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Performance Evaluation of a Ventilated Stone Façade after 48 Years of Service Life

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Abstract

This study evaluates the technical feasibility of reusing 48-year-old marble panels (Plavi Tok marble, originating from the Republic of Serbia) installed in a ventilated façade on a commercial building in Ljubljana. A combined approach was used: visual on-site inspection of the cladding and laboratory testing of panels removed from the west façade, including petrographic examination, water absorption, flexural strength, dowel hole strength, and bowing under cyclic thermal exposure.

Inspection revealed that approximately 30% of panels exhibit measurable concave bowing (5–12 mm/m), most pronounced on the west façade, and that nearly all panels show dark stains around dowelholes caused by silicone sealant migration into the marble pores. Some panels also display damage in anchoring zones, attributed to improper installation.

Laboratory tests confirm that the intrinsic stone quality remains good after almost five decades of exposure: water absorption is low (0.2 wt.%), flexural strength is characteristic of high-quality carbonate stones (10.1 ± 1.3 MPa), and the dowel hole strength of original holes is statistically equivalent to that of newly drilled holes (≈950 N). However, accelerated bowing tests show that specimens taken from in-situ panels still have potential for further deformation, with the highest bowing almost 1 mm/m after 50 heating–cooling cycles—above the 0.40 mm/m threshold defined in SIST EN 16306:2022.

The results show that, beyond staining caused by the use of an unsuitable sealant in the dowel holes, the observed deformation originates from the marble's continuing sensitivity to thermal cycling, while its mechanical properties remain good after nearly five decades of service - providing a basis for informed decisions on partial reuse or replacement of existing panels in façade refurbishment.

Keywords

Bowing, Marble, Ventilated stone cladding, Reuse, Durability.

1 Introduction

Ventilated natural stone façades installed in Slovenia between 1960 and 2000 represent a significant component of 20th-century architectural heritage. In Ljubljana, carbonate stones — particularly marbles and limestones sourced from former Yugoslavia and neighbouring regions — were the dominant cladding material. Typical examples include Sivec dolomite marble (North Macedonia), Carrara marble (Italy), Hotavlje limestone (Slovenia), Lipica limestone (Slovenia) and the Plavi Tok marble studied here. Many of them are nearing the end of their design life, raising questions about how to extend their service life through maintenance, refurbishment, or panel reuse.

One of the most significant deterioration phenomena affecting marble cladding is bowing: a concave or convex curvature of the panels (Cohen et al. 1991). Severe bowing can lead to panel detachment, posing serious risks, as illustrated by the well-known case in the Southeast Europe region of the Zagrebčanka building in Zagreb.

Although bowing is traditionally linked to the thermal anisotropy of calcite and the resulting hysteresic expansion of marble (Siegesmund et al. 2000, 2008; Logan 2004),leading to grain-boundary separation (Koch & Siegesmund 2002; Mauko et al. 2009), it has also been documented in granitoids (Mauko et. al. 2006; Vázquez et al. 2011, Siegesmund et al 2018) and in other building materials. Microstructural features — grain size, grain interlocking, lattice-preferred orientation (Scheffzük et al. 2004), and panel cutting direction (Siegesmund et al. 2008) — further influence the degree of bowing. Extrinsic drivers include thermal cycling, directional solar exposure, and moisture ingress; the combined action of moisture and temperature can induce anomalous expansion and progressive bowing over relatively short timescales, as demonstrated in the TEAM (FP7) project (Schouenborg et al. 2007).

The objectives of the present study were to assess the technical feasibility of extending the service life of an existing Plavi Tok marble cladding installed in 1978 in a commercial building in Ljubljana, including its structural integrity, bowing magnitude, and reuse potential; and to advance the understanding of long-term performance of carbonate stone cladding by integrating petrographic, mechanical, and accelerated thermal-cycling data.

2 Materials and methods

2.1 Materials

Plavi Tok marble originates from quarries near Požega, Serbia. The deposits lie along the Vardar fault, where the original Triassic limestone and dolostone were metamorphosed during ophiolitic obduction in the Late Jurassic (Márton et al. 2022). The studied façade panels show uneven distribution of lighter and darker bands; locally occurring light-brown dolomitic inclusions are well-bonded to the matrix and do not weather out (Fig. 1a).

Petrographic examination shows that the rock is dominated by recrystallised calcite (85–90%), medium- to coarse-grained (>100 μm), with well-developed polysynthetic twinning (Fig. 1 b). Crystals are anhedral to subhedral with well-defined boundaries, forming a mosaic texture typical of recrystallised carbonate. Localised microfractures and cataclastic fragmentation indicate dynamic metamorphism. Dolomite (10–15%) occurs in isolated grains or small clusters; trace feldspar, quartz, pyrite, apatite, and magnetite are also present, alongside relict micritic domains with fossil fragments and minor dark phases of organic or iron-rich origin.

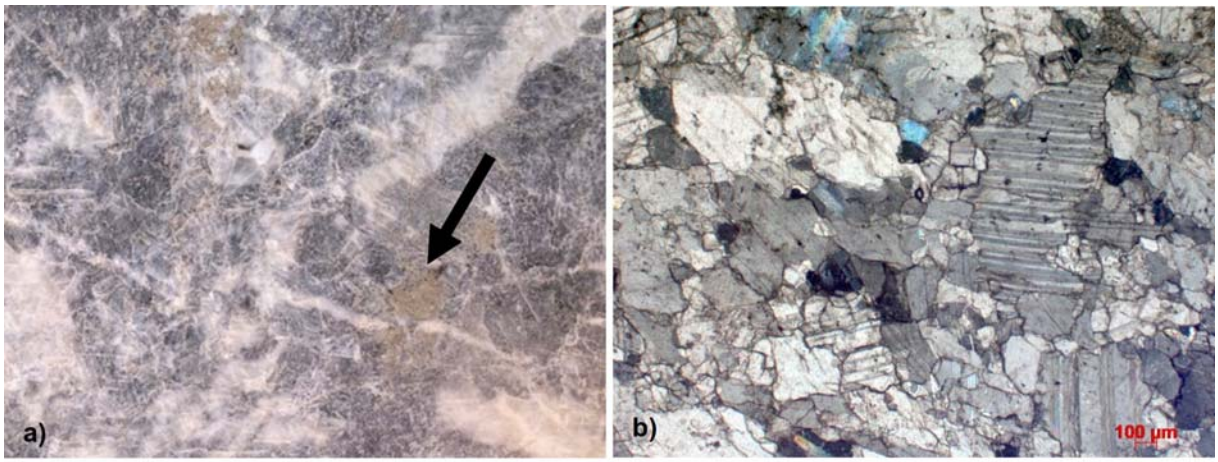


Fig. 1 Visual appearance of the inbuilt Plavi Tok stone (a) - the arrow indicates a light-brown dolomitic inclusion well-bonded to the matrix - and microscopic image of recrystallised calcitic matrix (b).

2.2 Methods

Visual on-site inspection was performed in September 2025 from the ground and from scaffolding on the north and west façades. Some panels had already been dismantled at the time of inspection and catalogued for potential replacement by Marmor Hotavlje company.

Laboratory tests were performed on specimens cut from panels removed and prepared by Marmor Hotavlje. Petrographic examination followed SIST EN 12407:2019, with thin sections from the upper exposed side. Flexural strength under concentrated load was determined according to SIST EN 12372:2022 at a loading rate of 0.25 MPa/s. Water absorption was determined per SIST EN 13755:2008 on 50 × 50 × 30 mm specimens. Dowel hole strength (SIST EN 13364:2002) was used to compare original anchoring holes with newly drilled holes in the same panels. Bowing was tested per SIST EN 16306:2022 on 30 × 100 × 400 mm specimens, partly immersed in water and subjected to 50 cycles of heating from above with infrared lamps and cooling, with temperature regulated via a black reference on the upper surface. The bowing measure B was calculated from the normalised height difference (H_N) (see Eq. 1).

$$B = \frac{H_N}{L_N} = \frac{(\Delta H \frac{L_N}{L})}{L_N} \quad (1)$$

Where L_N Normalised length (1 m)

ΔH Measured height difference

L Distance between supporters under the specimens (0.35 m)

3 Results and discussion

Visual inspection revealed a ventilated cladding structure typical of 1970s stone façades in Slovenia, with stone panels attached to a galvanised substructure anchored to the building's reinforced concrete wall (Fig. 2 a). A 25 cm ventilation gap included 10 cm of glass wool insulation. Most panels were attached to the substructure with four 6 mm wide dowel anchors installed laterally in vertical expansion joints, in 10–11 mm diameter holes 35–40 mm deep, filled with silicone sealant that was still elastic at the time of inspection. The majority of panels measured 125 × 60 × 3 cm, with smaller numbers at 160 × 60 × 3 cm and other sizes. The lower and upper rows of panels were drilled frontally (Fig. 2 b), with 20 mm openings narrowing to 10 mm after 2–3 mm of depth. Some holes contained corroded dowel remnants or showed damage caused by dismantling or the original installation.

Dark stains were observed around anchor holes on all frontal surfaces (Fig. 2 c), caused bythe silicone sealant migrating into the stone's pore system through diffusion or capillary action. The stains extended ~5 cm laterally and 7–10 cm vertically from panel edges, significantly affecting the façade's appearance and remaining visible from a distance (Fig. 2 d).

Concave bowing was clearly identified on numerous dismantled panels from the north façade (Fig. 3 a) and on panels still installed on the west façade (Fig. 3 b). Bowing ranged from 5 mm/m on the north

façade to 12 mm/m on the west façade, with an estimated 30% of panels warped by more than 5 mm/m.

Laboratory results of the mechanical and physical properties testing on specimens taken from in-built panels are summarised in Table 1, while bowing curves of individual specimens during 50 heating–cooling cycles are shown in Fig. 4.

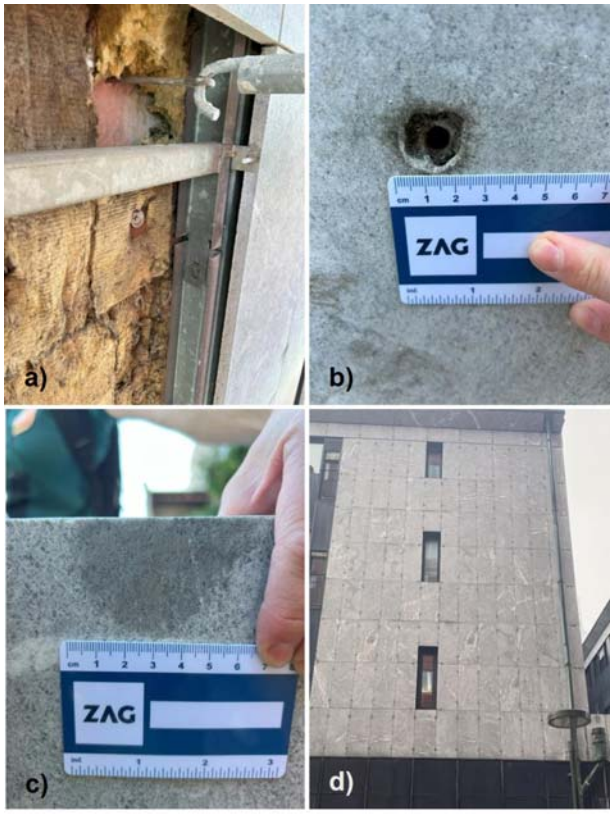


Fig. 2 Ventilated Plavi Tok marble cladding with dowel holes in vertical joints and a metal substructure anchored to the concrete bearing wall (a). Smaller panels near the ground and roof were attached frontally with screws (b). Stains around the dowel holes (c) are visible across the entire façade (d).



Fig. 3 Protruded edges of panels due to concave bowing on the north façade (a) and west façade (b).

Table 1. Mechanical and physical properties of specimens taken from the inbuilt Plavi Tok marble panels.

Parameter	**Value**
Water absorption at atmospheric pressure (wt.%)	0.2 ± 0
Flexural strength under concentrated load (MPa)	10.1 ± 1.3
Existing dowel hole strength (N)	950 ± 161
New drilled dowel hole strength (N)	950 ± 151
Bowing after 50 heating–cooling cycles (mm/m)	0.362 ± 0.374
Maximum bowing after 50 heating–cooling cycles (mm/m)	0.963
Minimum bowing after 50 heating–cooling cycles (mm/m)	-0.008

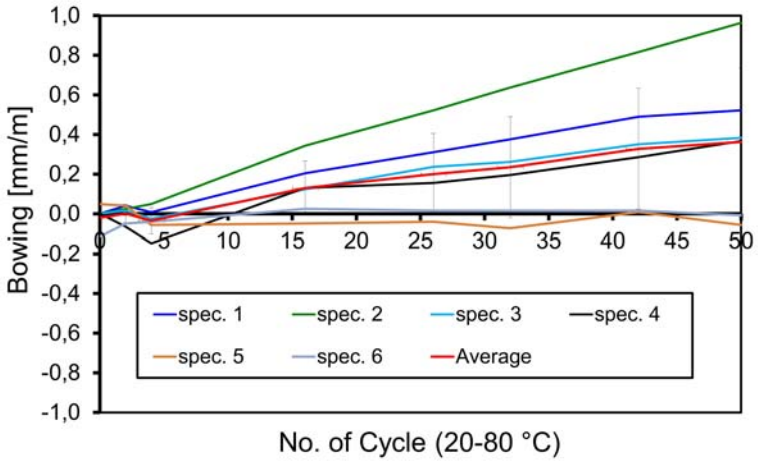


Fig. 4 Bowing of Plavi Tok marble specimens during 50 heating–cooling cycles (20–80 °C).

Field inspection identified two limitations to reusing the existing panels. First, nearly all panels show stains around anchor holes from silicone sealant penetration into the marble pores which are practically impossible to remove because silicone migrates several hundred micrometres deep; mechanical–chemical methods such as helical vortex cleaning can address them but risk damaging the carbonate stone. Although not structurally harmful, the stains are visually unacceptable**.** Second, at least one third of panels — particularly those facing west — exhibit bowing. Laboratory tests, however, confirm good intrinsic stone quality even after 48 years of service life: low water absorption (0.2 wt.%), flexural strength typical of quality carbonate stones (10.1 ± 1.3 MPa), and statistically equivalent dowel hole strength between original (950 ± 161 N) and newly drilled holes (950 ± 151 N). Properly centred holes are therefore not inherent weak points, and without the installation-related defects and visual cracks the stone would be suitable for reuse.

The bowing test shows that specimens taken from panels exposed for ~48 years still have potential for further deformation: bowing after 50 cycles averaged 0.362 ± 0.374 mm/m — close to the 0.40 mm/m limit for outdoor marble cladding (SIST EN 16306:2022, Annex A), with individual values exceeding it. There is also a large discrepancy between bowing of individual specimens; the highest measured bowing in laboratory test was 0.963 mm/m, while at the same time, almost no bowing or little bowing was identified in the case of two specimens. The high standard deviation likely reflects both specimen position on the bowed panel (edge vs. concave centre) and mineralogical or microstructural variation (microcracks, grain size, calcite vs. dolomite content). Notably, laboratory bowing results for nominally identical marble can vary considerably under SIST EN 16306 (2013, 2022) due to the material's sensitivity to thermal exposure. The AGA index (Åkesson et al. 2006) also does not always correlate with bowing degree, as previously noted by Bellopede et al. (2016). Plavi Tok marble illustrates this: despite a complex grain interlocking, this recrystallised limestone still exhibits some bowing. Different cut directions of panels from the same stone may further contribute to scatter (Siegesmund et al. 2008; Menningen et al. 2018).

4 Conclusions

Field inspection and laboratory testing of a 48-year-old Plavi Tok marble cladding in Ljubljana indicate that the intrinsic quality of the stone remains good after 48 years of exposure. Water absorption (0.2 wt%), flexural strength (10.1 ± 1.3 MPa), and dowel hole strength of original anchors (≈950 N) are all in the range expected for sound carbonate cladding and properly executed dowel holes are not weak points relative to freshly drilled ones. Approximately 30% of panels show bowing of 5–12 mm/m — predominantly on the west and southwest-oriented façades — and silicone-induced staining around anchor holes is widespread and difficult to remove without damaging the stone. Accelerated cyclic-thermal testing demonstrates that bowing is a continuing process: specimens taken from in-built panels still bow after 50 heating–cooling cycles (0.362 ± 0.374 mm/m. It can be assumed that marble bowing is therefore not concluded after almost five decades, and reused panels would impact aesthetic visual of the cladding and may be susceptible to further deformation. Further research on additional façade and pristine samples would be needed to better link laboratory and in-situ observations and the reason for high heterogeneity of bowing degree among different laboratory specimens.

Acknowledgments

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