I are presented in Table 1.

Table 1. Mechanical characteristic of granodiorite from Cezlak I according to MIRTIČ ET AL (1999)

REAL DENSITY (kg/m^3)	2687		
APPARENT DENSITY (kg/m^3)	2726		
DENSITY COEFFICIENT	0.986		
POROSITY (%)	1.4		
WATER ABSORPTION (%m/m)	0.3		
ABRASION RESISTANCE (cm^3/50 cm^2)	5.9		
TENSILE STRENGTH (MPa)	max.	min.	medium
dry	241	200	225
water saturated	199	165	185
after 25 freeze/thaw cycles	202	160	182
FLEXURAL STRENGTH (MPa)	max.	min.	medium
dry	24	20	23
water saturated	22	18	20
after 25 freeze/thaw cycles	21	18	19
LINEAR COEFFICIENT OF THERMAL EXPANSION (mm/m °C)			
(-20)°C TO +70°C	0,0084		
THERMAL CONDUCTIVITY (W/mK)	1		
MODULUS OF ELASTICITY (MPa)			
static modulus	41437		
dynamic longitudinal modulus	45204		
dynamic transversal modulus	19684		
dynamic Poisson's number	0.13		
SLIP RESISTANCE			
Polished surface	13.6		
Honed surface	78.8		
FROST RESISTANCE AFTER 25 FREEZE/THAW CYCLES (%m/m)	0.08		

Due to its good mechanical properties, as well as to the possibility of quarrying blocks of large dimensions, both structural and ornamental functions have been historically attributed to “Pohorje granite”. This stone has been frequently used for external and internal paving, for stone façade cladding, for monuments and others.

The façade cladding consists rectangular panels of granodiorite, of different sizes. The most frequently used type of panels is 1700 mm high and 375 mm wide. Smaller panels with a height of 1385 mm are situated in the bottom row. The measured thickness of panels varies between 16.2 mm and 24.7 mm, though most of them are less than 20 mm thick. The texture of stone was not considered by the manufacturer, when the panels were cut and the preferred orientation of the mineral grains in panels varies. The top and bottom edges of the slabs are clipped (Fig. 1), and their surface is coarse textured. The panels were cut with Fe-particles, which were later washed with HCl.

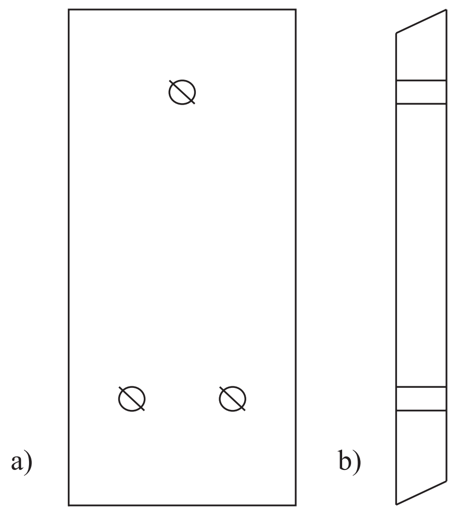

Figure 1. Illustration of the panel from the front (a) and lateral view (b)

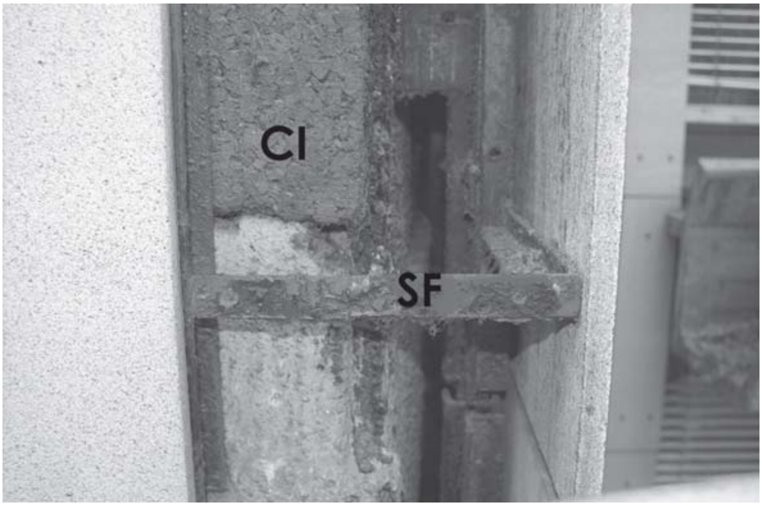

Figure 2. Construction of the façade. The slabs are fixed onto a steel frame (SF). The concrete structure is covered by cork isolation (CI)

The stone cladding is ventilated from the rear side. The clearance between the cladding and the cork isolation on the top of the reinforced-concrete walls is approximately 150 mm. Three steel dowels, up to one cm in diameter, anchor the rectangular panels onto the supporting steel frame (Fig.1, 2). Two of them pass through dowel holes drilled a few centimetres from the bottom edge of the panel and one passes through a hole, which is located a few centimetres from the panel's upper edge. Such a method of anchorage allows a certain clearance between the holes and the anchors. The expansion joints between adjoining slabs are suitable large, approximately 10 to 15 mm and are sufficient for their expansion.

Climatic Conditions

The city of Ljubljana, Slovenia's capital, is situated at about 300 m above sea level. Ljubljana has a continental inland climate, with relativelycold winters with frost and hot dry summers. The average annual temperature is 9.8 ^{o}C. Average annual precipitation amounts to 1393 mm, and average annual insulation to 1712 hours per year.

The local climate of the building is not the same in all directions of the compass. The north façade and almost the entire west façade is open to the square, whereas the south and the east façades, as well as part of the west façade, are in the shade caused by surrounding buildings. This is the reason for the exposing time of the parts of façade to the sun and to the rain is different and also the intensity of heating, cooling, wetting and drying is distinctly different.

Experimental

The field investigations were carried out according to Nordtest Method NT Build 500 - Cladding panels: Field method for measurement of bowing. Two deteriorated panels were dismounted from the façade and subsequently tested in the laboratory. The flexural strength test according to SIST EN

12372: 2000 and petrographic examination according to SIST EN 12407: 2002 were performed in order to correlate the observed deterioration of the panels with a loss of flexural strength and mineralogical-structural alteration at the microscopic level. Laboratory measurements of bowing potential on fresh stone samples and samples used on the façade were conducted at Rambřll in Denmark according to improved Nordtest method NT Build 499. Three sets of rectangular panels of 400x100 mm, partly immersed in water, were heated to 80 °C in three hours. After 4 hours of exposure at 80 °C specimens were cooled down to ambient temperature. Bowing was measured and calculated after every fifth cycle according to following formulas (TEAM WP6.1-RMB-041112):

$$B = H_N / L_N \quad (1)$$

and

$$H_N \approx H \cdot \left(\frac{1\,\mathrm{m}}{L} \right)^2 \quad (2)$$

where:

- B is the bowing expressed in mm/m,
- H_N is the normalized height difference expressed in mm,
- H is the measured height difference expressed in mm and
- L is the distance between the supports under the specimens (0.35 m).

For the field measurements of bowing a *bow-meter* with total length of 2000 mm was used, which was made according to NT Build 500. The bow meter is an aluminium measuring bridge with two supporting mounts, one with two legs and the other with one, which is insuring the stability. The measuring bridge is equipped with a ruler so the distance between two supporting points is adjustable and measurable. The measuring mount also includes a vernier calliper, with precision of 0.01 mm.

Six locations were selected for the measurement of bowing, this selection being made basically with regard to accessibility by lift

Figure 3. Bowing measurements of panels, which had been detached from the west façade

and the amount of observed bowing. Bowing was measured at the mid-point of the vertical mid-line due to the panel's small width (Fig. 3). The distance (L) between the supporting points depended upon the size of the panel.

The measured results have been presented in the form (NT Build 500):

$$B = \frac{d}{L} \cdot 1000 \qquad (3)$$

where:

B is the bowing expressed in mm/m to the second decimal,

d is the measured value of bowing in mm to the second decimal,

L is the measuring distance in mm to the nearest mm.

Results And Discussion

Bowing

Results of onsite bowing measurements are listed in Table 2-3. All of the examined panels demonstrated concave bowing (i.e. the edges of the panels protruded outwards, away from the building). Because of remote edges water penetration behind the stone facade increased and speeded up the deterioration of the steel structure behind it. The development of concave bowing (Fig. 4) was not restricted by lateral fixing, since panels are anchored frontally.

The largest amount of bowing (B = 12.8 mm/m) was measured on the west façade on the bottom row of panels. In general, the panels on the west façade are more bowed than those on the east, although this assumption cannot be statistically proved due to the scarcity of measurement results. Lateral bowing was not observed. A visual inspection of the entire façade revealed that bowing is most pronounced on the south

Table 2. Results of measurements carried out on the east façade

Stone mark	Height (mm)	Width (mm)	Thickness (mm)	L (mm)	d (mm)	Type of bowing	B (mm/m)
M2-5.1	1385	375	194	1285	2.96	concave	2.30
M2-4.1	1385	373	177	1285	2.93	concave	2.28
M2-1.1	1695	375	194	1595	1.62	concave	1.02
M2-1.4	1685	375	187	1585	3.81	concave	2.40
M2-2.4	1372	375	192	1272	3.30	concave	2.59
M1-2.6	1385	223	162	1285	4.70	concave	3.66
M1-1.6	1700	223	194	1600	5.90	concave	3.69
M1-5.6	1385	225	188	1285	5.26	concave	4.09
M1-1.4	1700	375	230	1600	5.06	concave	3.16
M1-1.3	1700	373	247	1600	2.64	concave	1.65
M1-1.2	1700	224	190	1600	3.24	concave	2.03
M1-1.1	1700	375	192	1600	3.03	concave	1.89

Table 3. Results of measurements carried out on the west façade

Stone mark	Height (mm)	Width (mm)	L (mm)	d (mm)	Type of bowing	B (mm/m)
M3-1.8	1700	375	1600	20.35	concave	12.72
M3-5.7	1700	375	1600	15.81	concave	9.88
M3-4.5	1380	375	1280	11.33	concave	8.85
M4-5.3	1380	375	1280	7.45	concave	5.82
M6-1.2	1380	375	1280	11.52	concave	9.00
M3-6.8	1375	375	1275	10.11	concave	7.93
M3-1.6	1700	223	1600	12.55	concave	7.84
M3-5.1	1375	375	1275	4.11	concave	3.22
M3-2.1	1375	370	1275	5.17	concave	4.05
M3-1.1	1700	375	1600	8.29	concave	5.18

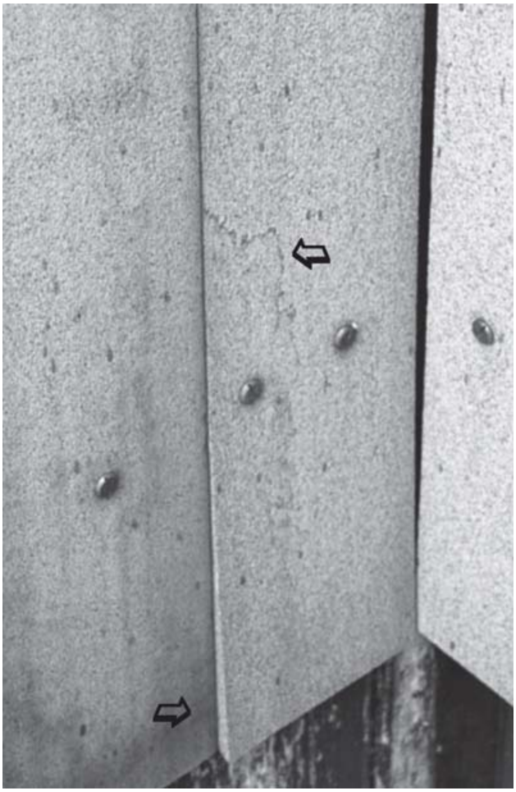

Figure 4. Concave bowing of granodiorite panel on the west façade (left arrow) and crack in chlorite vein (right arrow)

façade. Pronounced bowing was also observed on south facade of the neighbouring building, which was built in the beginning of 1980ies and is covered with the same granodiorite panels (Fig. 5).

Figure 5. Bowing on the south facade of neighbouring building

Table 4. Results of measurements carried out in the laboratory on the panels which were detached from the east façade

Stone mark	Height (mm)	Width (mm)	Thickness (mm)	L (mm)	d (mm)	Type of bowing	B (mm/m)
M6-1.3*	1700	320	160	1600	9.04	concave	5.65
M7-1.1	1320	224	140	1220	5.60	concave	4.59
M7-3.1	1220	223	180	1120	4.78	concave	4.27

*Laboratory tests (optical microscopic analyse and a flexural strength test) were performed on this slab

Other Deterioration Features

Ljubljana is a mostly residential city, and there is hardly any heavy industry. Severe stone deterioration due to pollutants therefore does not occur to a significant degree. Chemical deterioration of the panels is characterized by the appearance of stains on the surface of the panels, which have an influence mainly on the aesthetic appearance of the façade. Four types of stains were distinguished:

- stains formed due to mineral alteration (especially minerals, which contain iron, such as pyrite),
- corrosion stains formed mainly by chemical attack of the supporting steel frame,
- stains formed by oxidation of remaining iron particles from the cutting process,
- stains due to bird excrements.

The stains formed by the alteration of iron minerals and solubility of minerals which contain iron (e.c. biotite) due to weathering conditions are yellowish-brown in colour. They appear in the groundmass as well as in the veins of pegmatite and aplite, where they are more obvious due to the white colour of the substratum. Such stains can form very quickly after installation in unfavourable weathering conditions (this phenomenon has been observed on several buildings with granodiorite cladding in Ljubljana). The staining of stone by iron hidroxides as the result of pyrite and biotite alteration were proved on different stones, such as limestone (Bilbija, 1984) and other igneous stones (Winkler, 1994; Bilbija 1984; Matias & Alves, 2002) and also in concretes (Bilbija, 1984).

During the inspection, state of the supporting steel structure was also evaluated. It was concluded that steel framework was in poor shape, and that repair works are urgently needed. Rainwater had penetrated into and under the stone façade through the joints between the panels and through other

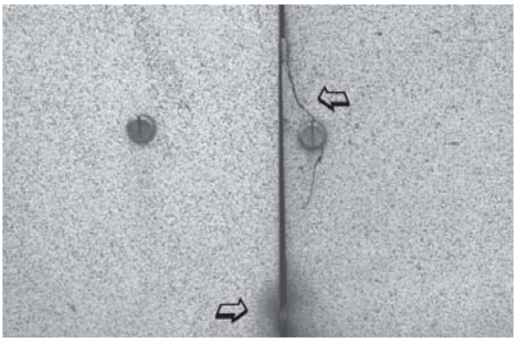

Figure 6: Corrosion stains (left arrow) formed due to oxidation of metal subframe and crack near the dowel (right arrow)

openings like cracks and breakouts, and had attacked the steel structure (BORTZ ET AL, 1988). As a result stains begin to appear on the edges of the panels, around the anchors and along cracks. Such corrosion stains (see Fig. 6, 7) are more obvious on the west façade, where variations in temperature and moisture are greater. The corrosion of the steel framework due to temperature and moisture variations was studied also by BILBIJA (1984).

Many birds' nests were observed under the edge of the roof. Bird excrements accelerate the deterioration processes of the stone. Organic acids from excrements cause the dissolution and other changes of the stone minerals in the presence of the rain water. Reactions of this type has previously been studied by (WINKLER, 1975; 1994).

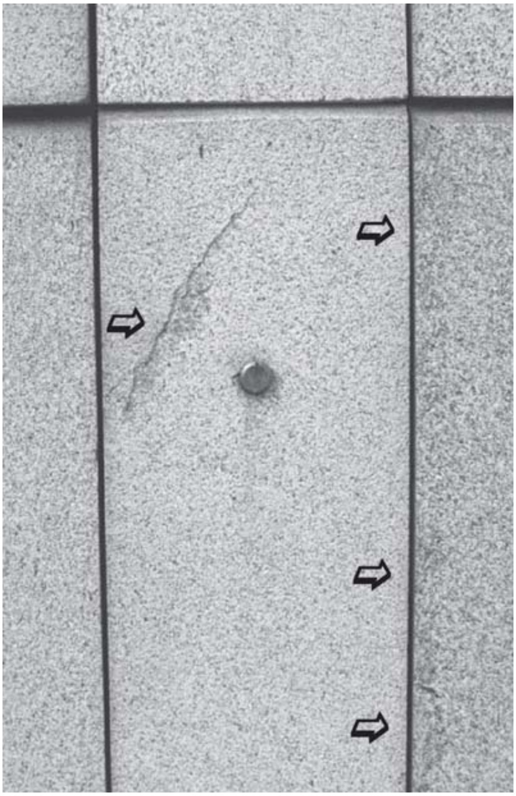

Figure 7. A crack formed on the boundary between the matrix and the lens of mafic minerals (left arrow) and corrosion stain on the edge of the panel (right arrows)

Apart from aesthetic façade colour changes, a certain amount of mechanical damages was observed. This can be attributed to:

- some degree of poor workmanship,
- deterioration due to physical and mechanical changes in the rock.

Signs of poor workmanship are damages due to the incorrect treatment and installation of stone panels. Such damages are rare, but can sometimes be visible as double-drilled anchor holes and broken edges. Double-drilled holes are areas with a high potential for failure and water leakage in façade system. Installation of panels with different thickness panels and chlorite veins are also a sign of poor workmanship, although scarce standardisation and recommendation existed at the time of construction.

Several different types of mechanical deterioration were also observed:

- cracks near the dowels (Fig. 6),
- cracks on the boundaries with the mafic lenses (Fig. 7) ,
- cracks in the aplite veins (fig. 8),
- cracks in chlorite veins (Fig. 4),
- broken slabs.

Thin chlorite veins can be observed in the fresh rock (ZUPANČIČ, 1994). Blocks with chlorite veins are usually rejected in the extraction process due to their low mechanical resistance.

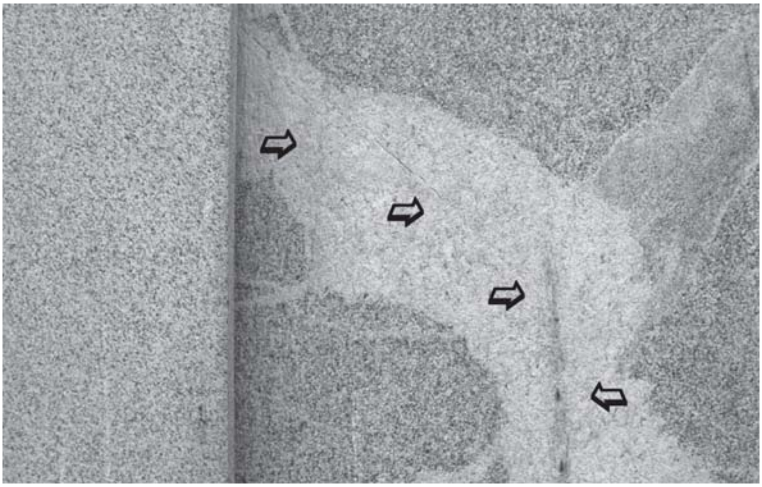

Figure 8. Cracks in an aplite vein (left arrows) and a vertical stain formed by bird excrement (right arrow)

Laboratory Research

Microscopic inspection was carried out on one of the demounted panels, but no major alteration of minerals in comparison with fresh rock, except kaolinization of the feldspars, was observed (Mladenovič et al, 2003). Comparison of samples taken from one of the removed panel and from fresh rock shows higher frequency of transgranular and intragranular cracks in the case of deteriorated panel (Fig. 9). From the same

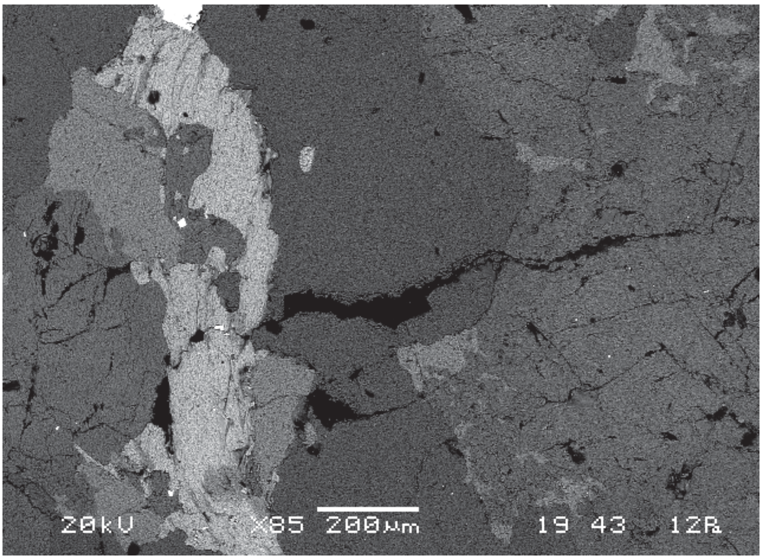

Figure 9. Formation of transgranular cracks in specimen taken from the exposed panel. SEM, BSE

panel six test specimens were cut for flexural strength test. The average flexural strength of the six specimens was 16MPa (MLADENOVIČ ET AL., 2003).

A comparison with the results for fresh rock (which shows a flexural strength of between 15 and 20 MPa) showed, somewhat surprisingly, no difference. Prediction was made that granodiorite stone is more stable because of lack of soluble minerals. The most common minerals, which compose granodiorite, are very inert.

Laboratory determination of bowing potential was conducted on two sets of granodiorite panels of different thickness and on one set of specimens taken from removed panel. Almost no bowing was observed on 30 mm (Fig. 10) or 10 mm (Fig. 11) thick panels although slight difference in curvature of average bowing curve was observed between two sets of specimens (Fig. 12). Clear bowing tendency was observed on specimens taken from removed panel (Fig. 12). After 15 cycles of heating and cooling a bowing of approximate 2 mm/m was determined.

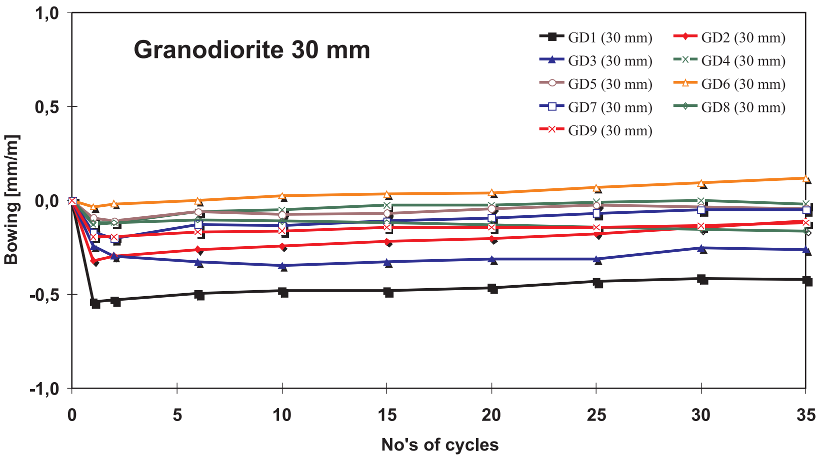

Figure 10. Bowing of 30 mm thick panels during 35 cycles

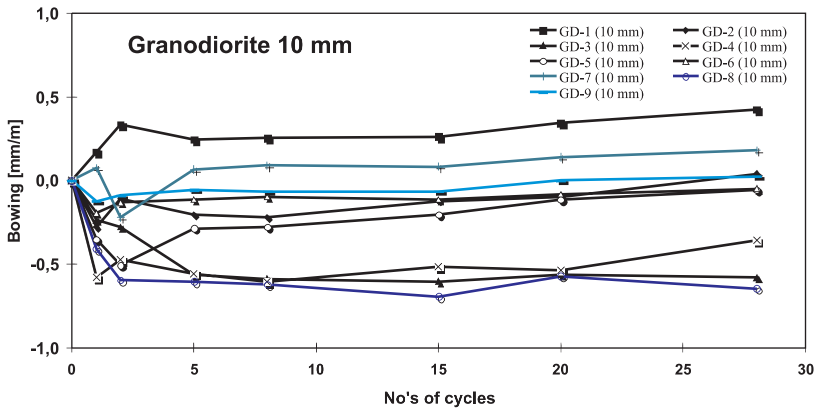

Figure 11. Bowing of 10 mm thick panels after 28 cycles of heating and cooling of partly immersed specimens from 20 to 80 °C

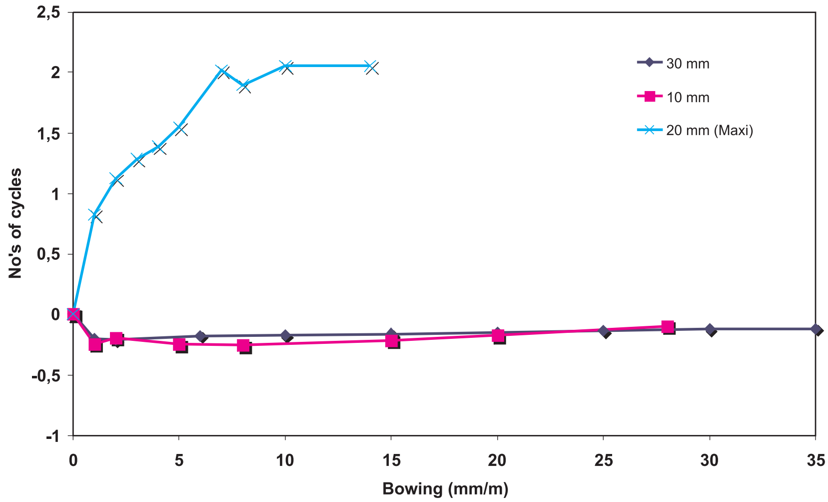

Figure 12. Comparision of average values of three sample sets

The pattern that the fresh granodiorite panels show less bowing than weathered panels was also determined for fresh and weathered marble panels (Grelk et al, 2004). Because of different mechanical characteristics more brittle deformations (transgranular, intragranular cracks) are observed in the case of granodiorite bowing than in the case of marble bowing, which is characterised by granular decohesion on the microscopic level (Alnaes et al, 2004). Additional factor of bowing development is small thickness of façade panels, since no bowing was observed on thicker panels in the case of other granodiorite façades in Ljubljana (Mauko et al, 2005) and which was also proved in laboratory. The influence of thickness on development of bowing is also visible on some marble façades in Ljubljana (Mauko, 2004).

Conclusions

In the case of granodiorite façade of Maximarket, a significant shape and dimension changes of the granodiorite panels has been observed. Observed bowing is probably produced by a number of factors, which can act in a complementary or even catalytic manner, but it most likely is governed by the same factors as it seen in the bowing of marble panels. This is supported by the fact, that the façade panels, which were removed from the building after 33 years, bowed significantly during the accelerated weathering test - bow test developed for marble panels. This indicates that moisture and temperature variations are very important parameters for granodiorite bowing. Due to thermal expansion of quartz crystals, which is followed by formation of transgranular and intergranular cracks and due to hydric expansion, dimensional change of granodiorite panels occur. Since accelerated aging of fresh panels in the controlled conditions shows almost no bowing or very slow increase of panels deformation, we can assume that smaller residual deformation due thermal cycling is formed than in the case of some calcitic rocks. Because of this deformation of facade panels in the form of bowing develops slower and less distinctive than in the case of some marble panels. Further investigation within the scope of this and other similar projects should reveal the role of texture orientation due to panel's orientation. Also the influence of surface treatment and production processes should be included, such as increase of porosity due to surface treatment with chloric acid. Besides bowing other types of deteriorations were observed, such as stains on the surfaces, cracks, breakouts, and signs of poor workmanship. Some of these deteriorations are unfavourable only from the aesthetic point of view, while others are more critical. The most critical areas on the stone cladding are those with cracks and cracks initiations, and for these restoration and replacement of the affected slabs are necessary and urgent. It is expected that this should take place in the near future, when the steel frame, which carries the stone façade, will be repaired.

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