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Expected service life of natural stone wall cladding

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Extended abstract

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1. Introduction

This dissertation falls within the research field developed by Gaspar (2002), Sousa (2008) and Gaspar (2009), of service life prediction of constructions. This research field is extremely important, as it will result in more rational use of construction materials, and is a useful tool for defining pro-active maintenance plans, bringing not only improved performance to those materials, and as a result a longer service life, but also reducing urgent repairs and, therefore, associated costs.

2. Expected service life theories

2.1. The service life concept

A building's life cycle is defined by Gaspar (2002) as the continuous process of degradation from the moment it is built. Gaspar also states that this process has a slow and practically imperceptible evolution at the start, but that it accelerates as time goes on during use.

Service life is defined according to ISO 15686 (Service Life Planning) as the period of time after construction in which the building and its materials equal or exceed the minimum performance requirements. In accordance with the amendment proposal drawn up by the Higher Council for Public Works (2004), the RGE (General Regulation on Urban Construction) defines a building's service life (BSL) as the period in which a structure's materials do not undergo wear as a result of environmental conditions which compromise its initial structural safety. Throughout their service lives, buildings undergo various kinds of wear which ultimately lead to the end of that service life. Gaspar (2009) defines the end of a building's service life as the point in time in which it is no longer able to safeguard the activities held within it, due to factors which are not always objective and quantifiable. The end of a building's service life may occur through functional obsolescence, lack of economic viability or physical wear of its key materials (Gaspar, 2002). Moser (1999), on the other hand, claims that the end of service life is dependent on functional, safety or aesthetic criteria. This limit is hard to define as it depends substantially on the demands of each individual.

The service life of constructions may however be prolonged through regular maintenance (Flores (2002), Takata et al. (2004), Donca et al. (2007)). Maintenance has a strong influence on buildings' life cycles, and is necessary when the building's condition changes due to wear (physical service life) or the demands of society (functional service life) (Takata et al., 2004).

Durability is another extremely important concept, which is sometimes confused with that of service life. According to Silva (2001), service life may be seen as the quantification of durability which is taken as being only one quality of the structure.

3. Description of natural stone

Natural stone was formed a very long time ago and is greatly varied in its characteristics, even within the same kind of stone, which is a factor in stone cladding's degradation. Therefore an evaluation of its mechanical, physical and chemical characteristics is needed to use it correctly in building works.

To work effectively over its service life, natural stone cladding requires certain factors to be taken into account. The location of the building with this cladding is perhaps the most important factor, as it determines the choice of stone and fixing type. The selection of materials must be done carefully as well, to cope with a diversity of situations. The choice of finishing is made essentially on aesthetic grounds; however, that choice may affect the resistance and durability of the natural stone, and should therefore be made to suit the intended purpose.

3.1. Description of anomalies

The main anomalies in natural stone wall cladding fall into four distinct groups:

- Aesthetic anomalies;
- Joint anomalies;
- Fixing anomalies;
- Integrity loss.

As a general rule, the aesthetic anomalies affect the look of the cladding and do not present a risk to stability. These are the most common anomalies, and are present in most stone cladding.

However, the joint anomalies describe situations in which the cladding joints do not perform their job adequately, for various reasons. These anomalies may also lead to the occurrence of other anomalies.

The fixing and integrity loss anomalies are the most serious. The first kind undermines the cladding's safety requirements. The second affects the natural stone, and repairs are always noticeable, contributing to the cladding's visual deterioration.

3.2. Main causes of the anomalies

Identifying the likely causes of cladding anomalies on existing buildings is fraught with countless difficulties, since in the majority of cases, the anomalies arise from a combination of factors, which may occur simultaneously or follow each other over time. The main causes of anomalies may be grouped into human action, environmental action, or accidents.

Human action is one of the main causes of anomalies, either due to inadequate design and execution of the cladding, use of inadequate materials or solutions, or vandalism. In some cases, human inactivity can also be a cause. Periodic maintenance is an essential process for cladding's durability.

On the other hand, environmental action is partly responsible for degradation. This action may be physical, chemical or biological. Finally, accidents are unpredictable, and may have natural (earthquake, storms, floods) or human (explosions, fire, flood, collisions) origins.

4. Field work

4.1. Definition of levels of degradation

Several scales of degradation have been developed, to create expected service life models for construction materials. Shohet and Paciuk (2004) created a degradation scale for external cladding with five performance levels, from 0 to 100, where 100 represents a cladding without defects or signs of flaws. Gaspar (2002) and Gaspar and Brito (2005) have already defined five degradation levels in the specific case of coatings, in which **level 0** signifies no visible degradation and **level 4** shows generalised degradation. More recently, Sousa (2008) used a similar methodology for the expected service life of ceramic cladding of façades, defining four groups of anomalies, allocating degradation levels to them based on the research performed previously.

In this current analysis, a methodology analogous to that followed by Gaspar (2002), Gaspar and Brito (2005) and Sousa (2008) is used. Thereby degradation levels were defined for each anomaly group according to the extent of the area of cladding affected. Within each group, the anomalies were prioritised according to their seriousness, which led to degradation level definitions (Table 4.1 to 4.4).

Table 4.1 - Definition of degradation levels for aesthetic anomalies

Degradation levels	Description of anomalies	% area of natural stone cladding (NSC) affected
Level 0	No degradation visible	-
Level 1 *Good*	Surface dirt	> 10%
	Moisture signs Localised marks Colour changes	≤ 15%
	Smoothness flaws	≤ 10%
Level 2 *Slight wear-and-tear*	Moisture signs Localised marks Colour changes	> 15%
	Biological growth Parasitic vegetation Efflorescence	≤ 30%
	Smoothness flaws	> 10% and ≤ 50%
Level 3 *Moderate wear-and-tear*	Biological growth Parasitic vegetation Efflorescence	> 30%
	Smoothness flaws	> 50%

Table 4.2 - Definition of degradation levels for joint anomalies

Degradation levels	Description of anomalies	% area of NSC affected
Level 0	No degradation visible	-
Level 2 *Slight wear-and-tear*	Degradation of the material	≤ 30%
	Loss of material – open joint	≤ 10%
Level 3 *Moderate wear-and-tear*	Degradation of the material	> 30%
	Loss of material – open joint	> 10%

Table 4.3 - Definition of degradation levels for fixing anomalies

Degradation levels	Description of anomalies	% area of NSC affected
Level 0	No degradation visible	-
Level 2 *Slight wear-and-tear*	Fragmenting of the stone element in the area of the fixings and edges Partial gap in the stone component	≤ 20%
	Torsion and twisting of the metal components Corrosion of metal components	≤ 10%
Level 3 *Moderate wear-and-tear*	Fragmenting of the stone element in the area of the fixings and edges Partial gap in the stone component	> 20%
	Torsion and twisting of the metal components Corrosion of metal components	> 10%
	Detachment Unfastening	≤ 10%
Level 4 *Generalised wear-and-tear*	Detachment Unfastening	> 10%

Table 4.4 - Definition of degradation levels for integrity loss anomalies

Degradation levels	Description of anomalies	% area of NSC affected
Level 0	No degradation visible	-
Level 1 *Good*	Degradation of the material ≤ 1% of the thickness of the panel	-
	Degradation of the material ≤ 10% of the thickness of the panel	≤ 20 %
	Cracks ≤ 1 mm in thickness	
Level 2 *Slight degradation*	Degradation of the material ≤ 10% of the thickness of the panel	> 20%
	Degradation of the material > 10% and ≤ 30% of the thickness of the panel	≤ 20 %
	Cracks ≤ 1 mm in thickness	> 20%
	Cracks > 1 mm and ≤ 5 mm in thickness	≤ 20 %
	Fragmentation	≤ 5 %
Level 3 *Moderate degradation*	Degradation of the material > 10% and ≤ 30% of the thickness of the panel	> 20%
	Degradation of the material > 30% of the thickness of the panel	≤ 20 %
	Cracks > 1 mm and ≤ 5 mm in thickness	> 20%
	Cracks ≥ 5 mm in thickness	≤ 20 %
	Fragmentation	> 5% and ≤ 10 %
Level 4 *Generalised degradation*	Degradation of the material > 30% of the thickness of the panel	> 20%
	Cracks > 5 mm in thickness	
	Fragmentation	> 10%

A convenient system was established to evaluate cracks' thickness in inaccessible parts of the cladding; this system evaluates crack thickness by measuring the distance at which these may be detected without the use of binoculars.

5. Degradation models

In terms of the models adopted, Gaspar (2002) set out degradation level 3 as the end of the service life for coatings; in this dissertation, the same criterion is adopted, thereby assuming that stone cladding with a degradation level of 3 or above have reached the end of their service life, and are not fit to carry out the role they were designed for. Therefore generalised repairs are necessary to re-establish the characteristics essential to its proper performance.

In this dissertation, the models proposed by Gaspar (2002) (2009) were used; the first was seen as inappropriate when applied to the specific case of stone cladding; the second on the other hand brought satisfactory results, which are used to describe degradation evolution.

5.1. Degradation indication according to Gaspar's model (2009)

Gaspar (2009) proposes the indicator *S*, which designates the severity level of the degradation of façades, normalised to a benchmark area of the façade. In this dissertation, it was decided to calculate the degradation severity through the ratio between weighted size of the cladding and the maximum level of possible degradation, as indicated in the formula **(5.1)**, due to the differences in degradation levels adopted between coating and stone cladding. This ratio brings a variation of the severity level for cladding degradation of between 0% and 100%; an easily understandable indicator.

$$S_{w,rp} = \frac{\Sigma(A_e \times k_n \times k_{a,n}) + \Sigma(A_j \times k_n \times k_{a,n}) + \Sigma(A_f \times k_n \times k_{a,n}) + \Sigma(A_i \times k_n \times k_{a,n})}{A \times \Sigma(k_{\max.})} = \frac{E_w}{E_{w,\max.}} \quad \textbf{(5.1)}$$

Where:

S_w - severity of cladding degradation, expressed as a percentage;

A_e - area of cladding affected by aesthetic anomalies, in m^2;

A_j - area of cladding affected by joint anomalies, in m^2;

A_f - area of cladding affected by fixing anomalies, in m^2;

A_i - area of cladding affected by integrity loss anomalies, in m^2;

k_n - multiplication factor for n anomalies, as a function of their degradation level (k varies between 0 and 4);

$k_{a,n}$ - weighting coefficient according to relative weight of the anomaly detected; $k_{a,n}$ takes the value 1 in case of lack of any specification;

A - total cladding area, in m^2;

$\sum(k_{max.})$ - sum of the weighting constants equal to the highest level of degradation of cladding with area A; this sum takes the value 14 (3+3+4+4 – aesthetic, joint, fixing and integrity loss anomalies, respectively);
E_w - the cladding's weighted degradation level;
$E_{w, max.}$ - the cladding's maximum weighted degradation level.

Gaspar (2009) evaluated two scenarios for determining degradation indicators: in a first (benchmark), he assumed all anomalies take on equal importance ($k_{a,n}$ = 1) and, in a second, he allocated weighting coefficients according to the seriousness of the anomalies. The second scenario supplied values closer to reality. In other words, it supplied degradation indicators that better reflected the real degradation of the façades inspected.

Thus weighting coefficients were defined through the seriousness of the anomalies, and this was influenced by various factors, such as the fulfilment of minimum requirements, their propensity for originating new anomalies, or their repair cost (Table 5.1).

Table 5.1 - Parameters affecting the weighting coefficient estimation

Anomalies	Performance criteria Requirements		Likelihood of originating new anomalies	Repair cost	Average weighting coefficient $k_{a,n}$
	Safety	Waterproofing			
Aesthetics	○○	●○	●○	15%	0,15
Joints	●○	●○	●●	60%	0,6
Fixings	●●	●●	●●	120%	1,2
Integrity loss	●●	●●	●●	100%	1,0

○○ - no correlation; ●○ - correlation likely; ●● - high correlation

Special significance was given to anomaly repair costs in defining weighting coefficients. These costs were assessed by means of the bibliography and through contact with companies and price simulators, with an effort to adjust the model to the current state of affairs in Portugal. Thus, a weighting coefficient scale could be drawn up based on the repair costs for each anomaly group (Fig. 5.1). These costs relate to the cost at the time at which the repair is needed, not accounting for the evolution of that cost over time.
After defining all the degradation indicators and the weighting coefficients for the different anomaly groups, the different degradation indicators required matching; this correspondence was made based on Gaspar's model (2009), with the values adapted for stone cladding - Table 5.2.
As mentioned above, level 3 was taken as the service life limit; thus, the cladding with degradation above 20% are taken as having reached the end of their service life; the definition of this limit, as mentioned above, is not clear; however, from the physical point of view, it is an acceptable limit.

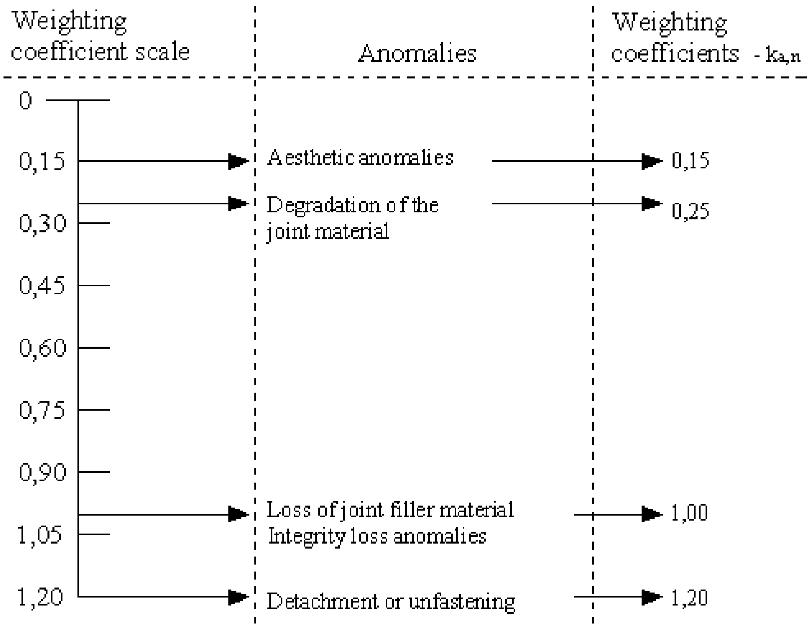

Fig. 5.1 - Weighting coefficient scale based on the repair costs of each anomaly type

Table 5.2 - Correspondence between the degradation indicators

Degradation levels	Severity
0	$S_{w,rp} \leq 1\%$
1	$1\% < S_{w,rp} \leq 8\%$
2	$8\% < S_{w,rp} \leq 20\%$
3	$20\% < S_{w,rp} \leq 45\%$
4	$S_{w,rp} \geq 45\%$

By calculating the degradation in 120 cases researched, the degradation evolution could be plotted over time (Fig. 5.2).

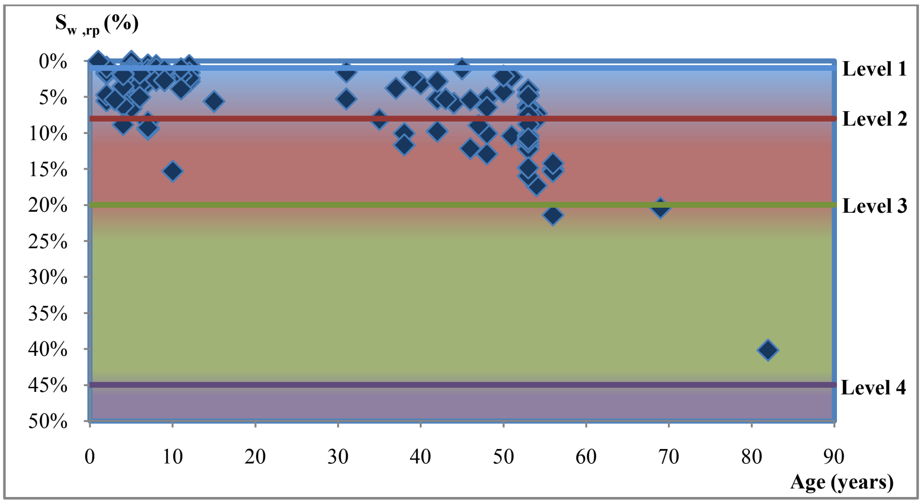

Fig. 5.2 - Distribution of degradation in 120 cases researched with relative weighting between anomalies and definition of the degradation levels

5.2. Degradation curves

The degradation curves obtained from the data collected in the fieldwork express the behaviour of the stone cladding over time. These degradation curves were obtained through a linear regression, in which a base 3 polynomial line is adjusted to the point cloud created by the cases researched. In this case, the degradation curve obtained is an 'S'-shaped line, which indicates a tendency to tolerate early anomalies, which apparently set in over time but create accelerated degradation in the terminal phase of its life.

Four main situations were analysed: the first relating to the 120 cases researched (Fig. 5.3); the second relating only to cladding over 5 years old (outside the warranty period) (Fig. 5.4); the third with cases located in Parque das Nações excluded (cases located less than 1 km from the sea and which show a high degree of degradation in an early phase of their lives) (Fig. 5.5); and, finally, an analysis only of cases fixed directly to the support (Fig. 5.6); the correlation produced satisfactory results, improving the degradation curves from the first to the final analysis.

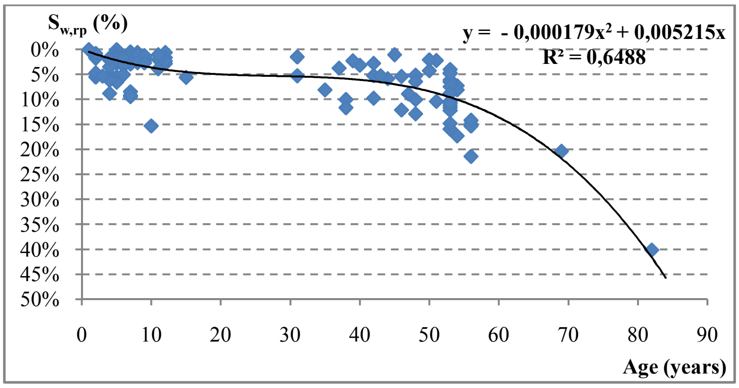

Fig. 5.3 - Degradation curve obtained from 120 cases analysed in the fieldwork

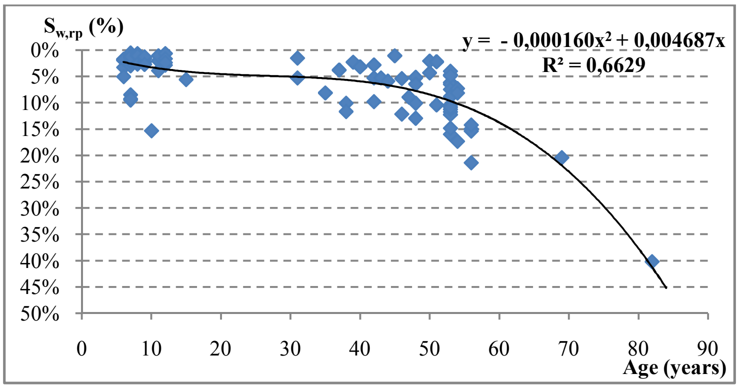

Fig. 5.4 - Degradation curve obtained for cladding more than 5 years old

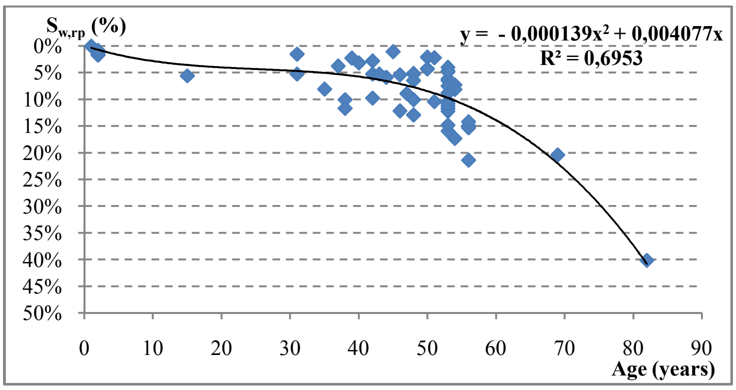

Fig. 5.5 - Degradation curve obtained omitting cases located in Parque das Nações

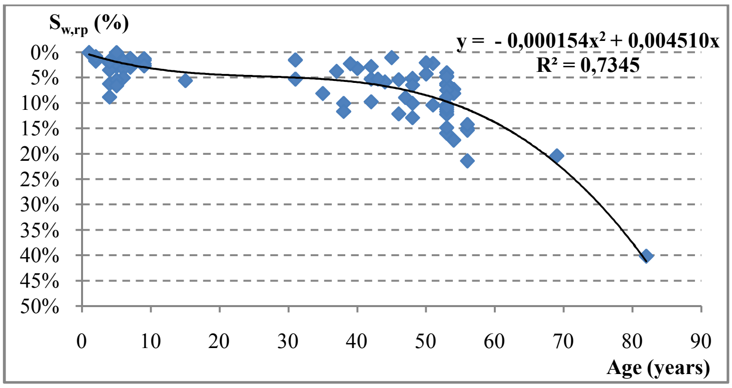

Fig. 5.6 - Degradation curve obtained only for cladding fixed directly to the support

To extend the research, further cladding characteristics were analysed that influence the evolution of the degradation (Fig. 5.7 to 5.11); reasonable correlation values were obtained in some cases; however, due to the low sample size, some caution should be exercised regarding their statistical significance.

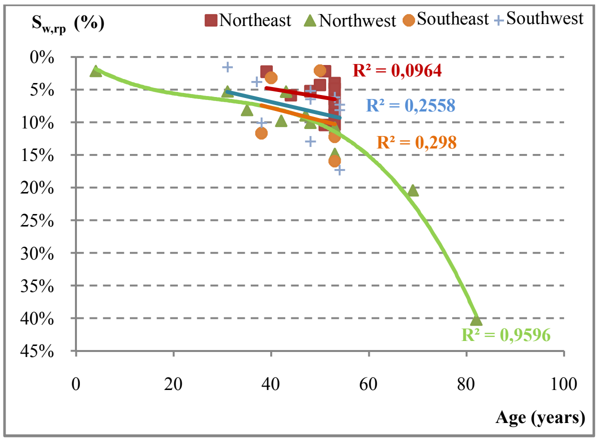

Fig. 5.7 - Degradation curves according to the façade alignment

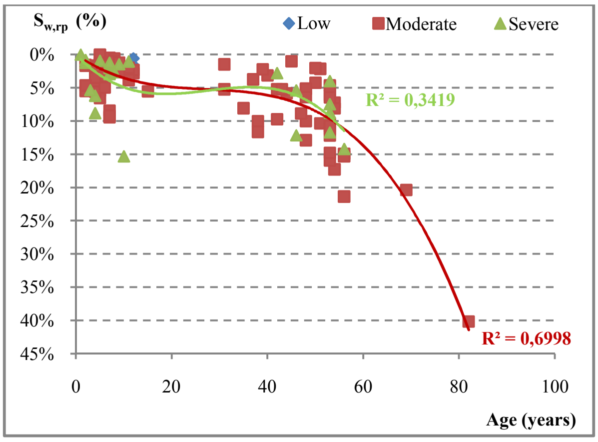

Fig. 5.8 - Degradation curves according to exposure to wind/rain action

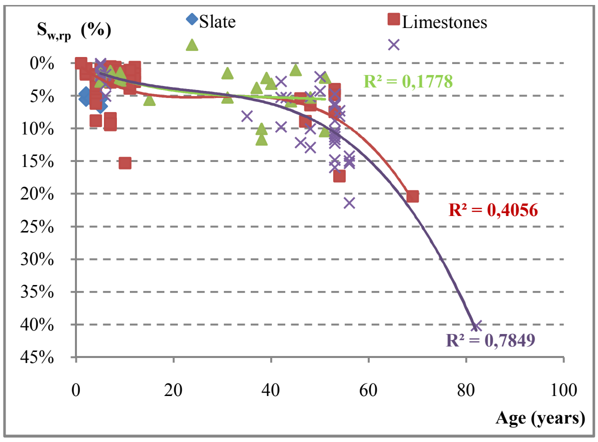

Fig. 5.9 - Degradation curves according to the type of stone in the cladding inspected

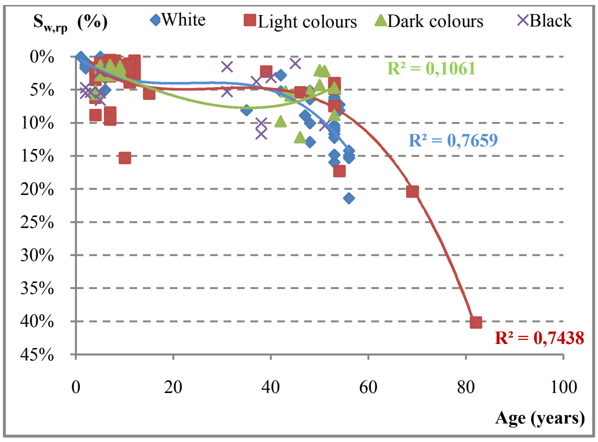

Fig. 5.10 - Degradation curves according to natural stone colour

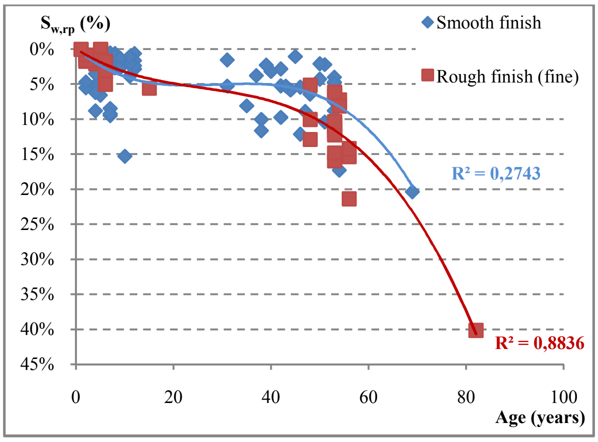

Fig. 5.11 - Degradation curves according to the type of finishing on the cladding inspected

5.3. Discussion of the results

Since this dissertation has followed the research field taken up by Gaspar (2002), Gaspar (2009) and Sousa (2008), a comparison of results is appropriate; Gaspar (2009) obtained a correlation coefficient of around 0.9 for coatings, thereby concluding that the model was a close match to reality; on the other hand, Sousa (2008) obtained values of around 0.4 for adhesive ceramic cladding, thereby not managing to draw any conclusion about its evolution.

This fact may be explained by the greater or lesser susceptibility of these three cladding types to external factors. Shohet and Laufer (1996) establish the susceptibility of cladding to construction, usage and maintenance factors (Table 5.3). It shows that adhesive ceramic cladding is the most susceptible to the factors listed there, followed by stone cladding and coatings; given that the preservation status survey is only performed through visual inspections, in which it is difficult to see anomalies due to design and construction errors, the results obtained are taken as showing a degree of consistency.

Table 5.3 - Cladding susceptibility to construction, usage and maintenance factors (adapted from Shohet and Laufer, 1996)

Factors external to the cladding	Cement filler	Synthetic filler	Adhesive ceramic cladding	Mechanically fixed stone cladding	Directly fixed stone cladding
Building activity	Moderate to high	Moderate to high	High	Low	Very high
Material quality	High	Moderate	Very high	High	High
Application quality	High	Moderate to high	Very high	Very high	High
Workmanship quality	Moderate to high	Moderate to high	Very high	Very high	Very high
Structural integrity loss	Moderate	Moderate	Very high	Moderate to high	Low to moderate
Ease of maintenance	Very high	Excellent	Very high	Variable	Moderate

The benchmark service life, obtained through the degradation curves, was 67 years long. This value was aligned with the variation interval values defined by Shohet and Paciuk (2004) for a lower minimum performance level (Table 5.4).

Table 5.4 - Benchmark service life values versus minimum demandable levels (Shohet and Paciuk, 2004)

Minimum performance level	Benchmark service life	Variation interval
60 (physical degradation and colour changes)	40	39-50
40 (localised degradation)	64	59-70

Since the results were satisfactory, it is deemed a priority to extend this research.

The sample analysed in this dissertation comprises two large groups of cases, with the first made up of cladding aged less than 15 years and the second made up of those between 30 and 60 years; thus a disparity exists in the constructive methodology regarding the two groups of cases. Therefore, in future research, a wider sample with a greater homogeneity of ages should be analysed. It would also be interesting in future research to evaluate durability of different construction materials making up the cladding, to gain an understanding of the influence of these in the overall degradation (metal fixing components, material for seating the natural stone, among others).

It may also be relevant to evaluate the perception of risk when developing the methodology, through surveys among residents and owners, to try and quantify degradation through analysis of the satisfaction of those surveyed towards the cladding.

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