Multiphysics Analysis of Salt-Induced Degradation in Porous Materials

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KEYWORDS: *Salt crystallization, Capillary uptake, Localized damage, Structural masonry*.

Salt crystallization is a primary factor contributing to the deterioration of porous building materials, including masonry, concrete, and natural stone. Salt damage occurs when a porous medium contains both soluble salts and moisture. Dissolved ions, such as chlorides, nitrates, and sulfates, are transported by liquid water through the interconnected pore network via capillary flow. Moisture ingress can result from hygroscopic absorption, rainwater infiltration, condensation, or capillary rise from the ground, the latter being particularly common and difficult to mitigate. Under conditions that promote evaporation or temperature fluctuations, supersaturation may develop, leading to the nucleation and growth of salt crystals within the pore structure.

Salt crystallization can induce surface exfoliation or the development of microcracks due to crystallization pressure. The latter process, referred to as subflorescence, is particularly damaging, as crystal growth within pores generates expansive forces that lead to the initiation and propagation of internal damage within the material.

This paper focuses on the mechanical analysis of the effects of salt crystallization in porous materials, with primary emphasis on structural masonry components. In the first part of the study, inelastic constitutive relations governing deformation in the presence of salt crystallization are presented. Instead of explicitly modeling crystallization pressures, which are difficult to quantify due to complex pore geometry, the approach extends classical rate-independent plasticity by introducing an additional internal variable, viz. the pore volume fraction occupied by crystallized salt, defined as an explicit function of time. Subsequently, a coupled hydro–chemo–thermal framework for modeling salt crystallization in porous masonry materials is outlined. The formulation integrates moisture transport, dissolved salt advection–diffusion, temperature-dependent solubility, and kinetic crystallization laws within a finite element framework. The evolution of porosity and permeability induced by salt precipitation is explicitly incorporated, enabling reliable prediction of transport–crystallization interactions under transient environmental conditions.

Two independent benchmark problems are analyzed first to validate the transport formulation. These involve (i) a cooling–warming simulation focused on the evolution of dissolved salt concentration and crystallization dynamics under cyclic thermal loading, and (ii) the simulation of a drying process that captures evaporation-driven supersaturation and surface-dominated precipitation. The mechanical effects of crystallization are examined by analyzing a masonry specimen subjected to tension parallel to the bed joints. The spatial distribution of precipitated salt obtained from the transport analysis is incorporated into the mechanical model, and the localized fracture mechanism is analyzed by employing a constitutive law with embedded discontinuity. The crystallization effects are introduced through degradation of strength parameters at the brick–mortar interfaces. In addition, another heuristic example is provided, in which a masonry triplet is subjected to a sustained lateral load under a prescribed temporal history of salt deposition. This loading scenario leads to a spontaneous loss of stability of the specimen.