Revealing Absence: Translucent Glass for the Restoration of Marble Monuments

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Background

Marble restoration commonly relies on new marble additions or clearly contrasting contemporary materials. New marble restores formal continuity but may obscure the distinction between original and restored fabric, whereas new materials like steel, concrete or gypsum remain recognisable but can disrupt the monument's visual hierarchy. This tension reflects a central conservation principle: replacements should integrate harmoniously while remaining distinguishable from the original fabric (ICOMOS, 1964).

Structural glass offers a third approach, reconstructing missing volumes while retaining the legibility of loss (Barou et al., 2018a, 2018b). Van Nimwegen (2020) explored cast-glass replacement of missing Parthenon column drums, but primarily at a theoretical level. This research extended that precedent through experimental material development, optical characterisation, lighting simulation and expert evaluation. The Parthenon's west colonnade served as a heavily documented reference case rather than an immediate implementation proposal.

Research question

How can cast-glass be developed as a conservation-compatible restoration insert for marble monuments, using light, translucency and materiality to harmonise with the original fabric while preserving the perceptual legibility of absence, authenticity and reversibility?

The broader research also examined interface design and reversibility. However, this paper focuses on the material, optical, lighting and perceptual findings most relevant to daylight research.

Methods

A research-by-design methodology combined material experimentation, optical characterisation, lighting simulation and expert evaluation. Three batches of kiln-cast soda-lime glass specimens were produced by varying firing schedule, cullet size, placement method, colour recipe and cullet arrangement. Their effects on translucency, colour, veining and casting quality were assessed. Selected specimens were compared with Pentelic marble through illuminance and reflectance spectrophotometry, measuring transmittance, chromatic response, lightness, chroma and gloss.

The measured properties informed ClimateStudio renderings under clear and overcast daylight across seasons and times of day. A night-time scenario approximated the existing Acropolis perimeter lighting using technical information supplied by lighting designer Eleftheria Deko (E. Deko, personal communication, 2026).

Material photographs and rendered stimuli were evaluated through a bilingual expert survey involving 37 respondents from architecture, conservation, archaeology, engineering and lighting design. The survey assessed translucency, visual compatibility, visual subordination, preservation of dignity and integrity, the appropriateness of glass and the clarity of the narrative of "revealing absence". Descriptive statistics and Spearman rank-order correlations were calculated.

Results

The material experiments showed that higher firing temperatures increased flow and transparency, larger cullet increased light transmission, the flowerpot technique promoted marble-like veining and alternate stacking produced clearer veins than stochastic mixing.

No specimen reproduced Pentelic marble across all criteria, consistent with the objective of distinguishability. Specimen B3T2C1R6-2-3 provided the most balanced result, combining controlled transmittance (1.68%), low chroma ($C = 1.03^*$), low gloss (2.65 GU), a relatively warm transmitted-light response and legible internal veining. Its reflective lightness remained lower than that of marble. Compatibility was therefore approached through controlled translucency, colour, gloss and internal structure rather than direct imitation.

The simulations showed that appearance changed substantially with sky condition, solar direction, season, scale and viewing distance. In daylight, the glass maintained a marble-like visual weight while its translucency preserved material distinguishability. Under night-time artificial illumination, excessive transparency or luminosity risked making the insert visually dominant, demonstrating that material and lighting responses must be calibrated together.

The expert evaluation was cautiously positive. Preservation of the monument's dignity and integrity received the strongest overall rating, while visual compatibility was more contested. Narrative clarity and visual compatibility showed the strongest relationship (Spearman's $\rho = .832$, $p < .001$), indicating that acceptance increased when the intervention was understood as revealing absence rather than imitating marble.

Conclusions and limitations

Translucent cast-glass can develop a marble-like yet distinguishable character when formulation, surface finish and lighting response are considered together. Daylight operated as a design variable governing compatibility, subordination and legibility, while artificial lighting extended the assessment across the monument's full visual cycle.

The principal contribution lies in connecting experimental material development and optical measurement with context-specific lighting simulation and expert perception. The results showed that visual compatibility depended not only on numerical resemblance to marble, but also on whether the intervention communicated historical absence meaningfully.

The study remained at feasibility level. Specimens were laboratory-scale, lighting was evaluated through renderings rather than full-scale mock-ups, and the survey represented expert perception. Further research should include larger casts, physical daylight and artificial-light mock-ups, durability testing and lower-risk pilot applications before the approach is considered for highly sensitive monuments.

References

Barou, L., Oikonomopoulou, F., Bristogianni, T., Veer, F., & Nijsse, R. (2018a). Structural glass: A new remedial tool for the consolidation of historic structures. *Heron, 63*(1–2), 159–198.

Barou, L., Oikonomopoulou, F., Bristogianni, T., Veer, F., & Nijsse, R. (2018b). Dematerialization of the ruins. *Proceedings of Challenging Glass 6*, 11–26.

International Council on Monuments and Sites (ICOMOS). (1964). International charter for the conservation and restoration of monuments and sites (The Venice Charter).

Van Nimwegen, B. (2020). Cast glass restoration of marble monuments (Master's thesis). Delft University of Technology.

Appendices

A1. Material parameters influencing optical behaviour.

Firing schedule, cullet size, placement and arrangement were varied to control glass flow, translucency, colour distribution and internal veining.

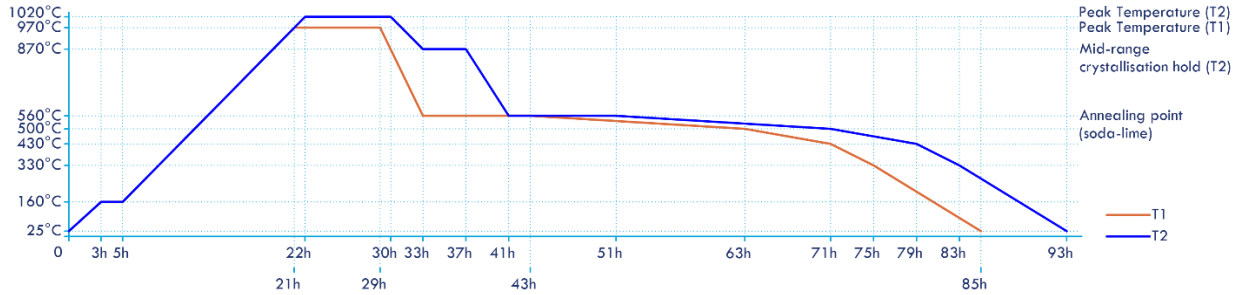


Figure 01. Firing schedules used for the experiments of this chapter. Temperature-Time graph. Created by author.

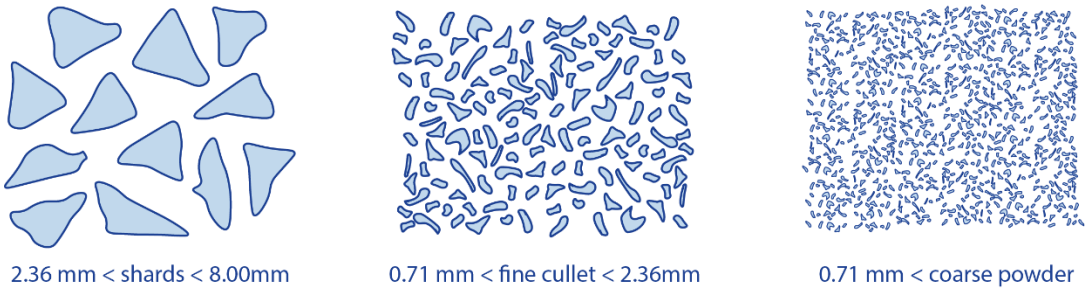


Figure 02. Cullet sizes tested in the experimental process. Created by author. Inspired by Isidora Matskidou (2022).

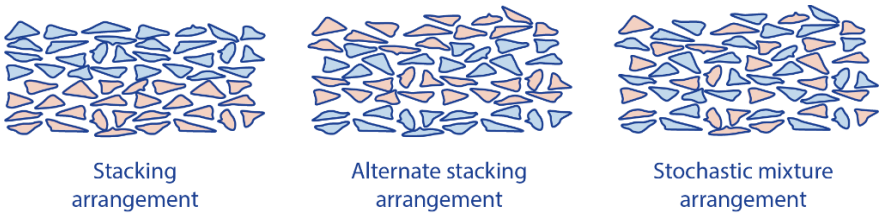


Figure 03. Cullet arrangement configurations tested in the experimental process. Blue indicates clear glass; Orange indicates coloured glass (n=1-3) utilised during testing. Created by author.

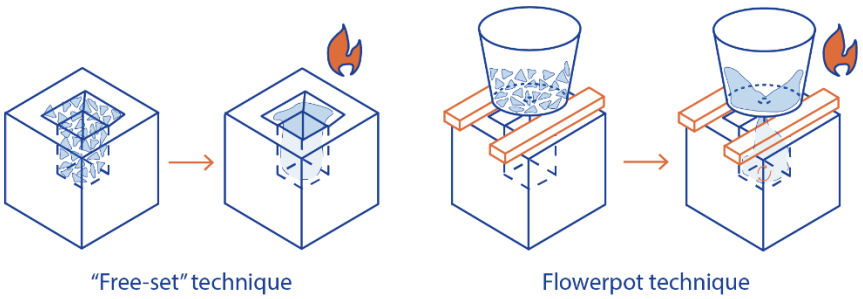


Figure 04. Cullet placement techniques tested in the experimental process. Created by author.

A2. Iterative development of the cast-glass specimens.

Successive batches moved from predominantly opaque, stone-like outcomes towards moderated translucency, warmer colour behaviour and more controlled internal veining.

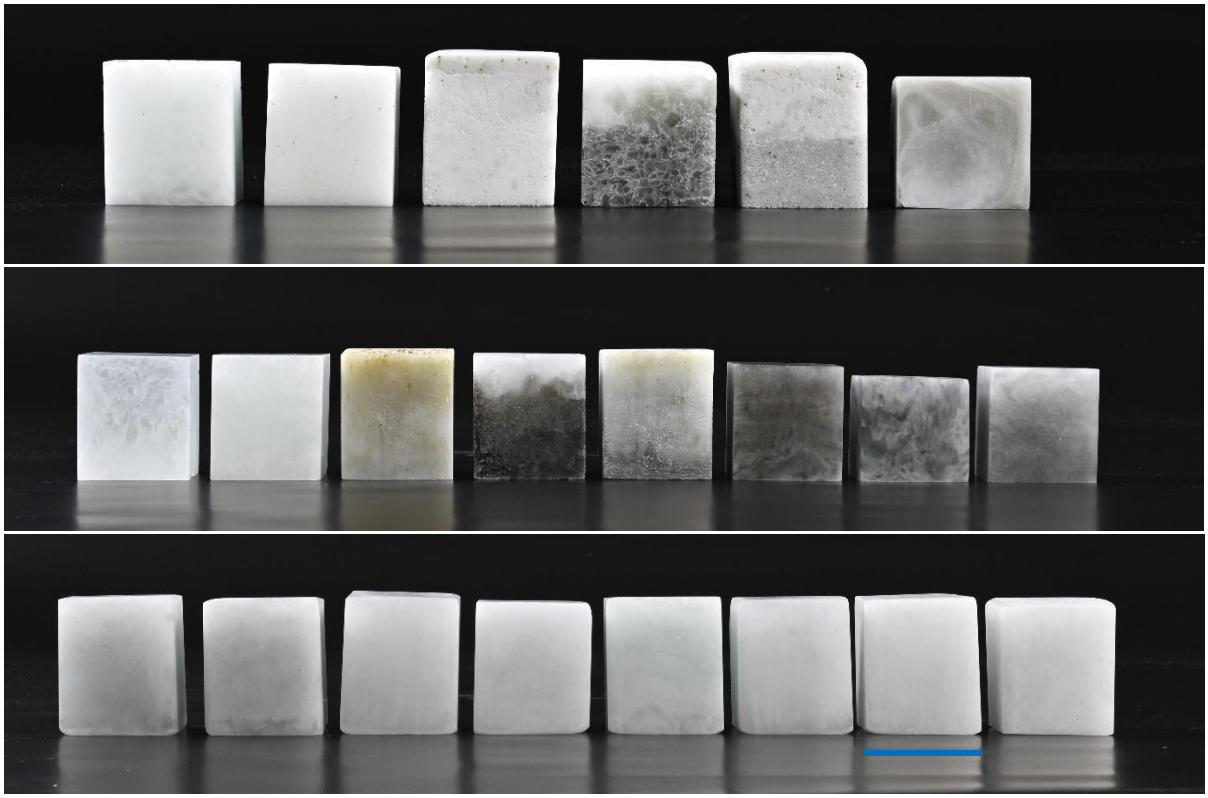


Figure 05. (top to bottom) B1 batch: marble-like but mainly opaque, B2 batch: more translucent but darker/bluer and less controlled, B3 batch: refined, softer and more consistent. Final candidate-specimen B3T2C1R6-2-3 is indicated with a blue underscore.

A3. Optical behaviour and selection of the preferred candidate.

The selected specimen did not replicate Pentelic marble numerically, but provided the most balanced combination of controlled transmission, warm colour response, low chroma, low gloss and distinguishable veining.

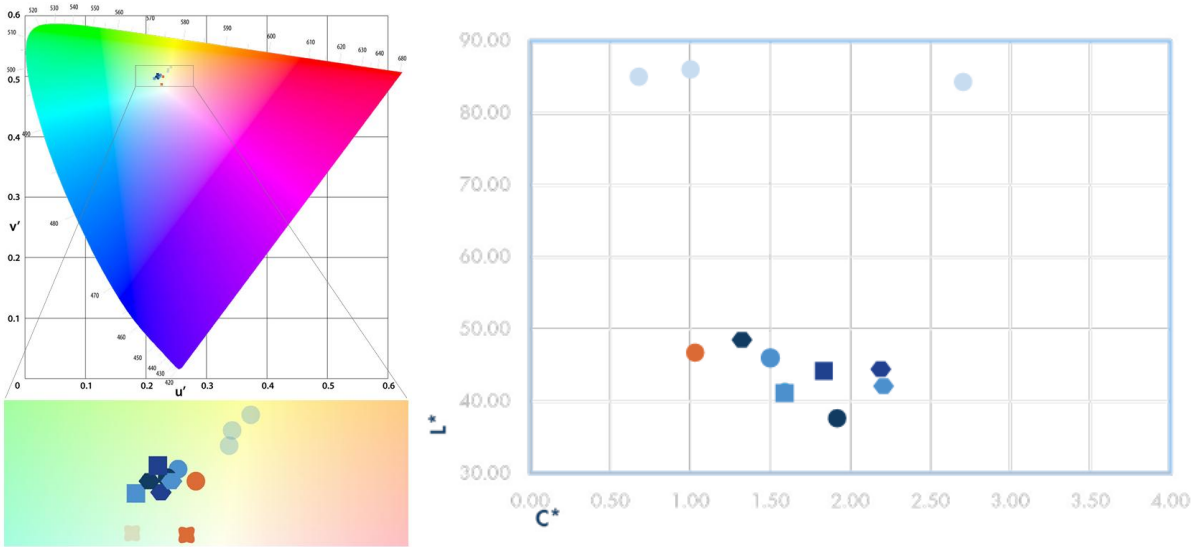


Figure 06. (left) Chromaticity diagram in CIE 1976 u'v' space showing the B3 candidate cast-glass transmission measurements with the non-polished Pentelic marble reference relative to the blank light source. The coloured field is shown as an approximate chromaticity reference background. The lower panel provides an enlarged view of the cluster. Created by author.
(right) CIELAB L*-C* plot of the B3 candidate cast-glass reflectance measurements with the non-polished Pentelic marble reference. The plotted points define the lightness and chroma range of the specimens' surfaces. Created by author.
Note: indicates marble series (M-B1a,M-B2a,M-B3a) measurements, indicates specimen B3-T2-C1-R3-2-3 measurements, indicates specimen B3-T2-C1-R3-2-4 measurements, indicates specimen B3-T2-C1-R4-2-3 measurements, indicates specimen B3-T2-C1-R4-2-4 measurements, indicates specimen B3-T2-C1-R5-2-3 measurements, indicates specimen B3-T2-C1-R5-2-4 measurements, indicates specimen B3-T2-C1-R6-2-3 measurements, indicates specimen B3-T2-C1-R6-2-4 measurements, indicates current light source measurements, indicates previous light source measurements

A4. Calibration and visual behaviour under daylight and artificial lighting.

Material calibration connected measured properties with observed appearance. Clear daylight increased contrast and legibility, overcast daylight produced a subdued reading and artificial illumination introduced a warmer, localised response.

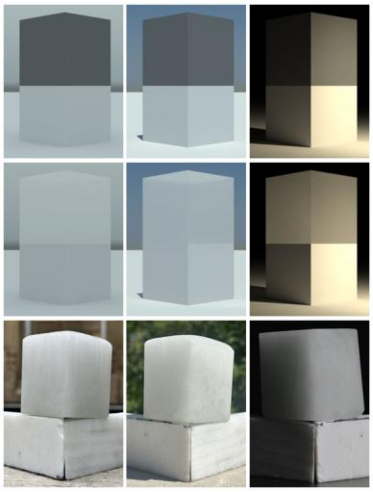


Figure 07.
Cube renderings and photographs of the best candidate cast-glass specimen (B3-T2-C1-R6-2-3) under different weather conditions.
(top row): glass_ measured definition/overcast, glass_measured definition/clear sky, glass_measured definition/night;
(middle row): glass_calibrated definition/overcast, glass_calibrated definition/clear sky, glass_calibrated definition/night;
(bottom row): B3-T2 C1-R6-2-3/overcast, B3-T2-C1-R6-2-3/clear sky, B3-T2-C1-R6-2-3/night.

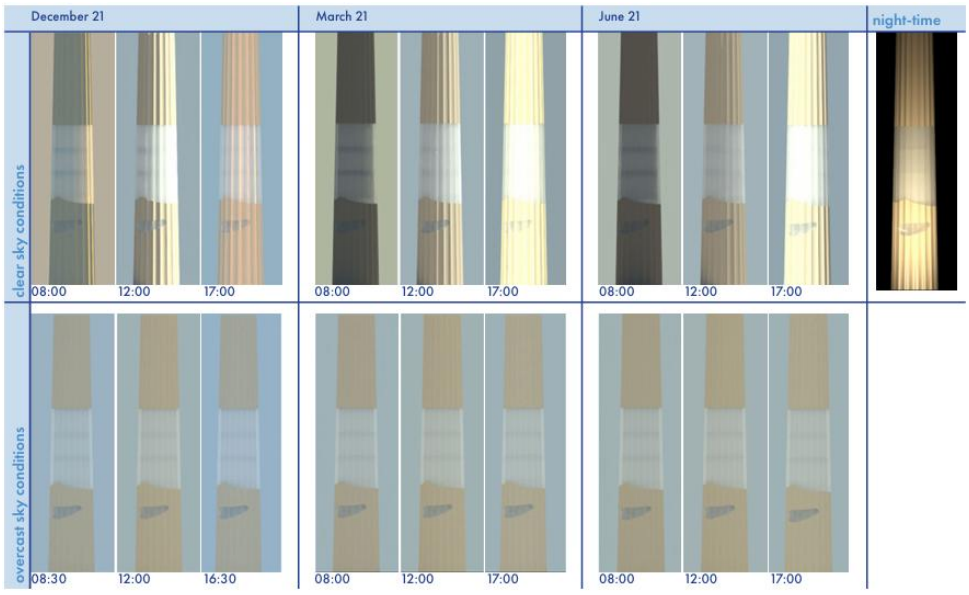


Figure 08. ClimateStudio column renderings using the calibrated glass and marble recipes under clear-sky, overcast and night-time lighting conditions. Daylight scenarios are shown for 21 December, 21 March and 21 June at morning, midday and late-afternoon hours. Created by author.

A5. Expert perception of translucency, compatibility and narrative clarity.

Expert evaluation favoured controlled marble-like translucency over high transparency. Acceptance increased when the intervention was understood as revealing absence, with narrative clarity strongly related to visual compatibility.

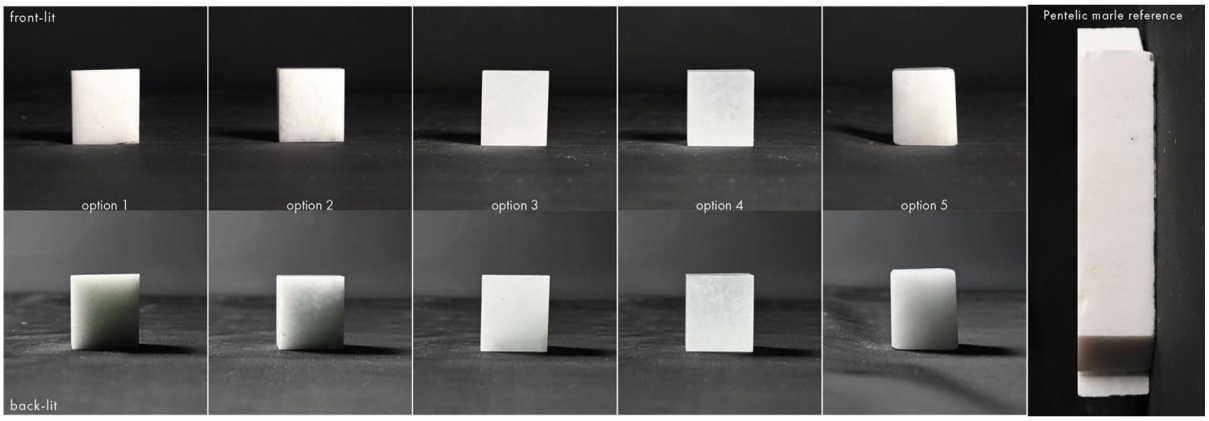


Figure 09. Image used for the translucency ranking of the material-scale part of the survey. Top row shows the selected specimens front-lit, whereas bottom row shows the specimens back-lit. (left to right): S1; B1T1C2R0-1-1, S2; B1T1C1R0-1-1, S3; B2T2C2R0-1-1, S4; B2T2C1R0-1-1, S5;B3T2C1R6-2-3, unpolished Pentelic marble slat.



Figure 10. Images used for the assessing of the "revealing absence" narrative of the monument-scale part of the survey. (left): daylight conditions, (right) artificial light conditions. Both images have been digitally edited to include a proposed intervention on the corner column, approximating its appearance at the monument scale. Created by author.

	Variable	Mean	Median	Mode	Interpretation
General evaluation	narrative of revealing absence	3.30	4.00	4	generally positive
	visual subordination	3.22	4.00	4	generally positive
	visual compatibility	2.89	3.00	4	mixed/moderate
	dignity and integrity	3.70	4.00	4	strongest overall evaluation
	glass as visually appropriate	3.49	4.00	4	generally positive

Figure 11.
General evaluation of the proposed glass intervention (N = 37). Created by author.

Note: higher values indicate more favourable evaluations.

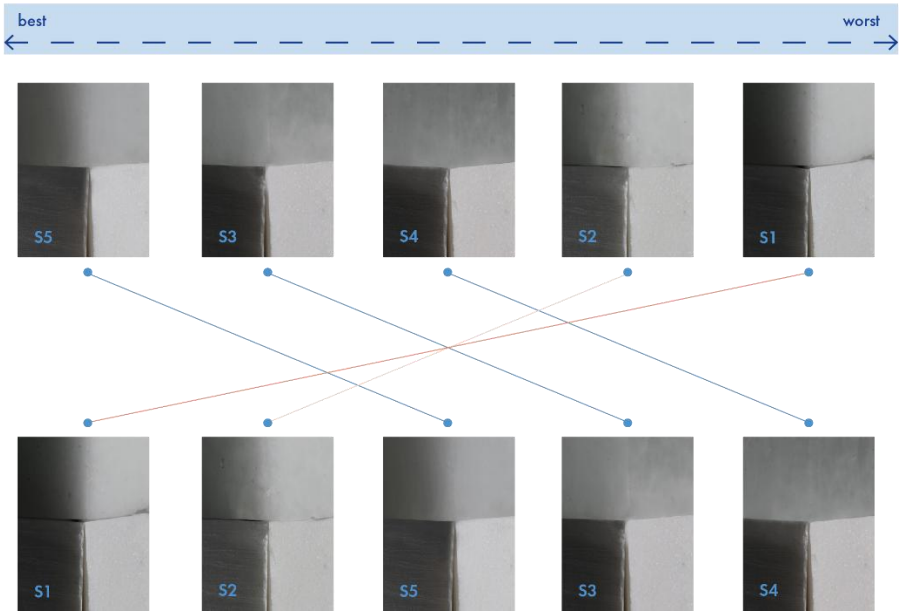


Figure 12. Cross-criterion comparison of the material-scale evaluation. (top) the column orders the samples according to descriptive translucency appropriateness, (bottom) the column orders them according to visual match with Pentelic marble. The connecting lines show how each sample shifts between the two criteria. Created by author.
Note: the translucency order is descriptive only, as the Friedman test for translucency ranking did not reach statistical significance.

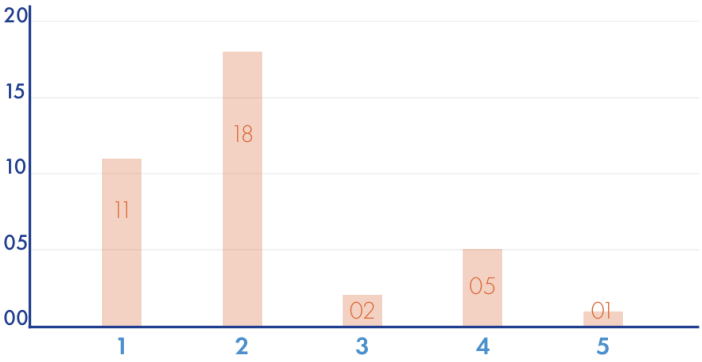


Figure 13. Preferred material expression for marble monument restoration (N=37) presented in a bar chart.
x-axis: response category, y-axis: frequency.
Created by author.

Note: 1 indicates more opaque/stone-like, 2 indicates marble-like translucency, 3 indicates high transparency, 4 indicates no preference, 5 indicates other.

Spearman correlations

Relationship	Spearman's ρ	p-value	Interpretation
narrative x visual compatibility	.832	< .001	very strong positive
narrative x dignity/integrity	.701	< .001	strong positive
visual compatibility x dignity/integrity	.701	< .001	strong positive
narrative x glass appropriateness	.640	< .001	strong positive
visual compatibility x glass appropriateness	.616	< .001	strong positive
visual subordination x glass appropriateness	.068	.690	not significant

Figure 14.
Key Spearman correlations between general evaluation variables (N = 37). Created by author.

Note: only theoretically relevant correlations are shown.