Application of the factor method to the service life prediction of architectural concrete

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1. Introduction

This dissertation intends to develop a methodology for predicting the service life of architectural concrete surfaces, through the application of the factor method. This study follows a research line, previously developed by other authors, on the topic of the service life of various claddings and other elements of the buildings' envelope. This study also intends to contribute to the knowledge on the durability of constructions elements, seeking to aid the definition and optimization of maintenance strategies, allowing reducing their cost. In this study, the methodology used is based on a campaign of visual inspections of buildings, in real conditions of use and exposure. This allows analysing the evolution of the degradation process for architectural concrete surfaces.

1.1 Definition of the concept of service life

According to ISO 15686 (2011), the service life is the period of time, after a building is put into use, during which the building and its elements meet or exceed the minimum performance requirements. The concept of service life, although always based on the same fundamental assumptions, presents slight differences between authors. Some of these differences are, for example, whether or not, the buildings should be subjected to periodic maintenance actions during this period (Matos, 2015). There are different reasons to establish the need of intervention in a building element, whether it is the replacement or a non-recurring intervention. It is possible to define different criteria for an element reaching the end of its service life, such as physical degradation, functional obsolescence or economic performance (Gaspar, 2009).

2. Architectural concrete

During decades, concrete has been essentially used as a structural material, covered by different types of cladding solutions. Currently, concrete has been increasingly used as a cladding solution. In this dissertation, only architectural concrete surfaces are considered, i.e. all the exposed concrete elements are not covered with any type of coating, except for paints or varnishes (Coelho et all, 2017).

The technology involved in the execution of architectural concrete surfaces and the formulation of the concrete applied as cladding solution have a high influence on the quality of the final surfaces. Since this study analyses the performance of architectural concrete based only on visual inspections, some aspects related with the design and execution of architectural concrete surfaces cannot be considered in the service life prediction model.

The main anomalies that can occur in architectural concrete are: stains; efflorescence; biological growth; erosion; bug holes; *graffiti*; mapped cracking; oriented cracking; disaggregation; spalling; flatness defects; honeycombing; fastening marks; dribbling; crusts; and formwork incrustation. These anomalies are divided in three main groups: i) aesthetic anomalies; ii) mechanical anomalies; and iii) constructive anomalies.

The severity of a given anomaly is defined according to the percentage of area affected by the anomaly. In this study, five degradation levels are established, ranging from level 0 (with no visible degradation) to level 4 (most unfavourable condition). Table 1 shows the different degradation levels for each anomaly and also the limits that correspond to each level.

The anomalies with more serious consequences for the degradation of architectural concrete surfaces are only represented at higher levels, for example, oriented cracking with an opening greater than 3 mm only appears at levels 3 and 4, as it is considered quite serious, compromising the integrity and safety of the concrete surface.

Table 1- Degradation level for the different anomalies (adapted from Serralheiro, 2016)

Anomalies group	Anomalies description	Degradation level				
		Level 0	Level 1	Level 2	Level 3	Level 4
Aesthetic anomalies	Dirt stains	No visible degradation	< 15%	15% to 40%	> 40%	-
	Moisture stains					
	Corrosion stains					
	Wear/erosion		< 10%	10% to 30%	> 30%	
	Bug holes					
	Biological growth					
	Efflorescence					
Mechanical anomalies	Disaggregation/spalling		-	< 10%	10% to 30%	> 30%
	Oriented cracking (≤ 0.5 mm)			< 5%	-	-
	Oriented cracking (> 0.5 mm e < 3 mm)			-	≥ 5%	-
	Oriented cracking (≥ 3 mm)			-	< 5%	≥ 5%
	Mapped cracking			-	< 50%	≥ 50%
Constructive anomalies	Flatness defects		< 20%	20% to 50%	> 50%	-
	Dribbling		< 10%	≥ 10%	-	
	Fastening marks		-	≤ 5%	> 5%	
	Honeycombing			< 10%	≥ 10%	
	Formwork incrustation					

3. Field work and degradation model

Before starting the fieldwork, the sample collected by Serralheiro (2016) was analysed, in order to identify the main gaps in the dataset. After the analysis was completed, it was possible to estimate the number of architectural concrete surfaces to be inspected, as shown in Table 2.

The buildings and surfaces to be inspected were selected considering the results previously obtained. During the visual inspections, the relevant information about the building and the surfaces' characteristics was recorded. The surfaces were also photographed, which allowed estimating, with the use of specific software, the areas of the facade affected by each anomaly observed.

Table 2 - Minimum number of surfaces to be analysed in the field work

Age (years)	Minimum number of surfaces to be analysed								
	Distance from the sea	Exposure to damp	Surface protection	Wind/rain exposure	Orientation	Colour	Type of finishing	Surface treatment	Total
0 a 11	0	0	0	0	0	0	0	5	5
11 a 22	5	0	0	5	0	0	10	30	30
22 a 33	20	10	10	10	25	0	10	30	30
33 a 44	25	15	15	15	40	15	15	45	45
> de 44	25	15	15	15	40	20	15	45	45
Total	75	40	40	45	105	35	50	155	155

In this study, 104 inspections were performed, and it was possible to overcome most of the debilities found in the original sample, resulting in a total of 278 case studies.

The degradation model adopted in this study was initially developed by Gaspar (2009) and intends to calculate a numerical index, called as severity of degradation (S_w), which indicates the level of overall degradation of an inspected facade, during the fieldwork - Equation (1).

$$S_w = \frac{E_w}{k} = \frac{\sum(A \times k_n \times k)}{A \times k} \times 100 \qquad (1)$$

Where S_w represents the severity of degradation of architectural concrete, in % (ranging between 0 and 100%); k is the multiplication factor for n anomalies, as a function of their degradation level (k varies between 0 and 4); $k_{,n}$ is the weighting coefficient according to the relative weight of the anomaly detected (equal to 1 if no specification is referred, i.e. equal to 1 by default); A is the total cladding area, in m^2; and E_w is the architectural concrete facade's weighted degradation level.

After calculating the value of S_w, for all the case studies inspected in this study, it was possible to define an average degradation curve, obtained through a third-degree polynomial regression analysis. Figure 1 presents the degradation curve obtained, which graphically represents the evolution of the degradation of architectural concrete surfaces over time. The coefficient of determination - R^2 (R^2 varies between 0 and 1, revealing a regression model with no correlation to the data and a perfect correlation, respectively) - obtained for the polynomial curve, which describes the average curve of degradation, is 0.74. The value obtained reveals a strong correlation between the curve and the sample analysed, in which 74% of the variability of the severity of degradation of concrete surfaces can be explained by their age.

Serralheiro (2016) defined, as the end of service life of architectural concrete, a value of S_w equal to 20%. This classification was also adopted in this work, thus allowing joining the two samples, collected in the fieldwork surveys performed in the two studies.

Once the service life limit was defined, it was possible to calculate the expected service life value for architectural concrete surfaces. In this study, a value of 43 years is obtained, which is in accordance with the value previously obtained by Serralheiro et al. (2017).

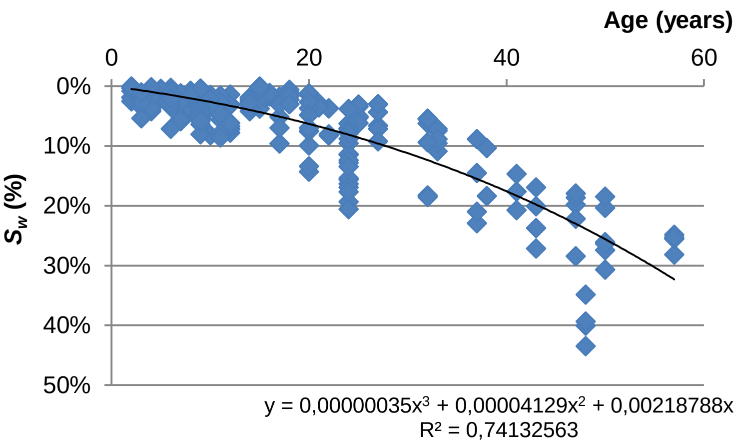

Figure 1 - Degradation curve obtained from total cases analysed in the fieldwork

In this study, all the factors that are considered relevant for the explanation of the degradation of architectural concrete are identified and analysed, which will serve as a basis for the application of the factor method. Figure 2 shows an illustrative example of the degradation curves established for the different characteristics of architectural concrete surfaces.

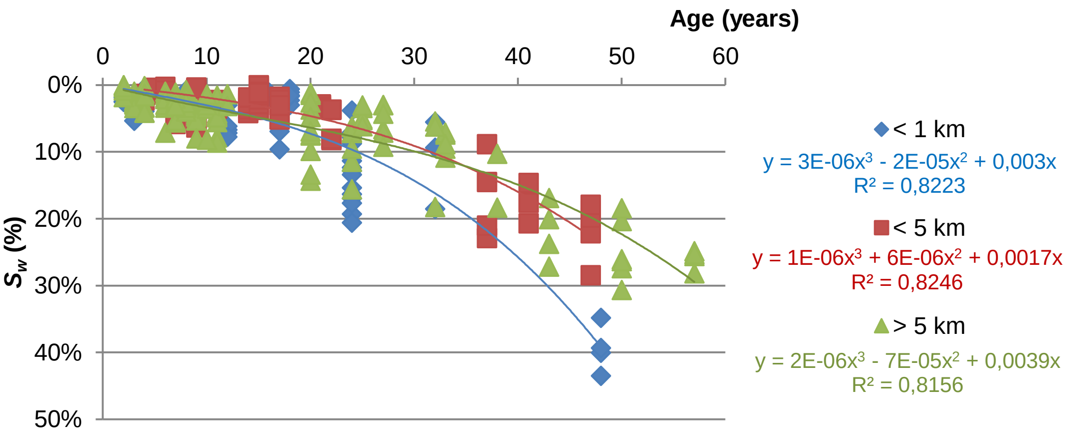

Figure 2 - Degradation curves in function of the distance from the sea

4. Factor method

4.1 Extrapolation of the degradation curve for each point

Before applying the factor method, the graphical method is applied to determine the estimated service life for all the surfaces under analysis.

For this purpose, the ordinates’ conversion factor method is used. In this method, the average degradation curve is converted into a new curve, which passes through each of the sample’s points. This method allows calculating the expected service life for each case study, and it is possible to correlate the predicted service life and the age of the case studies analysed (Figure 3).

The application of the graphical method to the sample, led to an average estimated service life of 48 years for architectural concrete surfaces. All the factors that had been previously studied, in the degradation curves, were analysed by the graphical method. As an example, Figure 4 shows the service life distribution over time according to the colour of the surfaces.

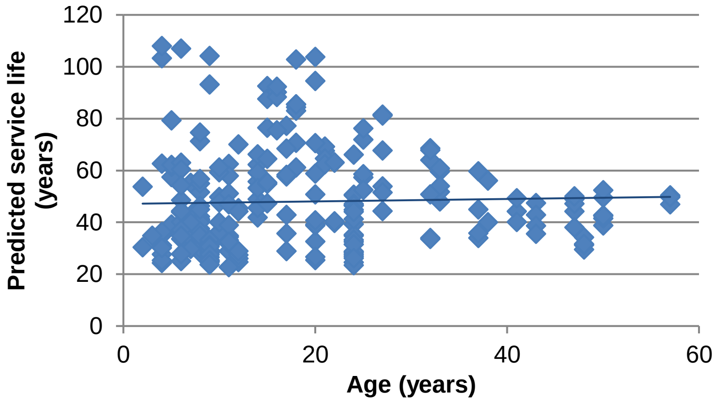

Figure 3 - Predicted service life distribution over time for all the case studies under analysis

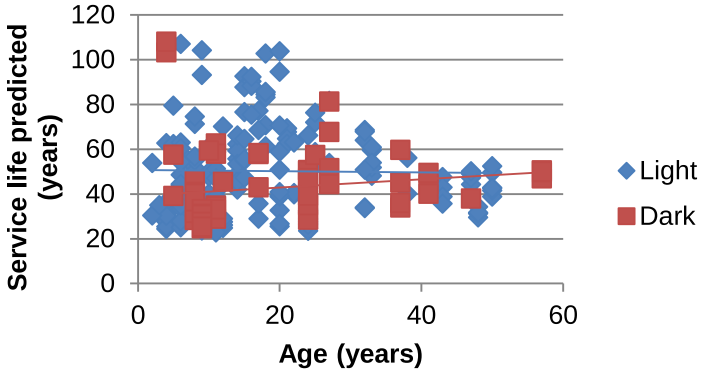

Figure 4 - Predicted service life distribution over time, according to the colour of the surface

The results obtained, through the graphical method, are generally very close to those obtained through the degradation curves. In three of the durability factors analysed, the results obtained by the graphical method are worse, but for other factors (e.g. type of finishing) the results obtained are better. The results obtained by the graphical method and by the degradation curves, for all the durability factors studied, can be observed in Table 3.

From the analysis of Table 3, the following main conclusions can be drawn:

- For the various factors analysed, the maximum expected service life is 67.5 years for surfaces with paint plus water repellent protection, and the minimum value is 36.5 years, for surfaces with varnish;
- The comparison between the results obtained by the graphical method and the degradation curves shows that the minimum value obtained increased from 35.5 years to 36.5 years, and the maximum value decreased from 79.1 years to 67.5 years;
- Concerning the colour of the surface, the application of the graphical method leads to better results than those obtained through the degradation curves, with light surfaces having a predicted service life higher than dark surfaces. This result is in accordance with the empirical knowledge, since darker concrete surfaces are more prone to degradation, due to the fact that these surfaces absorb more solar radiation, when compared with lighter surfaces, and are therefore subjected to greater thermal variations and in-

ternal stresses, which contribute to increased cracking and spalling defects (Wojciechowski *et al.*, 2014);

- For the type of finishing, the results obtained by the two methods are consistent. Although, in the sample analysed, textured surfaces are more durable than flat surfaces. This can be explained by the fact that textured surfaces tend to mask some defects, such as cracking, which are more difficult to detect on these surfaces;
- Regarding the exposure to damp, the results obtained, by the two methods, are consistent and correspond to what it would be expected, with surfaces with unfavourable conditions reaching the end of their service life sooner than surfaces with current exposure to damp;
- Concerning the surfaces' level of protection and exposure to wind/rain action, the results obtained using the graphical method are worse than the previous ones. Surfaces with "exposed" and "high" exposure have a higher expected service life than those with "current" and "low" exposure, respectively. This can be explained, in the case of exposure to wind / rain action, because 63% of the architectural concrete surfaces analysed, with low exposure to this action, are at the same time subjected to an adverse exposure to damp, which can biased the results obtained for the expected service life of these surfaces;

Table 3 - Service life predicted by the graphical method and by the degradation curves for the durability factors under analysis

Surfaces' characteristics			Graphical method	Degradation curves
Colour	Dark	*k*1	42.6	46.0
	Light	*k*2	50.2	42.6
Surfaces' treatment	Without protection	*k*1	47.3	43.9
	Paint	*k*2	48.9	39
	Water repellent	*k*3	49.2	39.3
	Paint + water repellent	*k*4	67.5	79.1
	Varnish	*k*5	36.5	42.7
Type of finish	Flat	*k*1	46.7	41.7
	Textured	*k*2	53.1	45.3
Orientation	North	*k*1	49.2	42.3
	West	*k*2	48.6	46.8
	East	*k*3	48.4	40.0
	South	*k*4	46.3	40.7
Distance from the sea	< 1 km	*k*1	47.3	35.5
	Between 1 km and 5 km	*k*2	52.0	44.5
	> 5 km	*k*3	46.0	48.5
Exposure to damp	Current	*k*1	51.5	45.9
	Adverse	*k*2	45.0	39.9
Surfaces' protection	Current	*k*1	47.3	45.3
	Exposed	*k*2	49.8	37.5
Wind/rain exposure	Low	*k*1	45.3	45.6
	High	*k*2	49.9	42.0
Ease of inspection	Yes	*k*1	47.3	45.3
	No	*k*2	49.8	37.5

- Concerning the surfaces' treatment and their orientation, the application of the graphical method leads to some improvements in relation to the degradation curves; however, the results obtained still disagree with what would be expected, which may be justified in part by the small number of case studies obtained for these characteristics, when the sample is decomposed into several categories;

- For the distance from the sea, the result for surfaces located at more than 5 km from the sea is clearly worse than that obtained by the degradation curves.

5.2 Calculation of the reference service life

To determine the value of the reference service life, the two previous average values of the estimated service life of architectural concrete surfaces are considered, but two additional methods are also considered.

First, the method of the average exposure conditions for a case is applied. In this method, the reference service life is calculated by estimating the average estimated service life of architectural concretes characterized by standard conditions (i.e. surfaces that feature all the subfactors equal to 1.0). The reference service life (RSL) is thus calculated for the case studies closest to the standard conditions. For the sample analysed, the RSL is calculated for surfaces with less than 3 factors different from 1.0. With this method, the reference service life value was 43.7 years.

The second method is that of average exposure conditions, for the entire sample. The following procedure was used: the reference service life was calculated for all surfaces in the sample; then, the relationship between the expected service life through the graphical method and the reference service life is calculated. Subsequently, the RSL is given by the average of the values where the ESL/RSL ratio's standard deviation is < 3%. Using this method, a RSL of 47 years is obtained.

The reference service life adopted is 45.4 years, corresponding to the average RSL obtained by the values obtained by the four methodologies used.

5.3 Determination of the estimated service life of architectural concrete surfaces

Once the durability factors are identified and after the determination of the reference service life, it is possible to establish the mathematical equation that enables the practical application of the factor method to the service life prediction of architectural concrete surfaces (Equation (2)).

$$ESL = RSL \times A1 \times A2 \times B1 \times E1 \times E2 \times E3 \times E4 \times E5 \times G1 \qquad (2)$$

Where ESL represents the estimated service life, RSL the reference service life (equal to 45.4 years), $A1$ the colour of the surface, $A2$ the type of the surface treatment, $B1$ is the type of finishing, $E1$ the surfaces orientation, $E2$ the distance from the sea, $E3$ the exposure to damp, $E4$ the surfaces level of protection, $E5$ the exposure to wind-rain action, and $G1$ the ease of inspection.

5.4 Scenarios considered

Finally, six different scenarios are analysed, described in Table 4, for the quantification of the durability factors. To compare and evaluate the different scenarios, it is necessary to define criteria to compare the statistical indicators resulting from each scenario.

The most relevant criteria considered are:

- The results obtained through the factor method (FM) must be credible and must therefore comply with the limits established for the expected service life of architectural concrete surfaces (ranging between 22 and 108 years), as estimated by the graphical method (GM);

- The cumulative frequency of the ratio between FM/GM, greater than or equal to 0.85, must be greater than 50%, and the cumulative frequency of the MF/MG ratio, greater than 1,50, should be less than 10%;
- The various iterations intend to maximize the number of case studies belonging to the range [0.85; 1.15], for the MF/MG ratio.

The values obtained for each durability factor, in the different scenarios analysed, are presented in Table 5.

Table 4 - Description of the six scenarios considered

Scenarios	Description
Scenario 1	In this scenario, it is considered the service life obtained through the graphical method (48 years) and the values obtained for each durability factor. The difference between the service life of each factor and the average estimated service life is calculated. For each year of difference, between the value of the variable and the average service life, a variation of 0.05 is assigned to the weighting coefficient.
Scenario 2	Scenario 2 follows the same methodology adopted in scenario 1 but applies the degradation curves to define the differences between the average estimated service life (43 years) and the values obtained through the degradation curves for each variable. For each year of difference, between the value of the variable and the average service life, a variation of 0.05 is assigned to the weighting coefficient.
Scenario 3	For this scenario, the value of 1 was assigned to all variables to study a neutral model.
Scenario 4	In this scenario, the ISO 15686 (2011) is used for the quantification of the durability factors. In this sense, a value 0.80 is assigned to unfavourable conditions, the value 1.20 is assigned to favourable conditions and the value 1.00 is assigned to current or difficult to assess conditions.
Scenario 5	Following the logic of the previous scenario, the value 0.90 is assigned to unfavourable conditions, the value 1.10 is assigned to favourable conditions and the value 1.00 is assigned to current or difficult to evaluate situations.
Scenario 6	This scenario is based on the results previously obtained and intends to obtain an optimized assignment of the values of the various durability factors, in order to achieve the best possible result.

Table 5 - Results obtained for the different scenarios

Conditioning factors			Scenario 1	Scenario 2	Scenario 4	Scenario 5	Scenario 6
Colour	Dark	*k*1	0.750	1.000	0.800	0.900	0.825
	Light	*k*2	1.100	1.000	1.000	1.000	1.150
Surface treatment	Without protection	*k*1	0.950	1.050	1.000	1.000	0.850
	Paint	*k*2	1.050	0.800	1.200	1.100	1.025
	Water repellent	*k*3	1.050	0.800	1.000	1.000	1.025
	Paint + water repellent	*k*4	2.000	2.800	1.200	1.100	0.900
	Varnish	*k*5	0.450	0.950	0.800	0.900	1.000
Type of finish	Flat	*k* 1	1.000	1.000	1.000	1.000	0.800
	Textured	*k*2	1.000	1.000	1.000	1.000	1.200
Orientation	North	*k*1	1.050	0.950	1.000	1.000	1.075
	West	*k*2	1.050	1.200	1.000	1.000	0.950
	East	*k*3	1.000	0.850	0.800	0.900	0.900
	South	*k*4	0.900	0.850	1.000	1.000	0.925
Distance from the sea	< 1 km	*k*1	0.950	0.600	0.800	0.900	0.825
	Between 1 km and 5 km	*k*2	1.200	1.050	1.000	1.100	0.925
	> 5 km	*k*3	1.200	1.250	1.200	1.100	1.000
Exposure to damp	Current	*k*1	1.150	1.150	1.000	1.100	1.050
	Adverse	*k*2	0.850	0.850	0.800	0.900	0.900
Surface protection	Current	*k*1	1.000	1.100	1.000	1.000	1.050
	Exposed	*k*2	1.000	0.700	1.000	0.900	1.050
Wind/rain exposure	Low	*k*1	1.000	1.100	1.000	1.000	1.100
	High	*k*2	1.000	0.950	1.000	1.000	1.000
Ease of inspection	Yes	*k*1	1.000	1.100	1.000	1.000	1.050
	No	*k*2	1.000	0.700	1.000	1.000	1.000

Table 6 presents the statistical analysis of the results obtained by the different scenarios, where in red are the results that do not comply with the criteria adopted.

The worst scenarios are 1 and 2, not complying with five of the defined criteria, since there are values where the differences obtained by the average sample and the specific characteristics, lead to weighting values of the durability factors with unrealistic values. In scenario 1, to the paint plus water repellent subfactor is assigned a value of 2.00 and to the varnish subfactor is assigned a value of 0.45, this situation is similar to what occurs in scenario 2, resulting in a considerable dispersion of the values obtained.

Table 6 - Statistical indicators of the scenarios considered

Scenarios		1	2	3	4	5	6
FM/GM average <1.05		1.17	1.07	1.09	0.92	1.05	0.95
Standard deviation		0.56	0.86	0.38	0.34	0.37	0.31
Amplitude of results	Factor method (years)	130.7	208.5	0.0	43.1	30.7	55.1
	Graphical method (years)	85.3	85.3	85.3	85.3	85.3	85.3
Extremes values obtained in the factor method	Maximum = 108 years	144.81	215.85	45.43	65.41	60.46	78.06
	Minimum = 22 years	14.07	7.33	45.43	22.33	29.80	22.93
FM/GM ≥ 0.85 (≥50%)		68.62%	53.14%	67.78%	55.65%	69.46%	66.53%
FM/GM ≥ 1.50 (< 10%)		23.43%	23.85%	16.32%	5.02%	10.88%	4.60%
0.85 ≤FM/GM ≤ 1.15		19.67%	16.74%	27.62%	35.98%	34.73%	46.44%

For scenario 3, the results obtained only fail to accomplish two of the criteria defined, which is an improvement over the previous scenarios. In scenarios 4 and 5, only one of the previously defined criteria is not fulfilled. For scenario 4, the average of the estimated service life, achieved by the application of the factor method, is quite reduced, in comparison with the average ESL obtained by the graphical method. In these two scenarios, only three values are used for the quantification of the durability factors, are too reductive (have low sensitivity and low adaptability), and do not have the capacity to significantly increase the percentage of elements with an FM/GM ratio within the range 0.85-1.15.

Scenario 6, where the values obtained were optimized, was the only one that fulfilled all the established criteria. 46% of the surfaces have a difference between the ESL obtained by the factor method and the graphical method, belonging to the range 0.85 to 1.15. Therefore, scenario 6 must be adopted in the quantification of the durability factors, for the application of the factor method to the service life prediction of architectural concrete surfaces.

5. Conclusion

The results obtained show that the values predicted by the model are in accordance with reality and the empirical knowledge regarding the durability of architectural concrete surfaces. However, the application of the factor method to the service life prediction to architectural concrete, and the mathematical equation proposed, as well as the quantification of the durability factors, as suggested in this study should not be taken as an absolute truth, but rather as the best approach to the sample analysed. This study is a first approach for the application of a standardised service life prediction method to architectural concrete surfaces, providing some guidance, which can be used in future research. In future studies, this method can be applied to a new universe of cases, since the larger the sample analysed, the greater the reliability and applicability of the factor method.

Despite the various limitations that this method presents, in an overall analysis, its application is considered expeditious and highly operational; especially when considering the complexity and the numerous factors that influence the evolution of the degradation of an external cladding. Due to these advantages, the factor method is selected as the basis of international standards, consisting in a general framework for estimating the service life of buildings and their elements.

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