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► **To cite this version:**

Michaël Dierkens, Bruno Godart, Jonathan Mai-Nhu, Patrick Rougeau, Lionel Linger, et al.. French national project 'PERFDUB' on performance-based approach : interest of old structures analysis for the definition of durability indicators criteria. 16th fib Symposium, Concrete Innovations in Materials, Design and Structures, May 2019, CRACOVIE, Poland. 8 p. hal-02545736

HAL Id: hal-02545736

<https://hal.science/hal-02545736v1>

Submitted on 17 Apr 2020

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FRENCH NATIONAL PROJECT “PERFDUB” ON PERFORMANCE-BASED APPROACH: INTEREST OF OLD STRUCTURES ANALYSIS FOR THE DEFINITION OF DURABILITY INDICATORS CRITERIA

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Abstract

The French National Project PERFDUB aims at setting up a methodology for justifying durability of concrete structures within a performance-based approach. The final objective is to make the performance-based specification operational and more commonly used by bringing together the current knowledge and feedback, to fill remaining gaps. This methodology relies on physical and chemical material properties which are called regarding the environmental conditions of the concrete structure. A major part of work in PERFDUB is to define durability criteria based on laboratory tests (durability indicators or accelerated ageing tests) in function of exposure classes and expected lifetime. This article deals, on the one hand, with the analysis of durability test results obtained from cores drilled out of ancient civil engineering concrete structures (built between 1912 and nowadays) compared with corrosion state of reinforcement. On the other hand, modelling works are presented dealing with carbonation, chloride ingress and corrosion rate (since design service life is presently considered to be defined by the time before appearance of first cracks induced by steel corrosion). The proposed durability criteria are taking into account both approaches, in order to benefit from all the available feedback on old structures and cross-check results obtained from theoretical modelling work. The aim is to ensure a soft transition between current practices and design based on performance-based approach. This study is closely related to work in progress on Exposure Resistance Class (ERC) at European level.

Keywords: Performance-based approach, Durability indicators.

1. Introduction

The PERFDUB research project aims at defining a methodology at the French national level to justify the durability of concretes (and concrete structures) through a performance-based approach, including the so-called "absolute" and "comparative" methods. In the “absolute” way the durability properties of the candidate concrete are compared to threshold values. In the “comparative” one the durability properties of a candidate concrete are compared to those of the reference concrete.

The objective of PERFDUB project is to aggregate knowledge and return of experience, to fill gaps, in a framework bringing together all the stakeholders concerned so that the performance-based approach becomes operational and commonly used on construction sites, which is not yet the case today. The application of the performance-based approach to durability is already authorized by the European standard EN 206 (and its national complement NF EN 206 / CN) and a first methodology is given in the new guideline n°65 of the CCTG (general technical clauses for public contracts).

Durability testing is the foundation of the performance-based approach to concrete durability. The objective of this ongoing national project is to select, for each exposure class of concrete defined in

standard NF EN 206 / CN, one or more durability indicators associated with sound and reliable tests that make it possible to compare and / or evaluate the capacity of concrete to resist a given deterioration.

The main task of the working group 2 of this national project, that is presented in this paper, is to deal with existing structures and to determine the present and initial values of the durability indicators of the concretes as well as the condition of the structure in order to define or validate the thresholds that would ensure the structure durability.

2. General methodology

One of the challenges of the project is to establish a framework for using durability tests in a context of assessing the durability of existing structures. The performance-based approach must indeed lead to the use of durable concretes resistant to the aggressions for which they have been specified. Durability tests help ensuring this before and during construction. These tests also make it possible to evaluate the durability of the concretes of the structures in service. This is a major challenge for Owners who need to know the condition of their structures and anticipate their deterioration to optimize their maintenance planning. Durability tests, carried out as part of diagnostics in combination with other techniques, are essential tools for the evaluation and prediction of the aging of structures in service; they are complementary to lifetime control parameters (chloride penetration profile, carbonation depth, degree of steel corrosion, etc...) which make it possible to follow the evolution of any potential pathology affecting the structures over time, and more generally the aging of the structures.

To achieve this objective, works are in progress in the field of PERFDUB in order to obtain four sets of data and tools:

- the durability properties of current concrete complying with deemed-to-satisfy provisions, in the field of PERFDUB project a large data (41 concrete) base is in progress,
- statistical data on the in-situ variability of durability indicators in order to define mean and fractile values as for the compressive strength,
- durability models including migration, depassivation and corrosion mechanisms, and the evolution of the durability indicators of concrete structures in their environment (due to the aging of concrete and external aggressions).

As part of the present study, five structures were selected from a panel of about ten pre-identified ones. These five structures already have data on durability measurements (water porosity, chloride diffusion, gas permeability, carbonation, etc.) obtained during their construction phase or during service phase monitoring. They are supplemented by a sixth case study consisting on test elements named BHP 2000 casted for a previous research project performed about 20 years ago.

Depending on the diagnostic elements available and the context of aggressiveness of the structure, the durability indicators (water porosity, chloride diffusion coefficient, gas permeability coefficient, etc.) will be measured at the current time, in the laboratory, based on samples taken in the field.

An in-depth analysis of the evolution of the durability indicators will be established. In particular, it will make it possible to check the relevancy of the thresholds currently proposed for each indicator and environmental class. The main interest of the study of these ancient structures is to be able to consider these thresholds with the hindsight of time.

3. Presentations of the main investigated structures

3.1. Bridge over the Bruche

The bridge of the RD 2420 on the Bruche at La Broque is located in the Vosges mountains. It has two spans (length: 12 m and 26 m, width: 11.5 m), and consists of a reinforced concrete slab resting on abutments and a masonry pier. It was rebuilt in 1947. The exposure class chosen for the structure is XC4. Given the low exposure to de-icing salts, except for runoff from cornices, as well as moderate frost, classes XF1 / XD3 can also be selected.

3.2. TCD Wharf on the Scorff

The TCD wharf, built in the years 1964 and 1965, is used for arming ships. The deck consists in a reinforced concrete slab 42 cm thick, free of stiffening beams; it rests on vertical and oblique steel piles by means of reinforced concrete coronation heads. The wharf is located in a marine environment (XS3). The intrados of the deck is exposed to spray. When the tidal coefficient is high, it can be exposed to splashing as well.

3.3. Vasco de Gama Bridge over the Tagus

The Vasco de Gama bridge (Portugal) is an exceptional structure (17.2 km long) for which a 120-year design lifespan was required as an essential criterion of the specifications laid down during its construction from 1995 to 1998. Due to its geographical location in the estuary of the Tagus, the durability of concrete subjected to the aggressive marine environment was a major concern during the design of this bridge; the corrosion of reinforcement induced by the penetration of chlorides being one of the main causes of possible degradation identified.

The results obtained are related to two formulas: concrete precast segments located at the base of the central viaduct piers, and concrete columns from the south viaduct. These data are supplemented by the chloride profiles (free and total) measured in the tidal range of these two structures (exposure class XS3).

3.4. Rion-Antirion Bridge

Built between 1999 and 2004, the Rion-Antirion Bridge is the world's longest multi-span cable stayed bridge, with a continuous deck of 2.252 m and over 600 m of approach viaducts, in addition to the access roads. It is located in Greece, in the Gulf of Corinth and is exposed to marine environment. The service life required in the specifications is 120 years. Two concrete samples are studied (from the same mix design): one coming from a durability test wall that was built at the base of pier (P2) of an access viaduct to minimize sampling on the structure (wall exposed to spray and splash), and the other coming from pier M2 in the tidal zone.

3.5. Bridge over the Rance

Built between 1987 and 1991, the Chateaubriand Bridge over the Rance consists in an arch bridge with a composite deck of 15 spans. Its total length is 424 m. It is located in a marine exposure. The results obtained are related to piers concerned with tidal area and sprays (XS3).

3.6. BHP2000 test elements

The test elements are trapezoidal concrete prisms (thickness equal to 400 mm at the base for 200 mm at the top) of height 0.95 m, length 1 m and having a heel (800 x 200 mm) to ensure their stability. These elements are reinforced for about half of their volume, so as to leave a part available for core drilling. These elements are located in three different sites: Paris region (XC4), La Rochelle (XS3) and Maurienne (XF4).

4. Modelling works

The durability criteria which will be proposed by PERFDUB National Project will take into account all the available feedback on old structures and cross-check results obtained from theoretical modelling work. Modelling is used in order to assess design service life which is presently defined as the time before appearance of first cracks induced by steel corrosion. Therefore, modelling should address corrosion initiation phase (carbonation or chloride ingress) and part of corrosion propagation phase. First phase is described on the basis of *fib* model-code 2010 (bulletin 34 and bulletin 76) with some adjustments and through a semi-probabilistic approach.

These adaptations for chloride ingress modelling are described here-after:

- Second Fick's law is used to determine free chlorides profiles, which are considered to be in direct relation with the time when propagation of corrosion can start,

- Within the European standard EN 206, the initial free chloride content is considered null $C_0 = 0$ as long as the initial total chloride content value is lower than the threshold mentioned in the same standard,
- Chloride content at the convection zone depth $C_{s,\Delta x}$ is determined by means of an enriching coefficient E , also called condensation index, applied to the free chloride content in water saturated porosity C_{sat} [weight-%/binder]:

$$C_{s,\Delta x} = E * C_{sat} \quad (1)$$

C_{sat} is calculated as follows:

$$C_{sat} = \varphi \frac{C_{env}}{M_b} \quad (2)$$

where C_{env} is the chloride concentration of seawater [g/l], φ is the concrete water porosity, and M_b is the binder content [kg/m^3],

- A mean value D_m should be used for the apparent diffusion coefficient D_{RCM} obtained by a rapid migration test for an exposure period to correct the 2nd Fick's law analytical solution; D_m is defined as the integral of D_{RCM} over the exposure duration.

E can be estimated from in-situ data but we aim at determining all the input modelling data from short-term laboratory tests. [Nagaski and al., 2013] reported that E is at least equal to 4 after 10-year exposure in seawater. From the BHP2000 Project results, E varies from 1.4 to 6.9 after a 10-year exposure and is very dependent on material composition. A good correlation has been found with concrete water porosity:

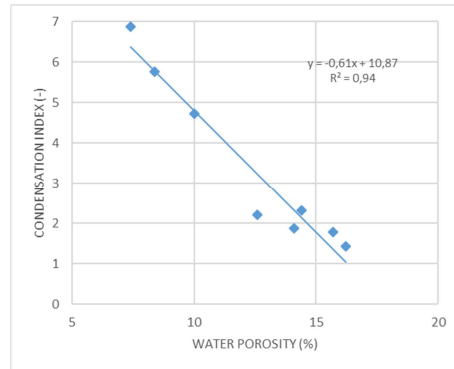


Figure 1. Correlation between concrete water porosity and condensation index E

More research is still needed on this field because all the concrete mixes studied within BHP2000 project were designed with very low porosity aggregates and it is likely that the above correlation would depend on aggregates water absorption value.

Modelling works about carbonation and corrosion propagation are still on-going and are not presented in this article.

5. First lessons from experimental results

In this chapter are presented some examples of analyses or conclusions that can be deduced from the PERFDUB National Project. They highlight the large typology of results which can be inferred from such a large experimental program.

5.1. Temporal evolution of durability indicators

Evolution of durability indicators over time is a key parameter for the performance of predictive models. Such laws of evolution can be inferred from the characterisation of durability indicator performed in various ages in some of the structures involved in PERDUB. The particular case of

chloride migration coefficient is presented below. A similar approach is being developed for other durability indicators.

Measurements of chloride migration coefficient have been performed in two structures at various ages: Rion-Antirion (CEM III/A 42.5, wall test) and Vasco de Gama bridges (composition 1: CEM I 42.5 and fly ash; composition 2: CEM IV with fly ash). Those results are exposed in Fig. 2. In each case, a law of evolution is proposed to fit the experimental measurements.

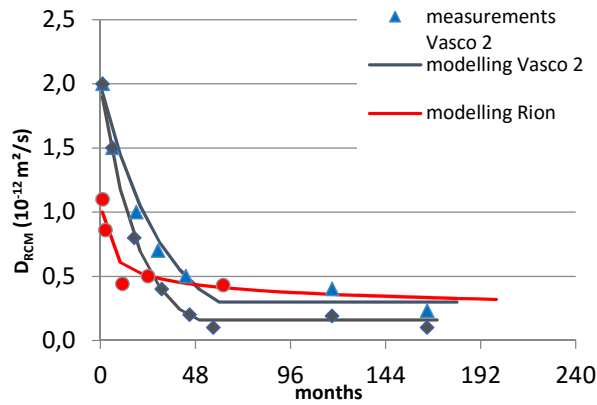


Figure 2. Chloride migration coefficient measurements and modelling versus time for three concretes
 (Rion-Antirion: $t < 120$ months: $D_{RCM}(t) = 1.1 \cdot 10^{-12} \cdot t^{-0.215}$; $t \geq 120$ months: $D_{RCM} = 3.5 \cdot 10^{-13} \text{ m}^2/\text{s}$.
 Vasco de Gama 1: $t < 48$ months: $D_{RCM}(t) = 2 \cdot 10^{-12} \cdot e^{-0.0527t}$; $t \geq 48$ months: $D_{RCM} = 1.6 \cdot 10^{-13} \text{ m}^2/\text{s}$.
 Vasco de Gama 2: $t < 60$ months: $D_{RCM}(t) = 2 \cdot 10^{-12} \cdot e^{-0.0322t}$; $t \geq 60$ months: $D_{RCM} = 3.0 \cdot 10^{-13} \text{ m}^2/\text{s}$)

It can be observed two very different shapes in the curves of evolution. By comparison with Vasco de Gama bridge, the curve of Rion-Antirion bridge presents lower values at the beginning, lower decreasing rate and higher long term values.

Those results show that the evolution of D_{RCM} over time is probably highly dependent on the nature of the binder and its reactivity (Rion-Antirion: slag; Vasco de Gama: fly ash).

For Rion-Antirion bridge, chloride ingress modelling according to chapter 4 (with a condensation factor value adjusted according to real profiles) leads to free chloride profiles which can be compared to real ones, after 2 and 5 years for durability wall (in spray and splash zone) and after 114 and 209 months for M3 pier (in tidal zone).

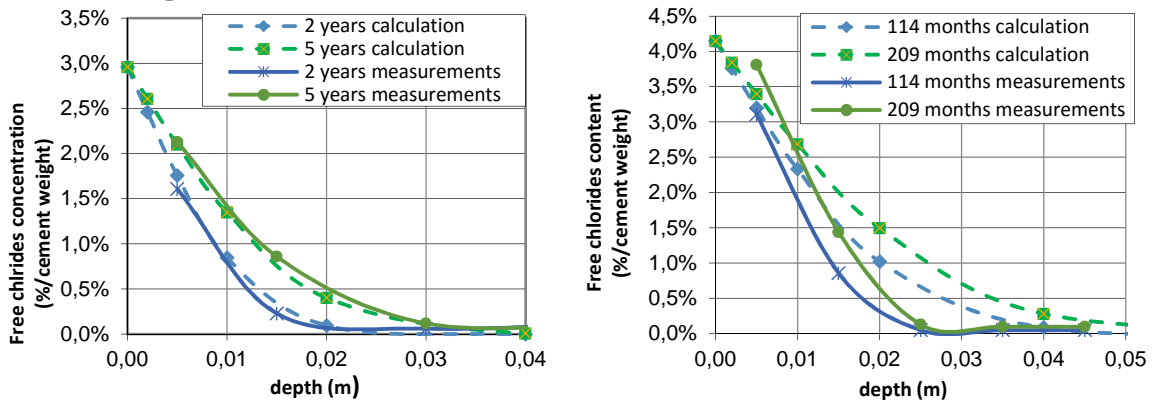


Figure 3 a) Durability wall chloride profiles

b) M3 pier chloride profiles

It appears clearly in the case of M3 pier that ageing factor is underestimated because it has been deduced from laboratory non-steady chloride migration tests (refer to Figure 2). Modelling is giving data that are on the safe side but we are still lacking a laboratory detailed method to capture in a few months a relevant value of concrete mix ageing factor.

5.2. Is total chloride profile a relevant criterion for corrosion probability evaluation?

Analyses of chloride penetration, coupled with electrochemical detection of corrosion probability, have enabled to highlight some limitations linked to the use of the total chloride concept.

The example shown here is based on the investigations performed on the Bridge Chateaubriand over the Rance (25 years old), whose P12 pier is submitted to marine exposure (XC4, XS3) due to the tidal zone and salt sprays. Generally, in this type of exposure, carbonation is very weak and corrosion of reinforcements is mainly linked to chlorides.

Electromagnetic detections in the tidal zone show that a significant proportion of horizontal reinforcements presents a too weak cover value with respect to the XS3 exposure requirements (average cover value: 35 mm; minimal cover value: 14 mm; 90% of cover values are included in the interval [23mm; 40mm]). Total chloride penetration profiles show (Fig. 4a) that chloride content clearly exceeds the threshold commonly admitted around reinforcement (0.40%/cement or 0.071%/concrete; but other values can be taken in consideration: see Angst et al 2009). The comparison of total chloride content and cover values shows that 100% of horizontal reinforcements are likely to be depassivated (Fig. 4b).

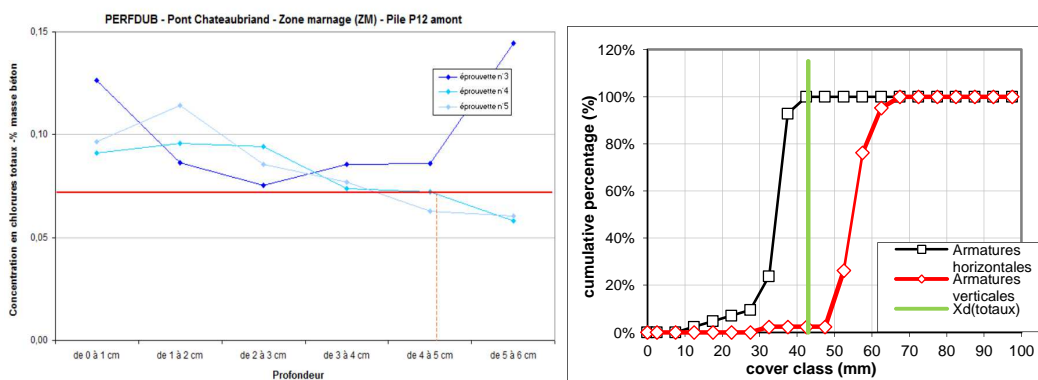


Figure 4. a) Total chloride penetration, b) Proportion of reinforcement likely to be depassivated.

Electrochemical measurements were performed on the horizontal reinforcements of the tidal zone. They show an altitudinal variation of the electrochemical potential (Fig. 5a), due to the effect of the tidal zone, but gradient values remain weak ($< 10\text{mV/cm}$) (Fig. 5b). None anodic area has been identified, despite the high probability of corrosion assumed by the chloride profiles and cover measurements.

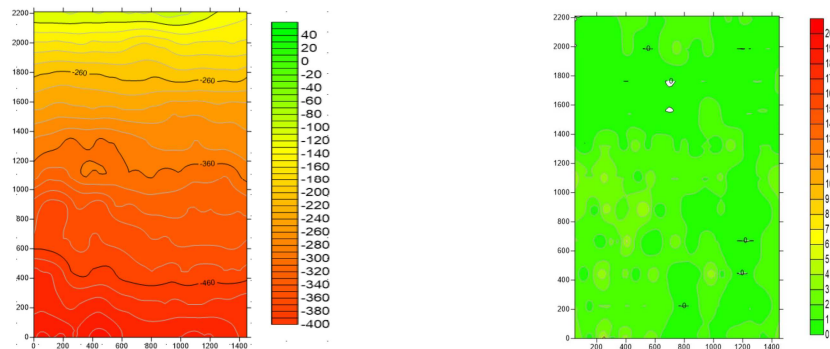


Figure 5. Electrochemical potential measurements a) local values b) gradients.

Those results highlight that total chloride content is not a sufficient approach for characterization of the risk of corrosion. As a part of chlorides remain bounded through cement matrix, the quantity of chlorides actually available to induce corrosion around the reinforcement are significantly lower and depending on the nature of the binder. A more detailed approach, based on the distinction between free chloride (i.e. chlorides available in the pore water) and bounded chloride (i.e. chlorides insoluble in water) seems to be more relevant for overall durability assessment.

5.3. Shape of chloride penetration profiles

Examination of large panel of compositions of concrete showed that the shape of the chloride penetration profile is highly dependent on the intrinsic quality of concrete.

The measurements exposed here below (Fig. 6) has been gathered from the BHP2000 experimentation. The “La Rochelle” site corresponds to concrete structures exposed in the sea tidal zone. The “Maurienne” site corresponds to a spray salt exposure due to the use of de-icing salt in mountain area.

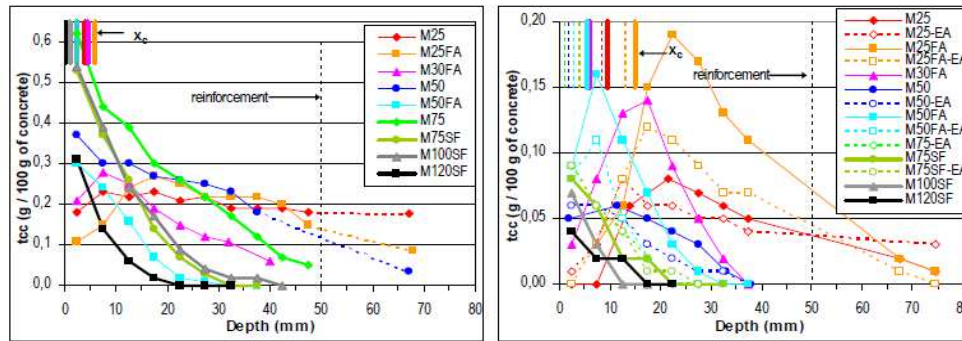


Figure 6. Chloride penetration profiles a) La Rochelle site, b) Maurienne site. (Baroghel-Bouny et al., 2013)

It can be observed that all ordinary concrete present a similar bell curve, with a maximum value clearly distant from the facing and clearly identified. This distance and the enriching coefficient E clearly depends on the composition of concrete (see chapter 4). Conversely, all high performance concretes present a decreasing curve with steep slope and maximum value in the facing.

5.4. A tool for the determination of conformity thresholds for the durability indicators

Structures whose concretes are around 50 years old are particularly interesting because lifetime indicators (depth of carbonation and chloride penetration) are easy to measure and can be in an intermediate level in regard to the overall expected life time of the structure. So those structures are useful for modelling. Some examples of typical results are presented below.

Table 1. Chloride migration coefficient measurements and modelling versus time (m: mean; σ : standard deviation; Pw: water porosity; Kg: gas permeability; D_{RCM} : apparent chloride migration coefficient; Res: electrical resistivity)

Structure investigated	Concrete Age (years)	First statement of occurrence of corrosion	Cover (first layer)	Durability indicators	Lifetime indicator
Bridge over the Bruche (XC4)	70	Before 1988. Only on reinforcement with few cover	m = 40 mm σ = 11 mm	Pw = 14.2 % Kg = $2000 \cdot 10^{-18} \text{ m}^2$ $D_{RCM} = 4.0 \cdot 10^{-12} \text{ m}^2 \cdot \text{s}^{-1}$	Carbonation depth: 25 mm Free chloride content near average cover = 0,025% /concrete
TCD Wharf on the Scorff (XS3)	51	Probably after 2003.	m = 39 mm σ = 11 mm	Pw = 12.8 % Kg = $89 \cdot 10^{-18} \text{ m}^2$ $D_{RCM} = 4.1 \cdot 10^{-12} \text{ m}^2 \cdot \text{s}^{-1}$ Res = 159 $\Omega \cdot \text{m}$	Total chloride penetration depth: 30 mm (criterion: total chloride content > 0,40% /cement)
Bridge over the Rance (Pier P11) (XC4 - XS3)	25	No corrosion	m = 54 mm	Pw = 15.6 % Kg = $415 \cdot 10^{-18} \text{ m}^2$ $D_{RCM} = 29.6 \cdot 10^{-12} \text{ m}^2 \cdot \text{s}^{-1}$ Res = 38 $\Omega \cdot \text{m}$	Carbonation depth: 2.6 mm Total chloride depth < 10 mm

In the case of the Wharf, corrosion can be induced by the weak values of covers (in relation to the highly aggressive exposure) or/and by the poor level of resistance to chloride attack. Indeed, even if the value of D_{RCM} is a medium level value ($4.1 \cdot 10^{-12} \text{ m}^2 \cdot \text{s}^{-1}$) close to the threshold value specified in the guideline n° 65 of the CCTG ($< 3.5 \cdot 10^{-12} \text{ m}^2 \cdot \text{s}^{-1}$, for XS3 exposure and a duration of use of 100 years), it can be considered that this value has been clearly improved due to the ageing factor (see chapter 5.1). If this value had been measured at the construction time (51 years before), it would have been significantly higher.

6. Conclusions

The French National Project PERFDUB appears to be a compressive and sound approach to improve the taking into account of durability and awareness of remaining issue for a reliable implementation of concrete performance-based approach. Some key lessons have already become apparent about corrosion induced by chloride penetration.

Of course, at it is more and more commonly accepted by international scientific community, propagation stages must be considered in addition of initiation period for overall durability assessment. The ageing factor is definitively an essential input to ensure the forecast of the residual lifetime of reinforced concrete with a reasonable margin of safety from tests performed with cores extracted at a given age. Another major point is the need to take into account the free chloride content instead of the total chloride content, to avoid the underestimating of the true residual lifetime during diagnostics and the unnecessary linked additional costs. Another one is that many factors amongst ageing factor and D_{RCM} , such as the enriching coefficient E for determination of surface Chloride concentration, the global shape of the chloride penetration curve... are highly dependent on the formulation of concrete, which need to be taken in consideration to improve the accuracy of inputs for modelling purpose.

Numerous data obtained from the French National Project PERFDUB are still being under analyse. The diversity of the investigated structures and the large panel of tests should ensure an improvement of the definition of thresholds for durability indicators to be used to state about the conformity of concretes in conjunction with implemented covers values. Recommendations based on feedback will ensure the transcription in contractual term of the performance-based approach.

Acknowledgements

The authors wish to acknowledge Veronique Baroghel-Bouny (IFSTTAR), Benoit Thauvin and Ronan Queguiner (Cerema), Abdelkrim Ammouche and Christophe Carde (SETEC/LERM) for their contribution to the study.

References

- Angst, U., Elsener, B., Larsen C. K. & Vennesland, Ø. (2009), Critical chloride content in reinforced concrete - A review. *Cement and Concrete Research*, 39, 1122–1138.
- Baroghel-Bouny, V., Dierkens, M., Wang, X., Soive, A., Saillio, M., Thiery, M. & Thauvin B. (2013), Ageing and durability of concrete in lab and in field conditions: investigation of chloride penetration. *Journal of Sustainable Cement-Based Materials*, vol.2, n°2, 67-110.
- Baroghel-Bouny V. et al., Concrete design for a given structure service life - Durability management with regard to reinforcement corrosion and alkali-silica reaction. State-of-the-art and guide for the implementation of a predictive performance approach based upon durability indicators, AFGC Scientific and Technical Documents (AFGC, Paris, issue in French: 2004, issue in English: 2007), 240p.
- fib* Bulletin 34. Model code for Service Life Design (2006). 116p.
- fib* Bulletin 76. Benchmarking of deemed-to-satisfy provisions in standards: Durability of reinforced concrete structures exposed to chlorides (2015). 204p.
- Guideline n° 65 of the General Technical Clauses for Public Contracts. 2017. Realization of civil engineering works.
- NF EN 206/CN (2014 december). Concrete - Specification, performance, production and conformity – National complement for the NF EN 206.