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Deterioration Patterns of Stone Claddings under Standard Conditions and Marine Environment

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Abstract

Building facades are exposed to degradation processes because of the direct exposure to various environmental impacts. Severe service conditions such as marine environment can drastically accelerate the deterioration of stone cladding. The objectives of the study were, as follows: exploring the typical deterioration patterns of the exterior natural stone cladding implemented by wet and dry fixing and estimating the predicted service life (PSL), in course of the exposure of cladding to the impact of the standard and marine environments. Although the dry fixed method has recently become highly ubiquitous in the modern building practice, no studies have yet investigated the effect of fixing technique on the durability and service life expectancy of cladding. The research method is based on a systematic evaluation of the visual and physical performance of the components during their life cycle. 87 data points were collected and classified by a type of cladding and the service conditions. Regression analysis and prediction intervals were used for statistical analysis. The results clearly indicate that the type of fixing technique plays a crucial role in the rate of stone cladding decay in both standard and marine environment. The results have also integrated the data provided by material scientists and geologists on the mechanisms of stone deterioration, as a function of stone type, service conditions and the effect of the contact between stone and the Portland cement mortar. It could be obviously observed that the PSL of the dry-fixed stone cladding is ~ 1.3 – 1.6 time more than in case of the wet fixed technique, in both standard and marine environment, with the upper limit of 60 year service life of the dry-fixed cladding exposed to the standard service conditions. This study provides useful information for designers, construction and facility management decision-makers and for effective planning of preventive maintenance plans.

Keywords: double skin facades; maintenance; marine environment; natural stone claddings; service life prediction.

1. Introduction

During their life cycle, exterior finishes of building facades are exposed to several environmental agents which cause the deterioration process starting as soon as the exterior finishes are implemented. Especially for the buildings located along the seashore, the degradation process can be drastically accelerated [1] because of the extremely aggressive offshore environment [2]. In fact, marine salt solutions penetrating the material can crystallize and cause high pressure resulting in cracking and spalling [3, 4].

Various types of the exterior finishes are used in the modern construction. Stone claddings are especially common thanks to their expected high durability. The method of stone fixing seems to play an important role in their long-term durability [4]. Dry fixing (Double Skin Facades) in natural stone claddings is a relatively new cladding method characterized by a cavity space between the facade layers. This fixing technique has nowadays become widely used worldwide thanks to their acoustic and energy efficiency [5], as well as their suitability for tall buildings. However, no studies have investigated the long term durability of cladding implemented by this technique. The main disadvantage is the much higher construction cost compared to the traditional wet fixed stone cladding.

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The current research follows the outlined methodologies set forth in previous studies implemented on renders, ceramic claddings and wet fixed stone cladding under standard service conditions [6 - 8].

2. Background

The Reference Service Life (RSL) of building components reflects the expected service life that a building or its components are expected to endure under a certain set of service conditions. ISO 15686-1 [9] has established the methodology for estimating RSL and this topic has attracted a growing interest worldwide as evidenced by the related international codes and regulations [10, 11].

Previous studies have reported the results of extensive fieldwork based on visual observations (empirical method) of the component performance of exterior finishes subjected to the different service conditions [8, 12]. In addition, during the last decade several studies were carried out using accelerated laboratory tests (minero-petrographic and chemical analyses; physical tests of porosity; hydric tests and durability; mechanical tests, etc.) [13, 14, 15], to simulate the natural weathering of stone claddings in standard conditions or marine environment. Although these studies provide some insight into the relationships between the micro-and macrostructure of stone and its deterioration, they are time and resource consuming. Consequently, statistical and probabilistic service life prediction methods provide a means to analyze the fieldwork collected data at different levels of complexity resulted from the concurrent analysis of multiple degradation factors [12, 16, 17].

Simple regression analysis has been used extensively to obtain the deterioration patterns that fit to the data points collected in the field, and to determine the average rate of degradation over time. The degradation level of each observed building component could be calculated as an average of the visual and physical performance values [6-7]. A prediction interval is used for the statistical evaluation of errors associated with the assessment of the predicted service life (PSL) of a building component at given age. Gaspar and de Brito [18], Galbusera [19], and Bordalo [20] made use of regression analysis. Silva et.al [21] examined the degradation process in 142 buildings with natural stone claddings directly adherent to the substrate.

Based on the same concept as simple regression analysis, multiple regression analysis enables the analysis of the relationship between more than two independent variables [22] as used by Silva et.al [12, 23], to predict the service life of building components. The report by Silva et al. [24], revealed the following variables to be responsible for the degradation of stone claddings: a) a distance of less than 5 km from the seashore was the most unfavorable; b) type of finishing: where a carved finishing was more prone to degradation than smooth and polished surfaces; and c) the size of the stone plates where larger stone plates were more vulnerable to mechanical deformation and, consequently, to degradation because of their larger dimensions and weight.

3. Objectives and Method

The objectives of the study were, as follows: exploring the typical deterioration patterns of the exterior natural stone cladding implemented by wet and dry fixing and estimating the predicted service life (PSL), in course of the exposure of cladding to the impact of the standard and marine environments. The research method is based on a systematic evaluation of the visual and physical performance of the components during their life cycle, based on the method described in [6 – 8].

3.1. Standard service conditions

The method used here for evaluation was developed in [6]. It is an empirical practice used for assessment of the degradation curve of building components and their consequent service life and is based on the direct observation of building components exposed to the same service conditions at different ages. The first step consists of the evaluation of the physical and aesthetical performance of building components according to systematic rating scales, as illustrated in Tables 1 and 2.

Table 2. Physical rating scale, Shohet and Paciuk [12]

Rating	Description of features
20	Significant portions of the cladding have peeled or fallen off. Cracks wider than 5mm have been developed.
40	Cracks wider than 1 mm have been developed on 5% or more of the cladding area. Portions of stone cladding have fallen off.
60	Cracks 0.5 mm wide cover less than 5% of the total cladding area. Up to 3 % of cladding elements have fallen off.
80	Capillary cracks have been developed on portions of cladding. Single cladding elements have fallen off.
100	Cladding is complete and undamaged. No cladding elements have fallen off. Some capillary cracking may be present.

Table 3. Visual rating scale, Shohet and Paciuk, [12]

Rating	Description of features
20	Significant portions of the cladding are missing or incomplete. Cracks have been developed on the cladding surface.
40	Damage is localized. Microorganisms have colonized over one third or more of the cladding.
60	Cladding surface is not uniform due to physical damage or discoloring.
80	Cladding surface is not uniform due to minor cracks, detached tiles, microorganisms or alterations in cladding color.
100	Cladding surface is undamaged and uniform (no visible cracks or missing elements and no discoloration).

This process gives a value for the component performance (CP) that ranges between 0 and 100 grading points, depending on the average of the aesthetic and physical performance state (100 = absence of any defect or failure, 40 = comprehensive failure). The performance score describes the symptomatic effects of deterioration caused by the interrelationship of several factors with the service conditions and the durability of the components. The typical deterioration patterns (TDP) of the building components can be derived by implementing regression analysis on the curve of the observed CP values plotted against the age of the building component used as the independent variable. These results represent the average degradation over time of the particular deterioration mechanism under analysis. Furthermore, the prediction interval enables an evaluation of the statistical errors associated with the assessment of the service life expectancy of future observations. The prediction intervals were established at 0.8 level of significance, as recommended by ISO 15686-1 (2011) [9].

Analysis of the typical deterioration patterns enables estimating the service life of building components at different levels of desired performance. The intercept between the typical deterioration patterns and a curve representing the minimum required component performance (MRCP) can be used to deduce the life expectancy (LE) [12]. Two levels of MRCP were considered [6, 7, 8, 23], as follows:

(1) MRCP = 60%, in cases where a high level of CP is required, i.e., in public or corporate buildings;

(2) MRCP = 40%, in cases where the owner of a building decides to minimize maintenance costs while compromising the quality.

It should be noted that this method is valid if only one specific agent of decay affects the building components. In order to calculate the life expectancy under exposure to multiple agents, this process must be reiterated for each of the deterioration mechanism studied.

The predicted service life interval (PSLI) is determined from the intercepts between the MRCP curve and the lower and upper boundaries of the computed prediction interval. This represents the time interval for which a (1-α) probability exists and a future life expectancy (LE) for the required CP can be established. In the same manner, the (1-α) predicted component performance interval (PCPI) can be deduced from the intersection between the component's age and the lower and upper boundaries of the computed prediction interval. In this case it reflects the possible error in predicting a future CP at a given service age.

3.2. Intensive service conditions

The standard service conditions determine the life cycle of building components subjected to normal weathering conditions without any severe aging hazards or intrinsic defects (e.g., poor quality of materials, faulty design, poor workmanship, etc.). The intensive and failure service conditions reflect the typical agents of deterioration, leading to premature degradation of exterior claddings. In this context, marine environment can be considered severe service conditions. This manuscript presents the typical deterioration path for the decay mechanism prevailing in marine environment, calculated for a sample of wet and dry-fixed stone claddings. The expected effect of this particular mechanism on the estimated service life of a building components (ESLC) can be estimated based on the life expectancy limited coefficient (LELC) [6,7,23], as presented in Eq.(1):

$$LELC = 1 - \left(\frac{SLE - LEDP}{SLE} \right) * IC \qquad (1)$$

Where,

LELC is the life expectancy limiting coefficient for the specific decay mechanism (for example, marine environment).

SLE is the standard life expectancy.

LEDP is the life expectancy of the deterioration path determined for the particular decay mechanism.

IC is the influence coefficient. IC values range between 0, for degradation agents that have no effect on the ESLC, and 1, for agents that have a strong impact. IC is determined empirically by experts. In the current study, where premature degradation was caused by an exposure to marine conditions, IC was taken to be 1, reflecting the high level of stone cladding vulnerability.

4. Results

Extensive fieldwork was performed in order to effectively model the evolution of stone cladding degradation over time. A total of 87 tall and high-rise (more than 4 floors) buildings with exterior stone claddings were graded and further categorized by the method of fixing technique and exterior service conditions. All the degradation paths of cladding techniques under analysis were found to fit linear patterns with different deterioration rates and regression coefficients, R^2, between 0.74 to 0.90, demonstrating a high level of significance. Three different scatter diagrams were carried out, as follows: (1) dry-fixed under standard conditions, (2) dry-fixed exposed to marine environment and (3) wet-fixed exposed to marine environment. The buildings in the sample exposed to marine conditions were located in close proximity to the seashore (less than 400 meters), taking into account the local breeze regime. Dry-fixed stone cladding is relatively new technique for external finishing in Israel, and has only been used on a large scale since approximately 1985. For this reason there is limited availability of data for this technique for buildings older than 30 years.

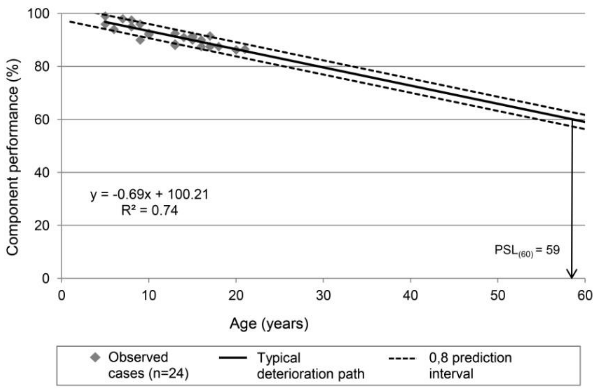

Figure 6. Deterioration pattern of wet-fixed stone cladding under standard conditions

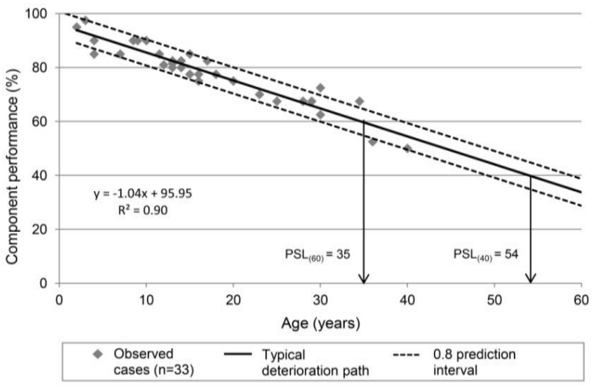

Figure 2. Deterioration pattern of wet-fixed stone cladding exposed to marine environment

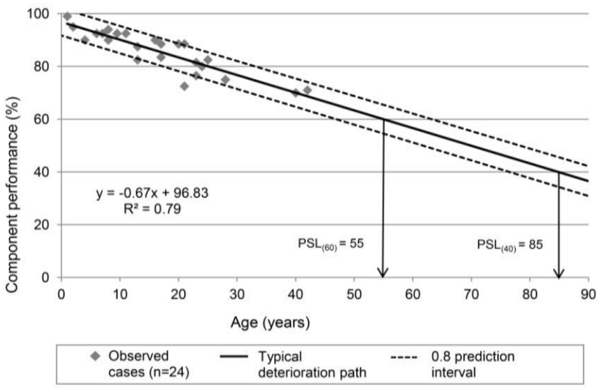

Figure 7.Deterioration patterns of dry-fixed stone claddings exposed marine environment

Table 3 summarizes the reference service life, PSLI and PCPI of wet- and dry-fixed stone claddings exposed to the different environmental conditions analyzed. It could be obviously observed that the PSL of the dry-fixed stone cladding is ~ 1.3 – 1.6 time more than in case of the wet fixed stone cladding, in both standard and marine environment, with the upper limit of 60 year service life of the dry-fixed cladding exposed to the standard service conditions.

Table 3. Predicted service life (PSL), Predicted service life interval (PSLI) and Predicted component performance interval (PCPI) of wet- and dry-fixed stone cladding

Service conditions	Wet-fixed		Dry-fixed	
	Standard	Marine environment	Standard	Marine environment
Predicted service life MRCP60%	44	35	59	55
Predicted service life MRCP40%	64	54	88	85
Predicted service life interval* MRCP60%	39 – 50	30– 40	55 – 63	47 – 63
Predicted service life interval* MRCP40%	59 – 70	49 – 59	84– 92	76 – 93
Predicted component performance interval*at life expectancy of MRCP60%	52– 69	55 – 65	57 – 63	55 – 66
Predicted component performance interval*at life expectancy of MRCP40%	32 – 49	35 – 45	38– 43	34 – 46

*p = 0.80 (p – statistical probability)

The LELCs concerning the impact of the marine environment on the predicted service life (PSL) of wet and dry-fixed stone claddings were, as follows: (1) 0.79 - 0.84 for the MRCP of 60% and 40%, respectively, for wet fixed technique, and (2) 0.94 – 0.97 for the MRCP of 60% and 40%, respectively, in case of the dry-fixed technique. These data reveal the main differences in the impact of marine environment on the performance of two fixing techniques under discussion.
Based on these results, the impact of the exposure environment can be calculated according to Eq. 2, as follows:

$$EF_{A-B} = \frac{1 - LELC_A}{1 - LELC_B} \qquad (2)$$

Where

EF_{A-B} – environmental factor coefficient for the two alternative fixing techniques *A* (Wet-fixed) and *B* (Dry-fixed).

$LELC_A$ and $LELC_B$ – Life Expectancy Limiting Coefficients for Wet and Dry-fixed stone claddings, respectively. According to the values of LELC abovementioned, EI_{A-B} for $MRCP_{60\%}$ and $MRCP_{40\%}$ are 3.5 and 5.3, respectively. These values indicate that the impact of a marine environment on deterioration of wet-fixed stone cladding is 3.5 to 5 times higher than on dry-fixed stone cladding.

5. Discussion and Conclusion

The results reported in Table 3 clearly indicate that the fixing technique had a strong effect on the rate of exterior cladding decay. Dry-fixed stone claddings were characterized by a longer service life under both standard conditions and marine environment. On the contrary, wet-fixed cladding, which had already manifested a higher rate of decay than the dry-fixed one in both environments, also showed a strong impact of marine environment on the predicted service life (PSL). These findings could be explained by the differences in the fixing technique of the stone to the background wall. The stainless steel anchors used in the dry-fixed technique are specially designed and controlled in the industrial manufacturing process. Therefore, they are able to improve the quality and reliability of the dry-fixed connection. Hard limestone, marble and granite used for the dry-fixed stone cladding, are characterized by low water absorption and are more resistant to marine environment than porous sedimentary stones [24]. The deterioration mechanism in wet-fixed stone cladding is mostly related to the effect of Portland cement mortar on stone. Natural stones are highly vulnerable to the impact of Portland cement mortars (PCM), which can be attributed to the high pH > 12 of the mortar and high humidity level maintained at the back surface of stone plates. These conditions lead to the formation of limonite (rust) crystals which cause opening of stone veins and, consequently, cracking of limestone and sandstone containing the secondary iron minerals [24]. High humidity levels behind the stones prevent the passage of air and lead to cycles of hygric expansion and shrinkage [*ibid*].

The current research contributes to a better understanding of the impact of marine environment on the performance of exterior stone claddings. The main causes of stone cladding deterioration were explored and quantified in years, in terms of Predicted Service Life. These results can be assimilated in maintenance planning and for decision making related to the design of single and double skinned stone facades.

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