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Review

Biological colonization and biodeterioration of architectural ceramic materials: An overview

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ABSTRACT

This work presents the first review on biodiversity, biodeterioration and bioreceptivity of architectural ceramics. Literature dating from 1972 to 2014 was compiled and analysed in order to summarise the current knowledge and to facilitate a better understanding of the subject. Data regarding biodiversity found on architectural ceramic materials was described for three typologies: bricks, roofing tiles and glazed wall tiles. A vast biodiversity has been identified on these ceramic materials, from bacteria to more complex organisms, such as plants. Bricks were the most studied substrate, while literature on glazed wall tiles was scarce. The highest biodiversity was found on bricks, may be due to the fact that this was the most studied typology. Several works regarding the colonization of ceramic roofing tiles by lichens were found in the literature, which led us to realise that this is a topic that arouses the attention of several researchers. Photoautotrophic microorganisms found on glaze wall tiles represented a considerable biodiversity in this ceramic typology, with many genera in common with those identified on bricks and roofing tiles. Nevertheless, in the searched literature, different methods had been used to identify and characterize the organisms. This made the comparison of the global biodiversity found on these substrates difficult. Architectural ceramic materials exposed to outdoor conditions are often affected by biodeterioration. This worldwide problem can cause aesthetical, physical and chemical damages on ceramic materials. The distinct biodeterioration processes occurring on the different substrates found on architectural ceramic materials are explained in detail. The relationship between the ceramic intrinsic properties and bioreceptivity was discussed. Porosity and surface roughness seemed to play a major role in bioreceptivity to colonization. Ceramic microstructure has a strong influence on the resistance to biodeterioration. Finally, the authors come to the conclusion that there are many gaps in the knowledge, especially concerning glazed ceramics, and thus, further research was proposed.

1. Research aims

The main goal of this work was to perform a comprehensive overview of biological colonization and biodeterioration of architectural ceramic materials. The most common ceramic elements used in worldwide built Cultural Heritage were analysed: bricks, architectural sculptures, roofing tiles and glazed wall tiles. In addition, this manuscript strives to enlarge understanding of the main biochemical and biophysical damages of both unglazed and glazed ceramic substrates. By analysing the current literature, this work also highlights the significant gaps in knowledge on this issue, bringing to light future research topics, which are essential for the development of treatment and preservation measurements for ceramic materials.

2. Introduction

Architectural ceramics as building materials are used in the construction and ornamentation of architectural work being applied in masonry, roofing, cladding and ornamentation. Buildings and monuments with ceramic elements, whether in the form of bricks, wall and roofing tiles, architectural statuary or floor tiles can

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Fig. 1. Biological colonization of the unglazed and glazed ceramic elements of a garden bench situated in the historical centre of Sintra (Portugal).

be found throughout the world. This work deals with the biological colonization and biodeterioration of architectural ceramic materials, more specifically, traditional ceramics (clay-based), such as bricks, roofing and wall tiles. Utilitarian ceramic objects and technical ceramics are not considered. A significant number of architectural ceramic materials are part of our cultural heritage and therefore ought to be preserved since they have historical and artistic value. Fig. 1 illustrates microbial discoloration of glazed and unglazed ceramic elements of a garden bench in the historical centre of Sintra (Portugal).

The use of ceramic as a building material dates back to antiquity and has continued throughout history until present. Their selection for construction purposes has been motivated by questions of durability, availability, workability, cost, speed and appearance. Workability, cost and speed play a crucial role in the use of ceramics when compared to stone, owing much to the ease and economy of forming raw ceramic materials. Sun-dried clay bricks were used for construction, but with the passage of time, these started to be fired to enhance their resistance. The use of these fired ceramic bricks in buildings construction started in Egypt around 5000 B.C. and later spread to Europe during the Roman Empire [1,2]. In turn, the use of ceramic tiles as roofing materials started in China around 1500 B.C. [3]. Although glazes can be found on roofing tiles and bricks, they are most common on floor and wall tiles. Their usage began in the ancient Egypt around 3000 B.C., later spreading to the Near East and then to Europe [4,5]. Due to Islamic influence, glazed wall tiles gained great importance in Portugal, Spain and later in Brazil, being typical today of these countries' built cultural heritage [4].

Traditional ceramics are simply made of clay mixed with water, which are then shaped during the forming process. Subsequently, the material is air-dried and fired for permanent hardening. The composition, texture and porosity of the resulting ceramic body depend on the raw materials composition and their granulometry, and affected by the firing temperature and cycle to which they were subjected.

Some ceramics are complemented with a coating: an engobe or a glaze. The engobe is a coloured coating of fine-grained clay that is applied over the ceramic body to reduce surface roughness. The glaze consists of a vitreous coating, also applied over the surface of the ceramic body, to enhance mechanical strength. It is composed of a crystalline phase embedded in a glassy matrix, formed by the melting of the raw components during firing. This coating is impermeable and is usually very smooth. Glazes, as glass, can have a variety of colours, textures and glosses [6]. For this reason, the use of glazed ceramic elements in architecture has a strong aesthetical intension, and more than just colour, wall tiles are often made with illustrations of great artistic and historical value.

A wide range of raw materials and compositions can be used for the production of ceramic bodies, engobes and glazes, such as clay minerals (e.g. kaolinite, illite), quartz, feldspars, carbonates, silicates and oxides [7]. Ceramic production, from forming until the final coating application, can indeed involve a wide variety of methodologies, from traditional methods, such as manual forming, to more complex technologies, such as extrusion or pressure forming, which are nowadays used in industry [7].

Generally, ceramic deterioration, like in other building materials, is dependent upon the characteristics of the substrate (e.g. mineralogical composition, porosity surface roughness), environmental agents (e.g. wind, sunlight, temperature, rain, relative humidity), microclimatic conditions (e.g. local urban geometry, building design or adjacent materials), atmospheric pollution and biological colonisation. These factors can induce physical, chemical and biological decay on the architectural ceramic materials. Several studies have been performed concerning mineralogical, chemical and physical characteristics of ceramics used in construction, as well as the factors and mechanisms leading to their physical and chemical deterioration (e.g. [8–18]). Overviews of weathering and pathologies of roofing materials have been performed by Berdahl et al. [19] and Garcez et al. [20]. Likewise, Yiu et al. [21], Silvestre and de Brito [22] and Silvestre and de Brito [23] have described the most common decay factors affecting this architectural ceramic typology.

Biological decay or biodeterioration, defined as "any undesirable change in the properties of a material caused by living organisms" [24], has been reported as a very common phenomenon on outdoor ceramic materials (e.g. [25–39]). Despite being described, few studies have been performed focused on the identification of colonising microorganisms and their damages on ceramic materials, in comparison to studies on other building materials, such as stone (e.g. [27,40,41]).

The occurrence of biodeterioration is dependent on the presence of organisms on the materials. The susceptibility of a given material to colonization by organisms is based solely on its intrinsic properties and was defined by Guillite [42] in a concept called bioreceptivity. This author subdivided this concept in three types: primary bioreceptivity, as the intrinsic potential of a material to suffer biological colonisation; secondary bioreceptivity, as the ability of an altered material, changed over time by physical and chemical agents, to be colonised; and tertiary bioreceptivity, as the potential of biological colonisation of material altered by human hand (e.g. after a conservation treatment).

The biological communities present on an inorganic substrate are usually the result of successive colonisations by different organisms through time. The colonization process can be described as starting with the less complex organisms (e.g. bacteria, cyanobacteria, algae, fungi) to the more complex ones (e.g. mosses and plants [40,43]). Ceramic materials can be colonized by different organisms, such as bacteria, fungi, algae, cyanobacteria (or blue-green algae), lichens, mosses (bryophytes) and plants.

Today the important role of organisms in the deterioration of cultural heritage building materials is well established [44–48]. Nevertheless, control and mitigation methods for these biodeterioration processes are still far from being solved. Yet, there is a consensus regarding biodeteriorogens identification and knowledge of biodeterioration mechanisms as crucial steps for any conservation and restoration intervention of biologically colonized assets [49]. Regarding biodeterioration of architectural ceramic materials, there is no literature review on this subject making it a very difficult topic to study. In fact, the data regarding this subject is scattered and difficult to access. Therefore, it is urgent to make