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Strain measurements during capillary water infiltration in porous limestones

Mohamed Ahmed Hassine, Kévin Beck, Xavier Brunetaud, Muzahim Al-Mukhtar *

Univ. Orleans, INSA-CVL, PRISME - EA4229, 8 rue Leonard de Vinci, France

HIGHLIGHTS

- Local strains of limestones are measured during imbibition using strain gauge rosettes.
- Contraction at the height just above the water front induces local tensile stress.
- Tensile stress could generate a crack parallel to the surface exposed to water infiltration.
- Alternating vertical contraction and extension strain could be the origin of spalling.

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ABSTRACT

Building stones are highly affected by environmental conditions. Differential stress/strain due to hydric dilation resulting from water front movements are suspected to be involved in the damage processes of surface decay, especially spalling. The present study investigated the strains that develop at different depths from the surface of limestones submitted to capillary water infiltration. Local strains were measured during water imbibition using strain gauge rosettes whereas global displacement of the sample was measured by a dial gauge. The results show differential strains between the surface and the core of the stone due to water ingress. They demonstrate the existence of a local contraction zone and expansion zone in each direction separately and show clearly the thickness of the surface which can be significantly stressed due to the progress of water in the stone during imbibition. Contraction at the height just above the water front can result in the development of significant tensile stress if the boundary conditions are restrained. This tensile stress, in the order of magnitude of tensile strength, could be the origin of a crack parallel to the surface exposed to rain. This contributes to assess the role of water movements in surface degradation processes.

1. Introduction

The building stones of historical monuments suffer degradation over time. Their physicochemical and mechanical properties change, particularly due to environmental conditions. The methods of investigation focus on durability tests such as aging tests by freeze-thaw cycles [1,2], wetting-drying tests [3], and swelling pressure measurement [4–7]. Walbert et al. [1] concluded that some stones which have a high critical degree of saturation and a high permeability, have a low predicted frost durability. However, while durability tests allow assessing the comparative performance of stones, they may not provide information about the process of degradation of actual surface decay *in-situ*.

Water transfer is considered as the main common factor for surface decay by many researchers [5–10]. Water induces stone decay either indirectly by the transport of pollutants such as soluble salts, or directly by the dissolution of minerals and modifications of stone properties or through freezing and thawing. Moreover, water content changes and water transfer are important parameters causing hydric dilation and changes in mechanical properties. These changes are particularly pronounced when stones contain clay minerals [4,9,10] and have a high porosity [11]. Al-Omari et al. [2,12] demonstrated that the two limestones used in the construction and restoration of the "Château de Chambord" (tuffeau and Richemont stone) are not subject to freeze-thaw degradation *in situ*. Beck and Al-Mukhtar [3] applied 50 wetting – drying cycles over three years and created a patina on the tuffeau surface. This patina modifies the mineralogical properties of the stone and creates non-homogenous behavior with respect to water transfer that could induce deterioration.

* Corresponding author.
E-mail address: muzahim.al-mukhtar@univ-orleans.fr (M. Al-Mukhtar).

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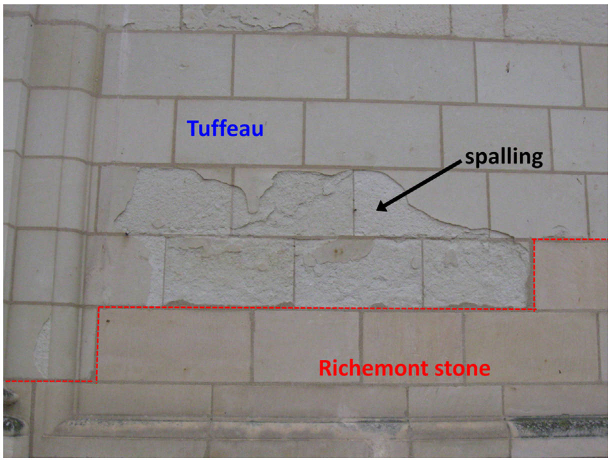

Fig. 1. Spalling of Tuffeau in the wall of the "Château de Chambord" and the replacement stone (Richemont stone).

Surface degradation patterns, like powdering, flaking, and spalling, are common, but their degradation processes are not clearly identified and demonstrated, especially for spalling [13–17]. Spalling can be described as the formation of a crack parallel to the surface of the stone exposed to the environment, generating a plate whose thickness is in the order of 1 cm. This plate eventually flakes off, leaving a powdered surface [16]. This degradation patterns concerns many different materials [15]. Among the different proposed mechanisms for spalling, several researches concluded that differential hydric dilation could be involved in such degradation [7,17–19].

The aim of this paper is to assess local effects in terms of strain and physical properties generated by water front movement could be involved in surface degradation processes of porous limestone. In this objective, we decided to measure the local strain generated in porous limestones during capillary imbibition with water. Studies carried out on stone strain induced by water flow usually consider the studied stone globally by measuring the total displacement and not the local strain. The changes in the stone are often assessed either by global measurements during monitoring (P-wave velocity, elastic modulus, porosity, hardness) or only at the end of the tests applied. This paper proposes to monitor local changes in the stone as the experiment progresses. The originality of the study, therefore, is to measure the strains generated in the stone at different depths during water transfer due to capillary imbibition. The paper presents the results of an experimental campaign applied to two building limestones used in the 'Centre Val-de-Loire' region of France: tuffeau and Richemont stone. They were commonly used for the construction and restoration of cultural heritage buildings in the Loire Valley such as the "Château de Chambord" [2,12,20].. Tuffeau, which is a very porous stone and contains clay minerals, is mainly affected by spalling (see Fig. 1), while no spalling is observed on Richemont stone, a less porous stone with no clay minerals content.

2. Materials and methods

2.1. Materials

Tuffeau is the limestone used for the construction of most of the monuments in the "Centre Val de Loire" region. Thanks to its whiteness, its lightweight, and its softness, it was exploited to build the most sumptuous castles of the French Renaissance along the Loire Valley. Tuffeau has been studied in many previous research investigations [2,13,14,16,21],. This limestone is composed of a major calcite phase (50%), a high siliceous fraction (40%: opal CT and quartz) and a significant clay minerals content (10%: glauconite, smectite, illite) (Fig. 2). Thanks to its high proportion of silica, tuffeau is classified as a silico-calcareous stone. This limestone is very porous (≈45% of porosity), with a bi-modal (first peak at 8 μm; the second at 0.01 μm) porous network [2]. It includes a wide range of pore diameter sizes, from 0.002 μm to 20 μm, with a mean pore diameter of 1.8 μm [2]. The water content at total saturation (w_{sat}: weight of water/weight of solid particles) when the porosity of tuffeau is completely saturated is about 37%. In the 'Château de Chambord', tuffeau limestone is affected by many types of surface degradation such as spalling (see Fig. 1), granular disintegration, flaking and exfoliation [20].

Richemont stone is a monomineralic calcitic stone, less porous and with higher mechanical properties than tuffeau. It was employed as a restoration limestone to replace tuffeau in the 'Château de Chambord' in the early 1950s [20]. This stone is composed of 95% of calcite and quartz (≈5%) (Fig. 2). It is less porous than tuffeau, with a porosity close to 25%. It has a monomodal pore size distribution, with a main peak at the diameter of 2 μm. The water content when the porosity of Richemont stone is completely saturated is about 14%, which is much lower than that of tuffeau. In the 'chateau de Chambord', Richemont stone is only impacted by exfoliation and is reported to be more resistant than tuffeau [20].

The stones of tuffeau tested in this experimental campaign were extracted from the Maquignon quarry in the Vienne department, in the Loire Valley, while Richemont stones came from the Rocamat quarry in the Charente-Maritime department in the Center-West of France.

2.2. Strain measurement and sample preparation

To follow the strain changes in the sample during water capillary ingress, measurements of local strains were carried out in different directions.

In general, studies on construction materials (concretes, rocks, bituminous materials, etc.) use unidirectional gauges. In [22], individual electrical strain gauges were used to measure compression or tensile strain in order to study the level of damage occurring in concrete beams. Pham et al. [23] studied the hydromechanical behavior and water transfer behavior of mudstone in the underground galleries of a nuclear waste storage facility. They measured strains in the axial and orthoradial directions using two independent gauges glued on cylindrical samples of mudstone at hydric equilibrium along the drying–wetting path. Blanc et al. (2015) [24] used two radial gauges placed at mid-height of the specimen, along the circumference and two gauges placed vertically, on opposite sides of the specimen to determine the axial and radial strain on bituminous mixtures. The common aim of all these experiments was to determine the average value of the strain occurring in the sample, and not the local strain.

Another type of gauge, strain-gauge rosettes, is often used in studies of metals to predict residual stress distribution in aluminum alloy forgings [25] or to establish a universal, accurate and efficient fracture criterion for ductile metals [26]. Täljsten [27] used strain measurements with strain-gauge rosettes to determine the strain distribution in the fiber direction over the height of the concrete beams tested. In fact, the anisotropy and local inhomogeneity of natural materials make it difficult to use rosettes to determine and analyze results of local strain.

Only few studies on building stones used strain-gauge rosettes. In the study of Kourkoulis and Ganniari-Papageorgiou [28], they focused on the mechanical behavior and the size and shape-effects for natural building stones. The strain gauge rosettes were antidiametrically glued on two mutually perpendicular diameters at the mid-height of the specimens to enable comparison with results obtained with axial displacement LVDTs. Al-Omari et al. [29] also used strain gauge rosettes for the coupled thermal–hygric characterisation of elastic behavior for tuffeau.

To understand the local alterations of building materials due to water movements, it is essential to determine the local strain measurements in different directions along the exposed stone surface and within the stone. To achieve, these measurements, in all the tests presented here, strain gauge rosettes were used.

The sample preparation method was the same for both tuffeau and Richemont limestones. The stone samples are cylindrical, 40 mm in diameter and 80 mm in height, and were cored in the direction parallel to the bedding plane, i.e. the axis of the stone sample cylinder is parallel to the bedding plane (Fig. 3). This direction was chosen to simulate a real *in situ* imbibition process due to rain on the stonework. For every sample, four strain gauge rosettes were glued on the lateral surface of the cylindrical sample, at different heights: 10 mm (J1); 20 mm (J2); 40 mm (J3); 70 mm (J4). Each strain gauge rosette was composed of three strain gauges, oriented at 0°, 45° and 90° depending on the eigenvectors of the loading, which correspond to the same directions as the axes of symmetry of the sample (Fig. 3). The rosettes were "KFG 120" type from Kyowa and were glued using "CC-35A" glue. The diameter of each rosette is 1 cm. Before testing, the samples were oven-dried at 60 °C during 92 h. Then, they were cooled down in a desiccator with a drying salt that maintains an almost zero relative humidity.

2.3. Mechanical test

Before performing the imbibition test, cyclic mechanical loading tests were conducted to assess the quality of gluing of the strain gauges by controlling the repeatability of measurements. Mechanical tests were also used to control the orientation of the gauges by analyzing the orientation of strain with respect to the eigenvector of loading.