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Validation of an inspection and diagnosis system for anomalies in natural stone cladding (NSC)

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ABSTRACT

Based on a proposal for a classification system for anomalies and their probable causes in natural stone cladding (NSC) an inspection plan was developed for recent buildings with anomalies in this type of cladding, to validate the system. This field work generated data from 59 buildings whose cladding exhibited various anomalies, in a grand total of 288. A specific area of Lisbon city (Portugal) was selected for most of the inspections: The Parque das Nações – an urban area that was regenerated for the Expo'98 World's Fair. Based on these inspections, a comparative analysis was performed on various surfaces clad in this material, i.e. pavements versus walls and indoor versus outdoor applications. The resulting data underwent a statistical analysis and post-treatment, providing conclusions that could lead to actions to prevent degradation of this type of cladding and its substrate, with the aim of achieving a better quality and less costly built environment.

1. Introduction

Natural stone is currently generally used more for cladding walls and pavements than as a structural material. Technological and scientific evolution has been important for this type of cladding, leading to an increase in the use of stone and to innovative products being launched on the market, a wider scope of application, easier manufacturing of non-standard sized elements (e.g. thinner) and new methods to place and fasten stone cladding plates.

To obtain better results, construction using natural stone cladding (NSC) must be founded on scientific, physical and economic criteria, i.e. the process starts with an appropriate and demanding prescription, based on factors such as the properties and quality of the materials, the location of the cladding and the conditions the stone material is subjected to throughout its service life. Good practice manuals have been produced by Winkler [30], Lewis [15], Cohen and Monteiro [6], Chacon [4], Siegesmund et al. [21], Hooker [14], and Donaldson [8], as well as the Marble Institute of America [16] and the American Society for Testing and Materials [2].

However defects that arise in NSC often belie the expectations of a cladding which should perform well and be durable. In fact pathological situations in natural stone cladding have been occurring more often, especially in the first service years. This may be due to lack of selection criteria and ignorance as to what stone to apply, a merely economic comparative analysis of materials, overly tight schedules, lack of education and awareness on the part of the technicians involved at the design and execution stages, non-specialized workmanship, stone type unsuited to the surrounding environment, technical ignorance and exclusive consideration of aesthetics. The frequent lack of coordination among speciality designers and other actors on site results in omissions or incompatibility of the various elements of the prescribed solution (e.g. the fastening system and the substrate) that are detected only at the execution stage. Omissions in the tender specifications also contribute to anomalous final results and undesired, sometimes serious, defects.

Technicians from various countries have helped to combat this by studying NSC durability in sets of buildings in various locations. The purpose is to understand and explain the defects by testing and evaluating the characteristics of NSC, and by performing risk analysis and predicting service life in order to improve the safety and trustworthiness of the cladding. One such study is the TEAM EC Project [26] that studied around 200 buildings, mostly with marble and limestone cladding, in order to further understand the durability of this stone cladding.

Within this context, and taking into account the investment required later for maintenance and repair of the built heritage, it is essential to create, calibrate and disseminate tools that may be useful to planning an appropriate maintenance strategy for natural stone cladding.

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As part of the requirements for a Master's dissertation [18], an innovative set of tools has been created to back the inspection and diagnosis of natural stone cladding (NSC) on walls and pavements. Inspections can be systematized and made objective and could be included as part of a maintenance plan to prevent degradation of the cladding and its substrate.

Correlation matrices were built based on data on anomalies and their probable causes: anomaly-cause; inter-anomaly; anomaly-diagnosis methods and anomaly-repair techniques. Furthermore, files with data related to each type of anomaly, diagnosis method and repair technique were put together [19]. The matrices put together before most inspections were made were then calibrated after extensive field work (inspection of 128 NSC in 59 buildings) backed by inspection and validation files, thus validating the system. A statistical analysis of the data collected in the inspections campaign was then performed and various interesting conclusions were drawn concerning the pathological phenomena that may occur in NSC and the actions needed to prevent its degradation and that of its substrate. The purpose of this paper is therefore twofold: show how the expert system was validated and present and comment upon the statistical data acquired during the validation process.

Along similar lines, Silva [22] completed a Master's dissertation on the service life prediction of NSC on walls and defined a degradation path and a reference service life for it [23].

2. Pathology and classification system

The most important causes of anomalies in wall and pavement NSC are related to the responses of stone to external actions, its mineralogical and physical–mechanical characteristics, the fastening system used, atmospheric agents, design and execution errors, and the care taken after installation (maintenance and cleaning).

The difficulty of establishing cause-effect relationships (given the variety of anomalies observed) jeopardizes the determination and evaluation of the anomalies' causes based on their manifestations and consequences. For the sake of systematization and objectivity a classification system is proposed for anomalies and their causes. It is based on the expert literature, the inspections carried out and the experience of the authors, all of which made it possible to class each anomaly in a specific group and then identify its direct and indirect cause(s). This information was the basis for building matrices that provide the degree of correlation between anomalies and their causes and also the relationship of each anomaly with the others. Though beyond the scope of this paper, the classification system also comprises the classing of diagnosis methods and repair techniques and their corresponding correlation matrices with the anomalies.

This global classification system and its tools have been detailed in another paper [19], and have proved extremely useful to backing up NSC inspection work within an integrated maintenance strategy. The system has the same general architecture as that proposed for other materials and elements [3] – road bridges; [10] – epoxy floors; [24], 2010 – ceramic cladding; [27] – roof waterproofing membranes; [9] – gypsum plasterboards; [20] – gypsum plasters).

2.1. Anomaly classification

The NSC anomalies' classification proposed here classes them in 7 families and 18 subfamilies, based on visual observation criteria, i.e. without *in situ* or laboratory tests.

Within the seven groups identified in the field work there are the anomalies located in the cladding plate, i.e. related to the stone itself and changes to its characteristics, and three groups related to anomalies in the cladding system, which includes the stone plate, the joints and the fastening elements (Table 1), inspired in related literature [13,1]:

- A-A: Color change.
- A-F: Fracture and cracking.
- A-B: Presence of biological or other agents.
- A-P: Loss, volume change or deterioration of the stone.
- A-DE: Loss of adherence or loosening of the stone plate.
- A-JU: Joint defects.
- A-Fi: Defects in the fastening elements.

Some of the anomalies mentioned as being located in the stone plate may in the medium-term contribute to the anomalies cited as being located in the cladding system (e.g. fracture of a plate may contribute to partial or total loosening of a cladding element). But loosening may also have been caused by scaling in the areas where the metal fastening elements are fitted.

Each anomaly detected during the *in situ* inspections was evaluated in terms of its severity/intervention urgency level, according to the following criteria:

Table 1
NSC defects classification [18].

Location	Groups	Sub-groups	Description of the manifestation
Stone plate	A-A	A-A1	Stain or difference of color shade
	Color change	A-A2	Peripheral chromatic change
	A-F	A-F1	Fracture
	Fracture and cracking	A-F2	Cracking
	A-B	A-B1	Biological colonization
	Presence of biological or other agents	A-B2	Vegetation
		A-B3	Other organisms/materials
	A-P	A-P1	Volume decrease of the stone (laminar spalling, wear, granular disaggregation, pulverization, pitting, cavities)
	Loss, volume change or deterioration of the stone	A-P2	Alteration or deposition (surface deposit, efflorescence, film, concretion, crust)
		A-P3	Partial lacuna in the stone
Cladding system	A-DE	A-DE1	Loss of adherence of the stone element (partial or total)
	Loss of adherence or loosening of the stone plate	A-DE2	Loosening of the stone element (partial or total)
		A-DE3	Flatness deficiencies of the cladding surface
	A-JU	A-JU1	Degradation or loss of joint filling material (partial or total)
	Joint defects	A-JU2	Non-linearity or inappropriate design of the joints
		A-JU3	Cracking or fracture of the stone element near the joints
	A-Fi	A-Fi1	Scaling of the stone near the fastening spots and/or corrosion of the metal fastening elements
	Defects in the fastening elements	A-Fi2	Bending and rupture of the metal fastening elements