Quantification of exposure classes in The European Standard EN 206-1

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ABSTRACT

The recently completed EU-project Life Cycle Management of Concrete Infrastructure for Improved Sustainability (Lifecon) has developed a generic and predictive Life Cycle Management System (LMS) for maintenance optimisation and planning of buildings. The system facilitates the change of today's reactive practice of maintenance management into a predictive life cycle based maintenance management system. To enable simplified prediction of service life and maintenance interval in such a predictive life cycle management system, a quantitative classification system for environmental loading is needed. At present there are a number of standards containing quantitative classification of environmental loading onto structures and building materials, e.g. ISO 15686-4, EOTA and ISO 9223. The governing standard for concrete structures such as bridges and tunnels is the European Standard EN 206-1 Concrete – part 1: Specification, performance, production and conformity. This standard divides the environmental loading into 18 exposure classes, which cover environmental loads from atmosphere, seawater, fresh water, groundwater and soil, but also the decisive parameters for moisture and chlorides. Almost all exposure classes within the standard include only qualitative descriptions. To make the standard EN 206-1 valid for LMS the standard has to be further developed into a quantitative classification system for environmental loading. A proposal of a quantitative classification of the exposure classes within the standard EN 206-1 regarding corrosion induced by carbonation is presented in this paper. The proposed classification is partly based on the extensive work performed in the Lifecon project, partly based on literature studies. The proposed classification is validated through comparison of real measurements made on a bridge located in Sweden and calculations using a full probabilistic degradation model. It is believed that such exposure classification is possible to use in a LMS to provide simplified service life analysis and possibilities to map the risk of degradation.

KEYWORDS

Quantitative classification, exposure classes, carbonation, EN 206-1

1 INTRODUCTION

In the beginning of 2001 the EU-project, the G1RD-CT-2000-003788 “Life Cycle Management of Concrete Infrastructures for Improved Sustainability” (Acronym: Lifecon) was launched. The aim of the project was to develop a European model of a predictive and generic Life Cycle Management System (LMS) and to promote the turn of today’s reactive approach of maintenance management towards a predictive life cycle based approach [Söderqvist & Vesikari 2003]. LMS is aimed to support all types of decision-making within maintenance management of buildings and infrastructures. It will include optimal planning of maintenance, repair and rehabilitation (MR&R) over time. The system includes an inventory part and condition assessment part, a service life and maintenance analysis part and a maintenance optimisation and planning part. The system is predictive, which means that it is possible to predict the service life performance of a building or a component over a period of time. Consequently, it will be possible to find the most appropriate maintenance action and intervals. The service life performance analysis is based on degradation models developed for a number of material families. These degradation models describe the material degradation rate affected by environmental loads. Simplified service life analysis cannot be done without systems for characterisation and quantitative classification of environmental loads. At present there are a number of standards containing quantitative classification of environmental loads onto structures and building materials e.g. ISO 15686-4, EOTA and ISO 9223 [Haagenrud & Krigsvoll 2003]. The governing standard for concrete structures such as bridges and tunnels is the European standard EN 206-1 [EN 206-1 2000]. This standard contains a qualitative classification system of environmental loads describing 18 different exposure classes. When to utilise the standard in service life performance analysis a quantitative description of the exposure classes is preferred. This paper presents a proposal of possible quantitative classification of the exposure classes within the standard EN 206-1 regarding corrosion induced by carbonation. The proposal is partly based on the extensive work performed in the Lifecon project, partly based on literature studies. The proposed classification is applied on a bridge in order to validate the quantitative exposure classification. The validation is done through comparison of real measurements and calculations of corrosion induced by carbonation.

2 BRIEF INTRODUCTION TO EN 206-1

The objective of the European standard EN 206-1 is to provide a harmonised Euro standard that will work as a base for CE-marking of concrete [EN206-1 2000]. The standard is valid for concrete for in-situ constructions, prefabricated constructions and for prefabricated structural elements. The requirements of concrete due to its performance to withstand influences from the surrounding environment is expressed in limit values or derived from performance based dimension methods. The requirements must take service life aspects into consideration, where the intended service life should be at least 50 years including moderate maintenance [EN 206-1 2000]. When to specify the requirements of concrete property for a certain structure, the environmental loads have to be characterised and classified due to the location of the structure. Exposure category as corrosion induced by carbonation, chlorides from seawater and from de-icing salts, freeze/thaw attack and chemical attack are classified and described. The only exposure category that provides a quantitative description of the exposure classes is chemical attack. This study will, however, focus on corrosion of reinforced concrete induced by carbonation and how a qualitative description of the exposure classes could be translated into a quantitative description. The current qualitative description of the classification due to corrosion induced by carbonation is to be seen in table 1.

Corrosion induced by carbonation		
Where concrete containing reinforcement or other embedded metal is exposed to air moisture, the exposure shall be classified as follows:		
XC1	Dry or constantly wet	Concrete inside buildings with low air humidity Concrete permanently submerged in water
XC2	Wet, rarely dry	Concrete surfaces subject to long-term water contact Many foundations
XC3	Moderate humidity	Concrete inside buildings with moderate or high air humidity. External concrete sheltered from rain
XC4	Cyclic wet and dry	Concrete surfaces subject to water contact, not within exposure class XC2

Table 1. Exposure classification due to carbonation [EN 206-1 2000]

3 INFLUENCING PARAMETERS ON CORROSION INDUCED BY CARBONATION

Corrosion of reinforcement in concrete induced by carbonation consists of two partial processes; 1) the initiation phase where the carbonation process takes place, 2) the propagation phase where corrosion of the re-bars starts and propagates. The whole process is a diverging process where a rise in relative humidity will decrease the carbonation process but increase the corrosion rate on the re-bars on condition that the surrounding concrete is depassivated. Except for material resistance parameters and relative humidity, environmental loading parameters represented by climate factors such as temperature and rain and pollution factors such as carbon dioxide, will have an influence on the degradation rate. Although carbon dioxide have a great impact in the carbonation process the exposure classes within EN-206 due to corrosion induced by carbonation only takes into account moisture factors as relative humidity and rain.

3.1 Relative humidity

Because corrosion of reinforced concrete induced by carbonation is a diverging process, affected by the relative humidity, the classification of the relative humidity needs to take both partial processes into account. Steffens *et al*. [2002] assumed that a maximum carbonation reaction rate is reached when the relative humidity exceeds approximately 90 %. Based on experimental tests they derived an empirical function that showed a distinct decrease in diffusion coefficient at a relative pore humidity of 60 %. At a relative humidity above 82 % the diffusion coefficient were only 10 % of its value for dry concrete [Steffens *et al*. 2002]. According to Neville [1995] the highest rate of carbonation occurs at a relative humidity between 50 and 70 %. In Betongrapport 11 [2002] a description of the influence of relative humidity on concrete is divided into four classes, table 2.

RH in concrete [%]	Carbonation	Corrosion induced by carbonation
< 45	1	0
45-65	3	0
65-85	2	1
85-99	1	3
100	0	1

Table 2. Risk of deterioration due to carbonation influenced by relative humidity (RH). Risk factors: 0 = negligible, 1 = low, 2 = moderate, 3 = high [Betongrapport 11 2002]

Tuutti [1982] concluded that the highest corrosion rate due to carbonation was obtained at a relative humidity of 90-95 %. He also concluded that corrosion rate induced by carbonation were insignificant at relative humidities lower than 80 %. In the Lifecon project a parameter study was performed, using a full-probabilistic model of carbonation where both the initiation phase and the propagation phase were taken into account [Lay *et al*. 2003]. The influence from average annual relative humidity were divided into five classes (0-4), see fig. 1. According to the parameter study the relative humidity has the greatest influence on the propagation between 81 and 91 % and lowest influence below 60 % and above 93 %, see table 3.

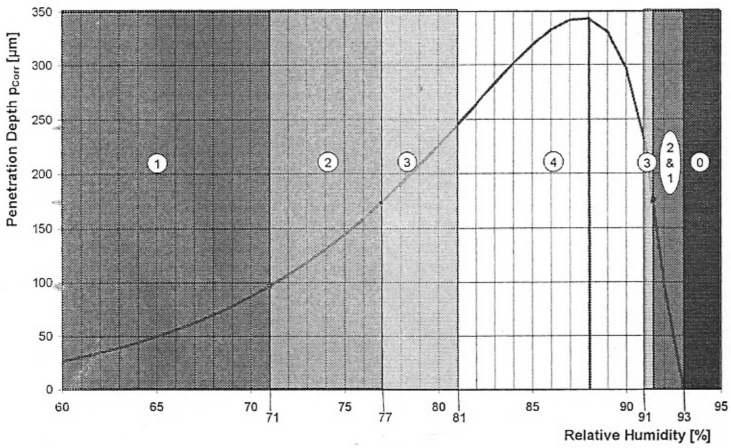


Figure 1. Variation of penetration depth in the re-bars due to the relative humidity regarding a sheltered structure 100 years of service life [Lay *et al.* 2003]

Class	0	1	2	3	4
RH (%)	< 60	60 – 71	71 – 77	77 – 81	81 – 90
	>93	-	-	90 – 91.5	-

Table 3. Classification of average annual relative humidity due to corrosion induced by carbonation [Lay *et al.* 2003]

3.2 Time of wetness

As the exposure classification due to carbonation induced corrosion within the EN 206 includes the effect from wetness this has also to be included in a quantification of the exposure classes. The time of wetness has the same diverging effect on the carbonation process as the relative humidity. The longer the concrete is exposed to wetness, the slower the carbonation rate. On the other hand, the higher the moisture content, the higher the corrosion rate. Concrete constantly exposed to water, including a surrounding relative humidity of 100 %, will not suffer due to carbonation. A simulation of the influence from the time of wetness (ToW) on corrosion induced by carbonation was performed assuming a 100-year-old horizontal structure located in an average relative humidity of 75 % [Lay *et al.* 2003]. The conclusion from the simulation is that corrosion will occur if the ToW is between 0 and 6.5 %. The ToW is defined as the quotient between the numbers of days with decisive rain more than 2.5 mm per day and the number of days per year [Lay *et al.* 2003].

4 QUANTITATIVE CLASSIFICATION

When concerning corrosion induced by carbonation it is important to take the corrosion rate into consideration. Limit values of relative humidity affecting the corrosion rate presented by Tuutti [1982], Lay *et al.* [2003] and in Betongrapport 11 [2002] is roughly summarised in table 4. Based on the limit values presented in table 4 and the qualitative descriptions in EN 206-1 the suggestion is that the exposure classes could adopt the quantitative limit values presented in table 5.

	RH limits according to:		
Corrosion rate	Tuutti	Lay *et al.*	Betongrapport 11
Insignificant	<80 or 100	<60 or >93	<65

Moderate	80-90	60-81	65-85 or 100
High	90-95	81-90	85-99

Table 4. Summary of limit values of relative humidity affecting corrosion rate induced by carbonation

Class	Qualitative description	Quantitative description, RH [%]	Quantitative description, ToW [%]
XC1	Dry or constantly wet	< 60 or ≥ 100	0 or 100
XC2	Wet, rarely dry	> 95	> 6.5
XC3	Moderate humidity	60 – 85	0
XC4	Cyclic wet and dry	85 – 95	0 – 6.5

Table 5. Proposal of quantitative description of the exposure classes due to corrosion induced by carbonation

The ToW limit values are based on the study made by Lay *et al*. [2003]. In order to prove the validity of the proposed classification, it has to be validated. In this study the validation is performed by comparison of the results from calculations and measurements. The calculations are based on the same degradation model as was used by Lay *et al*. [2003] while the results from measurements are based on carbonation depth measurements performed on a bridge located in Gävle, Sweden [Grändås 1994].

5 DEGRADATION MODEL DUE TO CARBONATION INDUCED CORROSION

The carbonation depth and the corrosion rate are estimated by using the same degradation model as used by Lay *et al*. [2003]. The model, described by Gehlen [2000], includes both the initiation phase and the propagation phase. The initiation phase is defined in eq.1. It describes the carbonation depth due to a number of parameters.

$$Xc = \sqrt{2 \cdot K_{RH} \cdot K_c \cdot (K_t \cdot R_{ACC,0}^{-1} + \varepsilon_t) \cdot \Delta C_s} \cdot \sqrt{t} \cdot \left(\frac{t_0}{t}\right)^w \qquad (1)$$

Xc is the carbonation dept at time t, K_{RH} is a relative humidity factor, K_c is a curing factor, K_t is a test factor, $R_{ACC,0}$ is the effective carbonation resistance measured in an accelerated test, ε_t is an error factor, ΔC_s is the gradient of CO_2 concentration, t is the time in service, t_0 is a reference period, i.e. when the accelerated test is performed and w is a weather exponent. In this study, the humidity factor and the weather exponent are of special interest. The humidity factor is a function influenced by the relative humidity while the weather exponent is a function influenced by the time of wetness.
The propagation of corrosion on the re-bars is defined as:

$$P(t) = V_{corr} \cdot \alpha \cdot t_{prop} \qquad (2)$$

P(t) is the progressive loss of re-bar diameter, V_{corr} is the corrosion rate related to surface area, α is the pitting factor, t_{prop} is the time during propagation (t-t_{init}), i.e. the time after initiation phase. Hence, the link between the two phases is the time during initiation. Redefining eq. 1 the time during initiation phase is solved, eq. 3.

$$t_{init} = \left(\frac{Xc}{\sqrt{2 \cdot K_{RH} \cdot K_c \cdot (K_t \cdot R_{ACC,0}^{-1} + \varepsilon_t) \cdot \Delta C_s} \cdot (t_0)^w}\right)^{\frac{1}{0,5-w}} \qquad (3)$$

It is assumed that during the initiation phase, no propagation of corrosion will take place. Applying Faraday's law the corrosion rate is expressed as:

$$V_{corr} = 11.6 \cdot i_{corr} \qquad (4)$$

where i_{corr} is the corrosion rate density which can be expressed as:

$$i_{corr} = \frac{k_0}{p(t)} \cdot F_{cl} \cdot F_{galv} \cdot F_{o_2} \qquad (5)$$

k_0 is a constant regression parameter, F_{cl}, F_{galv} and F_{O2} take into account the influences from chlorides, galvanic effects and availability of oxygen respectively. The p(t) factor takes into account a number of factors concerning temperature, relative humidity, chlorides, test method and curing.

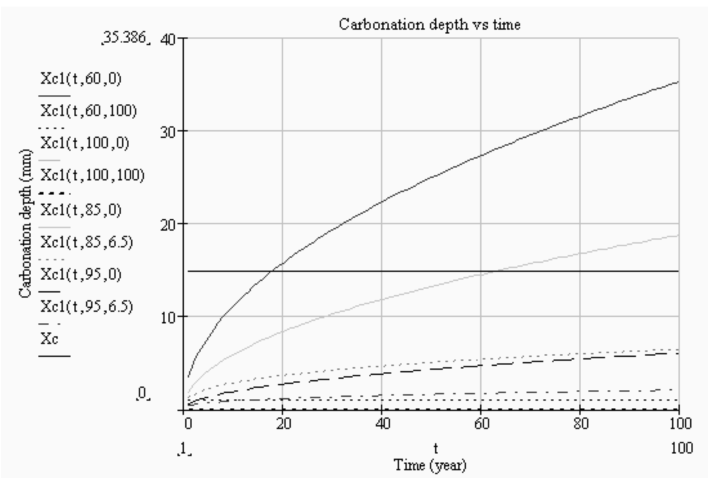
6 RESULTS FROM CALCULATIONS AND COMPARISONS TO REAL MEASUREMENTS

In 2004, the bridge in Gävle had been in service for 66 years. In 1994, i.e. after 56 years in service, carbonation depth measurements were performed on the side of the beams and on the underside of the slab [Grändås 1994]. Two samples were taken from the side of the beams and three samples from the underside of the slab. The result from the measurements is given in table 6. According to the classification in EN 206 both the beams and the underside of the slab would be classified as XC3. The result from the measurements shows, however, an appreciable difference in carbonation depth between the two structure types.

Component	Concrete cover [mm]	Exposure class EN 206	Sample	Carbonation depth underside [mm]	Carbonation depth under the surfacing [mm]
Beam	30	XC3	1	33	-
Beam	30	XC3	2	23	-
Slab	15	XC3	3	5	0
Slab	15	XC3	4	5	0
Slab	15	XC3	5	8	0

Table 6. Carbonation measurements on the bridge in Gävle [Grändås 1994]

Many parameters in the degradation model are hard to define without measurements, therefore the same values as was used by Lay *et al.* [2003] and by Gehlen [2000] are used in this validation. The input values of relative humidity and time of wetness refers to the proposed classification in table 5. According to the calculations, the carbonation depth varies between 14 mm and 26,5 mm considering a structure in exposure class XC3, made of "poor" concrete, sheltered from rain. The results well correspond to the measurements on the beams but not to the measurements on the slab. As can be seen in figure 2, the variations in carbonation depth are quite large. As an example, for a 60-year-old structure in exposure class XC3, the carbonation depth will vary from 15 mm to 27 mm. If the structure is exposed to rain, the carbonation depth will be very low, below 10 mm after 100 years of exposure. Even if calculations of corrosion propagation on the re-bars are not comparable to measurements due to the fact that there are no corrosion measurements done, it is important to present the calculation result in order to show the effect from the proposed classification. For a 56-year-old structure in exposure class XC3, made of same type of concrete as used above and with concrete cover



of 15 mm, the corrosion depth will vary from 0 to 180 µm. In figure 3 the corrosion rate varies due to different relative humidity regarding a 56-year-old structure with a concrete cover of 15 mm. The highest rate of corrosion occurs at a relative humidity around 70 to 80 %. In figure 4 the corrosion rate is presented over time for different relative humidity. The higher the relative humidity, the higher the rate of corrosion. On the other hand, the higher the relative humidity, the later the corrosion will begin.

Figure 2. Different carbonation depths due to the limit values stated in the proposed classification described in table 5

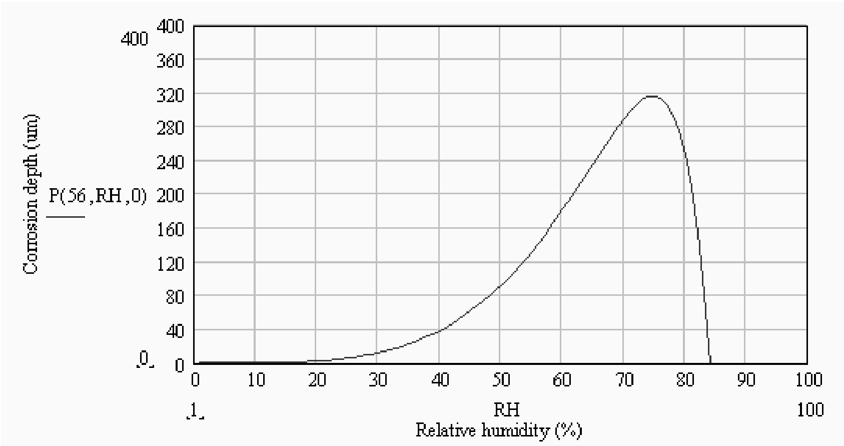


Figure 3. Varying corrosion depth due to variations in relative humidity. The concrete cover is 15 mm.

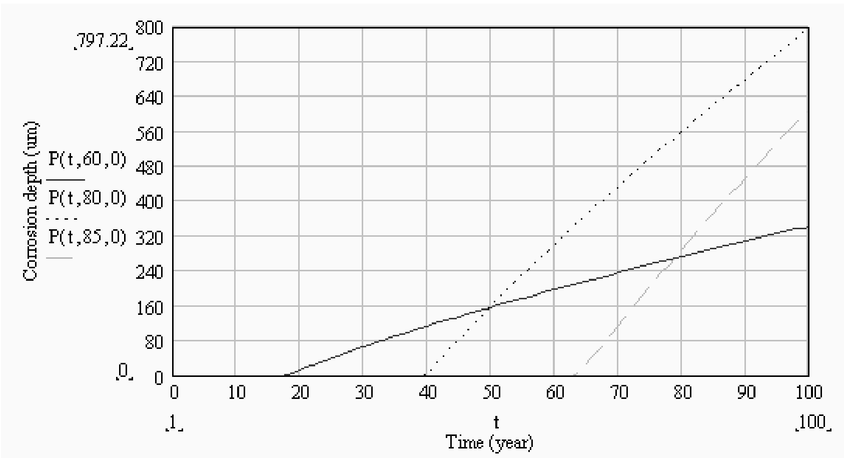


Figure 4. Varying corrosion depth over time due to variations in relative humidity. The concrete cover is 15 mm.

7 CONCLUSIONS AND RECOMMENDATION OF FURTHER WORK

A quantitative description of the exposure classes due to corrosion induced by carbonation is presented and validated through a case study of a bridge structure. It is believed that such quantitative exposure classification is possible to use in LMS in order to provide simplified service life analysis and provide possibilities to map the risk of degradation on structures. Validation of the quantitative classification shows some differences between calculations and measurements of carbonation depth. There is also some differences between the calculations made in this study and the study made by Lay *et al*. [2003]. The measured carbonation depths are different at different location of the bridge. This is expected, due to the fact that different locations of the bridge are exposed to different environmental loads. The environmental loads, exposing the bridge, have, however, not been identified nor quantified. Corrosion measurements have not been made on the bridge, which makes it impossible to compare calculations and measurements of corrosion depths. Nevertheless, the bridge demonstrate severe corrosion damages due to either carbonation or chloride ingress. It is recommended one improve the validation of the proposed quantitative exposure classification by extending the number of case studies. A prerequisite is that case studies should include well-documented structures, well-documented damages and well-defined environmental loads. The latter include mapping of relative humidity and wetness spreading at the structure surface. Such mapping, including measurements and photography, could be added in to a 3-D model of the structure in order to provide 3-D virtual demonstration of different exposure zones. The including parameters in the degradation model have to be correctly defined. Preferable by a thorough investigation of the material properties of every including structures. Other future work would be to quantify the other exposure classes in EN 206 in order to make the complete standard valid for a LMS.

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