Estimation Method on Deterioration of Marine Concrete Structures Due to Chloride Attack

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Contents

- Outline of deterioration process of marine concrete structure
- Examination of durability for marine concrete structure in durability design
- Simulation model of corrosion of reinforcement in concrete
- Evaluation of structural performance of concrete structure deteriorated due to corrosion of reinforcement

Outline

of

Deterioration Process


'91 4 25


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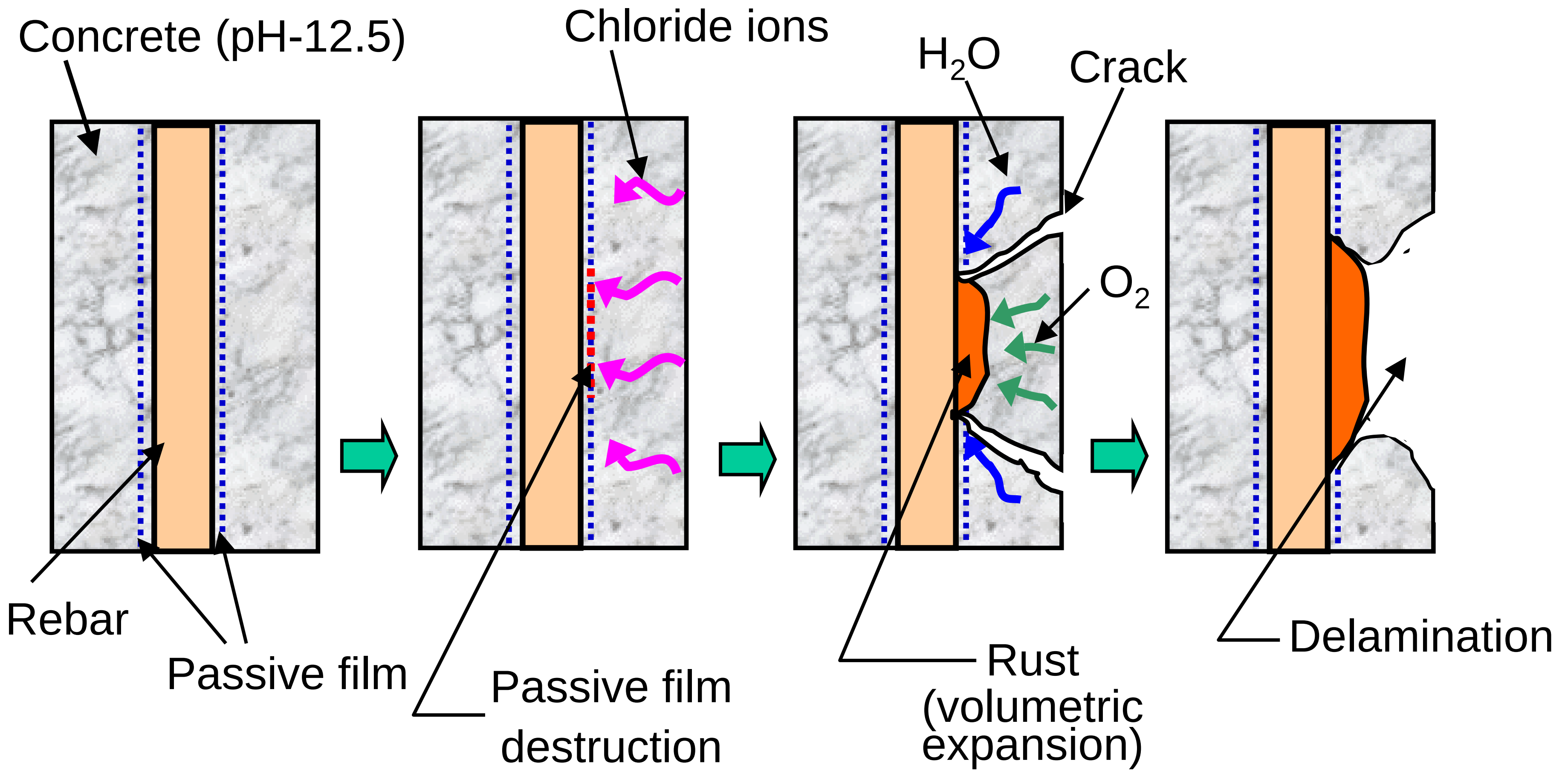
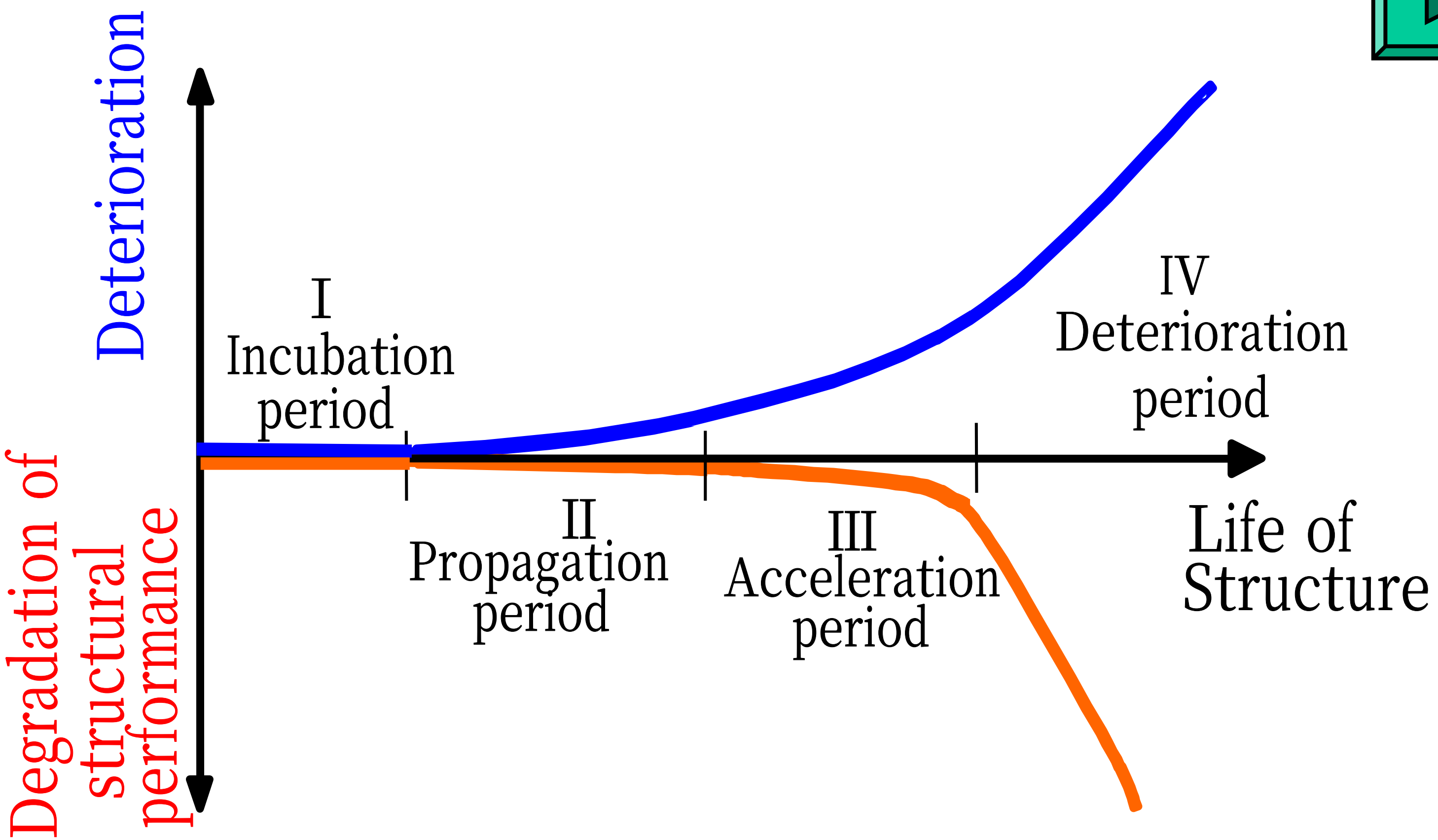
Deterioration process on marine concrete structures



Chloride-induced deterioration process

Deterioration process on marine concrete structures



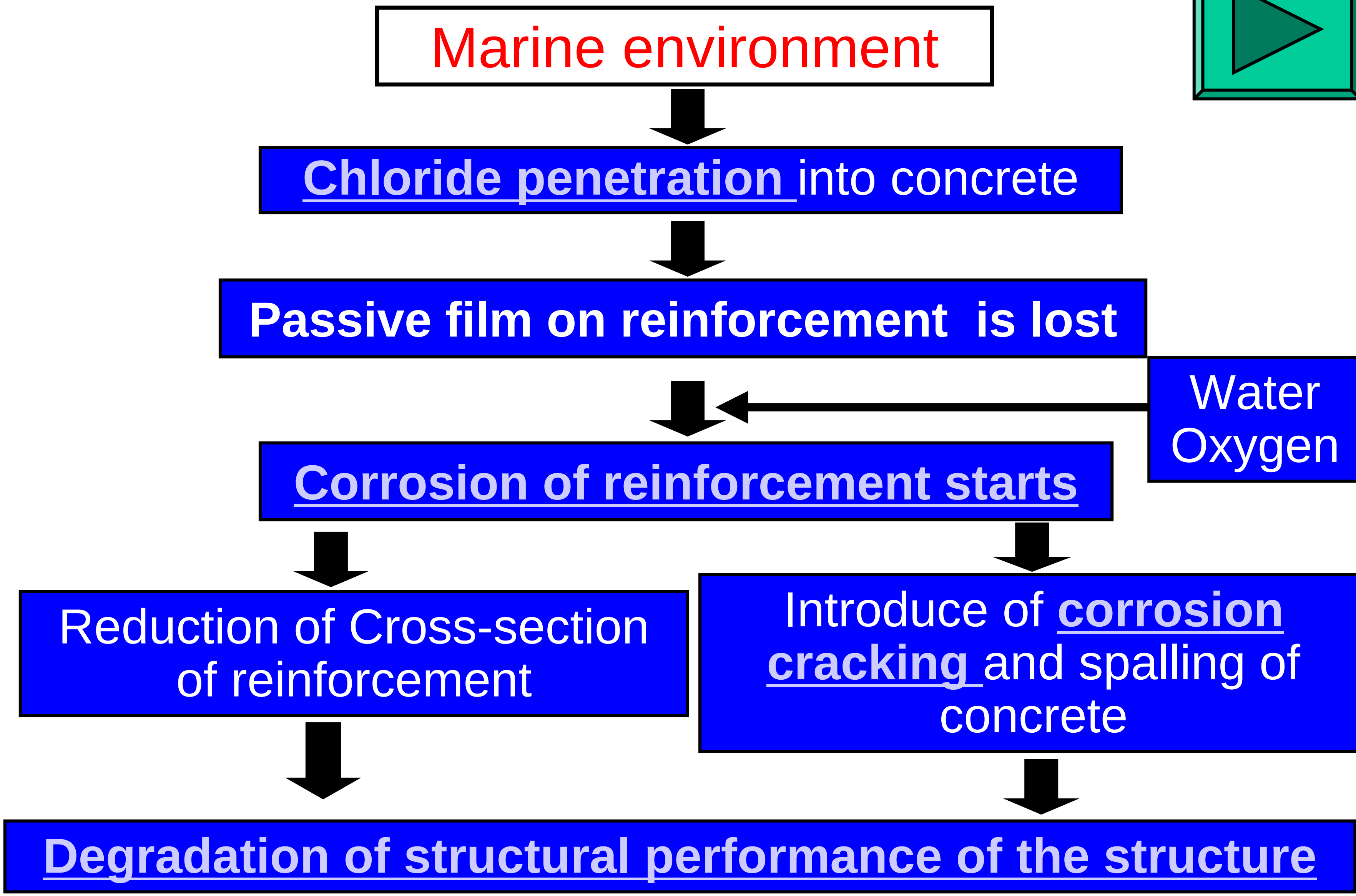
Chloride-induced deterioration process

Deterioration process on marine concrete structures

Definition of stages in the deterioration process and primary factors characterizing each stage

Stage No.	Definition of period	Primary factors characterizing the deterioration
I	Period of chloride penetration until the chloride concentration around rebars up to the threshold value	• Chloride diffusion rate • Cover thickness
II	Period of the corrosion progress on rebar until concrete cracks due to the corrosion appear	• Rebar corrosion rate • Resistivity against cracking of concrete
III	Period of the corrosion progress on rebar after appearance of concrete cracks	• Rebar corrosion rate • Width of cracks due to rebar corrosion
IV	Period of degradation of structural performance induced by rebar corrosion and concrete cracks	

Deterioration process on marine concrete structures



Deterioration process on marine concrete structures

Penetration of chloride into concrete

In sea water, Splash zone, **Marine atmospheric Zone**

↓

Penetration of Cl^- via pores to the interior of concrete

↓

Cement hydrate binds some of Cl^- chemically

Fredel's salt ($C_3A \cdot CaCl_2 \cdot nH_2O$)

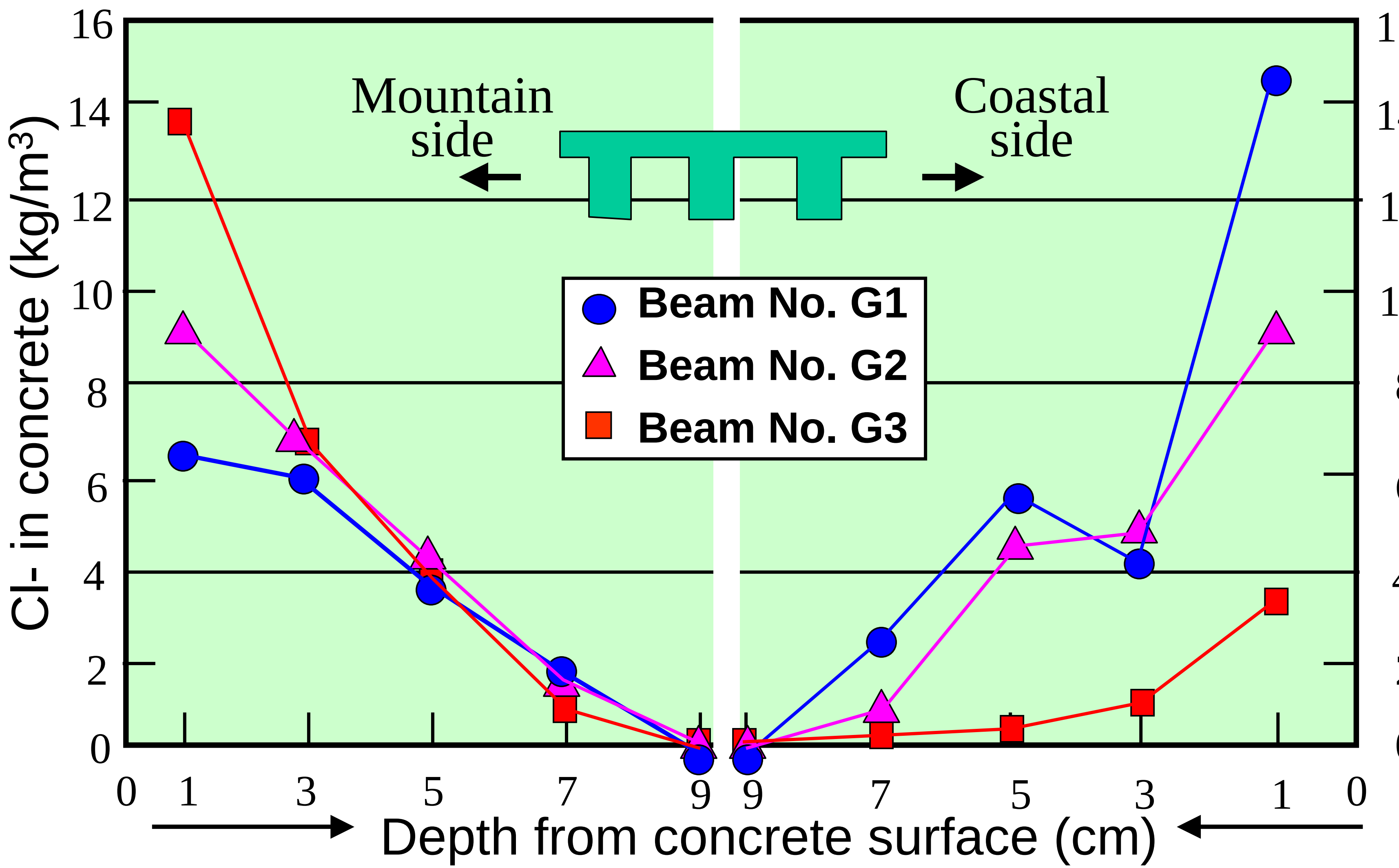
↓

Only the **free chloride diffuses** into concrete

↓

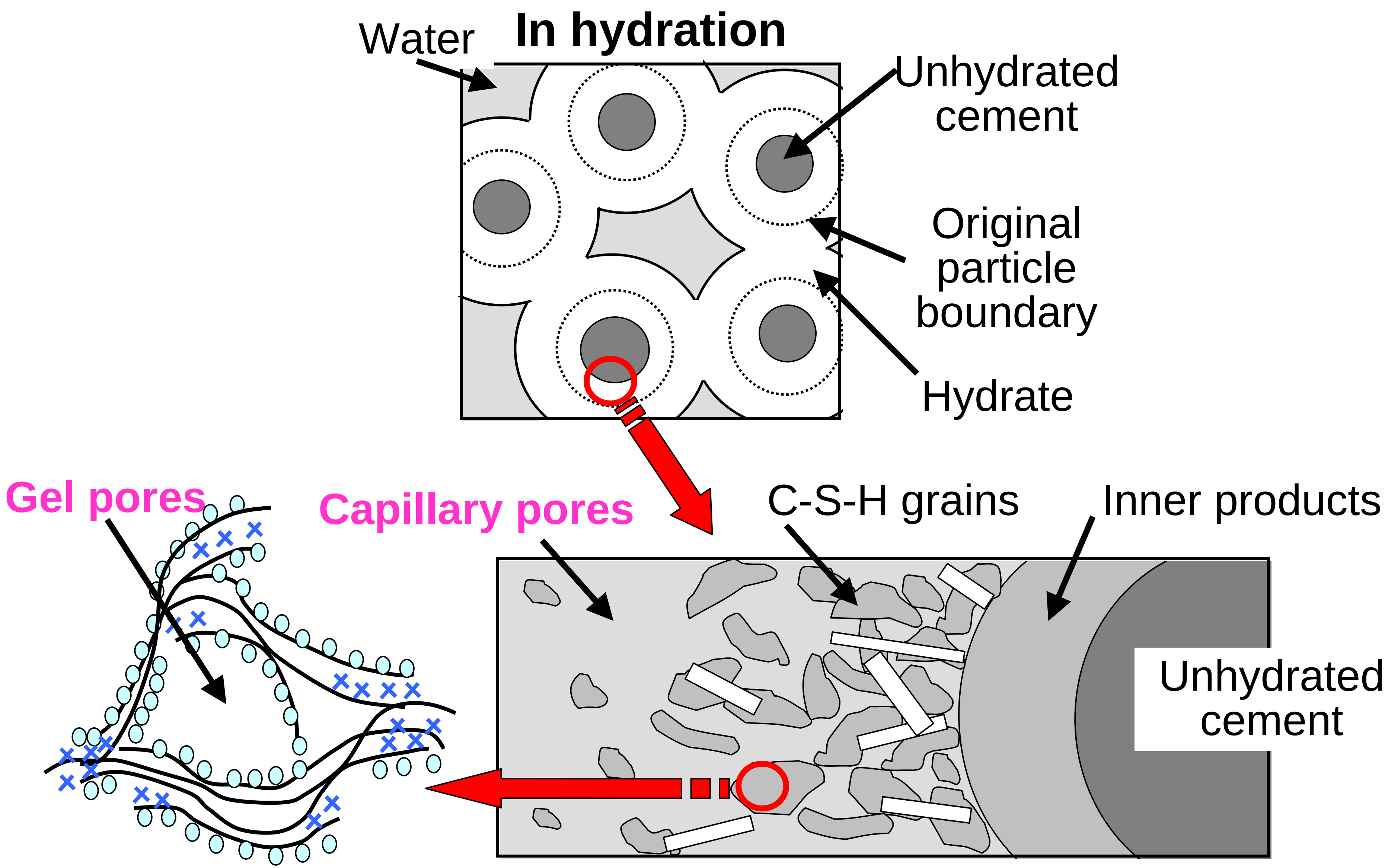
When **critical concentration** of free Cl^- accumulates on reinforcement surface, corrosion starts on it

Example of chloride penetration profile into concrete

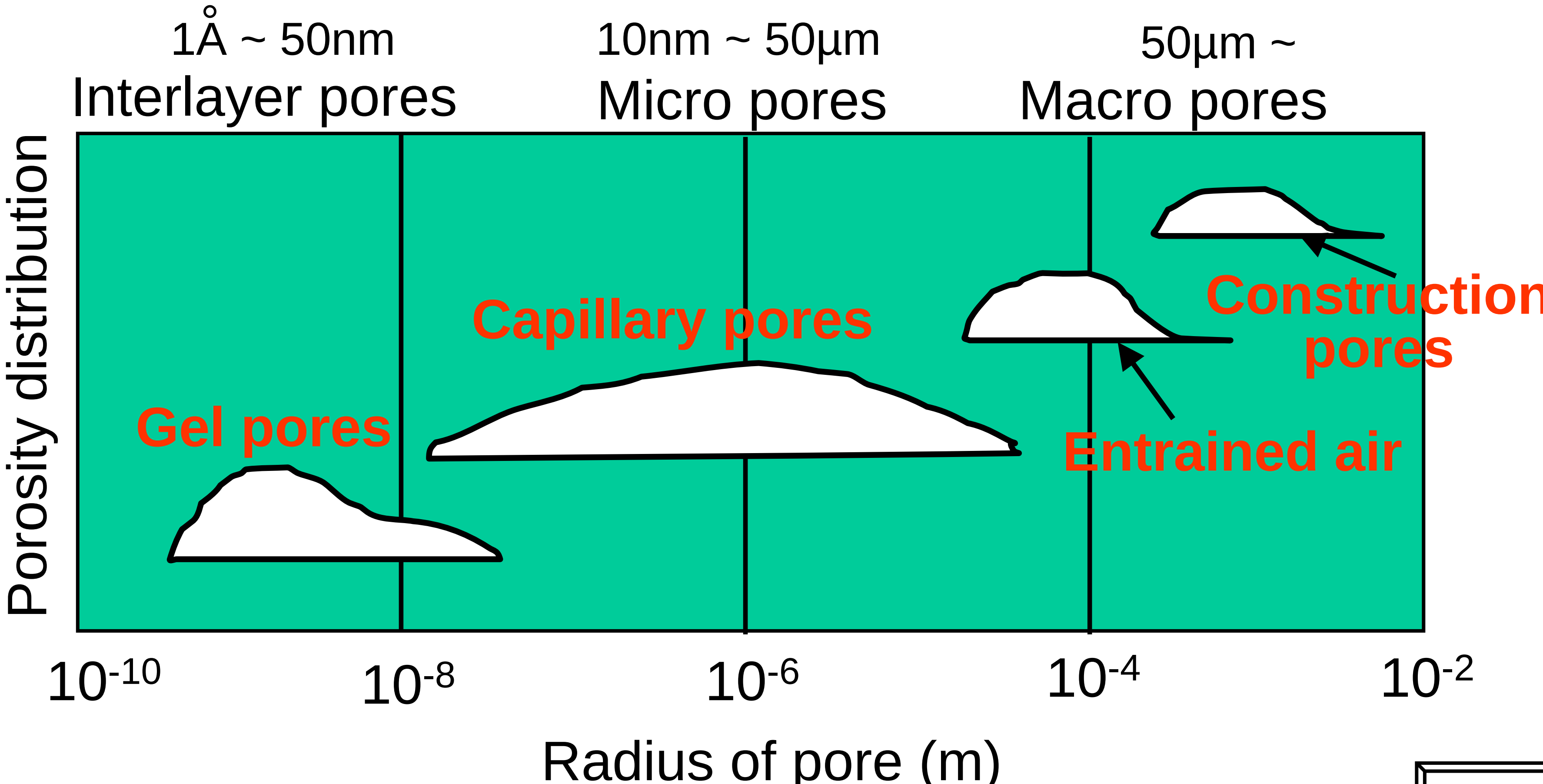


Chloride distribution profiles in concrete bridge beams in coastal zone after 17 years of service

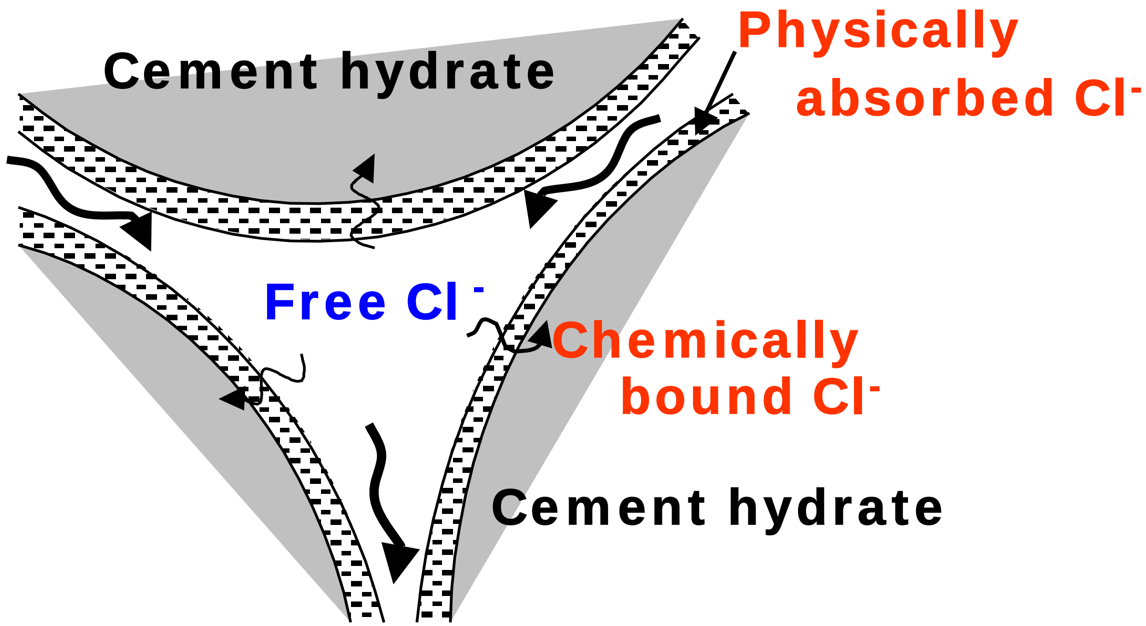
Microstructure of Cement paste



Schematic representation of porosity classification in concrete



Binding of chloride ions into cement hydrate



Chemical binding equation

$$3CaO \cdot Al_2O_3 \cdot 6H_2O + CaCl_2 + 4H_2O$$
$$\rightarrow 3CaO \cdot Al_2O_3 \cdot CaCl_2 \cdot 10H_2O$$

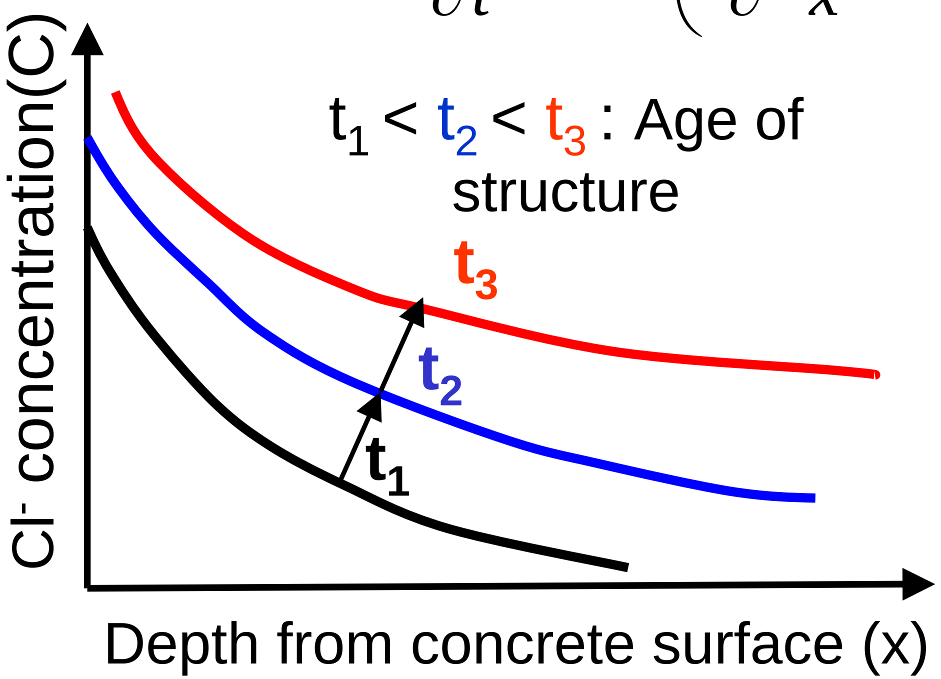
Fredell’s salt

Deterioration process on marine concrete structures

Penetration of chloride into concrete

Diffusion equation (Modified Fick's second low)

$$\frac{\partial C}{\partial t} = D\left(\frac{\partial^2 C}{\partial^2 x} + \frac{\partial^2 C}{\partial^2 y} + \frac{\partial^2 C}{\partial^2 z}\right) - K \cdot C$$



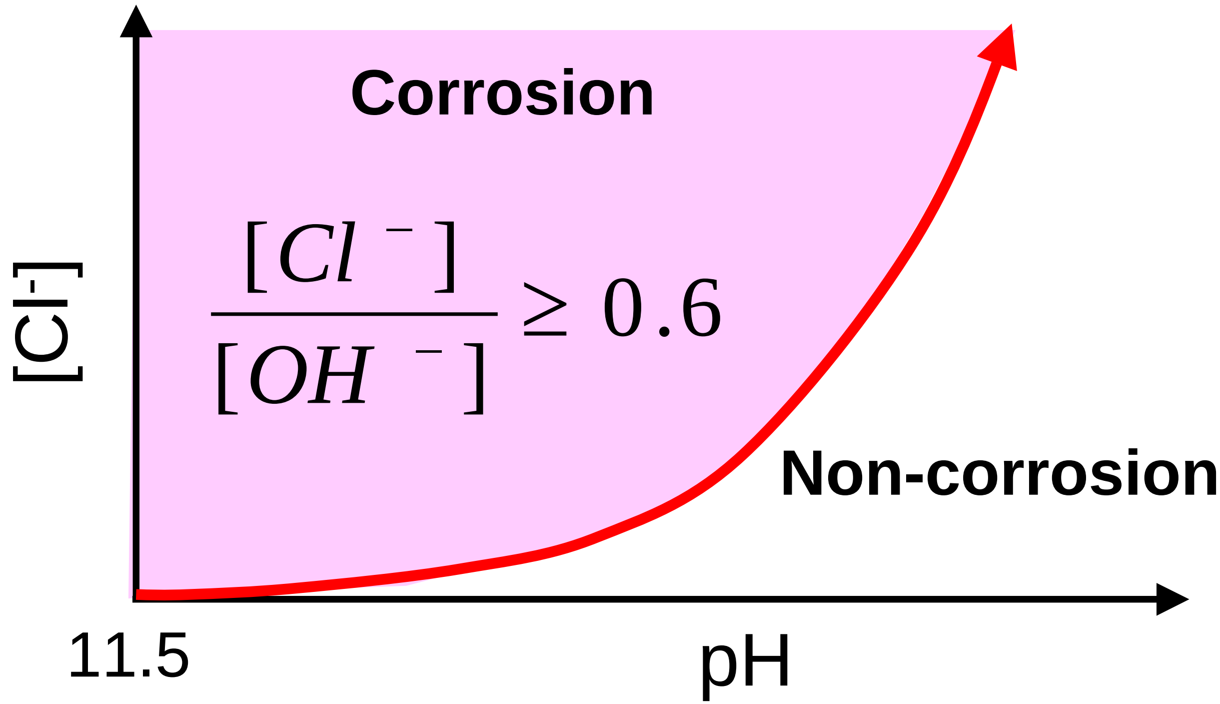
C: Concentration of Cl^- at depth (x,y.z) after t

D: Diffusion coefficient

K: Cl^- binding coefficient

Deterioration process on marine concrete structures

Critical chloride content



Effect of Chloride concentration and pH on initiation of corrosion

Deterioration process on marine concrete structures

Critical chloride content

In case of ordinary reinforcing bar in concrete

0.05% Cl^- related to the weight of Concrete

||

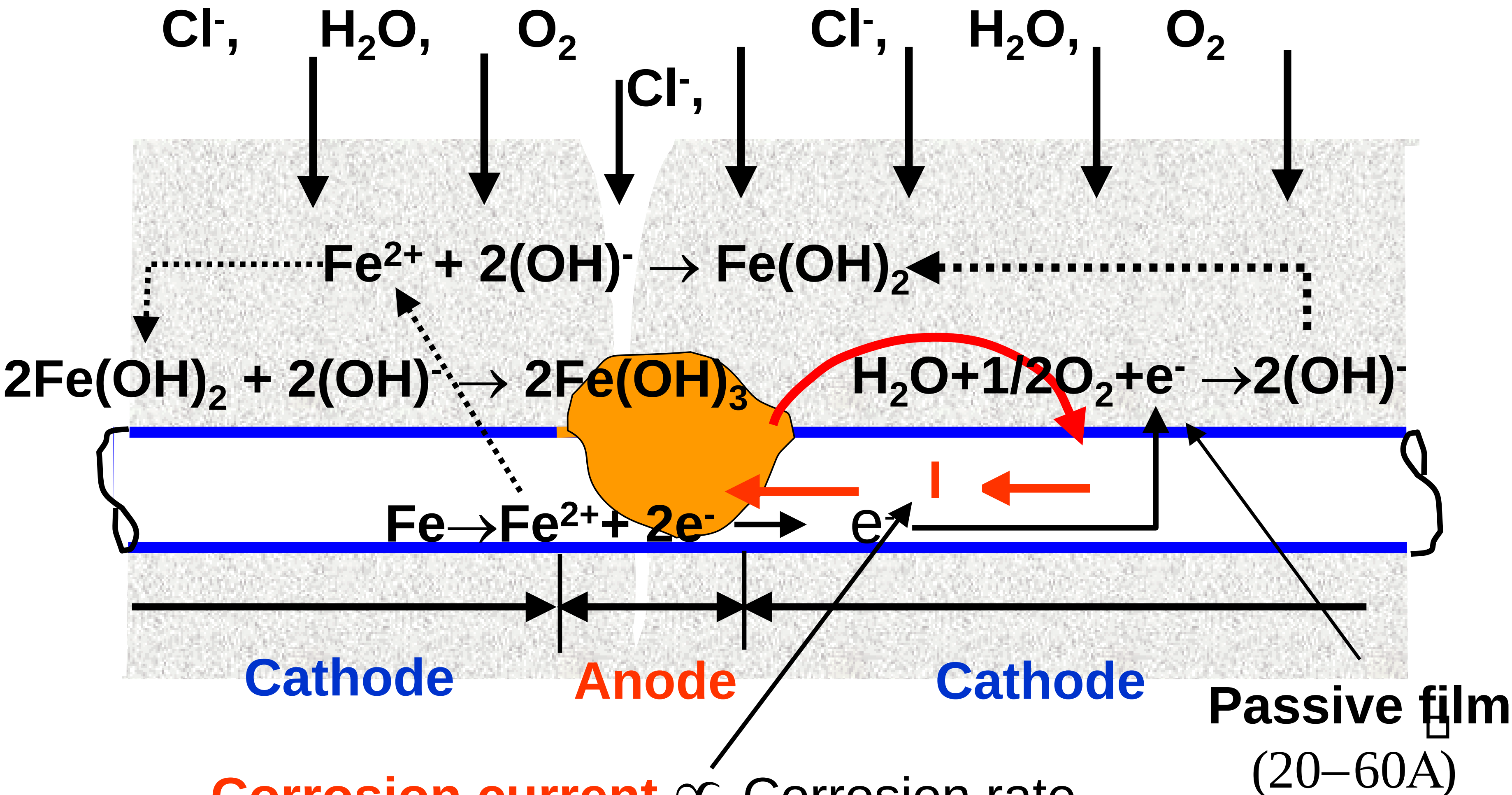
0.4% Cl^- related to the cement weight

or

1.2 kg/m^3 of Cl^- per unit concrete volume

Deterioration process on marine concrete structures

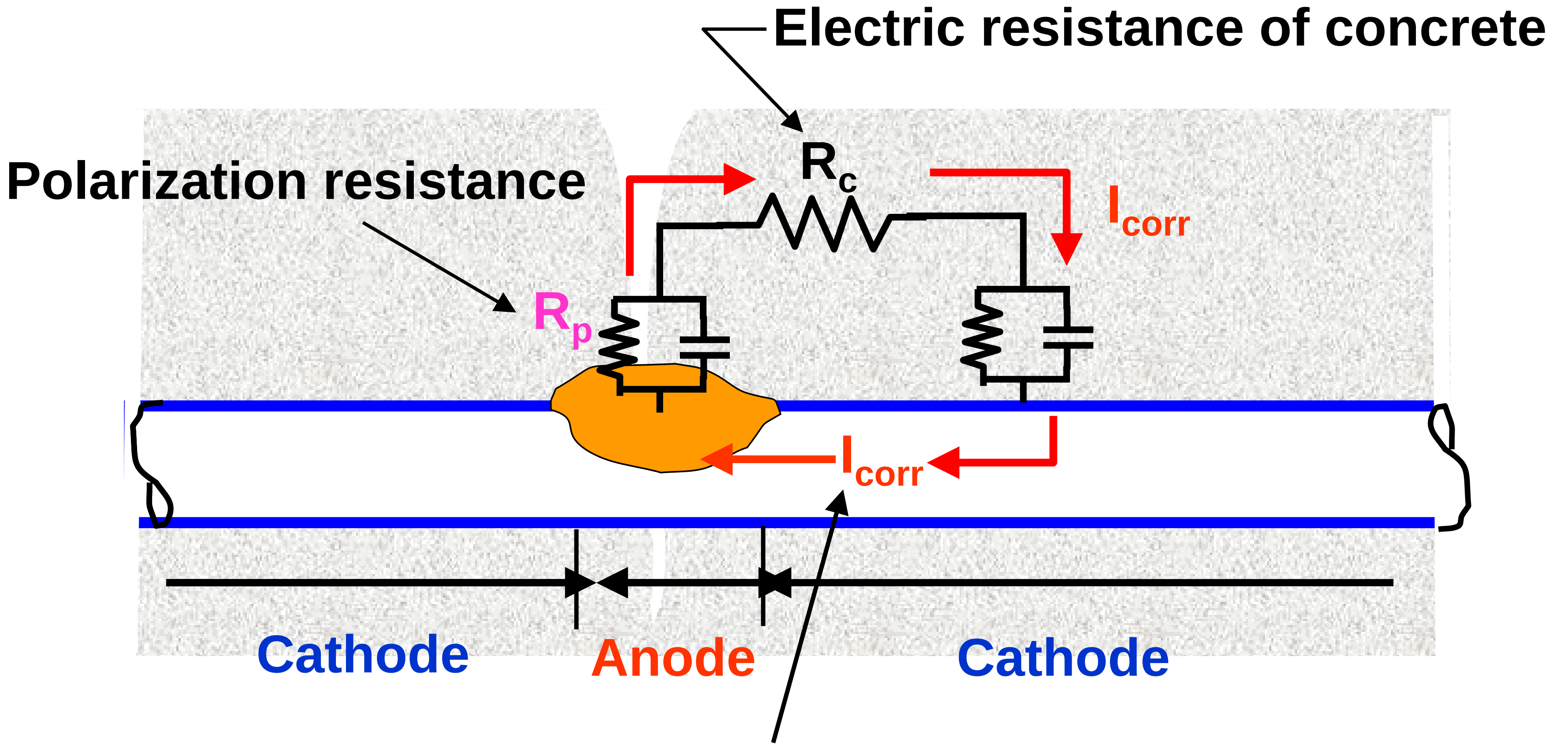
Corrosion process on reinforcement



Corrosion current ∝ Corrosion rate

Deterioration process on marine concrete structures

Corrosion process on reinforcement



Corrosion current ∝ Corrosion rate ∝ $1/R_p$

Deterioration process on marine concrete structures

Corrosion process on reinforcement

Corrosion weight loss of reinforcement (W)

Corrosion current: $\boldsymbol{I_{corr}}$

$$I_{corr} = k \cdot \frac{1}{R_p}$$

R_p: Polarization resistance

k: Constant (25~50mV)

Corrosion Weight loss: ***W***

$$W = \frac{[Fe]}{n \cdot F} \cdot I_{corr} \cdot t$$

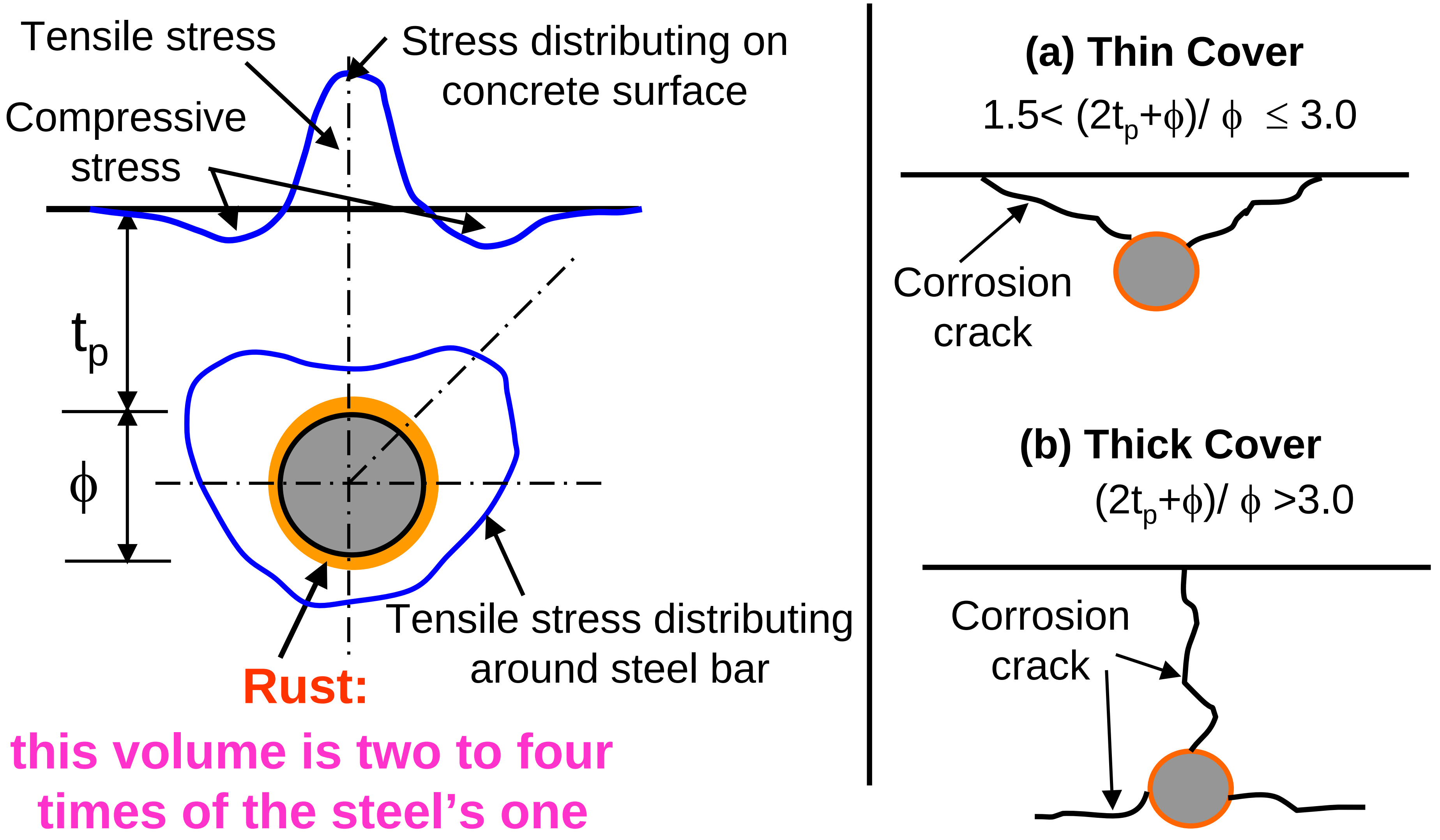
[*Fe*]: Atomic weight (55.84 *g*)

n: Atomic value (*Fe*: *n*=2)

F: Faraday's Constant (96,500 *A/sec*)

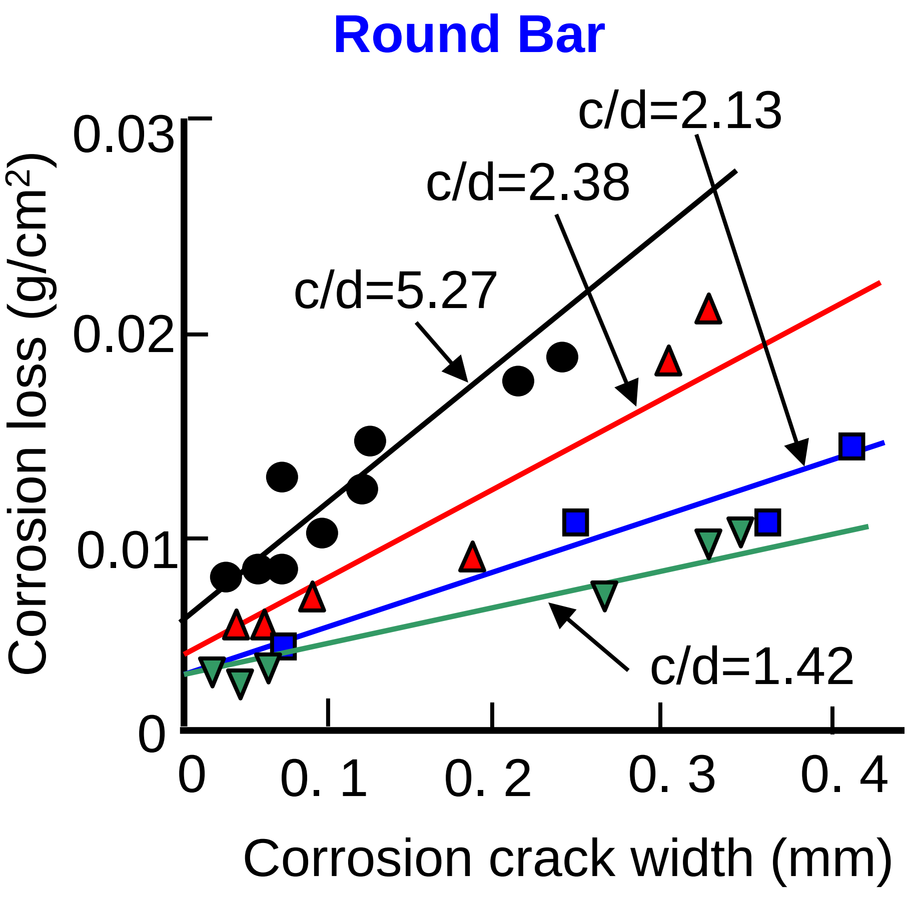
Deterioration process on marine concrete structures

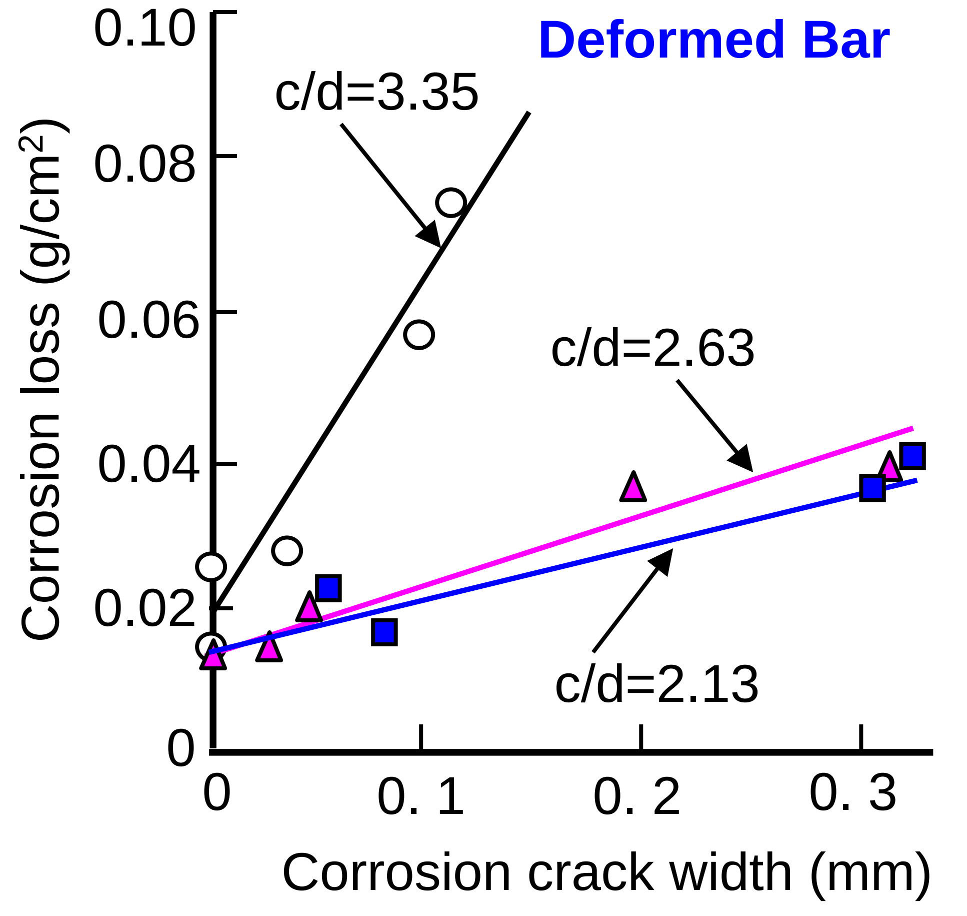
Corrosion crack on concrete



Deterioration process on marine concrete structures

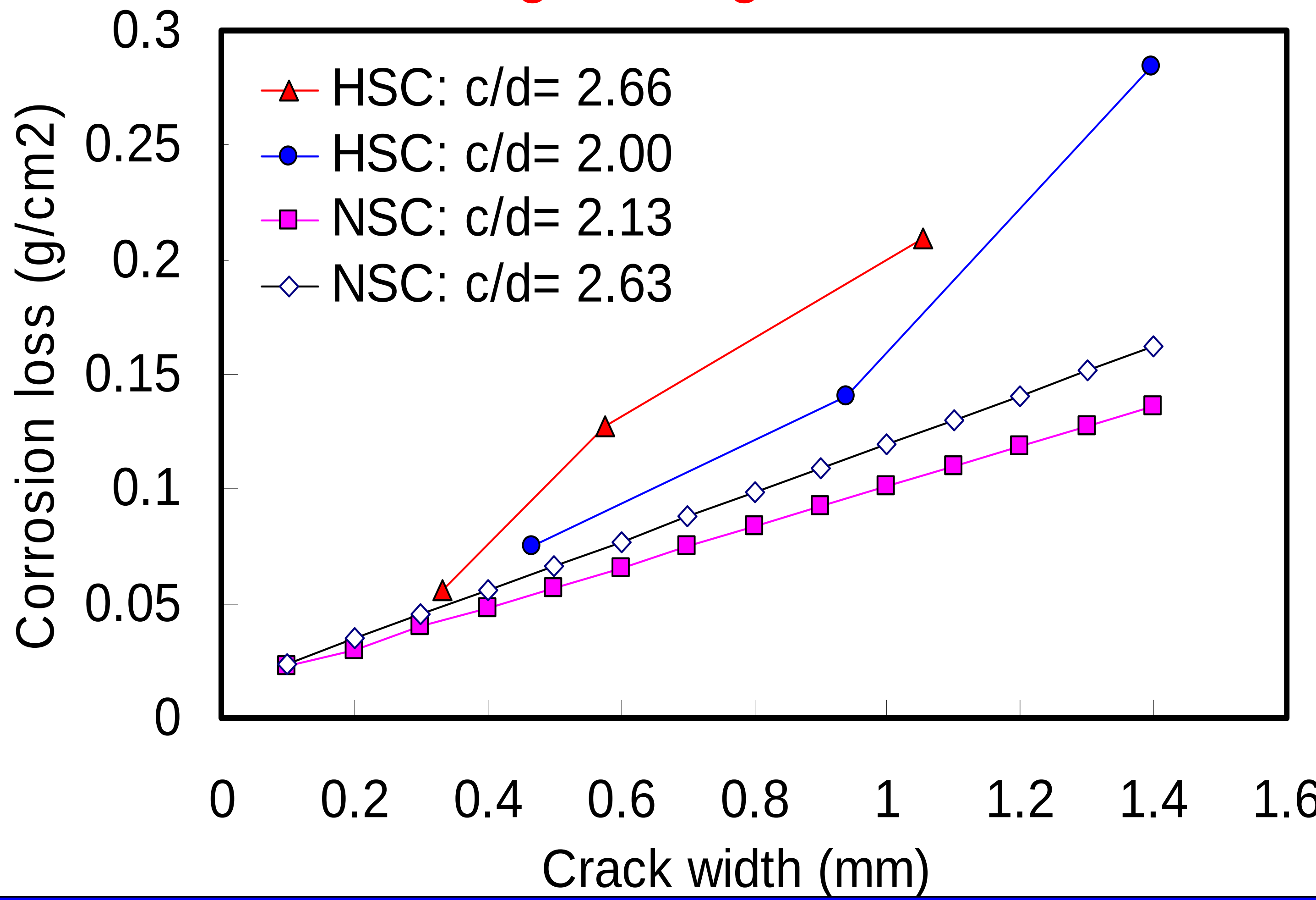
Relationship between corrosion amount and corrosion crack on concrete





c/d: Cover thickness/diameter of rebar

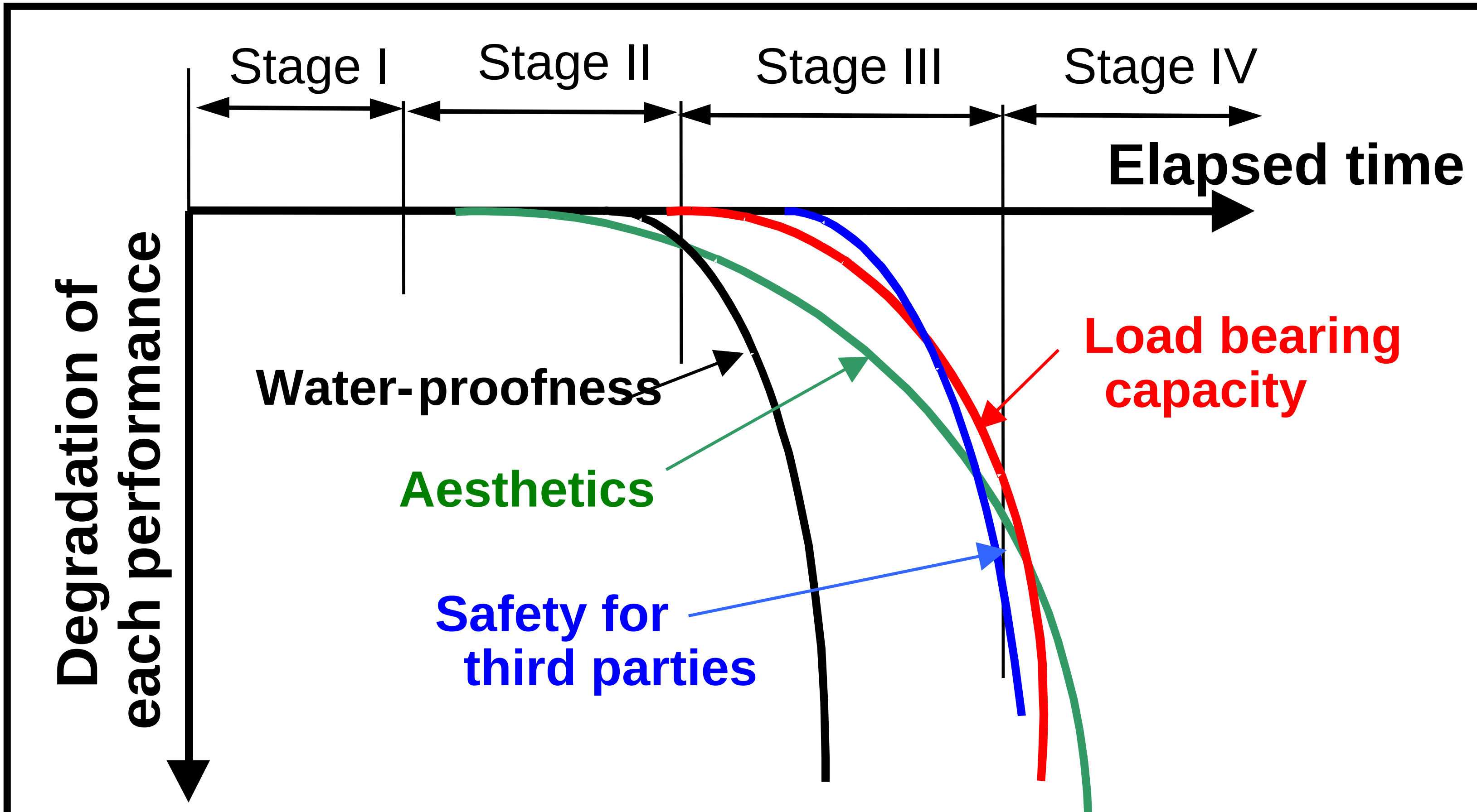
Relationship between corrosion amount and corrosion crack on high strength concrete



- **High strength concrete have smaller crack width opening than normal strength concrete for same corrosion loss**
- **Concrete strength also influences on the crack width opening**

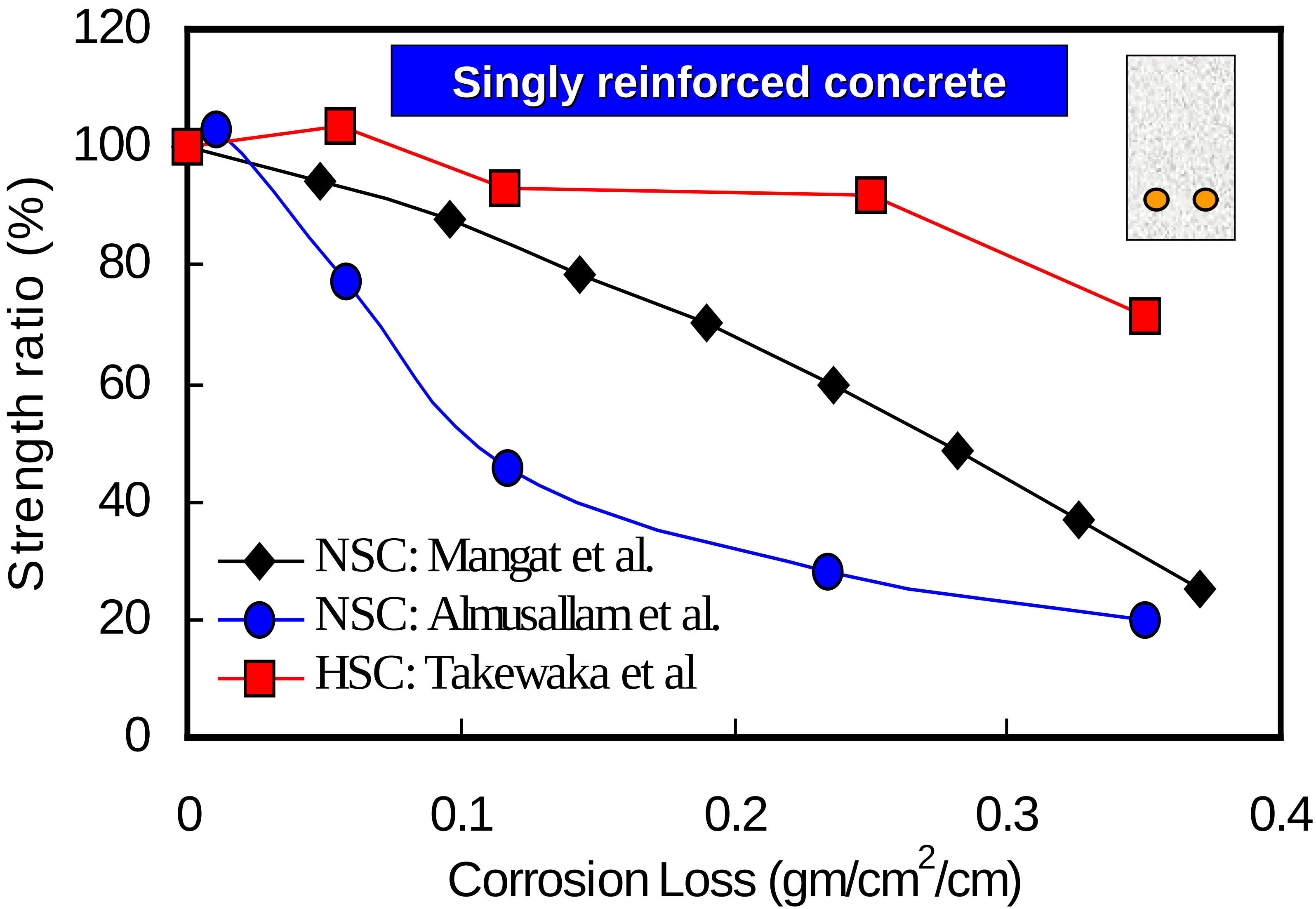
Deterioration process on marine concrete structures

Conceptual figure of degradation process of performance on structure



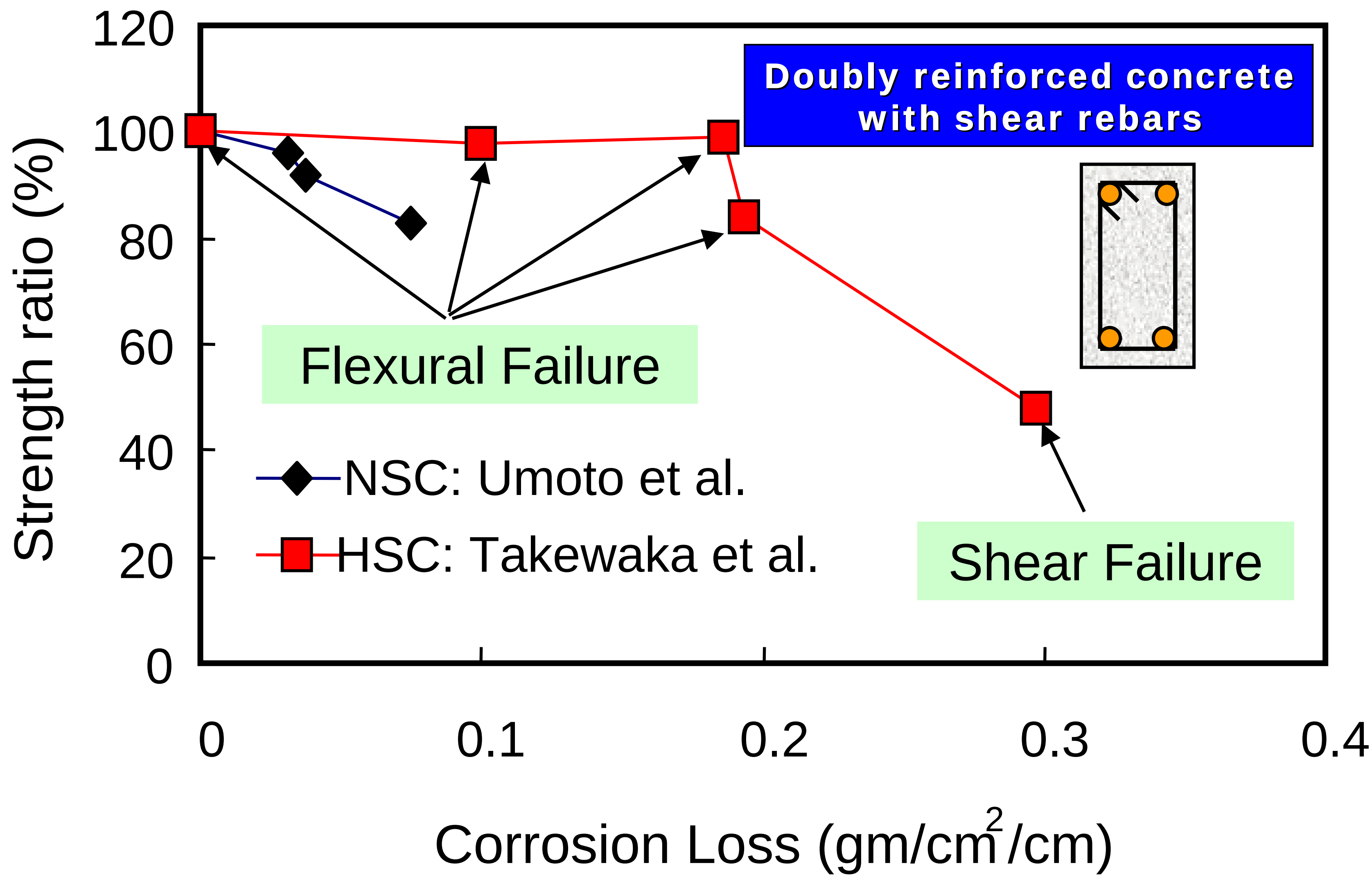
Example of performance degradation on RC beam due to rebar corrosion

Experiment result for loss in load-bearing capacity



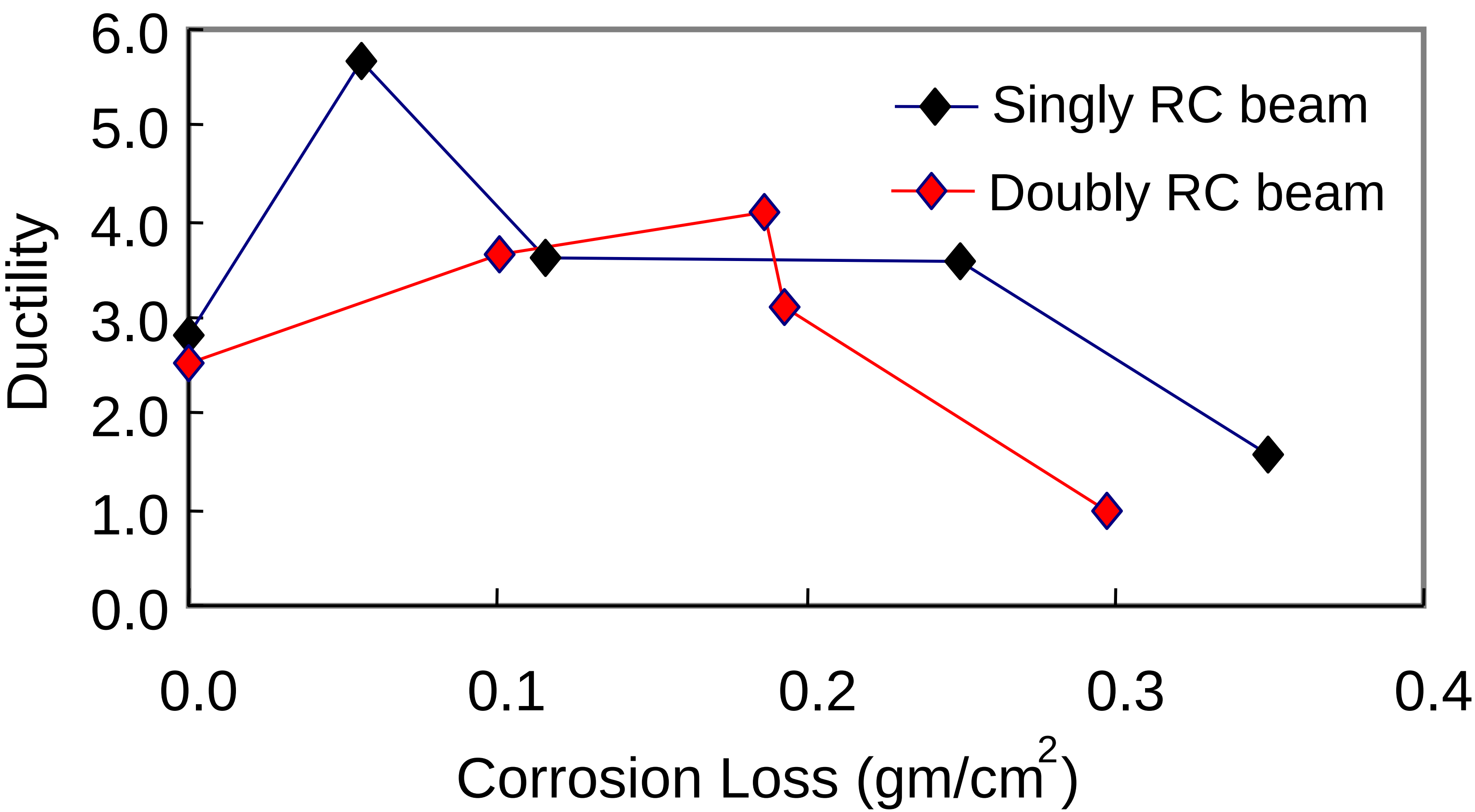
Example of performance degradation on RC beam due to rebar corrosion

Experiment result for loss in load-bearing capacity



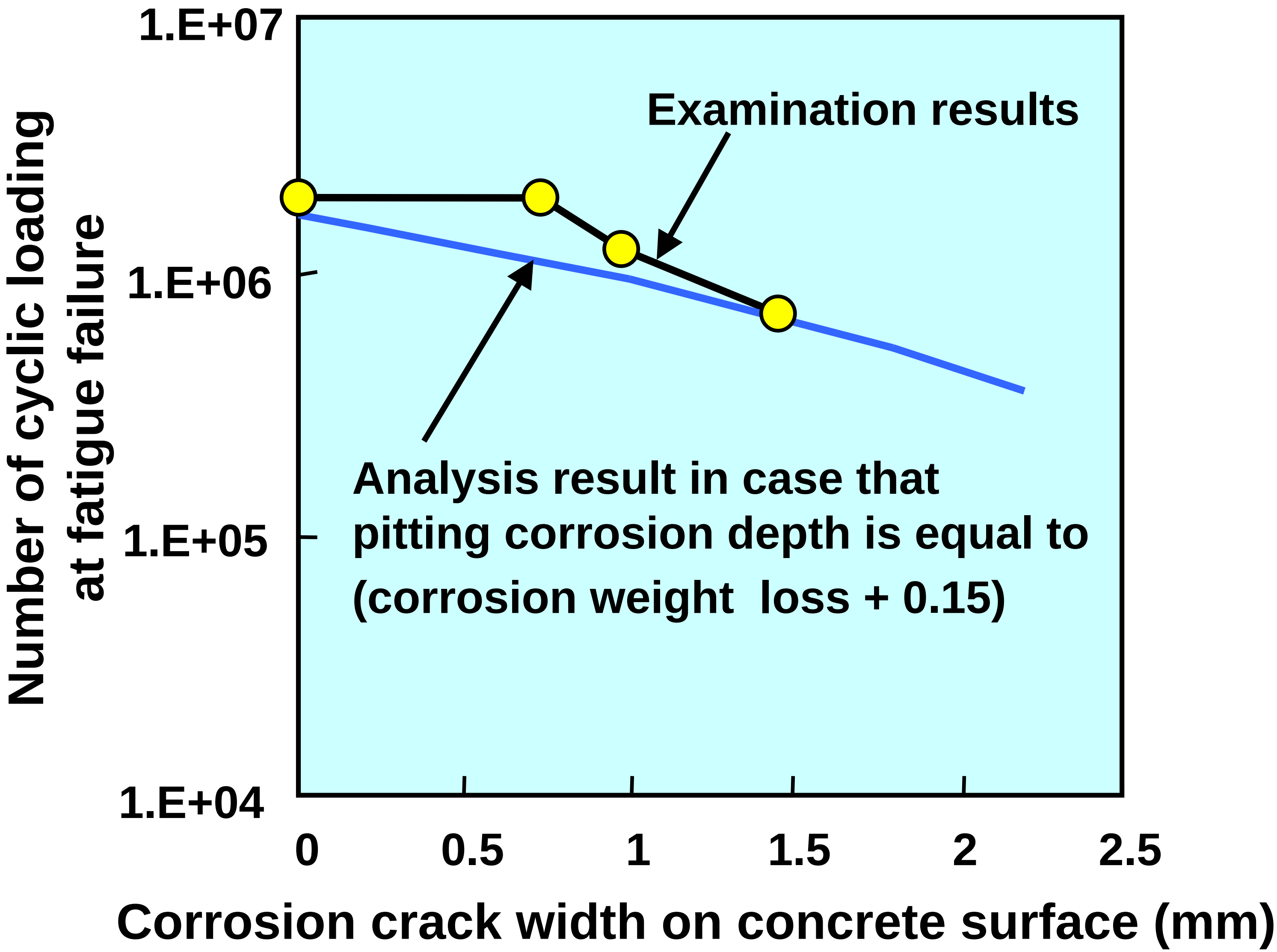
Example of performance degradation on RC beam due to rebar corrosion

Experiment result for loss in ductility of RC beam

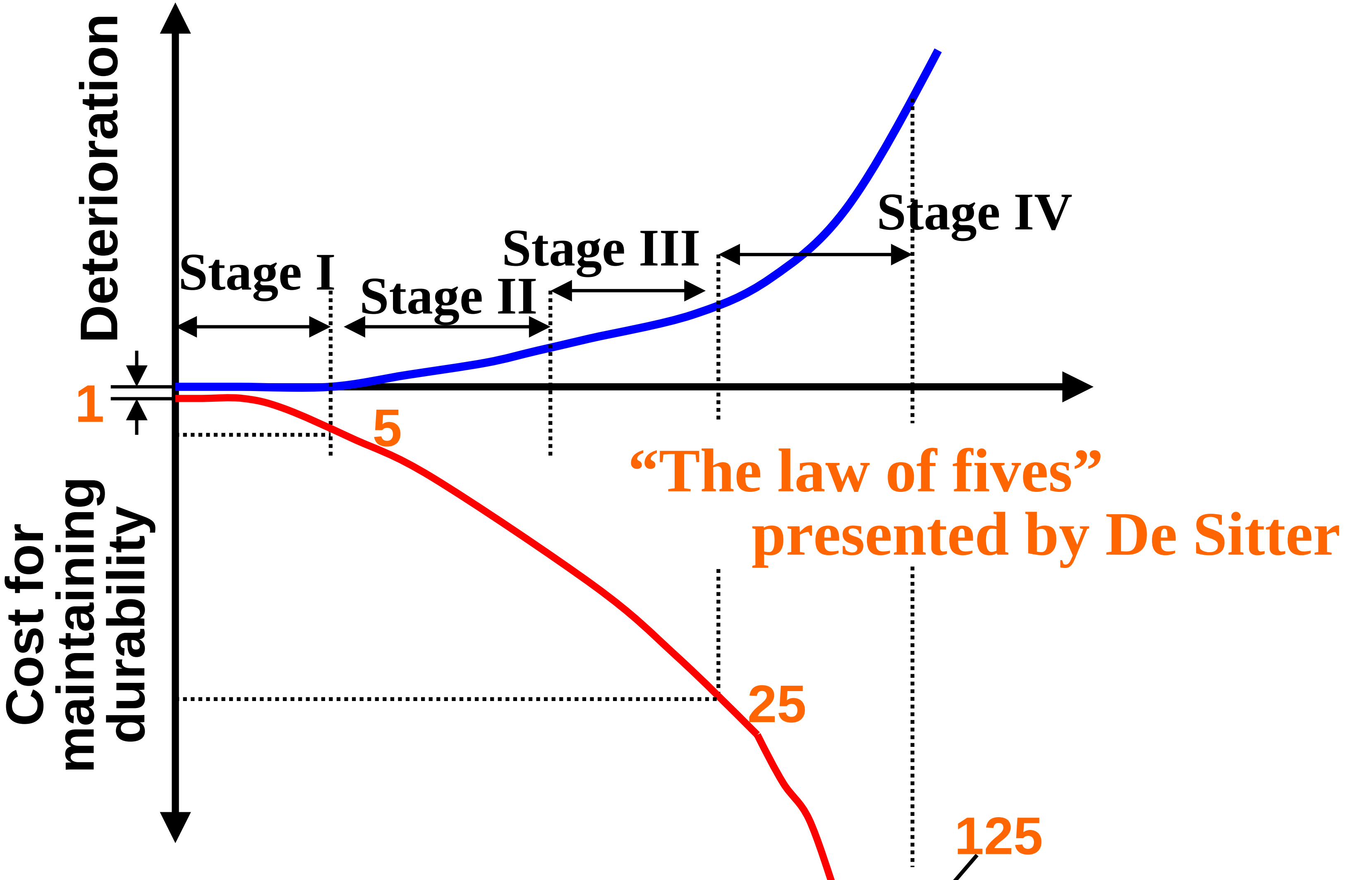


Example of performance degradation on RC beam due to rebar corrosion

Analytical result for loss in fatigue property



Extra Costs for maintaining durability of structure during the service life



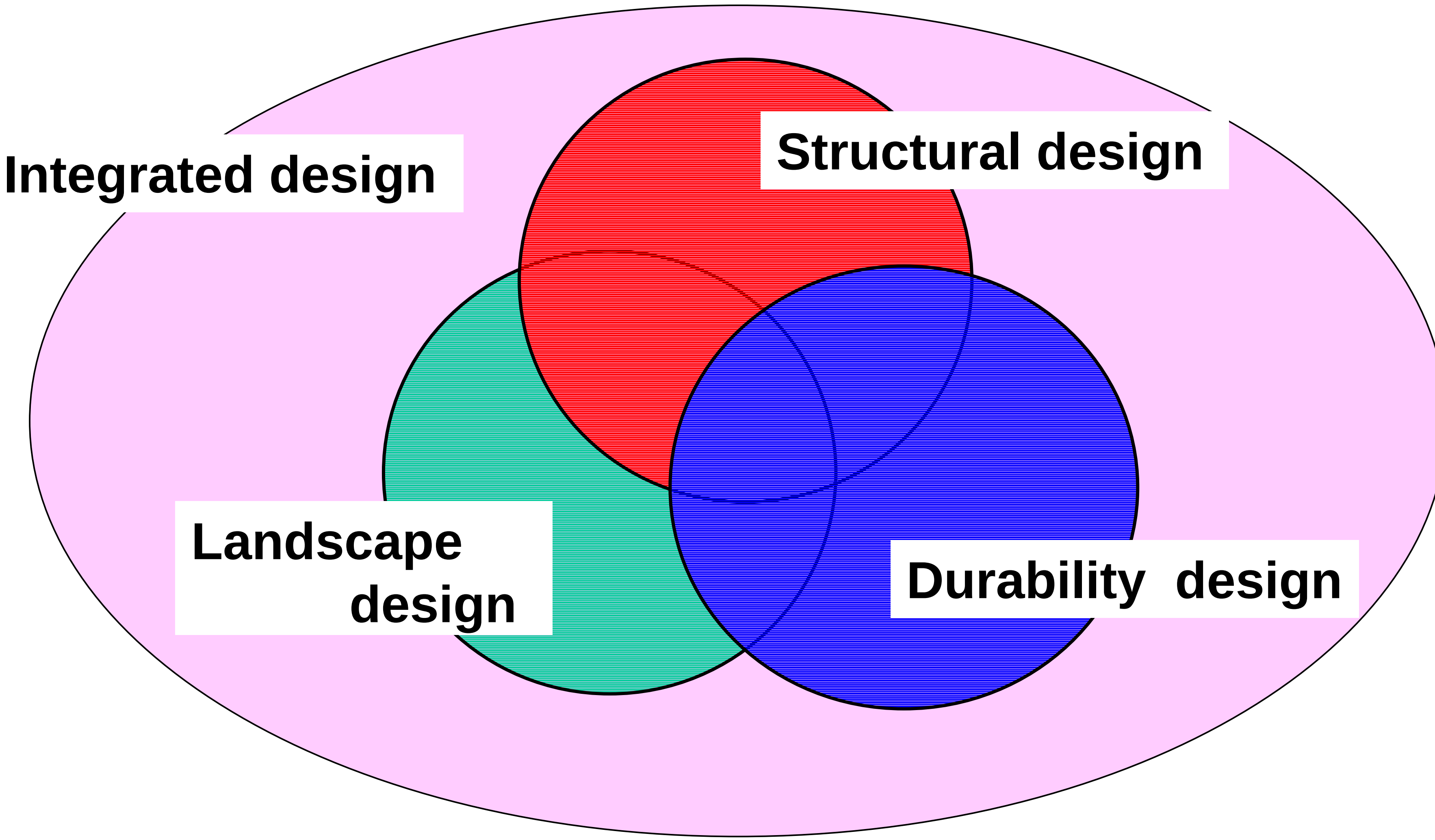
Examination

in

Durability Design

Schematic of design for structure

Performance-based design



What is “ Durability of structure”

Qualitative performance

↓

Resistance against deteriorating actions from surrounding environment

↓

To keep the all of required performances on structure to their levels more than the required ones during the service life

Durability design

Design carried out to ensure that the structure can maintain its required performance (functions) during the service life under environmental actions

defined by Asian concrete model code

↓

Evaluation of long-term-performance

Examination of durability

General principle

All required performances for structure, such as serviceability, restorability and safety under actions in normal use, wind action and seismic action, shall be examined respectively in regard of **their long-term performances in the service life**.

Examination of durability

Examples of durability-limit-state

***Durability-limit-state A*: All performances maintain the initial conditions.**

***Durability-limit-state B*: Though some material used in structure deteriorates, negligible decay in any performance of structure occurs.**

***Durability-limit-state C*: Though some structural performance deteriorates, function of structure keep in the required condition and the damages are repairable.**

Examination of durability

Durability Limit state

Class A

No deterioration of both structure performance and material.

corrosion initiation time

Class B

Some deterioration on material, No deterioration of structure performance.

Corrosion crack Generation time

(initial period +propagation period)

Class C

Deterioration can occur on both performance of structure and material within allowable range .

Examination of durability

Durability-limit-state for marine concrete structures

***Durability-limit-state A*:**

- All performances maintain the initial condition

$$t_d \leq t_{cr}$$

t_d : Design service life of marine concrete structure

t_{cr}: Duration until reinforcement starts to corrode

↓

t_{cr} is seemed to be the duration until concentration of Cl^- accumulating on reinforcement surface reaches a critical value for starting corrosion

Examination of durability

Evaluation method in durability-limit-state A

$$\gamma \cdot \frac{C_{(c,Td)}}{C_{\lim}} \leq 1.0$$

$C_{(c, Td)}$: Chloride content at reinforcement position during service life of structure

C_{lim} : Critical chloride content

γ : Safety factor

This concept was Introduced in 1999 version of JSCE standard specification for design of concrete structure as the verification method of durability of concrete structure

$C_{(c,Td)}$

Simplified Fick's second law

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial^2 x}$$

C: Concentration of Cl^- at depth x after t

D: Diffusion coefficient

Theoretical analysis

- **In sea water or tidal zone**

$$C_{(c,Td)} = C_0\left[1 - erf\left(\frac{c}{2\sqrt{D \cdot T_d}}\right)\right]$$

here,

$$erf(s) = \frac{2}{\sqrt{\pi}}\int_0^s e^{-\eta^2} d\eta$$

- **In splash zone or atmospheric zone**

$$C_{(c,Td)} = 2W\left[\sqrt{\frac{T_d}{\pi D}} \cdot \exp\left(\frac{c^2}{4DT_d}\right) - \frac{c^2}{2D}\left[1 - erf\left(\frac{c}{2\sqrt{D \cdot T_d}}\right)\right]\right]$$

C_0 : Chloride content on concrete surface

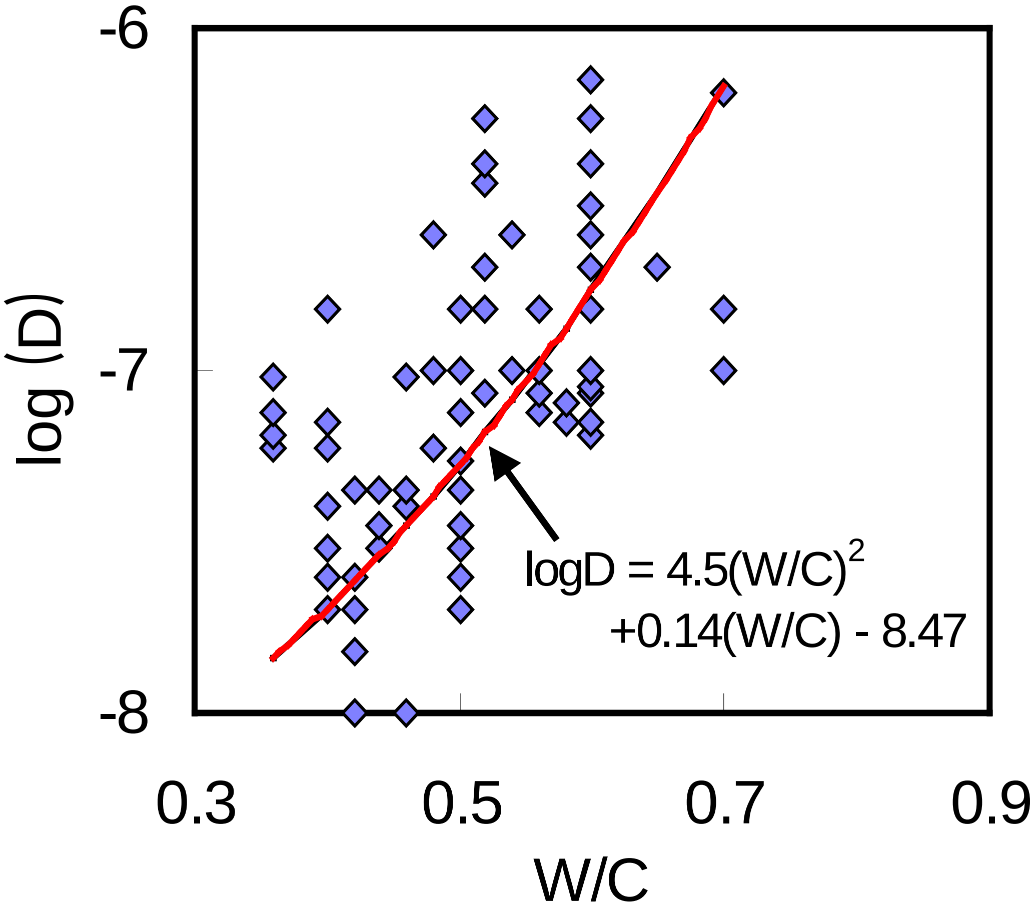
D : Chloride diffusion coefficient of concrete

T_d : Design service life

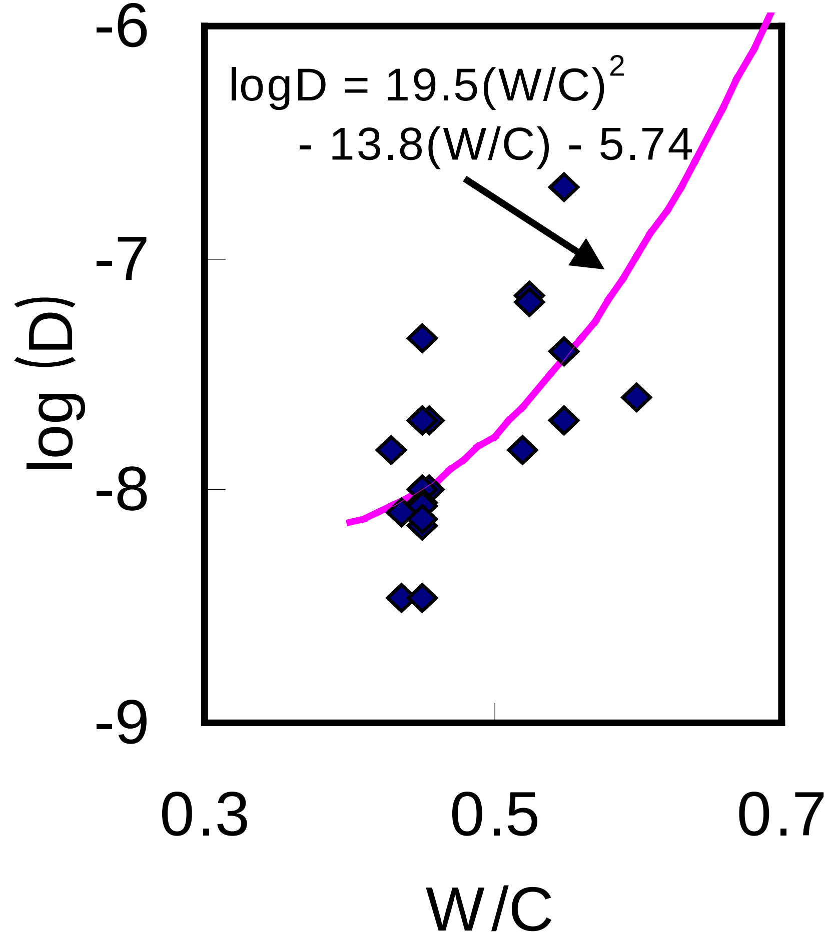
c : Minimum cover thickness

W : Accumulated chloride amount on concrete surface during unit time

Relationship between chloride diffusion coefficient and W/C of concrete



(a) In case of OPC



(b) In case of BFSC

Durability-limit-state for marine concrete structures

***Durability-limit-state B*:**

- Though some material used in structure deteriorate, negligible decay in any performance of structure occurs

$$t_d \leq t_{cr} + t_{ck}$$

t_d : Design service life of marine concrete structure

t_{cr}: Duration until reinforcement start to corrode

t_{ck}: Period of corrosion progress on reinforcement from start of corrosion until occurrence of corrosion crack on concrete

$$t_d = t_{cr} + t_{ck}$$

***t_{cr}*: Duration until reinforcement start to corrode**

$$t_{cr} = \frac{c^2}{4D_d \cdot [erf^{-1}(1 - C_d / C_0)]^2}$$

***t_{ck}*: Period of corrosion progress on reinforcement from start of corrosion until corrosion crack occurs on concrete**

$$t_{ck} = \frac{1.7\alpha_N (1 + \alpha_\phi \cdot c)^{0.85} \cdot c \cdot \left[\frac{1}{(W/C)} - 1 \right] \cdot \alpha_C}{E_h \cdot \beta_t}$$

$$t_{ck} = \frac{1.7\alpha_N (1+\alpha_\phi \cdot c)^{0.85} \cdot c \cdot \left[1/_{(W/C)} - 1 \right] \cdot \alpha_C}{E_h \cdot \beta_t}$$

c **:** Concrete cover

W/C **:** Water to cement ratio

α_N **:** Factor for strength of concrete: = 0.5/(W/C)

α_ϕ **:** Factor for diameter of rebar(ϕ): = 2/ϕ

E_h **:** Factor for environment: = 1.5 (in sea water)
2.5 (tidal zone)
3.5 (splash zone, coast line)
2.0 (others)

β_t **:** Factor for average temperature: = 0.7 (under 10°C)
1.0 (10 ~ 20°C)
1.3 (over 20°C)

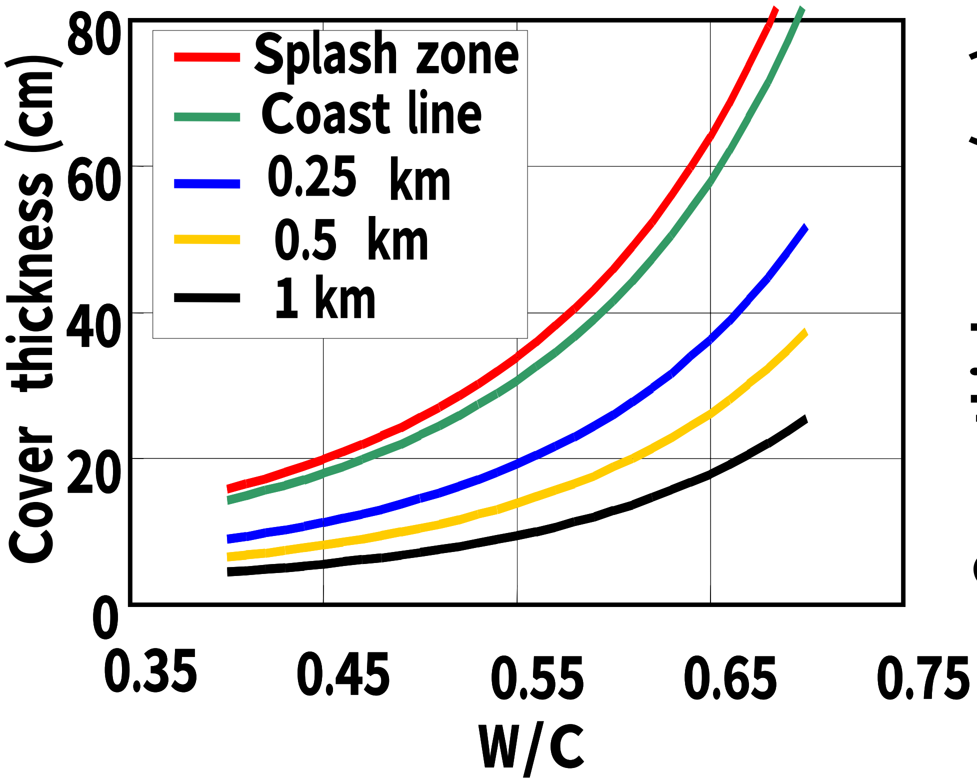
α_C**:** Factor for type of cement: = 1.0 (OPC)
1.25 (BFSC)

Relationship between minimum cover thickness and maximum W/C required for durability

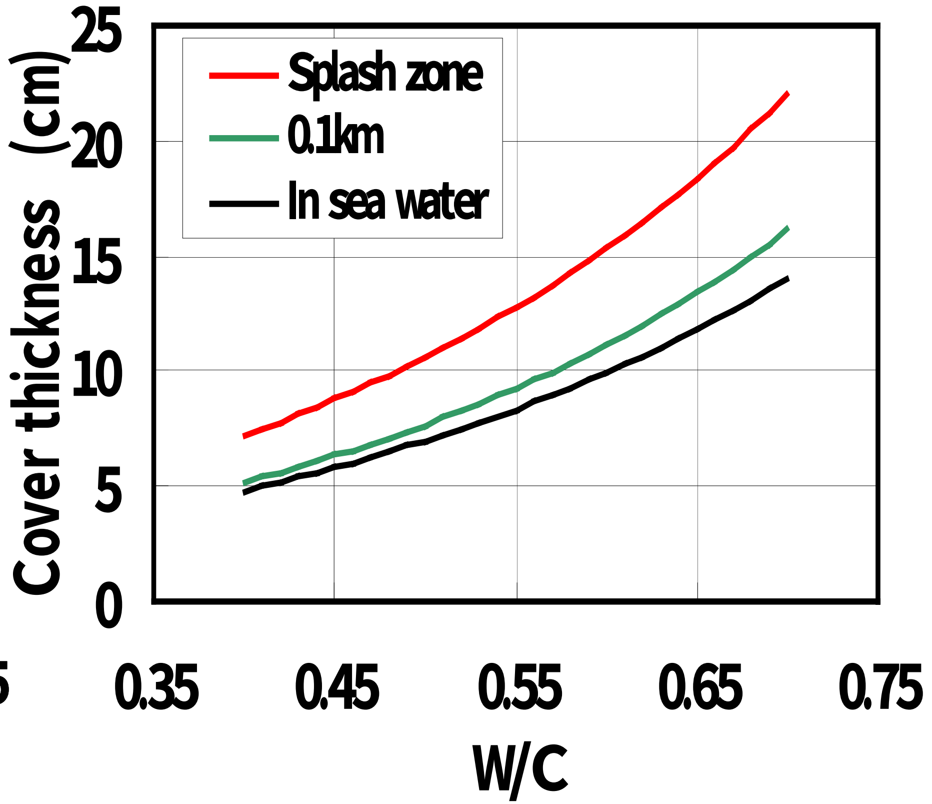
Design condition

OPC, Design service life: 50 years

Durability-Limit-state A



Durability-Limit-state B

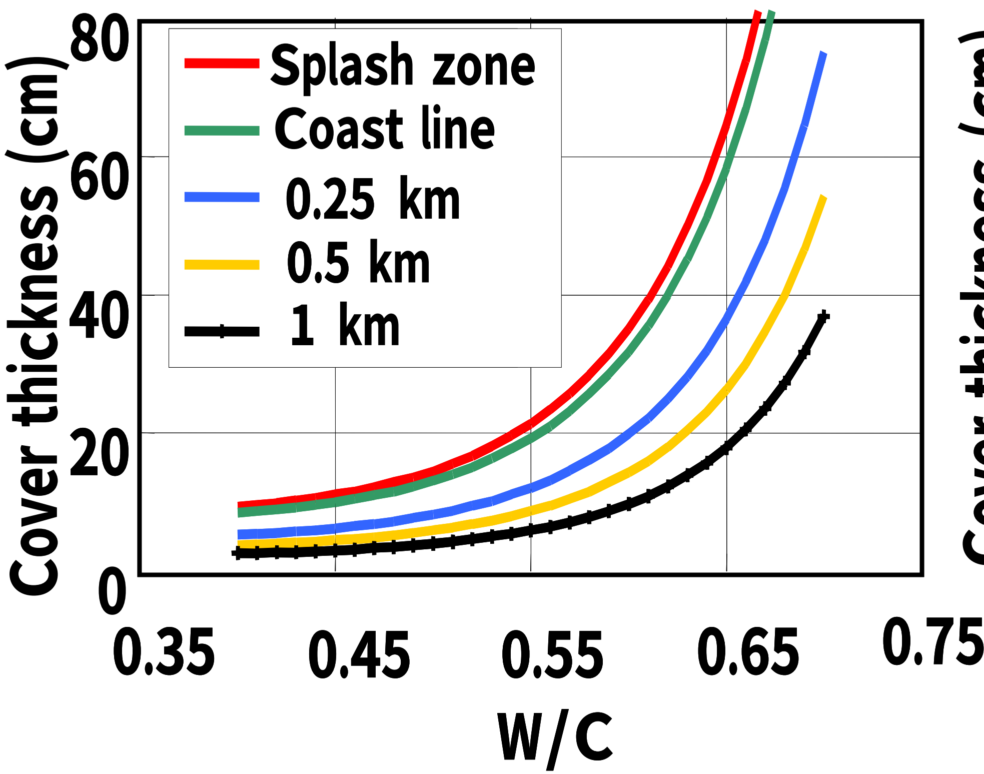


Relationship between minimum cover thickness and maximum W/C required for durability

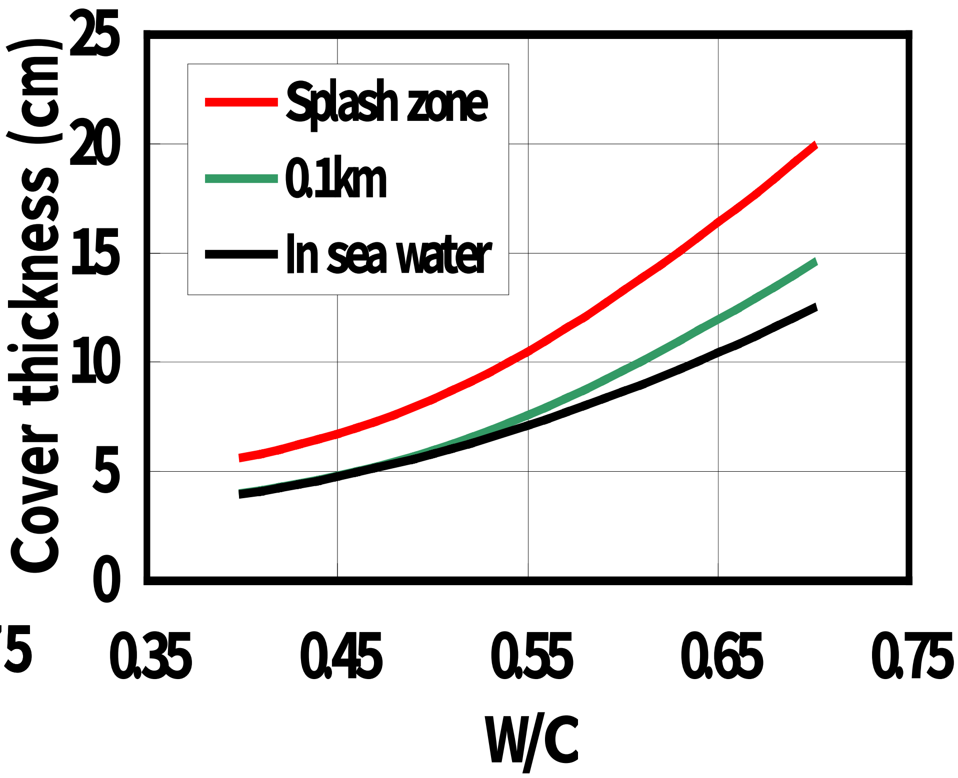
Design condition

Blast furnace slag: 50%, Design service life: 50 years

Durability-Limit-state A



Durability-Limit-state B



Computer Simulation Model

Simulation model for deterioration of concrete structure in marine environment

To evaluate more directly the durability in actual condition by using deterioration simulating model

↓

Simulation model

- Concrete model considering scatter of quality
- Penetration model of chloride and oxygen
- Corrosion model of reinforcement

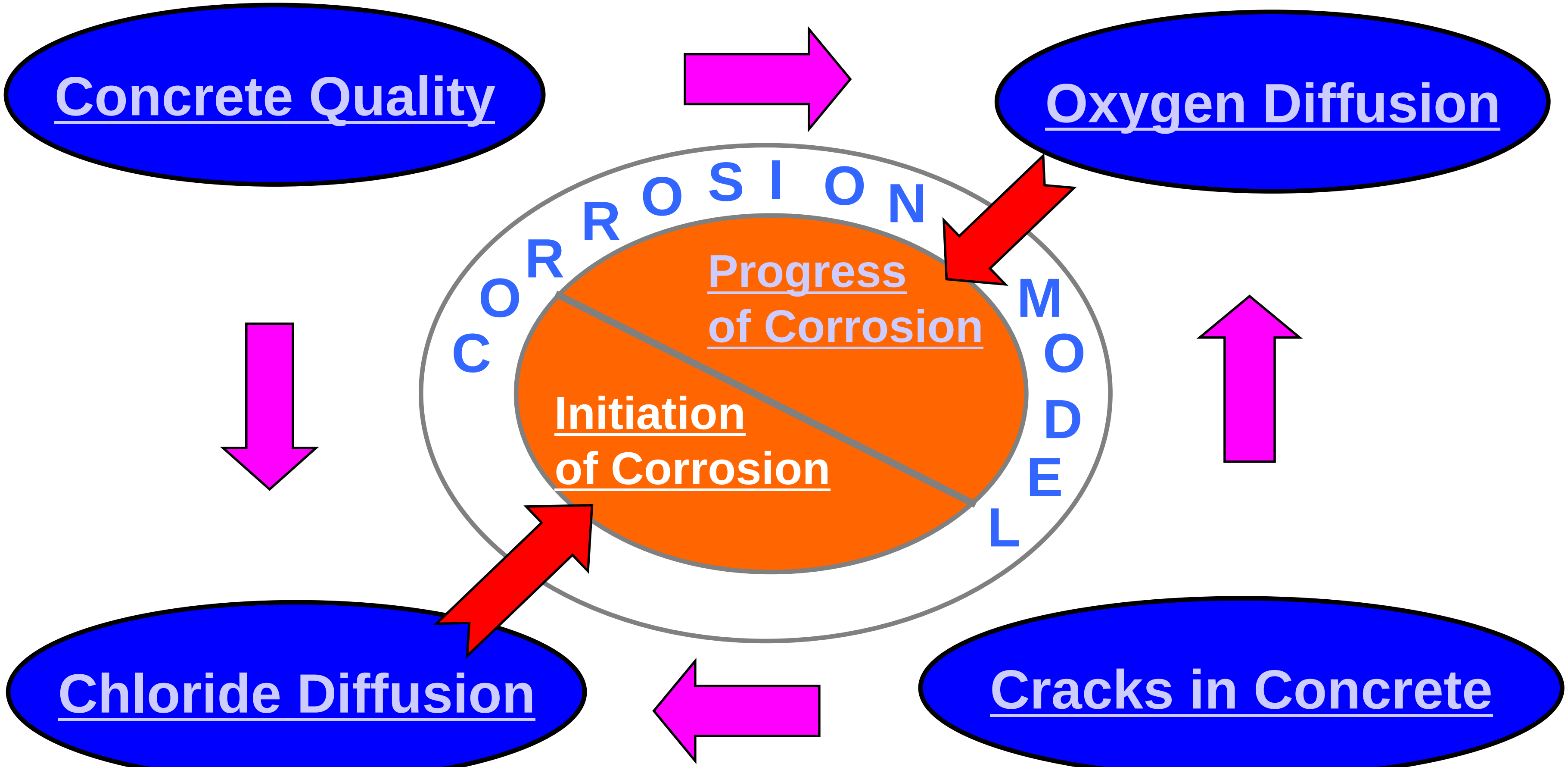
↓

Estimation

- Progress of corrosion of reinforcement
- Period of corrosion crack generation

Simulation model for deterioration of concrete structure in marine environment

Framework of Corrosion Simulation model



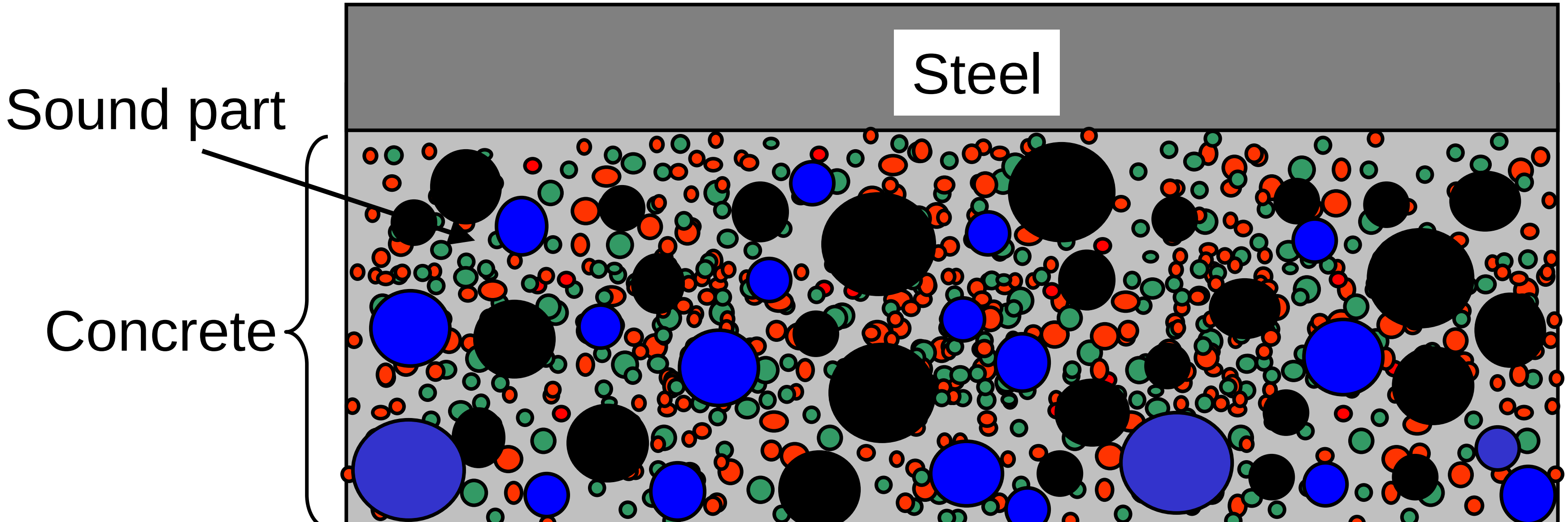
circular-pore

Outline of the concrete model

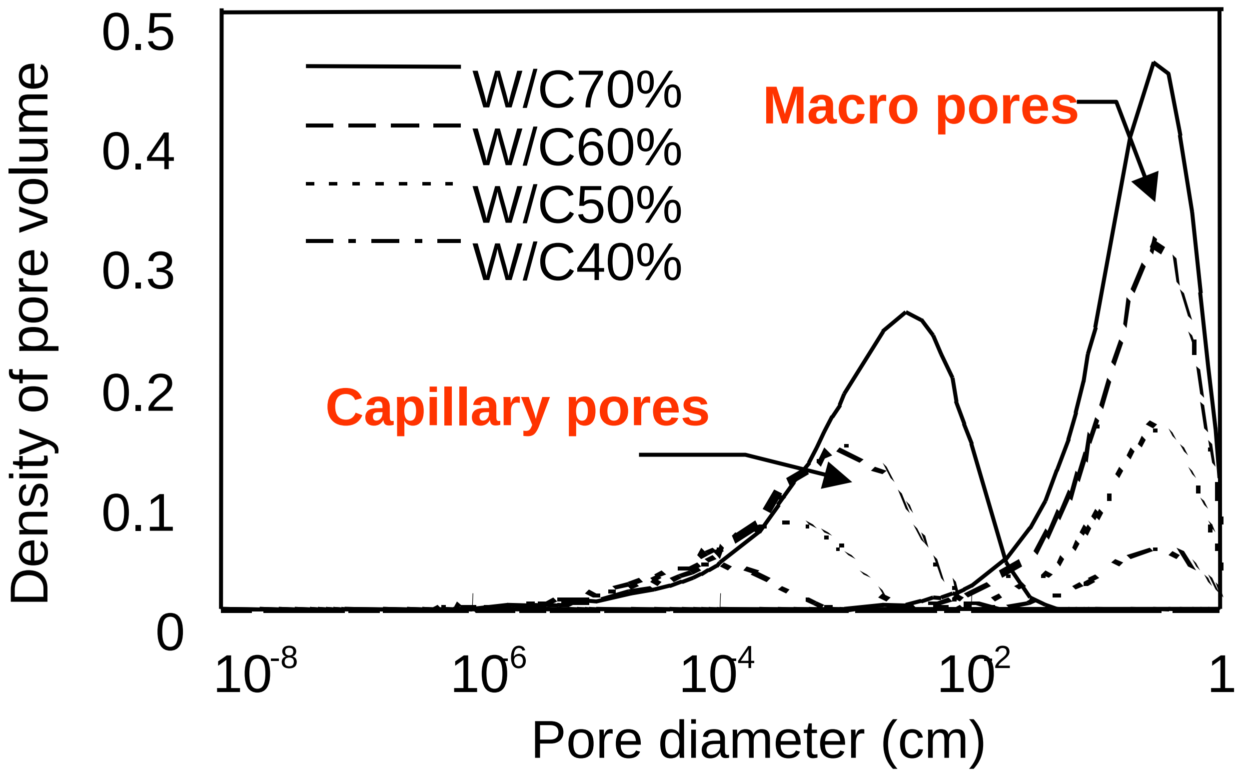
2 dimensional reinforced concrete model

Pore distribution in concrete → Circular-pore distribution
- Randomly located
- Considering W/C and RH

Aggregate distribution in concrete → Circular-Aggregate distribution
- Randomly located
- Considering ITZ



Modified pore distribution



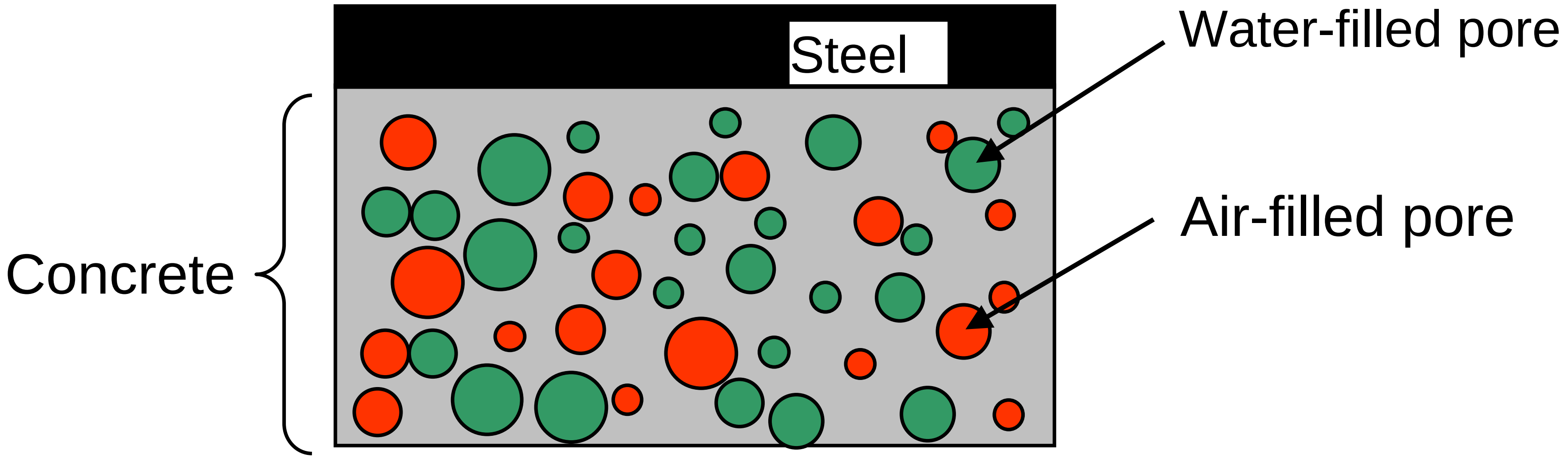
(by Shimomura et al)

$$V'(r) = V'(\infty) \cdot B \cdot C \cdot r^{C-1} \cdot \exp(-Br^{C})$$

$V'(r)$: Density of pore volume

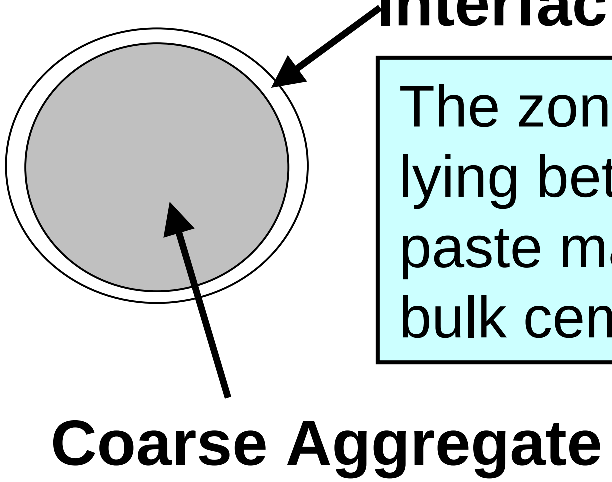
B, C: Parameters depending on W/C

Modified relative humidity



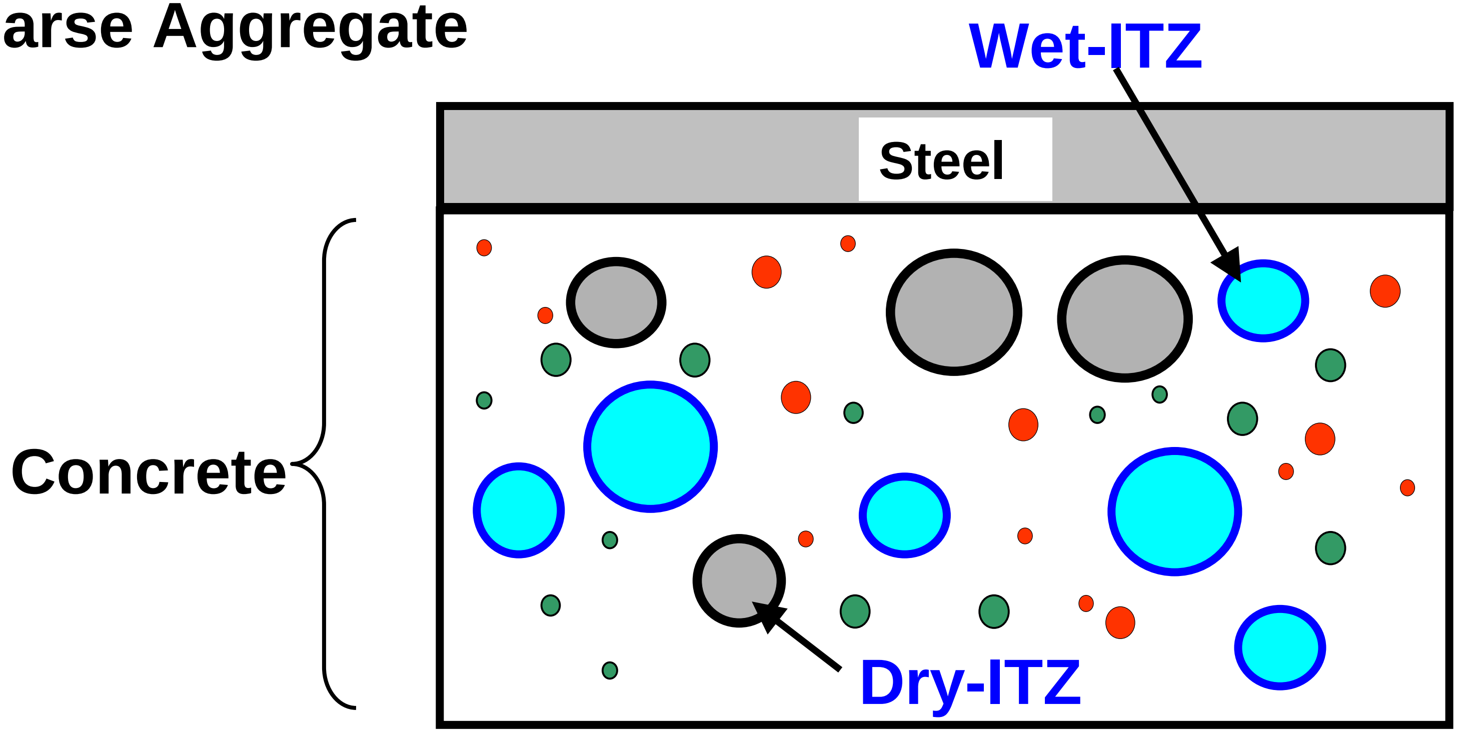
$$\textit{Relative humidity} = \frac{\textit{Water-filled pore volume}}{\textit{Total pore volume}}$$

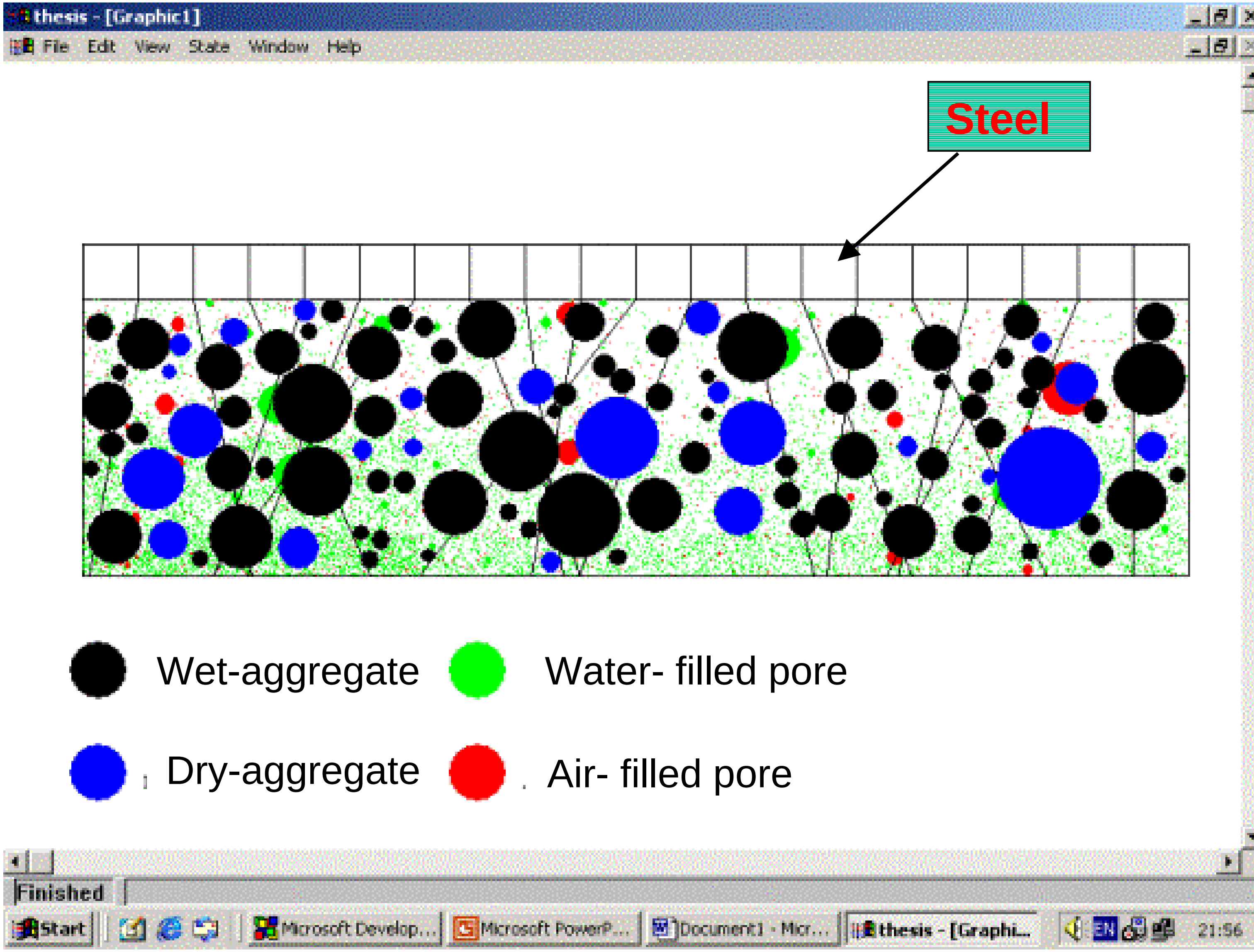
Model of aggregate



Interfacial transition zone (ITZ)

The zone with several micrometers thickness lying between aggregates and hardened cement paste matrix, which has higher porosity than the bulk cement paste

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File Edit View State Window Help
Steel
Wet-aggregate
Water- filled pore
Dry-aggregate
Air- filled pore
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Specification of a route on which chlorides reach rebar in minimum diffusion time

For each section (1cm)

↓

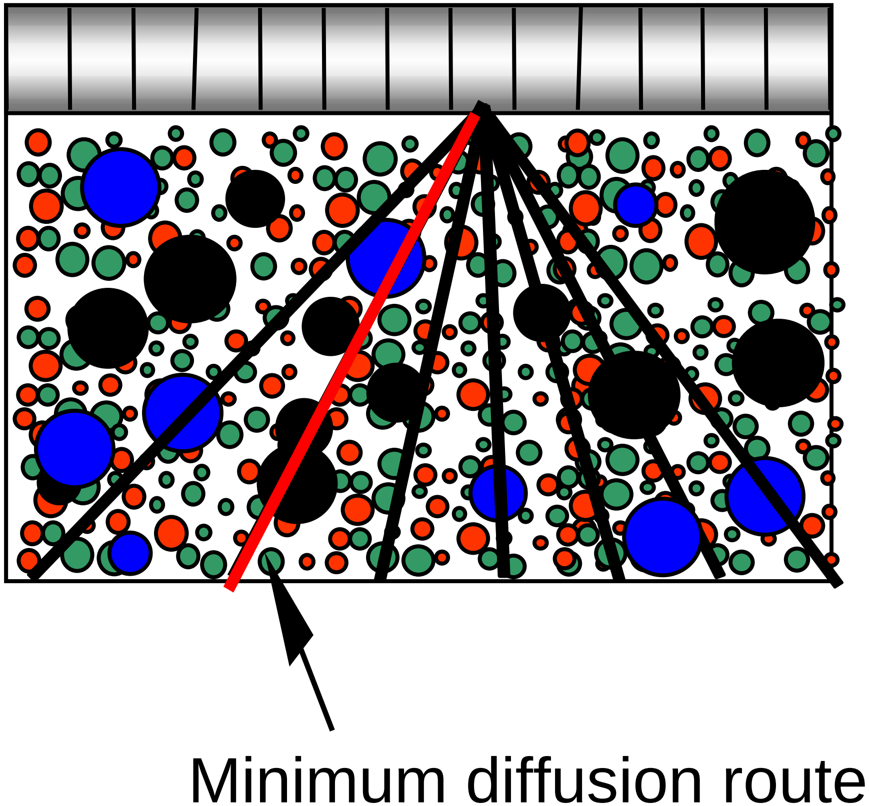
Many diffusion route

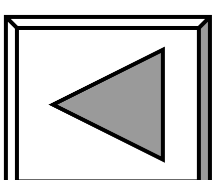
↓

Minimum diffusion time

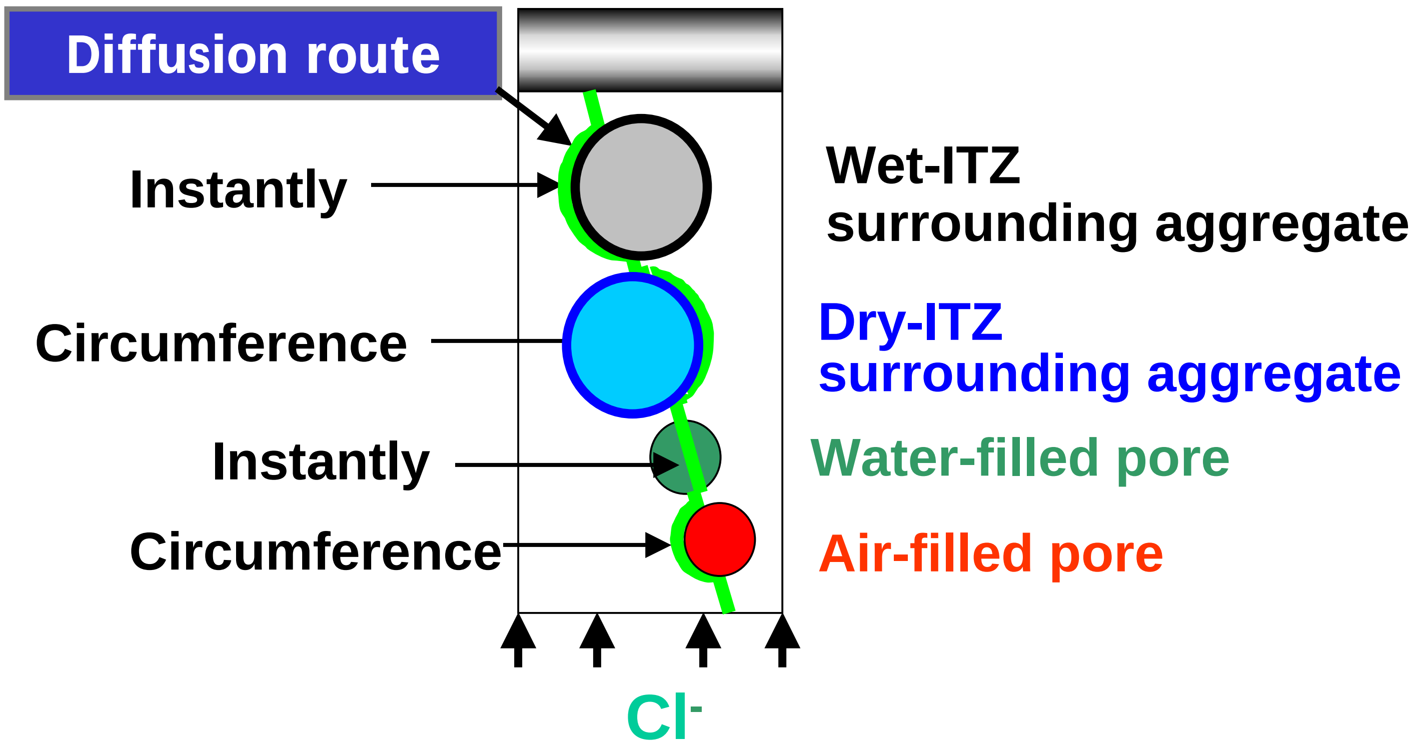
↓

One specific route





Chloride Penetration Model



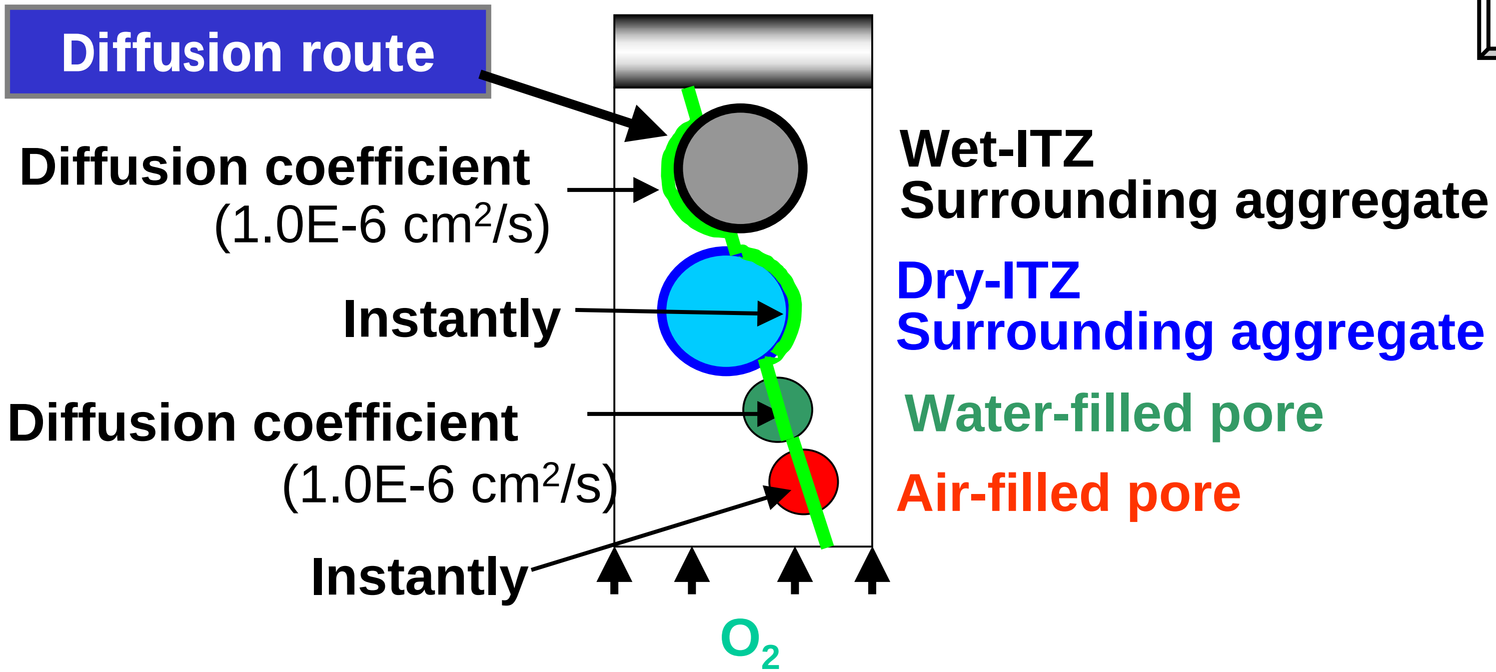
Diffusion of *Free chloride* described by Modified Fick's 2nd law

$$\frac{\partial C_f}{\partial t} = D\frac{\partial^2 C_f}{\partial x^2} - KC_f$$

Cf : free chloride concentration

K : combined coefficient

Oxygen Penetration Model



Diffusion of *oxygen* described by stationary state condition

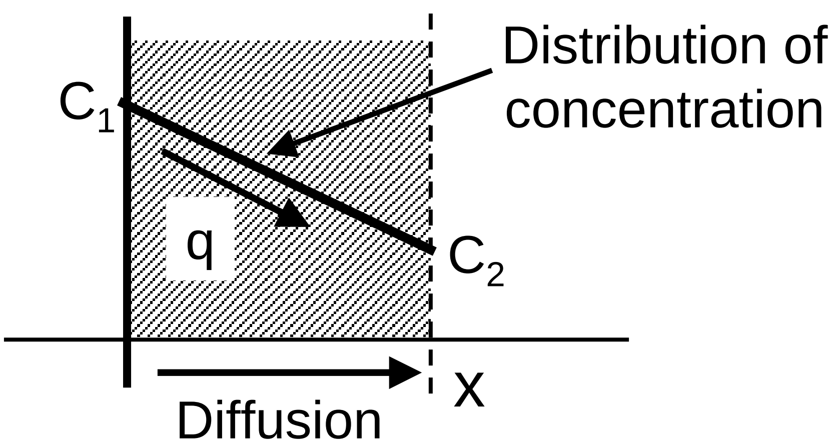
$$q = D\frac{dC}{dx}$$

(Fick's first low)

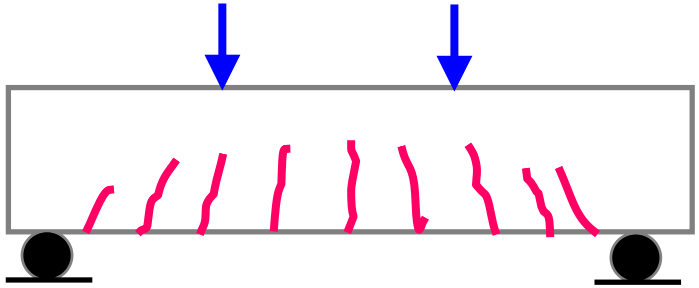
q : Flow rate of substance

C: concentration of substance

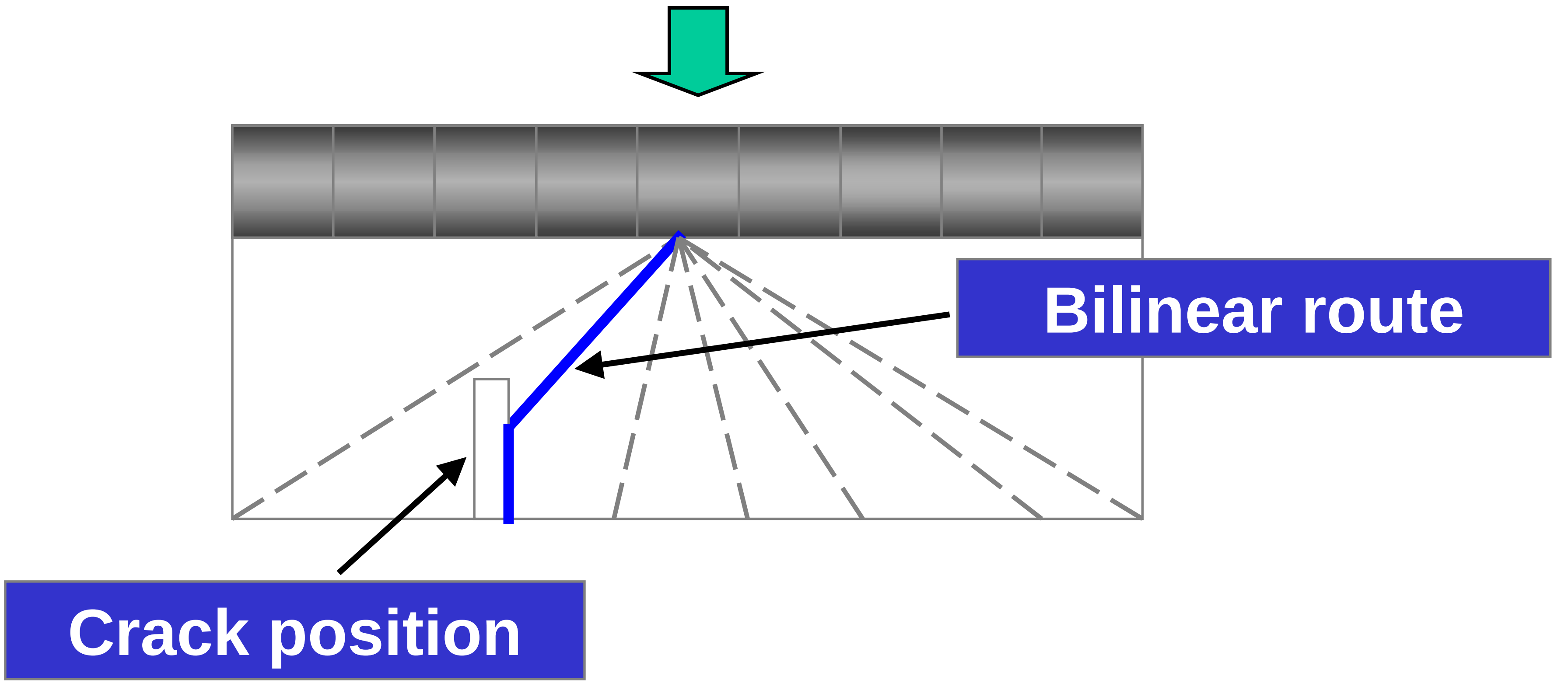
D: Diffusion coefficient



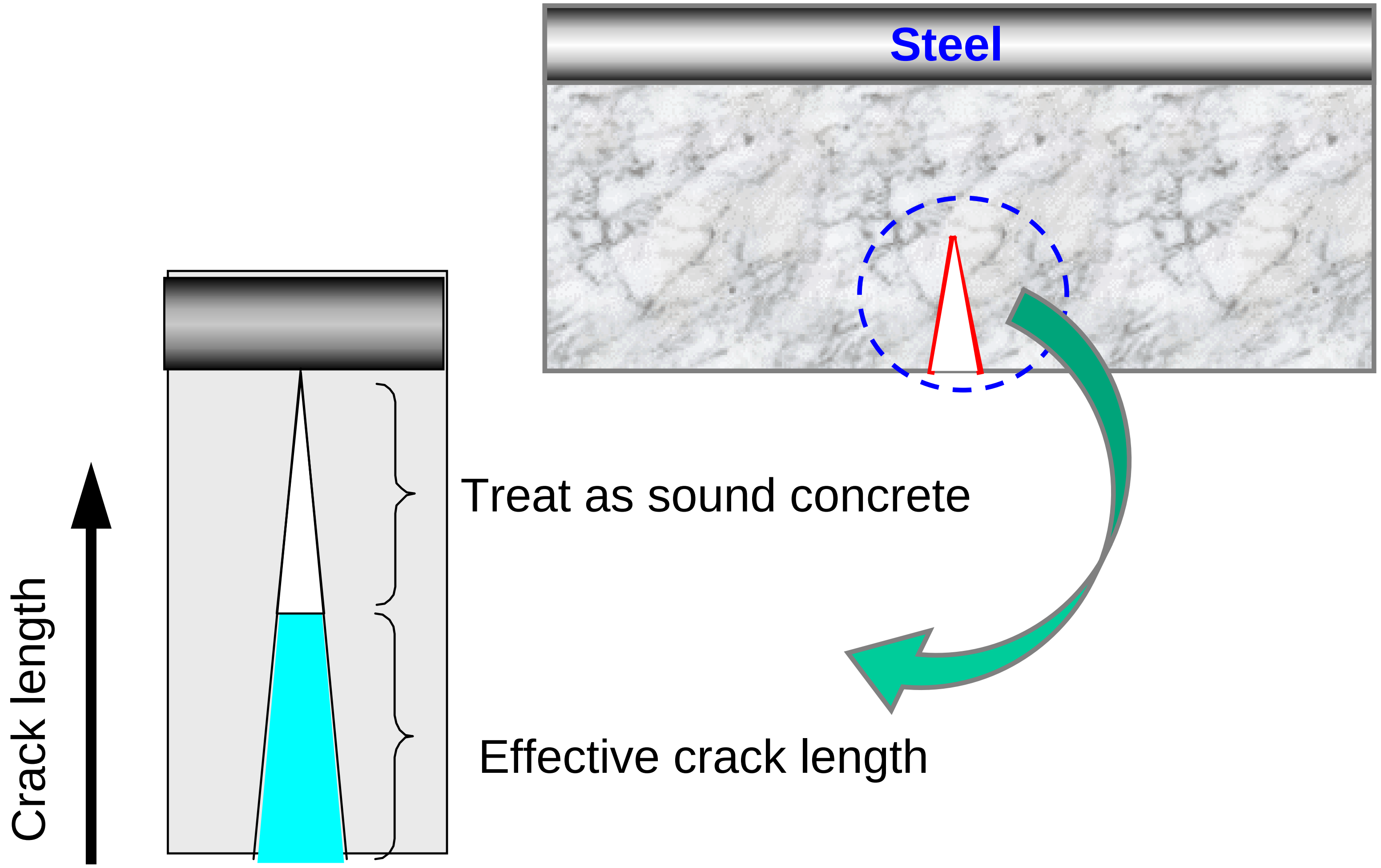
Cracked concrete Model



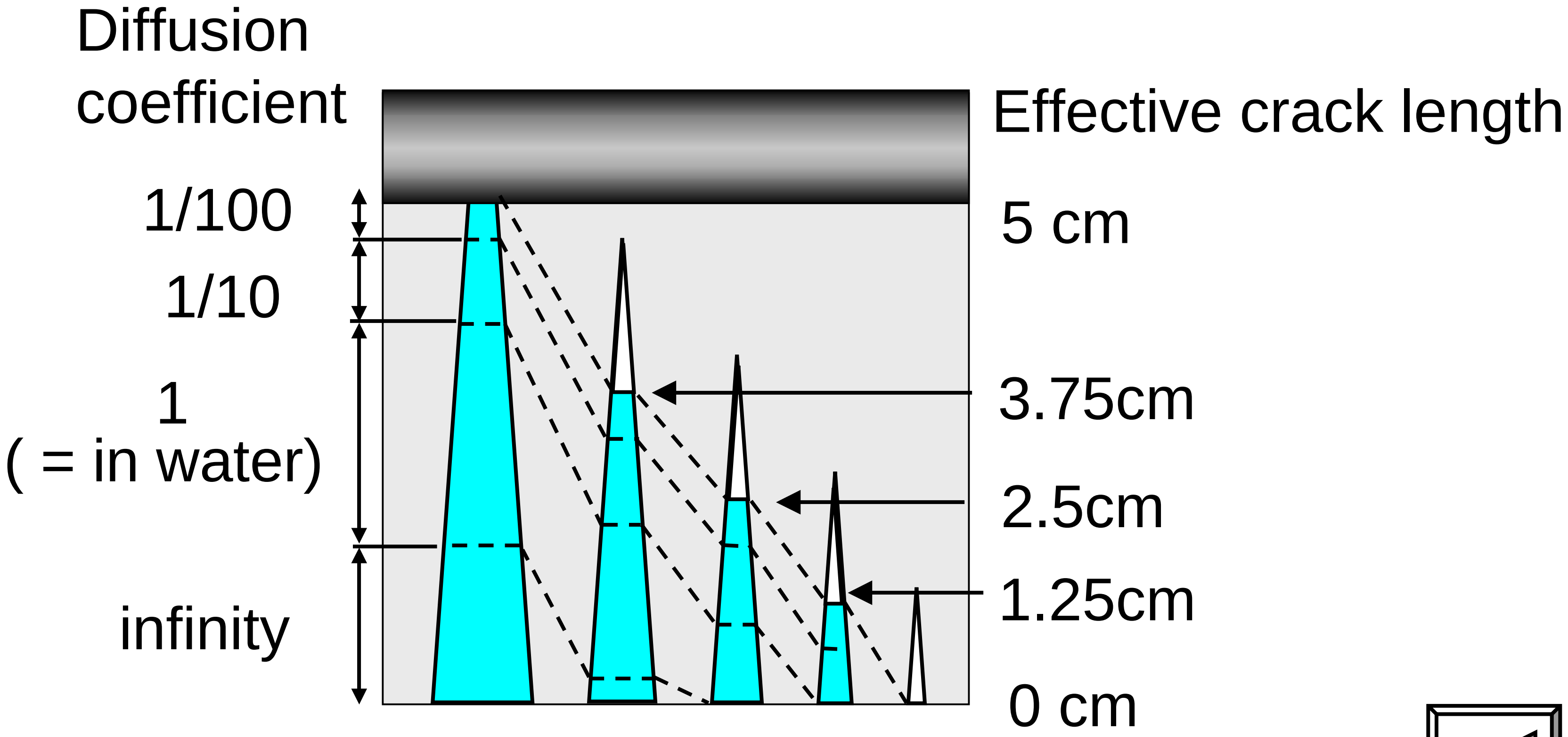
Cracks may exist by external loading, drying shrinkage etc..



Definition of effective crack length



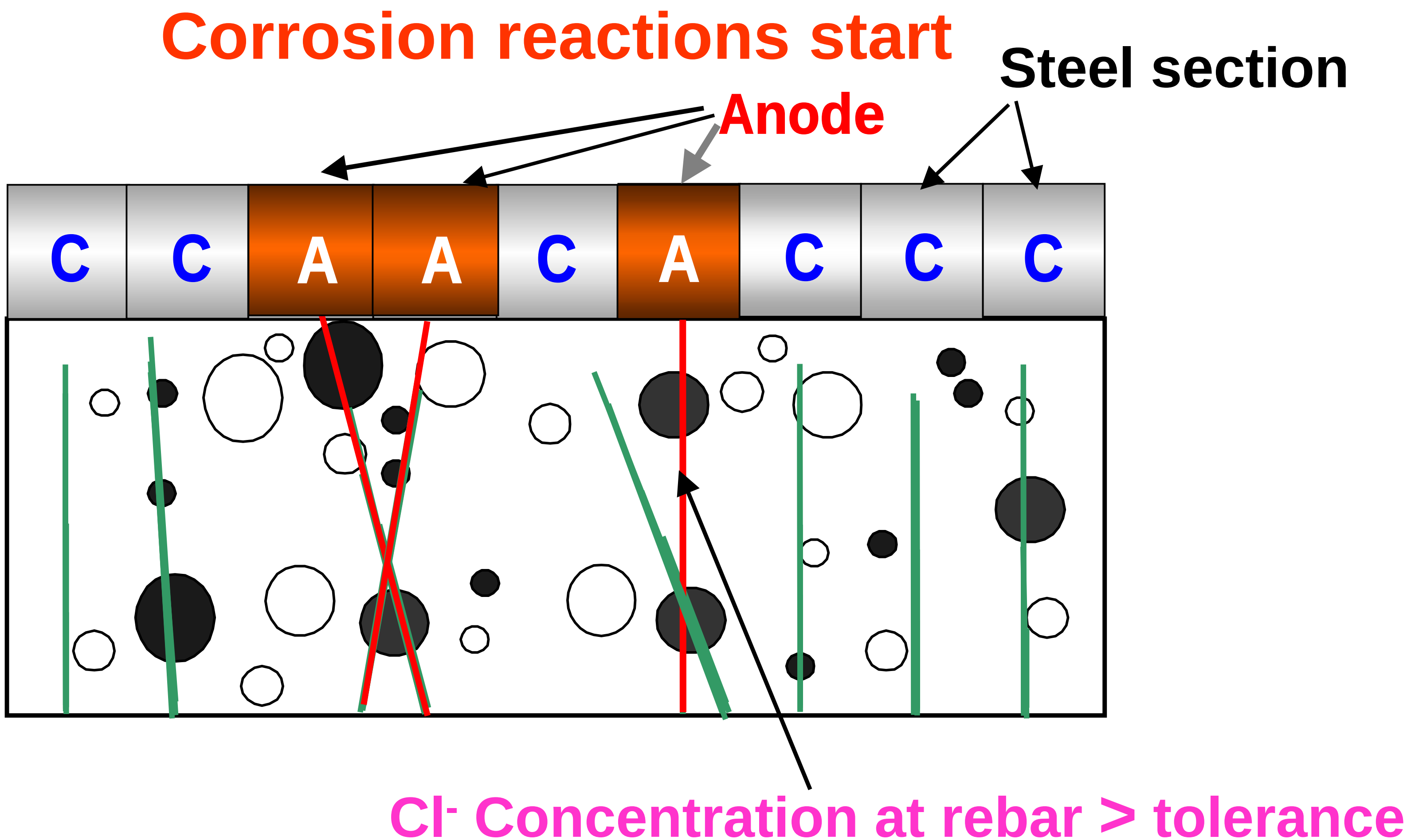
Relationship between effective crack and diffusion coefficient



Corrosion model

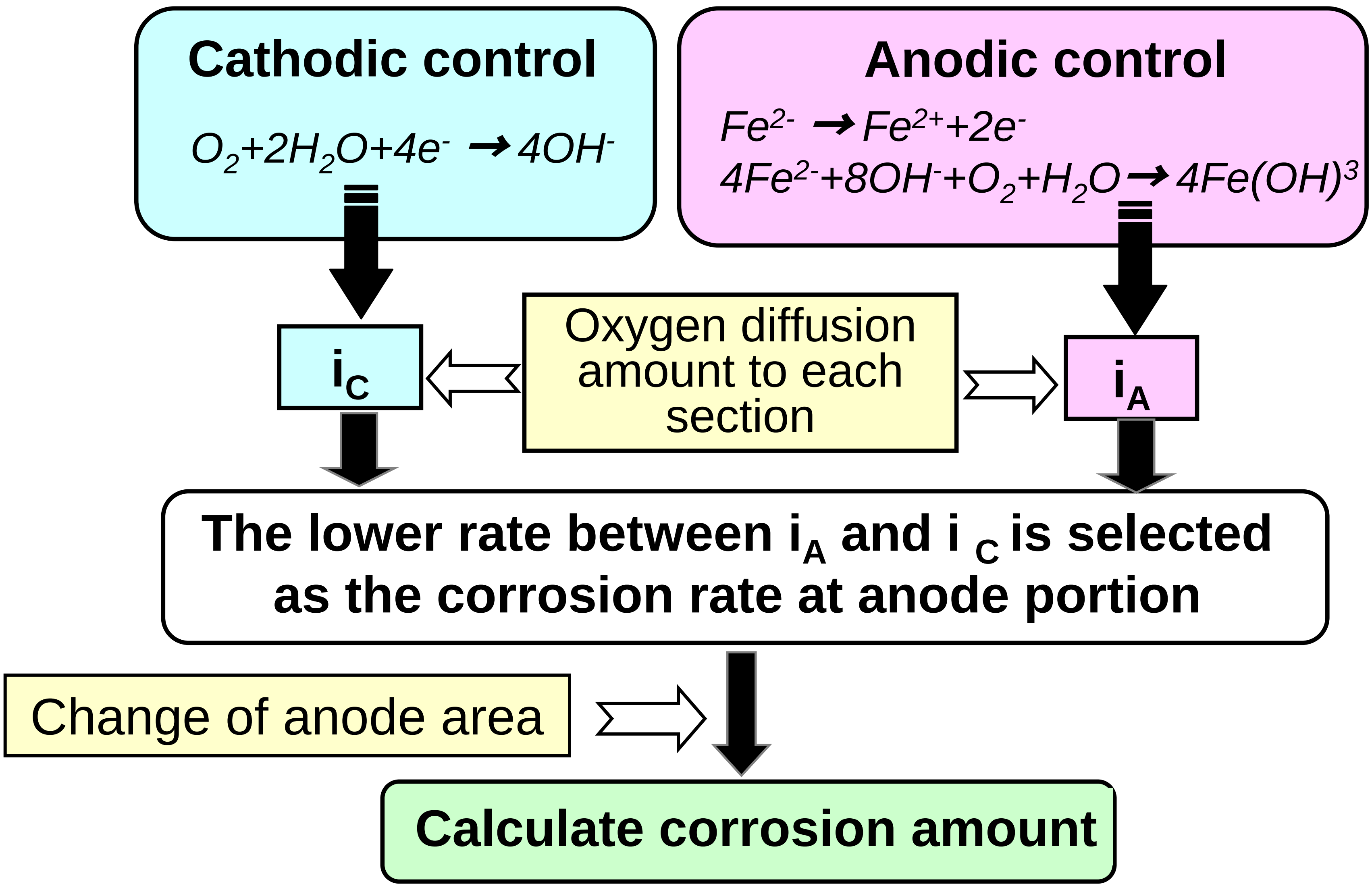
- based on macrocell corrosion theory-

Specification of Anode and Cathode area



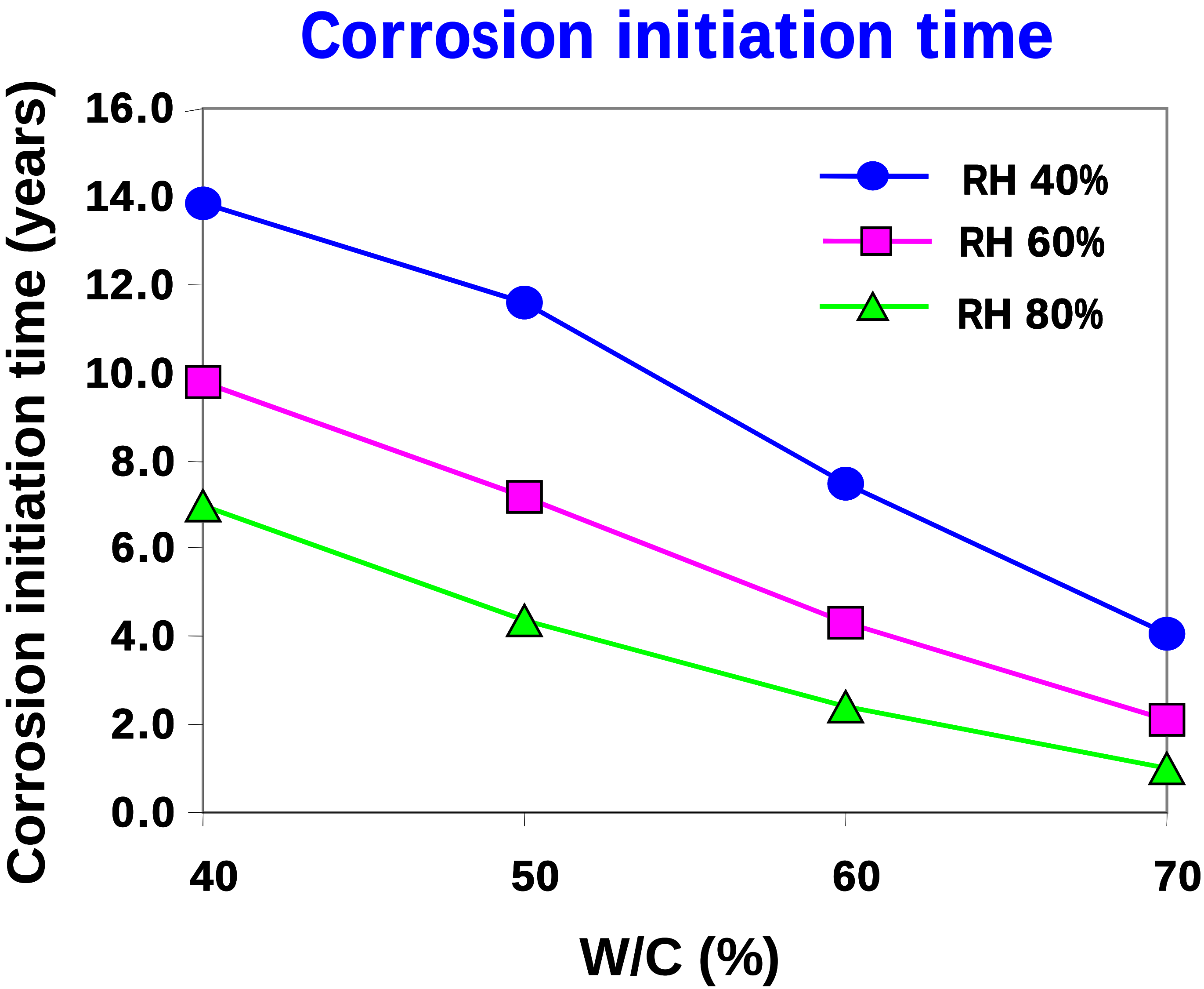
Corrosion model

Estimation of corrosion rate



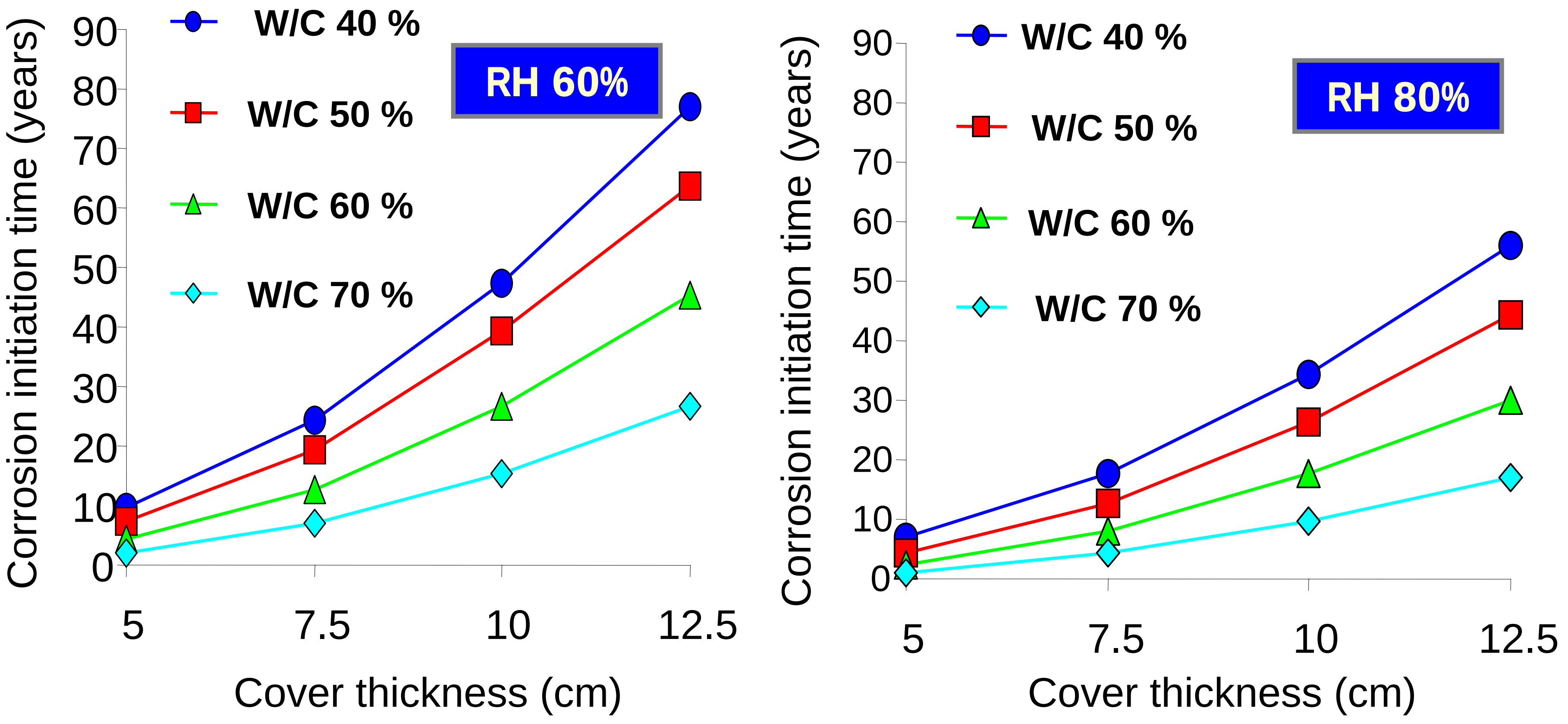
SIMULATION RESULTS

SIMULATION RESULTS



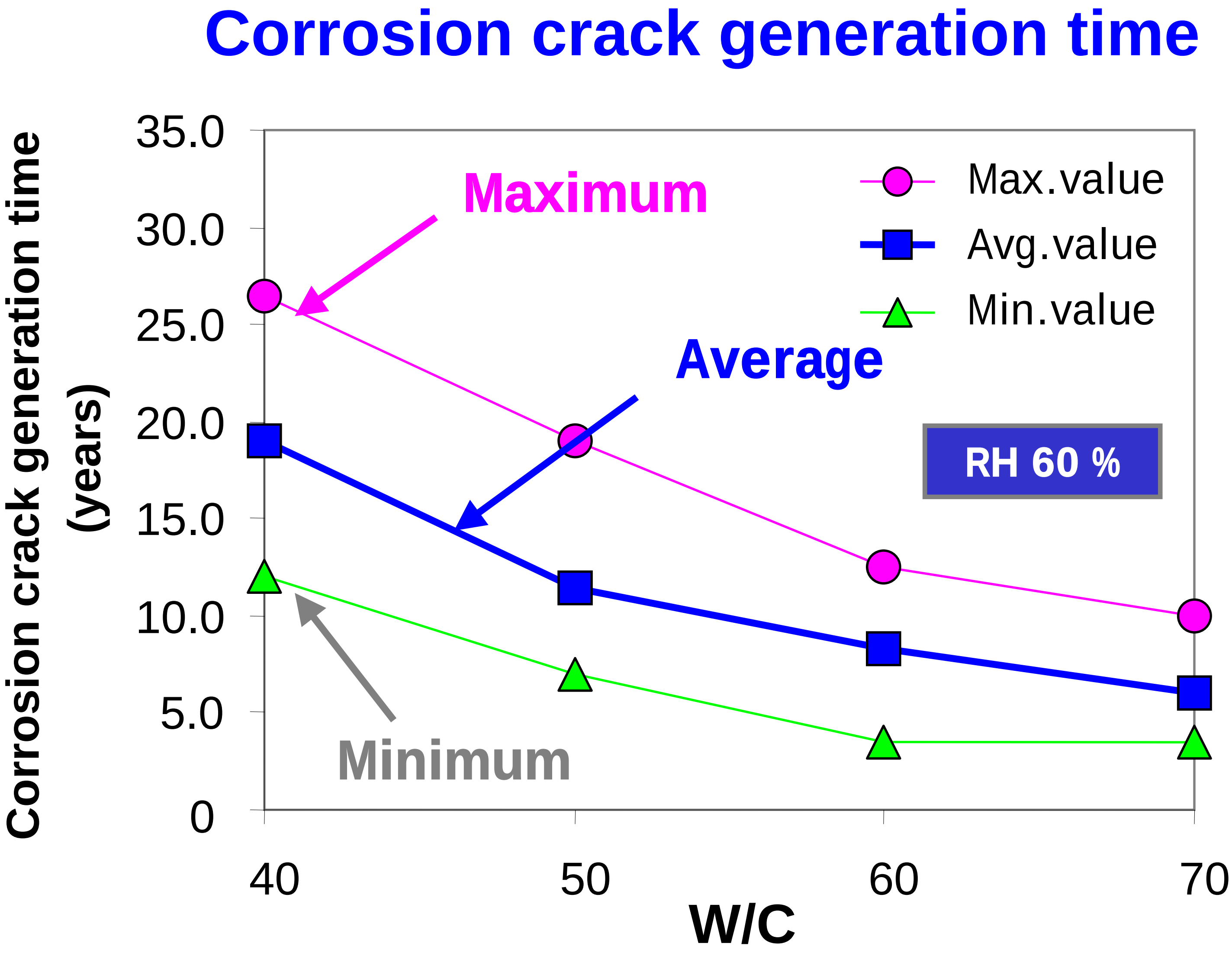
SIMULATION RESULTS

Corrosion initiation time

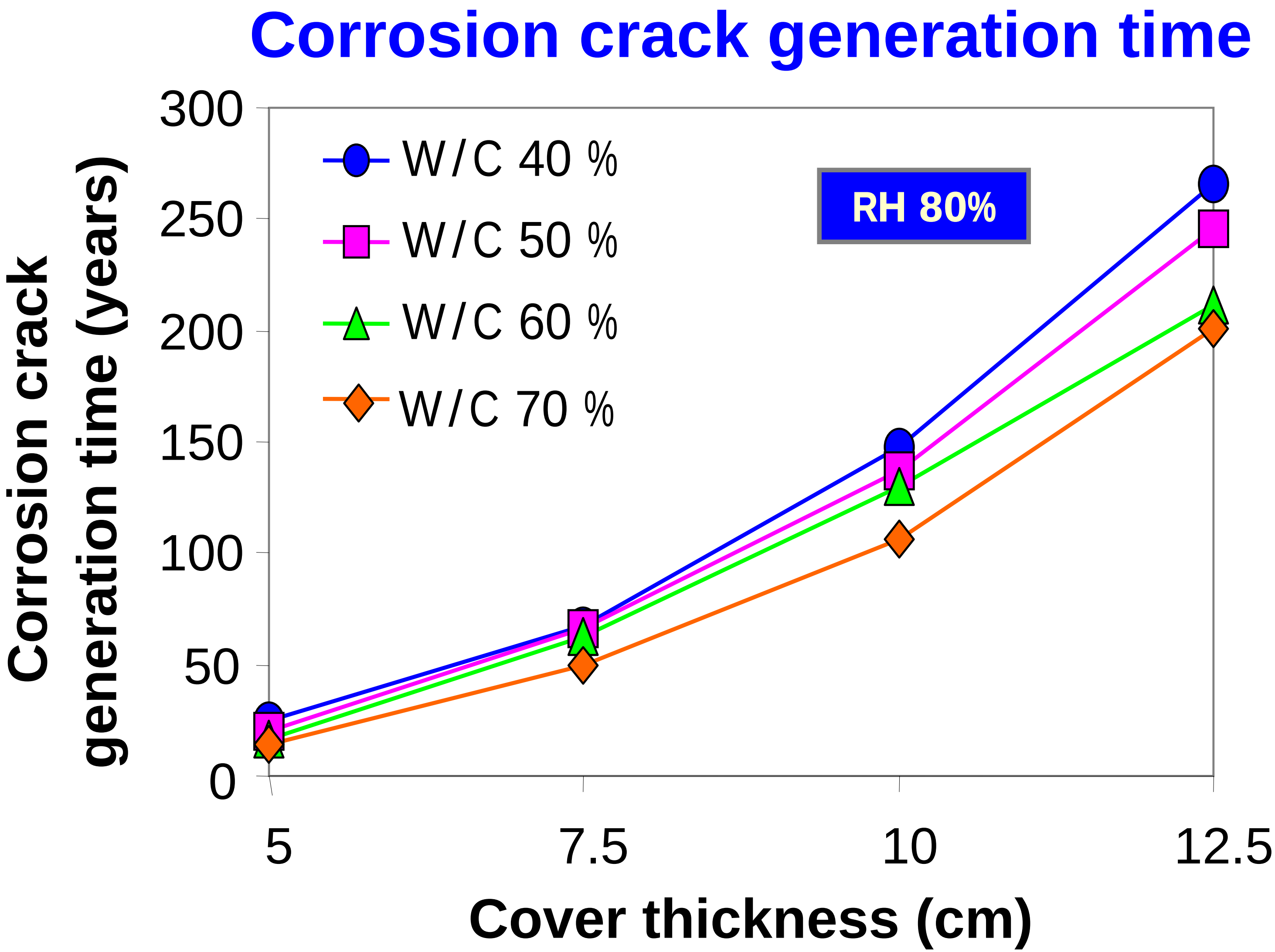


- the larger the cover thickness, lifetime increases clearly.
- Relative humidity is also influential parameter.

SIMULATION RESULTS



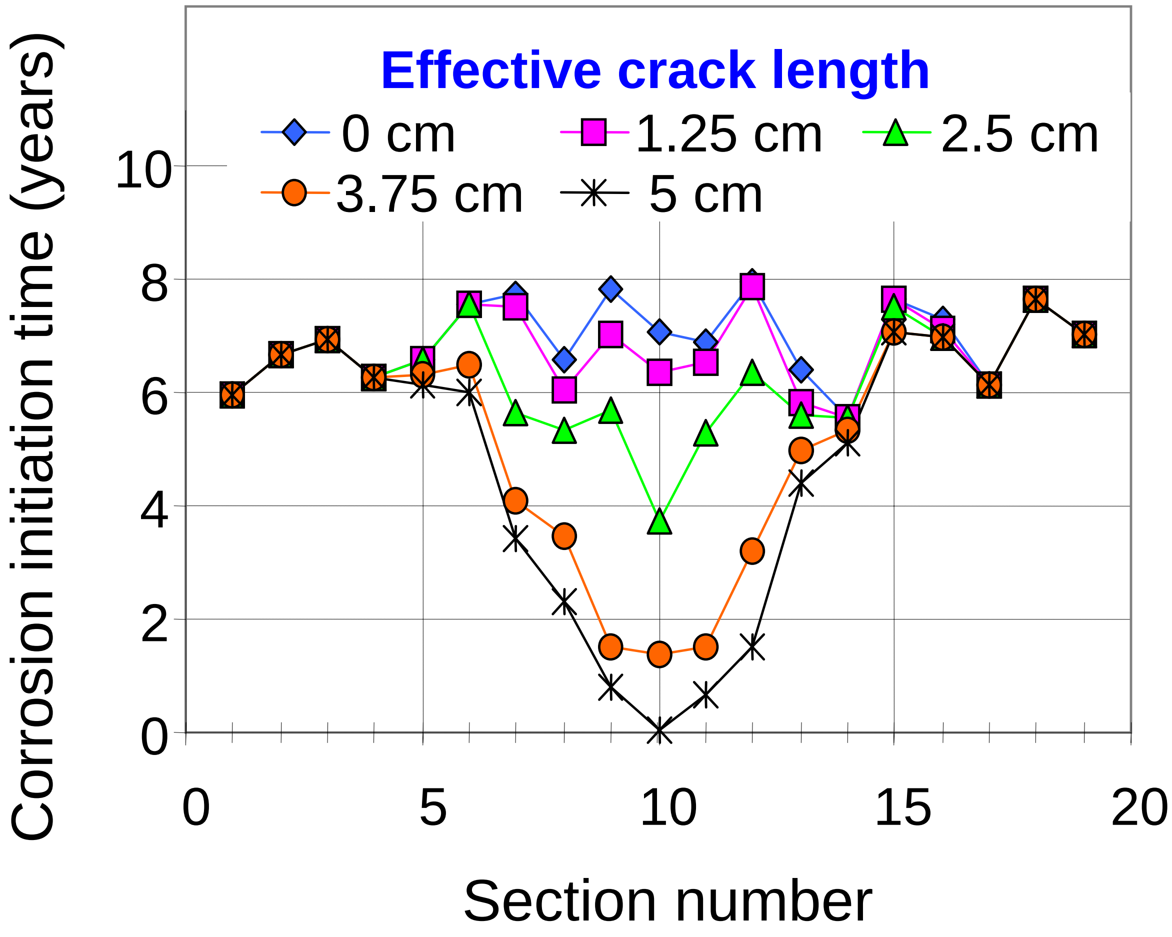
SIMULATION RESULTS



SIMULATION RESULTS

Initial crack model

Corrosion initiation time

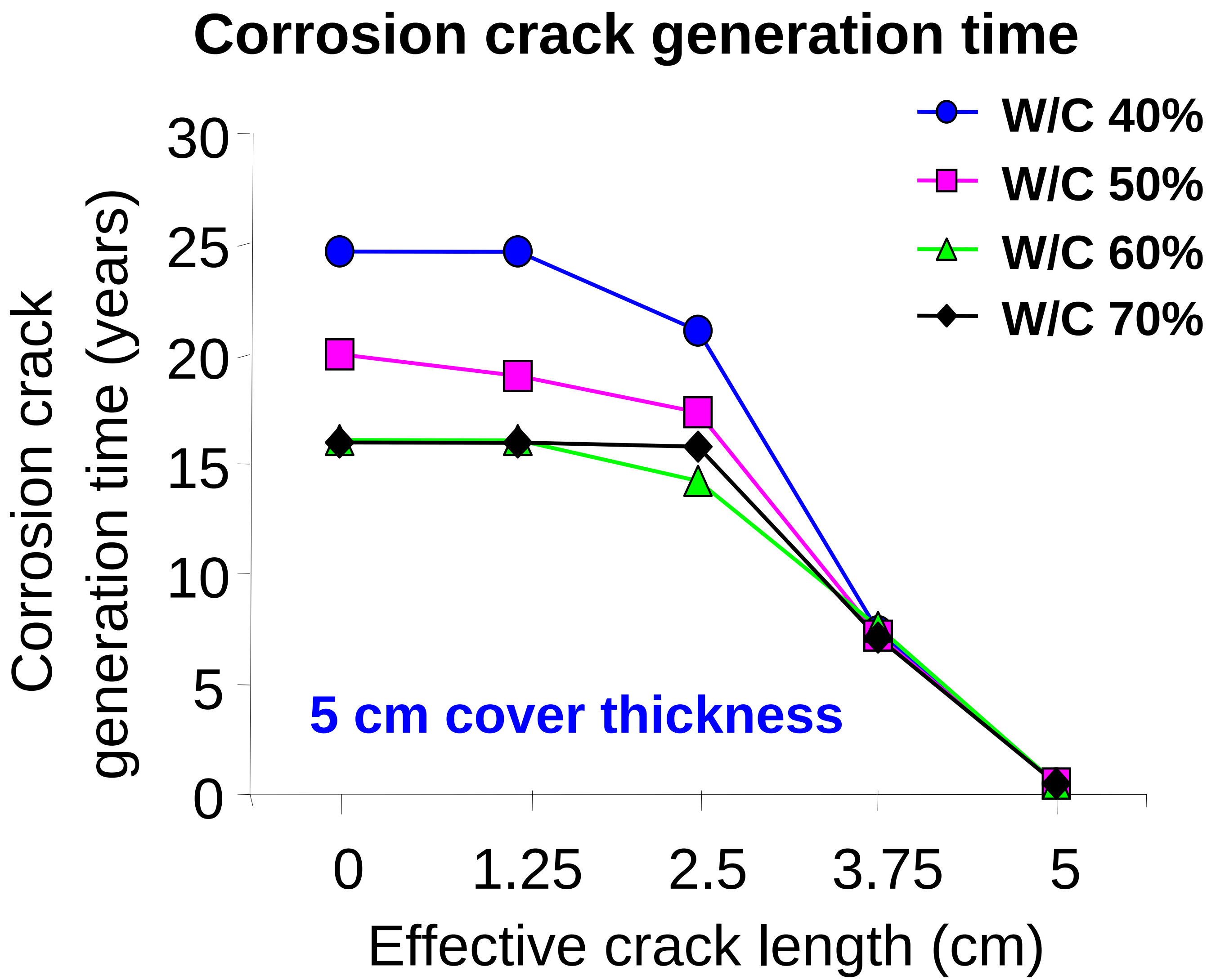


W/C 40%

5 cm of cover thickness

SIMULATION RESULTS

Initial crack model



Example for evaluation of structural performance of deteriorated RC structure

DYNAMIC BEHAVIOR OF REINFORCED CONCTERE STRUCTURES DETERIORATED BY CORROSION OF REINFORCEMENT

Introduction

- some structures in the severe environmental condition may be in a deteriorated condition due to the corrosion of reinforcement

- piers are relatively vulnerable to earthquake because it is suffered with a very large inertial force

Introduction

Corrosion of Reinforcement

Large Earthquake

Some pier with corrosion of reinforcement may not have the structural capacities it was designed for

Rehabilitation and Repairing is being popular

Evaluation of the dynamic behavior of the piers deteriorated by corrosion becomes necessary

Introduction

Objective

- Evaluate the dynamic properties such as, **stiffness**, **ductility** and **energy absorption** of the piers deteriorated by the corrosion of reinforcement

- Behavior of the corroded piers against the cyclic loading which are designed by
  - Ordinary design, using JSCE code.
  - Seismic design part of JSCE along with the verification of ductility according to JRA’s specification

Methodology

Specimen Type

S. No.	Designation	Design Principle	Axial Load	Corrosion Loss $gm/cm^2/cm$
1	POA-1	Using JSCE code for ordinary reinforced concrete design	200 kN	0.00
2	POA-2			0.19
3	POA-3			0.38
4	POA-4			0.56
5	PON-1		0	0.00
6	PON-2			0.19
7	PON-3			0.38
8	PON-4			0.56

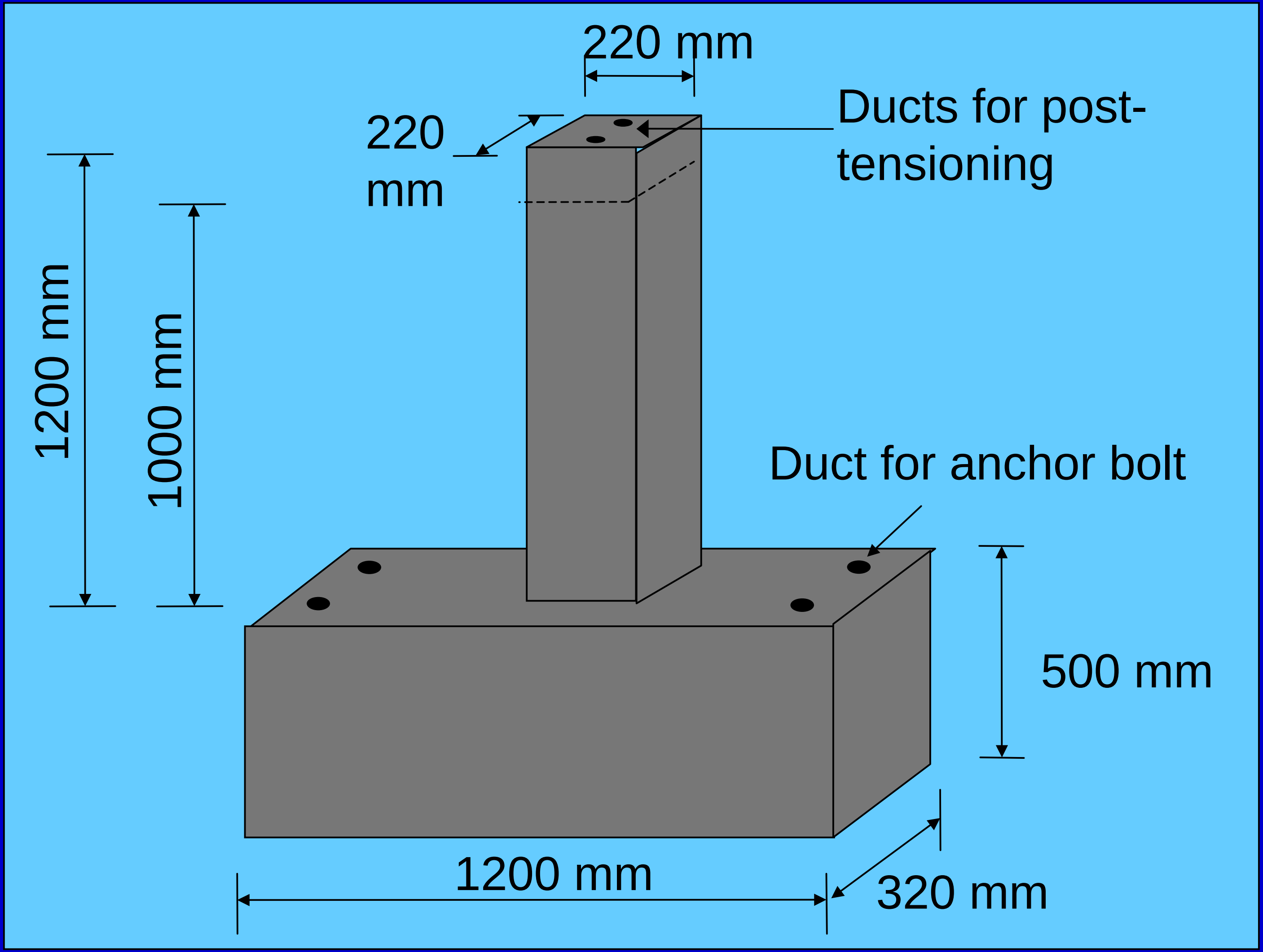
Methodology

Specimen Type (Contd..)

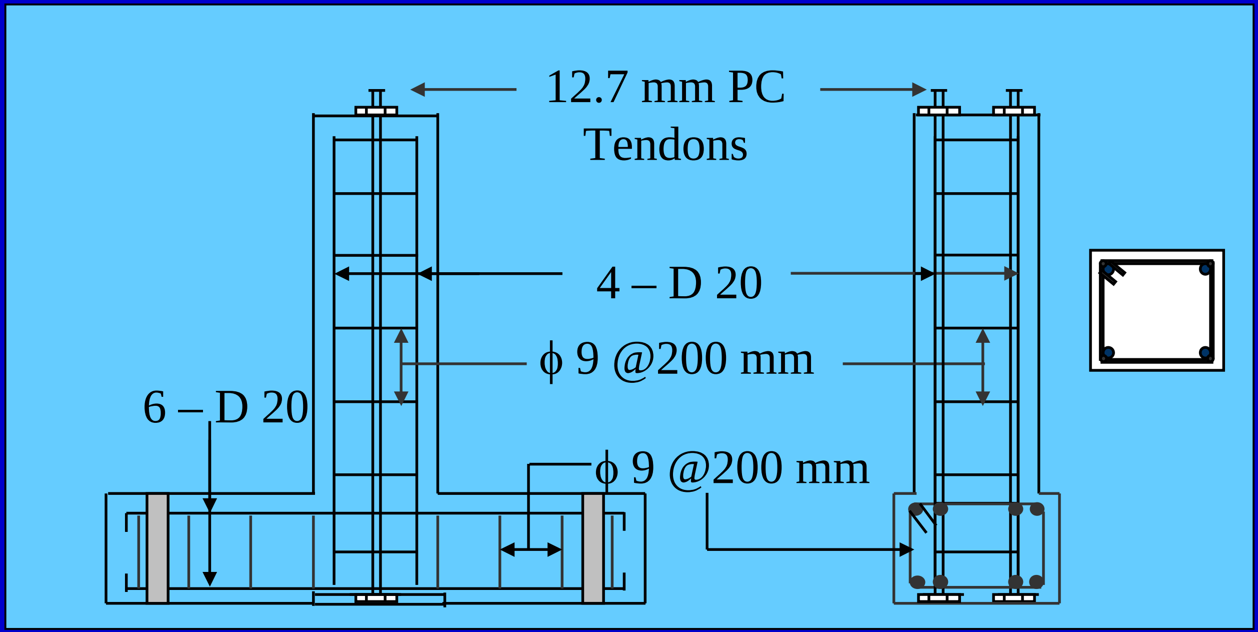
S. No.	Designation	Design Principle	Axial Load	Corrosion Loss gm/cm^2/cm
9	PEA-1	Using seismic resistant part of JSCE code in conjunction with JRA's specification	200 kN	0.00
10	PEA-2			0.19
11	PEA-3			0.38
12	PEA-4			0.56
13	PEN-1		0	0.00
14	PEN-2			0.19
15	PEN-3			0.38
16	PEN-4			0.56

Methodology

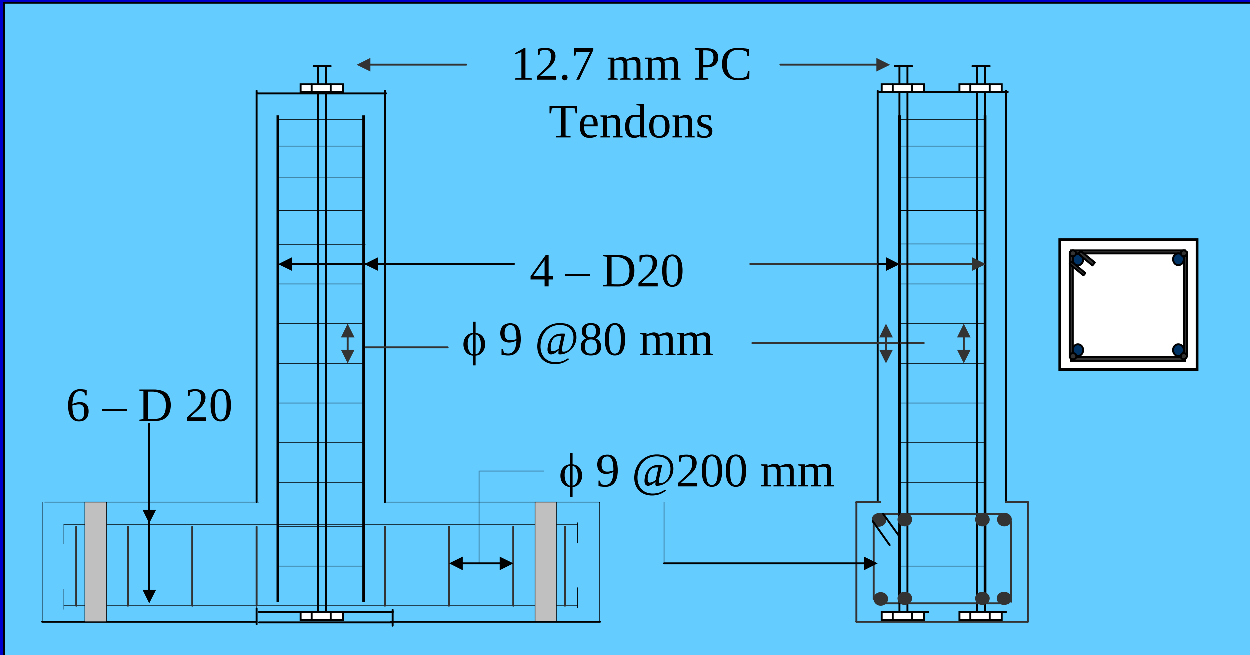
Specimen Size



Reinforcement Arrangement

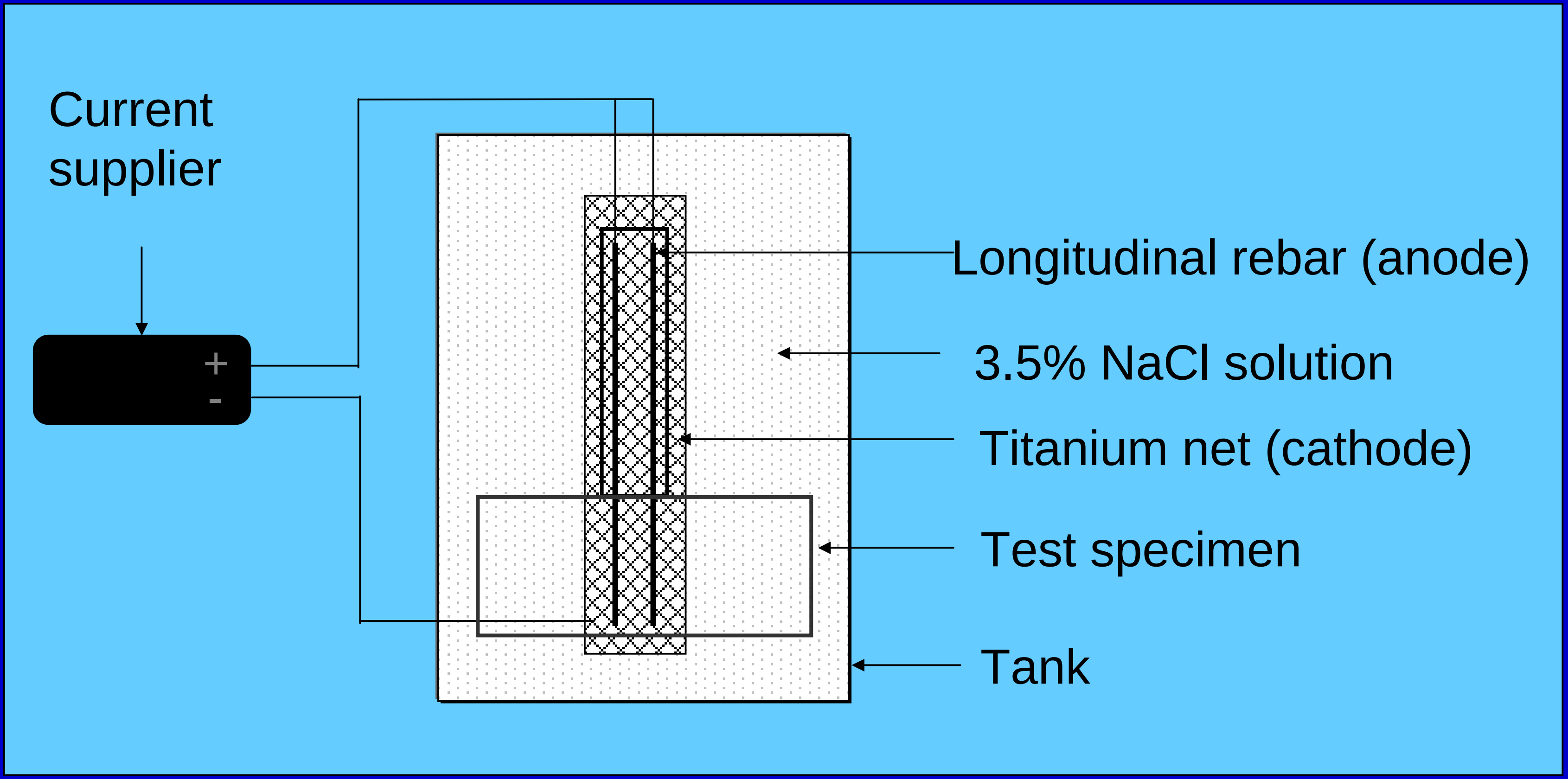


Ordinary Design

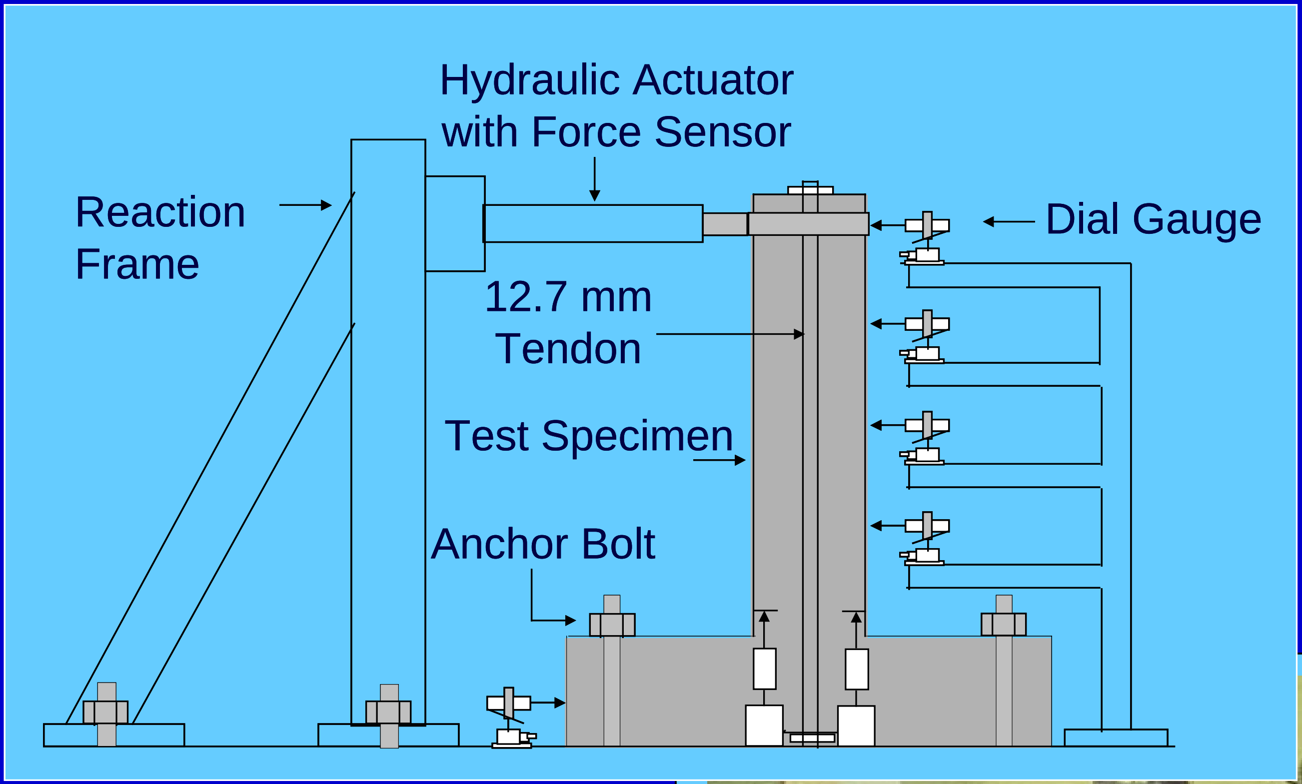


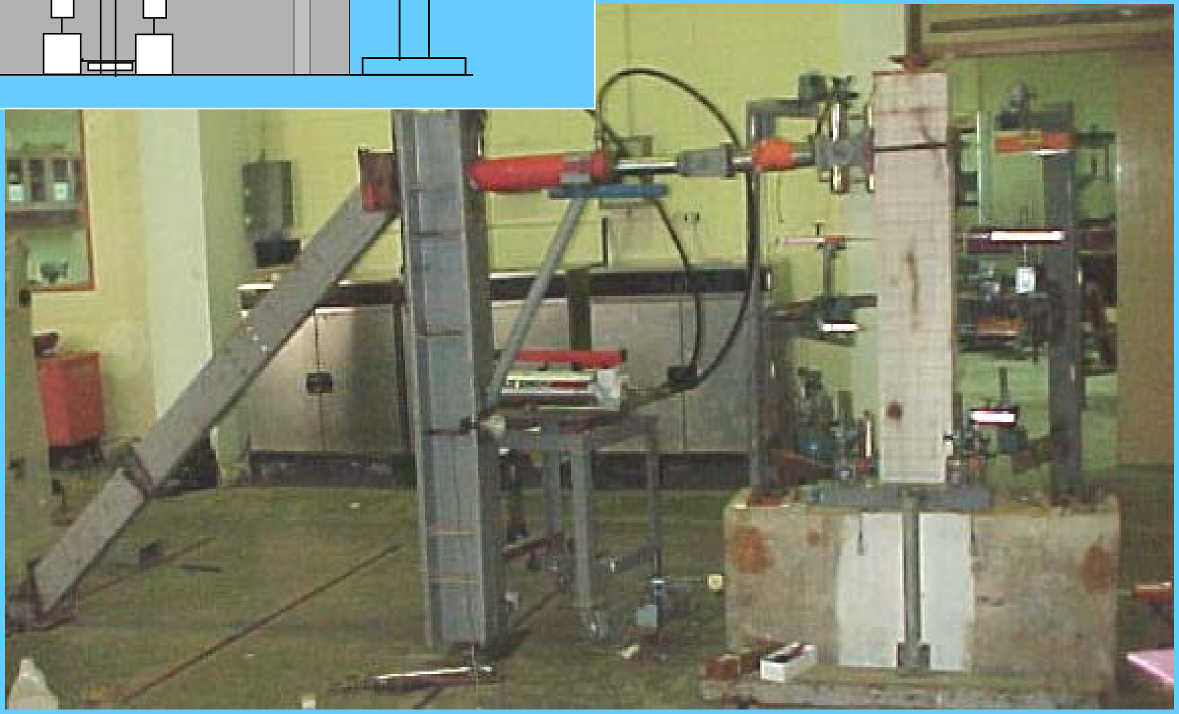
Seismic Design

Accelerated Corrosion Test

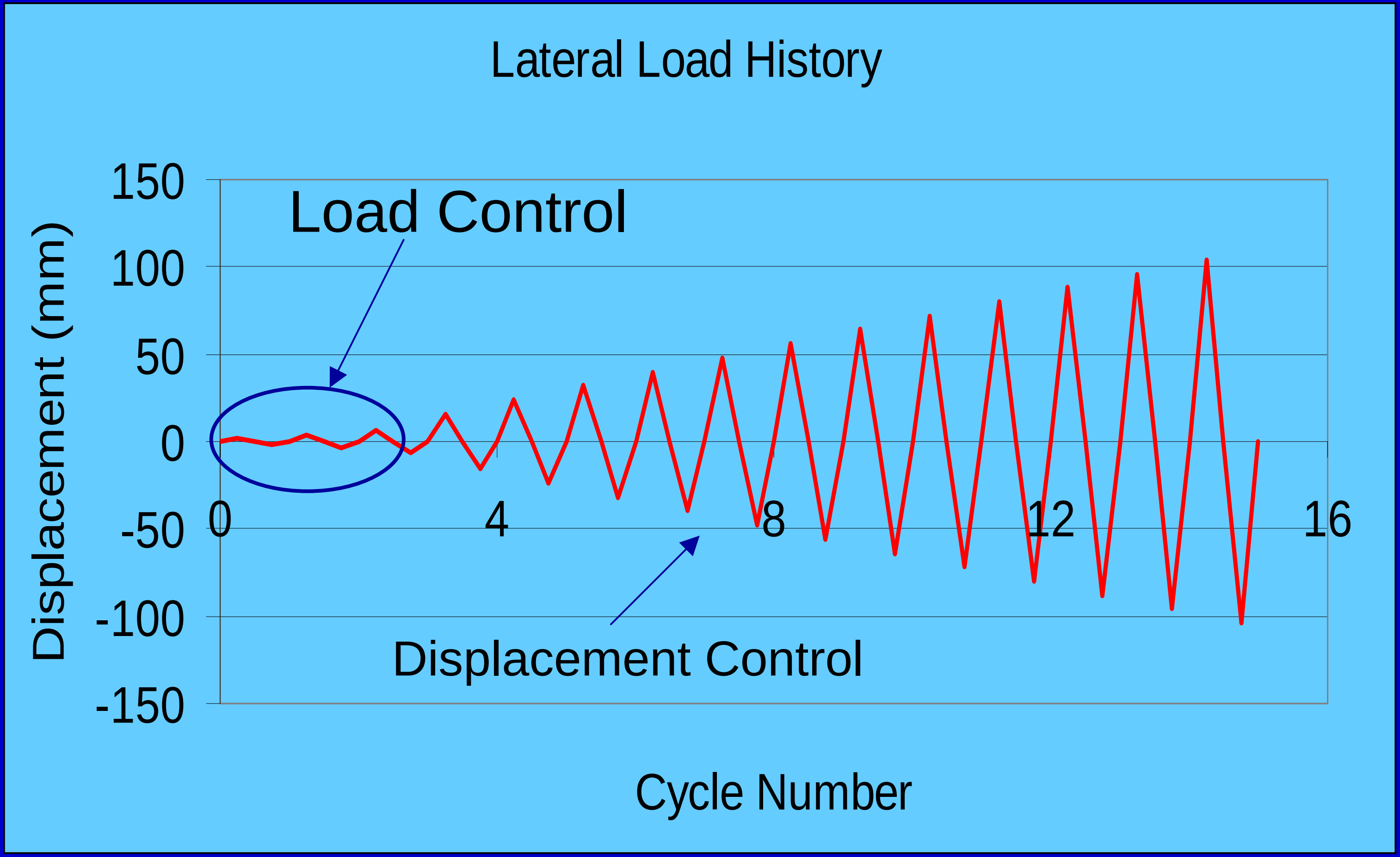


Loading Test Condition





Loading Cycles



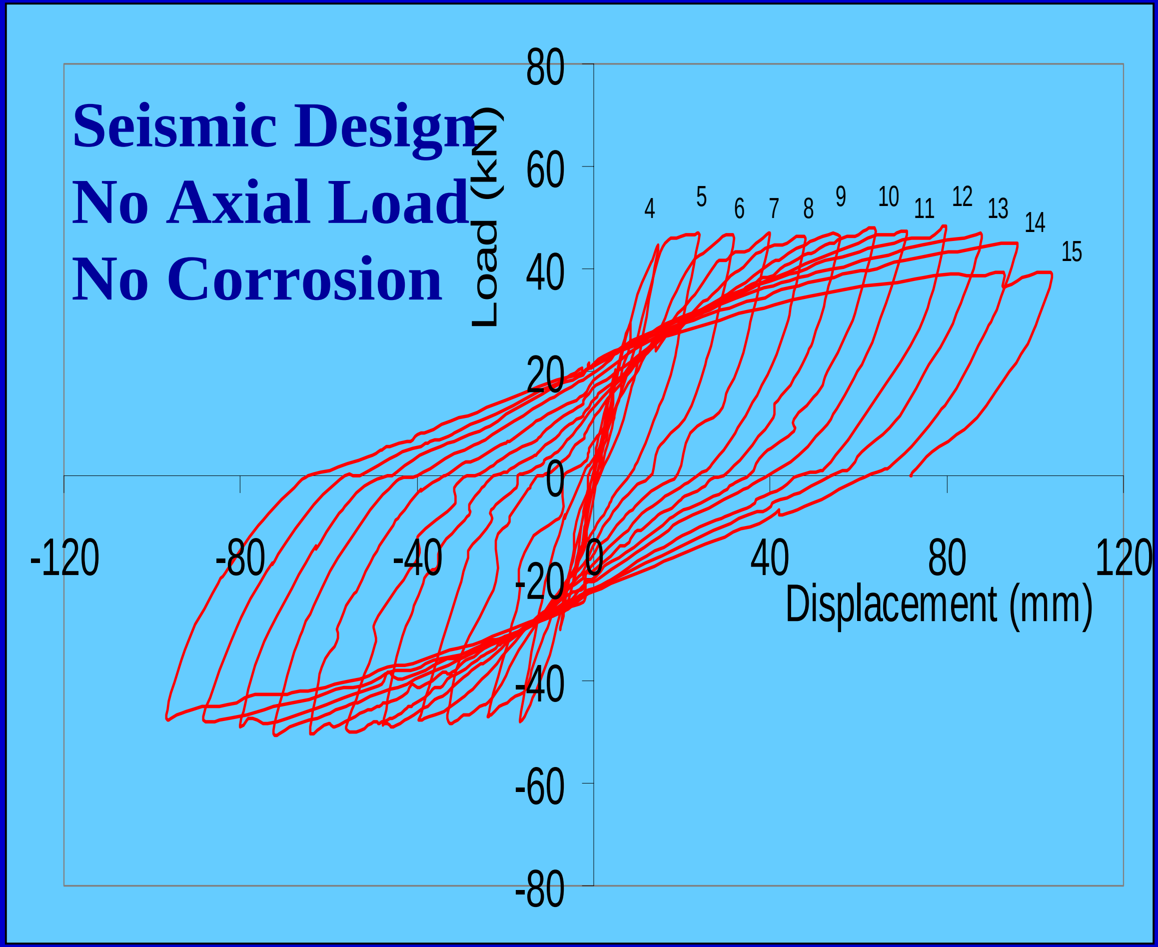
Methodology

Comparison of Various Corrosion Loss

0.0 gm/cm^2 0.04 gm/cm^2 0.13 gm/cm^2 0.45 gm/cm^2

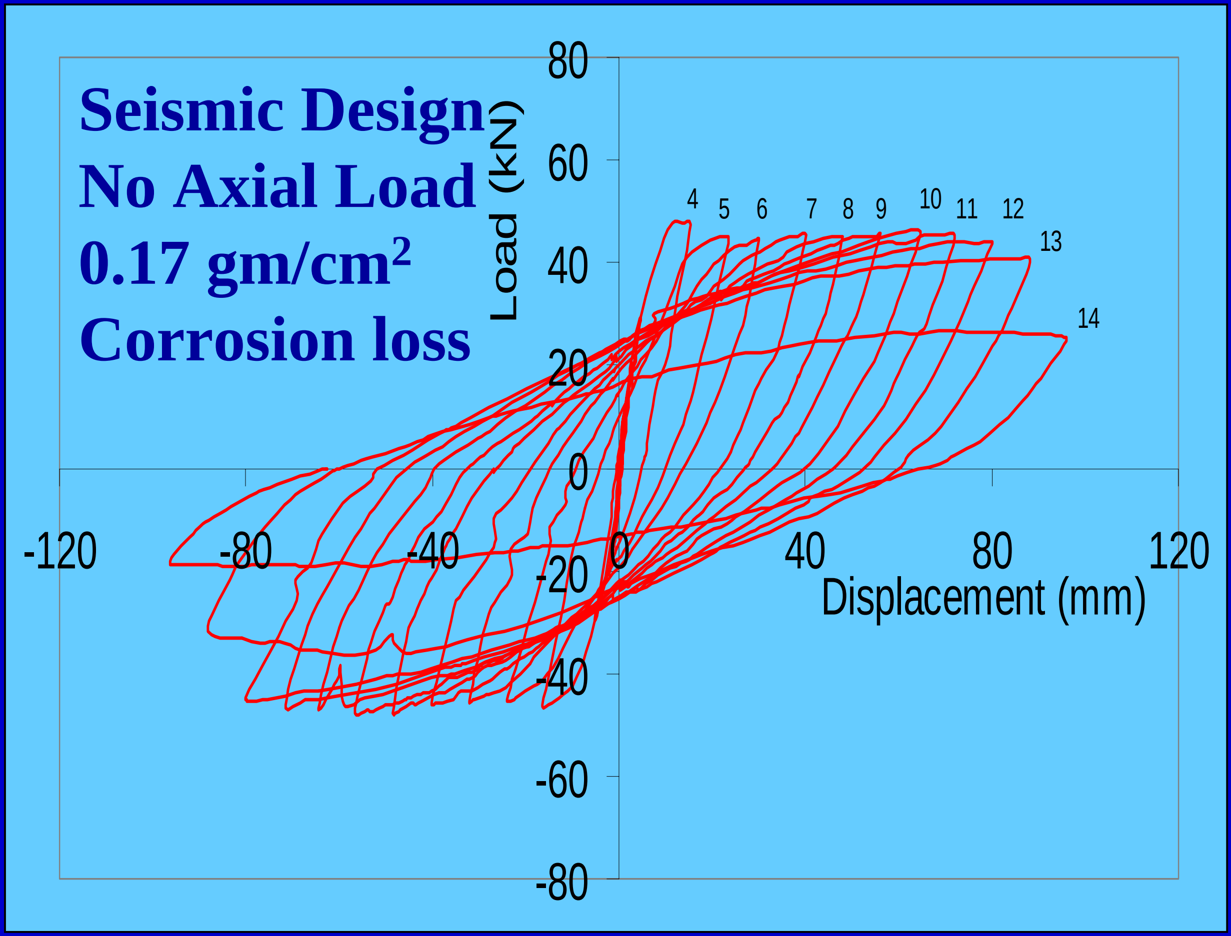
Results and Discussion

Load Displacement Curve



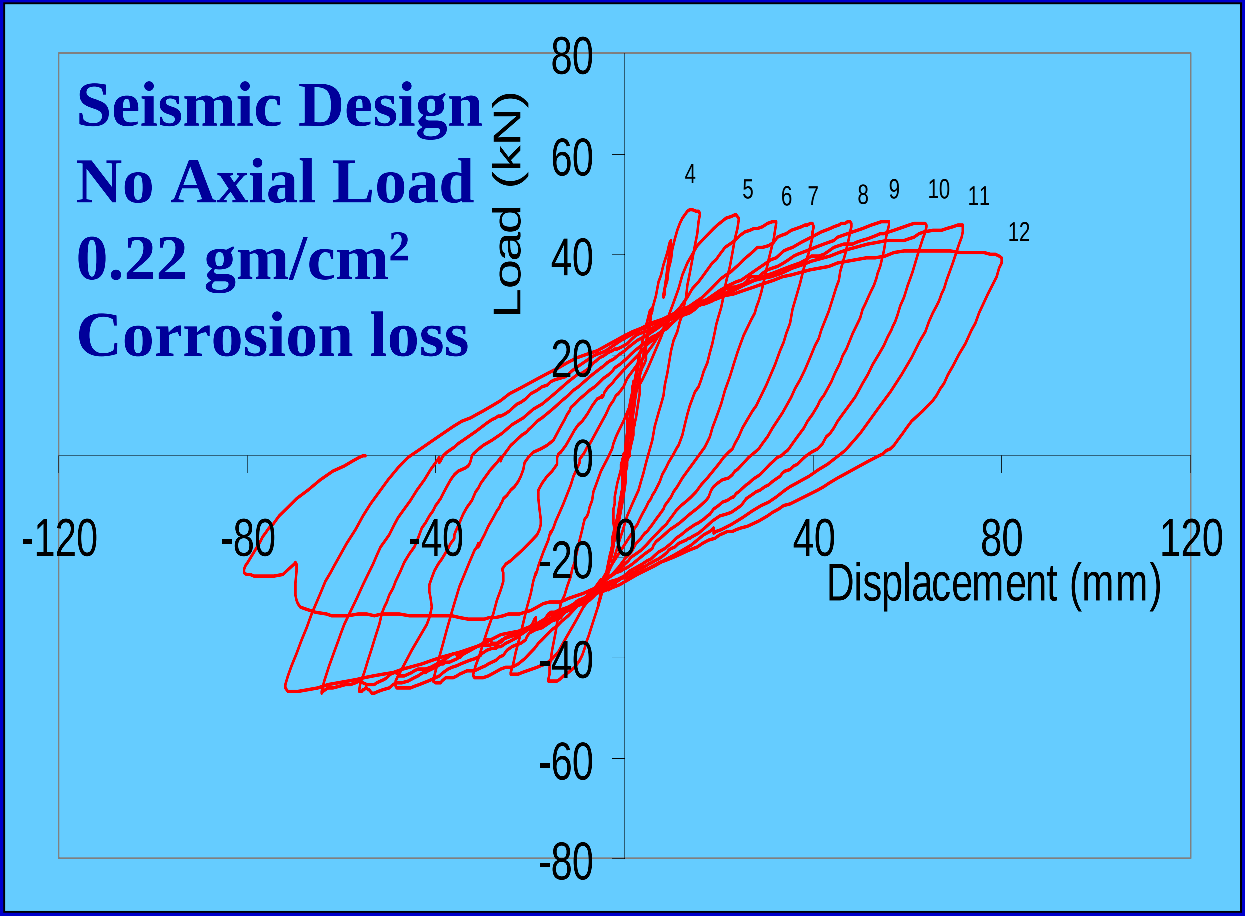
Results and Discussion

Load Displacement Curve



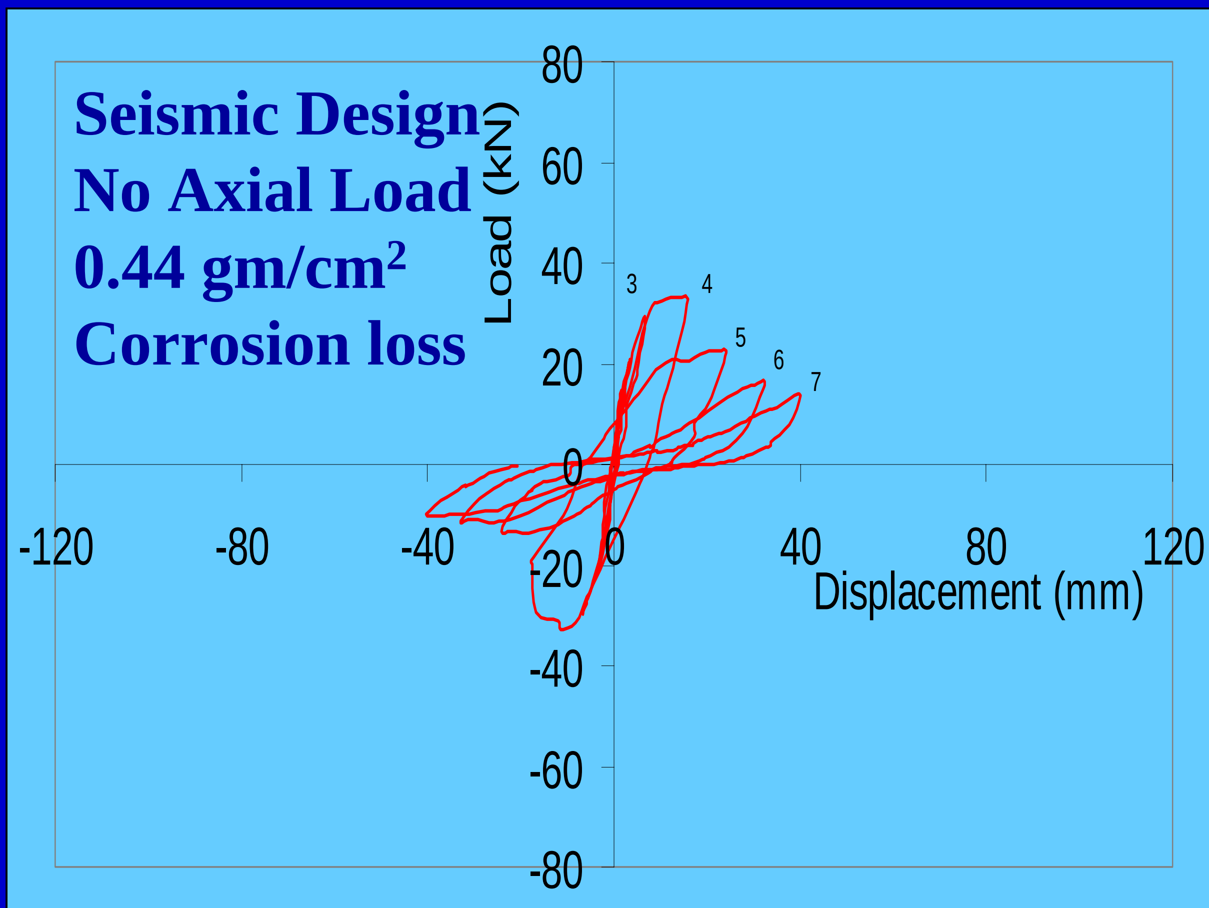
Results and Discussion

Load Displacement Curve



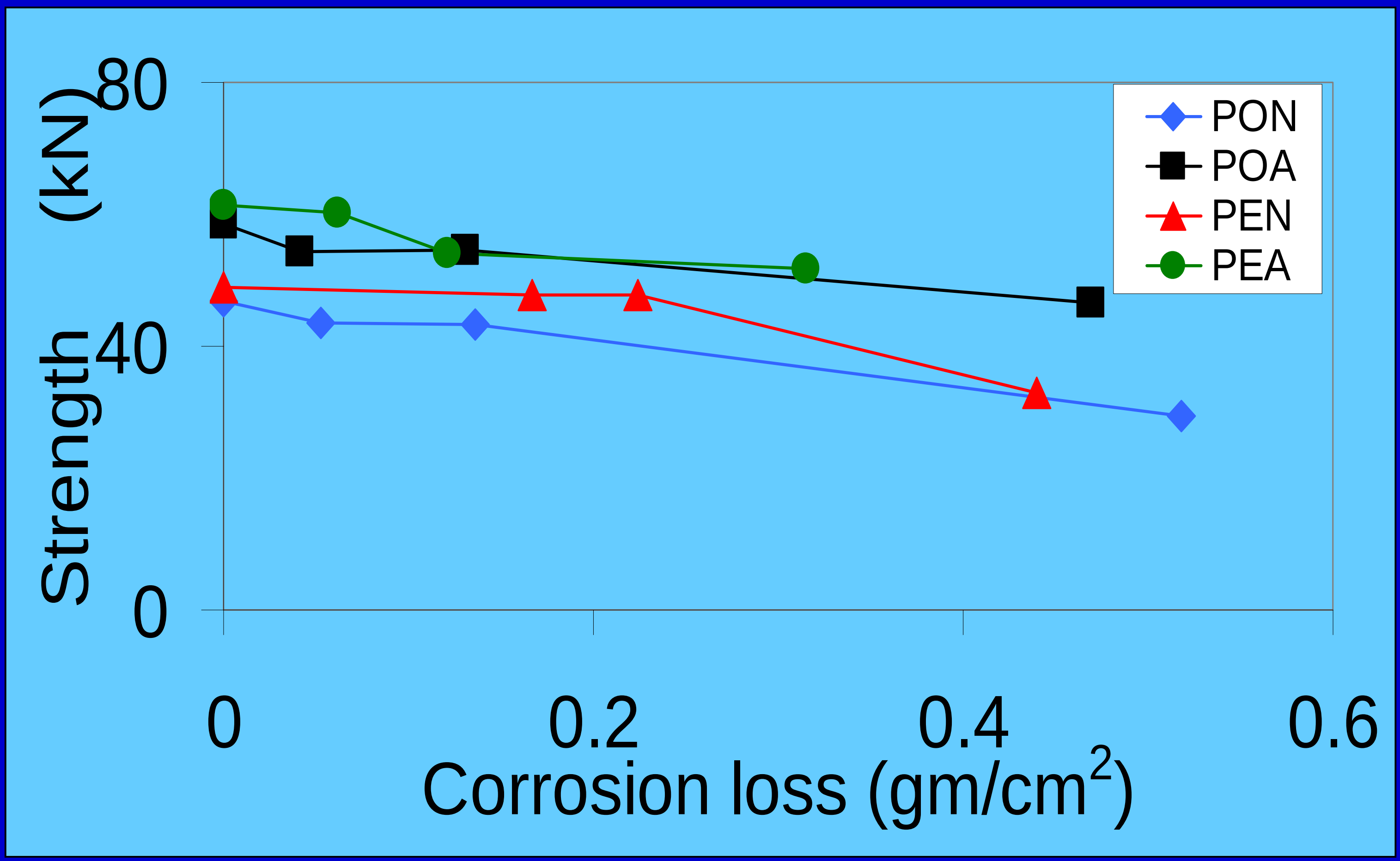
Results and Discussion

Load Displacement Curve



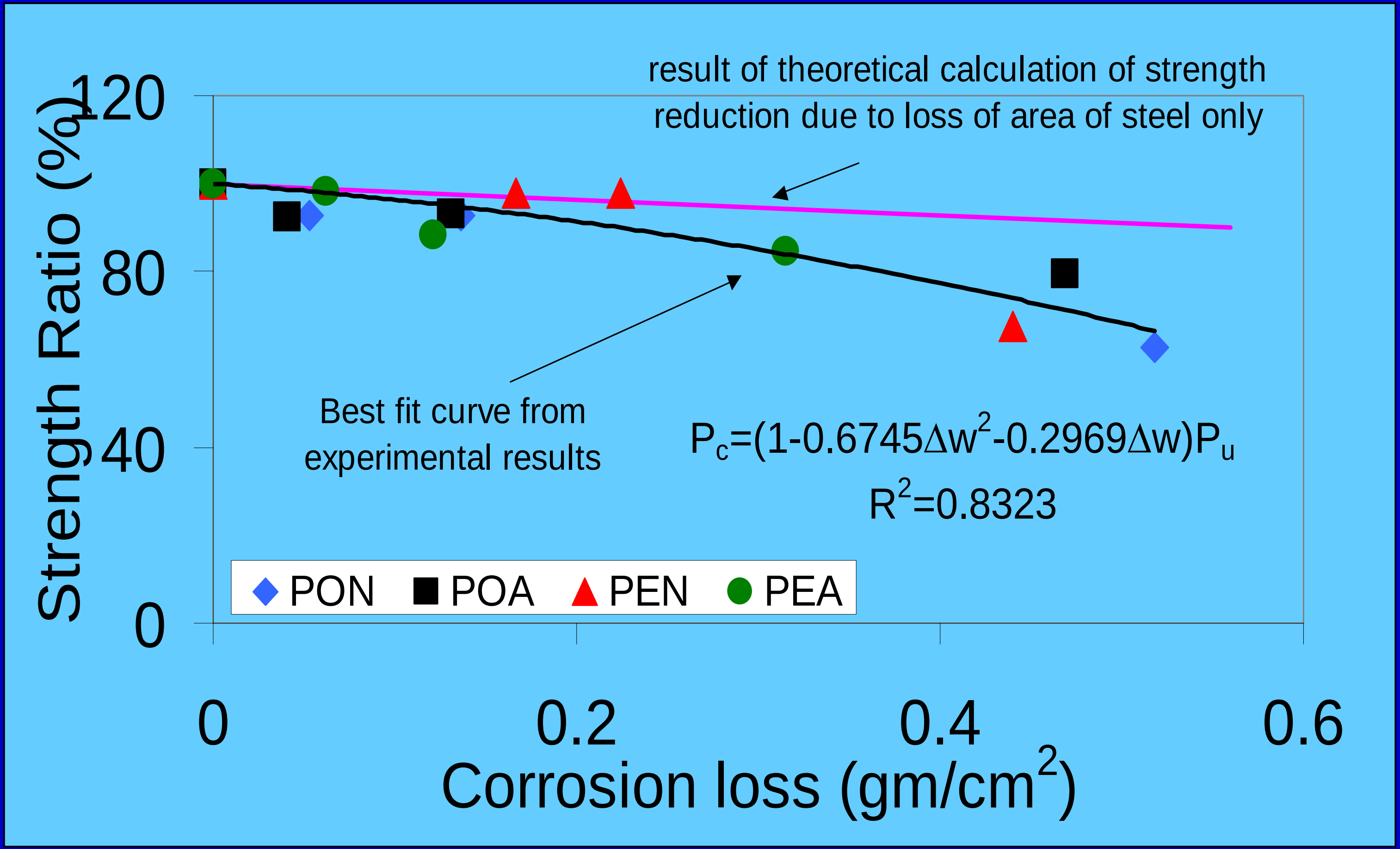
Results and Discussion

Strength Degradation



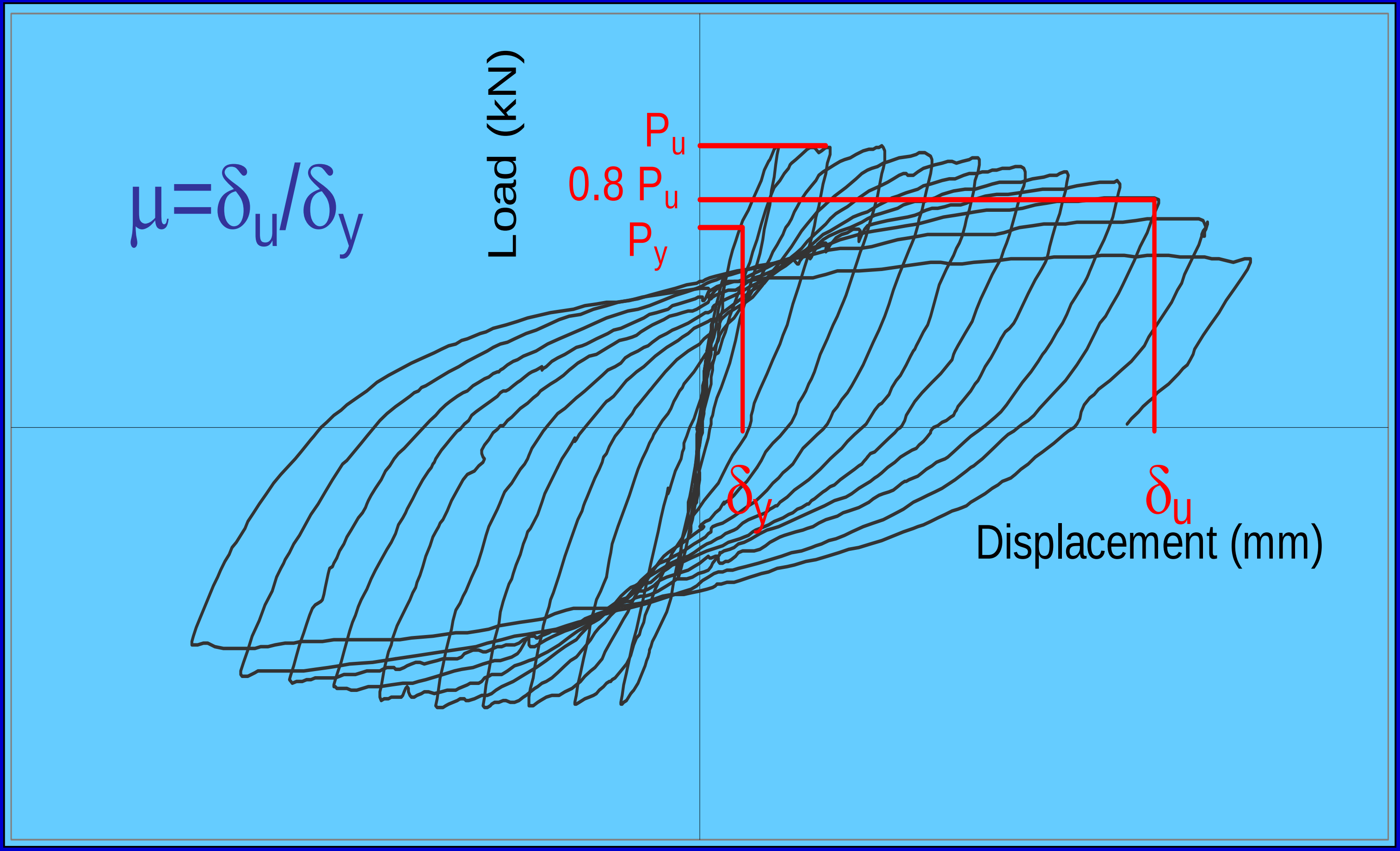
Results and Discussion

Strength Degradation (Contd…)



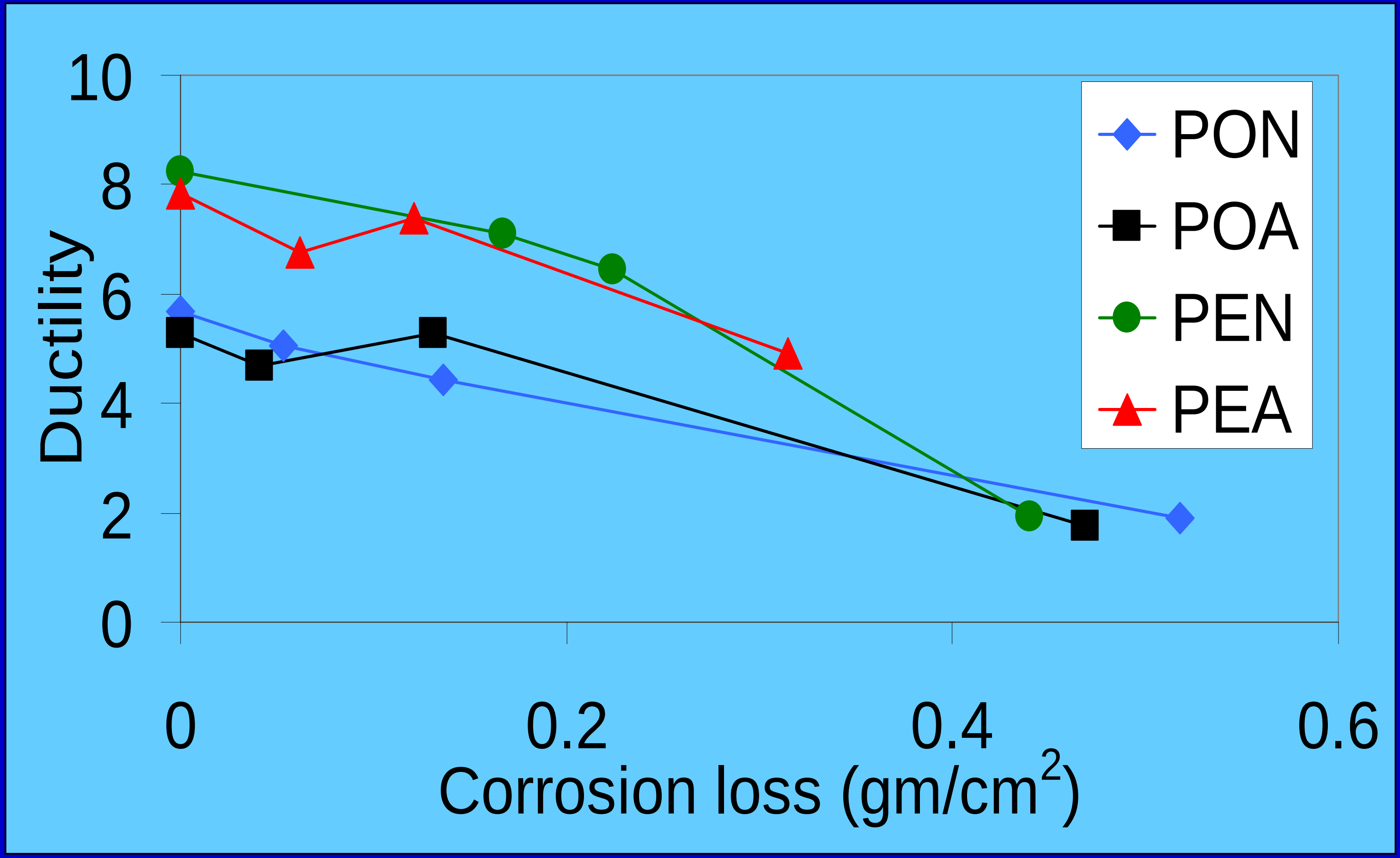
Results and Discussion

Ductility Degradation



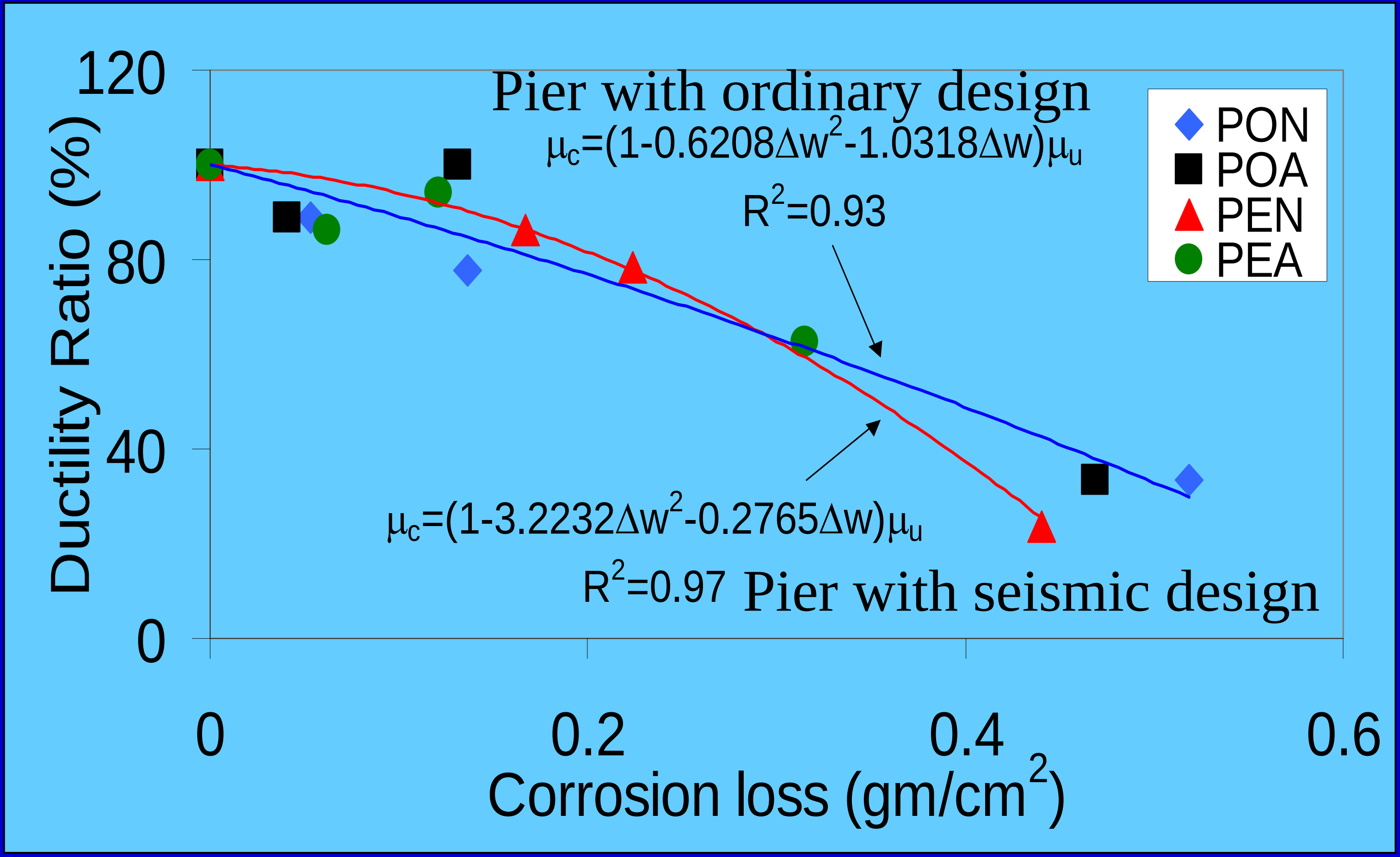
Results and Discussion

Ductility Degradation (Contd…)



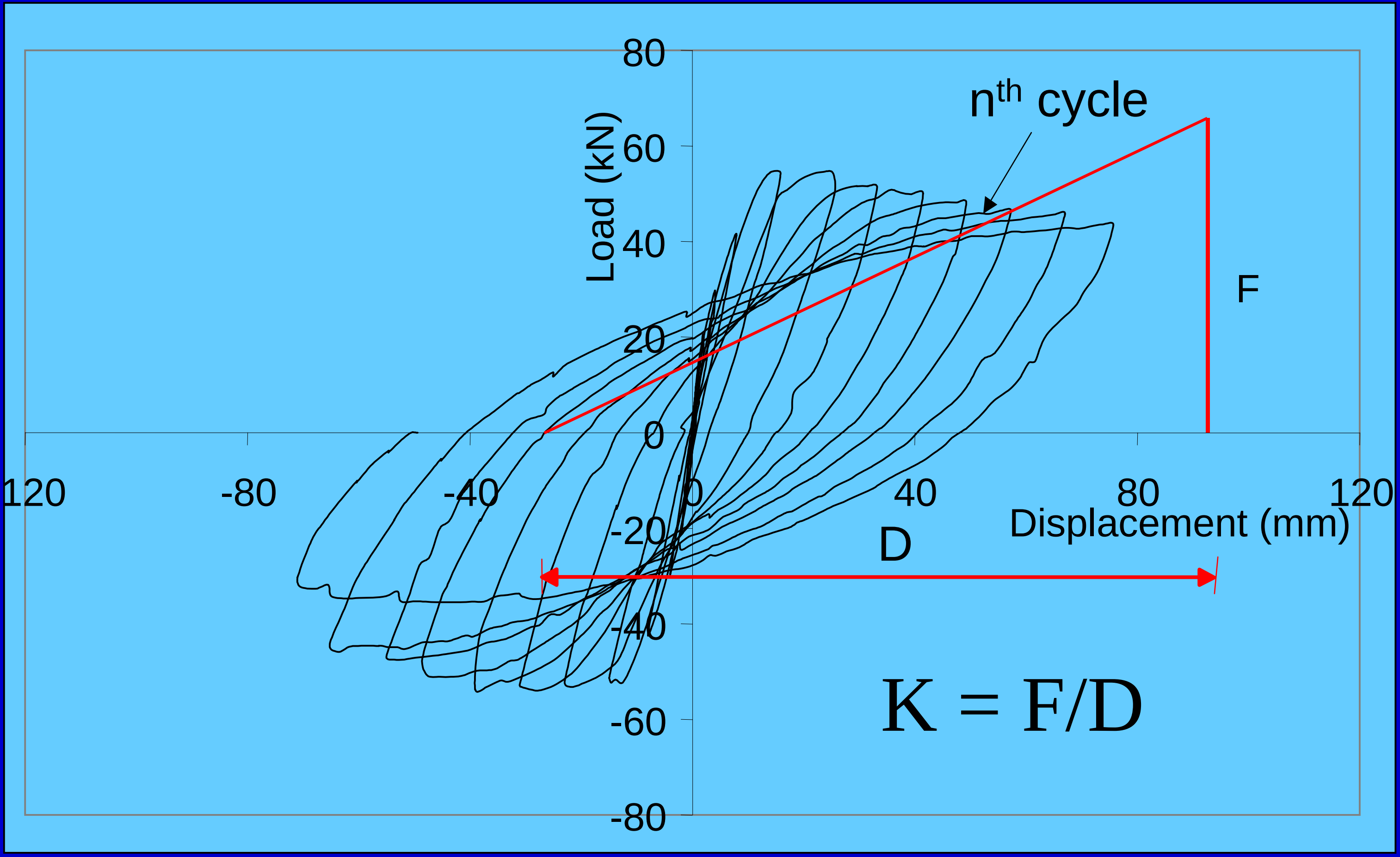
Results and Discussion

Ductility Degradation (Contd…)



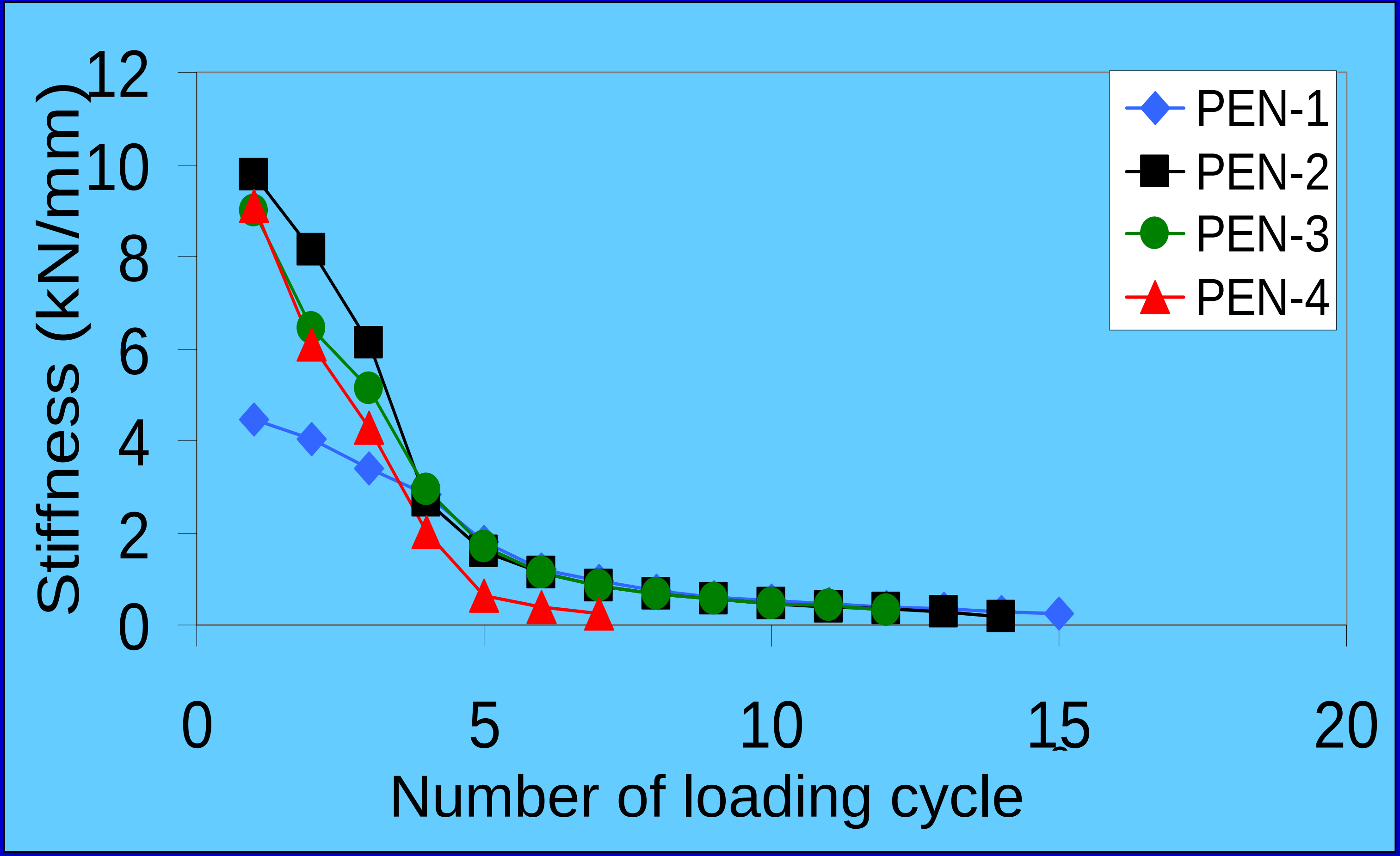
Results and Discussion

Stiffness Degradation



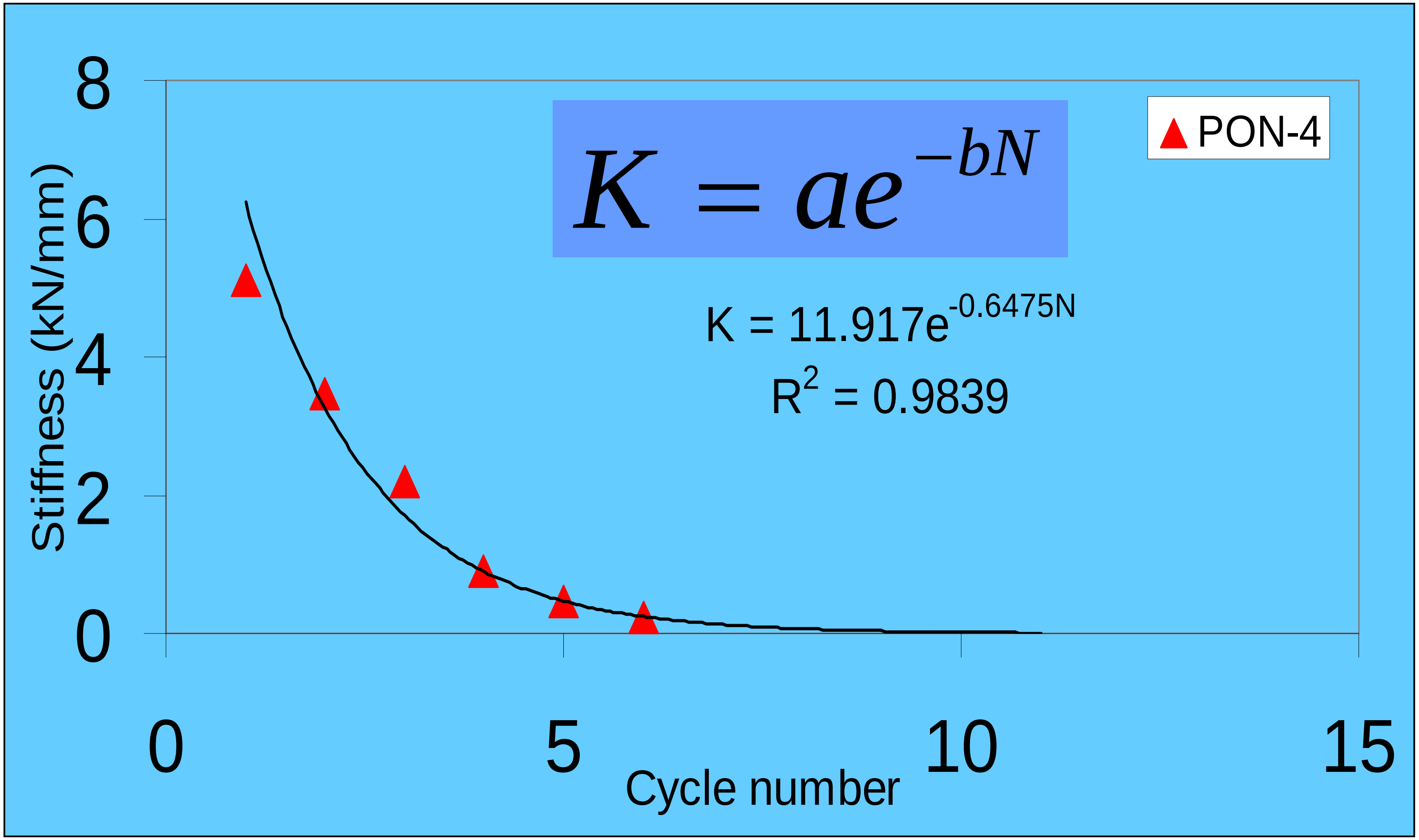
Results and Discussion

Stiffness Degradation (Contd)



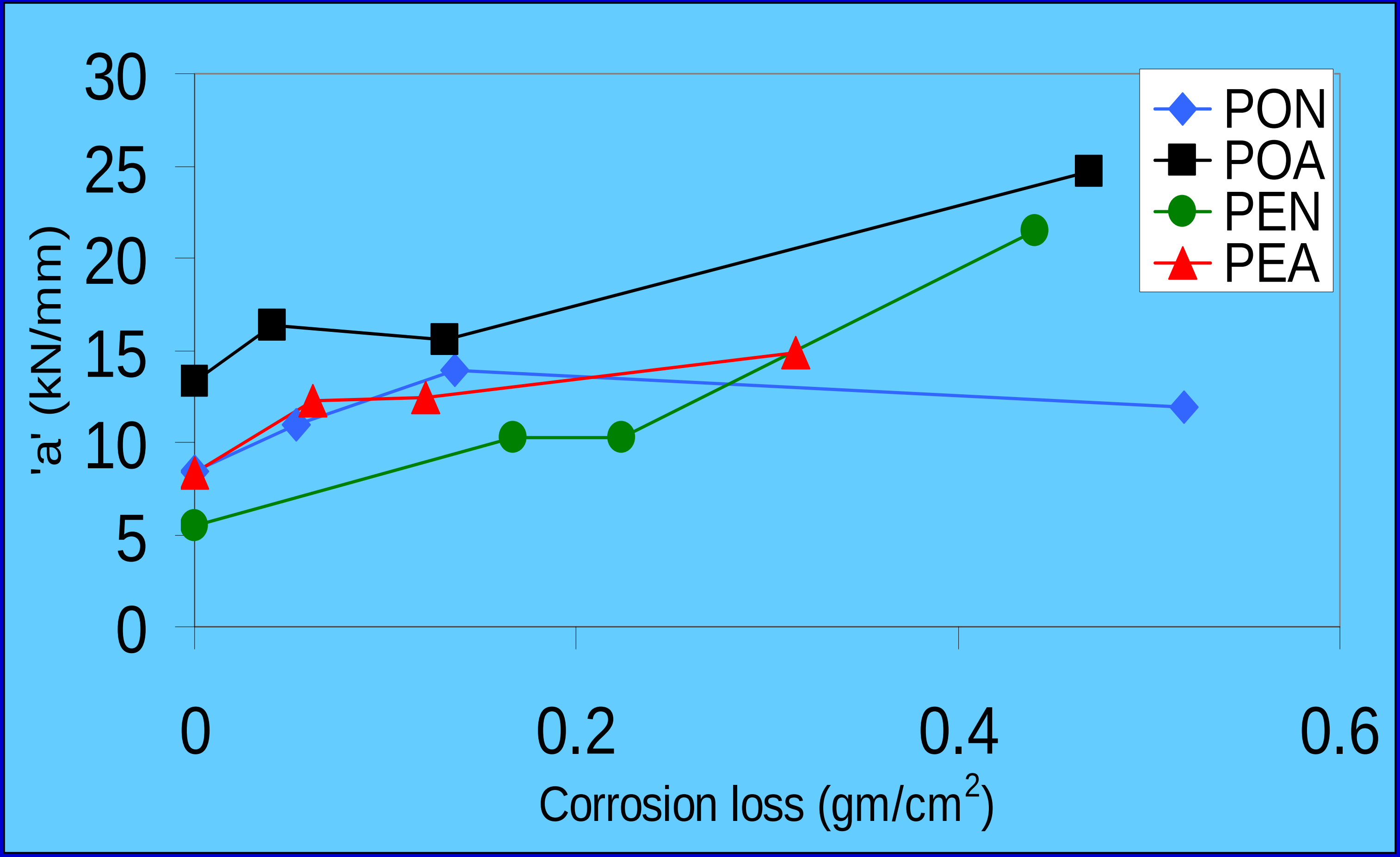
Results and Discussion

Stiffness Degradation (Contd…)



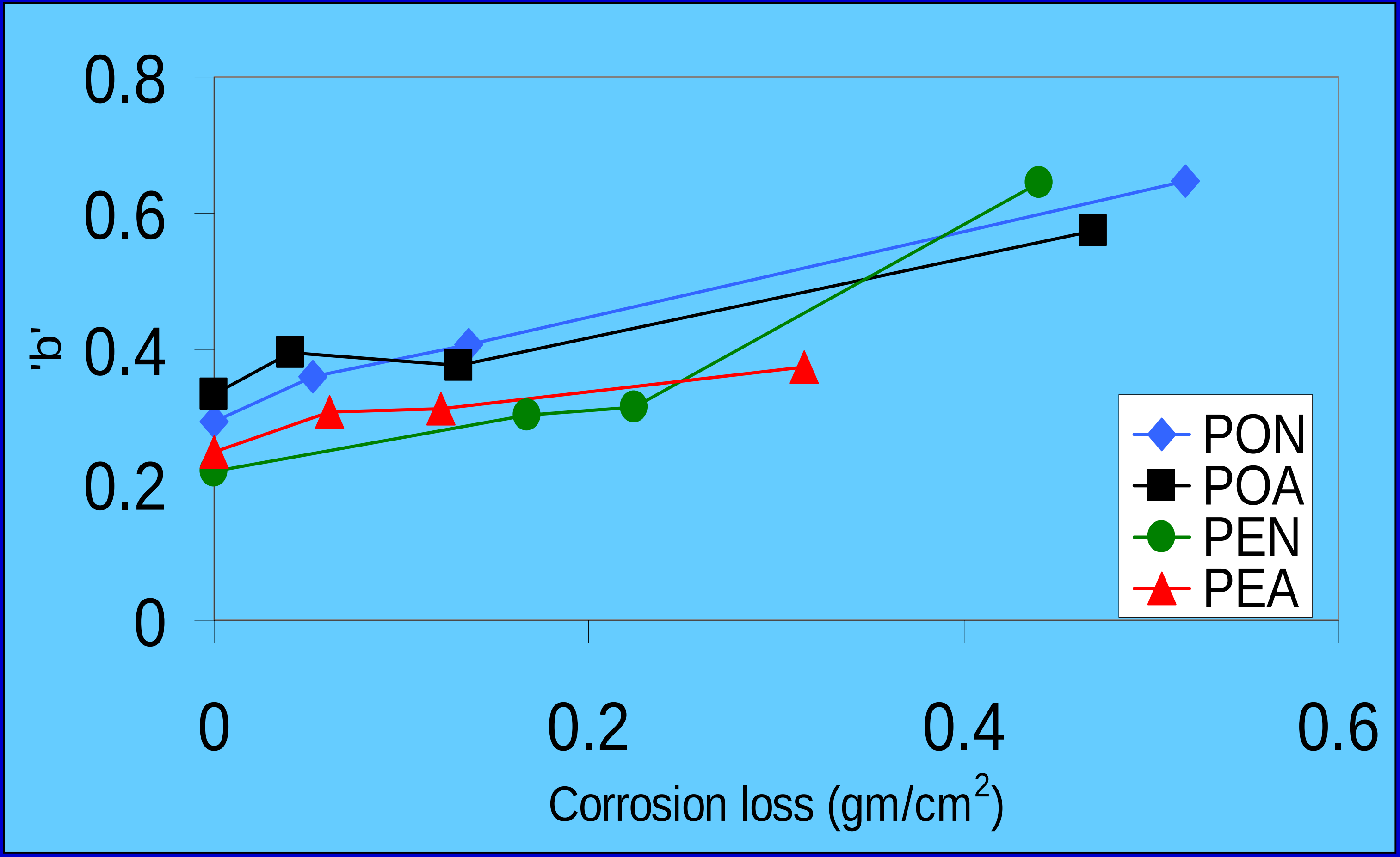
Results and Discussion

Stiffness Degradation (Contd….)



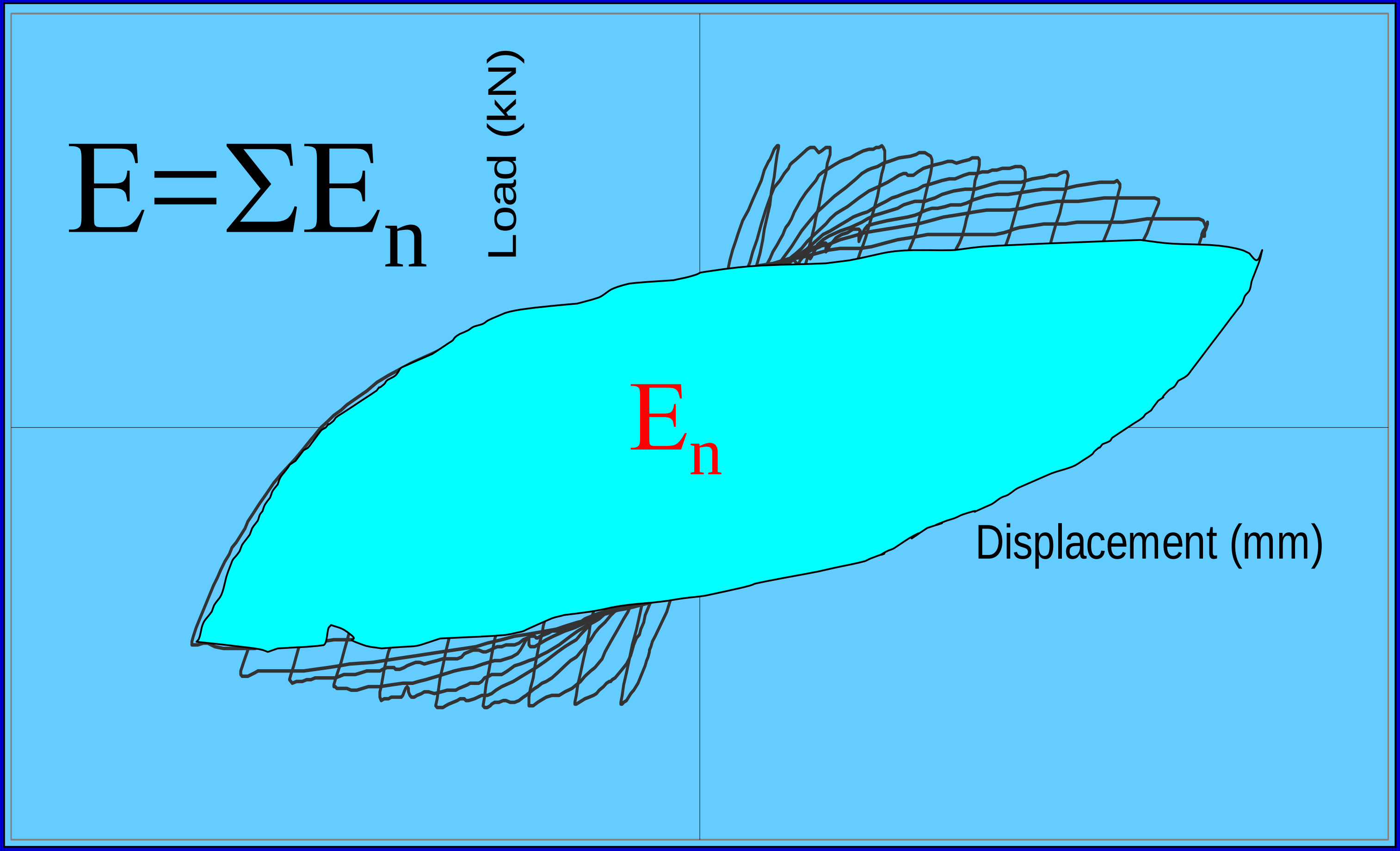
Results and Discussion

Stiffness Degradation (Contd….)



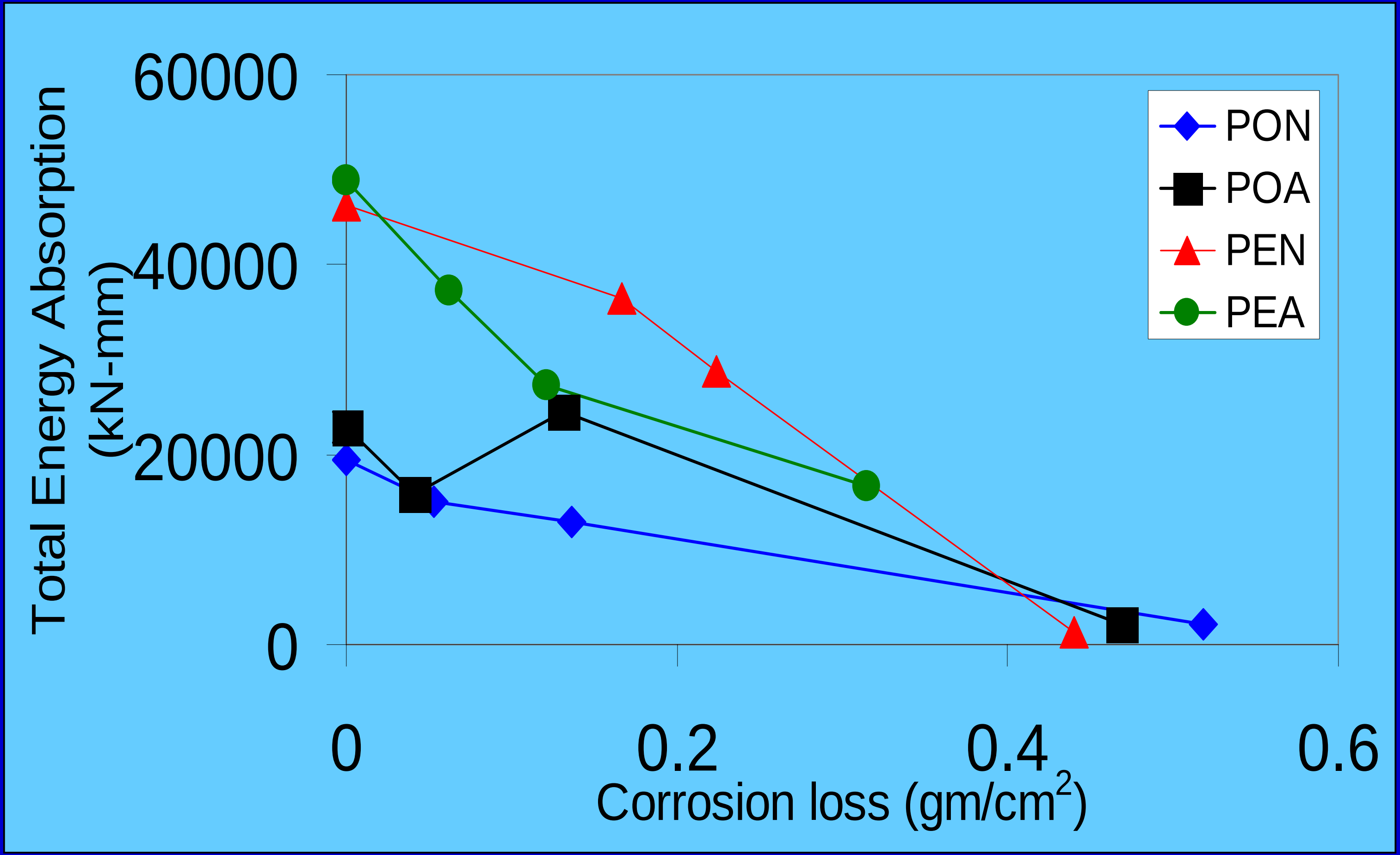
Results and Discussion

Energy Absorption Degradation



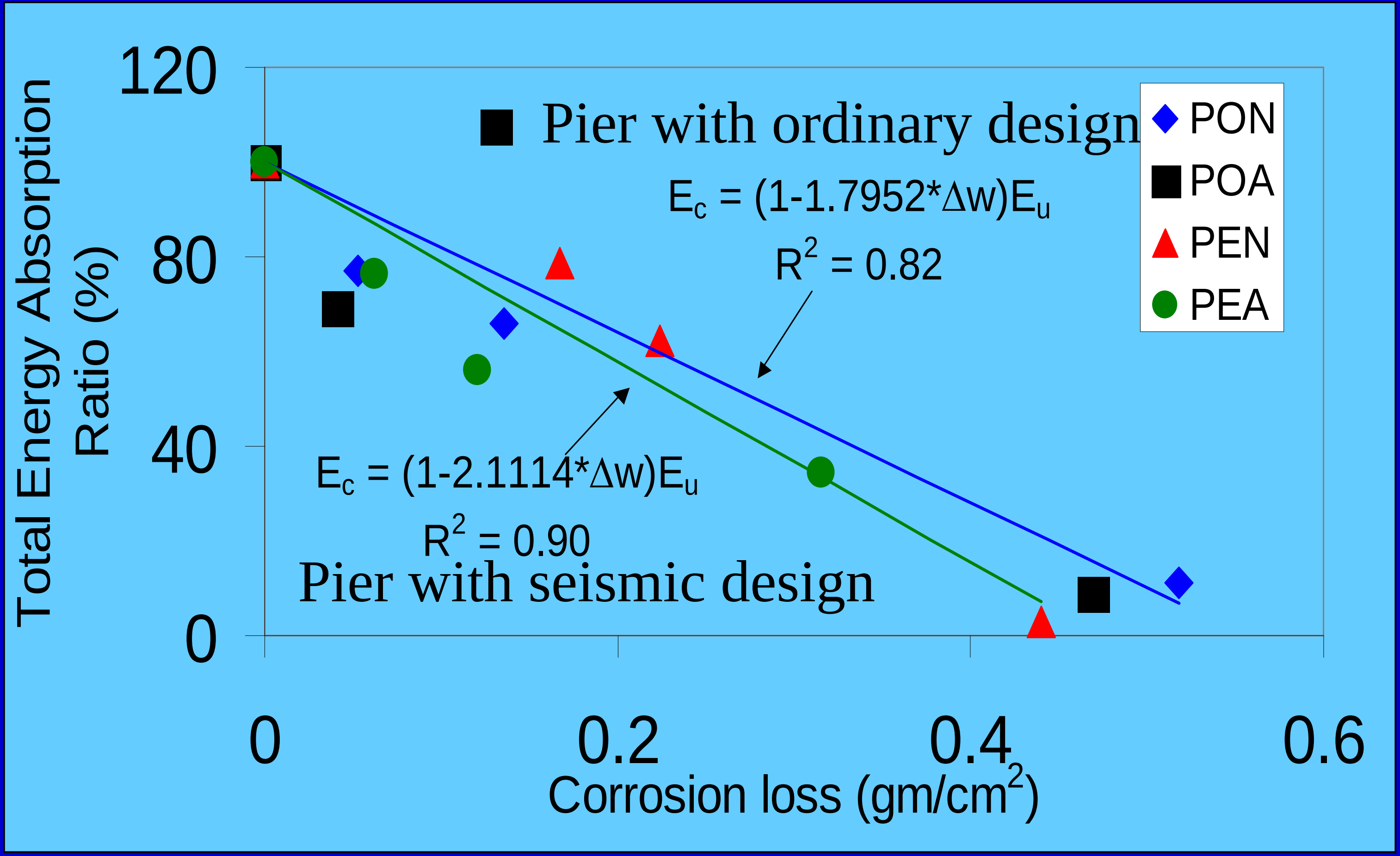
Results and Discussion

Energy Absorption Degradation



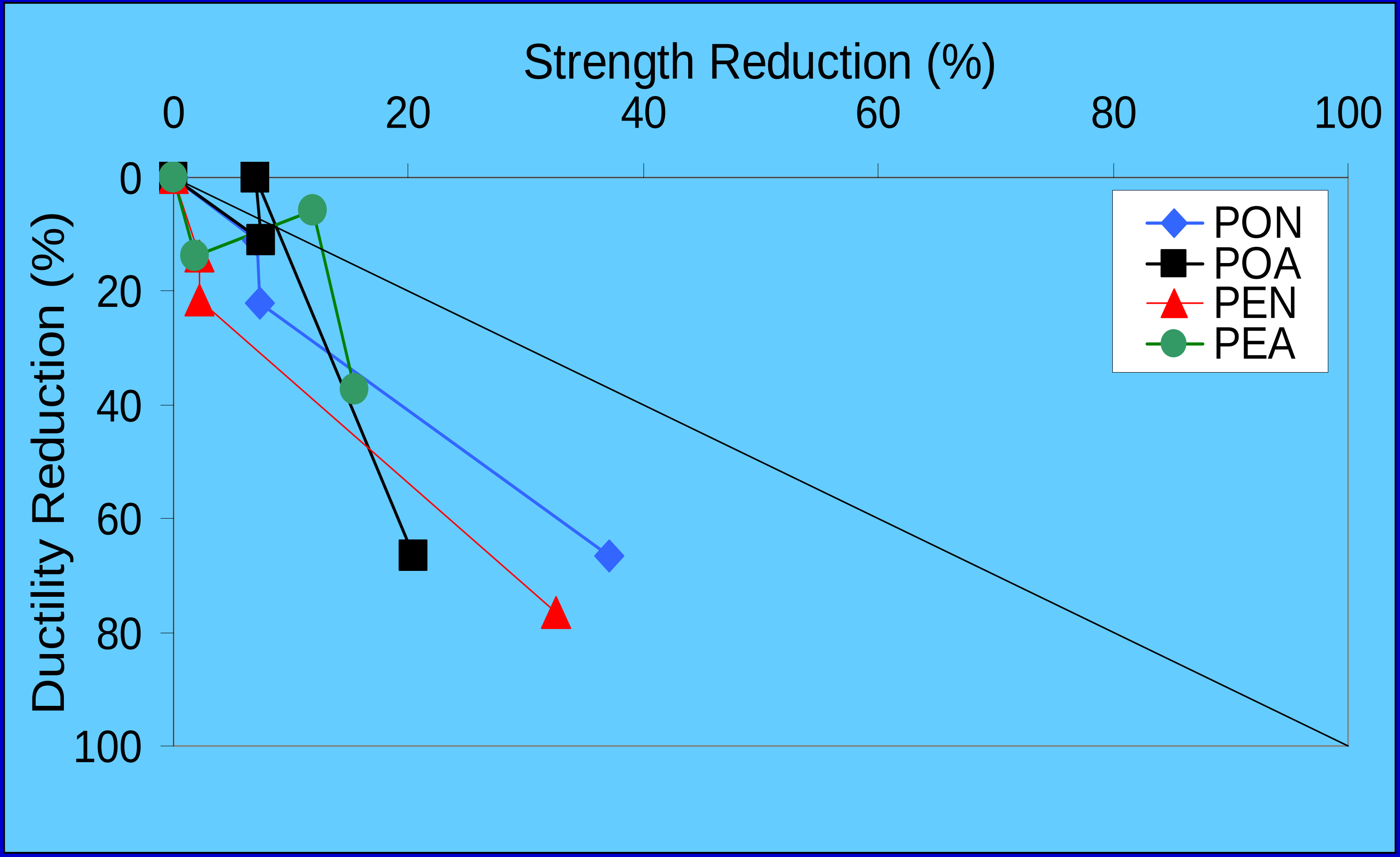
Results and Discussion

Energy Absorption Degradation (Contd…)



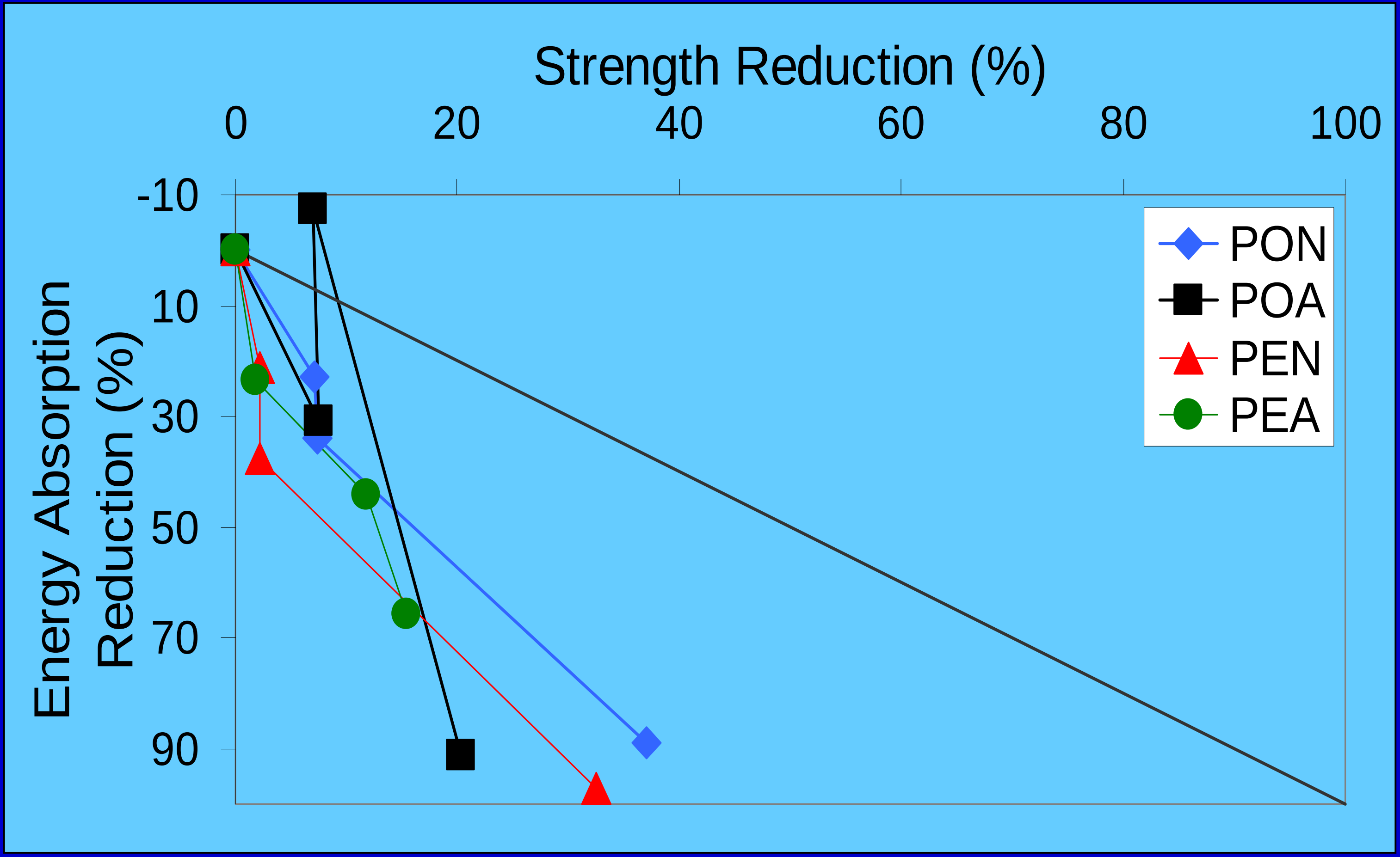
Results and Discussion

Comparison of Strength and Ductility



Results and Discussion

Comparison of Strength and Energy Absorption



Conclusions

- Seismic performances of reinforced concrete structures are seriously affected by corrosion of reinforcement.

- Strength of the pier is slightly reduced with the small increase in corrosion loss and with further increase degradation rate of strength is larger.

Conclusions

- Small corrosion amount in reinforcement increases stiffness significantly. However, within few cycles it degrades quickly

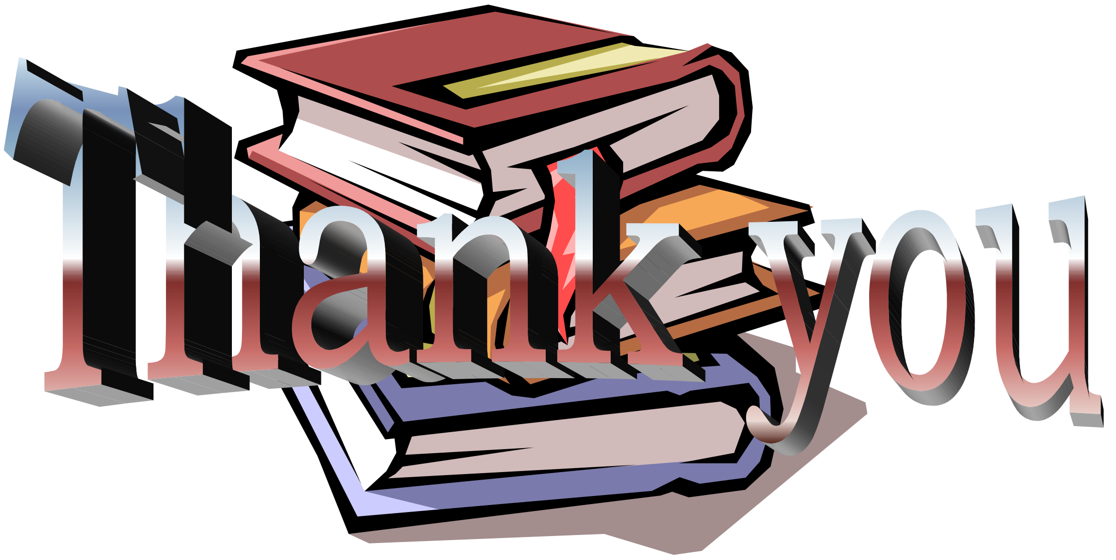
- With the increase in the corrosion loss of reinforcing bars, reduction rate of ductility and energy absorption of the pier is much higher than that of strength

Final Remarks

Final remarks

Problems awaiting solutions in near future

- To complete modeling performance degradation of structure with reinforcement corrosion process
- To evaluate environmental condition more correctly
- To evaluate construction works, including compaction, curing , etc.
- To establish life cycle cost evaluation method
- To systematize maintenance
- To establish total monitoring system including predictions of both chloride penetration and corrosion of reinforcement


Thank you