The Complexity of Urban Stone Decay

Stone decay has been a part of urban life throughout history. More than 2,000 years ago, Roman architects and engineers wrote about the adverse effects of the elements on their buildings, statuary, and networks of paved roads.

Stone, hewn from rock forged deep within Earth, naturally breaks down at Earth's surface. Regardless of location, dry, semiarid, and humid climates all take their toll on building stone. However, predictable geologic weathering has had major competition over the past 200 years. Since the beginning of the Industrial Revolution, the rate of most types of stone decay has increased dramatically in our cities. Expanding municipalities, climbing populations, and burgeoning factories have had a direct impact on city environments and surrounding areas. Factories — once powered by water or wind — turned to wood-burning, then coal-burning, furnaces to push production and smoke stacks to new heights. The soot and mixture of gases from these factories blackened and corroded the foundations of our cities. We are all familiar with the photographs and paintings of the darkened buildings of 19th-century European and American cities.

Transportation has also had a major impact on the urban landscape. Increased numbers of trucks and cars have spewed vast quantities of noxious gases into city air. Carbon monoxide, ozone, nitrous and sulphuric oxides — all products of automobile and truck exhaust — react to corrode building surfaces when they mix with atmospheric moisture (rain and humidity).

Fortunately, we have recognized the problem and are attempting to remedy the situation. In the United States and much of Europe, strict rules have been implemented to reduce the major problems caused by transportation and industrial pollution. These polluting agents include increased levels of ozone and acid rain that damage the facing stones of buildings, even buildings that are far from a sulfur source. We are still plagued with smaller, yet ubiquitous, problems like the unsightly damage caused to the stone bases of buildings by de-icing salts. Understanding the physical and chemical nature of the problem will help us develop means to maintain the beauty of facing stone.
Stone decay in the urban-industrialized Rhein-Ruhr area of Germany has accelerated since industrialization began about 1850. This sculptured relief of the stoning of St. Stephen was carved about 1130 and photographed for the first time in 1893 (top). Seventy-five years later when it was rephotographed, no images were left.

PHYSICAL PROPERTIES OF STONE

Architects and engineers are interested in the physical properties of building stone. They learn that each major group has a set of characteristic properties that allow them to determine the best stone for a particular project. When choosing a stone type for a project, the most significant properties are rock pores and porosity, water sorption, bulk specific gravity, rock hardness, compressive strength, tensile strength, the moduli of rupture and elasticity, and thermal properties of the rock and constituent minerals. The dry-to-wet strength ratio indicates the expected durability; the ultrasound travel velocity readily correlates with density and strength. Light transmission is occasionally desired for special effects.

Once a decision is made to use a particular stone, architects and engineers must be on guard for the natural deformities of the rock. Brittle rock fracture, such as jointing and faulting, can render an ordinarily durable rock useless. The presence of plumose markings or discoloration along joint surfaces may indicate that a rock has been subjected to internal stresses and groundwater penetration. These stresses can weaken the stone, thus making it a poor choice for construction. No one wants to see signs of deterioration in stone after it has been set into the side of a multistory building.

It is important to know the source of the stone. A quick glance around a quarry will reveal much about the potential behavior of a particular stone. For example, the “tenting” of granite slabs caused by stress-releasing sheeting parallel to the surface can give direct evidence of the future appearance of the granite cladding.

URBAN STONE DECAY

Today we have evidence that stone decay occurs about twice as rapidly in cities as in rural areas. Stone-damaging moisture is generally derived from two sources: acid rain and humidity in the atmosphere, and corrosive groundwater. It is well known that acid rain with varying pH levels can cause accelerated dissolution of carbonates and iron minerals. In addition, rising groundwater, rain-water seepage, and leaky plumbing fixtures are common sources, of damage-causing moisture. Even high relative humidity can push moisture into the narrow capillaries of facing stone. Nor does water work alone. Dissolved salts from obvious sources, such as de-icing salt on sidewalks and roads, as well as from more subtle origins like ocean spray or groundwater seepage, can wreak havoc on stone surfaces by producing a variety of unsightly discoloring, including efflorescence, spalls, and flakes.

Rainwater has always been mildly acidic, with an average pH near 5.6. As rain droplets fall through the atmosphere they absorb many of their constituent gases. This process actively cleanses the air of noxious components. It also changes the chemistry of the rain water.

Domestic heating, as well as industrial and automotive combustion, have produced a large amount of other gases, such as sulfates, nitrates, ozone, and carbon dioxide. The interaction of these gases changes the composition of the atmosphere. The presence of ozone (O₃) tends to oxidize sulfur dioxide (SO₂) to sulfate (SO₄). SO₃ forms sulfuric acid droplets, one of the most corrosive and reactive ingredients in the atmosphere.

A detailed study of the pH distribution of rainfalls in the city of Montreal, Canada, in 1990 recorded ranges from 3.56 to 4.6 — with an average pH of 4.26. Two isolated rainfalls reached 6.9. Minimum values are usually not given but play an important role because such low values accelerate the dissolution of carbonates and ferric minerals like hematite, goethite — and particularly the amorphous hydroxide, limonite (natural rust) — which increases exponentially with acidity. Dust, rich in calcite and transported by winds from the arid and semi-arid Southwest, may have a neutralizing effect on acidity as far away as Montreal. The few extreme incidences of acid rain, however, may be sufficient to dissolve calcite and ferric iron in spite of the
The presence of calcite dust. The broad range recorded for Montreal can be considered typical of most urban areas. It is thus the minimum pH (maximum acidity) that determines the dissolution and transport of carbonates and ferric oxides. While acid rain affects many of the carbonate building stones, a more alkaline rain damages silica-rich stones such as granite.

Moisture in the atmosphere is the only source of entry for water molecules into stone capillaries smaller than 0.1 micron. The $\text{H}^+$ sides of the molecule will attach to the negatively charged sides of the capillaries. Additional water molecules will attach to the negative side of the wall molecules, forming an "ordered" ice-like structure. Such ordered water is considered responsible for the high pressures of moisture expansion. Fine capillaries are characteristic of granite rocks with microcracked quartz, caused by 4.5 percent contraction during cooling from the originally liquid magma. Porosity, moisture content, and rock strength of quartz-rich igneous rocks are closely related to one another. Expansion of liquid water trapped in capillaries larger than 0.1 micron can also be quite destructive.

Moisture in humid atmospheres can cause problems wherever there is an abrupt drop in temperature. Anyone who wears glasses knows the frustrating experience of having them fog up as soon as you step from an air-conditioned building into the moist heat. The same process occurs with stone buildings when warm moist air hits cooler stone. The basilicas of San Marco in Venice and in Pisa are just a few of many examples where granite columns flake near the church entrance because of the condensation of warmer, humid air.

Secondary crust of calcite leached from lime mortar by outward seepage of condensation water along window. White lime crusts contrast well with red, calcite-free sandstone in the Muenster (cathedral) of Freiburg, Germany.
De-icing salt has deeply corroded a base block of gray granite on this building in Chicago. Large flakes above the fretting are caused by the combined effect of porosity by microcracks, relief of locked-in stresses, and crystallization of dissolved calcite from the block of Indiana limestone set above the granite.

Surface water from flooding or rising groundwater can bring corrosive substances into contact with building stone. Liquid water can act as a solvent of the water-soluble grain cements of carbonates, limestone, siderite, marble, and dolomite. Capillary action draws water up from below. A capillary only one micron in diameter can transport water to a height of 10 meters and a length of about 15 meters. In this manner, salts in solution may be transported and will effloresce and corrode the stone surface of buildings far from their sources.

Dissolution, redeposition, and frost action are all potential problems. As the drying powers of sun and wind cause surface moisture to evaporate, moisture in the stone capillary travels to the stone's surface. The stone's inner moisture, in turn, evaporates, leaving the dissolved constituents behind in the form of surface induration and efflorescence. The dissolved material is often derived from the dissolution of grain cement or microscopic salt crusts left behind from previous soakings. The presence of these crusts means that degradation is occurring beneath the stone's surface.

Water is the prime catalyst for stone decay, yet damage can increase exponentially if the water contains dissolved salts. The presence of salts in stone is not always evident, but is more common than we realize. Salts are usually hidden within the stone substance, but often effloresce as coatings that are powdery, white, grainy, and often irregular. Damage can be observed as stones crumble near the ground surface; the decay may become so deep that entire stone blocks have to be replaced. Such salts in urban areas can be of different solubility and sources.

Calcite may be leached from blocks of limestone in mortar and concrete, or by acid rain or condensation water. Later, it is redeposited as secondary external stalagmatic crusts. These deposits are difficult to remove from any stone surface. Limewater dissolved from carbonate stone blocks can seep into a granite base course and deposit calcite in the capillaries of the granite, causing flaking.

Wind-blown mineral dust, with mostly calcite, clay minerals, and silt-size quartz, helps to neutralize acid rain. Urban industrial dust sources often include considerable quantities of iron, which settles on stone surfaces as hematite or limonite or as black iron sulfide after reacting with atmospheric sulfate. Acid rain can "solution-attack" such crusts, carrying iron into mostly pervious sandstones where it readily oxidizes to rust. It is impossible to clean such a stone surface. The Cotta'er sandstone of Dresden, Germany, is encountering this problem.

Even as far away as 200 miles from ocean shores, salts may infiltrate stone as airborne ocean spray. Oceans and inland lakes supply mostly halite, which settles on top of buildings and visibly effloresces on upper stone and brick masonry. The surfaces of many buildings in New York City, for example, are crowned with irregular white salt rings, carried by spray from the Atlantic. Dust blown from desert floors is another source of salt. Rainwater, however, tends to wash much of the soluble salts downward into streams and groundwater.

Surface and underground salts may also originate from excess fertilization of lawns and landscape plants, appearing as mostly residual sodium chloride rejected by vegetation. Capillary action can push these salts to astonishing heights within masonry. The
The deep corrosion in this base course of Indiana limestone is more than 30 millimeters deep. Salt is blocked to below the brickwork (above). Pellets of salt halite lie scattered on this walkway in Chicago.

The least soluble sulfates precipitate near the ground while the less common sulfates settle above. The solubility of these salts determines how high they will rise and precipitate. The chlorides of maximum solubility rise highest.

The concentration of salts can be considerable along irrigation canals in semiarid and arid floodplains and deltas. The Nile floodplain and delta, for example, have accumulated salts by the recycling of irrigation water and excessive evaporation. Such salts have entered obelisks, the Sphinx, and many other ancient monuments in the Egyptian desert, resulting in decay that is often beyond repair.

Today, de-icing salts are most plentiful in urban areas. They are often spread in excessive quantities along roadways and sidewalks. These salts are either crushed halite (NaCl) or more reactive and highly soluble (CaCl₂). Calcium chloride does not crystallize easily in humid climates but remains in solution and attracts moisture from the atmosphere, forming permanently corrosive wet areas instead of efflorescence. The low solubility of halite readily crystallizes and effloresces, causing mechanical dissociation of granites and sandstones near the upper fringe of the salts.

Rock will continue to be a favorite building medium. Its varied textures, colors, and inherent durability make it the choice of architects, civil engineers, and artists. Knowing more about its properties and the effect of natural and human activities on those properties will help us preserve our urban edifices for millennia.

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Additional Reading


