Canadian Science Publishing | Canadian Journal of Civil Engineering

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

Journal:	*Canadian Journal of Civil Engineering*
Manuscript ID	cjce-2018-0452.R1
Manuscript Type:	Article
Date Submitted by the Author:	02-Dec-2018
Complete List of Authors:	Jardim, André; Universidade de Lisboa Instituto Superior Tecnico Silva, Ana; Instituto Superior Técnico, Technical University of Lisbon, Department of Civil Engineering and Architecture Brito, J. de; Instituto Superior Técnico, Civil Engineering, Architecture and Georesources
Keyword:	service life, factor method, architectural concrete
Is the invited manuscript for consideration in a Special Issue? :	Durability and Climate Change

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

A. Jardim[1], A. Silva[2] and J. de Brito[3]

- Word count: 8992 equivalent words -

Abstract:

Architectural concrete surfaces are a durable solution, but their deterioration process is unavoidable, beginning as soon as the element is built. This study establishes a methodology for predicting the service life of architectural concrete surfaces, through the application of the factor method. For this purpose, 239 architectural concrete surfaces in in-service conditions are analysed. Different durability factors are studied, evaluating their impact in the service life of architectural concrete surfaces. Different scenarios are analysed for the quantification of the durability factors. Scenario 4 presents the best results, leading to a higher similarity between the estimated service lives predicted by the factor method and obtained by the graphical method. The application of the factor method, as described in this study, allows predicting the service life of architectural concrete surfaces. An estimated service life ranging between 43 and 48 years was obtained, which agrees with the literature and empirical knowledge.

Keywords: service life, factor method, architectural concrete.

---

[1] Master in Civil Engineering, Instituto Superior Técnico (IST) - University of Lisbon, Av. Rovisco Pais, 1049-001, Lisbon, Portugal, e-mail: andrefjardim2@gmail.com

[2] PhD in Civil Engineering, IST - University of Lisbon, Av. Rovisco Pais, 1049-001, Lisbon, Portugal, e-mail: ana.ferreira.silva@tecnico.ulisboa.pt, Corresponding author

[3] Full Professor, Department of Civil Engineering, Architecture and Georresources, IST - University of Lisbon, Av. Rovisco Pais, 1049-001, Lisbon, Portugal, e-mail: jb@civil.ist.utl.pt

1. Introduction

For decades, concrete has been essentially used as a structural material, protected by different types of coatings. Currently, concrete has been progressively used as a decorative solution, designated architectural concrete. In this study, architectural concrete is defined as any concrete surface used as exterior finishing of a building or structure, without any coating other than paint or varnish (Silva et al. 2017). The main difference between architectural concrete and structural concrete lies on the exposed surfaces of architectural concrete, which is more relevant than the strength of the material (Peurifoy and Oberlender 2011). These exposed concrete elements can present countless color tones, shapes and types of finishing, resulting in a cladding solution with a remarkable aesthetic quality (Cassar et al. 2003; Freedman 2007).

Despite being a durable solution, the degradation process of architectural concrete is inevitable, and starts as soon as the element is put into use. Nowadays, various studies have been performed to evaluate the durability and service life of concrete structures (Liang et al. 2002; Ahmad 2003; Alghamdi and Ahmad 2014). Nevertheless, as mentioned by Hongke et al. (2016), these studies are limited to the material itself, neglecting the real exposure conditions. In this sense, the research related with the service life of architectural concrete under real exposure conditions is insufficient, since the environmental degradation agents, the age of the element and other durability factors are rarely considered in existing research works.

In current practice, under most circumstances, the repair works performed in architectural concrete surfaces are the same regardless of the cause and the extent of the anomaly observed (Farahmandpour et al. 2000). This situation occurs mainly due to the lack of knowledge regarding the impact of different degradation mechanisms in the durability and service life of architectural concrete surfaces. Therefore, the definition of maintenance strategies depends on the knowledge regarding the expected service life of the element, under specific conditions of use, as well as the quantification of the actions required during this period of time (Kessler et al. 2017). This knowledge could lead to more effective measures and different repair techniques according to the different anomalies observed, aiding the optimization of the periodicity of maintenance plans, which is crucial to evaluate the economic and environmental impacts of concrete surfaces through the building's life cycle (Flores-Colen and de Brito 2010).

This study intends to propose a methodology to predict the physical service life of architectural concrete surfaces, through the application of the factor method. The model proposed allows encompassing different durability factors, related with the quality of the materials, design characteristics and environmental exposure conditions, which influence the physical service life of architectural concrete surfaces. The factor method (FM) is established based on the analysis of the degradation state of 239 architectural concrete surfaces in in-service conditions. The observed reality is translated by a numerical index and a graphical method (GM), which allow estimating the service life of each architectural concrete surface analysed, according to the anomalies observed, their severity and extent. The results obtained by the FM are compared with those obtained by the GM (which portrays the reality observed in fieldwork), for each case study within the sample analysed.

2. Background

The service life prediction of buildings components has been gaining importance, for several reasons. The resources available for maintenance and rehabilitation actions are scarce and should be planned in order to maximize the results obtained. To achieve this goal, the decision to intervene should be based on the knowledge of the degradation processes and their interaction with the building materials (Leira et al. 1999). The service life of a building component is intrinsically linked to its sustainability; data regarding the durability of a building component, when subjected to specific conditions of use, are essential to compare the durability and, consequently, the economic and environmental impacts, of different solutions over the same period of time.

According to ISO 15686 (2011), the service life is the period of time, after a building is put to use, during which the building and its elements meet or exceed the minimum performance requirements. The performance requirements are strongly related with users and owners demands and expectations, and the “minimum” acceptable level of performance is usually conditioned by subjective criteria, such as aesthetic reasons, the building’s social and economic context, the funds available for maintenance actions, among others. The concept of service life, although always based on the same fundamental assumptions, presents slight differences between authors. Some of them concern, for example, whether or not the buildings should be subjected to periodic maintenance actions during this period (Silva et al. 2016).

Currently, there are various methodologies for the service life prediction of buildings and their components. Among these, the factor method stands out, since it is considered a general framework for service life prediction and its application is standardised by ISO 15686 (2011). This method, initially proposed by the Architectural Institute of Japan (AIJ 1993), introduces an easy and expedient way to calculate the estimated service life (ESL) of a component, considering all variables, which are likely to affect its degradation process. This methodology is based on a reference service life (RSL), which is the expected service life for that component, under standard conditions of use. The reference service life is subsequently multiplied by a number of factors that affect the durability of the building element under analysis (as shown in Equation (1)), either positively or negatively, depending on whether the elements’ characteristics are better or worse than those considered as the reference (ISO 15686: 2011; Straub 2015).

$$ESL = RSL \times A \times B \times C \times D \times E \times F \times G \qquad (1)$$

Where *ESL* represents the estimated service life, *RSL* is the reference service life, factor *A* is the quality of the construction material, factor *B* is the design level, factor *C* is the level of execution, factor D is related to the characteristics of the external environment, factor E concerns the characteristics of the indoor environment, factor F depends on the characteristics of use and factor G is the maintenance level.

The factor method has been criticized due to the simplicity with which it models a complex phenomenon. Some of the criticisms refer that this method only provides an empirical estimate of the service life of a given component (Hovde 2002; Marteinsson 2003). The correct application of this method requires that the different durability factors are well known and adequately quantified, to ensure that credible results are obtained (Hovde 2004). In addition, the method has a high sensitivity for small variations of the data, and there is no clear methodology for estimating the reference service life. Despite this, the factor method remains the only standardised methodology for predicting the service life of a building component, due to its simplicity and ability to adapt when new techniques or information arise.

3. Degradation phenomena of architectural concrete facades

The degradation phenomena of architectural concrete surfaces are analysed based on the evaluation of the degradation condition of several case studies in-use conditions, with different ages and characteristics. In this sense, the degradation condition of 239 architectural concrete surfaces is evaluated, during an extensive fieldwork. Each architectural concrete surface is evaluated through a visual inspection, gathering the relevant information to characterise this case study, mapping all the anomalies present in the surface.

The main anomalies that can occur in architectural concrete are (Silva et al. 2017): 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 (Figure 1): i) aesthetics anomalies; ii) mechanical anomalies; and iii) constructive anomalies.

3.1. Degradation model

To evaluate the overall degradation condition of the architectural concrete surfaces inspected, a numerical index, called severity of degradation (S_w), is used. This numerical index, initially proposed by Gaspar and de Brito (2008, 2011), considers the area affected by each anomaly, its degradation level and the relative weight of the anomaly detected - Equation (2).

$$S_w = \frac{\sum(A_n \times k_n \times k)}{A \times \sum(k_{max.})} \qquad (2)$$

Where S_w represents the severity of degradation of architectural concrete surfaces, in %, A is the area of the architectural concrete surface affected by the anomaly n, in m^2, k is the multiplication factor for the anomaly n, as a function of their degradation level (k_n varies between 0 and 4, as shown in Table 1), $k_{a,n}$ 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 surface area, in m^2 and $\sum(k_{max.})$ is the sum of the weighing coefficients, corresponding to the highest possible level of degradation.

The coefficient k allows taking into account the severity of a given anomaly, by defining different degradation levels according to the percentage of area affected by the anomaly, as well as the impact of this anomaly in the overall degradation of the architectural concrete surface. In this study, five degradation levels are established, ranging from A (with no visible degradation) to E (most unfavorable condition). Table 1 shows the different degradation levels for each anomaly considered 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, e.g. oriented cracking with an opening higher 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.

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 2 presents the degradation curve achieved, 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 analyzed, in which 74% of the variability of the severity of degradation of concrete surfaces can be explained by their age.

In this study, it is conventionally considered that an architectural concrete surface with a value of S_w equal to 20% has reached the end of its physical service life. To illustrate the physical condition associated to the end of physical service life of an architectural concrete surface, Figure 2 presents a case study that has reached the end of its physical service life. Once the service life limit is defined, it is possible to calculate the expected service life value for architectural concrete surfaces. In this study, an average estimated service life of 43 years is obtained, based on the degradation curve.

3.2. Extrapolation of the degradation curve for each point of the sample and calculation of the estimated service life for each case

Based on the overall degradation curve, a graphical method can be adopted to determine the estimated service life for all the surfaces under analysis. For this purpose, the ordinates' conversion factor method is used, in which a new curve is drawn (similar to the overall degradation curve), which passes through each of the sample's points, determining the age after which a severity of degradation of 20% is reached.

In the ordinates' conversion factor method, a factor *k*, which corresponds to the ratio between the ordinates of two points *A* and *M*, is determined. *M* is a point on the average degradation curve, which has an age equal to A ($x_A = x_M$). The ordinate of A is the value of its severity of degradation (calculated by Equation (2)) and the ordinate value of M is the value of the degradation curve for that age. The value of k is multiplied by the function f (equation of the average degradation curve), to estimate a function f', as presented in Equation 3, which contains the point A (i.e., the degradation curve that intersects A, thus representing the specific degradation curve of this point) (Magos et al. 2016).

$$f' = k \times f = k \times a \times x^3 + k \times b \times x^2 + k \times c \times x \quad (3)$$

Where f represents the function of the average degradation curve, f' is the function of the degradation curve for each point, k is the ratio factor between the two curves and a, b and c are the polynomial curve constants of degree 3 that define the function f.

The application of this graphical method to the sample led to an average estimated service life of 48 years for architectural concrete surfaces.

4. Identification and weighting of the factors that influence the durability of architectural concrete facades

ISO 15686 (2011) suggests seven durability factors, divided into: material characteristics (A); design conditions (B); execution conditions (C); inner environment characteristics (D); external environmental characteristics (E); use conditions (F) and maintenance level (G). Some of the factors mentioned in ISO 15686 (2011) are not considered in this study, either because it is not possible to obtain reliable information during the fieldwork survey or because they are not relevant for the service life prediction of architectural concrete surfaces (Marques et al., 2018). In this study, the following factors are considered relevant for the explanation of the degradation of architectural concrete:

- **Factor *A*** - regarding the materials characteristics, two durability factors are analysed, the first related with the color of the surface ($A1$) and the second related with the surfaces' treatment ($A2$);

- **Factor *B*** - for the design characteristics, the type of finishing (*B*1) is the only factor analysed;
- **Factor *C*** - in this study, this factor is not considered, since the execution conditions are difficult to evaluate only based on visual inspections carried out on surfaces many years after their execution; moreover, the case studies found with serious failures due to execution errors were excluded from this study, because they did not represent the natural degradation evolution of an architectural concrete façade over time, i.e. this study intends to predict the service life of architectural concrete surfaces, modelling the natural degradation process of these elements, in this sense, discrete or unpredictable events can not be modelled mathematically;
- **Factor *D*** - this factor is not considered in this study, because the conditions of the interior environment did not influence the degradation process of the outer coatings;
- **Factor *E*** - the characteristics of the external environment strongly influence the degradation process of external architectural concrete surfaces. In this durability factor, five durability factors are considered: surfaces orientation (*E*1); distance from the sea (*E*2); exposure to damp (*E*3); the surface's level of protection (*E*4); and exposure to wind/rain action (*E*5);
- **Factor *F*** - the use conditions factor is difficult to estimate; the only situation resulting from incorrect use is *graffiti*. However, actions such as vandalism or accidents cannot be modelled since they do not evolve in a predictable way over time. Therefore, this factor is not considered;
- **Factor *G*** - regarding the maintenance conditions, only the factor "ease of inspection" is considered.

The quantification of the weighting values of the durability factors considered in this study is done based on two methods (Silva et al. 2016): i) degradation curves, in which an average degradation curves is established for the different characteristics of architectural concrete surfaces, estimating the average estimated service life for each characteristic; ii) and using the graphical method, estimating the average estimated service life for the surfaces with the characteristic under analysis. Moreover, the quantification of the durability factors also considers their physical meaning.

ISO 15686 (2011) proposes three values for quantifying the durability factors included in the factor method: 1.2 for favorable conditions and characteristics, which positively affect the service life of the element analysed; 1.0 for reference conditions (or when it is not possible to draw clear conclusions regarding the influence of this factor on the service life of the building component); and 0.8 for conditions and characteristics that adversely affect the service life of the element analysed. McDuling et al. (2008) suggests a broader approach, proposing the adoption of five possible values for the quantification of the durability factors, according to the exposure conditions: 1.2 (clearly favorable); 1.1 (slightly favorable); 1.0 (slightly aggressive); 0.9 (aggressive); 0.8 (very aggressive). These values are thus adopted in a preliminary quantification of the durability factors (in section 5.3 various scenarios are analysed, to fine tune the quantification of the durability factors, to improve the capability of the factor method to describe the observed reality).

Table 2 shows the preliminary quantification of the durability factors, considering the estimated service life obtained by the graphical method and the degradation curves. The results achieved through the graphical method are generally very close to those obtained through the degradation curves. These results allow understanding the influence of the different factors analysed on the degradation of architectural concrete surfaces, i.e. it is possible to quantify the effect of each sub factor to increase or decrease the estimated service life of these surfaces, thus allow distinguishing the favorable from the unfavorable situations.

As for the color of the surface, the application of the values obtained by the graphical method reveals that light-colored surfaces present a predicted service life higher than dark surfaces. Darker concrete surfaces tend to show higher degradation levels, since they absorb more solar radiation, than those with lighter shades, and are therefore subjected to greater thermal variations and internal stresses, which contribute to increase cracking and spalling anomalies (Wojciechowski et al. 2014).

For the various factors analysed, the maximum and minimum values of estimated service lives are obtained according to the surfaces' treatment. The maximum value is around 79 years for surfaces with paint plus water repellent protection, and the minimum value is 36.5 years, for surfaces with varnish. The fact that the extreme values are obtained for this characteristic reveals its relevance to the degradation of architectural concrete surfaces. Custódio and Eusébio (2006) refer that external varnished surfaces are extremely susceptible to degradation phenomenon due to the exposure to solar radiation. These surfaces can present an estimated service life between 5 to 10 years (Hopper 2007) and, if not properly maintained, the end of the varnish's service life may adversely affect the natural process of degradation of a concrete surface. Therefore, in this study, surfaces without protection and with varnish are considered the unfavorable situation. On the opposite, surfaces with paint plus water repellent protection present the highest estimated service life, corresponding to the most favorable condition.

For the type of finishing, the results obtained by the two methods are consistent. In the sample analysed, textured surfaces present a higher estimated service life than smooth surfaces. This finding is not consensual in the literature. Various authors (PCA 2007; Lahdensivu et al. 2013) refer that textured surfaces are more prone to dirt deposition and biological growth.Köliö et al. (2016) refer that concrete surfaces treated while fresh (e.g. brushed or floated) present a more open porous system, which increases the carbonation rate in dry periods, but also promotes a faster wetting of the surfaces subjected to driving rain.

Hurd (1990) refers that smooth concrete surfaces are not easy to obtain, since it is difficult to achieve completely uniform surfaces, without defects due to the casting process and free from bug holes, which leads to the premature appearance of anomalies. The author refers that some designers choose to adopt textured surfaces rather than smooth ones, to avoid these problems. In a preliminary analysis, the type of finishing is considered a neutral factor, but when the durability factors are fine-tuned, it is considered that textured surfaces correspond to the favorable condition, to be coherent with the results observed during the fieldwork survey.

The surfaces' orientation is divided in four categories (Silva et al. 2016; Serralheiro et al. 2017): North (N); Northeast, East and Southeast (NE/E/SE); West and Northwest (W/NW); and South and Southeast (S/SE). The concrete surfaces analysed are located in Portugal (north hemisphere), and therefore, the discussion of the influence of the surfaces' orientation in their degradation condition is performed accordingly with the region under analysis. In the sample analysed, S/SW oriented surfaces are the less durable, reaching the end of service life sooner. In Portugal, surfaces facing S/SW present longer periods of UV radiation, which promote the occurrence of anomalies due to higher thermal gradients (Serralheiro et al. 2017). W/NW and NE/E/SE correspond to an intermediate situation, without a clear pattern of which orientation is worse. Surfaces facing SE/E/NE also present a higher exposure to the direct incidence of UV radiation (Garrido et al. 2012); surfaces facing W/NW are more exposed to the combined effects of wind and rain (Silva et al. 2016). Surfaces facing North present higher estimated service lives; even though these surfaces are more exposed to damp, it seems that the lower incidence of solar radiation increases the durability of architectural concrete surfaces. The results obtained seem to indicate that UV radiation is a degradation agent with a significant impact on the surfaces' service life, promoting the occurrence of aesthetics anomalies (e.g. discoloration and darkening) and cracking.

Concerning distance from the sea, the results obtained through the degradation curves are coherent, revealing that concrete surfaces in coastal areas (less than 1 km) are the unfavorable condition, reaching the end of service life sooner. The further away from the coastline, the higher the surfaces' estimated service life will be. Concrete surfaces more distant from the coastline are less prone to chemical, physical and mechanical degradation due to the presence of sea salts (e.g. chloride ions), which induce the occurrence of severe anomalies (Islam et al. 2018).

Regarding exposure to damp, Pereira et al. (2018) refer that damp is an aggressive degradation agent and one of the main causes of defects, being responsible for intense changes in the overall appearance of concrete surfaces. The results obtained in both methods are consistent, revealing that surfaces with a high exposure to damp reach the end of service life sooner.

Concerning the surfaces' protection and exposure to wind/rain action, the results obtained by the degradation curves are more reliable. The surfaces' protection considers the surrounding conditions, such as vegetation and adjacent buildings, which increase the surfaces' protection against the environmental agents. As expected, surfaces with unfavorable exposure conditions (without protection and with high exposure to wind-rain action) reach the end of service life sooner, since the incidence of prevailing winds and precipitation lead to higher stresses in concrete surfaces, promoting the degradation of these elements (Pakkala et al. 2014, 2016).

Regarding the ease of inspection, this factor considers the height of the building, assuming two categories (Silva et al. 2016): surfaces that are easily observed (i.e. yes), for buildings up to three storeys high; and surfaces that are not easily inspected, for buildings with more than three floors. Taller buildings present a lower ESL (according to the degradation curves), since they are more exposed to the degradation agents (e.g. wind and rain), which increase the propensity to present higher degradation levels (Lahdensivu et al. 2013).

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

5.1. Reference service life

This study addresses the physical service life of architectural concrete surfaces, considering that a surface that reaches a degradation condition corresponding to a severity of degradation of 20% comes to the end of its service life. In this sense, 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 (Galbusera et al. 2014; Emídio et al. 2014; Silva et al. 2016).

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 analyzed, the *RSL* is calculated for surfaces with less than three factors different from 1.0 (since none of the case studies present all the subfactors equal to 1.0). With this method, the reference service life value was 42.1 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 44.8 years is obtained.

The reference service life adopted is 43.8 years, corresponding to the average *RSL* obtained using these four methodologies.

5.2. Calculation formula

Once the durability factors are identified and the reference service life is determined, 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 (4)).

$$ESL = RSL \times A1 \times A2 \times B1 \times E1 \times E2 \times E3 \times E4 \times E5 \times G1 \quad \textbf{(4)}$$

Where ESL represents the estimated service life, RSL the reference service life (equal to 43.8 years), $A1$ the color 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.

5.3. Quantification of the factor method's sub-factors

For the quantification of the durability factors, four scenarios are analysed, always considering the physical meaning of the results obtained in the previous sections, which allow evaluating the influence of each factor in the degradation of architectural concrete surfaces. In this sense, the factors with an unfavorable effect in the estimated service life of architectural concrete surfaces always present a k value lower or equal to average and favorable conditions. The following scenarios are thus considered:

- **Scenario 1** is a neutral scenario, in which a value of 1.00 is assigned to all the durability factors analysed in this study. This scenario allows evaluating the neutral behavior of the proposed model and is only used as comparison with other models. The analysis of this scenario intends to evaluate the relevance and usefulness of applying the factor method to the service life prediction of architectural concrete surfaces;
- In **Scenario 2**, the values of each sub factor are assigned according to the ISO 15686: 2011, i.e. 0.80 for the factors that have an unfavorable effect in the estimated service life of architectural concrete surfaces, 1.00 for current situations or difficult to access, and 1.20 for the factors considered as favorable;
- **Scenario 3** adopts a similar methodology as scenario 2, but in scenario 3, the k

values are 0.90, 1.00 and 1.10. This scenario allows analysing the sensitivity of the model to small variations in the quantification of the durability factors (Emídio et al. 2014; Marques et al. 2018);

- Finally, **scenario 4** corresponds to an optimised scenario, in which the durability factors are quantified through an iterative process, intending to obtain the combination of *k* values that minimise the deviation between the estimated service life obtained by the factor method and the values observed in fieldwork (graphical method).

Table 3 shows the quantification of the durability factors according to the different scenarios considered.

6. Discussion of the results

The different scenarios are analysed and validated through the comparison between the estimated service life obtained using the factor method (using the different scenarios for the quantification of the durability factors) and the graphical method. The graphical method is based on the reality observed during fieldwork, describing, in a mathematical way, the degradation condition of the surfaces analysed, evaluating the real influence of the different factors to their estimated service life. Therefore, to evaluate the accuracy of the different scenarios proposed, different statistical indicators are used, which consider the ratio between the estimated service life obtained through the factor method (FM) and the estimated service life obtained through the conversion to the average degradation curve (GM), as follows (Emídio et al. 2014; Silva et al. 2016; Marques et al. 2018):

- The relationship between the average ESL, using the factor method and the graphical method, should not differ from 1 by more than 5% (i.e. the maximum range is [0.95; 1.05]);
- The amplitude of the results obtained through the factor method must be lower than

the amplitude of the results obtained through the graphical method;

- The results obtained through the factor method must be credible and therefore comply with the limits considered as acceptable for the expected service life of architectural concrete surfaces. In this study, as a minimum value an ESL of 22 years is considered, which corresponds to around half the average expected service of architectural concrete surfaces, according to the sample analysed; moreover, Köliö et al. (2014) refer that the visible damage in concrete facades became visible within 21 and 25 years after construction. For the maximum limit, an estimated service life of 100 years is assumed (PCA, 2007);
- The cumulative frequency of the ratio between MF/MG, greater than or equal to 0.85, must be greater than 50%;
- The cumulative frequency of the MF/MG ratio, greater than 1.50, should be less than 10% (i.e. the number of failed estimations should be less than 10%);
- The various iterations should maximise the number of surfaces belonging to the interval from 0.85 to 1.15, for the MF/MG ratio.

Table 4 shows the statistical indicators resulting from the application of each of the scenarios considered. As expected, scenario 1 presents the worst overall results, with the higher percentage of failed estimations. For scenario 2, the average of the ratio between the results obtained using the factor method and the graphical method presents a variation higher than 5%. In this scenario, the average estimated service life, achieved through the factor method (around 36 years), is quite reduced, in comparison with the average ESL obtained by the graphical method (around 48 years). In scenario 3, the average of the ratio between the FM and the GM is 0.97, fulfilling the defined criteria. This scenario presents an improved performance when compared with the previous scenarios analysed. Nevertheless, the results obtained seem to indicate that the values proposed by the ISO 15686: 2011 standard are too broad (have low sensitivity and adaptability) and do not have the capacity of significantly increasing the number of cases whose MF/MG ratio is in the range of 0.85 to 1.15.

Scenario 4, as expected, presents the best overall results, since the quantification of the durability factors is based on an iterative process to maximise the similarity between the ESL predicted by the factor method and the ESL observed in reality (GM). This scenario fulfills all the defined acceptance criteria. In this scenario, a MF/MG ratio of 1.02 is obtained and the percentage of case studies whose MF/MG ratio is in the range of 0.85 to 1.15 is also the highest of all scenarios (45.1%), thus revealing that about 45% of the sample has a variation of less than 15% compared to the ideal situation, which would be to obtain a service life estimated by the factorial method equal to the service life estimated by the graphical method. Scenario 4 shows a significant improvement (about 11%) in terms of the cumulative frequency of MF/MG results between 0.85 and 1.15, compared to the second-best scenario (scenario 3).

The methodology followed in this study has been adopted by the authors to other building components, with good results, namely to renderings (Gaspar and de Brito 2008), ceramic claddings (Galbusera et al. 2014), natural stone claddings (Emídio et al. 2014; Silva et al. 2016), paintings (Magos et al. 2016) and ETICS (Marques et al. 2018). Nevertheless, in the specific case of architectural concrete surfaces, the factor method led to worse results than when applied to other elements of the buildings’ envelope, which reveal that some relevant factors are not included in the proposed model. The technology involved in the execution of architectural concrete surfaces and the formulation of the concrete applied as cladding solution have a significant influence on the durability of the 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 (e.g. the concrete formulation and composition, the exposure class, the cover’s thickness) cannot be considered in the service life prediction model. This limitation can explain the variability of the degradation phenomena that is not encompassed in the proposed model.

This study is a first approach for the application of the factor method to the service life prediction of architectural concrete surfaces in Portugal, and future studies are required to improve the proposed model. Nevertheless, the results obtained are in accordance with the reality and the empirical knowledge regarding the durability of architectural concrete surfaces. Figure 3 shows the histogram of the estimated service life predicted by the factor method, adopting the quantification of the durability factors proposed in scenario 4, and the histogram of the service life predicted by the graphical method. The different methodologies lead to coherent results ranging between 43 years (for the overall degradation curve, presented in Figure 2) and 48 years (GM). The average estimated service life obtained by the proposed model for architectural concrete surfaces is in accordance to different studies related with the durability and service life of architectural concrete: i) adopting a similar methodology, Serralheiro et al. (2017) obtained an estimated service life of 44 years for architectural concrete surfaces; ii) Pakkala et al. (2014) refer that the expected service life of architectural concrete surfaces should be lower than 50 years, which is the service life conventionally accepted for structural concrete, considering that these surfaces are directly exposed to the degradation agents; iii) Takahashi et al. (2008) proposed an estimated service life of 50 years for precast concrete applied as external claddings.

7. Conclusions

Currently, there is a lack of reliable data and methodologies to evaluate the durability and service life of architectural concrete surfaces in in-service conditions. Moreover, the existing studies only address the characteristic of concrete (mechanical properties, composition, among other parameters), neglecting the influence of the real exposure conditions and the environmental degradation agents in the degradation of concrete elements. Moreover, the lack of knowledge regarding the impact of different degradation agents in the service life of architectural concrete surfaces usually leads to the adoption of standardised measures for maintenance and repair of these elements, regardless of the cause, the extent and the severity of the anomaly observed.

Therefore, this study intends to propose the application of the factor method for the service life prediction of architectural concrete surfaces, thus allowing encompassing different durability factors that influence the service life of architectural concrete surfaces. In this study, 239 architectural concrete surfaces are analysed *in situ*.

This study proposes a mathematical equation for the practical application of the factor method to the service life prediction of architectural concrete surfaces. In order to apply the proposed equation, practitioners should use the durability factors quantified by scenario 4, which shows the best overall results, i.e. this scenario allows maximising the similarity between the ESL predicted by the factor method and the ESL observed in reality. 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 of 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. In this sense, the equation and the quantification of the durability factors proposed in this study can be used, as proposed, in similar contexts (with similar exposure to environmental conditions). Moreover, the proposed method can be applied in other geographical contexts (mainly in Europe and other developed countries in the North hemisphere), with some adaptations (e.g. considering the effects of freeze/thaw cycles). The proposed model can be easily adapted, by tailoring the durability factors, adjusting the mathematical formulation to the specific reality and context of the architectural concrete analysed.

The factor method is an adequate and easily applicable tool for the service life prediction of architectural concrete surfaces, which can aid the establishment of maintenance and repair requirements, according to the potential degradation mechanisms and the correspondent estimated service life.

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 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 the basis of international standards, as a general framework for estimating the service life of buildings and their elements.

Acknowledgements

The authors gratefully acknowledge the support of the CERIS-ICIST Research Institute, IST, University of Lisbon and the FCT (Foundation for Science and Technology) through project PTDC/ECM-COM/5772/2014.

References

Ahmad, S. 2003. *Reinforcement corrosion in concrete structures, its monitoring and service life prediction - a review*, Cement and Concrete Composites, V. 25, No. 4-5, pp. 459-471.

Alghamdi, S.A., Ahmad, S. 2014. *Service life prediction of RC structures based on correlation between electrochemical and gravimetric reinforcement corrosion rates*, Cement and Concrete Composites, V. 47, pp. 64-68.

Cassar, L., Pepe, C., Tognon, G., Guerrini, G.L., Amadelli, R. 2003. *White cement for architectural concrete, possessing photocatalytic properties*, 11th International Congress on the Chemistry of Cement, Durban, South Africa, pp. 2012-2021.

Coelho, F., Silvestre, J., Brito, J., Silva, C. 2017. *Inspection, Diagnosis, and Repair System for Architectural Concrete Surfaces*, Journal of Performance of Constructed Facilities, V. 31, No. 6, pp. 04017097-1.

Custódio, J., Eusébio, M. 2006. *Waterborne acrylic varnishes durability on wood surfaces for exterior exposure*, Progress in Organic Coatings, V. 56, pp. 59-67.

Emídio, F., Brito, J., Silva, A., Gaspar, P. 2014. *Application of the factor method to the estimation of the service life of natural stone cladding,* Construction and Building Materials, V. 66, pp. 484-493.

Farahmandpour, K., Jennings, V., Willems, T., Davis, A. 2000. *Evaluation techniques for concrete building envelope components*, Proceedings of RCI Building Envelope Symposium, Seattle, USA.

Flores-Colen, I., Brito, J. de 2010. *A systematic approach for maintenance budgeting of buildings façades based on predictive and preventive strategies,* Construction and Building Materials, V. 24, No. 9, pp. 1718-1729.

Freedman, S. 2007. *Architectural precast concrete*, PCI (Precast/ Prestressed Concrete Institute), Chicago, USA.

Galbusera, M.M., de Brito, J., Silva, A. 2014. *Application of the factor method to the prediction of the service life of ceramic external wall cladding*, Journal of Performance of Constructed Facilities, V. 29, No. 3, pp. 04014086-1-10.

Garrido, M., Paulo, P., Branco, F. 2012. *Service life prediction of façade paint coating in old buildings*, Construction and Building Materials, V. 29, pp. 394-402.

Gaspar, P.L., de Brito, J. 2008. *Service life estimation of cement-rendered facades*, Building Research and Information, V. 36, No. 1, pp. 44-55.

Gaspar P., de Brito J. 2011. *Limit states and service life of cement renders on façades*, Journal of Materials in Civil Engineering, V. 23, No. 10, pp. 1393-1404.

Hongke, P., Zisheng, Y., Fuwei, X. 2016. *Study on concrete structure's durability considering the interaction of multi-factors*, Construction and Building Materials, V. 118, pp. 256-261.

Hopper, L. 2007. *Landscape architectural graphic standards,* John Wiley & Sons, New Jersey, USA, 547 p.

Hovde, P. 2002. *The factor method for service life prediction: From theoretical evaluation to practical implementation*, CIB9332, Norway, 10 p.

Hovde, P.J. 2004. *Engineering design methods for service life prediction. Performance based methods for service life prediction. State of the art, Part A*, CIB W080 / RILEM 175-SLM, Norway, pp. 1-51.

Hurd, M.K. 1990. *Avoiding arguments over architectural concrete. Architects and contractors need good specifications and a realistic understanding of available technology,* Publication# C 900759, The Aberdeen Group, Boston, USA.

Islam, Md. M., Alam, M.T., Islam, Md. S. 2018. *Effect of fly ash on freeze-thaw durability of concrete in marine environment*, Australian Journal of Structural Engineering, DOI: 10.1080/13287982.2018.1453332.

ISO 15686: 2011. *Buildings and constructed assets. Service life planning*, International Organization for Standardization, Switzerland.

Kessler, S., Strauss, A., Caspeele, R. 2017. *Present and future probabilistic challenges for maintenance of reinforced concrete structures*, In: Caspeele R., Taerwe L., Proske D. (eds.), 14th International Probabilistic Workshop, Cham, Germany, pp. 521-537.

Köliö, A., Pakkala, T.A., Annila, P.J., Lahdensivu, J., Pentti M. 2014. *Possibilities to validate design models for corrosion in carbonated concrete using condition assessment data*, Engineering Structures, V. 75, pp. 539-549.

Köliö, A., Niemelä, P.J., Lahdensivu, J. 2016. *Evaluation of a carbonation model for existing concrete facades and balconies by consecutive field measurements*, Cement and Concrete Composites, V. 65, pp. 29-40.

Lahdensivu, J., Mäkelä, H., Pirinen, P. 2013. *Durability properties and deterioration of concrete balconies of inadequate frost resistance*, International Journal of Sustainable Building Technology and Urban Development, V. 4, No. 2, pp. 160-169.

Leira, B., Lindgård, J., Nesje, A.; Sund, E., Sægrov, S. 1999. *Degradation analysis by statistical methods*, 8th International Conference on Durability of Buildings Materials and Components, Vancouver, pp. 1436-1446.

Liang, M.-T., Lin, L.-H., Liang, C.-H. 2002. *Service life prediction of existing reinforced concrete bridges exposed to chloride environment*, Journal of Infrastructure Systems, V. 8, No. 3, pp. 76-85.

Magos, M., de Brito, J., Gaspar, P.L., Silva, A. 2016. *Application of the factor method to the prediction of the service life of external paint finishes on facades*, Materials and Structures, V. 49, No. 12, pp. 5209-5225.

Marques, C. de Brito, J., Silva, A. 2018. *Application of the factor method to the service life prediction of ETICS*, International Journal of Strategic Property Management, V. 22, No. 3, pp. 204-221.

Marteinsson, B. 2003. *Durability and the factor method of ISO 15686-1*, Building Research & Information, V. 31, No. 6, pp. 416-426.

McDuling, J.J., Horak, J.J., Cloete, C.E. 2008. *Evaluation of environmental degradation factors for service life prediction*, 11th International Conference on Durability of Building Materials and Components, Istanbul, Turkey, 11-14 May 2008.

Pakkala, T., Köliö, A., Lahdensivu, J., Kiviste, M. 2014. *Durability demands related to frost attack for Finnish concrete buildings in changing climate,* Building and Environment, V. 82, pp. 27-41.

Pakkala, T., Lemberg, A.-M., Lahdensivu, J., Pentti, M. 2016. *Climate change effect on wind-driven rain on facades*, Nordic Concrete Research, The Nordic Concrete Federation, Publication No. 54, pp- 31-50.

PCA 2007. *Architectural precast concrete,* Portland Cement Association, Third edition, Canada, 609 p.

Pereira, C., de Brito, J., Silvestre, J.D. 2018. *Contribution of humidity to the degradation of façade claddings in current buildings*, Construction and Building Materials, V. 90, pp. 103-115.

Peurifoy, R., Oberlender, G. 2011. *Formwork for concrete structures*, 4th Edition, McGraw-Hill, Columbus, USA.

Serralheiro, M.I., Brito, J., Silva, A. 2017. *Methodology for service life prediction of architectural concrete facades*, Construction and Building Materials, V. 133, pp. 261-274.

Silva, C., Coelho, F., de Brito, J., Silvestre, J., Pereira, C. 2017. *Inspection, diagnosis, and repair system for architectural concrete surfaces*. Journal of Performance of Constructed Facilities, V. 31, No. 5, pp. 04017035.

Straub, A. 2015. *Estimating the service lives of building products in use*, Journal of Civil Engineering and Architecture, V. 9, No. 3, pp. 331-340.

Wojciechowski, K., Skowera, E., Pietniewicz, E., Zukowska, G., Ven, L., Korczagin, I., Malanowski, P. 2014. *UV stability of polymeric binder films used in waterborne facade paints*, Progress in Organic Coating, V. 77, No. 2, pp. 298-304.

FIGURE CAPTIONS

Figure 1. Anomalies in architectural concrete: a) biological growth (aesthetics); b) mapped cracking (mechanical); and c) honeycombing (constructive)

Figure 2. Degradation curve obtained for the 239 architectural concrete surfaces analyzed, and an illustrative case study that has reached the end of its physical service life

Figure 3. Histograms of the ESL obtained by factor and graphical methods

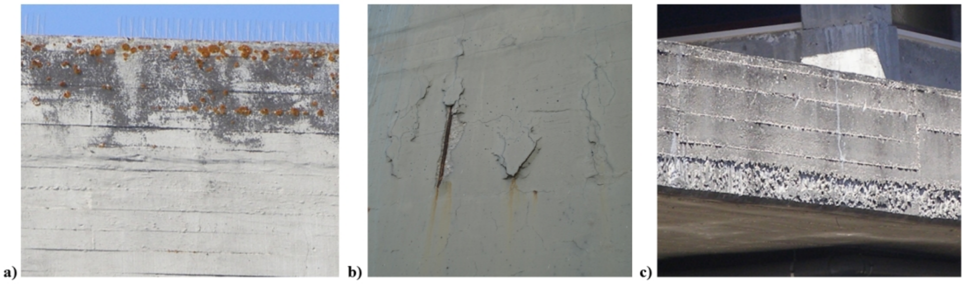

Figure 1. Anomalies in architectural concrete: a) biological growth (aesthetics); b) cracking and disaggregation/spalling (mechanical); and c) honeycombing (constructive)

138x46mm (300 x 300 DPI)

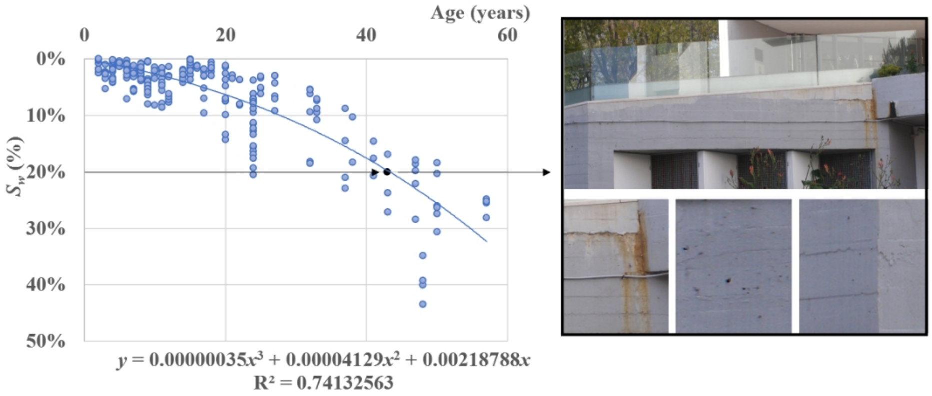

Figure 2. Degradation curve obtained for the 239 architectural concrete surfaces analyzed, and an illustrative case study that has reached the end of its physical service life

149x63mm (300 x 300 DPI)

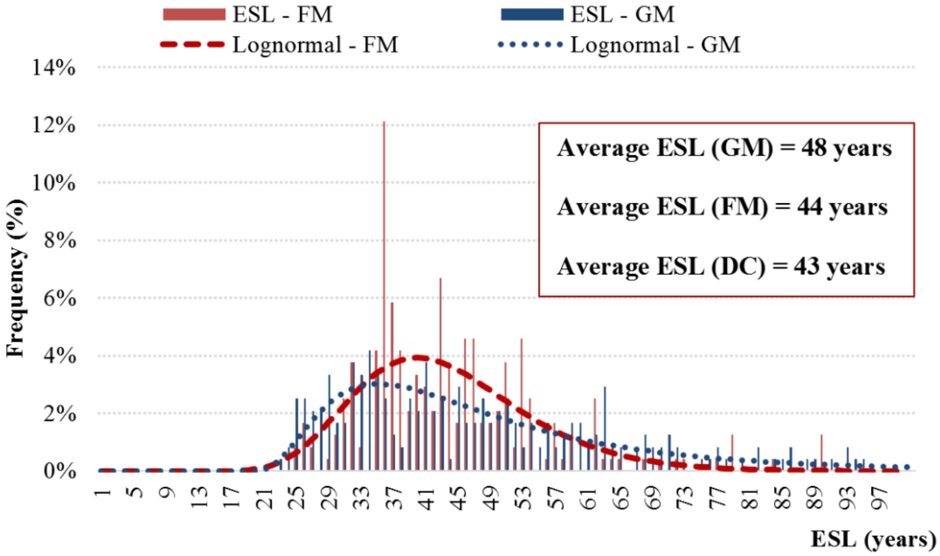

Figure 3. Histograms of the ESL obtained by factor and graphical methods

100x64mm (300 x 300 DPI)

Table 1. Degradation levels for the different anomalies observed in architectural concrete surfaces (data sourced from Serralheiro et al., 2017)

Anomalies group	Anomalies description	$k_{a,n}$	Degradation level				
			Level A	Level B	Level C	Level D	Level E
Aesthetic anomalies	Dirt stains	0.15	No visible degradation	< 15%	15% to 40%	> 40%	-
	Moisture stains	0.15					
	Corrosion stains	0.50					
	Wear/erosion	2.00		< 10%	10% to 30%	> 30%	
	Bug holes	0.10					
	Biological growth	0.60					
	Efflorescence	0.20					
Mechanical anomalies	Disaggregation/spalling	5.00/ 4.00		-	< 10%	10% to 30%	> 30%
	Oriented cracking (≤ 0.5 mm)	1.00			< 5%	-	-
	Oriented cracking (> 0.5 mm and < 3 mm)	1.00			-	≥ 5%	-
	Oriented cracking (≥ 3 mm)	1.00			-	< 5%	≥ 5%
	Mapped cracking	0.15			-	< 50%	≥ 50%
Constructive anomalies	Flatness defects	0.10		< 20%	20% to 50%	> 50%	-
	Dribbling	0.10		< 10%	≥ 10%	-	
	Fastening marks	0.10		-	≤ 5%	> 5%	
	Honeycombing	0.30			< 10%	≥ 10%	
	Formwork incrustation	0.10					

Table 2. Service life predicted by the graphical method and by the degradation curves for the durability factors under analysis

Surfaces' characteristics			**Graphical method**	**Degradation curves**	***k* initial value**
Color (*A*1)	Dark	*k*1	42.6	46.0	0.95
	Light	*k*2	50.2	42.6	1.00
Surfaces' treatment (*A*2)	Without protection	*k*1	47.3	43.9	0.80
	Paint	*k*2	48.9	39.0	1.10
	Water repellent	*k*3	49.2	39.3	1.00
	Paint + water repellent	*k*4	67.5	79.1	1.20
	Varnish	*k*5	36.5	42.7	0.80
Type of finish (*B*1)	Flat	*k*1	46.7	41.7	1.00
	Textured	*k*2	53.1	45.3	1.00
Orientation (*E*1)	North	*k*1	50.7	42.3	1.00
	W/NW	*k*2	47.7	46.8	0.90
	SE/E/NE	*k*3	48.3	40.0	1.00
	S/SW	*k*4	47.3	40.7	0.80
Distance from the sea (*E*2)	< 1 km	*k*1	47.3	35.5	0.90
	Between 1 km and 5 km	*k*2	52.0	44.5	1.00
	> 5 km	*k*3	46.0	48.5	1.10
Exposure to damp (*E*3)	Low	*k*1	51.5	45.9	1.10
	High	*k*2	45.0	39.9	1.00
Surfaces' protection (*E*4)	With protection	*k*1	47.3	45.3	1.00
	Without protection	*k*2	49.8	37.5	0.90
Wind/rain exposure (*E*5)	Low	*k*1	45.3	45.6	1.00
	High	*k*2	49.9	42.0	0.95
Ease of inspection (*G*1)	Yes	*k*1	47.3	45.3	1.20
	No	*k*2	49.8	37.5	1.00

Table 3. Factors for each of the scenarios considered

Conditioning factors			**Scenario 2**	**Scenario 3**	**Scenario 4**
Color	Dark	$k1$	0.80	0.90	0.900
	Light	$k2$	1.00	1.00	1.200
Surface treatment	Without protection	$k1$	0.80	0.90	0.800
	Paint	$k2$	1.00	1.00	1.100
	Water repellent	$k3$	1.00	1.00	1.025
	Paint + water repellent	$k4$	1.20	1.10	1.200
	Varnish	$k5$	0.80	0.90	0.900
Type of finish	Flat	$k\ 1$	1.00	1.00	0.800
	Textured	$k2$	1.20	1.10	1.200
Orientation	North	$k1$	1.20	1.00	1.100
	W/NW	$k2$	1.00	1.00	1.000
	SE/E/NE	$k3$	1.00	1.00	1.000
	S/SW	$k4$	0.80	0.90	0.850
Distance from the sea	< 1 km	$k1$	0.80	0.90	0.800
	Between 1 km and 5 km	$k2$	1.00	1.00	0.950
	> 5 km	$k3$	1.20	1.10	1.000
Exposure to damp	Low	$k1$	1.20	1.10	1.000
	High	$k2$	1.00	0.90	0.875
Surface protection	With protection	$k1$	1.00	1.00	1.050
	Without protection	$k2$	0.80	0.90	1.000
Wind/rain exposure	Low	$k1$	1.00	1.00	1.250
	High	$k2$	0.80	0.90	1.000
Ease of inspection	Yes	$k1$	1.00	1.10	1.050
	No	$k2$	0.80	1.00	1.000

Table 4. Statistical indicators of the scenarios considered

Scenarios		**1**	**2**	**3**	**4**
FM/GM average < 1.05		1.04	0.85	0.97	1.02
Standard deviation		0.37	0.37	0.35	0.37
Amplitude of results	Factor method (years)	0.0	58.31	37.63	65.60
	Graphical method (years)	85.29	85.29	85.29	85.29
Extremes values obtained in the factor method	Maximum = 100 years	43.42	72.67	63.49	89.89
	Minimum = 22 years	43.42	14.35	25.87	24.29
FM/GM ≥ 0.85 (≥ 50%)		64.85%	47.28%	61.51%	70.71%
FM/GM ≥ 1.50 (< 10%)		12.97%	5.86%	6.69%	8.79%
0.85 ≤ FM/GM ≤ 1.15		28.45%	31.96%	34.31%	45.19%