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Comparative study of deterioration forms on nearby granitic bridges from an urban setting in the NW Iberian Peninsula

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ABSTRACT

Stone coatings, biological colonization, efflorescence and detachments are frequent on granitic surfaces of our cultural heritage infrastructure. In order to find the different origins for each deterioration form, this paper studies and compares several coatings, efflorescence and flakes found on granitic surfaces of bridges from different ages built in the same area (Ourense in NW Iberian Peninsula at 90 km from the sea) under the same environmental and traffic conditions. The most recent bridge was the New Bridge built in the beginning of 20th century and the oldest one was the Roman Bridge with the 1st century AD foundations but its current structure was built in 17th century. The New Bridge has exhibited a greater variety of deterioration forms such as black crusts, carbonate crusts, efflorescence and biological colonization. On the Roman Bridge, black crusts, efflorescence to a greater extent, and flakes associated with salt crystallization processes have been identified. Scanning electron microscopy with energy dispersive X-ray spectroscopy, X-ray diffraction and Fourier transform infrared (FTIR) spectroscopy studies were carried out in order to establish their composition, and optical and electronic microscopies and X-ray microtomography were used to study their morphologies. As a result, anthropogenic factors (industrial activities, traffic pollution and fertilizers) are considered to be the main contributors to crusts, efflorescence and flake formation on both studied substrates (granite ashlars and mortars). To a lesser extent, natural factors (marine influence and bird droppings) should be taken into account.

1. Introduction

As almost all monuments in the NW Iberian Peninsula, bridges are made of granite and exhibit to a greater or lesser extent different deterioration forms, mainly crusts, biological colonization and efflorescence (ICOMOS, 2008; Sanjurjo-Sánchez, 2010). The blackening or greening effects that these deterioration forms have in the structures are far more than an aesthetic problem. The stone will be physically damaged, leading to flaking, scaling and granular disaggregation (ICOMOS, 2008). Hundreds of millions of dollars per year are spent on stone cleaning, stabilizing and replacing those that have been damaged. In order to reduce costs and enable more efficient cleaning results, information about the composition of the different deterioration forms is essential. Previous studies have been developed to identify these deterioration forms, being the scientific production scarcer on granite than on carbonate stones (Prieto et al., 2007; Sanjurjo-Sánchez et al., 2012; Alves, 2010; Sanjurjo Sánchez and Alves, 2012; Rivas et al., 2014).

Black crusts are developed on areas protected against direct rainfall in an urban environment (Brimblecombe and Grossi, 2005; Rivas et al., 2014). They are mainly composed of carbonaceous particles, in which heavy metals are trapped, and gypsum ($CaSO_4 \cdot 2H_2O$) produced by chemical reaction between the atmospheric pollutant SO_2 and Ca (Schiavon et al., 1995; Prieto et al., 2007; Rivas et al., 2014). While for limestones and marbles, Ca comes from the calcium carbonate from the stone (Schiavon et al., 2004; Brimblecombe and Grossi, 2005), in granite the Ca source is not so clear (Schiavon, 2000; Simão et al., 2006; Prieto et al., 2007; Sanjurjo Sánchez et al., 2011; Rivas et al., 2014). Simão et al. (2006) concluded that gypsum crusts were formed on granite surfaces through the calcium from acid dissolution of plagioclases and K-feldspars. Other authors asserted the Ca provenance is from mortars (Rivas et al., 1997, 2014). Sanjurjo Sánchez et al. (2009) identified six types of gypsum-rich coatings on granitic stones in buildings, mostly related with gypsum and calcium carbonate mortars.

Another kind of crusts are carbonate ones, commonly made of calcite in a multiple-layered deposit (ICOMOS, 2008). These calcite layers can be deposited following two different precipitation processes: on the

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one hand, calcite can be dissolved from mortars and then precipitated on the surface (Estrela, 1980). On the other hand, the precipitation can be performed under biological intervention by a range of taxa, from bacteria and archaea to eukarya (Meldrum and Cölfen, 2008).

Efflorescence is made of clear, salt crystals and it is caused by the evaporation of saline water in the joints and pore system of the granite, causing granular disintegration, scales and flakes. Halite, gypsum, niter, syngenite, calcite, aphthitalite, thenardite and epsomite are the most frequently observed salts in deteriorated granite monuments (Coussy, 2006; El-Gohary, 2011; Morillas et al., 2012; Gómez-Laserna et al., 2013).

Regarding biological colonization, bacteria, cyanobacteria, algae, fungi, lichen and plants are the main characters (Sterflinger and Piñar, 2013; Mihajlovski et al., 2015) and their ability to cover the stone surface will be dependent on the bioreceptivity of the stone (Guillitte, 1999).

In the case of buildings and infrastructure, both historical and modern ones, and besides the construction stones, another material to be subjected to study from the weathering point of view is mortar (lime and gypsum-based mortars were used mainly during past times until about two centuries ago and Portland cement-based mortars since the beginning of 20th century). The main component of cement and lime mortars is calcium oxide (CaO) and calcite ($CaCO_3$), respectively, although they can contain impurities due to the original stone composition. Brick, fly ash and lumps from lime kiln or pozzolanic fragments can be used instead of sand as aggregates, reducing the crack formation by drying and giving strength, hardness and porosity to the mortars; they can be coloured in grey, black, brown or yellow (Elert et al., 2002). The dissolution of mortars and the subsequent weakening of their structure starts with the formation of calcium sulphate and calcium carbonate coatings because of the interaction of the mortar with SO_x and CO_2, respectively (Sanjurjo Sánchez et al., 2008). Other gases, such as NO_x, can catalyse these reactions or increase the calcium carbonate reactivity (Sanjurjo Sánchez et al., 2008). This transformation occurs simultaneously with the deposition of air pollution particles in sheltered areas.

Different factors have been identified as contributors in developing the above-mentioned deterioration forms: natural factors (climate conditions, marine influence and natural weathering of granite forming-minerals) and anthropogenic factors (environmental pollution and extraction procedures from the quarry) (Silva et al., 2007; Sanjurjo Sánchez et al., 2011; Sanjurjo-Sánchez et al., 2012; Rivas et al., 2014; Almeida and Begonha, 2015).

The identification of the deterioration forms on granite surfaces and the sources of the components in coatings and efflorescence is essential in order to evaluate their state and to propose techniques for an efficient conservation and restoration management (ICOMOS, 2008).

Considering structures of great importance in the NW Iberian Peninsula, the masonry arch bridges had particular relevance in transport networks through history. In Europe, more than 70% of these bridges date from the 19th century and approximately 12% are from Medieval times or even from the Roman period (Riveiro et al., 2016). Maintenance strategies should be developed in order to keep their incalculable heritage value. The interest of the study centred on the deterioration forms in masonry bridges, particularly in the inner parts of the arches over the roads, is one of the most susceptible structures to deterioration due to the interaction with water, construction materials from the same bridge and the upper parts of the bridges (roads, highways, walkways, etc.) and pollutants. Furthermore, the distribution of the deterioration forms will be related to the distribution of construction materials and the pathways followed by water.

The aim of this paper is to characterize, study and discuss the main deterioration forms developed on two important closely-spaced bridges built with similar granite stones in an urban setting under humid environment, specifically on the inner arches influenced by the high level of traffic. Both bridges have been exposed to the same climatic conditions (temperatures, rainfall and winds) and air pollution levels (the bridges were over the same road). The identification of the genesis factors that have influenced the development of different deterioration forms, considering the type and the spatial distribution of the collected samples, is also discussed. This study provides useful information to design suitable restoration campaigns to remove the coatings and efflorescence but also to eliminate or diminish their promoting factors.

2. Materials and methods

2.1. Study area and selected bridges

Ourense (population 107,000) is an inner city of the NW Iberian Peninsula (Fig. 1A), which has hot summers (up to 40 °C), cold winters (−5 °C) and it is rainy (1200 mm rainfall) (Martínez-Cortizas and Pérez, 1999). The foggy weather during the winter, due to the presence of the Miño river, causes a high environmental moisture. These atmospheric conditions allow the development of deterioration forms in the structures that should have special maintenance to avoid serious problems.

Ourense is split in two parts by the Miño river, which is also crossed by 9 bridges (Fig. 1B). In this area, two bridges, the New Bridge and the Roman Bridge (Fig. 1B), were selected in order to study their deterioration forms. These monuments are separated by only 500 m. Both bridges are surrounded by green parks and cross over the N120 road, which supports heavy traffic flows as it used to be the main connection between Madrid and the Galician coast for years.

2.1.1. The New Bridge (Fig. 1C)

This bridge was inaugurated in 1918. The bridge has six masonry arches and one steel central arch with a span of 75 m. The joint mortar between 80 cm-long granite ashlars is composed of a binder mixed with a fine-grained aggregate. The top of the bridge is dedicated to a road that connects the two parts of the city, as shown in Fig. 1E.

2.1.2. The Roman Bridge (Fig. 1D)

The Roman Bridge is a Medieval walkway bridge built on Roman foundations (1st century AD). The structure was rebuilt, preserving the foundation stones in the 13th century and repaired again in the 15th century. Two centuries later, a definitive reconstruction was applied: the bridge is nowadays 370 m long with seven arched spans, the main span measuring 43 m (Ford, 1878).

Conversely to the New Bridge, most of the joints of the Roman Bridge do not show mortars, except in some points where it is possible to distinguish two types of mortar: a brownish one and a clear one. The top of the bridge is occupied by a pedestrian walkway built with granite cobblestones laid with Portland cement (Fig. 1F).

Therefore, the importance of these bridges results in an urgent need to know the state of deterioration. Once the spatial distribution of decay features is performed, maintenance and control strategies could then be designed.

Both bridges were built with a two-mica coarse- to medium-grained granite. This granite belongs to the alkali granites group, being a common local stone, highly represented in the NW Iberian Peninsula (IGME, 1985). It has an inequigranular texture and it is composed of quartz (31%), plagioclase (24%), muscovite (10%), microcline (27%), biotite (8%) and some accessory minerals (IGME, 1985). Grain sizes range 10–2 mm.

2.2. Sampling

The evaluation of the deterioration forms for both bridges was performed in the masonry arches located over the N-120 road, where the traffic flow is constant (Figs. 2A, 3A). In situ observations have revealed that the New Bridge (Fig. 2) exhibited a great variety of surface coatings: dark and clear crusts, biological colonization and efflorescence. The dark