Influence of Microclimate on the Deterioration Of Historic Marble Buildings

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Deterioration is not a simple result of marble's reaction to various weathering agents; neither the exposure nor the deterioration is uniform. Observations at several marble buildings, including the Merchants' Exchange in Philadelphia, document variations in deterioration at different locations on the facades.

Fig. 1. Rounded edges are left by dissolution. Balustrade, U.S. Capitol, Washington, D.C

Deterioration of marble in historic buildings results from the weathering characteristics of the marble and from extended exposure in the urban environment. Marble weathers when it is exposed to wind, rain, and freezing and thawing of ice; these agents act to smooth, dissolve, and break down the marble. Marble used in buildings is also exposed to urban pollutants that may accelerate this natural weathering. However, deterioration is not a simple result of the marble's reaction to various weathering agents; neither the exposure nor the deterioration is uniform.

Chemical, mineralogical, and physical variations in the marble account for some of the variation in durability; however, systematic examination of historic marble buildings shows that deterioration occurs in patterns that are not linked solely to stone characteristics. Some areas of a building show extensive loss of material and carved features, while other areas may appear dirty but with well-preserved original features. Such small-scale variations in stone deterioration result from microclimatic effects; although the building has experienced the same overall exposure to the amount of precipitation, seasonal temperature changes, and urban pollutants, these weathering agents have not had a uniform impact. In order to protect and preserve historic marble buildings, it is important to consider both the characteristics of marble deterioration and the factors that influence where and how extensively it will deteriorate.

Marble Dissolution

Calcite, the predominant mineral component of marble, readily dissolves in weak acid, such as the carbonic acid that is present in unpolluted rain from the reaction of carbon dioxide with water. In urban settings, rain acidity may become elevated because sulfur dioxide from power plants and nitrogen oxides from vehicle emissions react with moisture and oxidizing agents in the air to form sulfuric and nitric acids. The resultant increase in rain acidity accelerates marble dissolution.

Dissolution of marble may be manifested in several ways on a building. The original, smooth surface finish may be lost when dissolution occurs around the edges of individual grains of calcite in the stone; this is commonly called sugaring because of the way the surface texture appears after lengthy exposure. Minerals in addition to calcite (known as inclusions) may weather preferentially, resulting in grooves or pock marks where the inclusions became loosened and fell out when the surrounding calcite dissolved. In other cases inclusions are more resistant than the calcite, protruding above the dissolved calcite surface. Sharp edges and carved details may become rounded (Fig. 1) as the exposed parts of the stone are dissolved by rainfall or dripping water. In some exposed areas, catastrophic loss may occur; large chunks or whole architectural details may be missing. Although dissolution may have been a major contributor, other

Figs. 2 a,b. Exposed volute on the column capital, *left,* is almost completely gone but the sheltered portion, *right,* still retains intricately carved details. Merchants' Exchange, Philadelphia, Pa.

factors (such as freeze-thaw cycles, poor construction, or inappropriate design and material selection) may have accelerated the deterioration in these cases.

All examples of deterioration of marble from dissolution are located where the stone has been exposed to washing by rainfall or to water flowing over the stone. Where stone is protected from direct washing, it has dissolved by the acidic water. The Corinthian capital in Fig. 2 shows the striking difference in deterioration that can occur between an area exposed to rain and one that is sheltered.

Gypsum Crust Formation

However, rain protected areas are not free from the effects of urban exposure. Examination of sheltered areas shows that the stone is often covered by a disfiguring blackened crust; in some places the crust is blistered, revealing crumbling stone underneath. In sheltered areas, pollutants that are not regularly washed off the stone may react with moisture and calcite to form a new mineral phase on the surface. The blackened crusts are predominantly composed of gypsum (a hydrated calcium sulfate), which results from the reaction between sulfuric acid, water, and the calcium carbonate (calcite).

Gypsum is soluble in water, so although gypsum may form anywhere on marble that is exposed to sulfur dioxide, it accumulates in areas that are protected from washing by rain. Gypsum crystallizes as a network of bladed grains covering the surface. Although gypsum is a white to colorless mineral, with time the network of bladed crystals readily traps dirt and pollutants (Fig. 3), causing the crust to appear black. Blackened crusts can become quite thick in older buildings; underneath the crusts, the marble may be disaggregated by penetration of solutions that dissolve the calcite or by growth of new gypsum crystals between the calcite grains (Fig. 4). When the crusts are removed, the stone underneath is likely to be even more vulnerable to further attack and degradation because of its greater surface area and the greater accessibility to water penetration afforded by the grain disaggregation.

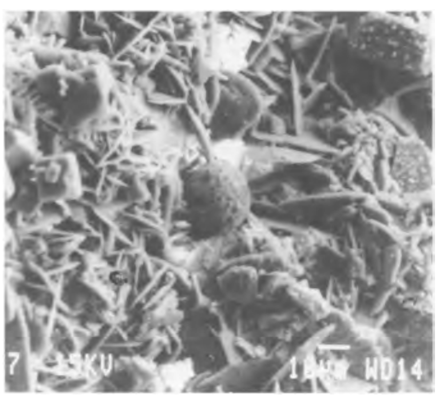
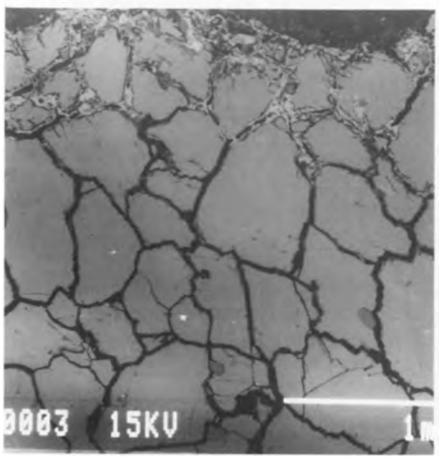


Fig. 3. Network of bladed gypsum crystals on marble traps particles to form the blackened alteration crust on marble; scale is 10 micrometers.

Aspects of Microclimate

Understanding the factors that contribute to the deterioration of marble aids in making appropriate protection and preservation decisions. In the largest sense, three factors influence the extent of deterioration: length of exposure, amount and type of pollutants, and degree of shelter from or exposure to washing by rain. Climatic factors such as temperature, humidity, wind direction and velocity, and precipitation amount and rate influence the degree to which pollutants can contribute to deterioration. For example, the rate at which airborne pollutants are transferred to building surfaces is strongly affected by moisture, and the presence of surface moisture enhances the reactions that form gypsum on the marble surface. However, these factors do not affect all marble buildings equally. Some marbles are intrinsically more susceptible to the deteriorating influences of the environment than others; two marbles used in the Merchants' Exchange Building in Philadelphia with identical exposure to climatic conditions show a visible difference in surface roughness (Fig. 5). Some marbles are so inhomogeneous that stone taken from different parts of the same quarry may vary greatly in its resistance to weathering. At the Lincoln Memorial in Washington, D.C., adjacent blocks of Colorado Yule marble with identical exposure have weathered quite differently (Fig. 6).

Some significant variations in stone deterioration are not attributable to stone characteristics however. For example, marble balusters behind the 80-year-old Organization of American States building in Washington, D.C., are blackened and blistered where they face a garden but are only slightly deteriorated where they face a patio (Fig. 7).



Figs. 4 a,b. The marble is badly disaggregated underneath the 0.8 mm thick blackened crust from the 160-year-old Merchants' Exchange, Philadelphia, Pa., as shown in this sample and detail at 1 mm scale.

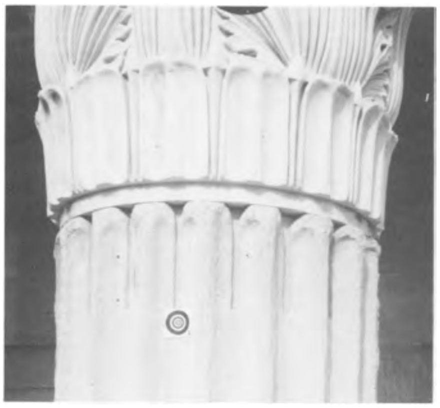


Fig. 5. Two marbles show significant differences in their resistance to weathering. The capital is Carrara marble; the shaft is Pennsylvania marble. This column is located on the south side of the east facade of the Merchants' Exchange, Philadelphia, Pa.

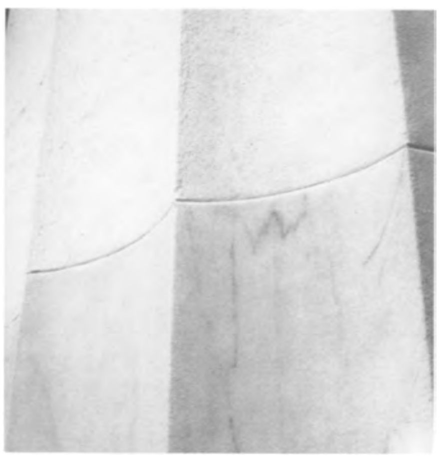
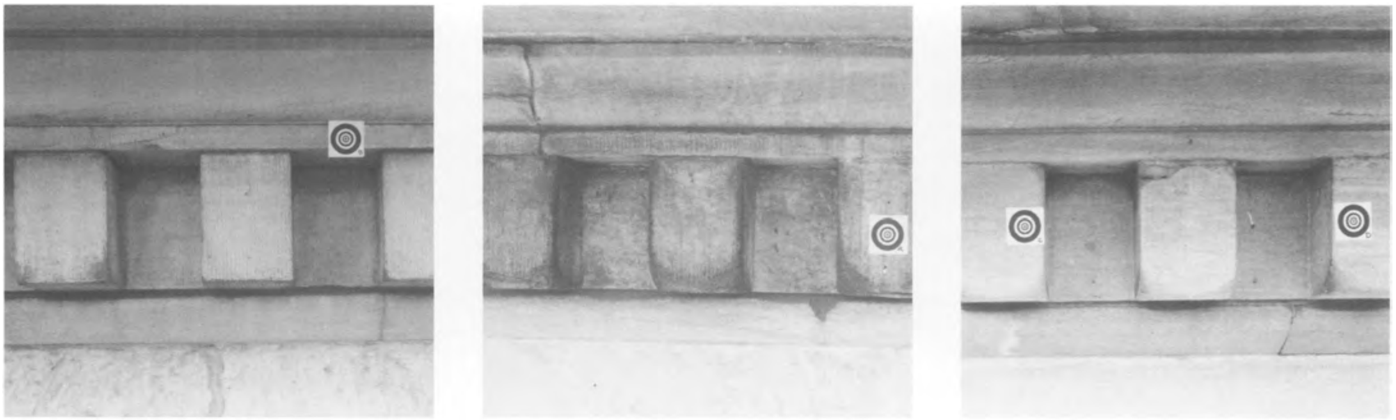


Fig. 6. One block of Colorado marble has sugared after about 70 years exposure, but an adjacent block of the same marble has been more resistant to weathering. Lincoln Memorial, Washington, D.C.

Figs. 7 a,b. The marble balusters facing the garden, *top,* are covered by a blackened alteration crust. The reverse sides, *bottom,* (facing a patio) show very little surficial alteration. Marble balusters at the Organization of American States Building, Washington, D.C.



Figs. 8 a,b,c. Dentils on the Merchants' Exchange, Philadelphia, Pa. *A, left,* west facade; *b, center,* north side of east facade; *c, right,* south side of east facade.

This difference must be due to small-scale differences in exposure; the nearby bushes may shield the balusters from rainfall, or the balusters may be cleaned during washing of the patio.

Such relatively small-scale variations in exposure conditions can result in dramatic variations in marble deterioration. These effects can be categorized as microclimatic effects. Microclimatic factors are defined as weathering agents that influence a limited area of a structure or whose influence varies from place to place within the structure. They include wind patterns and speed, amount and rate of washing by rain, solar

Fig. 9. West facade columns, Merchants' Exchange, Philadelphia, Pa.

radiation input, and stone surface wetness and temperature. In an urban setting, these factors can influence the delivery of pollutants to the stone and the accumulation of pollutants on the stone surface (see pp. 26ff.).

The Philadelphia Merchants' Exchange

The systematic examination of a building and measurement of building specific meteorological and pollution conditions will help us understand the relative importance of microclimatic effects in marble deterioration. Since 1987, a study with this goal has been conducted at the Philadelphia Merchants' Exchange, ca. 1832 (Dolske et al. 1990; Dolske and Sherwood 1992). Carrara marble was used in the column and pilaster capitals whereas Pennsylvania marble was used everywhere else in the building.

Architectural details that appear on both the east and west facades of the Merchants' Exchange afford the opportunity to make comparisons between deterioration and relative exposure. The runs of dentils are useful for comparisons because of their size, regularity in dimension and shape, and large number. The dentils along the west facade are in better condition than those along the east facade. The west facade dentils (Fig. 8a) retain sharp edges and original tool marks on the faces; the lower corners of the dentils are only slightly rounded, and accumulation of alteration crusts between dentils is only faintly evident. In contrast, the dentils on the east facade (Figs. 8b, 8c) have rounded edges and retain only faint suggestions of original tool marks. The lower corners of nearly all the east facade dentils are rounded, some quite significantly, and accumulation of a darkened alteration crust on the sides of several dentils is readily observed. Dentils along the north side of the east facade (Fig. 8b) show subtle differences in degree of deterioration compared with those along the south side of the east facade (Fig. 8c). On the north side, the dentils have a more visible alteration crust and retain more tool marks than on the south side.

Comparisons of stone loss on the columns and the Corinthian capitals are complicated slightly by the potential for original variations in the carved features. However, there are obvious differences in deterioration, greater than any likely variations in

Fig. 10. East facade columns, Merchants' Exchange, Philadelphia, Pa.

the carvings, that correlate with exposure and position on the building. Most carved features of the capitals are retained where the stone is sheltered from direct exposure to rain, but have lost definition when exposed to rain (Fig. 2). Capitals on the west facade all retain their exterior volutes (with no evidence of repair) (Fig. 9), but the outside volutes have been lost more or less completely on the east capitals (Fig. 10). As with the dentils, there are slight differences in the deterioration of capitals on the north and south sides of the east facade. The carved features on the exposed portion of the south capitals are much more worn (e.g., eroded and broken off) than on the counterpart north capitals. In particular, the details are lost or rounded on the south capitals. It is more difficult to make visual comparisons of differences in crust thickness, but close examination suggests a slightly thicker crust on the north capitals compared with the south capitals.

These differences in deterioration seem to correlate with position on the building, suggesting a difference in exposure to pollutants and other weathering agents. A north-facing column on the east facade of the building receives full sunlight right after sunrise in the summer; however, the south-facing counterpart is shaded until early afternoon. Differences in surface temperature and surface moisture influence the uptake of pollutants by the stone. A pilot study that monitored the surface moisture of columns and antefixae at the Merchants' Exchange documented the variation of the time stone surface wetness varied with orientation and time of day. To further quantify the effects of exposure, a meteorological station was established on the roof of the building. Sensors for air temperature, relative humidity, wind velocity, solar radiation, stone temperature and stone surface wetness have been installed on two columns on the east facade of the building, one facing north and the other facing south (Dolske et al. 1990). Filterpacks systems for measuring the airborne concentration of sulfate and nitrate particles, nitric acid, and sulfur dioxide are co-located with the micrometeorological sensors.

In conjunction with the aerometric monitoring program, washdown samples of soluble surface salts are routinely collected at two columns on the east facade when temperatures are above freezing. Preliminary data indicate that there are distinct differences in stone surface temperature and surface wetness on the north and south columns on the east facade. Variations in the accumulation of sulfate measured at various points by monthly surface washing appear to correlate well with computed sulfur deposition (Dolske and Sherwood 1992). An understanding of atmospheric exposure over the history of the building should result in a better understanding of the differences in marble condition observable today.

Summary

These systematic observations document that variations in marble deterioration result not only from factors such as degree of rain shelter, but are also influenced by position on the building. In this study, it is noted that architectural details on the west facade have been less affected by deterioration than have identical details on the east facade. Along the east facade, deterioration also varies with orientation. These differences have been linked to microclimatic factors and pollutant deposition measured by in situ monitoring. Examination of the deterioration of marble buildings, within the context of the microclimatic factors that contribute to the deterioration, may aid the search for appropriate methods for the protection and preservation of historic marble buildings.

Acknowledgements

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