PROBABILISTIC MODEL CODE

DRAFT CHAPTER ON ENVIRONMENTAL ATTACK

C. Andrade, D. Val, T. Vrouwenvelder

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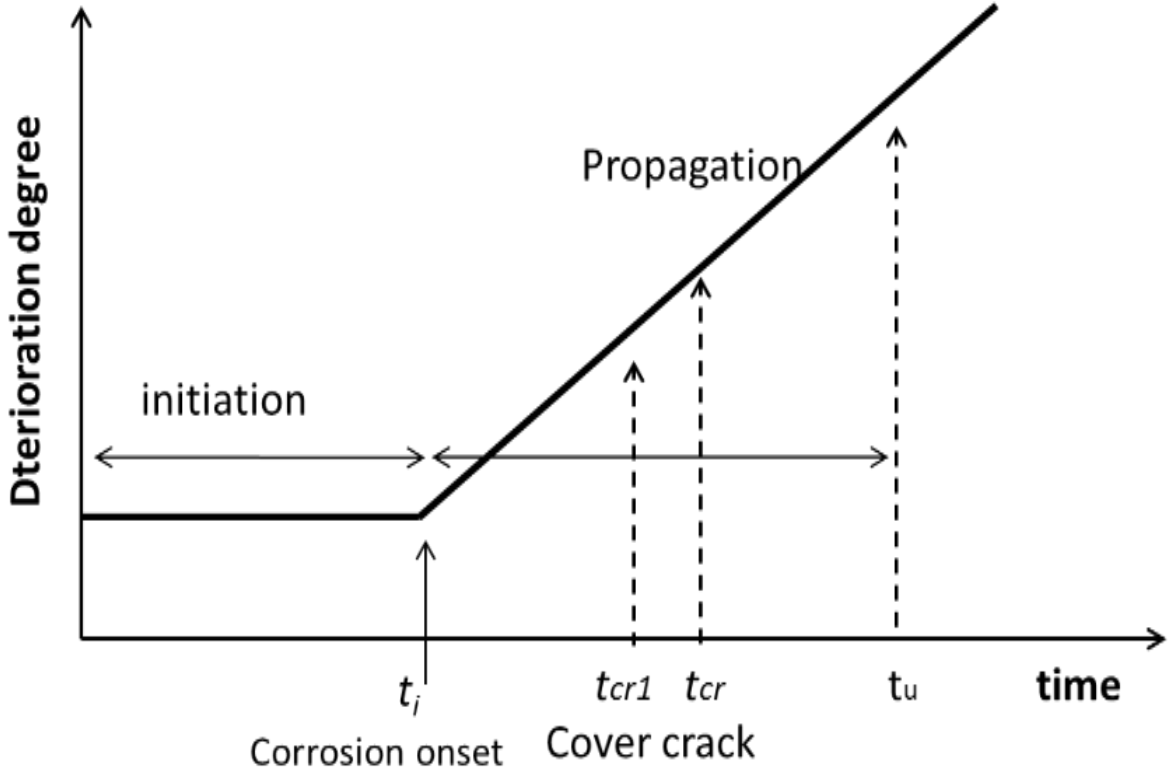
INTRODUCTION

- This section of the JCSS Model Code presents the state of the art on the models needed for the reliability analysis of structures subject to
  - carbonation
  - chloride attack
  - Corrosion poropagation
- It gives information on:
  - The service life models
  - Model parameters and their uncertainties
  - Limit states

BASIC SERVICE LIFE MODEL



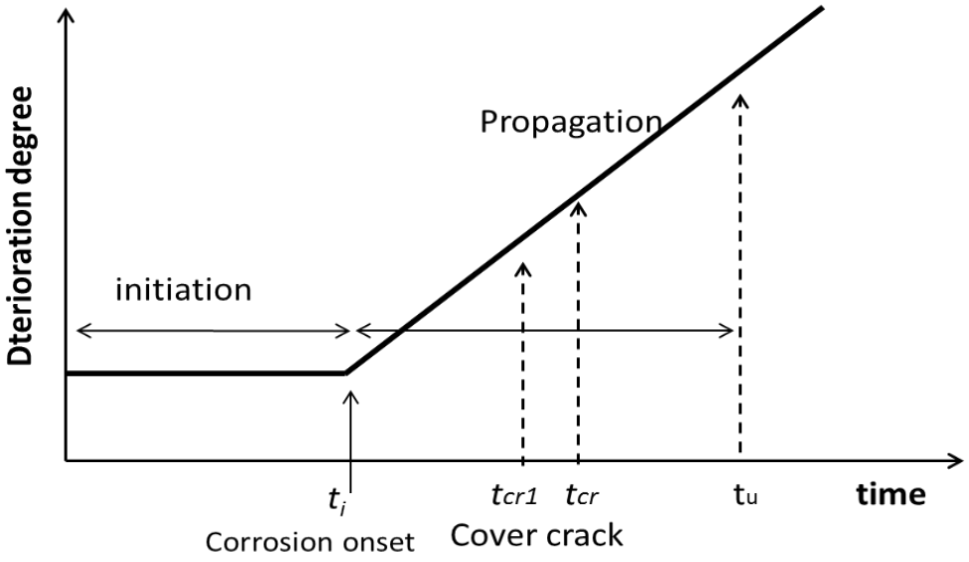
- The model in 3 steps:
  - Initiation
  - Onset of deterioration
  - Propagation
- The model has been delt with in a deterministic approach by RILEM and *fib* committees

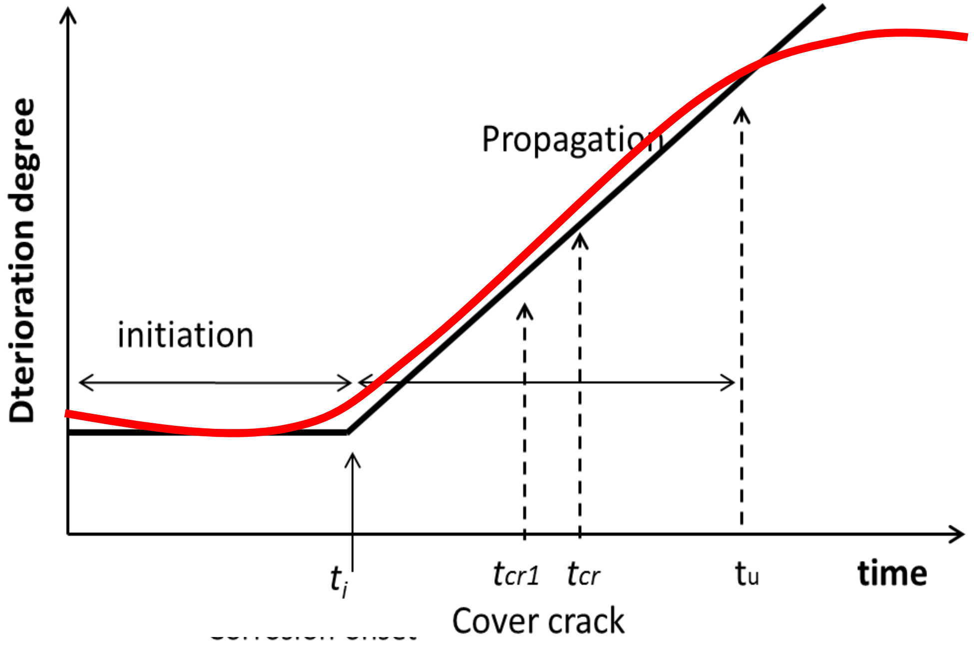
IT CAN BE APPLIED TO OTHER DETERIORATION PROCESSES

the three steps develop similarly

$$t_p\ (years) = \frac{(\emptyset_0 - \emptyset_t)}{V_{corr}} = \frac{P_{corr}}{V_{corr}}$$

$$t_p\ (years) = \frac{Exp_t}{V_{exp}} = \frac{crack\ width}{V_{exp}}$$





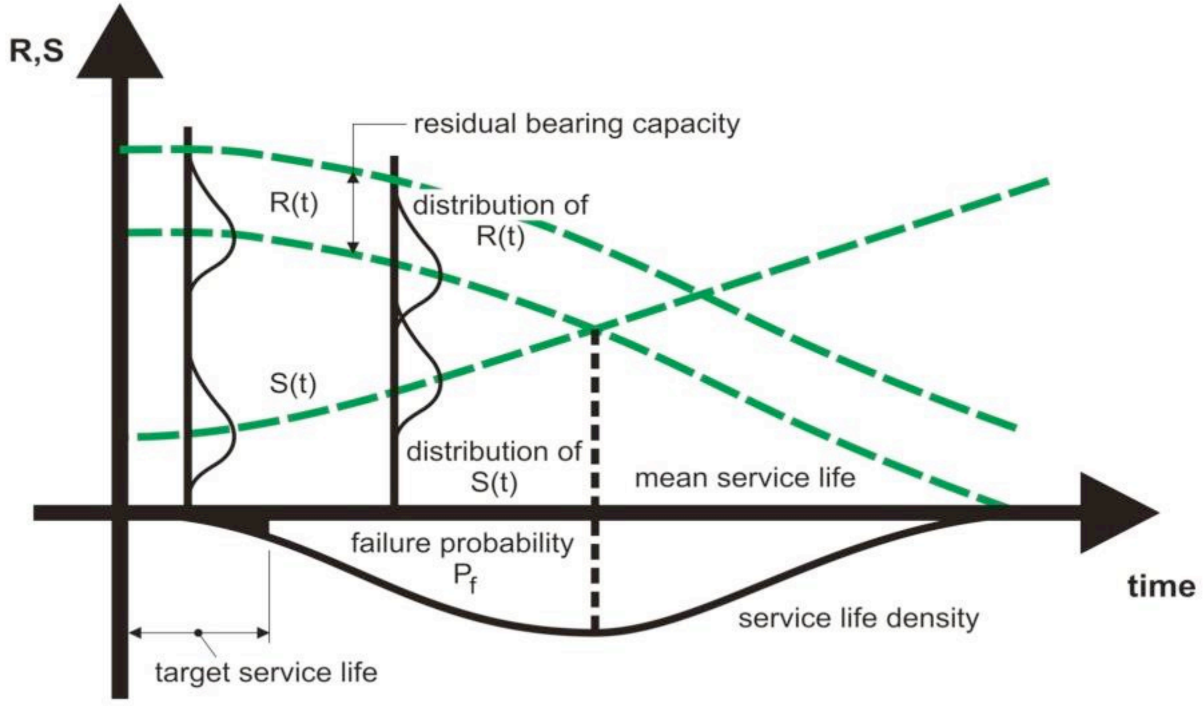
SPECIFIC OF JCSS IN SERVICE LIFE MODELLING
some considered at present, other lacking

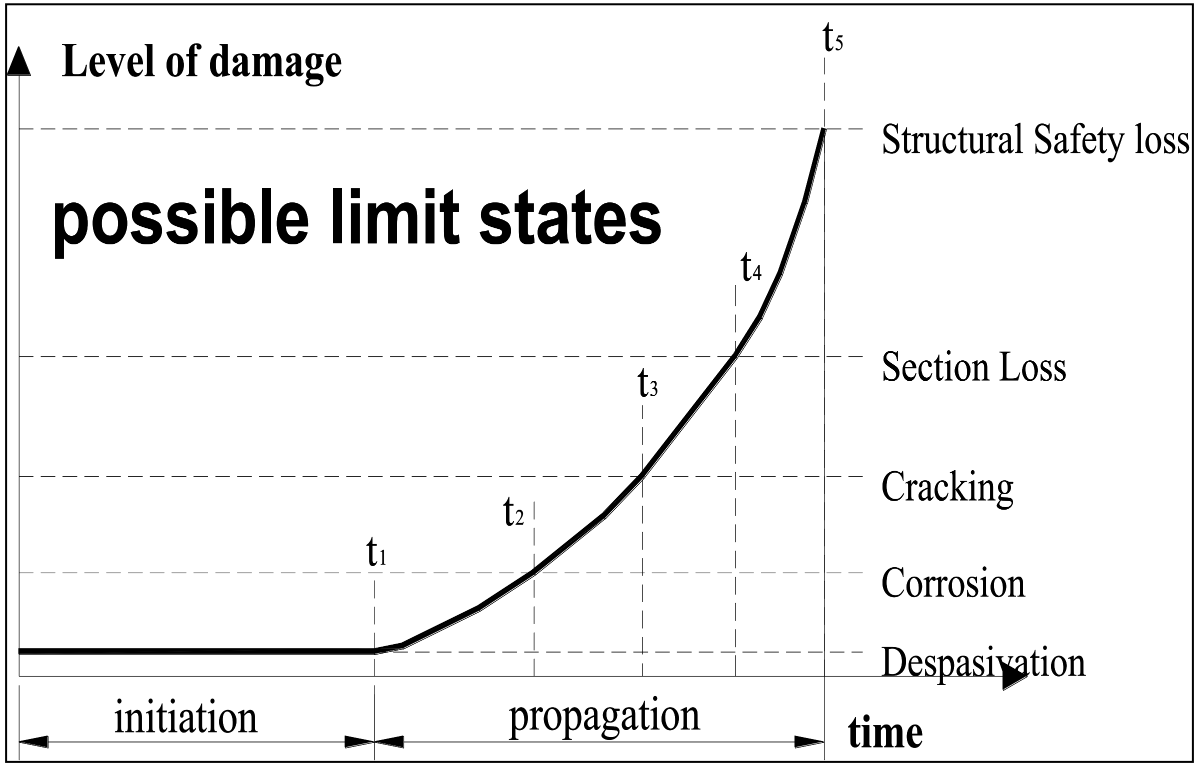
- Uncertainty and variability of:
  - Model uncertainty (calibration)
  - Input parameters
    - Environmental actions
    - Effects of the environmental actions
  - Test methods uncertainties
  - Factors from test to the structure

- Definition of limit states
  - Quantification of probabilities of failure
  - Spatial variability
- Existing structures
  - Time evolution: accumulated damage impact (progressive cracking effect)
    - Updating of input parameters
  - Relation to standard SLS and ULS

NEED OF ESTABLISHMENT OF A METHODOLOGY

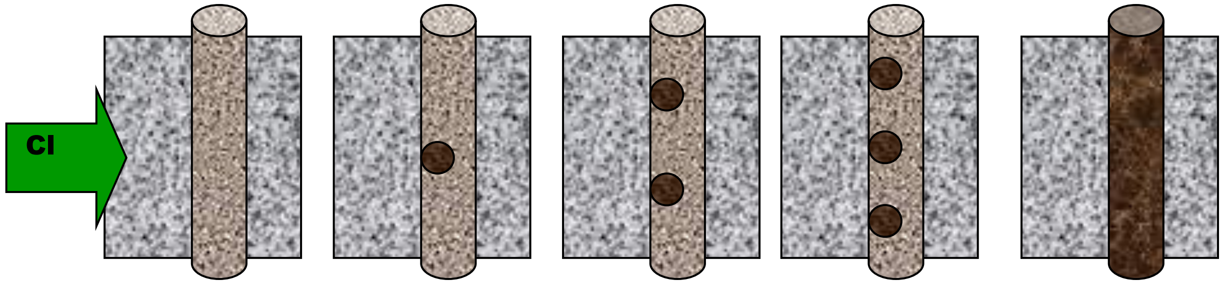
The failure probability regarding durability always increase with time

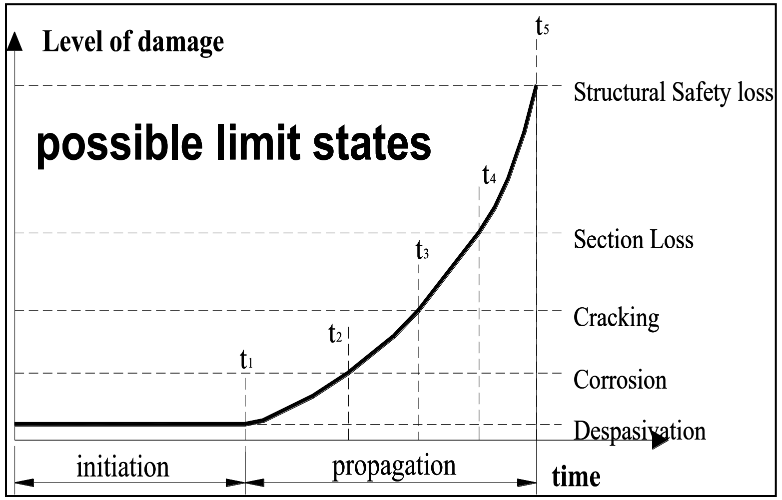


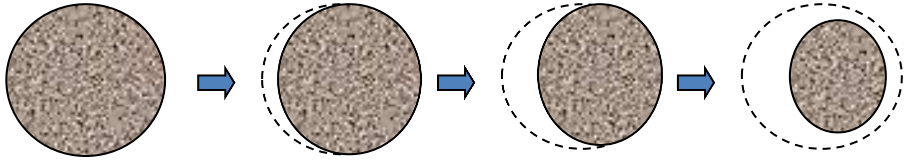


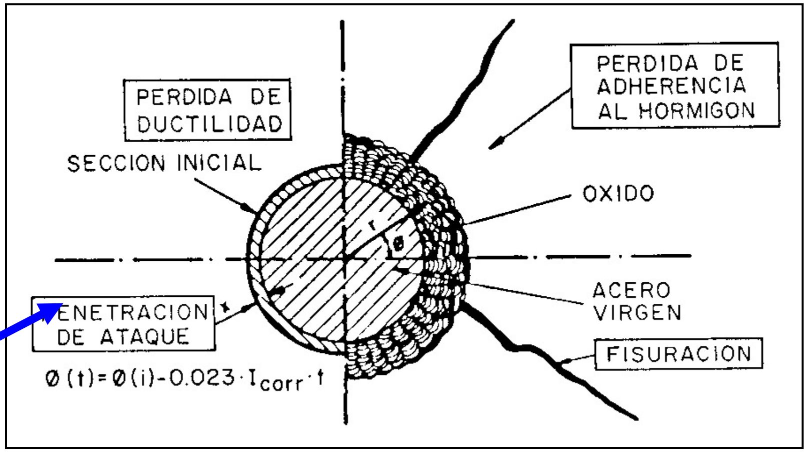
CORROSION PROCESS

- Progressive ingress of aggressives and loss in diameter: uniform or localized



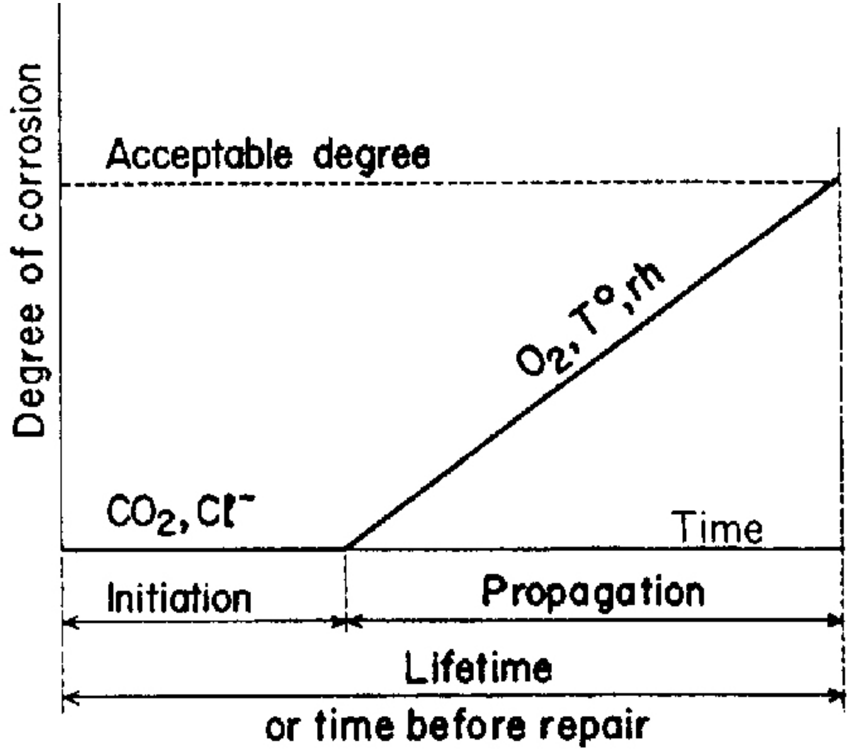


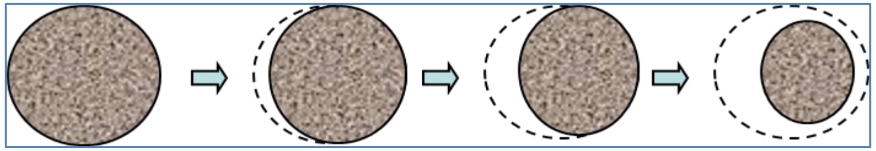


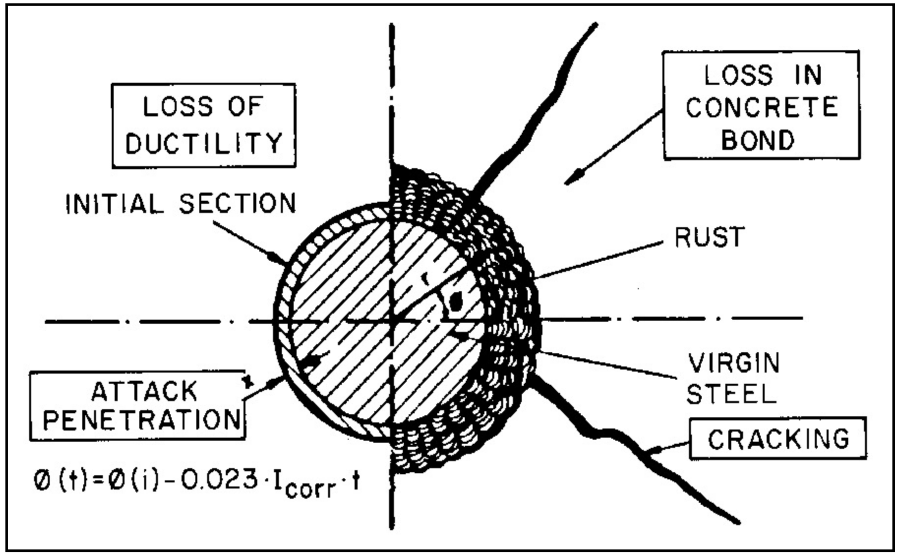


Manual CONTECVET 1990

STRUCTURAL CONSEQUENCES IN FUNCTION OF THE LOSS IN BAR CROSS SECTION P_{corr}





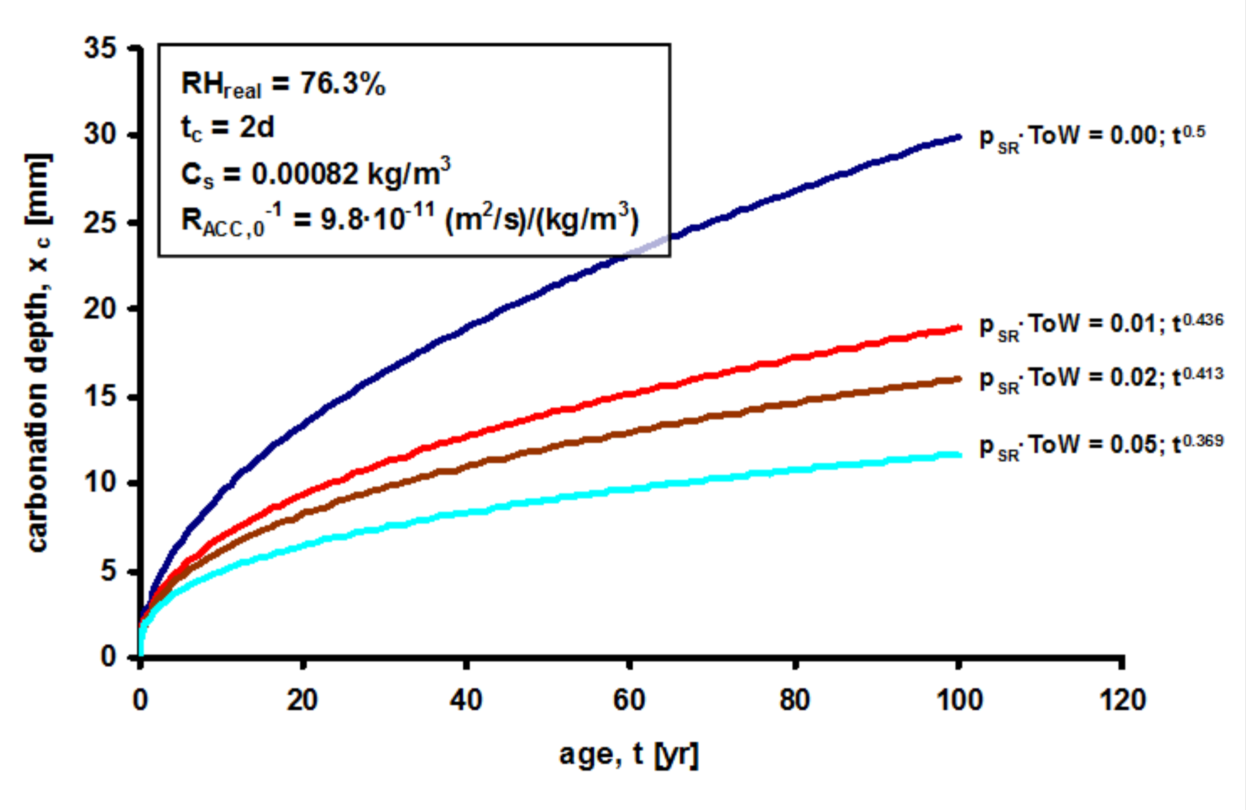


WHAT WE HAVE IN THE CHAPTER AT PRESENT?

fib MODEL ON CARBONATION

$$x_c(t) = \sqrt{2k_e \cdot k_c \cdot \left(k_t \cdot R_{ACC,0}^{-1} + \varepsilon_t\right) \cdot C_S} \cdot \sqrt{t} \cdot W(t)$$

$$x_c = A\sqrt{t}$$



- **The carbonation progresses depending on**
  - **concrete "Quality"**
  - **the moisture content of the concrete**
- **Lack of real data (except those of Prague Institute)**
  - **Bayesian updating**

INPUT PARAMETERS FOR MODELLING (PMC chapter)

	designation	unit	mean	scatter
c_s	Equivalent CO_2 concentration	kg/m^3	$8\ 10^{-4}$	V=0.12
R^{-1}_{NAC0}	Inverse resistance against carbonation	$(m^2/s)/(kg/m^3)$	Note (3)	Note (3)
RH	Equivalent RH at concrete surface	-	Note (1)	-
RH_{ref}	Reference value	-	0.65	-
b_c	Empirical constant	-	0.57	V=0.04
p_{sr}	Prob. of rain driving wind direction	-	Note (1,2)	-
k_t,	Regression coefficient in resistance	-	1.25	V=0.28
ε_t	error term in resistance	$(m^2/s)/(kg/m^3)$-	10^{-11}	V=0.15
ToW	Relative time of wetting	-	Note (1)	-
b_w	Coefficient weather function	-	0.446	V=0.36
t_o	Reference time weather function	s (d) (a)	$2.4\ 10^6$ (28) (0.077)	-

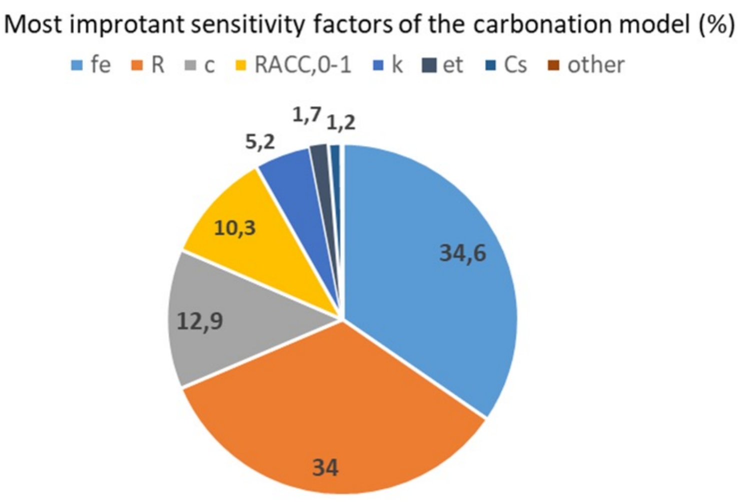
Cement type	$R^{-1}_{ACC,0}$ $[10^{-11}(m^2/s)(kg/m^3)]$					
	w/c_{eqv} [1]					
	0.35	0.40	0.45	0.50	0.55	0.60
CEM I 42.5 R	n.d.[2]	3.1	5.2	6.8	9.8	13.4
CEM I 42.5 R + FA (k=0.5)	n.d.[2]	0.3	1.9	2.4	6.5	8.3
CEM I 42.5 R + SF (k=2.0)	3.5	5.5	n.d.[2]	n.d.[2]	16.5	n.d.[2]
CEM III/B 42.5	n.d.[2]	8.3	16.9	26.6	44.3	80.0

fib MODEL EXAMPLE OF CALCULATION: sensitivity analysis

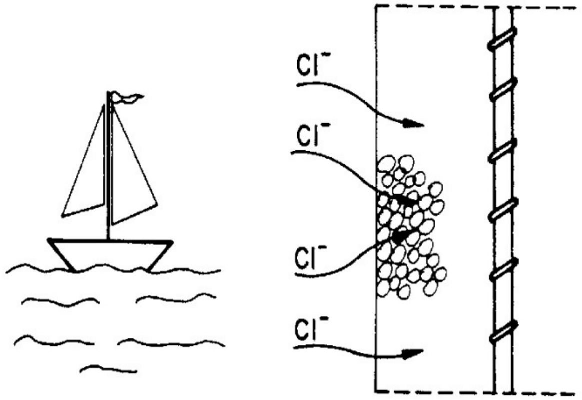
$$x_c(t) = \sqrt{2 \cdot \left(\frac{1 - \left(\frac{RH_{real}}{100}\right)^{f_e}}{1 - \left(\frac{RH_{ref}}{100}\right)^{f_e}} \right)^{g_e} \cdot \left(\frac{t_c}{7}\right)^{b_c} \cdot \left(k_t \cdot R_{ACC,0}^{-1} + \varepsilon_t\right) \cdot C_S} \cdot \sqrt{t} \cdot \left(\frac{t_0}{t}\right)^{\frac{(p_{SR} \cdot ToW)^{b_w}}{2}}$$

parameter	value		unit	Type of statistical distribution
	Mean m	Standard deviation s		
p_{SR}	0,12	-	[-]	deterministic
ToW	0,2	-	[-]	deterministic
t_o	0,0767	-	[d]	deterministic
t_c	1	-	[d]	deterministic
RH_{ref}	65	-	[%]	deterministic
f_e	5,0	-	[-]	deterministic
g_e	2,5	-	[-]	deterministic
b_c	-0,567	0,024	[-]	Normal
b_w	0,446	0,163	[-]	Normal
RH_{real}	76,3	12,9	[%]	beta
c	30	6	[mm]	Lognormal
$InvR_{ACC,0}$	13,4	5,223852	$[(10^{-11} m^2/s)/(kgCO_2/m^3)]$	Lognormal
k_t	1,25	0,35	[-]	Normal
e_t	315,5	48	$[(mm^2/yr)/(kgCO_2/m^3)]$	Normal
C_s	0,00082	0,0001	$[kgCO_2/m^3]$	Normal
t_{dsl}	output		[year]	deterministic

Service life (years)	P_f (%)
25	1,29
50	6,32
75	12,17
100	17,50



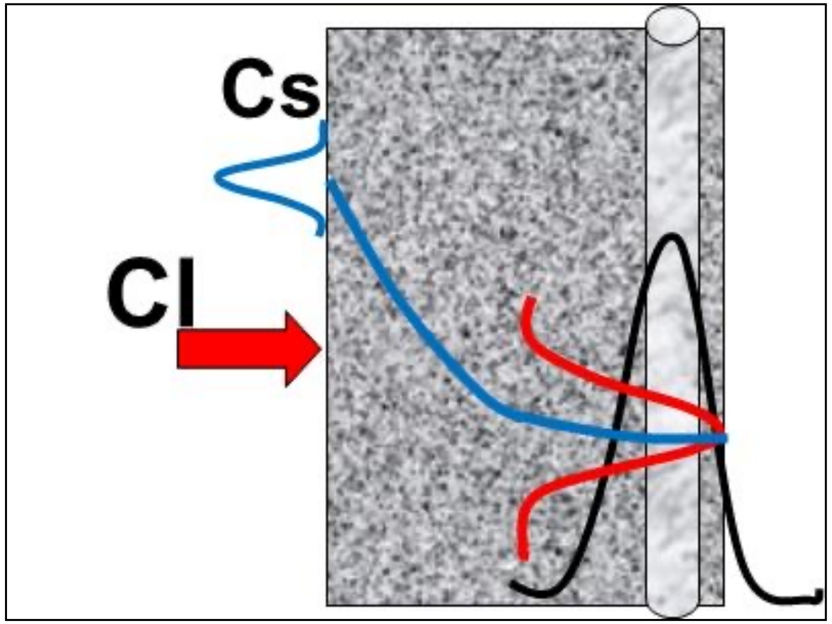
fib CHLORIDE INGRESS MODEL



$$C(x,t) = (C_0 + (C_{x-\Delta x} - C_0) \cdot (1 - erf\,\frac{x-\Delta x}{2\sqrt{D_{ap} \cdot t}})$$

$$D_{a,ref} = \frac{1}{1-m} \cdot k_T \cdot D_{ref,0}$$

$$D_{ap}(t) = D_0 \cdot (\frac{t_0}{t})^{-n}$$



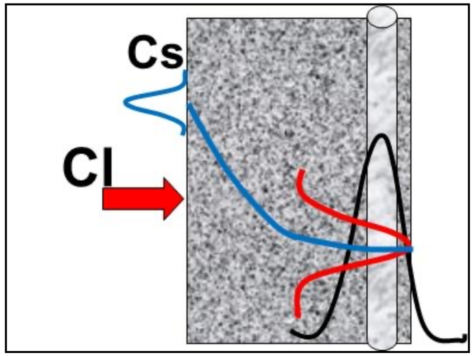
INPUT PARAMETERS FOR MODELLING (PMC chapter)

X	designation	unit	mean	scatter
Dref	chloride diffusion coefficient	$10^{-12}(m^2/s)$	Note 1	
m	Age factor	-	Note 2	
b_T	regression parameter (in K)	K	4800	V=0,146
Δx	Depth of absorption zone	mm	9 (see note 3)	0.6
$C_{s,\Delta x}$	Chloride concentration at depth Δx	%	Note 4	
C_{crit}	Threshold chloride concentration		Note 5	

Type of cement	Mean	COV
Ordinary Portland cement (OPC) CEM I; 0.40≤w/c≤0.60	0.30	0.40
OPC with fly ash (FA) CEM I +FA; FA≥20wt% cement; 0.40≤w/c_{eqv}≤0.62	0.60	0.25
Blast furnace slag cement (GBFS) CEM III/B; 0.40≤w/c≤0.60	0.45	0.44

Cement type	$D_{ref,0}$ $[10^{-12}(m^2/s)]$					
	w/c_{eqv} [1]					
	0.35	0.40	0.45	0.50	0.55	0.60
CEM I 42.5 R	n.d.[2]	8.9	10.0	15.8	19.7	25.0
CEM I 42.5 R + FA (k=0.5)	n.d.[2]	5.6	6.9	9.0	10.9	14.9
CEM I 42.5 R + SF (k=2.0)	4.4	4.8	n.d.[2]	n.d.[2]	5.3	n.d.[2]
CEM III/B 42.5	n.d.[2]	1.4	1.9	2.8	3.0	3.4

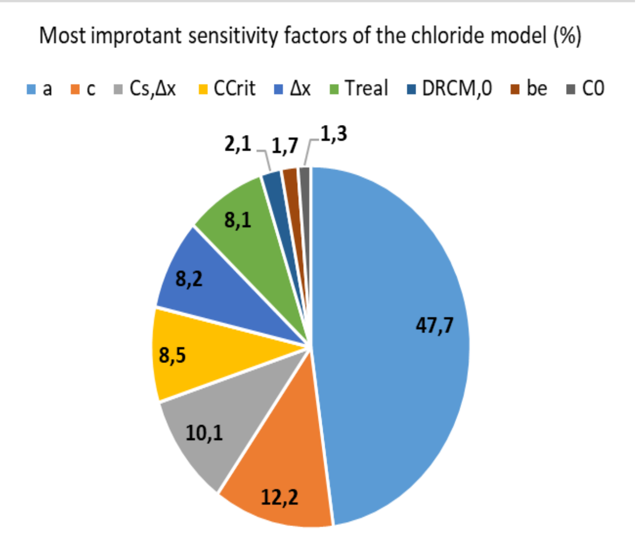
fib MODEL EXAMPLE OF CALCULATION: sensitivity analysis



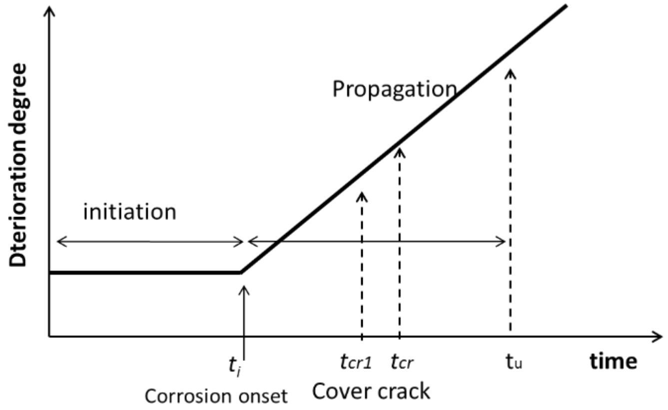
$$C_{crit.} = C(x=a,t) = C_0 + (C_{S,\Delta x} - C_0) \cdot \left[1 - \operatorname{erf} \frac{a - \Delta x}{2 \cdot \sqrt{D_{app,C} \cdot t}} \right]$$

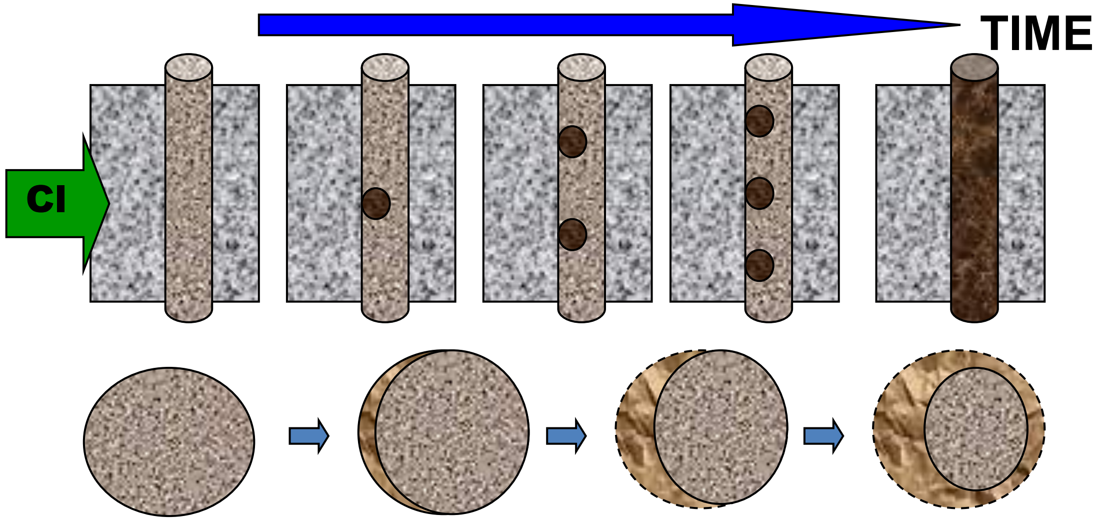
Design service life (years)	P_f (%)
25	20.1
50	30.4
75	36.8
100	40.4

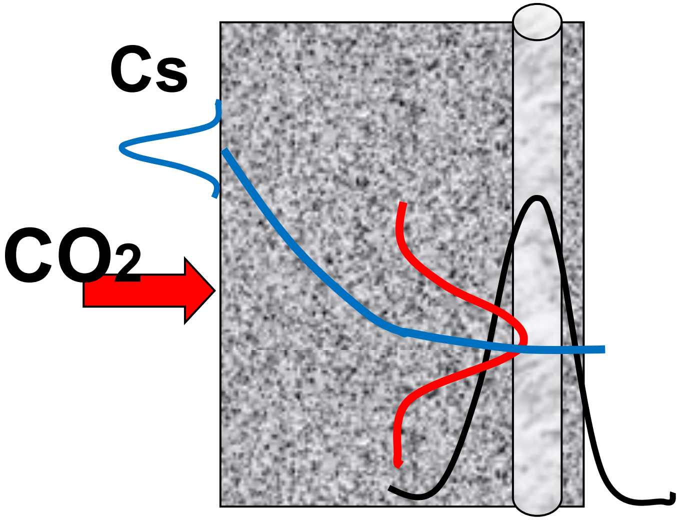
Parameter	μ	σ	COV	Unit	Distribution	Description
C_0				%m/m binder		Initial chloride content of the concrete
$C_{s,\Delta x}$				%m/m binder		Chloride content at a depth Δx and a certain point of time t
C_{crit}				%m/m binder		Critical chloride content
c				mm		Cover depth
Δx				mm		Depth of the convection zone
$D_{RCM,0}$				10^{-12} m^2/s		Chloride migration coefficient
a				-		ageing exponent
t_0				year		Time of refrence of first testing
t				year		Design service life
b_e				K		Regression variable
T_{ref}				K		Standard test temperature
T_{real}				K		Temperature of the structural element or the ambient air
k_t				-		Transfer parameter

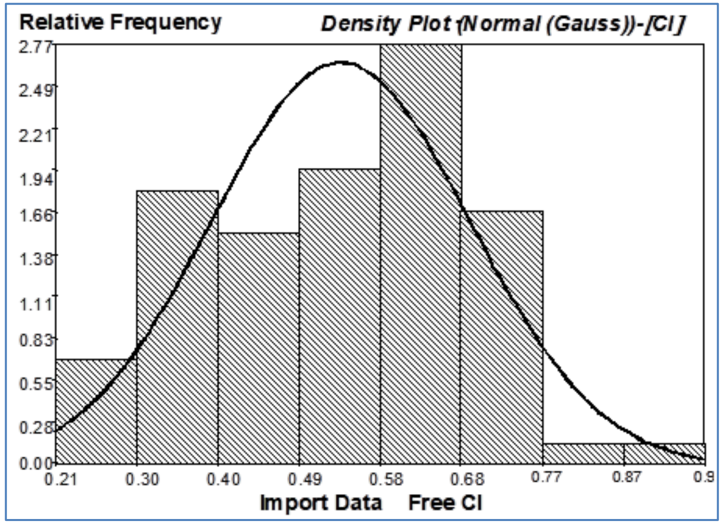


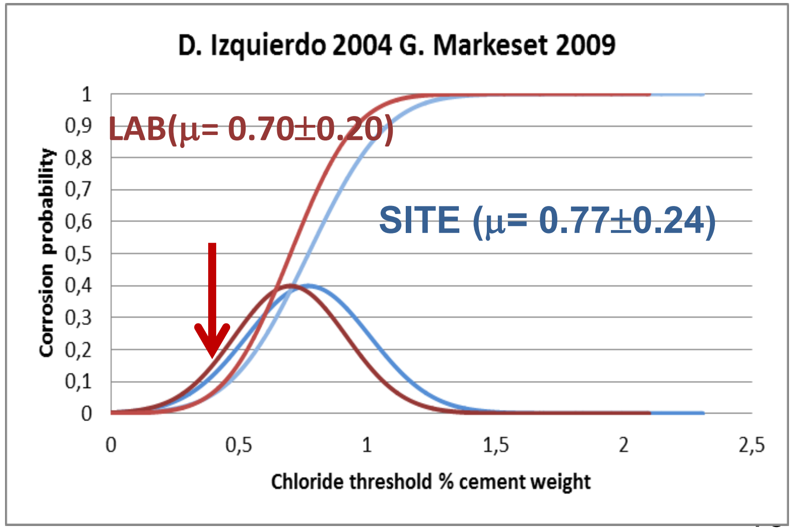
PROBABILISTIC TREATMENT OF CHLORIDE THRESHOLD





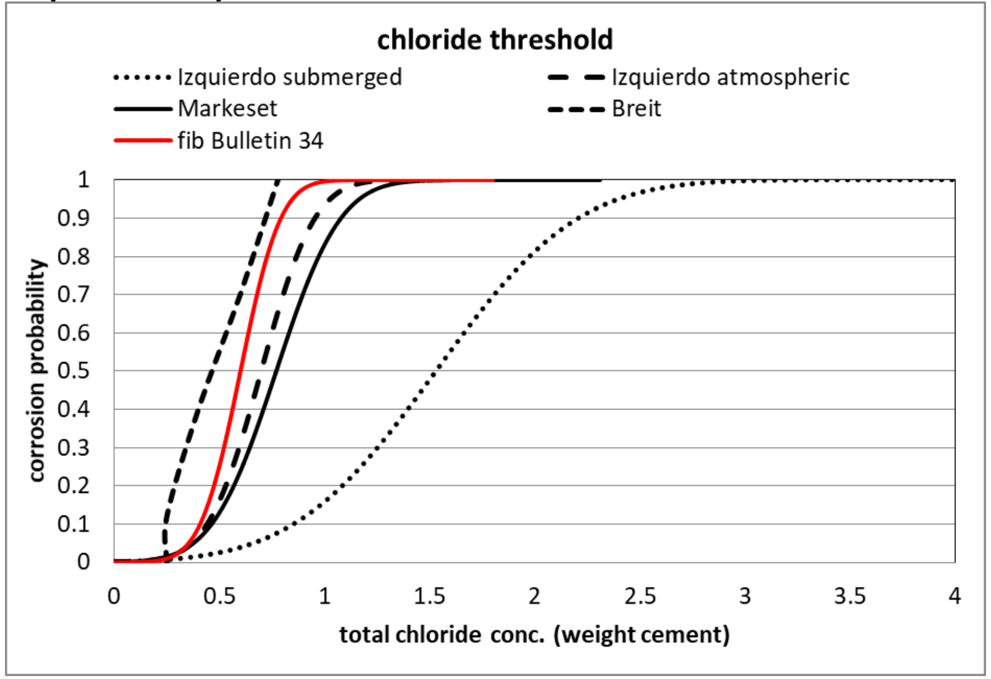


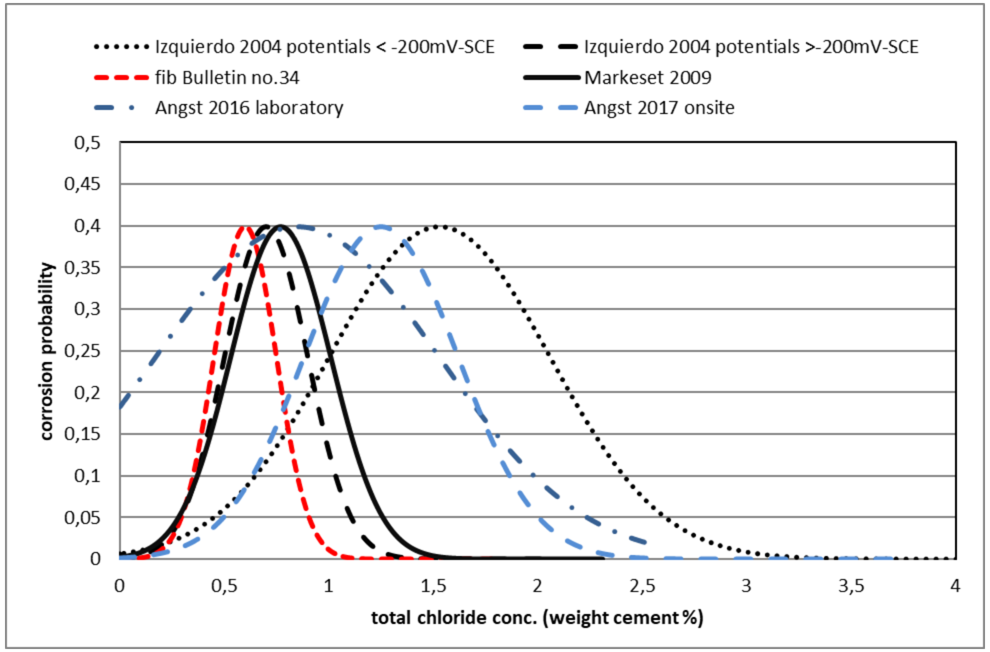




CHLORIDE THRESHOLD AT *fib* MC 2020

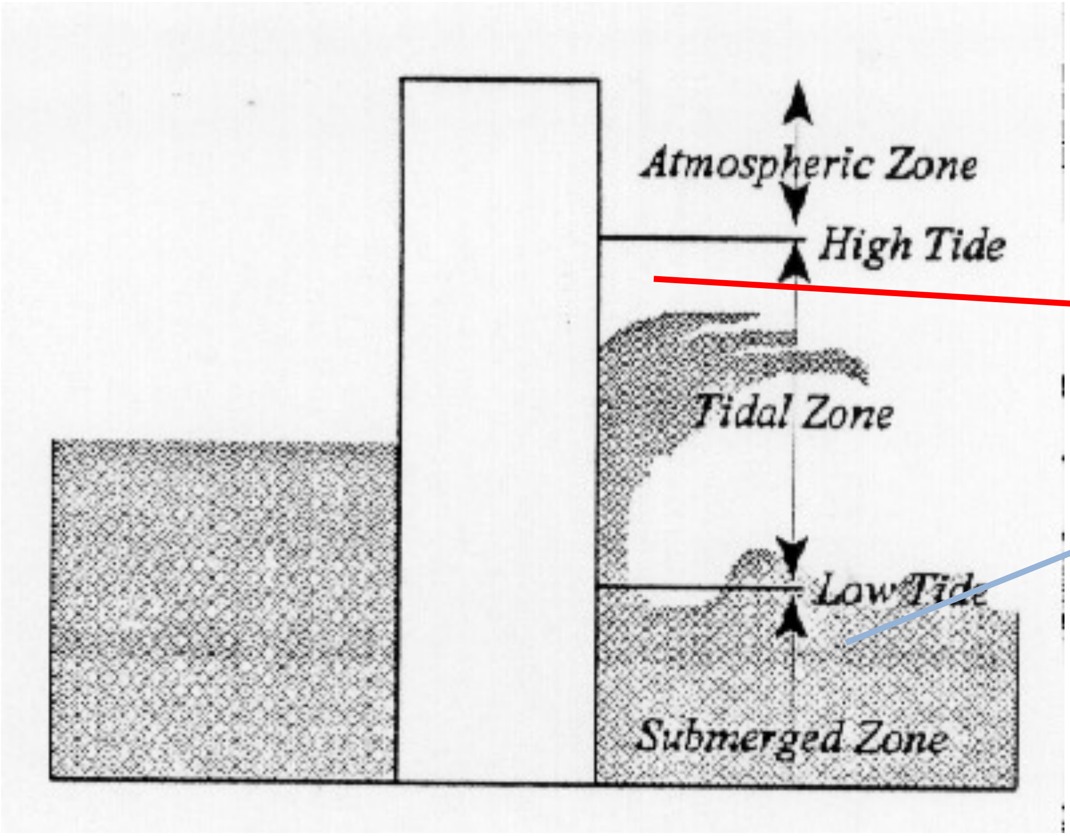
Statistical distributions of the chloride threshold in atmospheric and submerged conditions by Izquierdo (1), by Markeset (2), by Breit (3) and by fib-Bulletin 34 (4) (in RED) with mean =0.6 and σ=0.15

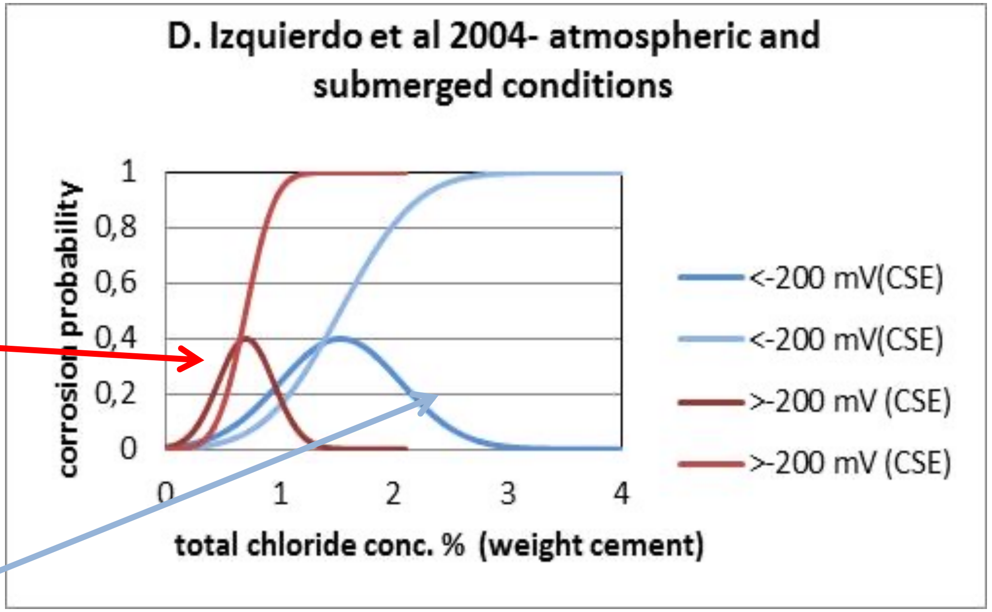




1. *Izquierdo, D., Alonso C., Andrade C., Castellote M. (2004). Potentiostatic determination of chloride threshold values for rebar depassivation Experimental and statistical study.-Electrochimica Acta 49(17-18): 2731-2739.*
2. *Markeset G. - Critical chloride content and its influence on service life predictions -Materials and Corrosion 2009, 60, No. 8593-596.*
3. *Breit W. (1997) Untersuchen zum Kritischen Corrosion auslösened Chloridgehalt von Stahl in Beton* Aachen Technische Hochschule. Disertation.
4. *fib Bulletin 34*
5. *Angst U. (2019) Predicting the time to corrosion initiation in reinforced concrete structures exposed to chlorides Cement and Concrete Research 115 pp. 559–567.*

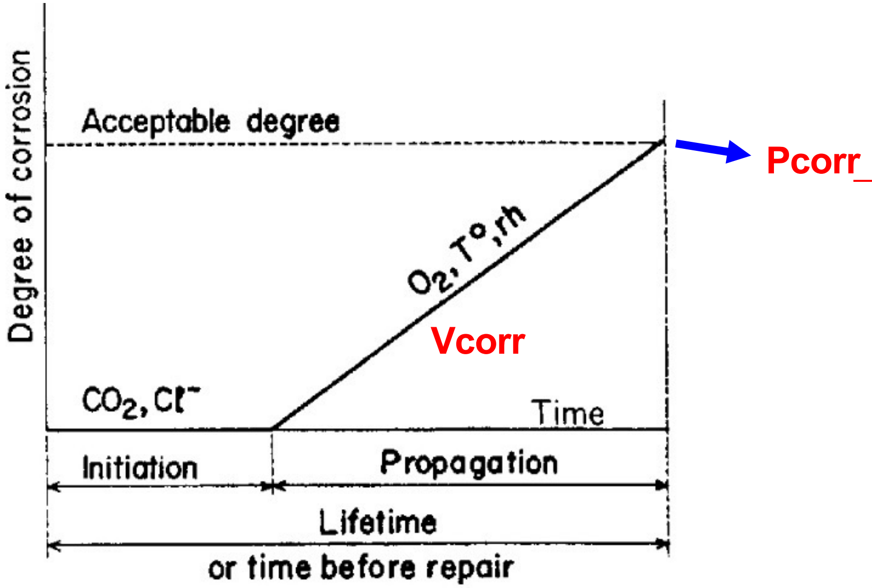
PROBABILISTIC TREATMENT OF CHLORIDE THRESHOLD SUBMERGED CONDITIONS

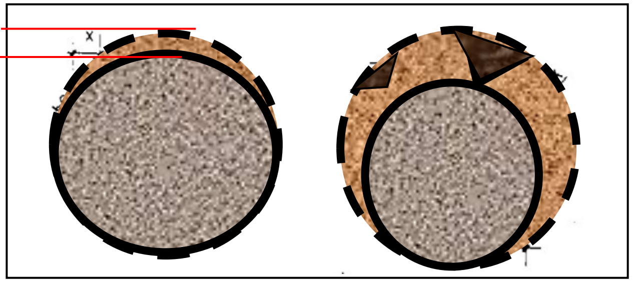


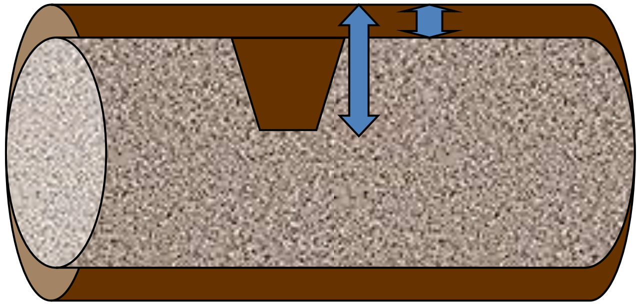


Average value	
Aerial	0.70±0.20
submerged	1.53% ±0,53

CORROSION PROPAGATION MODEL







C.Andrade, et al, Proceedings IABSE Symposium on Durability, Lisbonne, (Sep. 1989), pp. 359-363

$$t_p = \frac{P_{corr}}{V_{corr}}$$

$$P_{corr} = V_{corr} \cdot \alpha \cdot t$$

Pitting factor

$\alpha = 10$

Table 6: Characterization of the pitting factor

Samples	Mean	Standard deviation	Distribution
51	9.28	4.04	Normal

Residual diameter

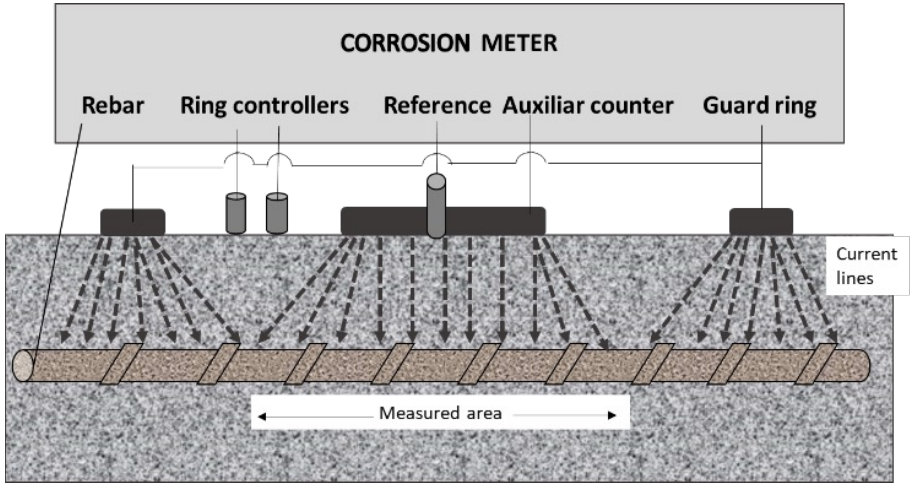
$$\phi_t = \phi_o - P_{corr}$$

Pcorr / Loss in diameter is the accumulated corrosion in a time period

SITE CORROSION RATE BY A PORTABLE CORROSION-RATE-METER CONFINING THE CURRENT

Icorr	Vcorr
< 0.1 μA/cm²	**< 1 μm/year**
0.1 - 0.5 μA/cm²	1 - 5 μm/year
0.5 – 1 μA/cm²	5 - 10 μm/year
1 – 10 μA/cm² >10 μA/cm²	10 - 100 μm/year > 100 μm/year

$$I_{corr} = \frac{B}{Rp \cdot A}$$

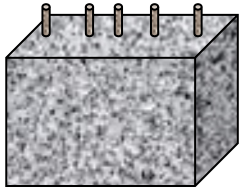


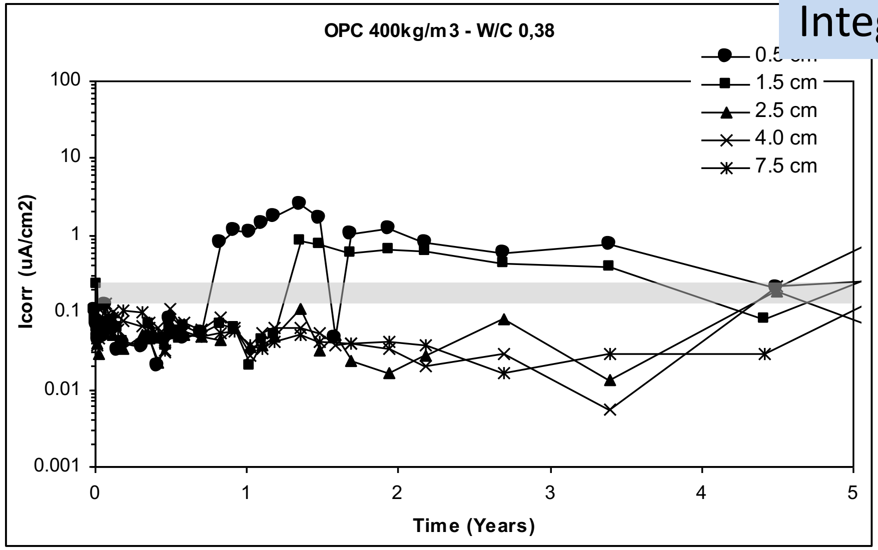
Polarization Resistance

Andrade C, Alonso C, Gulikers J, Polder R, Cigna R, Vennesland Ø, Salta M, Raharinaivo A, Elsener B. (2004). "RILEM TC 154-EMC :Electrochemical Techniques for Measuring Metallic Corrosion. Recommendations Test methods for on-site corrosion rate measurement of steel reinforcement in concrete by means of the polarization resistance method." Materials & Structures 37(273): 623-643.

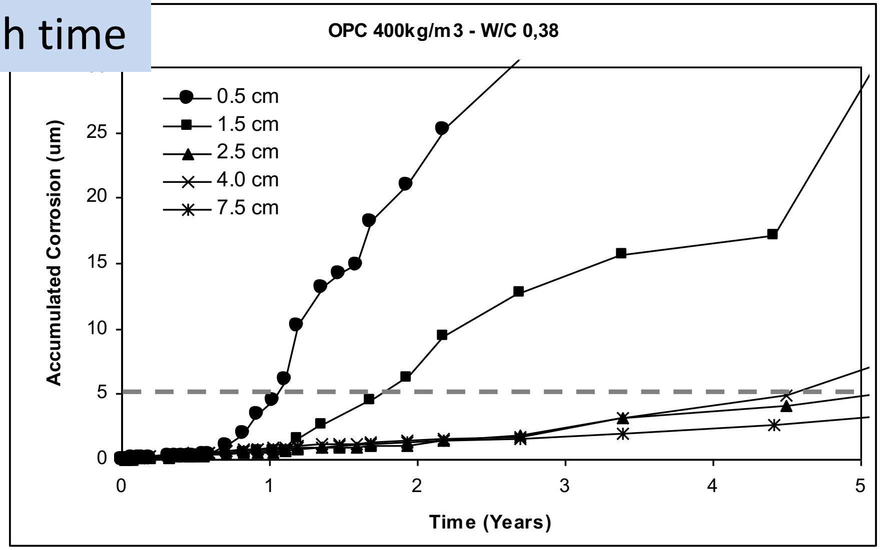
INSTANTANEOUS (Icorr) AND ACCUMULATED (Pcorr)

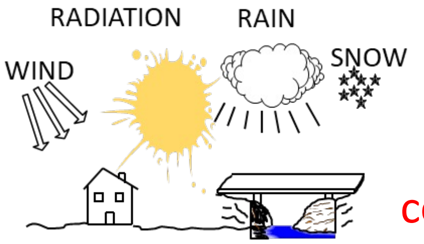
Sea water





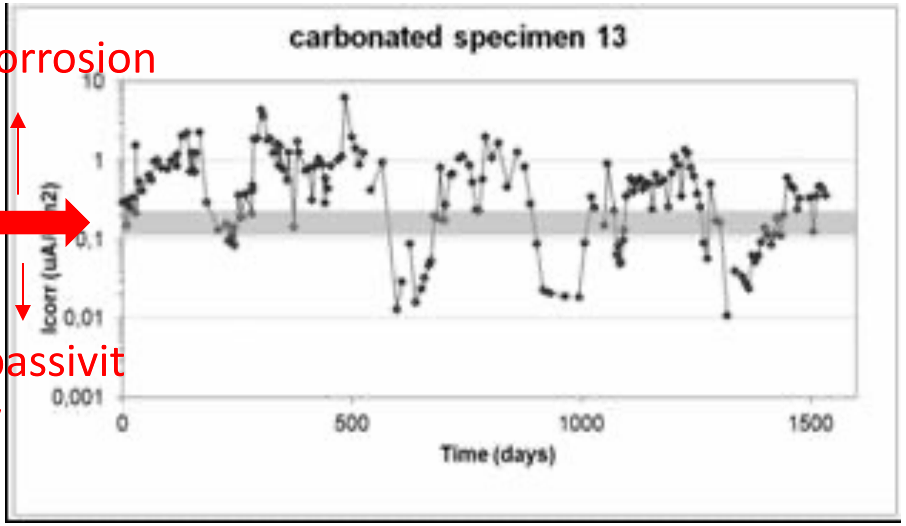
Integration with time

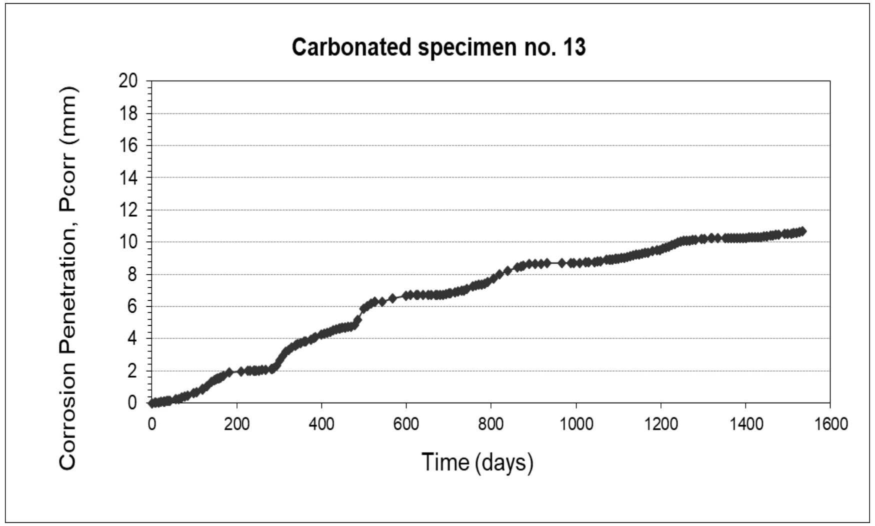




corrosion

passivity



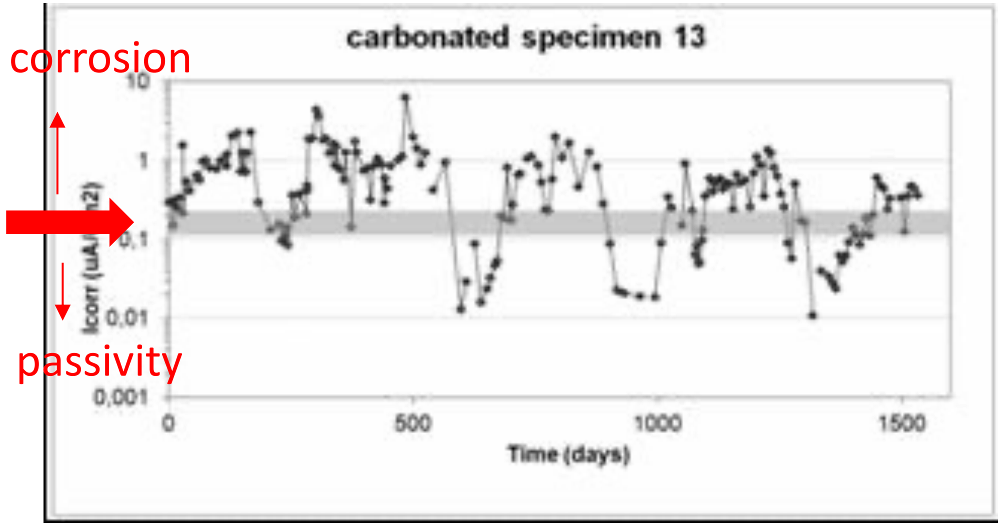


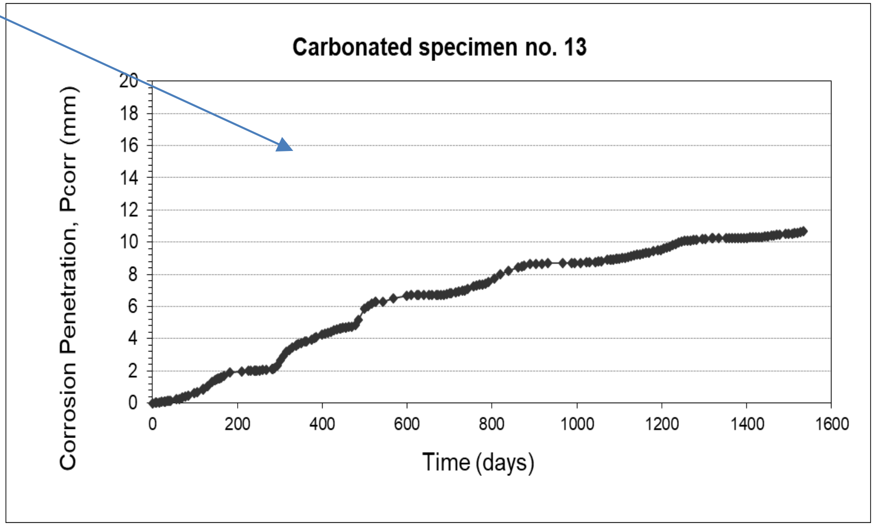
ATMOSPHERE
CARBONATION

VARIABILITIES OF CORROSION RATE

- **After corrosion starts,**
  - **Spatial variability:**
    - **intrinsic inhomogeneity of concrete as composite material,**
  - **Temporal variation**
    - **concrete aging**
    - **Evolution of external climate**

INSTANTANEOUS (Vcorr/Icorr) and ACCUMULATED (Pcorr)



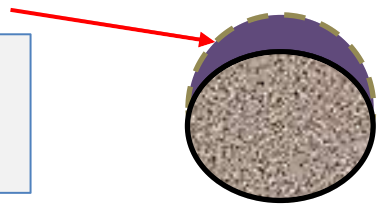


PROPAGATION

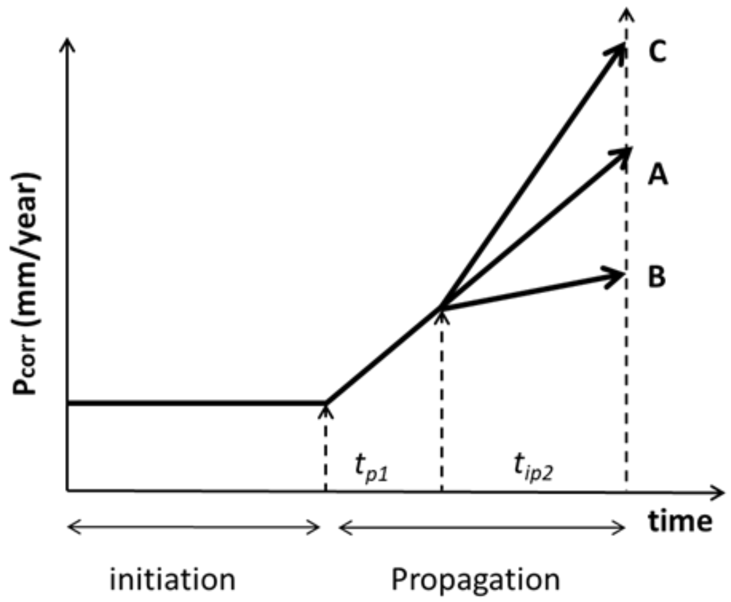
VALUES of Icorr IN FUNCTION OF EXPOSURE CLASS

The corrosion propagation period model is

$$t_{prop} = \frac{\phi_0 - \phi_t}{V_{corr}} = \frac{P_{corr}}{V_{corr}}$$



EXPOSURE CLASS		$V_{corr,\ REP}$ (µm/year)
0	No risk of corrosion, very dry	0
XC1	Dry or permanent wet	0
XC2	Wet rarely dry	4
XC3	Moderate humidity	2
XC4	Cyclic wet dry	5
XD1	Moderate humidity	4
XD2	Wet, rarely dry	30
XD3	Cyclic, wet and dry	30
XS1	Airborne salt conditions	30
XS2	Submerged	Not corrosion expected or 10
XS3	Tidal, splash and spray zones	70



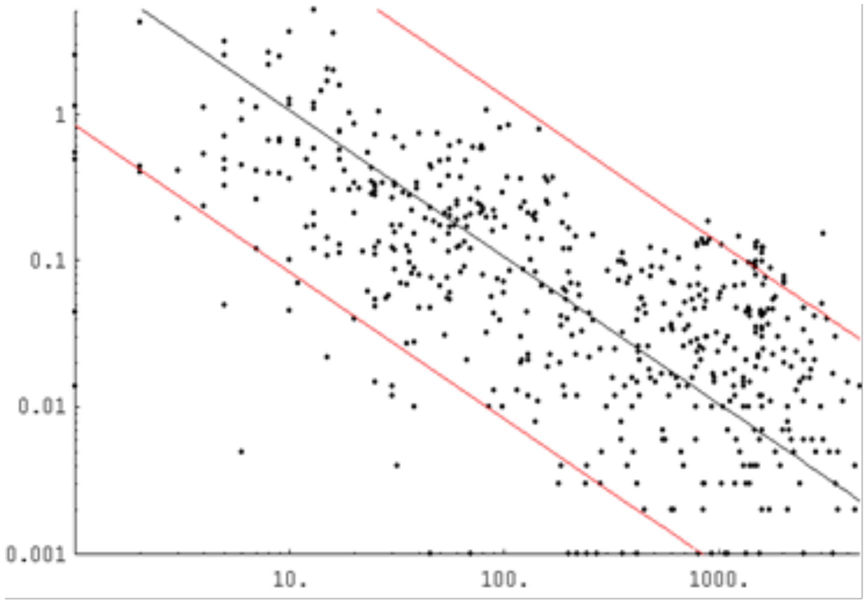
The corrosion rate can be annually constant or the corrosion can be accelerated or attenuated

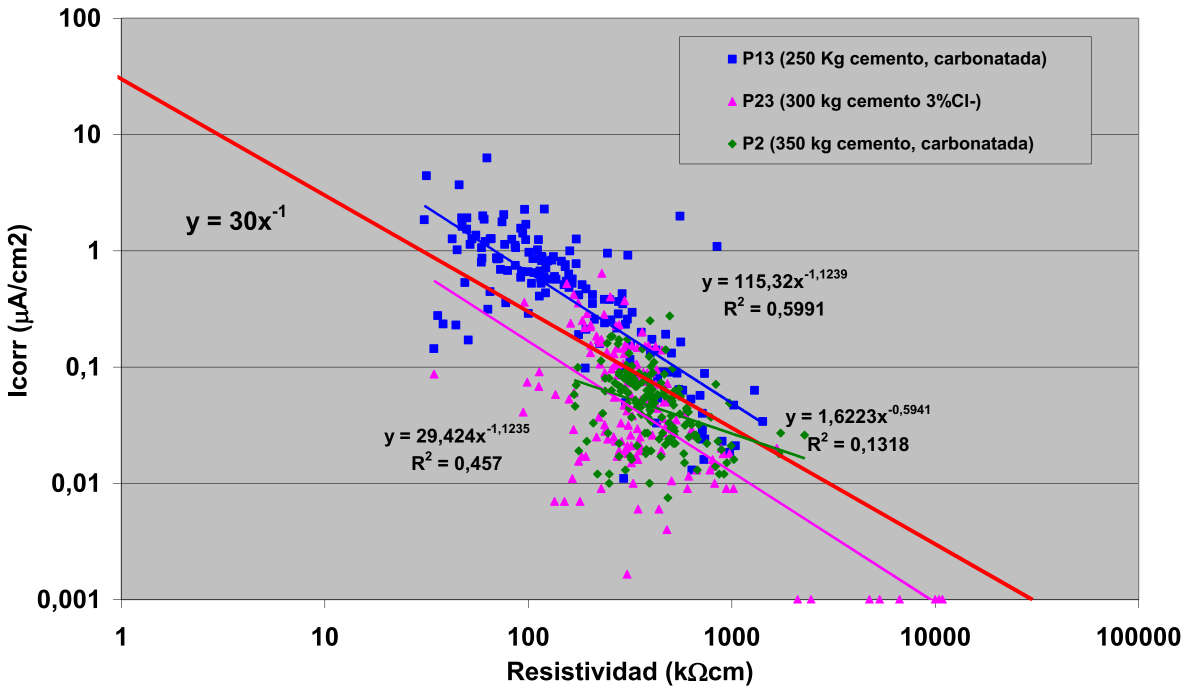
$$t_p = t_{p1} + t_{p2} = \frac{P_{corr1}}{V_{corr1}} + \frac{P_{corr2}}{V_{corr2}}$$

MODEL OF V_{CORR} BASED IN THE RESISTIVITY CHARACTERIZATION OF *K*

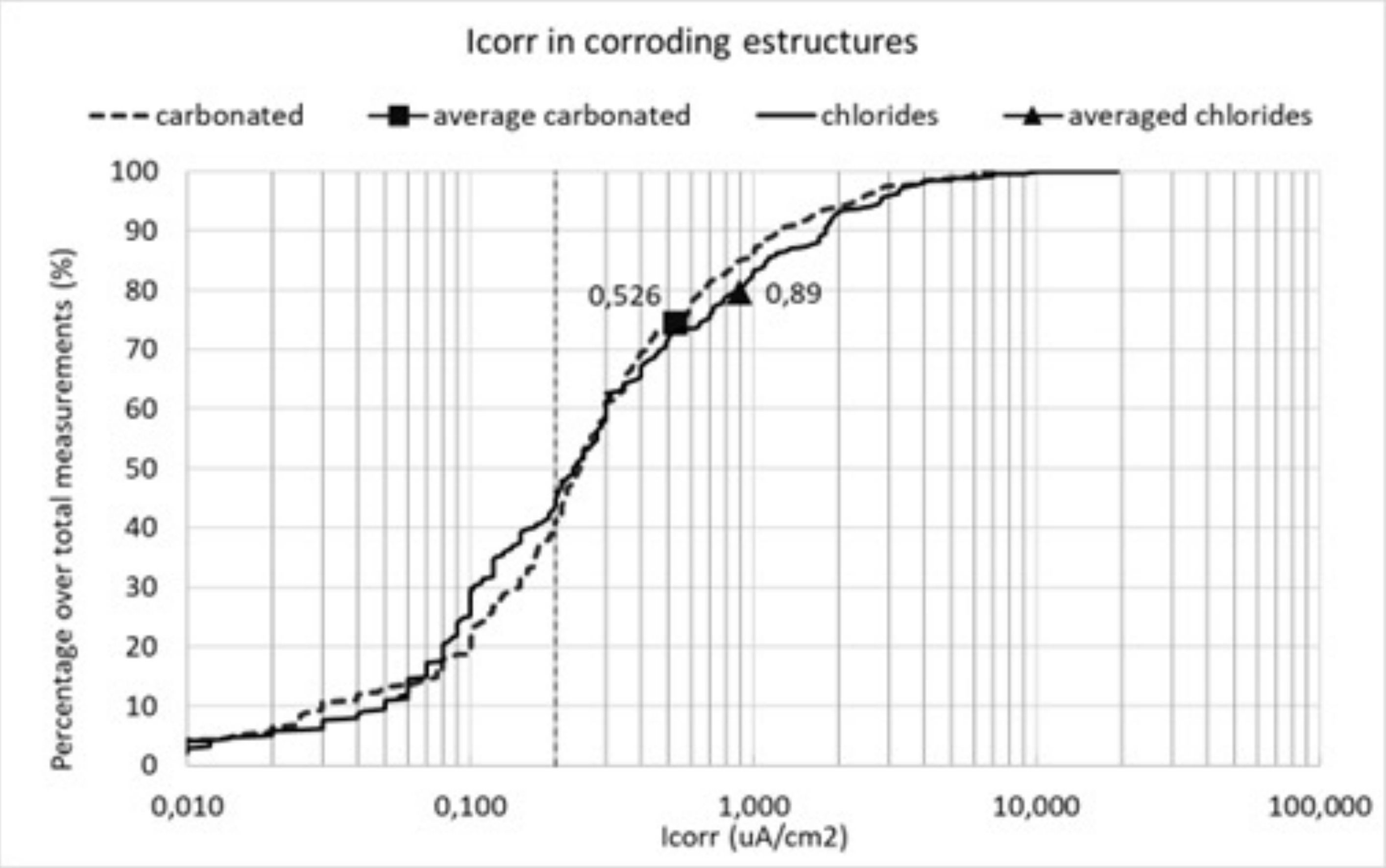
$$V_{corr,d} = \frac{K_{\rho}'}{\rho_d} = \frac{301.6}{\rho_d}$$

Data	Regression formula	Correlation coefficient
All structures	I_{corr} *[A/cm²]* =105.3/ρ *[·m]*	0.651
With chlorides	I_{corr} *[A/cm²]* =76.0/ρ *[·m]*	0.627
Without chlorides	I_{corr} *[A/cm²]* =133.1/ρ *[·m]*	0.642



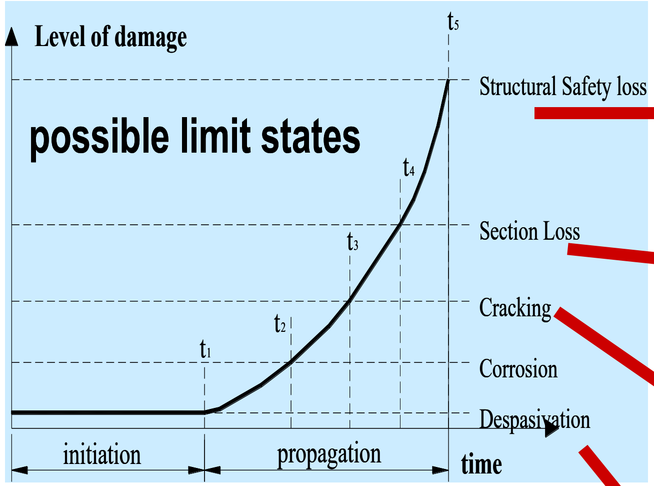


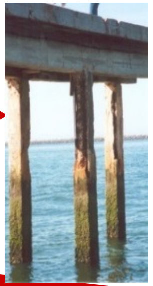
PROBABILITY OF HAVING A Vcorr IN REAL STRUCTURES almost identical for chlorides and carbonated

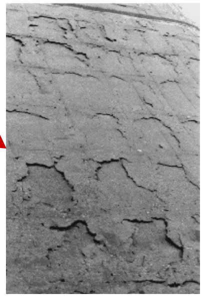


Type of contamination	Probability	Averaged corrosion rate µA/cm²	Coefficient of variation
carbonation	75%	0.526	177.30 %
chlorides	80%	0.89	221.86 %

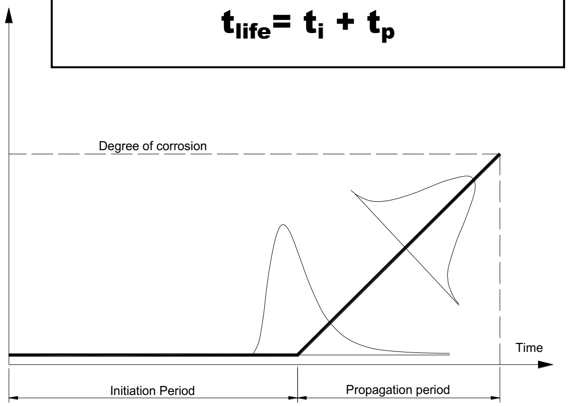
NEW CONDITION/DETERIORATION LIMIT STATE





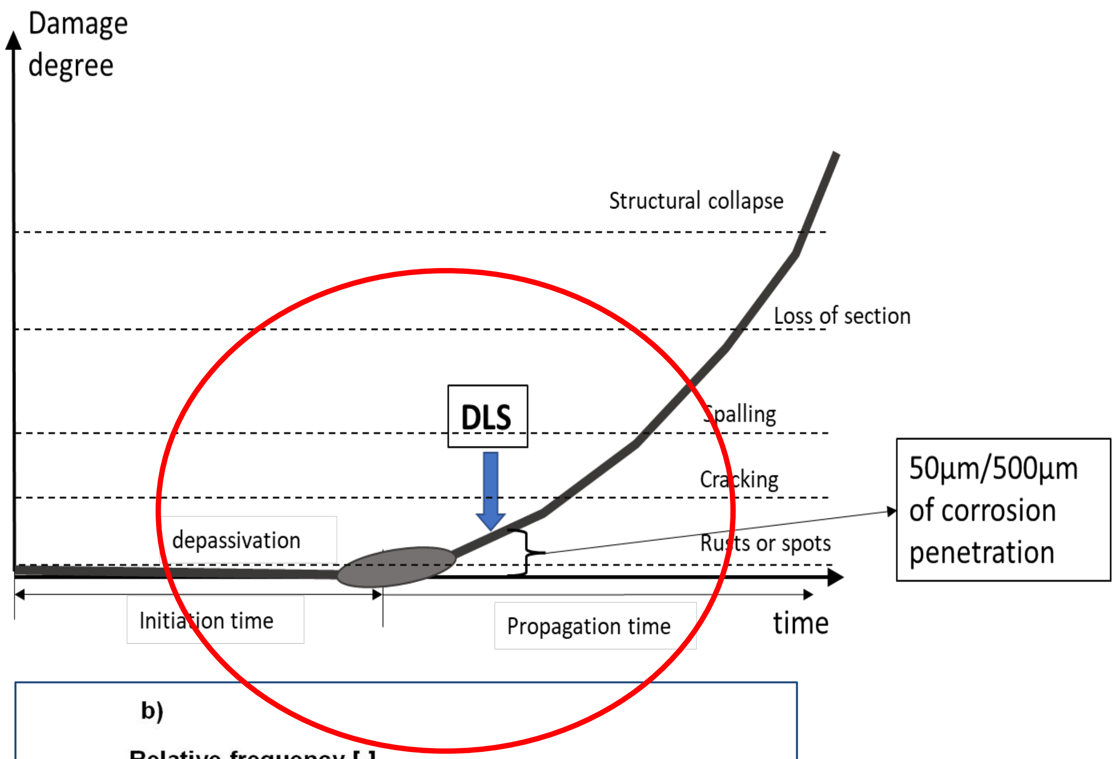


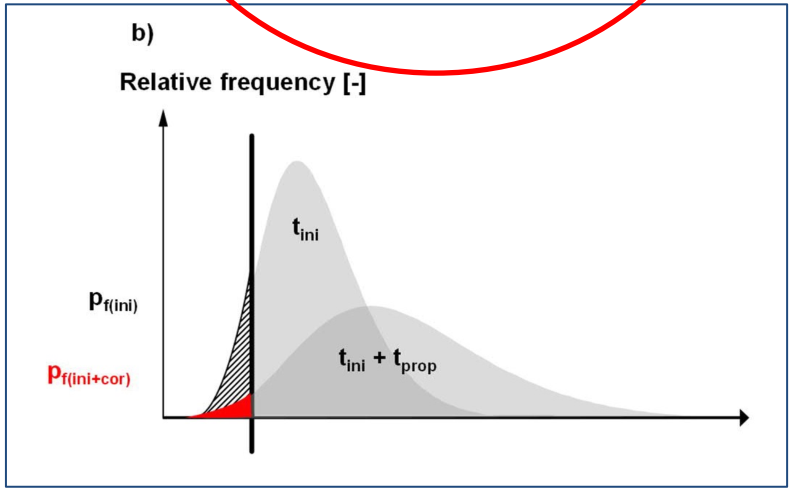
$$t_{life} = t_i + t_p$$

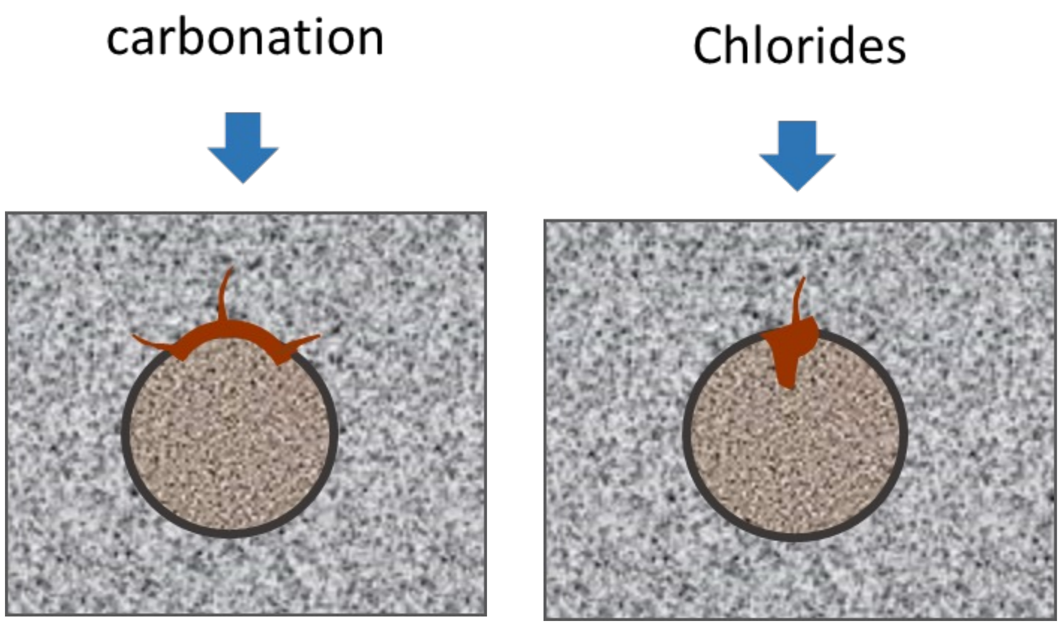


one reason is that in practice the depassivation onset **CANNOT BE VERIFIED** unless permanente sensors are used

CONDITION/DETERIORATION LIMIT STATE

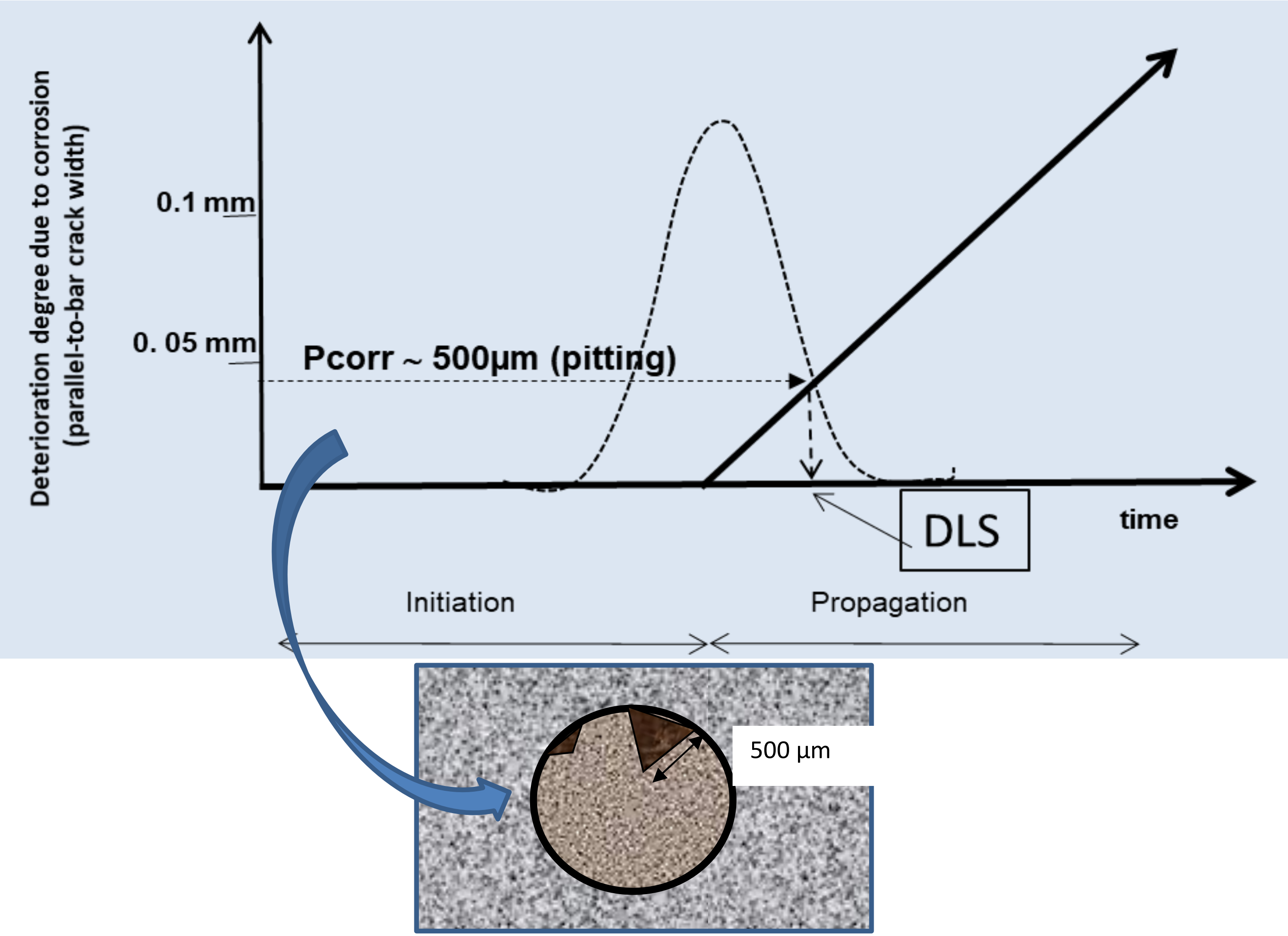


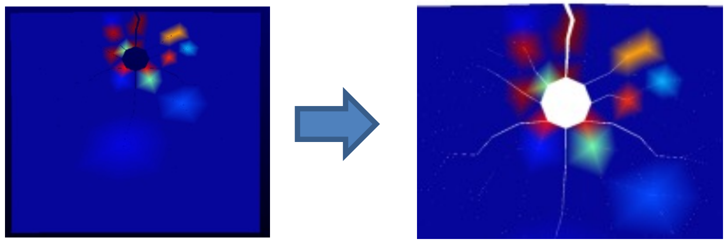




This β = 1,5 value was considered as being compatible with current normally used cover depths

DETERIORATION LS FOR CHLORIDES: Localized corrosion

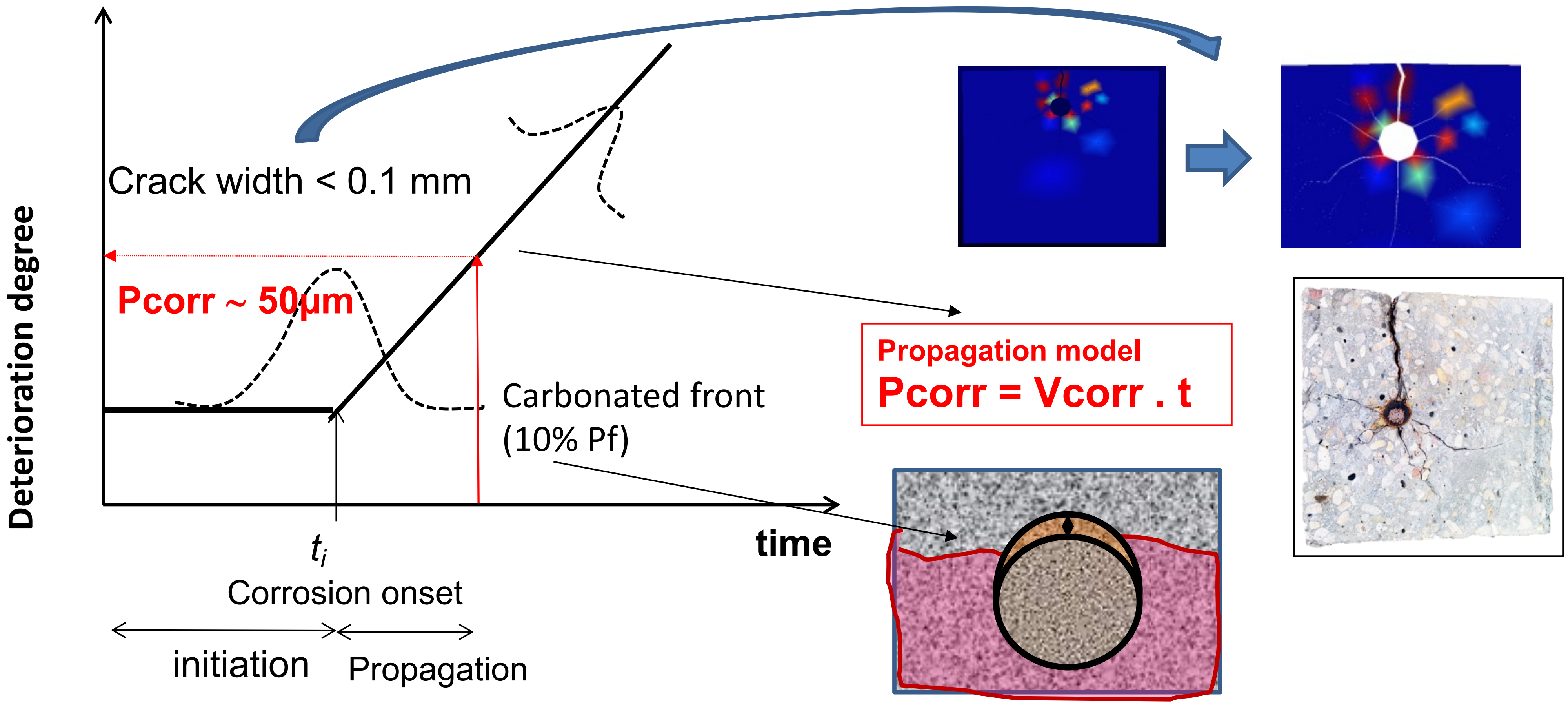




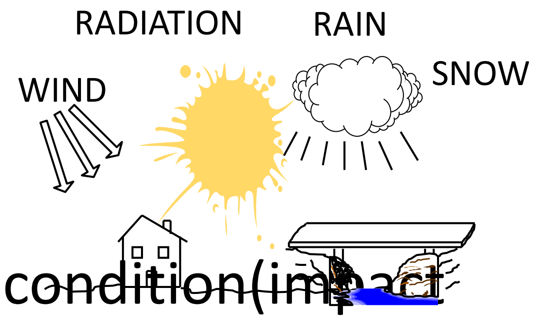
The limit is before the crack appears in the Surface

With ~10% probability

DETERIORATION LS FOR CARBONATION: uniform corrosion



FINAL COMMENTS



- The chapter is a starting point
- Examples of what is still needed are:
  - Statistical characterization of climate, annually and prediction
  - Relation between external environment and internal concrete condition(impact of local climate)
  - Statistical characterization of difusion coefficients/carbonation in real conditions
  - Models error at 50-100 years (calibration)
  - Spatial distribution in real conditions
  - Impact of progressive deterioration in the input parameters
  - Calibration of Corrosion limit state (Pcorr= 50 and 500 µm)
  - Partial factor format
  - Link with structural Limit States
  - Etc ....

Thanks for your attention