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SOME ASPECTS OF DESIGNING CONCRETE STRUCTURES BASED ON DURABILITY

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ABSTRACT

Designing concrete structures (CS) with calculated durability implies meeting the provisions defined in codes, usually the EN for structures (Eurocode-EC). Their implementation in practice is considered to lead to durable CS in operation, contributing to reach their required service life (SL). However, experiences with CS located in aggressive environment and without major maintenance costs indicate that they do not meet the requirements of durability, particularly if the required SL is significantly longer than 50 years (100 or more). The modern approach to reliable CS design is based on performances during SL, or the so-called. "Performance based design". The probabilistic approach (based on probability and reliability) to design enables a more accurate forecast of the CS behaviour to be made during its SL, but it is a complex procedure and the possibility of its practical application is still not fully developed. Reviewing the literature and contemporary codes, this paper analyses some aspects of durability based CS design. The emphasis is on performance-based design along with some proposals for the revision of the EN 1992 and EN 206, based on previous experiences and the latest research.

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1. Introductory remarks

Up to the 1980's, SL was not defined by contemporary and applicable CS design codes, while durability was treated implicitly [12, 16] and [30]. This approach has been proven insufficient, particularly in conditions of the increasing environmental pollution, which accelerated the degradation of CS, reduced their SL, and increased their maintenance costs [12, 15] and [16].

Nowadays, the required SL for major facilities is 100 or 200 years, without the need for major maintenance costs, [30]. Current design codes provide the recommended SL implicitly (in EN 1990 [9], it is 50 years for buildings) and without a defined end of SL, [25]. Most of these codes lack quantified guidelines for SL based CS design with longer than 50 years [15] and [30]. Therefore, it was necessary to introduce the calculation of the required SL, or behaviour (performance) based durability during the operation in CS design, [2, 3, 4, 11, 16, 19, 26] and [31]. This is essential for seaside structures, major industrial and infrastructure facilities, designed with longer SL where deterioration processes (DP) often cause damage to the CS, [13,17,20] and [31]. This requires a special treatment in the process of design and construction, and regular maintenance and occasional structural interventions during the operation. Designing these CS includes safety, serviceability, durability and maintainability [13] and [15]. The behaviour related requirements and criteria during the SL which should be met in interaction with the environment are defined depending on the type of the structure, its function and environment. These requirements and criteria are verified by monitoring the structure's behaviour using behavioural indicators, with the durability related requirements of concrete being verified based on durability indicators or indexes (DIs) [2, 3, 4, 16, 26] and [28].

The most important factor when analysing the CS durability is the permeability of concrete, i.e. the rate of penetration and transport of substances through the concrete structure, comprising pores of various types and sizes, separate and/or interconnected. Permeability of concrete is affected by micro fissures due to deformation induced by thermal shrinkage and/or drying shrinkage, premature and/or excessive loading, etc. The type and distribution of pores, as well as their connexity affect the mechanisms of penetration and transportation of substances from the environment in and through the concrete, and thus the mechanisms of deterioration, which adversely affect the behaviour of CS (security, usability, condition of the concrete surface, appearance of the building, etc.) over time. Substances from the environment penetrate the concrete cover and initiate DP, degrading its performances. Therefore, the thickness and quality of concrete in the cover are the main factors of protection of the CS against degradation.

According to the consequences they are leading to, DP and mechanisms are classified as damaging the concrete and damaging the reinforcement. Damages to concrete are related to physical effects, chemical (internal and external) effects and reactions, and microbiological effects. Damage to steel (reinforcement and prestressing tendons) in concrete usually occurs due to corrosion caused by chlorides and carbonization of cover. Corrosion of steel in concrete is the most serious problem of CS durability because it is more difficult to control than the other mechanisms of degradation, and therefore it is also the most studied. The most dangerous form of CS degradation is the corrosion of steel initiated by chlorides in concrete which usually come from sea water and/or salt used against freezing in winter (de-icing salt).

Some of these key issues which significantly affect the durability of CS are discussed in this paper by referring to relevant literature.

2. Durability and Service Life Design of CS

Durability of CS is difficult to quantify because it depends on a number of parameters of which the design process consists, from the actual performances during the construction through the maintenance. The SL based CS design concept has been introduced in the Model Code CEB-FIP 90, [5]. According to EN 1990 [9], the structure's durability is considered adequate in a given environment to the extent to which it fulfils the criterion of acceptability of its functions. Durability and SL are interrelated and defined in ISO 13823, [23]. Durability can be estimated using mathematical models (MM) which realistically describe the DP to which the CS will be exposed to during the use [11]. SL can be expressed quantitatively (years), wherein the design SL usually depends on the type and functions of the CS. According to ISO 2394 [22], and EN 1990 [9], analysing reliability SL (in years) is recommended for five categories of objects. According to the FIB Cod Model 2010 (MC 2010), [13], SL for structures near the sea is 35 years, for those designed based on the CEB-FIP Model 90 and EN 1992 it is 50 years, for bridges and tunnels 100 years, etc.

According to ISO 16204 [24], the designed SL is "the assumed period for which a structure or a part of it is used for its intended purpose with anticipated maintenance, but without major repair being necessary." At some point of time, the design SL is often corrected during the use of the CS because of degradation and deterioration of performances to the minimum acceptable level. This determines the structure's actual SL, which can be longer or shorter than designed, depending on the rate of degradation of the CS. The ISO 13823 [23], defines the actual SL as "the actual period of time during which a structure or any of its components satisfy the design performance requirements without major unforeseen maintenance and repair." Current CS design codes do not include the calculation of structural degradation during SL, with design performances being considered consistent during the SL by implementing managerial and maintenance activities, which is not always the case, [12]. Planning and assessing the actual SL is a complex activity because the initial and permanent performances of materials are not precisely known, as well as due to difficulties related to predicting the conditions of the object's use. A rough estimate of SL is provided in ISO 15686, [12] and [15].

In the early 1980's, intense research activities were undertaken in Europe (especially Netherlands) and the United States aimed at defining the calculation of durability of CS, [15] and [30]. These became the basis for the development of SL based CS design, [15] and [30]. Therefore, SL is taken into consideration from technical, functional and economic aspects, [15] and [29]. Technical SL implies the period of exploitation in which unacceptable deterioration occurs, whose modelling in time consists of phases of initiation and propagation (the process of CS degradation is accelerated), [15] and [29]. CS's with longer initial phase and slower propagation phase are more durable. In ideal case, the duration of the initial phase corresponds to the defined SL, [15].

Key to the development of CS durability design were CEB [5] and RILEM [6], and especially the TC 130-CSL Report [6], which opened the way to the calculation of CS durability on the same basis as the calculation of capacity and usability. This changes the approach to CS durability from deterministic to probabilistic method by defining MM for certain DPs' and setting an explicit SL and its reliability, [6, 11] and [22]. Probability of failure, $P_f(t)$, increases over time and can be expressed through the reliability index (β), where resistance $R(t)$ and the effects of the $S(t)$ function of a large number of time dependent factors are stochastic variables, [11]. There are different reliability classes for (RC) structures and classes of failure consequences (CC), with the class of choice depending on the way of reaching the limit state LS (ultimate limit state - ULS or serviceability limit state – SLS) and

the possible consequences, according to ISO 2394, [11] and [22]. The formulation of MM for specific DPs' and defining the MM parameters have been investigated in a number of projects (e.g. DuraCrete, Darts, etc.), [11]. In 2002, FBI has created the Task Group 5.6 for the purpose of developing the *Model Code for Service Life Design* (MC-SLD), which was founded on probabilistic basis, LS and reliability according to ISO 2394, and DuraCrete and Darts projects, [12]. MC-SLD was published in 2006, and incorporated in MC 2010 and ISO 16204 [24]. The standard ISO 16204 is based on integrated principles provided in ISO 2394, ISO 13823, MC-SLD and MC 2010 [24].

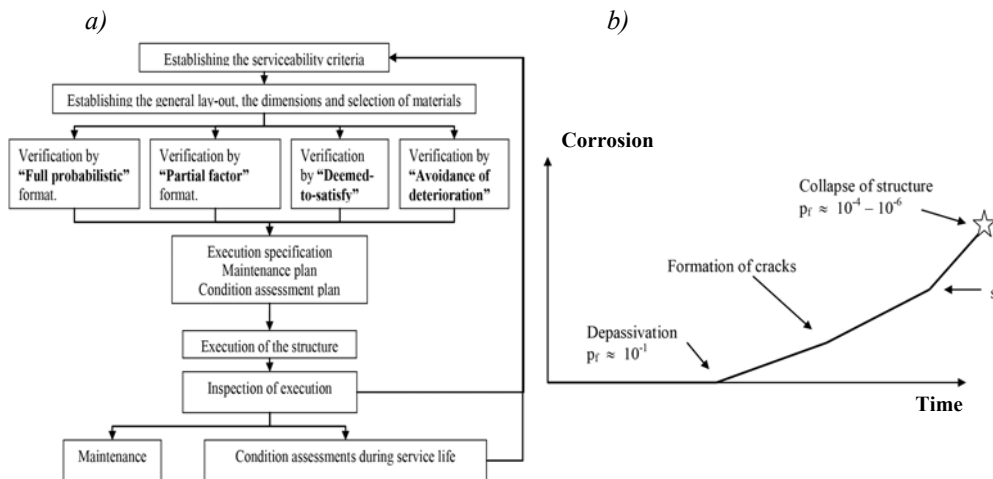


Figure 1. a) Flow-chart for Service life design (SLD) [24], b) Example for corrosion of reinforcement. Various LS and corresponding levels of reliability [20]

MC-SLD treats DPs for which there are generally accepted MMs in existence, [11]. The design phases are: defining MM for DP, quantifying the parameters in MM, defining the design LS, defining the LS type (SLS or ULS) and calculation evidence in four possible ways (Fig.1), [11, 13] and [24]. For reinforcement corrosion, the following is considered to be SLS: reinforcement depassivation (SLS1), fissure formation (SLS2), and concrete spalling (SLS3) (if there is no risk of falling-off of CS pieces, otherwise it is considered ULS1). For the same thing, the following are considered ULS: spalling of the protection layer, if there is a risk of falling off of concrete pieces (ULS1), loss of bond between concrete and reinforcement (ULS2), and fracture of structural element (ULS3), with the latter two being classical ULS, [12]. According to ISO 2394, MC SLD, MC 2010 and ISO 16204, for reinforcement corrosion values shown in Fig.1b are adopted for P_f [20]. β , or the selected safety coefficient (γ) is selected in accordance with the selected type of LS. The calculated SL is determined by defining LS (in years) with the level of reliability that during the SL it fails to reach LS. The period of initiation is usually adopted as the end of SL with the possibility of adding a part of propagation period (in massive CS) and comparing it with the analysed time period usually SL.

3. Design Strategies Durability

Current approaches to durability design can be classified into two basic, different strategies (A and B), proposed S. Roostam and P. Schiessel in 1994 [29]. Strategy A

("Avoidance of deterioration") is based on the principles of full protection of CS and consists of three possible approaches: changing the micro environment (A1), the choice of materials that do not react to potential effects (A2), and preventing reactions (A3). Strategy B minimizes deterioration by optimum design and choice of materials, and can be divided into four possible approaches, [12]: B1-"Deemed-to-satisfy"; B2-resistance based on the application of one (B2.1) or multiple phases of protection (B2.2); B3-Factor method (according to ISO 15686); and B4-"Performance based design", based on probability and reliability, which can be of "Full probabilistic" (B4.1) and "Partial factor" format (B4.2). The B.1 approach involves meeting requirements defined in codes and their application in practice. In most operating conditions this should result in permanent CS, but they are inadequate for structures located in aggressive environments and for SL exceeding 50 years. The factor method is considered to be improvement to the B.1 approach and a "connection" between simplicity (B1) and complexity (B4). The B4 approach involves using the MM DP. Its application is complex, particularly in the case of the effects of different DPs, when their synergetic effect should be simulated. The B4.1 approach should provide the most accurate forecast of CS behaviour which is difficult to achieve, because performances of materials and operating conditions are random variables and are difficult to simulate accurately, while the available data that simulate realistic statistical variables $R(t)$ and $S(t)$ are scarce. In applying the above strategies there are possible combinations and/or "overlaps" between the various approaches within a single strategy, and/or individual approaches from both strategies, [12] and [29].

4. Design durability to Eurocodes

According to EC, when designing CS, calculation methods are based on checking ULS and SLS, [9] and [10]. Designing CS durability is based on EN 206, EN 1992, and EN 13670. The EN 206 classes of exposure are shown in Table 1.

Table 1. Classes and subclasses of exposure, to EN 206 [8]

Classes	Description of the environment	Subclasses (i)
X0	No risk of corrosion	-
XC	Corrosion caused by carbonation	XCi(i=1,2,3,4)
XD	Corrosion caused by chloride (except sea water chloride)	XDi(i=1,2,3)
XS	Corrosion caused by sea water chloride	XSi (i=1,2,3)
XF	Impact of freezing/ melting with or without anti-icing agent	XFi (i=1,2,3,4)
XA	Chemical agent	XAi (i=1,2,3)

Requirements for each subclass of exposure are determined based on the permitted types and classes of materials (maximum w/c, minimum binder content, minimum pressure strength of concrete, and minimum air content in concrete if required), geometric properties (minimum cover), and the criteria of deviation from the design dimension. The national standards, according to local conditions and other selected parameters are defined in classes and subclasses of exposure and corresponding selected request which is relative to the EN 206 and/or distinguished from each other, e.g. max. w/c and min. cover, SL 50 and subclasses exposure XC3, XC4 and XS2, UK, NL, DE and NO, according to Table 2 [20] or, for example NS-206 has 8 classes of exposure, etc.

Table 2. Max.w/c i min. cover ua UK, DE, NL i NO for subclasses XC3, XC4 i XS2 [20]

Range of XC3 provisions for CEM I in Europe	UK \Rightarrow w/c < 0.55 and 25mm minimum cover	DE \Rightarrow w/c < 0.65 and 20mm minimum cover
Range of XC4 provisions for CEM I in Europe	NL \Rightarrow w/c < 0.50 and 25mm minimum cover	DE \Rightarrow w/c < 0.60 and 25mm minimum cover
Range of XS2 provisions for CEM I in Europe	UK \Rightarrow w/c < 0.50 and 35mm minimum cover	NO \Rightarrow w/c < 0.40 and 40mm minimum cover

The applicable durability design according to EN 1992 and EN 206:

- explicitly does not include structures (e.g. bridges) with the required SL exceeding 50 years, and for which some national standards (e.g. BS 8500 and BS EN 6349-1-4) where SL design guidelines of 50 and 100 years are provided [7], as well as SLD guidelines of 80,100 and 200 years in Netherlands, [19] and [30], etc.
- in EN 1990, EN is implicitly defined and without a precise meaning regarding the end of the SL [26],
- the impact of different types of binder and mineral supplements is generally not specified,
- does not include new types of materials (binder, reinforcement made of other materials, etc.), new CS types and under-researched or new types of aggressive environments,
- studies of performance of concrete are generally deterministic and neither contain controls important for durability (cover quality) nor possible deficiencies of the executed CS, etc.,
- in relation to national standards, there are certain non-conformities; for example, in similar local environmental conditions (e.g. UK, DEN, NL and NO, Table 2), for the same subclasses of exposure (XC3, XC4, XS2) different requirements were adopted for maximum w/c and minimum cover, which is explained by the different views of national standardization bodies regarding the exact end of SL, and the adopted level of reliability [20]; the reliability index (β) adopted in some national standardization bodies ranges between 1.8 (NL) and 0 (ES), while P_f varies from 4% to 50%, in case of SLS1 (depassivation of reinforcement) [21]; for the same class of exposure (XS) and the same required SL, recommendations provided in two national standards (BS EN 8500 and BS 6349-1-4) differ from one another, although they are based on the same MM calculation of migration of chloride ions [7], etc.

5. Performance Based Durability Design (PBDD)

PBDD is based on the SL model and treats the design of performance of materials and geometric properties of the cross section of structural components which are part of input parameters for the SL model and ensuring the required quality (Fig. 2) [3, 4] and [27].

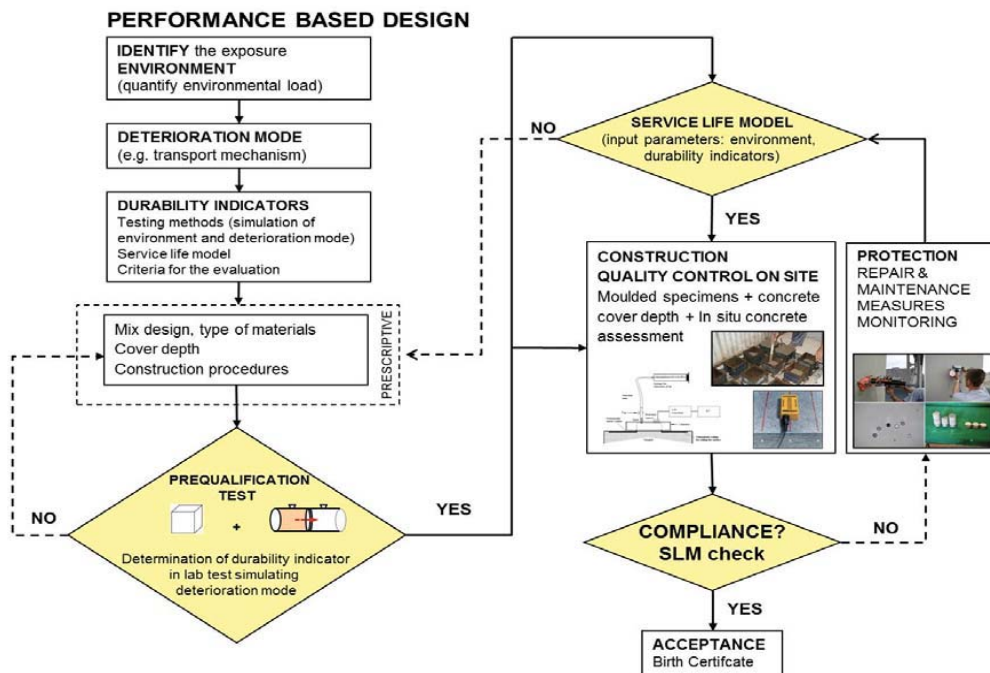


Figure 2. Procedure during performance based design, [3, 4] and [27]

Designing durability depends on aggressiveness of the environment that should be carefully identified and classified, [3]. In interaction between the environment and the concrete, the level of aggressiveness of the environment and performances of the hardened concrete predetermine the possible penetration and transport mechanisms of substances in the concrete, as well as the potential DP to be identified. PBDD for the required SL is based on functional requirements for hardened concrete and criteria of eligibility. Indicators of permeability of concrete (diffusion of chloride ions, water permeability, gas permeability, capillary absorption and porosity) usually are adopted for DIs, [2, 3, 4] and [28]. When designing durability for the required SL based on the structure's type and function, and the aggressiveness of the environment, the designer specifies the DI values that should be met by the hardened concrete. DIs are tested using standard methods and/or methods that have long been applied and the accuracy of which has been verified, [1, 2, 3, 4], and [5]. In addition, the testing part is performed before starting the works, while the acceptance part is performed on the construction site. The compliance with the functional requirements for the quality of concrete is determined after the completion of construction by inspecting the DI values, which are updated into the structure's "Birth certificate", [13] and [27]. For practical application of PBDDs, it is necessary to previously standardize the limit values, methods of testing the performances of hardened concrete, and establish a link between the performances of concrete required for a certain class of exposure and the required SL.

Netherlands has developed Guidelines for the SLD, [19] and [30], based on a modified DuraCrete methodology for the case of corrosion of steel in concrete initiated by chlorides, exposure classes XD and XS, and depassivation probability (10% for reinforcement and 5% for prestressing steel). Values of the diffusion coefficient were calculated for the chloride ion $-D_{RCM,28}$ for various sub-classes of exposure, dimensions of binder and types of cover, and for SL of 80, 100, and 200 years. The calculation model was

verified on infrastructure facilities also in sea environment. Table 3 shows the recommended values for the maximum $D_{RCM,28}$, for SL of 100 years, [19] and [30].

Table 3. Maximum $D_{RCM,28}$ for various cover depths as a function of binder type and environmental class for a design service life 100 years [19] and [30]

Mean cover [mm]		Maximum value $D_{RCM,28}$ [10^{-12} m ² /s]							
Reinforcing steel	Prestressing steel	CEM I		CEM I + III 25 – 50% S		CEM III 50 – 80% S		CEM II/ B-V CEM I + 20–30 % V	
		XD1	XS2	XD1	XS2	XD1	XS2	XD1	XS2
		XD2	XS3	XD2	XS3	XD2	XS3	XD2	XS3
		XD3		XD3		XD3		XD3	
		XS1		XS1		XS1		XS1	
35	45	3,0	1,5	2,0	1,0	2,0	1,0	6,5	5,5
40	50	5,5	2,0	4,0	1,5	4,0	1,5	12	10
45	55	8,5	3,5	6,0	2,5	6,0	2,5	18	15
50	60	12	5,0	9,0	3,5	8,5	3,5	26	22
55	65	17	7,0	12	5,0	12	5,0	36	30
60	70	22	9,0	16	6,5	15	6,5	47	39

In 2007 in France the AFGC has published the "Guide for the implementation of a predictive performance approach based upon durability indicators" [2]. For more on research, guidelines and/or recommendations, testing methods and procedures of DIs limit values see the literature (e.g. [1, 2, 3, 4, 18, 26] and [28]).

6. Future directions for design durability to EC

In 2010, the CEN TC104/SC1 and the CEN TC250/SC2 have formed a joint working group (JWG) for the revision and improvement of durability design in accordance with EN 1992 and EN 206 based on developing technologies and new knowledge, which should be completed by 2020, [25]. The basic parameters of the future EN 206 and EN 1992 are: revising the exposure classes; introducing classes resistance of concrete- R (for the reference SL of 50 years) with acceptable values of reliability index β (which correspond to the EN 1990 Annex C for SLS); rules relating to R ; requirements for minimum cover by classes of exposure; interaction of SL and R ; requirements for behaviour in the case of fissure occurrence, effects of AAR, etc. [25]. The required rules for exposure classes will be calibrated using the best technologies and methodologies accepted in practice, developed in DuraCrete, MC-SLD and ISO 16204, combined with the experience and observations of the existing CS, which were applicable in several types of binders, with relevant amendments. In EN 1990: 2002, the end of SL is implicitly defined and is not an operational definition for future design of CS, [20] and [25]. Preliminary classes R are given in Table 4, according to the criteria from Tables 5 and 6 [25].

Table 4. Definition of exposure resistance classes [25]

Corrosion of reinforcement						Deterioration of concrete			
Carbonation Resistance Class (RC)			Chloride Resistance Class (RSD)			Freeze/thaw Resistance Class		Chemical Aggressiveness Class (for later)	
RC (Low)	RC (Medium)	RC (High)	RSD (Low)	RSD (Medium)	RSD (High)	RF (Medium)	RF (High)	RCA (Medium)	RCA (High)
Definition of class is 50-years of exposure to XC3 (Rh 65%) with 10%-probability of carbonation front exceeding (mm)			Definition of class is 50-years of exposure to XS2, with 10%-probability of chloride concentration exceeding 0,5% at depth (mm)			Definition of class is 50-years of exposure to XF4, with 10%-probability of scaling loss exceeding (kg/m ²)		Definition of class is 50-years of exposure to XA3, ground water with SO ² 4 6000mg/l and 10%-probability of loss exceeding (g/m ²)[??]	
40	30	20	75	60	45	10	2	?	?

Table 5. Criteria for carbonation resistance classes [25]

Rate of carbonation, mm/years ^{0,5}	Carbonation resistance class
≤2,83	RC20
2,83≤4,24	RC30
4,24≤5,66	RC40

Table 6. Criteria for chloride resistance classes (RSD) depending on the initial chloride content class according to EN 206: 20xx, for SL 50 years (Daap(50)) [25]

$_x10^{-12} \text{ m}^2/\text{s}$, For Cl ⁻ 0.40	$_x10^{-12} \text{ m}^2/\text{s}$, For Cl ⁻ 0.20	$_x10^{-12} \text{ m}^2/\text{s}$, For Cl ⁻ 0.10	RSD
Dapp(50) ≤ 0.13	Dapp(50) ≤ 0.19	Dapp(50) ≤ 0.22	RSD45
0.13 < Dapp(50) ≤ 0.22	0.19 < Dapp(50) ≤ 0.35	0.22 < Dapp(50) ≤ 0.39	RSD60
0.22 < Dapp(50) ≤ 0.35	0.35 < Dapp(50) ≤ 0.55	0.39 < Dapp(50) ≤ 0.61	RSD75

In the future EN 1992, requirements for minimum cover will be related to the beginning of corrosion, occurrence of fissures, etc., and will be used in "mechanical design of structures" [20]. From the statistical distribution of cover, the rate of carbonation or the chloride diffusion coefficient, and the aggressiveness of environment, this criterion does not exclude a certain level of corrosion on a limited amount of reinforcement. Changing the criteria or the target reliability will be acceptable in conditions of exposure with a very long propagation period (e.g. for classes X0 and XC1). The relation between exposure classes, resistance classes and requirements for minimum cover (mm) from the future EN 1992 and EN 206 generations for SL of 50, 100 and 200 years is provided in [25].

7. Closing remarks

Most of the current national codes for CS design have no precise guidelines for designing the durability of structures with SL of more than 50 years, especially if exposed to more aggressive environment than the one classified in these codes. This conclusion also applies to the EC norms. Today, a SL of 100 or more years are required for important objects, with moderate maintenance costs, including the approach to CS design of these objects, which is based on performances and behaviour during the SL. The probabilistic approach to design allows more accurate forecast to be made regarding the behaviour of CS during its SL is in the stage of development through defining MM for the remaining and inadequately treated DP, and quantifying the MM parameters and their statistical processing, which will create the possibility of its wider practical application. The present paper discussed some current aspects of durability based CS design, with the emphasis on performance design based on the DIs of concrete. The current revision of EN 1992 and EN 206 is based on latest experiences, technologies, knowledge and research (particularly those contained in DuraCrete, MC-SLD and ISO 16204). The new generations of EN 1992 and EN 206 are expected to significantly improve the design of reliable CS in terms of durability based on performances and behaviour during the use and for the required SL, which is significantly over 50 years. **Acknowledgement:** This research is part of project TR 36017 founded by the Ministry of ESTD of the Republic of Serbia.

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