Durability design and the performance-based approach behind the upcoming Eurocode 2’s Exposure Resistance Class

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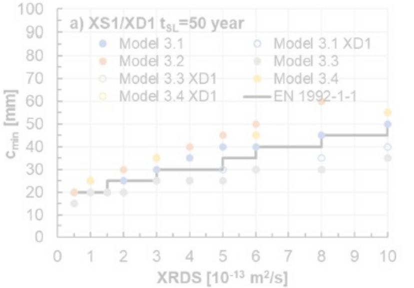
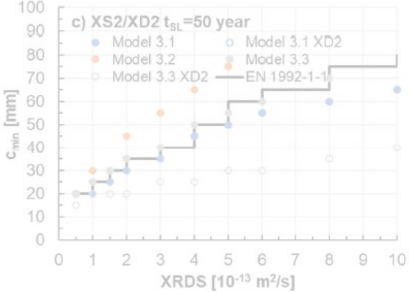
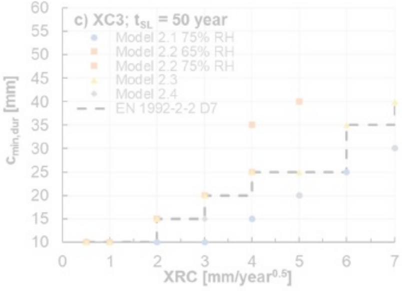
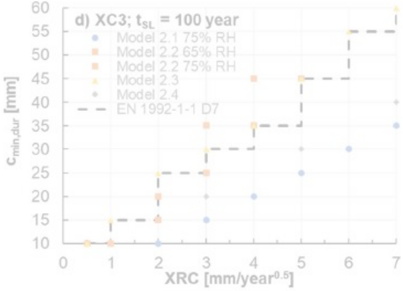
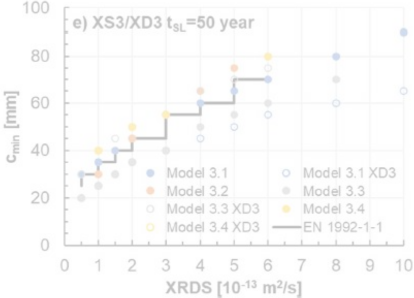




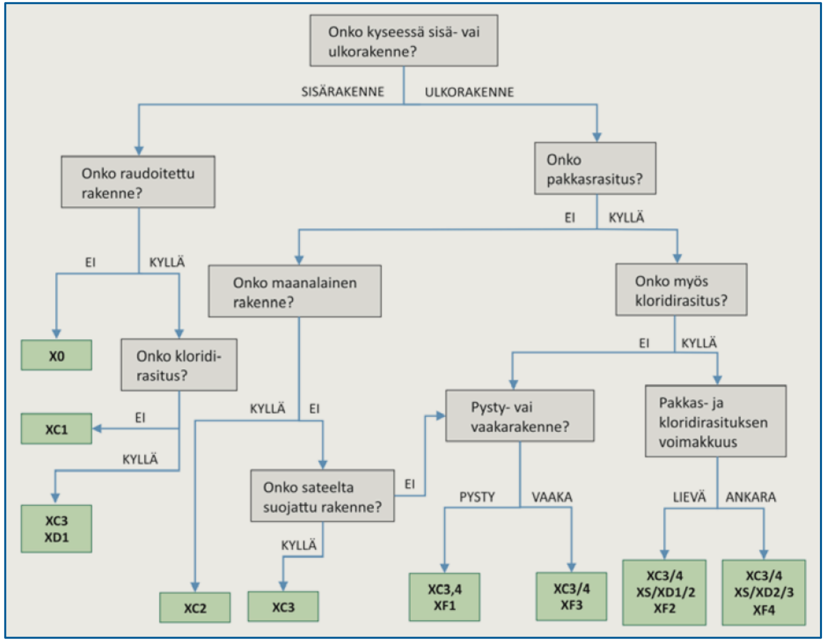


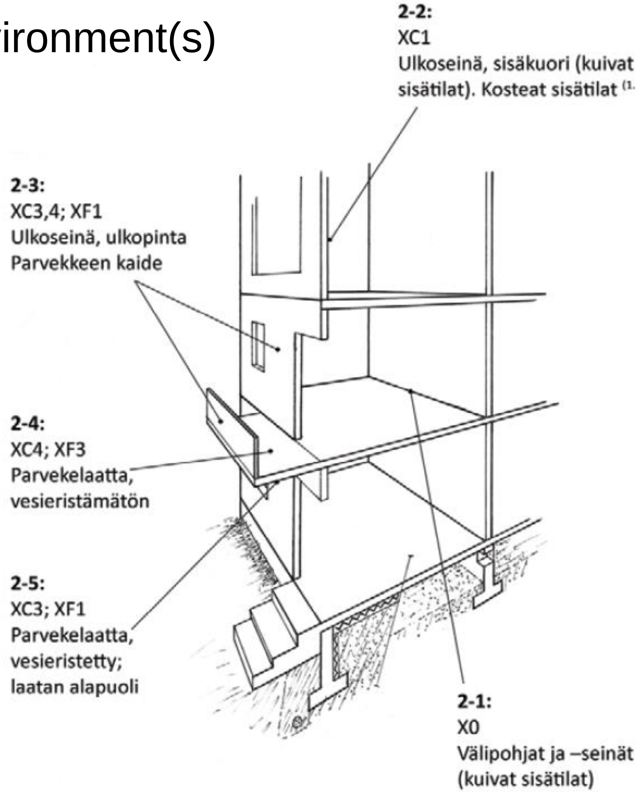




How do you design concrete for durability?

1. Quantify the aggressiveness of the environment(s)





by 68, Betonin valinta ja käyttöikäsuunnittelu – opas suunnittelijoille 2016

How do you design concrete for durability?

1. Quantify the aggressiveness of the environment(s)

Table 1 Exposure classes

Class designation	Description of the environment	Informative examples where exposure classes may occur
1 No risk of corrosion or attack		
X0	For concrete without reinforcement or embedded metal: All exposures except where there is freeze/thaw, abrasion or chemical attack. For concrete with reinforcement or embedded metal: Very dry	Concrete inside buildings with very low air humidity
2 Corrosion induced by carbonation		
Where concrete containing reinforcement or other embedded metal is exposed … shall be classified as follows:		
XC1	Dry or permanently wet	
XC2	Wet, rarely dry	
XC3	Moderate humidity	
XC4	Cyclic wet and dry	
3 Corrosion induced by chlorides other than fro…		
Where concrete containing reinforcement or other embedd… chlorides, including de-icing salts, from sources other than … lows:		
XD1	Moderate humidity	
XD2	Wet, rarely dry	
XD3	Cyclic wet and dry	…exposed to spray containing chlorides. Pavements, Car park slabs

Table 2 Limiting values for exposure classes for chemical attack from natural soil and ground water

Chemical characteristic	Reference test method	XA1	XA2	XA3
Ground water				
SO_4^{2-} mg/l	EN 196-2	≥ 200 and ≤ 600	> 600 and ≤ 3 000	> 3 000 and ≤ 6 000
pH	ISO 4316	≤ 6,5 and ≥ 5,5	< 5,5 and ≥ 4,5	< 4,5 and ≥ 4,0
CO_2 mg/l aggressive	EN 13577	≥ 15 and ≤ 40	> 40 and ≤ 100	> 100 up to saturation
NH_4^+ mg/l	ISO 7150-1	≥ 15 and ≤ 30	> 30 and ≤ 60	> 60 and ≤ 100
Mg^{2+} mg/l	EN ISO 7980	≥ 300 and ≤ 1 000	> 1 000 and ≤ 3 000	> 3 000 up to saturation
Soil				
SO_4^{2-} mg/kg[a] total	EN 196-2[b]	≥ 2 000 and ≤ 3 000[c]	> 3 000[c] and ≤ 12 000	> 12 000 and ≤ 24 000
Acidity according to Baumann Gully ml/kg	prEN 16502	> 200	Not encountered in practice	

a Clay soils with a permeability below 10^{-5} m/s may be moved into a lower class.

b The test method prescribes the extraction of SO_4^{2-} by hydrochloric acid; alternatively, water extraction may be used, if experience is available in the place of use of the concrete.

c The 3 000 mg/kg limit shall be reduced to 2 000 mg/kg, where there is a risk of accumulation of sulfate ions in the concrete due to drying and wetting cycles or capillary suction.

Table 1 *(continued)*

Class designation	Description of the environment	Informative examples where exposure classes may occur
4 Corrosion induced by chlorides from sea water		
Where concrete containing reinforcement or other embedded metal is subject to contact with chlorides from sea water or air carrying salt originating from sea water, the exposure shall be classified as follows:		
XS1	Exposed to airb… …n direct con…	Structures near to or on the coast
		Parts of marine structures
		Parts of marine structures
…ing agents		
…eeze/thaw cycles whilst wet, the exposure shall be classified as		
	…de-icing	Vertical concrete surfaces exposed to rain and freezing
	…ing agent	Vertical concrete surfaces of road structures exposed to freezing and airborne de-icing agents
	…agent	Horizontal concrete surfaces exposed to rain and freezing
	…nt or	Road and bridge decks exposed to de-icing agents; Concrete surfaces exposed to direct spray containing de-icing agents and freezing Splash zones of marine structures exposed to freezing
…soils and ground water, the exposure shall be classified		
	…ghtly aggressive chemical environment	Concrete exposed to natural soil and ground water according to Table 2
XA2	Moderately aggressive chemical environment	Concrete exposed to natural soil and ground water according to Table 2
XA3	Highly aggressive chemical environment	Concrete exposed to natural soil and ground water according to Table 2

SFS-EN 206:2014 + A2:2021 Concrete. Specification, performance, production and conformity

How do you design concrete for durability?

2. Consult the design codes for mix design limits

Maximum water/binder ratio, Minimum strength class, Minimum cement content, Minimum air content, and Other requirements

Table F.1 Recommended limiting values for composition and properties of concrete

	Exposure classes																
	No risk of corrosion or attack	Carbonation-induced corrosion				Chloride-induced corrosion						Freeze/thaw attack				Aggressive chemical environments		
						Sea water			Chloride other than from sea water									
	X0	XC 1	XC 2	XC 3	XC 4	XS 1	XS 2	XS 3	XD 1	XD 2	XD 3	XF 1	XF 2	XF 3	XF 4	XA 1	XA 2	XA 3
Maximum w/c[c]	–	0,65	0,60	0,55	0,50	0,50	0,45	0,45	0,55	0,55	0,45	0,55	0,55	0,50	0,45	0,55	0,50	0,45
Minimum strength class	C12/15	C20/25	C25/30	C30/37	C30/37	C30/37	C35/45	C35/45	C30/37	C30/37	C35/45	C30/37	C25/30	C30/37	C30/37	C30/37	C30/37	C35/45
Minimum cement content[c] (kg/m^3)	–	260	280	280	300	300	320	340	300	300	320	300	300	320	340	300	320	360
Minimum air content (%)	–	–	–	–	–	–	–	–	–	–	–	–	4,0[a]	4,0[a]	4,0[a]	–	–	–
Other requirements	–	–	–	–	–	–	–	–	–	–	–	Aggregate in accordance with EN 12620 with sufficient freeze/thaw resistance				–	Sulfate-resisting cement[b]	

[a] Where the concrete is not air entrained, the performance of concrete should be tested according to an appropriate test method in comparison with a concrete for which freeze/thaw resistance for the relevant exposure class is proven.

[b] Where sulfate in the environment leads to exposure classes XA2 and XA3, it is essential to use sulfate-resisting cement conforming to EN 197-1 or complementary national standards.

[c] Where the *k*-value concept is applied the maximum *w/c* ratio and the minimum cement content are modified in accordance with 5.2.5.2.

SFS-EN 206:2014 + A2:2021 Concrete. Specification, performance, production and conformity

How do you design concrete for durabilit…

2. Consult the design codes for mix de…

Maximum water/binder rati…
content, Minimum…

Taulukko 2–FI Betonin sideaineelle asetettavat vaatimukset

	Rasitusluokat																
	Ei korroosion tai rasituksen vaaraa	Karbonatisoitumisen aiheuttama korroosio			Kloridien aiheuttama korroosio						Jäädytys-sulatusrasitus				Aggressiivinen kemiallinen rasitus		
					Merivesi			Kloridit muusta kuin merivedestä									
	X0	XC 2	XC3	XC 4	XS1	XS 2	XS 3	XD 1	XD 2	XD 3	XF1	XF2	XF3	XF4	XA1	XA2	XA3
Sallitut sementtityypit	Ei säilyvyyden aiheuttamia rajoituksia Kaikki standardin SFS-EN 197-1 mukaiset sementit ovat sallittuja	I II/A-S II/B-S II/A-D II/A-V II/B-V II/A-LL II/A-M II/B-M4) III/A III/B	I II/A-S II/B-S II/A-D II/A-V II/B-V II/A-LL II/A-M II/B-M4) III/A III/B	I II/A-S II/B-S II/A-D II/A-V II/A-LL II/A-M II/B-M4) III/A III/B	I1) II/A-S II/B-S II/A-D II/A-V II/B-V II/A-LL II/A-M II/B-M4) III/A III/B	I1) II/A-S II/B-S II/A-D II/A-V II/A-LL II/A-M II/B-M4) III/A III/B	I1) II/A-S II/B-S II/A-D II/A-V II/A-LL II/A-M II/B-M4) III/A III/B	I1) II/A-S II/B-S II/A-D II/A-V II/B-V II/A-LL II/A-M II/B-M4) III/A III/B	I1) II/A-S II/B-S II/A-D II/A-V II/A-LL II/A-M II/B-M4) III/A III/B	I1) II/A-S II/B-S II/A-D II/A-V II/A-LL II/A-M II/B-M4) III/A III/B	I II/A-S II/B-S II/A-D II/A-V II/A-LL II/A-M II/B-M4) III/A III/B	I II/A-S II/B-S II/A-D II/A-V II/A-LL II/A-M II/B-M4)	I II/A-S II/B-S II/A-D II/A-V II/A-LL II/A-M II/B-M4) III/A III/B	I II/A-S II/B-S II/A-D II/A-V II/A-LL II/A-M II/B-M4)	I II/A-S II/B-S II/A-D II/A-V II/B-V II/A-LL II/A-M II/B-M4) III/A III/B	2) 3)	2) 3)
Seosainekertoimet Silika w/c ≤ 0,45 w/c > 0,45 Lentotuhka5) Masuunikuona	2,00 1,00 1,00 1,00	2,00 1,00 0,40 1,00			2,00 2,00 0,40 1,00			2,00 2,00 0,40 1,00			2,00 1,00 1,00 1,00	2,00 1,00 0,40 1,00	2,00 1,00 1,00 1,00	2,00 1,00 0,40 1,00	2,00 2,00 0,40 1,00		

Taulukk… …eltu

w/c enintään						
Vähimmäislujuusluokka						
Vähimmäissementtimäärä (kg/m3)				300	320	330
Ilmamäärä5) (%)	5,04)	4,04)	5,04)			

1) Lisäksi pakkasenkest…

2) Rasitusluokissa XF2 ja … …alle CEM I, CEM II/A-D CEM II/A-LL, CEM II/A-M ja CEM II/B-M taulukossa 2–FI esitetyin rajoituksin.

3) Betonin vesi-sementtisu… …ellyllä (Liite A). Tällöin tämän taulukon sarakkeissa XF1 ja XF3 esitettyjen vesi-sementtisuhde- tai ilmamäärävaatimusten ei tarvitse täyttyä, mutta be… …aa F-lukuvaatimus rasitusluokassa XF1 on 1,0 ja rasitusluokassa XF3 1,5.

F-luvun arvoja vesi-sementtis… …nktiona on esitetty taulukossa D.1–FI.

4) Ilmamäärävaatimus koske… …mellisraja on vähintään 16 mm. Ylänimellisrajan ollessa 12 mm ilmamäärävaatimusta nostetaan 0,5 %-yksikköä ja ylänimellisrajan ollessa 8 mm 1,0 %-yksikköä.

5) Yli 7 % tavoiteilmamäärä ei…

SFS 7022:2019 Betoni. Standardin SFS-EN 206 käyttö Suomessa

How do you design concrete for durability?

3. Concrete cover (C,min,dur)

Table 4.4N: Values of minimum cover, $c_{min,dur}$, requirements with regard to durability for reinforcement steel in accordance with EN 10080.

Environmental Re	
Structural Class	Exp X
S1	1
S2	1
S3	1
S4	1
S5	1
S6	2

Table 2.3. Minimum value of concrete cover $c_{min,dur}$ (nominal value – permitted dimensional deviation) regarding durability for different exposure classes.

Exposure class	Minimum value of concrete cover for a working life of 50 years [mm]		Minimum value of concrete cover for a working life of 100 years [mm]	
	Reinforcing steel	Prestressing steel	Reinforcement	Prestressing steel
X0	10	10	10	10
XC1	10	20	10	20
XC2	20	30	25	35
XC3, XC4	25	35	30	40
XS1, XD1	30	40	35	45
XS2, XD2	35	45	40	50
XS3, XD3	40	50	45	55

SFS EN 1992-1-1:2015 Eurocode 2: Design of concrete structures. Part 1-1: General rules and rules for buildings
By65 Concrete Code 2021, Betoniyhdistys.

From prescriptive towards performance-based design

- Focus on the mix design
  - **QUALITY ASSUMED**
  - How is **durability** measured?

  → It is not!
  - How is **service life** quantified?

  → It is not – ASSUMED

- Prescriptive
  - Deem-to-satisfy requirements
    - Maximum water/binder ratio
    - Minimum cement content
    - Minimum concrete cover

- Focus on performance
  - **QUALITY MEASURED**
  - How is **durability** measured?

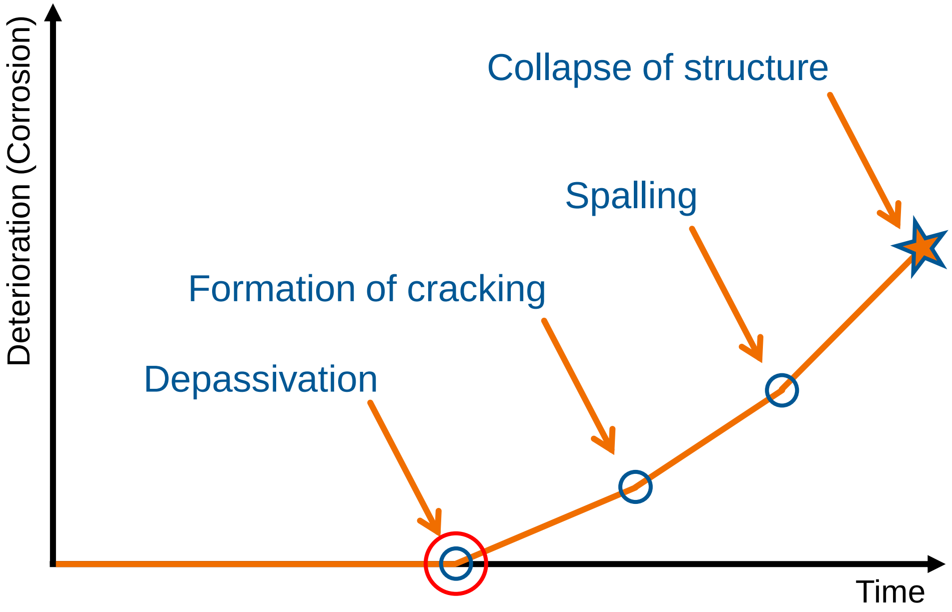
  → Performance tests
  - How is **service life** quantified?

  → Models to verify compliance with limit states

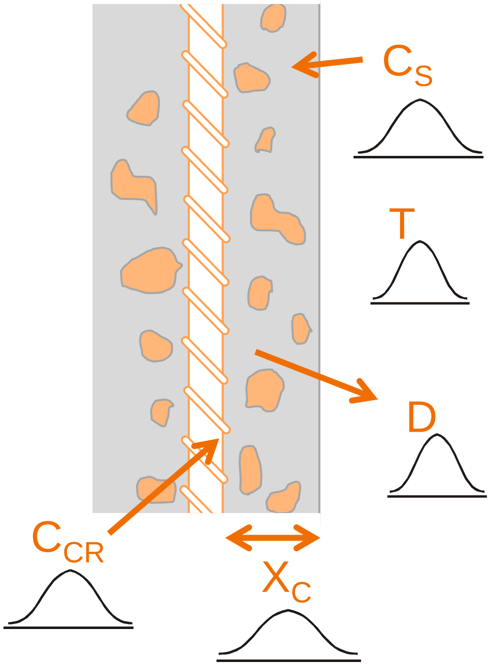
- Performance-based
  - Performance requirements
    - Penetration resistance (diffusion, carbonation resist.)
    - Minimum concrete cover

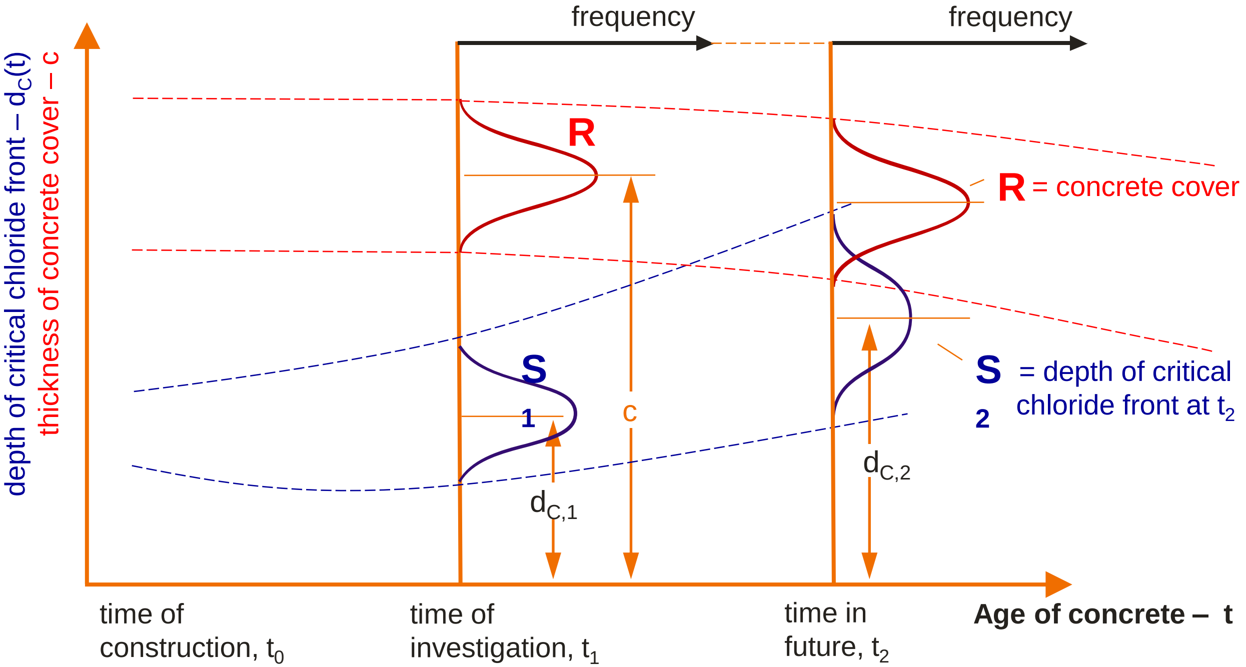
Designing with a performance-based approach

- Possible Limit States (LS) associated with durability and levels of reliability



Designing with a performance-based approach





$$C(x,t) = C_0 + (C_S - C_0)\cdot\left(1 - erf\,\frac{c-\Delta c}{2\sqrt{D_{ap}.t}}\right)$$

$$P_F = P(R - S \le 0)) \leftrightarrow P(C_{CR} - C(x,t) \le 0)$$

$P_{F,LS}$ - probability of depassivation

Designing with a performance-based approach

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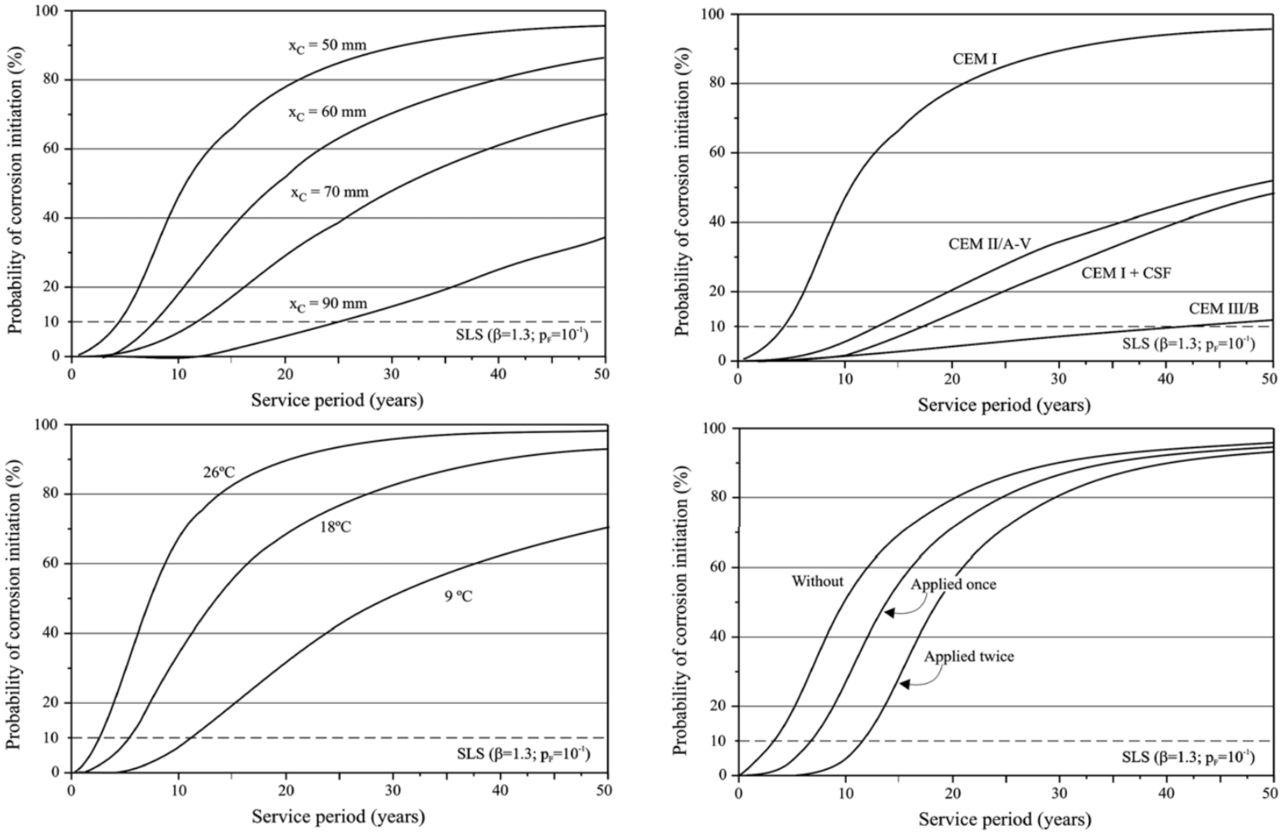

Optimization of RC structure performance in marine environment (2010) Engineering Structures - https://doi.org/10.1016/j.engstruct.2010.02.011.

New performance-based code (EN206-100)
Concept of Exposure Resistance Classes

- The structural resistance will be given by a combination of:
  - "*Exposure Resistance Classes*" (ERC) defined in Eurocode-2 and provisions for verification to be given in EN 206-100 (Concrete)
  - Cover to reinforcement to be given in Eurocode-2 (design standard EN 1992-1-1)
  - Curing provisions and tolerances for cover to be given in EN13670 (Execution standard).

- The ERC are defined in two notes in the EN 1992-1-1
  - These definitions represent the interface between Eurocode-2 and the EN 206

New performance-based codes (EN206-100)

Concept of Exposure Resistance Classes

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- ERC for carbonation designated XRC*n*
- ERC for chlorides designated XRDS*n*

Table 6.3 (NDP) — Minimum concrete cover $c_{min,dur}$ for carbon reinforcing steel — Carbonation

ERC	Exposure class (carbonation)							
	XC1		XC2		XC3		XC4	
	Design service life (years)							
	50	100	50	100	50	100	50	100
XRC 0,5	10	10	10	10	10	10	10	10
XRC 1	10	10	10	10	10	15	10	15
XRC 2	10	15	10	15	15	25	15	25
XRC 3	10	15	15	20	20	30	20	30
XRC 4	10	20	15	25	25	35	25	40
XRC 5	15	25	20	30	25	45	30	45
XRC 6	15	25	25	35	35	55	40	55
XRC 7	15	30	25	40	40	60	45	60

NOTE 1 XRC classes for resistance against corrosion induced by carbonation are derived from the carbonation depth [mm] (characteristic value 90 % fractile) assumed to be obtained after 50 years under reference conditions (400 ppm CO_2 in a constant 65 %-*RH* environment and at 20 °C). The designation value of XRC has the dimension of a carbonation rate [mm/√(years)].

NOTE 2 The recommended minimum concrete cover values $c_{min,dur}$ assume execution and curing according to EN 13670 with at least execution class 2 and curing class 2.

NOTE 3 The minimum covers can be increased by an additional safety element $\Delta c_{dur,\gamma}$ considering special requirements (e.g. more extreme environmental conditions).

Table 6.4 (NDP) — Minimum concrete cover $c_{min,dur}$ for carbon reinforcing steel — Chlorides

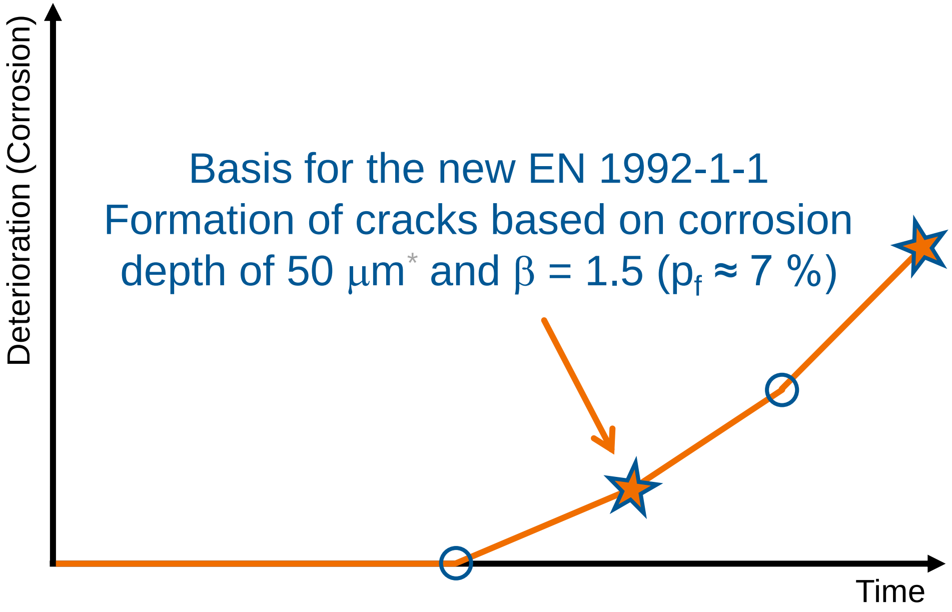
ERC	Exposure class (chlorides)											
	XS1		XS2		XS3		XD1		XD2		XD3	
	Design service life (years)						Design service life (years)					
	50	100	50	100	50	100	50	100	50	100	50	100
XRDS 0,5	20	20	20	30	30	40	20	20	20	30	30	40
XRDS 1	20	25	25	35	35	45	20	25	25	35	35	45
XRDS 1,5	25	30	30	40	40	50	25	30	30	40	40	50
XRDS 2	25	30	35	45	45	55	25	30	35	45	45	55
XRDS 3	30	35	40	50	55	65	30	35	40	50	55	65
XRDS 4	30	40	50	60	60	80	30	40	50	60	60	80
XRDS 5	35	45	60	70	70	—	35	45	60	70	70	—
XRDS 6	40	50	65	80	—	—	40	50	65	80	—	—
XRDS 8	45	55	75	—	—	—	45	55	75	—	—	—
XRDS 10	50	65	80	—	—	—	50	65	80	—	—	—

NOTE 1 XRDS classes for resistance against corrosion induced by chloride ingress are derived from the depth of chlorides penetration [mm] (characteristic value 90 % fractile), corresponding to a reference chlorides concentration (0,6 % by mass of binder (cement + type II additions)), assumed to be obtained after 50 years on a concrete exposed to one-sided penetration of reference seawater (30 g/l NaCl) at 20 °C. The designation value of XRDS has the dimension of a diffusion coefficient [10^{-13} m^2/s].

NOTE 2 The recommended minimum concrete cover values $c_{min,dur}$ assume execution and curing according to EN 13670 with at least execution class 2 and curing class 2.

NOTE 3 The minimum covers can be increased by an additional safety element $\Delta c_{dur,\gamma}$ considering special requirements (e. g. more extreme environmental conditions).

New performance-based codes (EN206-100)
Concept of Limit state



$t_{SL} = t_{INI} + t_{PROP}$

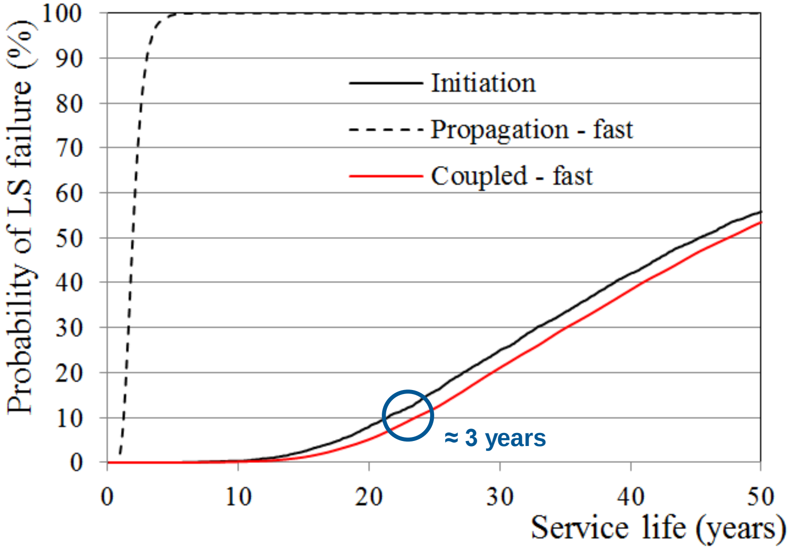
* - *50 μm* is value indicated for carbonation induced corrosion, and *500 μm* is the reference value for chloride induced corrosion.

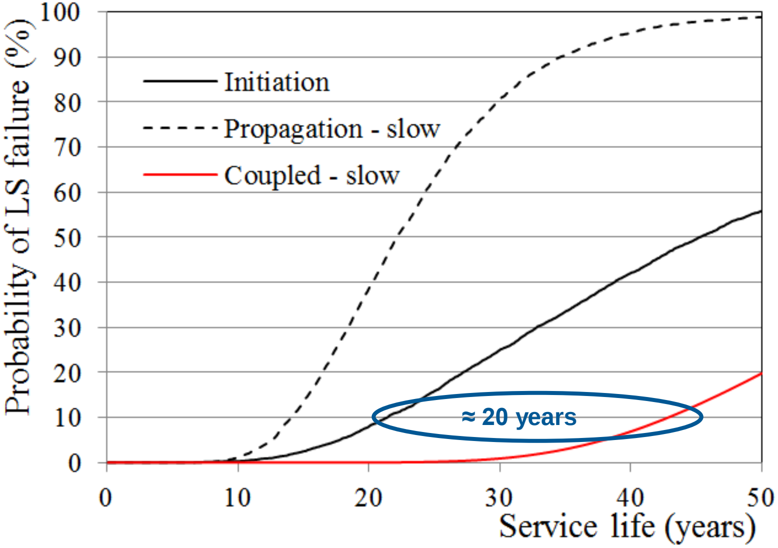
Determining service life for LS crack opening
Example of calculations behind definition of XRC/XRDS

- For initiation model:
  - CEM I 42.5 N with w/b ratio 0.50
  - Not the ideal cement type from a chloride ingress perspective

- For corrosion propagation model – two distinct corrosion rates
  - “fast” corrosion process (3.0 μA/cm2) – 0.035 mm/year
  - “slow” corrosion process (0.3 μA/cm2) – 0.0035 mm/year

Determining service life for LS crack opening
Example of calculations behind definition of XRC/XRDS





Designing concrete durability by coupling limit states of corrosion initiation and corrosion induced cracking of concrete cover (2016) Nordic Concrete Research Journal - https://nordicconcrete.net/wp-content/uploads/2016/11/17972-NCR-nr.-54.pdf

Final considerations

- New generation of codes will allow for performance-based durability design
  - Current approach is prescriptive, which has optimization limitations
- Designer can tailor durability performance to the explicit exposure
  - Currently possible only for carbonation and chloride induced corrosion
- Concrete producer has greater freedom to select appropriate mix design – fulfilling required performance
- Proposed performance-based approach will design for small amount of active corrosion
  - As opposed to current approach which consider damage free

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beyond

the obvious