Durability of concretes, Performance-based approach: State of the art

Nadare Matoiri Chaibati
LARIS, University of Angers, Angers, 49000, France

Abstract

The recent evolution of construction techniques and new manufacturing processes for concrete in a context of sustainable development have led to a new strategy, in order to qualify new concrete formulations. Concrete production and implementation generally follow a prescriptive specification. This guarantees almost a 50 years structural durability related to an environment by respecting design and maintenance rules. However, the innovation related to high-strength concrete and self-consolidating concrete are challenging in terms of the prescriptive specification. Therefore, the performance-based approach to concrete durability is proposed as an efficient alternative of prescriptive specification. This approach focuses on the performance criteria for the concrete. This could represents an opportunity for construction actors, in order to extend structural lifetime up to 100 or 150 years. In this paper, a state of the art is carried out in order to expose the evolution of the performance-based approach in the field of concrete production.

KEYWORDS: durability, performance-based approach, reference concrete, candidate concrete, durability tests, probabilistic approach, optimization.

1. INTRODUCTION

In general terms, prescriptive specification is used to provide a durable concrete. In Europe, the reference standard is EN 206/CN [2]. The concrete is defined in term of exposure classes. There are six exposure classes based on the type of environments. In each class, concrete formulation has to respect the type of authorized constituents, maximum w/c ratio, minimum cement content, minimum compressive strength class and minimum concrete air content (section 5.3.2) [1]. If EN 206/CN [2] is adapted in European countries, NF EN 206/CN [1] is the French complementary dispositions for implementation with specifics concrete formulations [1]. On one hand, the prescriptive specification is based on "well tried and proven" concept, especially regarding cementitious materials; and relies on operating experience to achieve an average life of 50 years for structure. On the other hand, performance-based approach is proposed as an experimental alternative to prescriptive specification. This approach is based on performances of concrete. Two concepts are developed for the performance-based approach: at first, the equivalent performance concept which is a comparison of performance criteria between a reference concrete (specification of concrete conforming to NF EN 206/CN [1]) and a candidate concrete (obtained by changing

prescriptive specification). The idea is to show that the candidate concrete is performing as well as a reference concrete (section 5.2.5.3) [1]. Secondly, performance-related design method (section 5.3.3) [1] defines performance criteria of a concrete with the using of performing parameters calling indicators of durability.
They are three categories of performance-based approach [3]: the preforming methods, the predictive models, and the equivalent performance concept.
The first two categories of performance-based approach use indicators of durability which come from tests that have been in existence for many years (porosity, water, permeability test, gas permeability test). There are general indicators (indicators valid for different degradations like water porosity) and specific indicators (valid for a particularly degradation, for example quantity of silica released by aggregates as a function of time for alkali-silica reaction) [4]. The third category uses both indicators of durability and related performance tests. In France, there are two documents showing the use of performance-based approach:

- the FNTP/FFB/CERIB/FIB Professional recommandations (March 2009) entitled « Méthodologie d’application du concept de performance équivalente des bétons »[18]
- the LCPC guide entitled « Maîtrise de la durabilité des ouvrages d’art en béton-Application de l’approche performantielle » [5].

There are the same concepts in other countries like the P2P Initiative in USA (Prescription to performance specifications), BRL 9340 Standard [9] in Netherland and E464-2005[19] Standard in Portugal. Many projects have been realized to implement tests and methodologies, in order to apply the performance-based approach; for example in France (Projet Applet 2010) [6] and other are underway (Projet Perfdub).
Durability tests must represent the mechanisms behind concrete deteriorations; some tests exist (examples: carbonation test, sulfate attack, leaching of concrete, freeze-thaw and chloride penetration). For each test method, it is important to know the real representativeness, characteristics for fidelity and robustness before using it in performance based approach. Durability tests are used to measure indicators of durability. For an indicator of durability, different values are obtained. The variability of the indicator is explained by some errors due to tests procedure. The use of probabilistic approaches allows to characterize the distribution of durability indicator.
For long time, design of structures has been deterministic. The engineers use safety factor to calculate ultimate limit state (ULS) and serviceability limit state (SLS). Nowadays designers use semi probabilistic and probabilistic methods to take into account the variability of parameters related to the ruin of the structure. These probabilistic methods are considered for the durability design. Probabilistic model of durability are developed for chlorides attack in marine environment [7] and carbonation of precast concrete [8]. The durability indicators become the model input data and are considered like random variables with their probability distributions. The optimization of the number of durability tests is not resolved by these probabilistic

models. The work is focus on the number of durability tests to do on a specimen to qualify a concrete for an environment with the performance-based approach.
This paper is organized as follow: the first section, presents introduction, the second section, performance-based approach of durability. The third section, presents probabilistic approach of concrete durability. The conclusion is presented as well.

2. PERFORMANCE-BASED APPROACH OF DURABILITY

2.1 The general context

The concept of performance-based approach of durability appeared, when actors of construction realized that maintenance and reparation of reinforced concrete structure become expensive. Performance based approach helps to reduce costs of construction and specify desired durability. Gradually, this concept is adopted in many countries in the world but until now the production of concrete is generally prescriptive.

2.1.1. European

The European Standard EN 206/CN (section 4.1) [1] is prescriptive with an alternative for the performance based approach. The concrete is defined with six exposure classes, which are:

- XO: No risk of corrosion or attach
- XC: Corrosion induced by carbonation
- XS: Corrosion induced by chlorides from sea water
- XD: Corrosion induced by chlorides other than from sea water
- XF: Freeze/thaw attack with or without de-icing agents
- XA: chemical attack

The six exposure classes are subdivided according to the specificities of environment, for example the XD class is subdivided in three classes:

-XD1: Moderate humidity
-XD2: Wet, rarely dry
-XD3: Cyclic wet and dry

The limit values of the concrete formulations are defined in (section 5.3.2) [1].
The requirements related exposure classes for the production of concrete can be achieve using performing methods of durability (section 5.3.3) [1].

2.1.1.1 France

The France Standard, NF EN 206/CN [1] adapts European standard EN 206/CN [2] and the requirements related with exposure classes for concrete formulations are given in Tables NAF1 for (Ready Mix Concrete) and Table NAF2 for (prefabricated concrete). For the using of additions in the cement, water/cement ratio is replaced by water (efficiency) b/ (cement +k * addition) ratio and minimum cement content by (cement*addition). "The *amount of (cement+ k *addition) shall not be less than the minimum cement content required for the relevant exposure class"* (section 5.2.5.2) [1]. The k value depends of addition type and variates between 0 and 2. The two types of addition are:

- Type I : nearly inert addition (limestones addition)
- Type II: pozzolanic or latent hydraulic addition (fly ash, silica fumes) (section NA 5.2.5.2.2)[1]

The prescriptive specifications can be used with some performing methods developed in France.

2.1.1.1.2 Preforming methods

- ***Transcribed prescriptive indicators of durability to performance data***

The term indicator of durability is used to indicate the material property. The indicator of durability is determined by durability tests. Many durability tests like (compressive strength, water porosity, water permeability, gas permeability) exist for years and give a quantity of data related to indicators of durability. Baroghel Bouny proposed a performing method in AFGC guidance "Conception des bétons pour une durée de vie donnée des ouvrage" (2004) [4]. The AFGC guidance classifies relevant indicators for assessment of concrete durability in an environment with a risk of carbonation, chlorides penetration and alkali-reaction [3]. The LCPC [5] guidance « Maîtrise de la durabilité des ouvrages d'art en béton » gives recommendations to implement this performing method for concrete structures. In AFGC guidance (2004) [4], some predictive models are developed in order to predict structural durability.

- ***Predictive Models***

The knowledge on mechanisms of degradation like carbonation, chlorides penetration, leaching and sulfate attack led to the implementation of predictive models of durability. The predictive models are time functions applied to new concrete. The concrete aging and the change of environment factors must be taken into account to readjust the predictive evolution to the reel degradation evolution. The AFGC guidance "*Conception des bétons pour une durée de vie donnée des ouvrage*"(2004) presents predictive models that use durability indictors as input data. The output data are called "lifetime telltale" [3]. The key parameters for predictive and performing models are durability indicators which are also used in the equivalent performance concept.

- ***The equivalent Performance Concept***

This method compares a candidate concrete with a reference concrete. The goal is to prove that the candidate concrete has at least the same durability that the reference concrete (5.2.5.3) [1]. In France, The FNTP/FFB/CERIB/FIB Professional recommendations (March 2009) gives provisional recommendations to qualify a candidate concrete (new formulation). The reference concrete has to respect the prescriptive requirements for each exposure class in Tables NAF1 (for Ready Mix Concrete) and NAF2 (for Prefabricated concrete) [1]. The document defined to criteria for the reference concrete:

- Water (efficiency)/binder(equivalent) ratio ≤ [Water(efficiency)/binder for NF EN 206 /CN]- 0.05
- Binder (equivalent) = minimum binder (equivalent) for (Table NAF1) +5 % or Water absorption < |0.5% + Water absorption for (Table NAF2)| [1].

The method focuses on some exposure classes that had performance durability tests as mentioned; like accelerated test of carbonation, Freeze and thaw test and sulfate attack. The two concretes; candidate and reference have to be tested in the same conditions. The comparison is between the indicators of durability measured on the two concretes. This method uses performing durability tests and indictors of durability defined in AFGC guidance [4].

Example: For the accelerated test of carbonation, the indictor of durability selected is the depth of carbonation in the concrete.

The averages of the measures on candidate concrete and reference concrete have to satisfy this inequality:

$$Depth\ of\ carbonation\ (candidate\ concrete \leq\ Depth\ of\ carbonation\ (reference\ concrete) \quad (1)$$

The existence of relevant durability tests for each exposure class defined in French standard [1] must allow the use of this method by all actors of construction.

Other countries in Europe implemented this concept in the field of concrete production.

2.1.1.2 Belgium

In Belgium, for the using of slag in the concrete, two standards apply the equivalent performance concept:

-The BRL 9340 standard (2004) [9] (is used for slag in pre-cast concrete from factory and structures)

-The Belgium standard project NBN B 15-534 [10]

To qualify a candidate concrete about the penetration of chlorides; the comparison of effective diffusion coefficient for the candidate concrete and reference concrete has to satisfy the following inequalities:

$$Deff, slag/candidate\ concrete \leq\ 1.40\ *D\ eff\ /reference\ concrete\ (BRL9340\ Standard) \quad (2)$$

$$Dcl, candidate\ concrete \leq 1.40 * \text{Dcl, reference concrete (NBN B15} - \text{534)}$$

(3)

2.1.2 South Africa

2.1.2.1 General context

The production of concrete in South Africa is guaranteed by *SANS 101000-2 Structural use of concrete Part-2: Materials and execution of works (Draft 2013)*[11]. This standard is prescriptive.

Exposure conditions defined are: (moderate, severe, very severe and extreme). The exposure conditions are given with cover depth requirements which are depending on class of concrete.

There are 5 strength classes of concrete 20, 25, 30, 40, and 50 (MPa).

The type of cement or Supplementary Cementing Materials (SCMs) used for concrete formulation are not specified. No requirement for maximum water/ cement ratio or for minimum content cement is given.

This standard has many negatives aspects and not clear for the production of concrete.

The solution founded is to adopting EN 206/CN with a guidance document that will incorporate useful material from current SANS 10100-2 [11].

The committee works for the adoption of EN 206/CN in south Africa proposed for the composition of a concrete , requirements like in EN 206/CN, about exposure class, maximum water/ cement ratio , minimum strength class, minimum nominal cover, air-content range, cement type and curing.

To take account of performance-based methods in South Africa, the guidance document incorporates the durability index (DI) approach [12].The goal is to allow the use of prescriptive and performance approach [**13].**

2.1.2.2 Durability Index (DI) approach

In South Africa, (DI) approach is developed to allow the use of performance-based approach [12]

The (DI) approach can be compared to Baroghel-bouny predictive model in France (guide AFGC 2004) [4]. The physical parameters use to specifier or predict concrete durability are: oxygen permeability, water sorptivity and chloride conductivity. These tree parameters are called durability Indexes. The method covers only environment with corrosion of reinforced concrete induced by carbonation or chlorides from Seawater. South Africa adapted EN 206/CN (Table 1); the exposure classes are: XC (Corrosion induced by carbonation) and XS (Corrosion induced by chlorides from sea water).

2.1.2.3 Implementation of (DI) approach

The implementation of the method has to respect the following steps:

- The owner and designer have to specify the environment and the desired service life.

-After the required cover value has to be specified.

- Specification of durability index values (there are two approaches: deemed-to-satisfy approach and rigorous approach. The first is used for majority of reinforced concrete and the second for critical structures durability).

-Establish limiting values for concrete mixtures (the limiting DI values haves to take account of statistical variability of test results and differences between as-built quality and laboratory-cured concrete.

- Establish tests controls to confirm the material potential quality (by supply on concrete specimens in a laboratory) and as-built quality (in-situ sampling of concrete members by the constructor).

In the deemed-to-satisfy approach, the DI values are given in prescriptive specifications.

The carbonation and chloride resistance of concrete are characterized respectively by oxygen Permeability Index (OPI) and chloride conductivity (CC). For a given service life, the values of: minimum cover, minimum OPI and (CC) maximum chloride conductivity (Binder combination) are specified. Deemed-to-satisfy approach is limited however the rigorous approach is flexible and the designer can change parameters like cover depth, environmental classification, desired life and material.

The characteristic values determined on the two approaches (deemed to satisfy or rigorous) are characteristic values to be achieved in the as-built structure. The material potential value as delivered to site and potential target value in laboratory specimen have to be determined according to variability inherent in concrete performance [14].

3. PROBABILISTIC DURABILITY APPROACH OF CONCRETE

3.1 Probabilistic approach for design durability of reinforced concrete

The design of reinforced concrete structures has been focus for a long time on mechanical aspects. The engineers take mechanical strength as main parameter to design reinforced concrete structures. The consideration of physico-chimical degradations stated when the owners released that the maintenance of their structures became expensive. The knowledges on physico-chimical concrete degradations allow proposing new concretes able to resist more to environment actions. Many construction standards propose performance approaches for concrete durability which are reviewed on the initials paragraphs. Predictive models are among those approaches (2.1.1.1.2). Predictive models use indicators of durability like input data for the model to obtain the service life witnesses [Baroghel-Bouny et al 2004]. Frequently, the average of

durability indicators is taken to obtain input data but the indicators of durability are variables parameters. The variability is due to the use of many constituents in a concrete formulation, conditions of production and realization of durability tests in laboratory or at the construction site. To take account of the variability of the indicators, probabilistic approaches are proposed by Deby [7] and Hyvert [8].
Deby proposed a method based on concrete formulation and chemical cement composition to estimate the corrosion risk through the Lind-Hasofer reliability index (the indicators of durability are evaluated with the associated incertitude). Hyvert developed a model for the carbonation of concrete [8]. The following paragraph presents only probabilistic method proposed by Deby [7].

3.2 Probabilistic approach for durability design of reinforced concrete in marine environment

3.2.1 Probabilistic performing approach

The major element of this approach is durability indicator.
There are two mainly points to implement performing approach: the selection of indicators of durability and accepting criteria specification according to the type of environment and service life specified. Service life of the structures exposed on a risk of corrosion is the time to achieve the reinforcement depassivation. If the structure is in a marine environment, the service life is the time that chlorides concentration reaches a critical chlorides concentration near the reinforcement. Predictive model adapted on the physical and chemical phenomena involved, has to be determined. In a marine environment, the model has to predict chloride ingress into reinforced concrete. The indicators of durability (input data of the model) as considered as random variables in order to take account of their variability.
The idea is to predict durability by the assessment of reinforcement depassivation probability.
To calculate this probability, the definition of a performance function E(X) is required. The vector X represent the realization of the random variables. The state of a structure is defined by two domains: failure domain $E(X) \leq 0$ and safety domain $E(X)>0$.
$E(X) = 0$ represents the failure surface or limit state function (Figure 1).

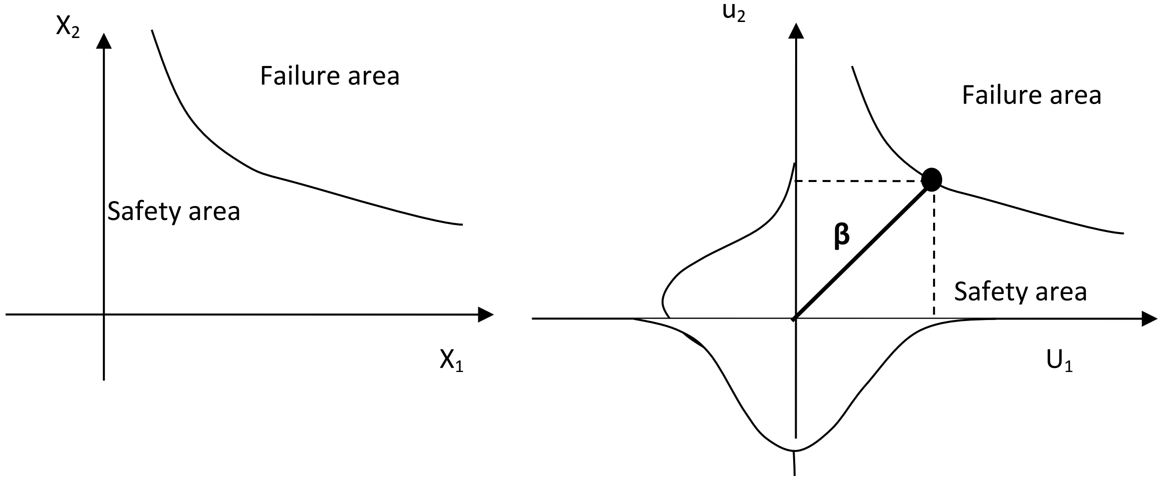

Figure 1 and 2 Limit state function and reliability index

The reliability P_r and the failure probability P_f are given by the following expressions:

$$P_r = E(X) > 0 \text{ and } P_f = E(X) \leq 0$$

Among reliability approaches, the approach based on the use of a reliability index (Hasofer-Lind index) to estimate the probability was chosen.

3.2.2 Application of Probabilistic performing approach

- **Concrete composition**

In this paragraph, probabilistic performing approach is applied to a reinforced concrete in marine environment. A high performance concrete composed by CEMI cement with W/C =0.4 ratio is used.

The constituents of the concrete and chemical composition of the cement are given in table (1 and 2)

Table 1 and 2 High strength performance concrete and chemical composition

Constituents	Dosage (Kg/m3)
Gravel	1152
sand	760
Cement	425
water	145
Superplasticizer	6

Chemical composition	[%]
SiO2	20.3
Al2O3	5.26
Fe2O3	2.24
CaO	63.71
MgO	1.12
SO3	3.49
K2O	1.1
Na2O	0.08
Loss on ignition	2.2

- **Selected indicators of durability**

The indicators of durability selected are: water porosity (p), chloride effective diffusion coefficient (De), chloride binding isotherm (C_b) and free chloride concentration (C).

Then are characterized by their distribution laws in table (3)

The porosity and volume percentage of cement paste are used for the determination of chloride effective diffusion coefficient [16]. For chloride binding, the quantity of CSH, AFm and free chloride by Hirao relation [15].

$De\ experimental\ = ErrD * De\ calculated$ And $c_b$experimental = ErrC * $c_b$calculated

Distrubution laws for ErrD and ErrC are estimated after a literature search to validate elementary model. To finish concrete cover is taken into account and consider us a random variable.

Variable	Distribution	Mean	Standard deviation
Porosity P	Lognormal	9.5%	0.38%
ErrD	Lognormal	1.02	0.42
ErrC	Lognormal	1.01	0.22
Cover C_{nom}	Lognormal	5 cm	1cm

Table 3 Random variable distribution selected for the durability model of ingress chloride

- **Prediction of durability**

The predictive model used for chloride penetration in concrete is modelled by Fick's law. The equation to be solved is:

$$\frac{\partial c}{\partial t} = D_{app} \frac{\partial^2 c}{\partial^2 x} \quad and \quad D_{app} = \frac{D_e}{p + (1-p) * \rho_s * \frac{\partial^2 C_b}{\partial c}}$$

(4)

De represents the effective diffusion coefficient (m2/s), C the free chloride concentration (mol/m^3 of solution), C_b the bound chlorides (mol/kg of dry concrete), p the porosity, and ρ_s the absolute density of material (Kg/m^3).

The reinforcement’s depassivation probability in marine environment is the probability that chloride concentration on reinforcement is over chlorides critical concentration. This situation is illustrated by the following equation:

E (p, ErrD, ErrC, Cnom) = Ccritical – Ctotal, cover (p, ErrD, ErrC, Cnom

(5)

$C_{crtical}$=0.4% critical chlorides concentration (AFGC 2004) [4].

Ctotal, cover is determined by equation (4) and the reliability index β with P* by linear optimization method (Rackwitz and al1979). The reliability is the complement of failure probability; if the reliability decreases, the failure probability increases. Figure (3), represents the time variation of the reliability index.

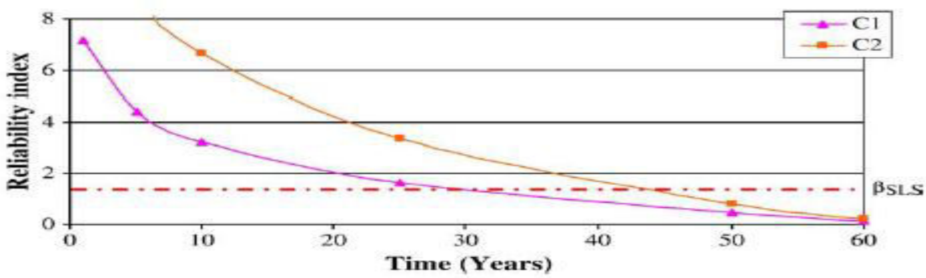

Figure3 Time variation of the reliability index [17]

4 CONCLUSIONS

Production and implement concrete, are used until now, prescriptive specifications but performance based approaches are increasingly adopted. Performance based approaches give some advantages to construction actors as use of new construction techniques, new concrete formulations (with high durability) in respect of the environment, and less expensive. Concrete durability is characterized by durability indictors (index) measured on a specimen in laboratory or on a construction site. In many projects, the durability characterization remains only on an average value of indicators. This can be problematic as structural durability can then be underestimated or overestimated. To solve this problem, variability of durability indicators has to be taken in account. This is made possible by probabilistic approaches where durability indicators are modeled as random variables with related distribution laws. Therefore an investigation must be performed in other to propose methods for durability tests optimization. For example what number of durability tests is necessary to qualify new concrete formulation for a given environment with a predefined confidence level?

References

1. Béton — Spécification, performance, production et conformité — Complément national à la norme NF EN 206.
2. Béton — Spécification, performances,production et conformité.
3. Emmanuel Roziere. Etude de la durabilité des bétons pour une approche performantielle.
4. AFGC, « Conception des bétons pour une durée de vie donnée des ouvrages », Documents scientifiques et techniques, 2004
5. LCPC Maitrise de la durabilité des ouvrages d'art en béton « Application de l'approche performantielle.
6. Projet Applet Durée de vie des ouvrages : Approche predictive performantielle et probabiliste 2010.
7. Fabrice Deby. Approche probabiliste de la durabilité des bétons en environnement marin 2008.
8. Nicolas Hyvert. Application de l'approache probabiliste à la durabilité des produits préfabriqués en bétons (2009).
9. BRL 9340. Nationale beoorderlingsrichtlijn 9340, combinatie van genalen hoogovenslak en portlandcement voor toepassing als bindmiddel en béton, Pays-Bas mars 2004.
10. NBN B15-534 : Méthodologie pour l'évaluation et l'attestation de l'aptitude à l'emploi de liants hydrauliques (ciments) et d'addition de type II destinés au béton, Projet pour la rédaction d'un document normatif-Version du 20 décembre 2005.
11. SANS (South African National Standard) 2013. SANS10100-2 2013. (Draft SA Standard), the StructuralUse of Concrete. Part 2: Materials and Execution of Work. Pretoria: SABS Standards Division.
12. Alexander, M G, Mackechnie, J R & Ballim, Y 2001.Use of durability indexes to achieve durable coverconcrete in reinforced concrete structures. In:Skalny, J P & Mindess, S (Eds), Materials Science
13. Journal of the South African Institution of Civil Engineering Vol 57 No 1, March 2015, Pages 47–58, Paper 1135
14. Performance-based durability testing, design and specification in
South Africa: latest developmentsM.G. Alexander & H. Beushausen University of Cape Town, Cape Town, South Africa
15.Hirao H., Yamada K., Takahashi H., Zibara H., « Chloride binding of cement estimated by binding isotherms of hydrates », Journal of Advanced Concrete Technology, vol.3, n° 1,2005, p. 77-84.
16. Tognazzi C., « Couplages fissuration dégradation chimique dans les matériaux cimentaires : caractérisation et modélisation », Thèse de doctorat, INSA de Toulouse, 1998.
17. Probabilistic approach for durability design of reinforced concrete in marine environment F. Deby □, M. Carcassès, A. Sellier
Université de Toulouse, UPS, INSA, LMDC (Laboratoire Matériaux et Durabilité des Constructions), 135, Avenue de Rangueil, F-31 077 Toulouse cedex 4, France.
18. FNTP/FFB/CERIB/FIB Recommandations Professionnelle provisoires (Mars 2009) « Méthodologie d'application du concept de performance équivalente des bétons »
19. E 464-2005, Betões – Metodologia prescriptiva para uma vida util de projecto de 50 e de 100 anos face às acções ambientais,
Documentação normativa especificação LNEC, Portugal, 2005