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Translucent marbles for building envelope applications: Weathering effects on surface lightness and finishing when exposed to simulated acid rain

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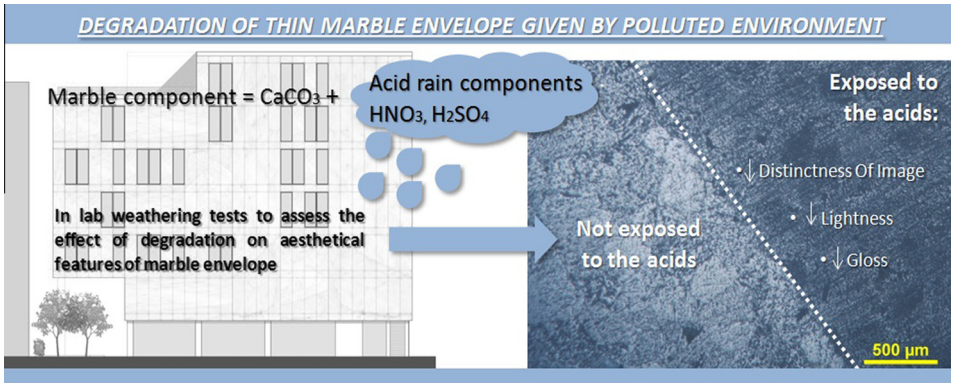
HIGHLIGHTS

- Two white marbles are considered to analyze their degradation due to acid rain.
- Aesthetical characteristics are investigated: color, gloss, Distinctness Of Image.
- Degradation caused statistically significant characteristics' modifications.
- Degradation caused color to darken.
- Degradation caused decrease both in Distinctness Of Image and gloss values.

GRAPHICAL ABSTRACT



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ABSTRACT

Marble thin panels are widely used for external building envelope application, due to their original light transparency effects during day-time and night-time. Considering their application in polluted environments and the interaction with aggressive agents, the aesthetical characteristics of this element could be compromised by degradation processes. To investigate such changes, experimental ageing test analyzing the effects of acid rain aggression on different marble samples is carried out in this research. Marbles' reactions are studied in terms of: lightness, gloss, and Distinctness Of Image. The main findings demonstrate how the acids hugely degrade both the marble typologies and quantify the modifications.

1. Introduction

Marble has traditionally been employed as massive construction element, even if some examples of marble and alabaster

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employed as light transmissive elements could be find in historical constructions (i.e. Greek and Roman buildings, III sec. A.D.). However, this kind of applications is increasingly taking place nowadays. Marble is cut in thin layers, also letting the light pass throughout the element itself, resulting in translucent surface. Recent valuable buildings use this technology as external envelope, and have a unique and distinctive aspect, strongly characterized by this bond between stone and light: some examples are the Christ Pavilion, built for the Expo 2000 of Hannover (by Von Gerkan, Mara and Partners); King Abdullah University of Science and Technology Library (Towel (Saudi Arabia), by HO + K Architects); Caja De Ahorros, located in Granada (Spain) by Alberto Campo Baeza; Cathedral of Our Lady of The Angels (Los Angeles (USA), by Rafael Moneo); Stone Museum (Nasu (Japan), by Kengo Kuma); Beinecke Rare Book and Manuscript Library (New Haven (USA) by Skidmore, Owings and Merril); Notre Dame de La Treille (Lille (France), Pl. Carlier and P. Rice); Church and Parish Center (Meggen (Switzerland) Franz Fueg).

Marble is a natural and precious material but it is often considered to be a traditional one, limited by its weight and its usual application in thick and heavy panels. However, the technology here analyzed could bring marble in competition with more modern and versatile materials also allowing the light passage, such as glass and u-glass. The surprisingly mutation (opaque during day, translucent at night for an external viewer), characterizing the façade covered with translucent marble technology, is even more vivid thanks to its veins, which are different on every panel and let the architecture be more alive, compared to the u-glass ones which produce a more uniform and industrial result. Additionally, further advantages coming with the application of white marble translucent envelope consist of its natural *cool* behavior due to its high solar reflectance, decreasing the indoor energy requirement for cooling and thermal comfort conditions in summer, as well as other strategies, namely green or cool roofs [1,2]. These features are crucial given the worldwide attention on energy saving and the large amount of energy consumption coming from the building sector [3]. The energy performance of light colored stone natural materials has already been considered in previous researches [4,5], confirming the benefits it brings to the building. Users' visual and thermal comfort perception of such materials as building components or urban paving has been assessed in [6]. However, these advantages come up beside some problems. Studies proved [7–9] that marble is sensible, through the years, to the environment. In fact, its main component calcite reacts with acids dissolved in the air [10]. Therefore, loss of material and change in color could affect the surface of the marble layer due to pollution [11,12], UV radiation [13] and freeze–thaw thermal cycles [14]. Usually, the degradation imputable to acid rains is a process that takes centuries, but in the last decades the upcoming urban anthropic agents, and therefore pollutants, strongly fastened such progressive damaging [15]. Especially considering the aggressive environment of big cities, this problem could compromise the durability and the aesthetical value of the architectures.

Considering the previously mentioned preciousness of the marble, especially when produced in thin layers, the associated cost in maintenance or replacement could affect its competitiveness versus other less expensive materials such as glass and u-glass. Furthermore, considering that marbles are identified in terms of colors and technical performances, the characterization of marbles in terms of resilience to degradation and aesthetical performance is crucial for the optimal selection of the specific type of marble in metropolitan areas and it consists of the motivation of this work.

Previous studies were focused on materials degradation due to the environment [16,17] and mostly on acid aggression [18–20]. However, even though marble reaction in general was analyzed [21–26], translucent marble was not explored in terms of resilience to degradation and aesthetical performance, while it is considered for thermal responses [27] and integrated thermal-energy analysis [4]. Regarding aesthetical performance of marbles in general, Careddu et al. [13] and Ozcelik et al. [14] studied the aesthetic parameter of gloss connected with UV and degradation caused by freeze–thaw cycles. Urosevic at al. [9,17] took in account colorimetry while studying stone decay caused by marine aerosol ageing.

In this panorama, the twofold purpose of this paper is (i) to quantify by means of experimental in-lab studies, the change in key optic characteristics of two types of white, thin marbles, i.e. *Bianco Carrara* and *Statuario*, for external envelope application, and (ii) to statistically compare the measured characteristics of the two marbles, for investigating the aesthetical decay caused by acid environment degradation with varying marble typology and, as first assumption, resistance to degradation. The comparison will support the marble building designers while selecting the most suitable materials for urban applications, from both aesthetical and technical points of view. The degradation assessment will be quantified via (i) lightness, (ii) gloss and (iii) Distinctness Of Image (DOI) variations. Therefore, the present research has relevant implications both for industrial producers and designers of buildings. In fact, the necessity to consider also the material resistance to urban pollutant agents as key choice parameters is showed in this work, as direct consequence of the experimental analysis performed in this work.

In this view, the research questions this work is aimed at answering are: (i) how strong is the degradation caused by polluted urban environment on thin marble envelope by mean of aesthetical changes? And (ii) which type of the considered marbles has a better performance within the acid environment, which one is more resistant to the aggressive environment, and then more convenient to use for this aim?

2. Materials

Two types of fine white marble are considered for comparative purpose. The chosen marbles are visually similar and almost completely white. Both the marbles come from Apuan Alps (Italy). The selected marbles are *Bianco Carrara* marble, addressed as BC (Fig. 1(a)), and *Statuario* marble, addressed as S, (Fig. 1(b)). They both are mainly composed of calcite, $CaCO_3$, with small impurities in a shape of veins. *Bianco Carrara* marble is white, with fine gray flecks and veins and it is fine grained (~30 μm). *Statuario* marble is a milky white, with few gray-brownish veins marble and it is medium-fine grained (~50 μm).

3. Research questions: hypotheses testing

(1) Are aesthetical changes on thin marble surface significant, given the degradation due to aggressive-polluted environment?
   - Hypothesis 1 (H1): the degradation is expected to be statistically significant, given the chemical interaction between main marble component and pollutants. Regarding both lightness and gloss measurements (gloss and DOI), a significant decrease of surface lightness, shininess and specular reflection is expected [13,14], given the corrosion of the external polished surface; this is expected to cause a loss of material and consequently a more irregular and corroded finishing.

(2) Is there going to be a significant difference between the two marbles' interaction with acids, regarding aesthetical degrade?
   - Hypothesis 2 (H2): the two chosen marbles are similar in color, grain size, connected porosity, water absorption at atmospheric pressure. However they are not identical: BC has slightly smaller grains, higher porosity, more veins