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Critical degree of saturation: A control factor of freeze–thaw damage of porous limestones at Castle of Chambord, France

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ABSTRACT

The paper analyzes the petrophysical and mechanical properties of two porous limestones that were used in the construction and restoration works at the castle of Chambord in France, a UNESCO World Heritage site. The original construction material, the tuffeau limestone with a total porosity of 45 ± 0.6%, and the replacement stone of later restorations, the Richemont limestone with a total porosity of 29 ± 0.7% were subjected to freeze–thaw tests under laboratory conditions to evaluate the role of critical degree of saturation and pore-size distribution in frost damage. Laboratory tests were coupled with in situ measurements of temperature and relative humidity at stone surface at the castle of Chambord. In situ data show that the stones in the castle experienced several freezing–thawing cycles annually. The limestone samples under laboratory conditions were subjected to up to 50 freeze–thaw cycles under eight different degrees of saturations. The total porosity, tensile strength, ultrasonic pulse velocity, the mercury intrusion porosimetry and scanning electron microscopy techniques were employed to analyze the conditions of samples during the cycles. The experimental results show that when the degree of saturation of the two studied limestones exceeds 80–85%, the freeze–thaw, damage occurs even after a few freeze–thaw cycles. The effect of freezing is very fast if the water saturation is sufficient. Moreover, results indicate that these stones have the same critical degree of saturation of about 85%, despite the differences in porosity. Finally, the results indicate that the increase in the number of freezing–thawing cycles has no effect on the critical degree of saturation, but the frost damage is mostly controlled by pore-size distribution rather than by total porosity. Accordingly, critical degree of saturation can be defined as an intrinsic stone property.

1. Introduction

Frost is one of the main causes of the damage in cultural built heritage in cold regions. The durability of stone structures against frost strongly depends on hydro–physico-mechanical parameters. It was demonstrated that intrinsic properties of the stones like total porosity, pore connectivity, pore size distribution, mechanical strength, mineralogy, grain-size, and environmental conditions affect both the stone's durability and mechanism of frost weathering (Mutlutürk et al., 2004; Yavuz et al., 2006; Takarli et al., 2008; Tan et al., 2011; Bayram, 2012; Jamshidi et al., 2013). Most of the previous experimental works dealing with the deterioration of stone under freezing–thawing conditions were performed on fully water saturated samples. However, natural stones are almost never fully saturated. Consequently, in order to understand the mechanisms of stone damage and simulating the real field problems, experiments with stones having various water contents are necessary (Matsuoka, 2001). It was also pointed out that effective microgelivation requires an initial degree of saturation in excess of 80% and it is followed by rapid freezing. However, Matsuoka (2001) also emphasized that rocks can uptake water during slow freezing, and thus, for a frost damage, a high initial water content is unnecessary. The role of porosity in the durability of porous stones have been studied in details taking into account the salt weathering susceptibility (Benavente et al., 2004; Yu and Oguchi, 2010) and pore structure (Benavente et al., 2001). The frost damage of porous materials was also explained by the critical degree of water saturation (Fagerlund, 1977a, 1977b). Sulfate attack is also considered as one of the main causes of damage observed on limestone buildings (Török, 2003; Siegesmund et al., 2007; Kloppmann et al., 2011), however this research focuses on other aspects of limestone decay. This paper provides information on the mechanism of freezing–thawing related to stone deterioration by using the example of the castle of Chambord in France. It uses two approaches: i) the in situ monitoring of stone surface temperature and meteorological data in order to identify the risk of damage by freezing to two limestones, the tuffeau and Richemont, that were used in the construction and restoration of the castle, and ii) laboratory experiments aiming to determine the critical degree of saturation and pore-size distribution that triggers the freezing damage of these two stones. Stones used in the construction of monuments such as

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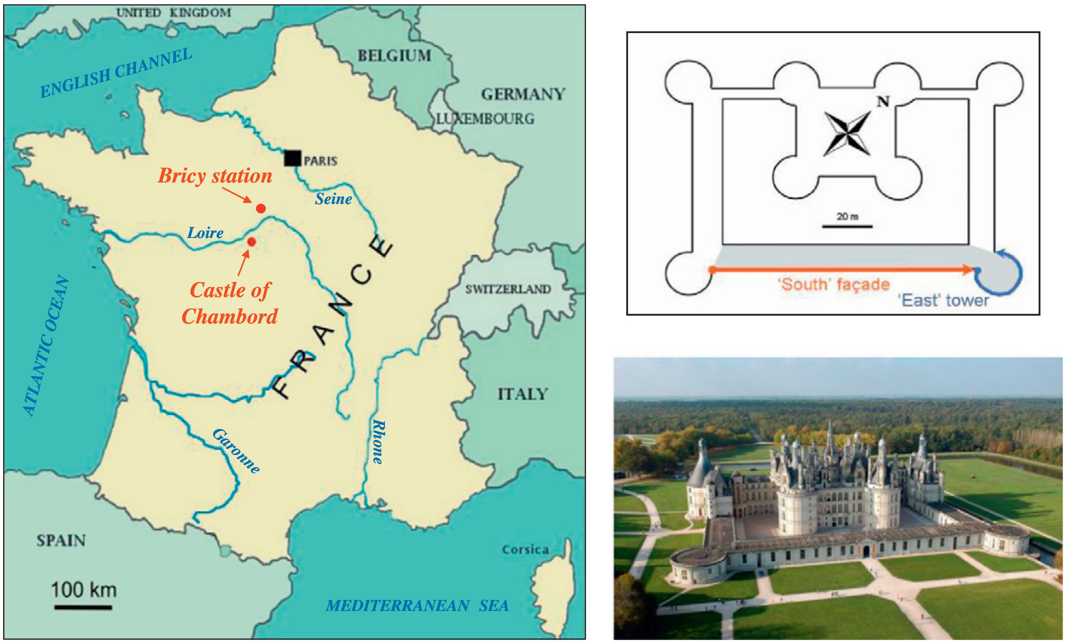

Fig. 1. Map showing the geographical setting of the castle of Chambord and Bricy Air-Base meteorological station (left). Ground plan of the castle showing the location of studied southern façade wall and the east tower (top left, after Janvier-Badosa et al., 2013b). Castle of Chambord-aerial view (bottom left).

Chambord castle can gradually deteriorate over a long period of time in response to the action of water and local environmental conditions. The deterioration in the castle of Chambord belongs to three main categories: biological colonizations (mosses and lichens), spalling (centimeter-thick) and flaking (millimeter-thick). The factors leading to these deteriorations have never been defined precisely.

2. The castle of Chambord and its building stones

The Royal Castle of Chambord at Loire Valley, in France, a UNESCO World Heritage site since 1981 is located in a rural area at a distance about 150 km to SW of Paris, and at latitude of 47°36 N, and longitude of 1°31 E. Its average elevation is about 84 m above sea level (Figure 1). The area experiences a mild humid temperate climate with warm summers and no dry seasons.

The castle of Chambord is the largest castle in Loire Valley (155 m × 115 m) built between 1519 and 1547; and the main building stone used for the construction is tuffeau, a highly porous siliceous limestone with a total porosity of about 45% (Beck et al., 2003). Moreover, there is no place in Chambord where tuffeau is in direct contact with soil, thanks to the systematic use of non-capillary limestone for bedrock. The castle had experienced many restoration works especially during the last century. Accordingly, a lot of the original limestones were replaced. Janvier-Badosa et al. (2013b) mentioned that more than 50% and 28% of the original stones have been replaced on the south façade wall, the main Royal entrance and the east tower of the castle, respectively. Richemont stone, a moderately porous limestone with a total porosity of about 29%, is the main stone used in the restoration works at the walls of the castle. It was used as a replacement stone in between 1953 and 1962. The main stone degradation features at the castle of Chambord were identified as biological colonization, crack formation, and especially scaling of stone in forms of spalling and flaking (Beck and Al-Mukhtar, 2005; Janvier-Badosa et al., 2010, 2013a, 2013b).

According to Bricy Air-Base meteorological station, about 45 km NE to the castle of Chambord, (Figure 1), the recorded data during 1997–2012 (Figure 2) revealed that the mean annual temperature is 11.4 ± 0.5 °C with winter minimum of −16 °C in February and summer maximum of 39 °C in August. The mean annual precipitation is 400 mm with maximums of 47.2 mm per day in summer in August. Therefore, the area under study is subject to high atmospheric temperature range, with daily temperature variations often in excess of 20 °C (Al-Omari et al., 2013).

3. Material and methods

3.1. The studied stones

Two French stones were presented in this study: tuffeau and Richemont stones. Tuffeau is a soft-porous stone and dates from the Turonian age, the upper Cretaceous period, approximately 88–92 million years ago. It comes from the quarries at Tuorain/Anjou close to Loire river (NW France). It is used in many numbers of the castles in Loire Valley-France because of its light weight, special esthetics with shine white and easy to form. Richemont is a fine-grained limestone that has the same geological age as for tuffeau but with higher strength properties. It is obtained from the quarry in Charente-Maritime (W France).

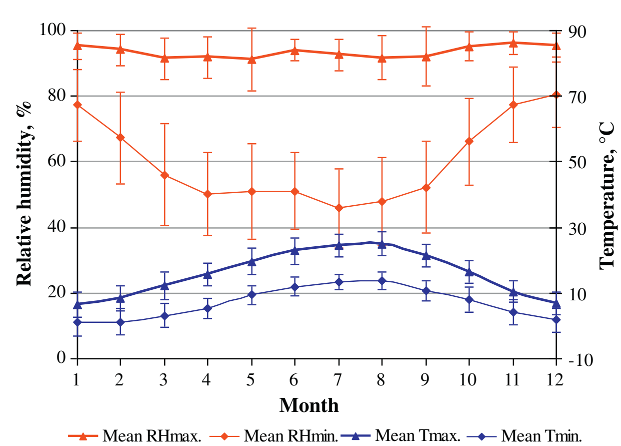

Fig. 2. Monthly variations in the extreme values of mean air temperature and mean air relative humidity for the period 1997–2012.