Marble Weathering in an Industrial Environment, Eastern Australia

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ABSTRACT / Qualitative evidence from monuments and buildings in industrialized countries indicates that rates of stone deterioration rise in the presence of urban and industrial pollutants. Measurements presented here on surface reduction of marble tombstones show that mean weathering rates have increased over the period 1885 to 1955. Weathering rates were lower before the establishment of sulfur dioxide-emitting plants. Marble weathering involved solution etching along grain boundaries and within individual grains, and proceeded by surface roughening and dislodgement of grains with little apparent accumulation of gypsum. Absolute surface reduction of marble was less than that recorded in industrial environments in Europe and North America.

Introduction

The rate of deterioration of materials exposed to the atmosphere increases in the presence of urban and industrial pollutants. Despite greater attention being directed towards the effects of acid pollutants in the environment in the early 1980s (Glass and others 1982; Whelpdale 1983; Environmental Resources Ltd. 1983), the general lack of quantitative documentation of possible materials damage (Henderson-Sellars 1984) has only recently begun to be redressed (for example, Reddy and others 1986; Feddema and Meierding 1987; Jaynes and Cooke 1987; Reddy 1988). Carbonate building and monumental stone is sensitive to the presence of sulfur dioxide in the weathering environment (Gauri and Holdren 1981): surface reduction of marble is greater in urban than in less-polluted rural areas (Winkler 1975) and greater at industrial than residential urban sites (Dragovich 1986). Experiments using field emplacement of limestone blocks support this relative sequence of weathering losses (Gerome-Kupper 1984).

Qualitative observations using photographic evidence documenting the rates of decay of statuary point to an acceleration in weathering rates accompanying industrialization (Winkler 1975, 1977; Amoroso and Fassina 1983; Skoulikidis 1988). Laboratory testing (Luckat 1980) and field monitoring of fresh rock samples (Jaynes and Cooke 1987) confirm that increased sulfur dioxide levels cause greater weathering on limestone and calcareous sandstone; and on-site weathering experiments demonstrate that increasingly acid deposition is associated with more rapid surface recession of marble and limestone (Reddy and others 1986).

Long-term quantitative data are rarely available for weathering rates of building stone in place, because the slowness of weathering usually precludes monitoring of material deterioration over periods of less than several decades. As well, the original position of the rock surface is generally not known. Recent short-term monitoring of limestone weathering on St. Paul's Cathedral, using embedded reference studs and a micro erosion meter, has emphasized the need for caution in interpreting short-term measurements (Trudgill and others 1989). The few circumstances in which long-term quantitative data can be obtained on the decay of building stone thus provide important information on rates of material deterioration in specific environments. In this study, data obtained on marble weathering rates of tombstones were examined for possible changes following a local increase in sulfur dioxide pollution. Any variability in weathering rates caused by aspect and degree of inclination of the stone was minimized by selecting only vertical surfaces facing east.

Methods

Measurements of surface reduction of marble were made on tombstones in a cemetery less than 2 km from the Port Kembla industrial area, which is located on the coast 85 km south of Sydney, Australia. As lead lettering weathers much more slowly than marble, weathering loss from marble surfaces was determined by measuring the height difference between lead lettering and marble. Tombstone inscriptions were assumed to represent the year in which the freshly polished marble was first exposed to weathering. No cleaning of the tombstones had been undertaken, and lawn sprinklers were not used in the cemetery.

All measurements were made with the same instrument and by the one person, on large letters. Only
letters that had no visible growth of lichens or algae or evidence of partial detachment from the marble surface were measured. Lead lettering was assumed to be flush with the marble surface at the time of tombstone emplacement, and no surface reduction was recorded on recently erected stones. Ten measurements were taken on each of 52 east-facing vertically emplaced stones. Possible changes in weathering rates over time were examined by converting values of mean measured surface reduction on each tombstone to 100-yr equivalent weathering rates and then determining if any trend were apparent. Weathering rates recorded on stones emplaced before the establishment of the steelworks in 1928 were compared with rates registered for post-1928 stones.

All tombstones were made from imported Carrara marble, which is generally fine-grained. Loose grains were gently brushed from some surfaces for examination by energy dispersive spectrometry (EDS) and scanning electron microscopy (SEM); and a small sample of fractured marble (collected from a broken tombstone) was embedded in epoxy resin and examined in an electron microprobe.

Results

The relatively uniform reduction of initially polished marble surfaces resulted in minimal visible deterioration in the general appearance of the tombstones. Surface roughening provided the main evidence for weathering loss. The mean 100-yr weathering rate was low (0.23 mm) compared with the 3 to 4-mm loss recorded in polluted atmospheres in Berlin (Beeger 1988). Between-stone variations in weathering loss at Port Kembla were considerable, with rates ranging from 0.14 to 0.69 mm. This occurred despite ten readings being recorded for each tombstone, compared with four to eight (Klein 1984) and nine (Cann 1974) in other studies. The direction of the cut face in relation to planes of weakness in the rock contributed to this variation. On large square tombstones, weathering rates on opposite sides were similar but rates on adjacent faces were different.

Measured surface reduction was greater on older than on more recent tombstones. Least-squares lines were fitted to “pre-1928” and “1928-onwards” data, using 1888 as “time-zero” for the pre-1928 stones, and 1928 for the latter group. The trend of weathering loss showed time-dependence for both groups, but losses in the more recent period were slightly higher than would be expected from projecting the 1888–1927 trend line (Fig. 1).

A least-squares line fitted to 100-yr equivalent weathering rates showed an increase in rates of surface loss over time (Fig. 2). Mean and median values were higher for individual measurements on tombstones with inscriptions dated from 1928 onwards than for earlier stones. Minimum rates were the same for both groups, but data for more recent stones were spread over a wider range (Fig. 3).

Weathering rates were significantly higher in the period since 1928 than before then: 0.29 mm compared with 0.21 mm (Table 1). Data were grouped into approximately 20-yr time periods (1888–1907, 1908–1927, and 1928–onwards), and significant differences in weathering losses were registered between the oldest tombstones (1888–1907) and the most recent group (1928–onwards). Weathering losses from stones with dates in the middle period (1908–1927) were not significantly different from those in the earlier and more recent periods (Table 1). The data demonstrated that weathering rates tended to rise over the entire period (1888–1955) rather than abruptly changing to a high rate.

To check whether marble tombstones in near-ocean but nonindustrial situations also registered increasing weathering rates over time, a group of 31 vertical east-facing tombstones were measured in Sydney. Inscription dates ranged from 1884 to 1955. On these stones, weathering losses were time-dependent and rates were not significantly different before and after 1928 (Mann-Whitney U test).

Only minor quantities of sulfur were found on marble grains brushed from tombstone surfaces when nonquantitative analyses were carried out using EDS. A marble sample examined in the electron microprobe contained two small areas having very minor amounts of gypsum along microfractures within 30 µm of the