

**EPFL**



# **Advanced cementitious materials, MSE 420**

## **Lecture 8: Durability of cementitious materials**

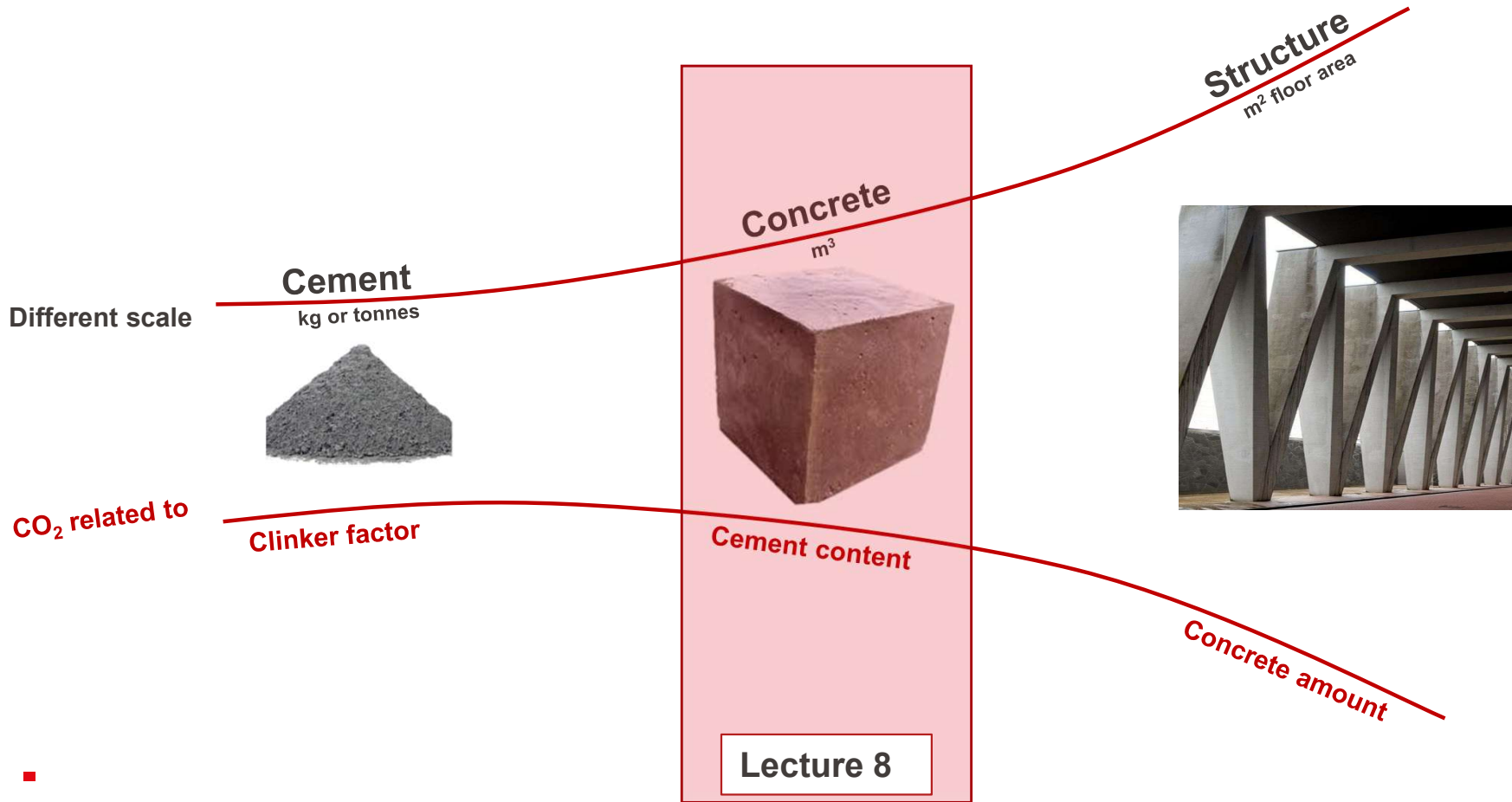
**Dr. Beatrice Malchiodi**  
**5 November 2025**

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# Course Schedule

Wk #	Class date	Title	Teacher
1	10/09/2025	Introduction Guidelines for Literature review	Prof. Karen Scrivener Dr. Alastair Marsh
2	17/09/2025	SCMs and LC3 - Limestone Calcined Clay Cement	Dr. Mehnaz Dhar
3	24/09/2025	Sustainable Concrete design	Dr. Beatrice Malchiodi
4	01/10/2025	Material saving through a better concrete structural design	Prof. David Ruggiero
5	08/10/2025	LCA - Life Cycle Analysis	Dr. Alastair Marsh
6	15/10/2025	<b>Presentation 1</b>	
7	29/10/2025	Analytical characterisation techniques for cementitious materials	Dr. Antonina Goncharov
8	05/11/2025	Durability of cementitious materials	Dr. Beatrice Malchiodi
9	12/11/2025	<b>Presentation 2</b>	
10	19/11/2025	Cement hydration	Prof. Karen Scrivener
11	26/11/2025	GBDI Informal sector	Dr. Nicole di Santo Dr. Ruvimbo Munemo
12	03/12/2025	Low-carbon clinker production and CCUS Study session	Dr. Maciej Zajac- Heidelberg LMC Team
13	10/12/2025	<b>Presentation 3</b>	
14	17/12/2025	Precast concrete 3D printing	Stef Maas Prof. Nicolas Roussel

# Embodied carbon at different scales



# Learning objectives

By the end of this class, you will be able to...

- **Define** durability and **interpret** its significance for concrete and concrete structures.
- **Describe** the main degradation processes affecting concrete and concrete structures, and **identify** the parameters influencing them.
- **Suggest** mitigation and prevention solutions for the major degradation processes affecting concrete and concrete structures.
- **Relate** concrete durability to the sustainability of real concrete structures.

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# **What is durability?**

**5min - Pair and present**



# Key definitions for durability

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# Key definition for Durability of cementitious materials

The **ability** of the construction to maintain,  
**over its designed service life**,  
the **performance** levels for which it was designed,  
given the **environmental characteristics** in which it is located  
and the **expected level of maintenance**.

*D.M.17/01/2018*

(duration + performance + causes + maintenance)

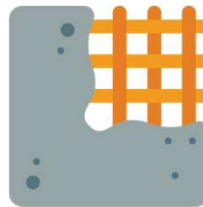
# Durability of cementitious materials

- Long-term property. It defines the service life.
  - Depends on material properties and environmental conditions.
  - Influences the performance of the structure.
  - Affects the sustainability of the structure (low durability - low sustainability).
- 
- Can be controlled by:

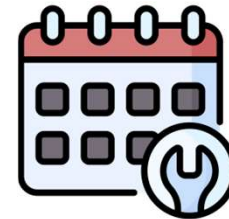


Good design  
(exposure conditions, material  
properties, cover depth etc.)

Lecture 3  
Concrete design



Good manufacturing  
(mixing, compaction,  
curing, etc.)



Good maintenance

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# What are the risks of not accounting for durability?

URL: [ttpoll.eu](http://ttpoll.eu)  
Session ID:  
L5MSE420



bungee jumping  
running  
hiking  
ice fishing  
jogging  
video games  
weight lifting  
swimming  
kayaking  
rock climbing

Response  
Counter

# The risks – Safety, not just performance!



Collapse of one of the most crucial highway viaducts in Italy: Ponte Morandi, Genova (IT)

14 August 2018, 11:36 am

43 victims,  
11 injured,  
566 displaced.



# **Before starting: Durability and general practises**

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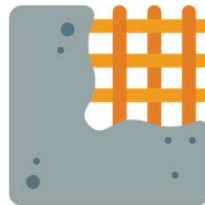
# Durability of cementitious materials

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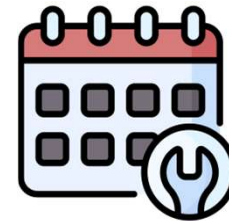
- Can be controlled by:



Good design  
(exposure conditions, material  
properties, cover depth etc.)



Good manufacturing  
(mixing, compaction,  
curing, etc.)



Good maintenance

■

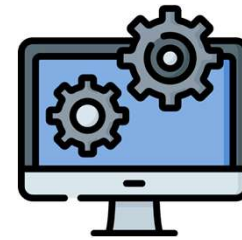
# The role of the mix design

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How do we proportion the components in the concrete mix?

This influences the:  
Sustainability  
Performance (Durability and Strength)

Lecture 3  
Concrete design



Good design  
(exposure conditions, material properties, cover depth etc.)

# The role of porosity



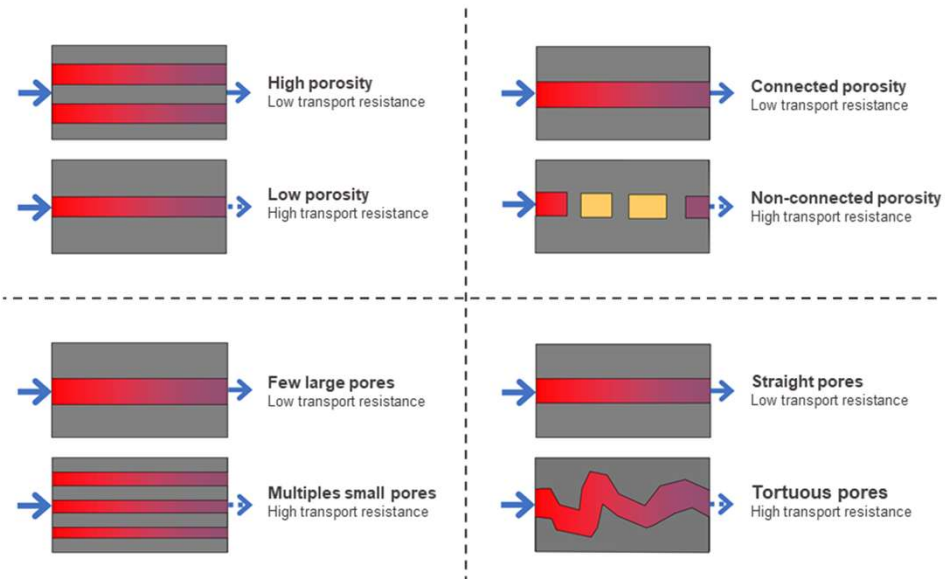
Good design  
(exposure conditions, material  
properties, cover depth etc.)

Recap from MSE-322.

Durability is strictly related to permeability ->  
Transportation mechanisms mainly occur in  
the cement paste.

Some overall recommendations to reduce  
permeability, thus increase durability:

- Reduce the total porosity
- Reduce connected porosity
- Reduce pore size
- Increase tortuosity



# The role of cracks – site practices

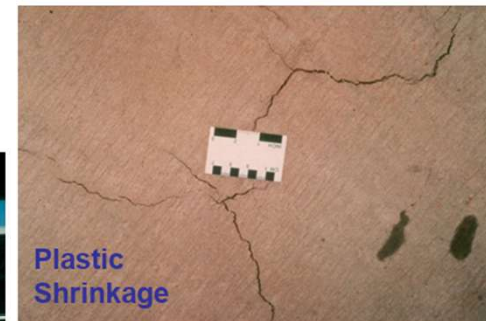
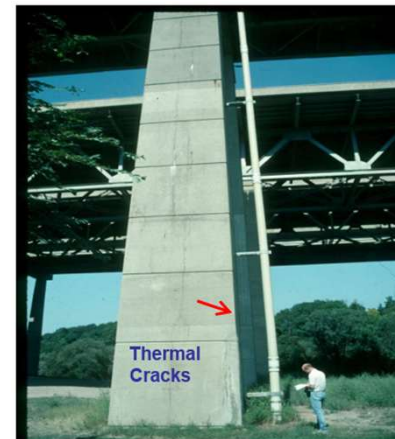
**Prevent cracking and other defects** to prevent aggressive agents from penetrating through the concrete.

Good inspection of site practices  
(**placing, compaction and curing**):

- Protect the fresh concrete from plastic shrinkage
- Keep the moisture to lower early drying shrinkage
- Minimize thermal cracking due to gradients from external sources (ie. protect from cold temperatures or the hot sun)



Good manufacturing  
(mixing, compaction,  
curing, etc.)



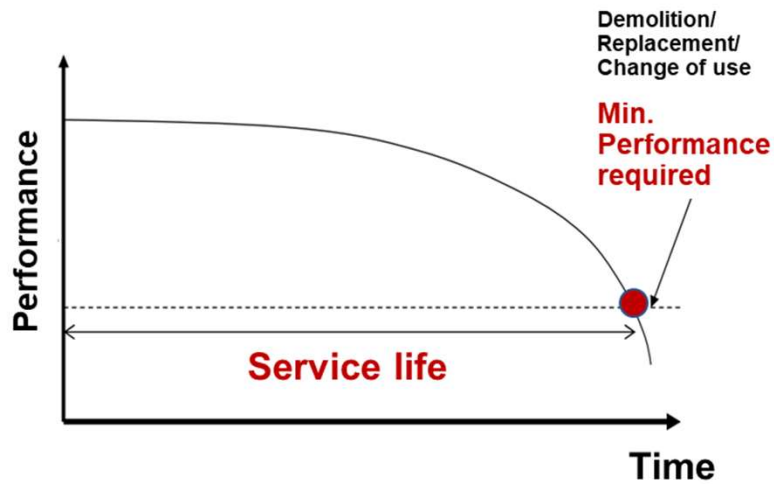
# Durability of cementitious materials

Def : (service life + performance + causes + maintenance)

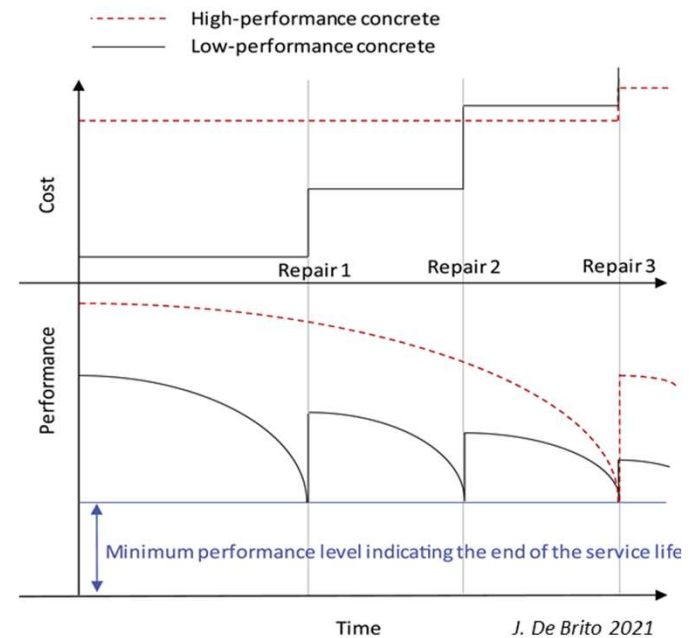


Good maintenance

## With the expected level of maintenance



## With repairs





Good maintenance

# Durability of cementitious materials

**Long-lasting design** = slowing resource flows by extending the technical lifetime of concrete structural elements and whole structures.

i.e. good structural design and good concrete mix design

For the built environment...

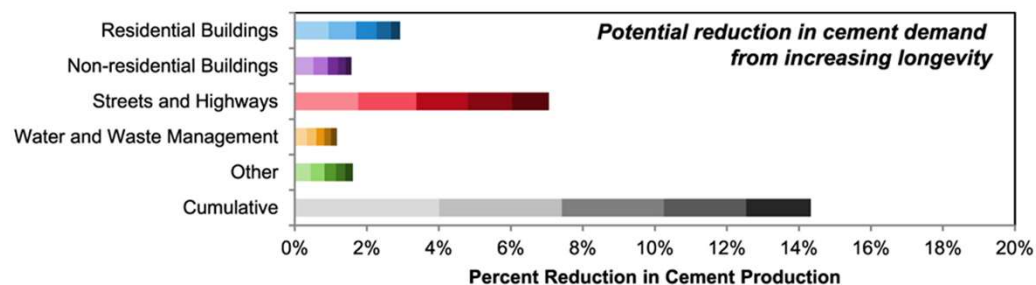
Concrete stocks –

Concrete inflows and outflows ↓

CO<sub>2</sub> ↓

Volumes of raw materials extracted ↓

- 10% inc. longevity
- 20% inc. longevity
- 30% inc. longevity
- 40% inc. longevity
- 50% inc. longevity



Miller (2020)

**Misconception n. 1**  
**Sustainability = Durability**

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# Sustainability and Durability are not synonyms

## Sustainability

The **capacity of a material, system, or process** to meet present functional and performance needs without compromising the ability of future generations to meet their own needs — by **minimizing environmental impact, optimizing resource use, and supporting social and economic well-being** throughout its entire life cycle.

## Durability

The **ability** of the construction to maintain, **over its designed service life**, the **performance** levels for which it was designed, given the **environmental characteristics** in which it is located and the **expected level of maintenance**.



**Warning:**  
**Sustainability = Durabilité**  
**Durability = Durabilité**

**Misconception n. 2**  
**Durability costs CO<sub>2</sub>**  
**(Durable solutions increases CO<sub>2</sub> emissions)**

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# Durability costs CO<sub>2</sub>

**Hypothesis:** the most sustainable concrete mix always leads to most sustainable durable solutions

**Exercise:** seawall application.



Option	Mix Description	Embodied Carbon (kg CO <sub>2</sub> e/m <sup>3</sup> )	Expected Service Life (years)	Notes
A	Standard concrete (low binder content, no special durability measures)	300	10	Low embodied carbon, but weak chloride resistance → early deterioration.
B	Durable concrete (optimized mix with SCMs, low permeability, corrosion inhibitors)	400	50	Slightly higher embodied carbon due to admixtures, but much longer service life.

# Durability costs CO<sub>2</sub>

**Hypothesis:** the most sustainable concrete mix always leads to most sustainable durable solutions

**Exercise:** seawall application

## Option 1 - Most sustainable mix

- 10 m<sup>3</sup> concrete needed
- 300 kg CO<sub>2</sub> eq/m<sup>3</sup>
- 10 years service life
- Rebuilt 5 times over 50 years life span
  
- 3'000 kg CO<sub>2</sub>eq for 10 m<sup>3</sup> concrete
- **15'000 kg CO<sub>2</sub>eq in 50 years**
- **More CO<sub>2</sub> in 50 years**

## Option 2 – Least sustainable mix

- 10 m<sup>3</sup> concrete needed
- 400 kg CO<sub>2</sub> eq/m<sup>3</sup> (+33%)
- 10 years service life
- Rebuilt 5 times over 50 years life span
  
- 4'000 kg CO<sub>2</sub>eq for 10 m<sup>3</sup> concrete
- **4'000 kg CO<sub>2</sub>eq in 50 years**
- **-73% Less CO<sub>2</sub> in 50 years**

## **Misconception n. 3**

# **Durability is an intrinsic property**

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# Beware of intrinsic durability

**Hypothesis:** Concrete and Concrete structures are intrinsically durable  
(long-service life and low CO2 emissions)

**BUT Facts (Picture) :** same concrete and concrete structure have different durability



- No cracking, no spalling
- Good concrete cover (no exposed rebar)
- Uniform texture and finish (good mix, placement and curing)
- Durable with respect to the environment



- Cracking, spalling
- Small concrete cover (exposed rebar)
- Poor surface finish (poor mix, bad placement and bad curing)
- Not durable in this environment

# Beware of intrinsic durability

Durability  $\neq$  Intrinsic property  
Durability  $\propto$  Environment

- There are no durable and non-durable materials/structures.
- We can define a material/structure as durable just referring to the environment to which it is exposed.
- Durability can and must be designed depending on the environment – Exposure class (water to cement ratio, porosity, cover depth – Ref to Lecture 6 Concrete design)

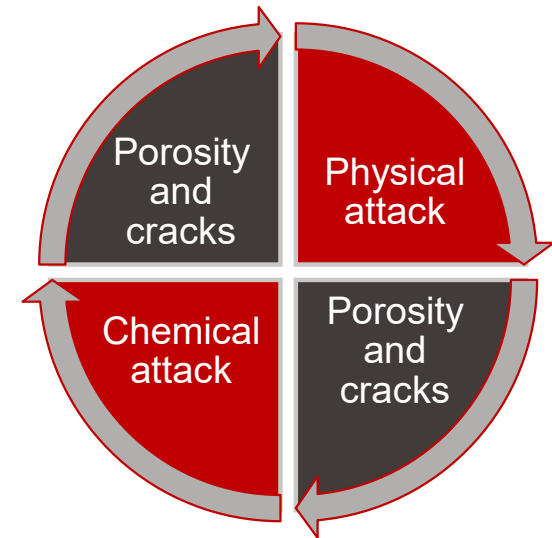
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# Durability – Degradation processes

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# Degradation processes

- Physical attack
  - Abrasion
  - Erosion
  - Cavitation
  - Physical salt attack
  - Freeze-thaw
  - Fire damage
  
- Chemical attack
  - Corrosion - Carbonation and Chlorides penetration
  - Alkali aggregate reaction
  - Sulphate attack
  - Acid attack
  - Biogenic attack



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# Outline for each degradation process

- Understand the deterioration process
- Identify the influencing parameters
- Suggest mitigation/prevention solutions
- Test methods

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# Physical Attack

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# Abrasion

# (1/4)

Physical wear from rubbing or friction due to external forces (vehicular traffic, studded tires, snow tire chains, steel/ hard rubber-wheeled traffic etc.).

Pavements, especially in bends.

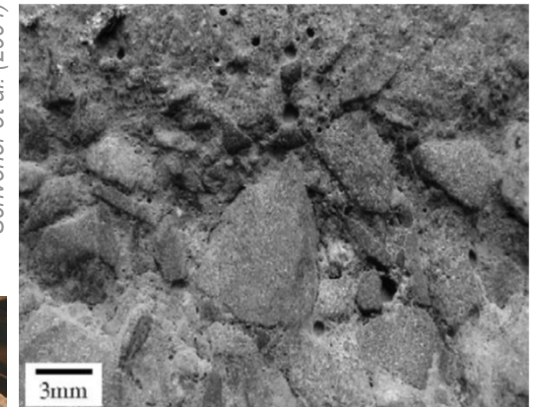
The abrasion resistance is improved if:

- Low surface porosity
- Surface finishing
- High compressive strength (low w/b, graded aggregates)
- Paste hardness and low content
- Hard and tough aggregates, good aggregate/paste bond
- Two-course floors

<https://blog.kryton.com/2021/08/concrete-abrasion-resistance-interview-part-1/>



Scrivener et al. (2004)



Pretty Handy GIRL.COM

# Erosion

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## (2/4)

Physical wear due to rainwater, flowing water or wind carrying solid particles. It depends on the particles' quantity, shape, size, hardness and speed.

Hydraulic structures, viaducts, bridges, and marine environment exposure.

*University of Sciences and of Technology  
Houari Boumediene, Algeria  
Hadja and Kharchi (2017)*

The erosion resistance is improved if:

- Low surface porosity
- Surface finishing
- High compressive strength (low w/b, graded aggregates)
- Paste hardness and low content
- Hard and tough aggregates, good aggregate/paste bond
- Low speed of water flow- Low slopes



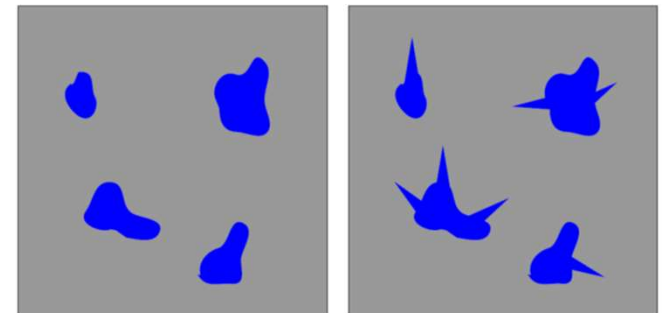
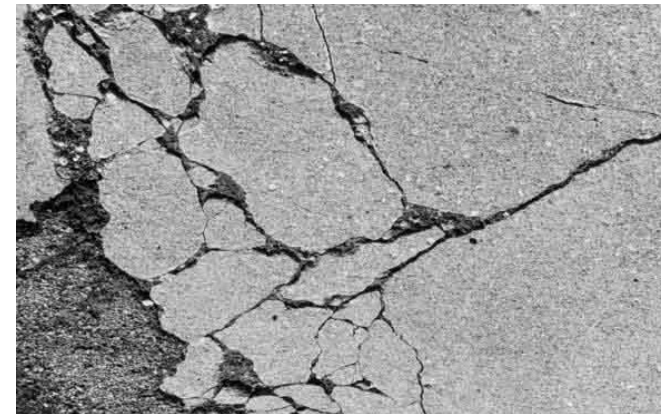
# Freeze-thaw



D-line cracking, popout and crumbling, fatigue damage.

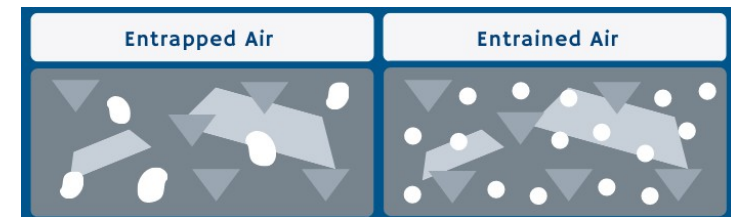
Hydraulic structures, areas with cyclic temperature changes, saturated or nearly saturated conditions, aggregates.

- Freezing: ice formation ( $V_{\text{ice}} = V_{\text{water}} + 9\%$ )
  - No cracks – exploitation of interconnected pores
  - Cracks – insufficient pore volume, high pressure
- Thawing: ice melting
  - Faster damage if cracks reach the surface, external water enters concrete



The freeze-thaw resistance is improved if:

- Unsaturated conditions
- Slow freeze-thaw cycles (not rapid temperature changes)
- Air-entraining agents
- Connected pore structure
- Use of chemicals/de-icing salts to lower the freezing point of water
- Aggregates not susceptible to freeze-thaw (small, non-porous, unsaturated)
- Early strength development



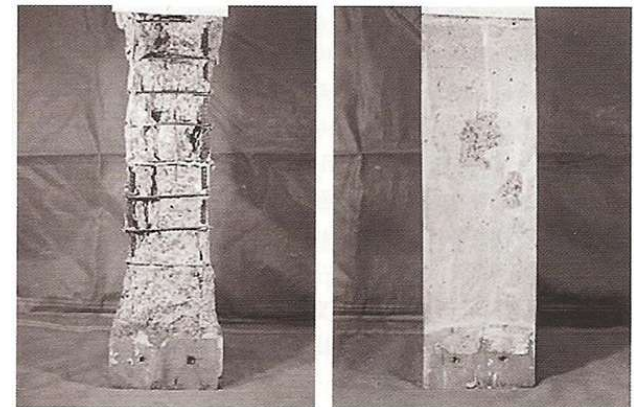
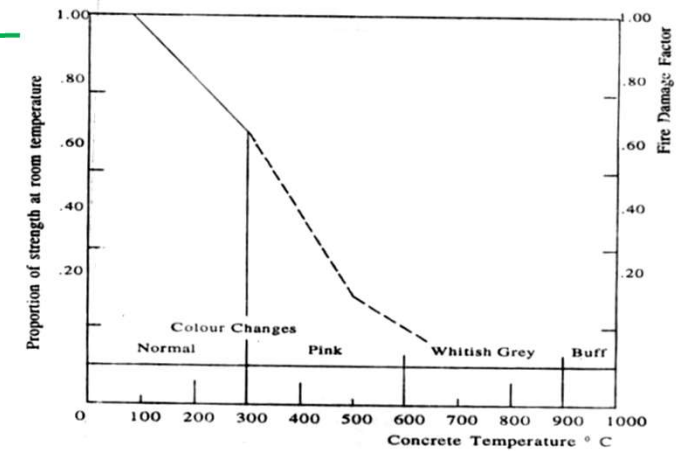
<https://www.polytrade.com.br/most-common-questions-about-air-entrained-concrete/>

LC<sup>3</sup> concrete behaves similarly to OPC concrete when de-icing salts are added.  
Good compatibility of air-entraining admixtures with LC<sup>3</sup>

Zunino et al. Limestone Calcined Clay Cements (LC<sup>3</sup>)

# Fire damage (4/4)

- Concrete is a good thermal insulator.
  - Operating T°C - Concrete and steel same thermal expansion
  - 100-150°C – Cracking paste/aggregate interphase
  - 500°C – Strength loss of steel
  - 750°C – Surface spalling paste/aggregate  
(Higher strength concretes spall more)
  - High T°C – Cover collapse and buckling  
(concrete and steel differential stresses)
  - Colour changes from grey to pink to buff
- Concrete cover: homogeneous, dense, thick.  
5 cm thick - 500°C in 3-4hours



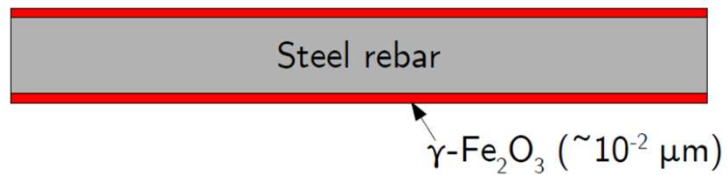
# Chemical Attack

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# Corrosion in reinforced concrete (RC)

How can steel reinforcement be stable in concrete?

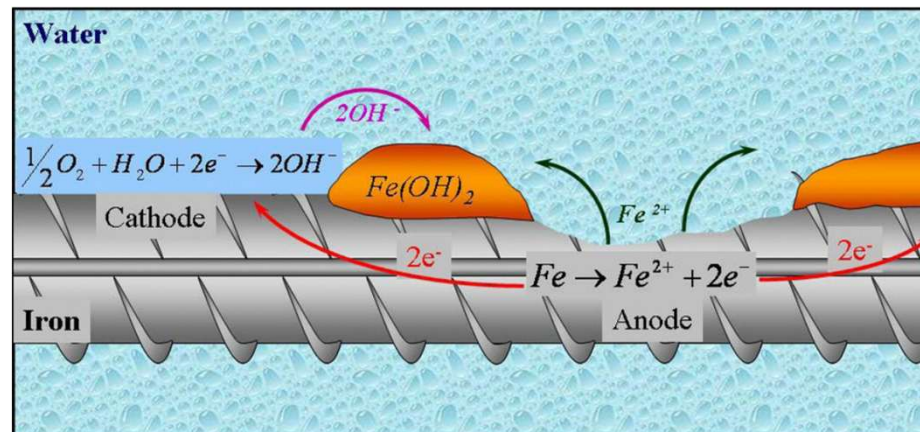
- Passivating layer
- Adequate concrete cover depth (to be designed)



Thomas, Folliard and Scrivener, 2008

# Corrosion in reinforced concrete (RC)

- Electrochemical process – anode and cathode & electrolytic solution
- Breakdown of passive layer or presence of two different types of metals
- Solution available in the concrete pores.

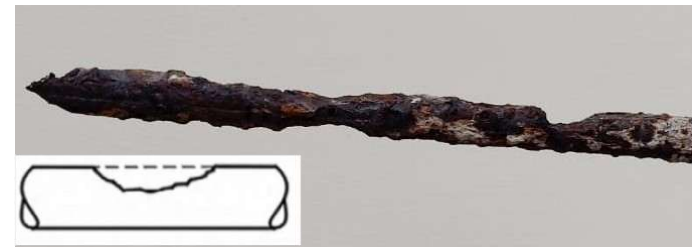


Thomas, Folliard and Scrivener (2008)  
Mehta and Monteiro, 2006

# Corrosion in reinforced concrete (RC)

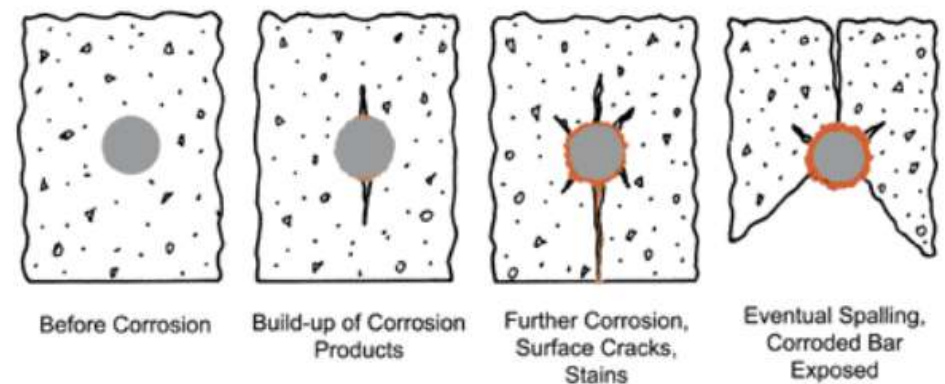
## Influence on steel

- Reduction of the cross-section
- Reduction in tensile strength

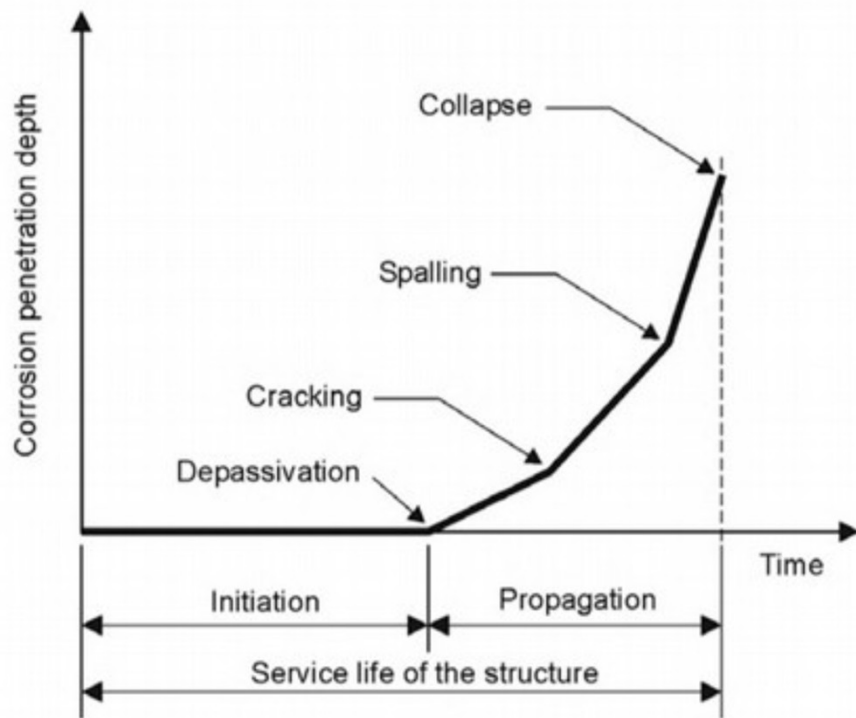


## Influence on concrete

- Cracking
- Spalling
- Reduction in compressive strength



# Corrosion in reinforced concrete (RC)



- Concrete cover: homogeneous, thick, low porosity, no cracks.
- If already degraded:
  1. removal of degraded concrete;
  2. scarification of existing reinforcing bars;
  3. passivating treatment of reinforcing bars;
  4. restoring concrete cover;
  5. concrete finishing;
  6. protective painting.



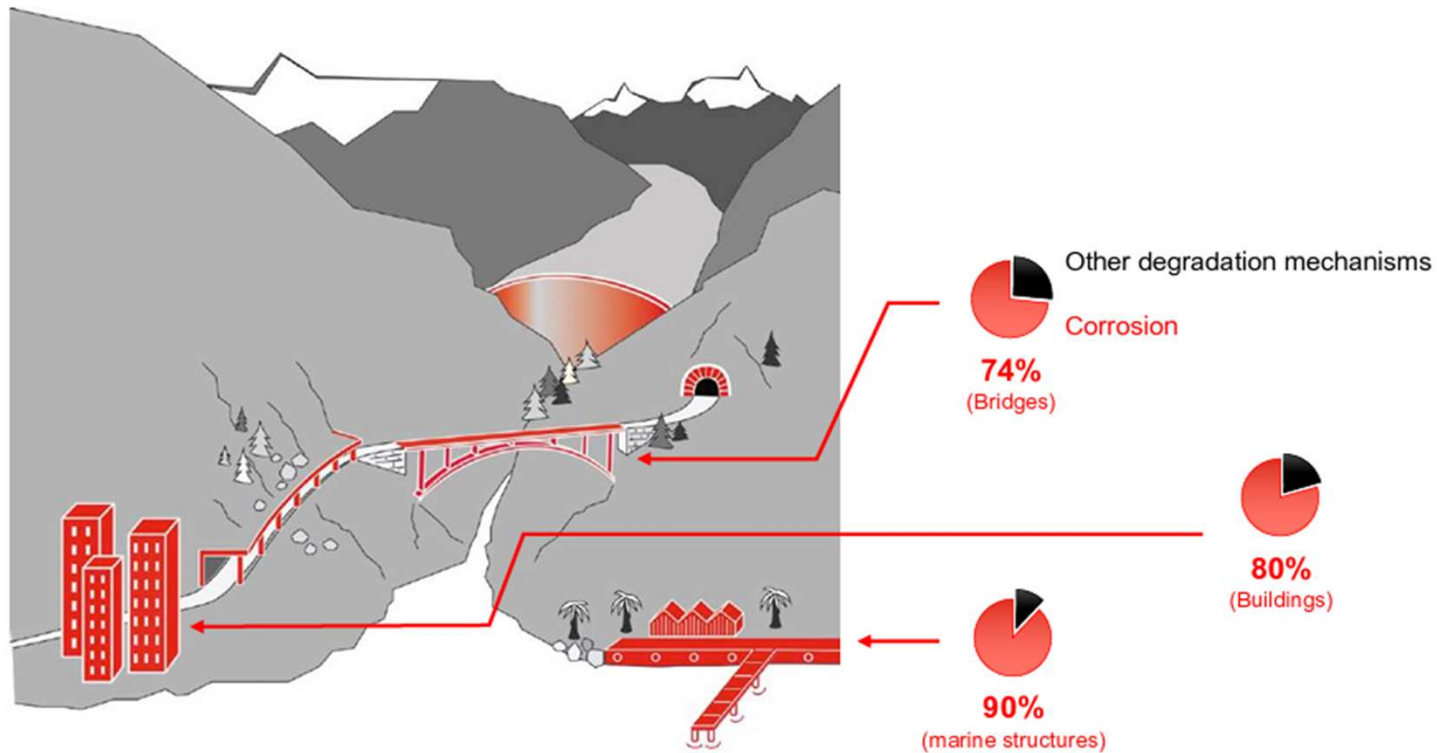
<https://theconstructor.org/practical-guide/cathodic-protection-of-reinforced-concrete-structures/5854>

■ Bertolini et al. 2013

# Corrosion in reinforced concrete (RC)

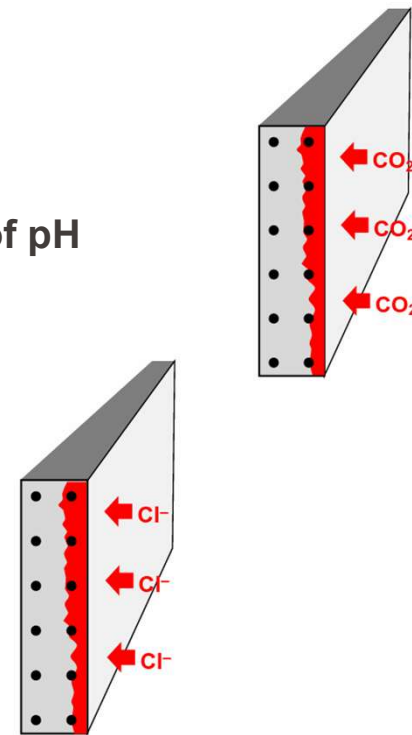


# Corrosion in reinforced concrete (RC)



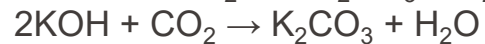
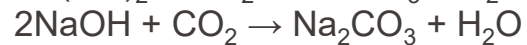
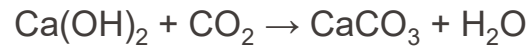
# Major reasons of corrosion

- Carbonation induced corrosion
  - $\text{CO}_2$  in the environment
  - Disruption of the passivating film due to **lowering of pH**
  - **Uniform degradation**
  
- Chlorides induced corrosion
  - De-icing salts, seawater, sand etc.
  - Disruption of passivating film at **high pH**
  - Pitting, **localized degradation**



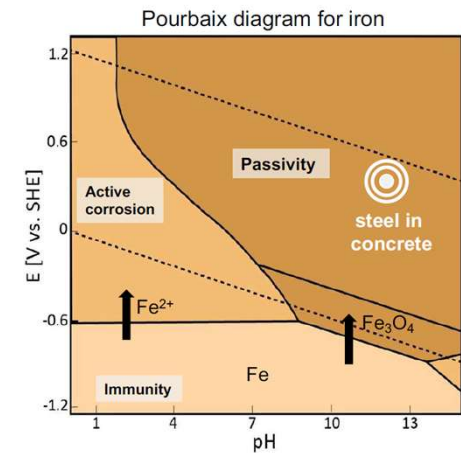
# Carbonation induced corrosion

- **Carbon dioxide reacts with alkalis** to carbonate them,



this reduces the pH of the solution from 12.6 to 8-9.

- Loss of passivity! Corrosion is possible
- Uniform corrosion: Anodic and cathodic partial reactions are randomly and microscopically distributed over the steel surface.



Porosity and microstructure measurements.

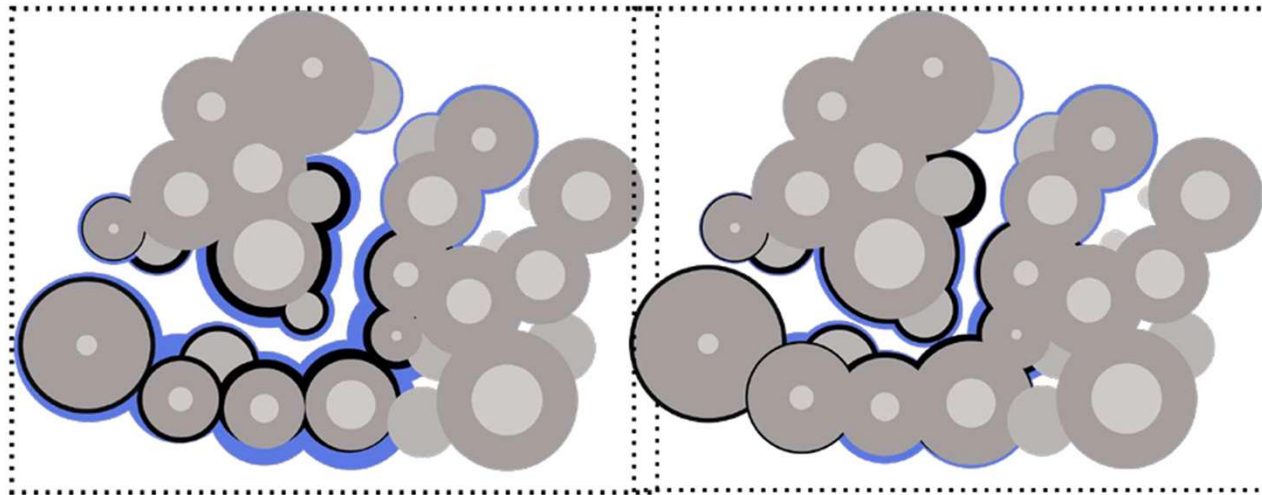
Lecture n. 7  
Characterisation techniques

Carbonation of C-S-H, ettringite, etc.

- reduces solid volume
- Increase in porosity

Carbonation of CH

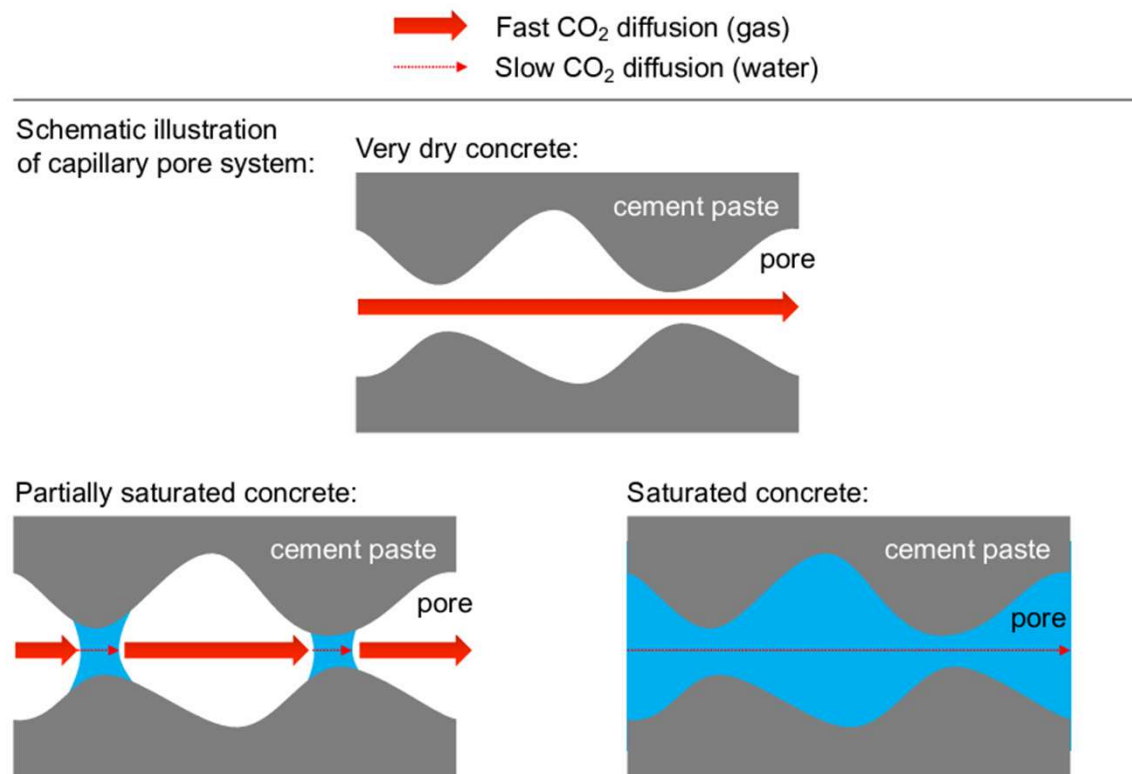
- Increases solid volume
- Reduction of porosity



Increase in porosity

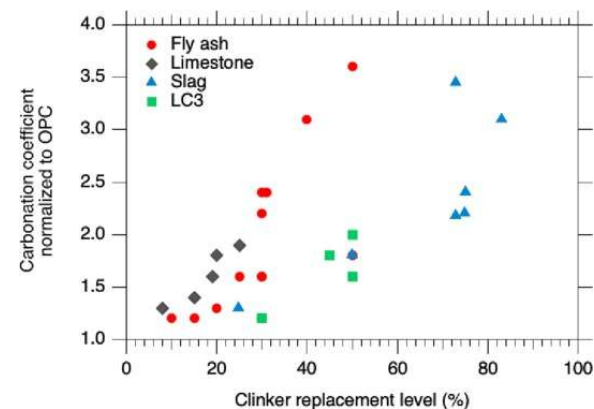
Reduction in porosity

# Carbonation induced corrosion

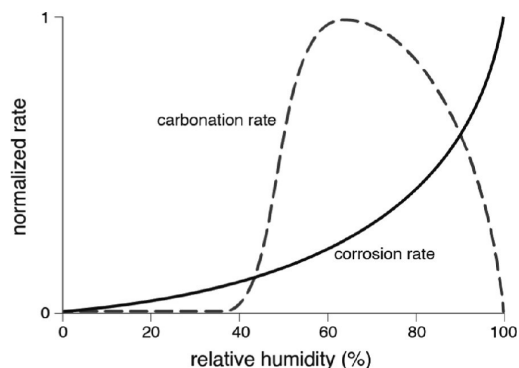


# Carbonation induced corrosion

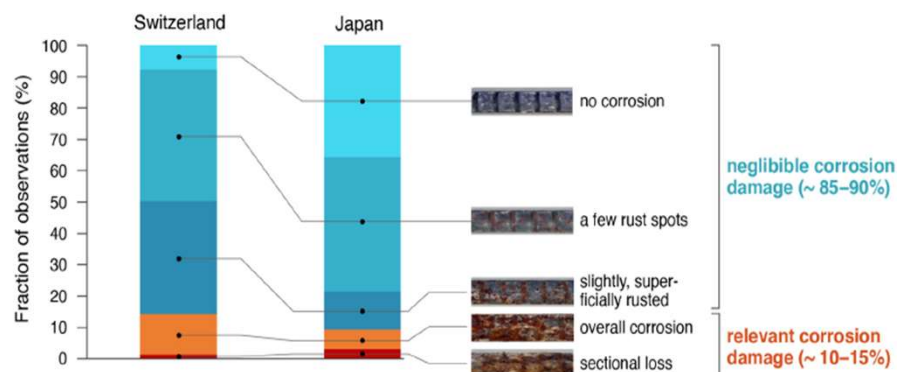
- Carbonation rate depends on diffusivity/permeability
- Binder composition/ reserve alkalinity (CH available to buffer CO<sub>2</sub>) →
- Environmental CO<sub>2</sub> concentration
- Temperature
- Relative humidity
- Exposure condition
- **Does not always lead to corrosion!**



Angst, 2023



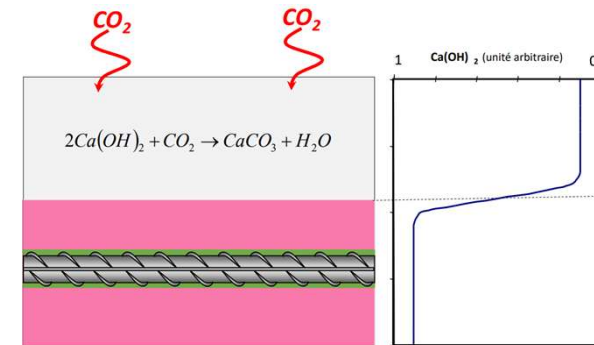
Angst, U.M. (2023). On the Carbonation Dilemma and How to Escape from It. 2023



U. Angst et al., RILEM Technical Letters (2020) 5: 85-100

# Carbonation testing

- Phenolphthalein test (thymolphthalein) (pink at pH > 9.2, colourless at pH < 9.2)
- pH
- Reserve alkalinity



- Measure: Carbonation depth

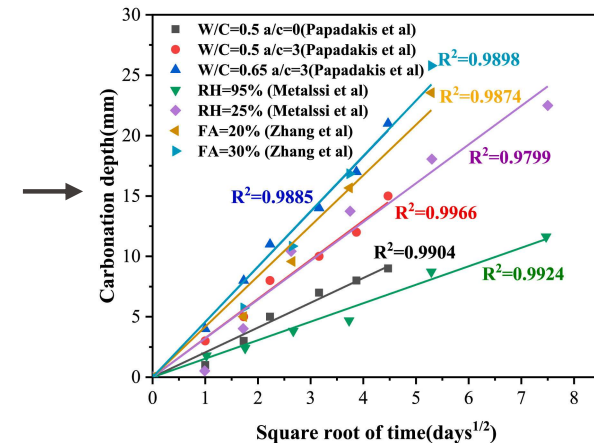
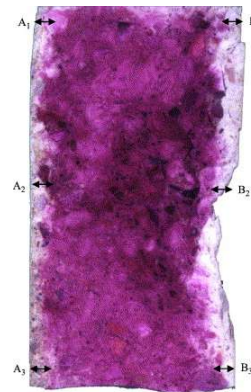
Square Root Law  $d = k\sqrt{t}$

$d$  = carbonation depth (mm)

$t$  = time (years)

$k$  = carbonation coefficient (mm/year<sup>0.5</sup>)

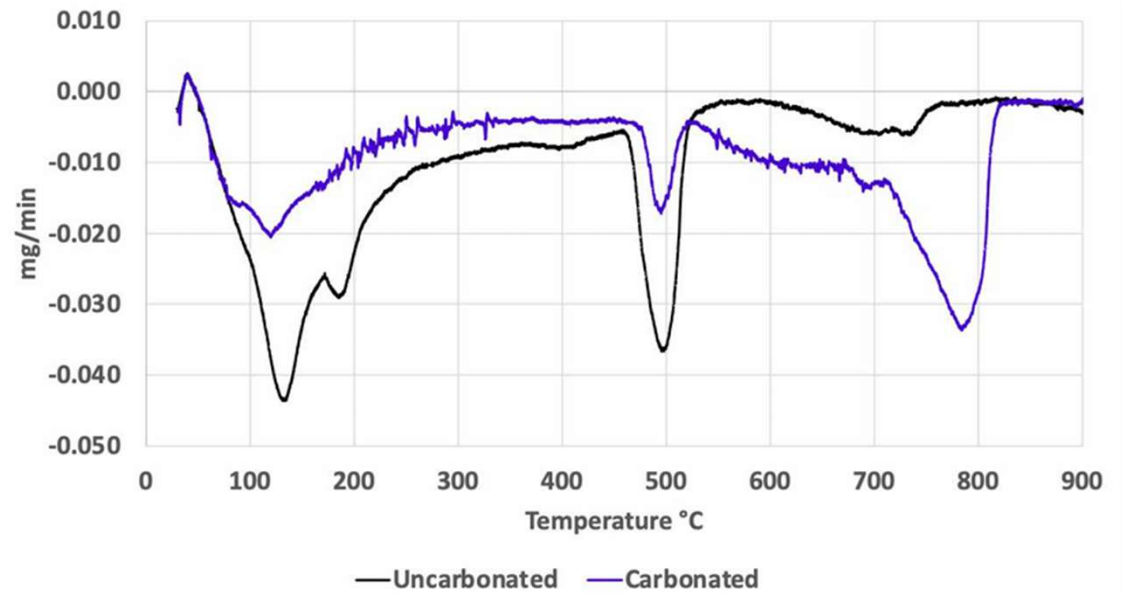
Higher the  $k$ , higher the rate of carbonation



# Carbonation testing

- Thermogravimetric Analysis (TGA)
- Other mineralogical techniques – typical phase assemblage

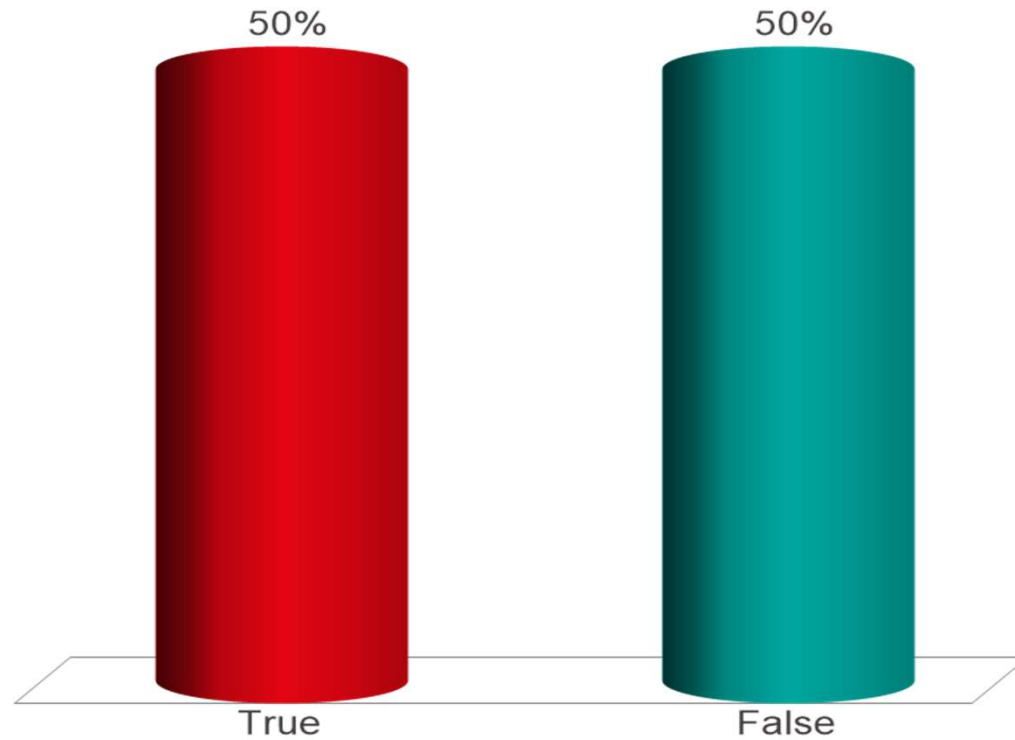
Lecture n. 7  
Characterisation  
techniques



# A material/structure is either durable or not durable



- A. True
- B. False

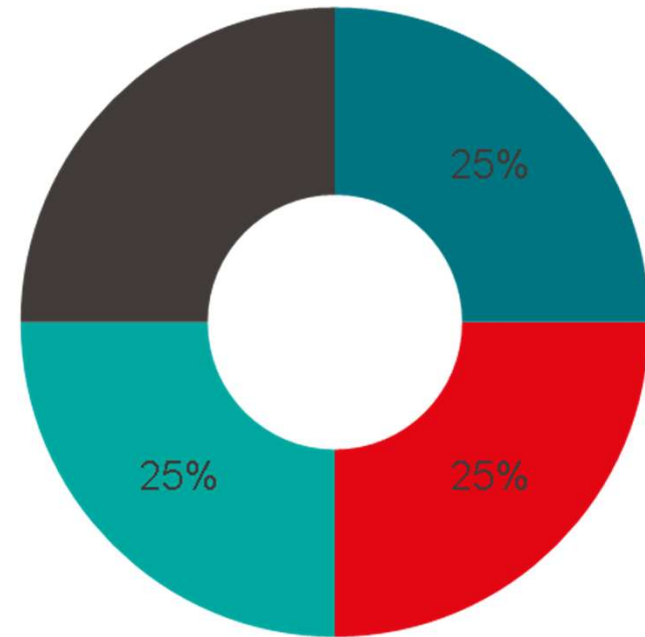


Response  
Counter

**Durability affects the service life of concrete structures. After a certain service life, the structure is not safe anymore (< min. performance required, collapse). Can we extend the service life?**



- A. No, it's not possible.
- B. Yes, doing maintenance.
- C. Yes, doing maintenance but it's not worth doing it. It's too expensive.
- D. Yes, through good design, good manufacturing, and maintenance.



■ A. ■ B. ■ C. ■ D.

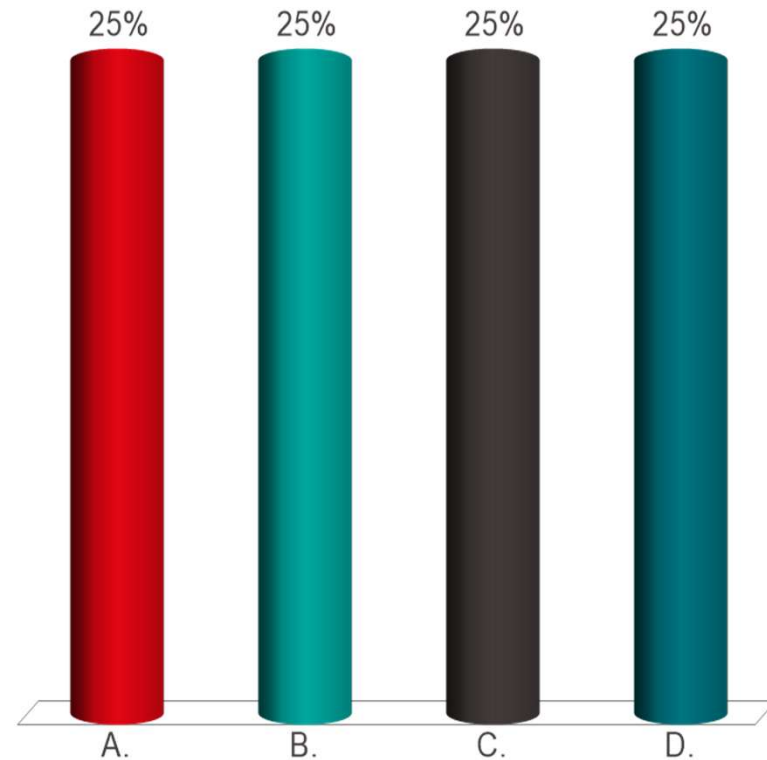
Response  
Counter

# How did you find the presentation so far?

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- A. The concepts were explained clearly and at the right speed
- B. The concepts were explained clearly but too fast
- C. The concepts were explained clearly but too slowly
- D. Concepts were explained at the right speed but unclearly



Response  
Counter



# Any suggestions for the following part?

---

bungee jumping  
running

hiking

ice fishing  
jogging

video games

weight lifting

swimming

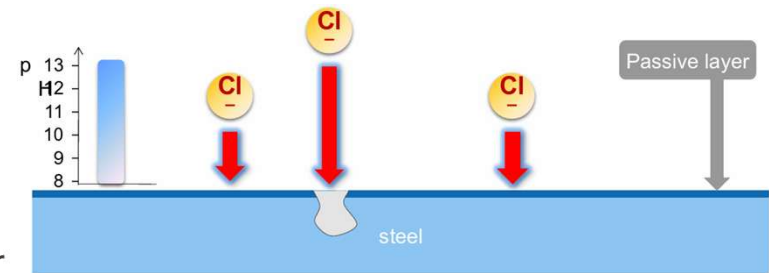
kayaking

rock climbing

Response  
Counter

# Chlorides induced corrosion

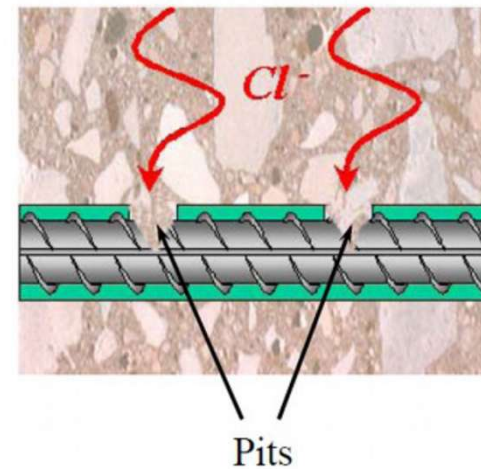
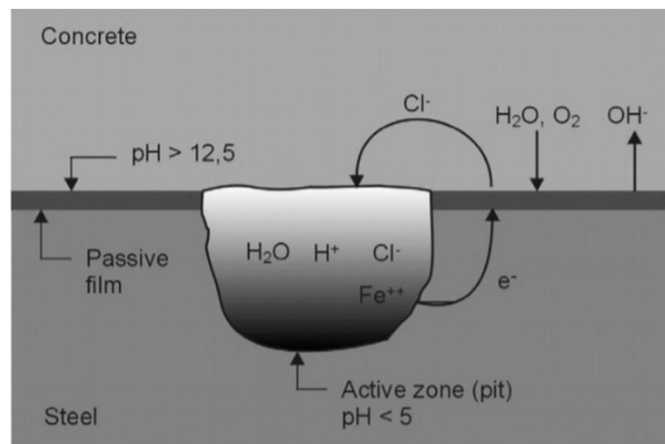
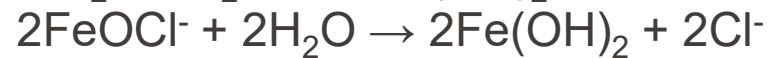
- Due to  $\text{Cl}^-$  ingress into concrete
- $\text{Cl}^-$  from different sources:
  - Seawater - Marine exposure (dams, harbors, bridges, etc.)
  - De-icing salts (350'000 tonnes/year in Switzerland)
  - Swimming pools
  - Underground structures
  - Raw materials
  - Accelerators
- Disruption of passivating film at high pH.
- Localized corrosion - Pitting



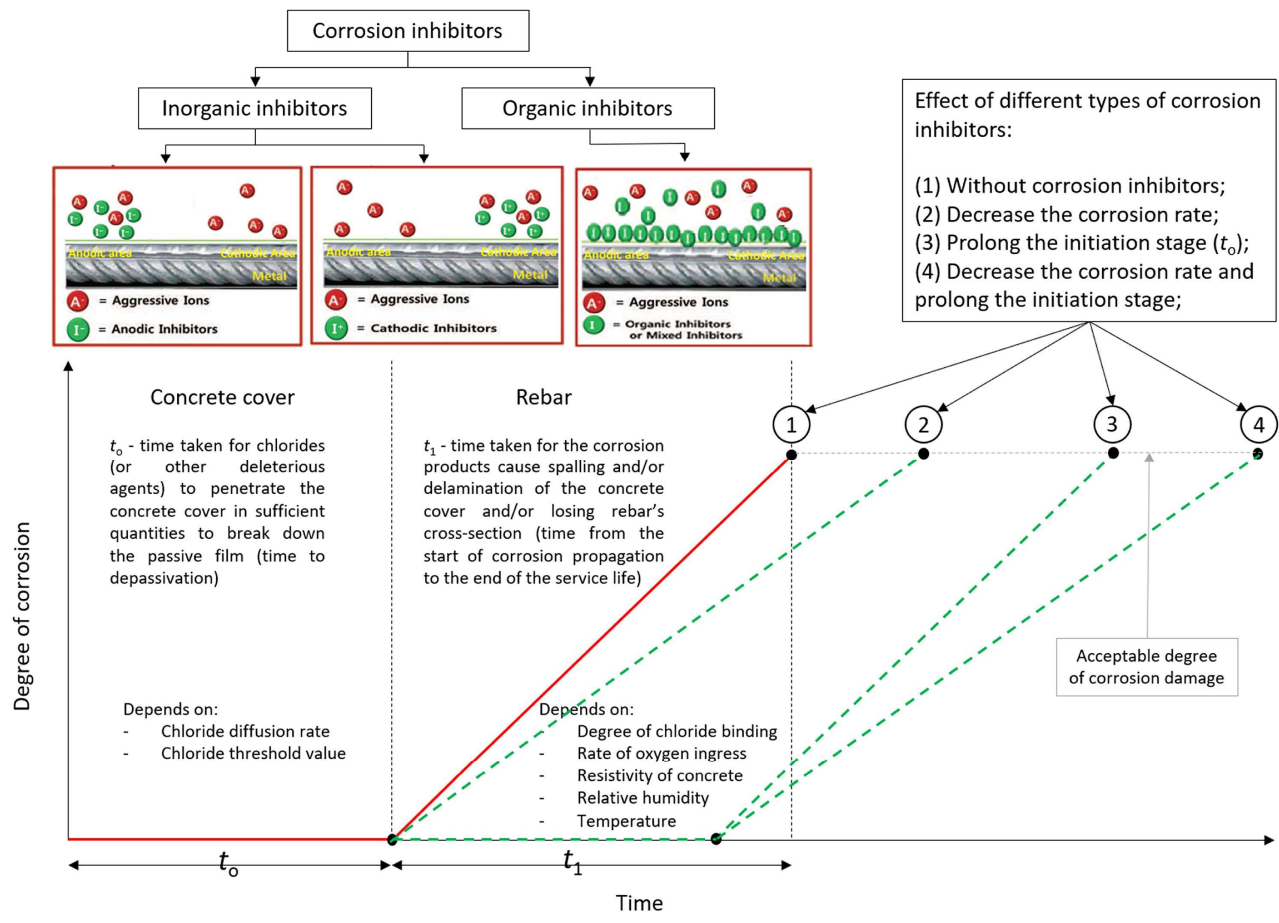
- Ferrous ions combine with the chloride ions to form ferrous chloride



- Self-propagating due to acidic conditions created



# Chlorides penetration

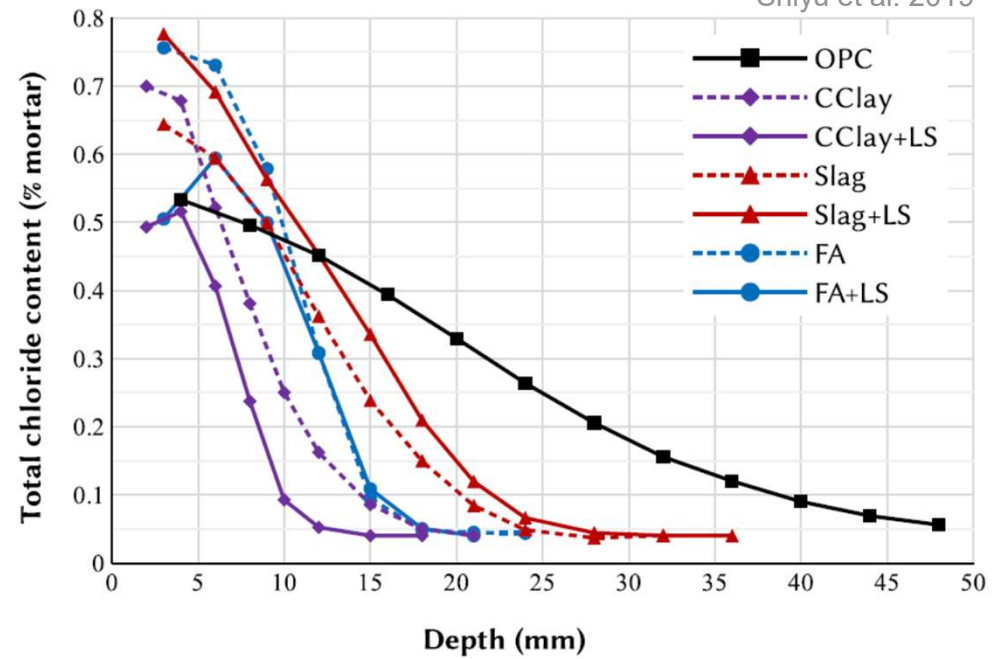


# Chlorides penetration - testing



Chloride content profile, ASTM C1152

Shiyu et al. 2019



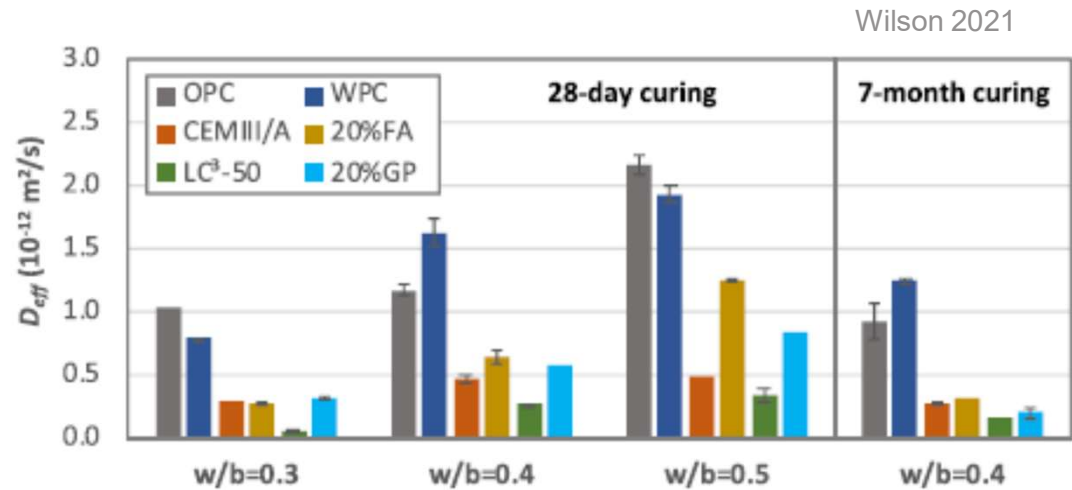
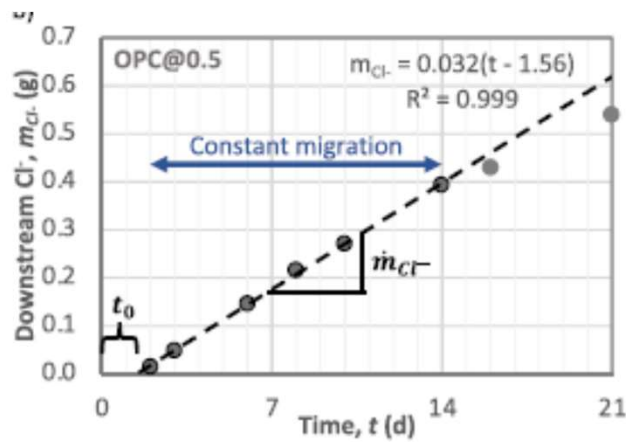
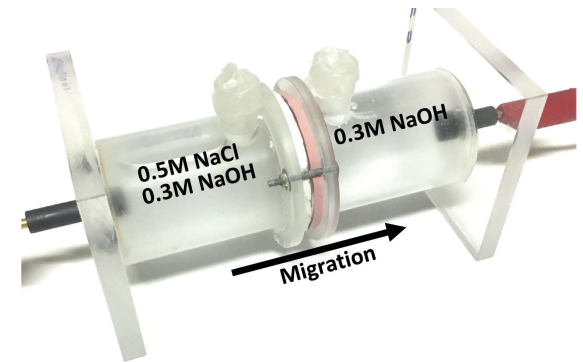
Georget 2020



# Chlorides penetration - testing

## Mini-migration (pastes)

- Upstream: 0.5 M NaCl, 0.3 M NaOH
- Downstream: 0.3 M NaOH
- Voltage is applied

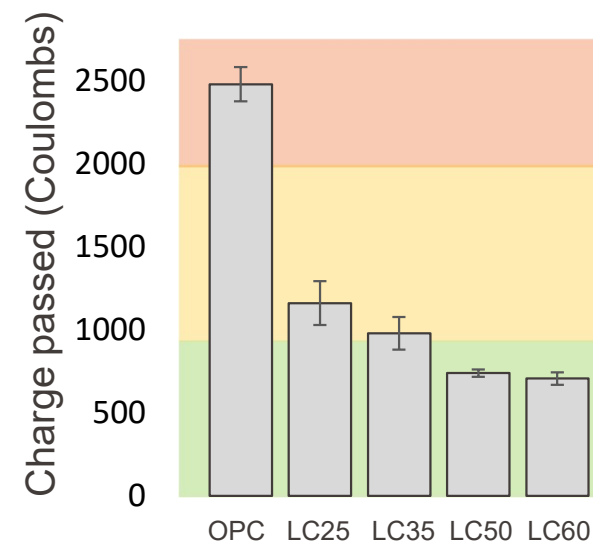


## Rapid Chloride Penetration Test - RCPT (concrete)

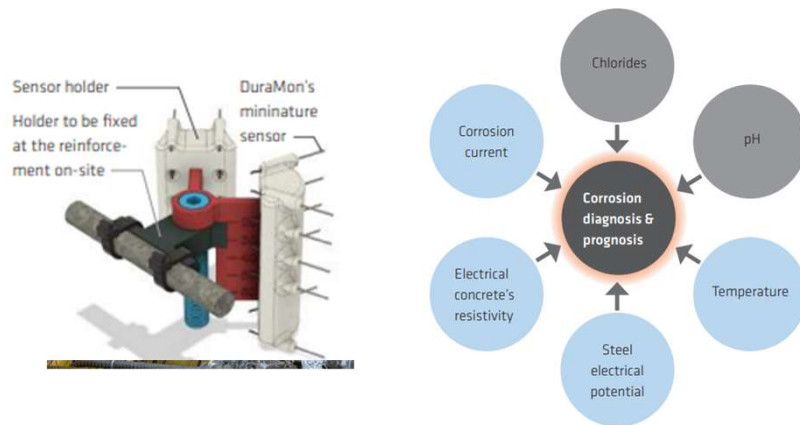
- ASTM C1202
- 0.5 M NaCl and 0.3 M NaOH.
- Voltage: 60 V, Test time: 6 h.
- Actual current ( $I$ , [mA])
- Charge passed (Coulombs):

$$Q = 900 (I_0 + 2I_{30} + 2I_{60} + \dots + 2I_{300} + 2I_{330} + I_{360})$$

Charge passed [Coulombs]	Chloride Ion Penetration
>4000	High
2000-4000	Moderate
1000-2000	Low
100-1000	Very low
<100	Negligible



# Corrosion in reinforced concrete (RC) – Last-generation monitoring techniques



- 1** Concrete cores are taken and removed from the structure
- 2** The concrete cores are fitted with DuraMon's Miniature sensors
- 3** Cables are cast in epoxy resin
- 4** Concrete cores are replaced in their original locations in the structure and connected to the surrounding concrete with a filling mortar that ensures a good bond and rapid equilibrium with the existing concrete
- 5** DuraMon's sensors are connected to DuraMon's data logger

- 1** DuraMon's Sensor System is fixed onto the steel reinforcement of the structure
- 2** Concrete is poured and distributed around DuraMon's sensor system

# Corrosion in reinforced concrete (RC) – Last-generation monitoring techniques



ONGOING

CAIBARIÉN, CUBA

Bridge in Caibarién



ONGOING

SAAS-FEE, SWITZERLAND

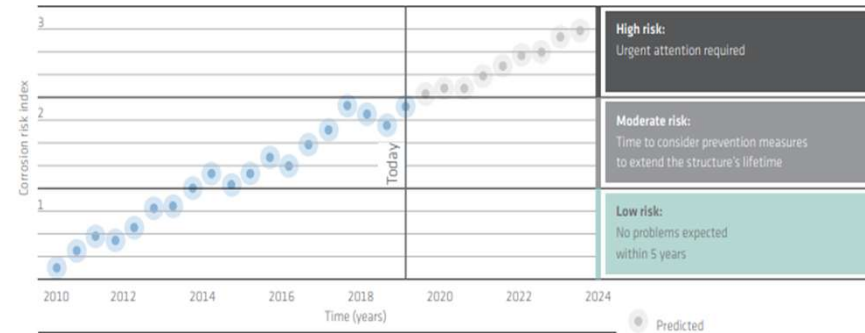
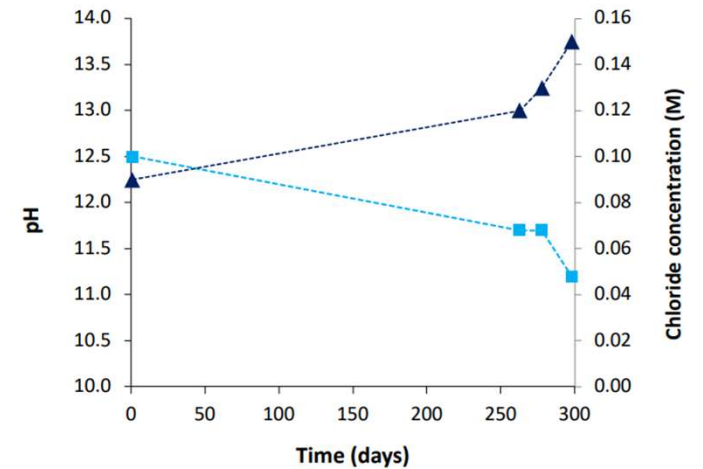
Parking garage P5 Saas-Fee



ONGOING

ZURICH, SWITZERLAND

Brunaubrücke



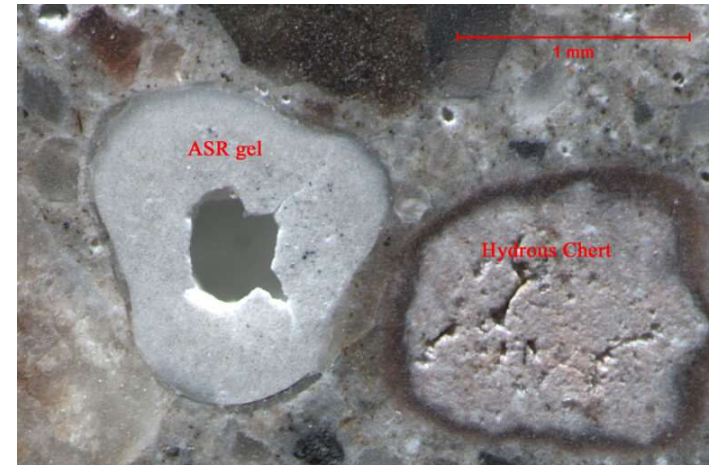
**High risk:**  
Urgent attention required

**Moderate risk:**  
Time to consider prevention measures to extend the structure's lifetime

**Low risk:**  
No problems expected within 5 years

○ Predicted

# Alkali Aggregate Reaction (AAR)



# Alkali Aggregate Reaction (AAR)

- Aggregates containing alkali reactive minerals should be avoided:
  - Alkali silica reaction (ASR)
  - Alkali carbonate reaction (ACR)
  
- Quality control for aggregate through petrographic analysis and expansion of mortar bars (UNI EN 8520-22, ASTM C295)

Reactive substance (mineral)	Chemical composition	Physical character
Opal	$\text{SiO}_2 \cdot n\text{H}_2\text{O}$	Amorphous
Chalcedony	$\text{SiO}_2$	Microcrystalline to cryptocrystalline; commonly fibrous
Certain forms of quartz	$\text{SiO}_2$	Microcrystalline to cryptocrystalline; crystalline, but intensely fractured, strained, and/or inclusion-filled
Cristobalite	$\text{SiO}_2$	Crystalline
Tridymite	$\text{SiO}_2$	Crystalline
Rhyolitic, dacitic, latitic, or andesite glass or cryptocrystalline devitrification products	Siliceous with lesser proportions of $\text{Al}_2\text{O}_3$ , $\text{Fe}_2\text{O}_3$ , alkaline earths and alkalis	Glass or cryptocrystalline material as the matrix of volcanic rocks or fragments in tuffs
Synthetic siliceous glass	Siliceous, with lesser proportions of alkalis, $\text{Al}_2\text{O}_3$ , and/or other substances	Glass

Thomas et al. (2013)

# Alkali Silica Reaction (ASR)

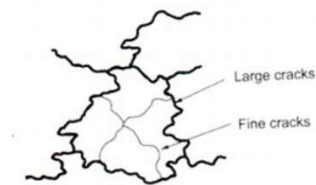
- Swelling and cracking (25-50mm depth)
- Usually a slow process (even after 30-40 years)
- Less often cause of failure than other mechanisms



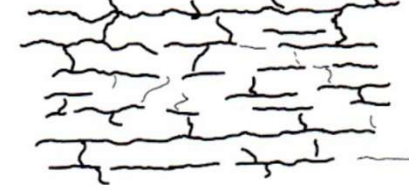
Richardson 2002



Unreinforced concrete



Reinforced concrete



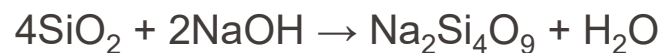
# Alkali Silica Reaction (ASR)

Microstructure.

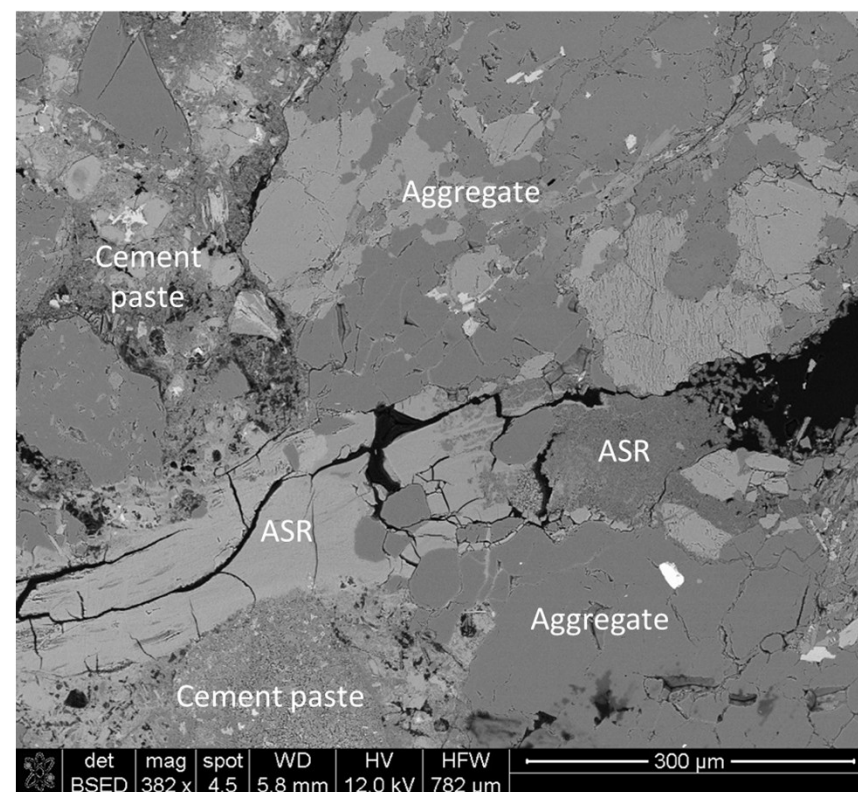
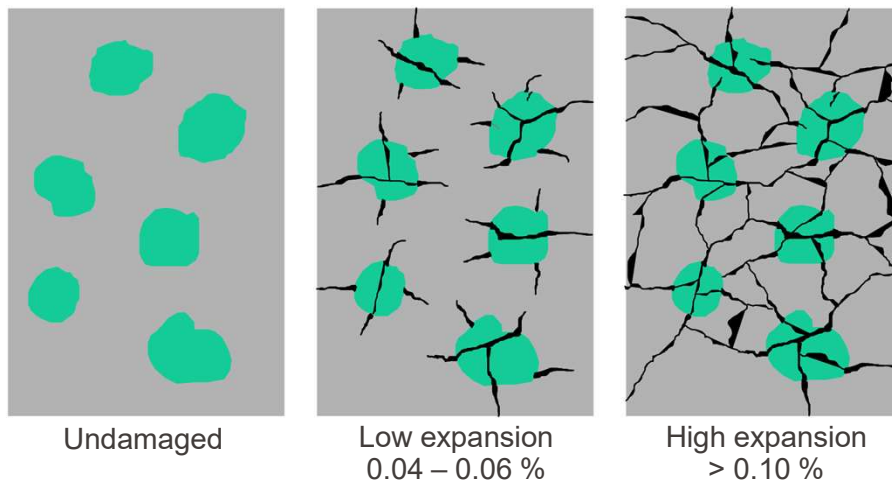
Lecture n. 7

Characterisation techniques

- Gel imbibes water – volume increase, expansion
- Restraint – stresses due to ASR expansion

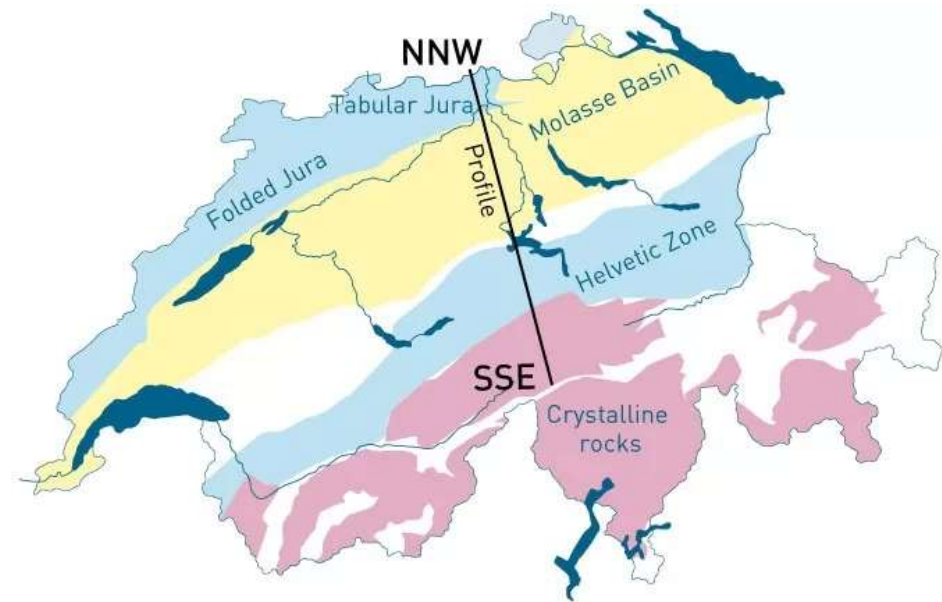


Scrivener Bachelor MX course – LMC website



# Alkali Silica Reaction (ASR)

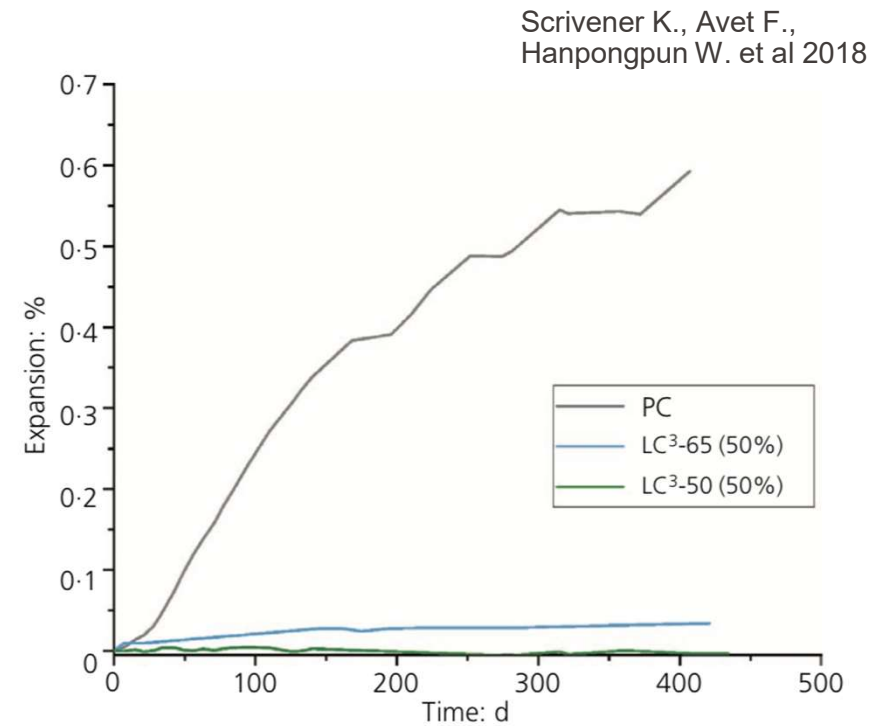
- More than 400 structures are affected (Merz et al. 2006).
- 20-30% of Swiss dams are affected.
- 90% of the aggregates were classified as potentially reactive to ASR (Merz & Leemann, 2012).



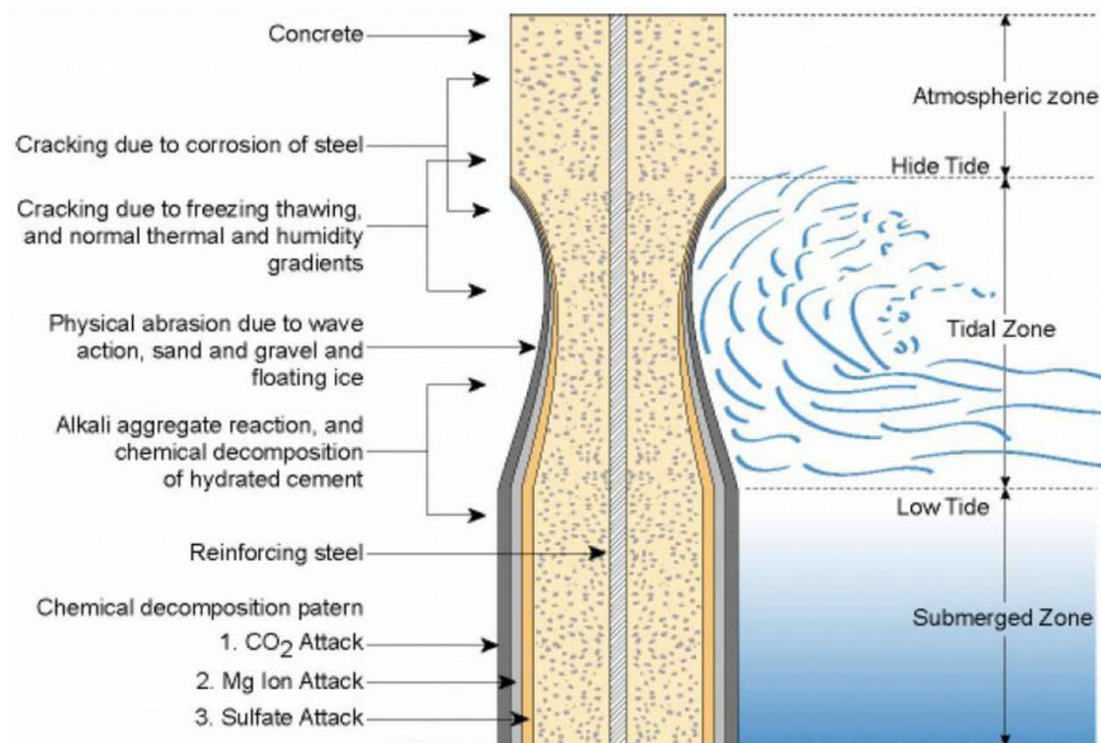
Swiss geology map from Nagra portal

# Alkali Silica Reaction (ASR)

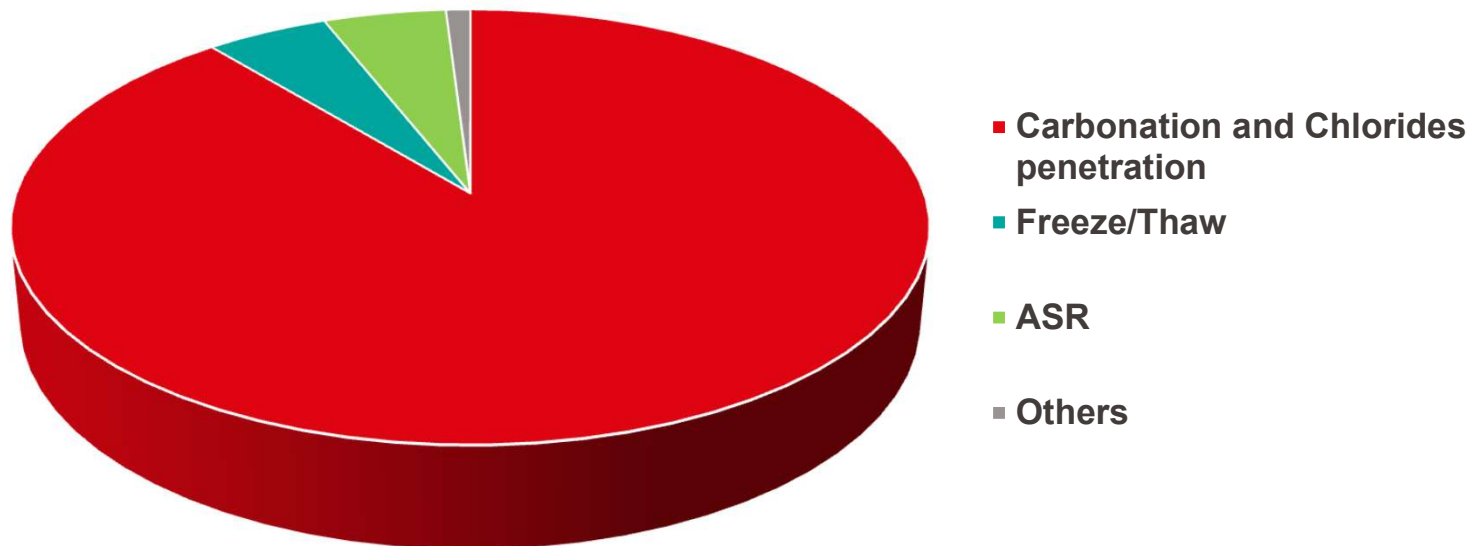
- Avoid reactive aggregates
- Use cement with low alkali content
- Add SCMs (calcined clays, fly ash etc.)
- Add air to compensate for stresses



# Multi degradation process



# Main degradation processes in concrete



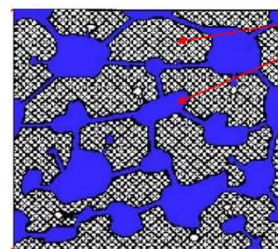
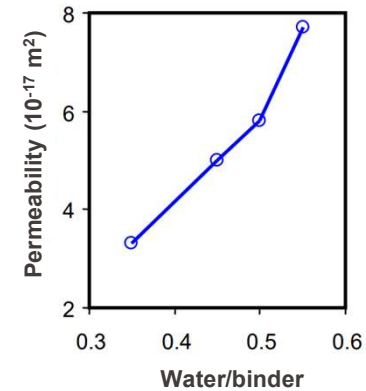
# Overall solutions to promote durability

1. *Cement level*
2. *Concrete level*
3. *Design level*

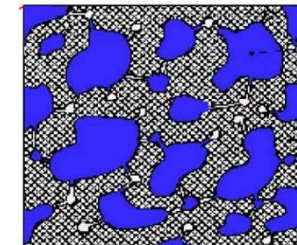
# How can we make durable concrete?

## Cement level:

- Low water/binder ratio
- Use supplementary cementitious materials
- Reduce the total porosity
- Reduce connected porosity
- Reduce pore size
- Increase tortuosity



C-S-H  
Capillary porosity,  
Connected

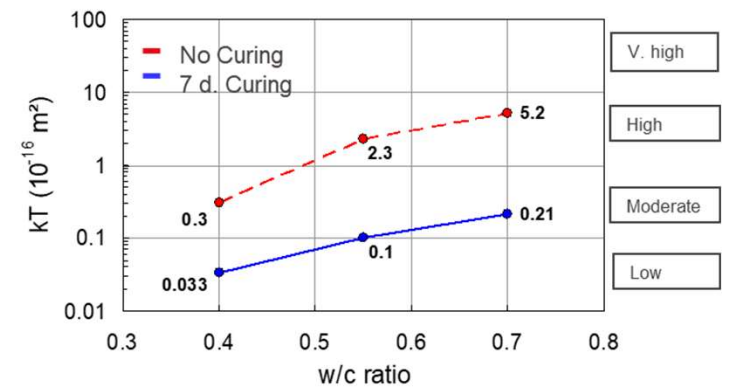
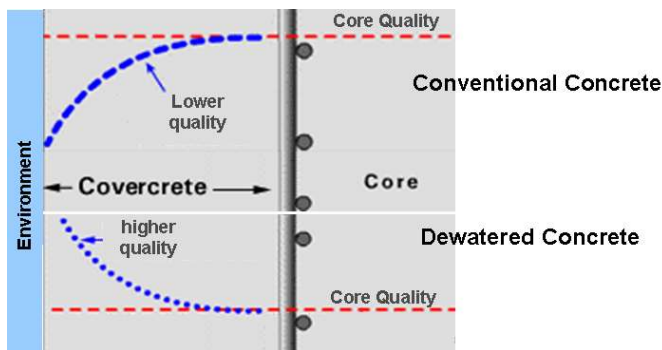
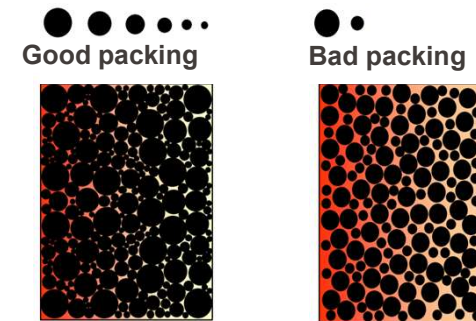


Ideal porosity

# How can we make durable concrete?

## Concrete level:

- Low binder content (particle packing)
- Add entrained air to the concrete mix
- Proper compaction
- Proper curing
- Proper surface finish
- Use washed aggregates



# How can we make durable concrete?

## *Design level:*

- Sacrificial layers
  - Render
  - Larger concrete cover
- Away from direct exposure whenever possible
  - Chlorides
  - Steep slopes against water
  - Highly reactive environment



# **Durability in Standards and Codes**

■

# Exposure classes – Classification 1/2

## 1 No risk of corrosion or attack

XC0	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

No risks

## 2 Corrosion induced by carbonation

(Where concrete containing reinforcement or other embedded metal is exposed to air and moisture)

XC1	Dry or permanently wet	Concrete inside buildings with low humidity. Concrete permanently submerged in water
XC2	Wet, rarely dry	Concrete subjected to long-term water contact. Many foundations
XC3	Moderate humidity	Concrete inside buildings with moderate or high air humidity. External concrete sheltered from rain.
XC4	Cyclic wet and dry	Concrete surfaces subject to water contact, not within exposure class XC2

Carbonation

## 3 Corrosion induced by chlorides other than from sea water

(Where concrete containing reinforcement or other embedded metal is subject to contact with water containing chlorides, including de-icing salts from sources other than sea water)

XD1	Moderate humidity	Concrete surfaces exposed to airborne chlorides
XD2	Wet, rarely dry	Swimming pools. Concrete exposed to industrial waters containing chlorides
XD3	Cyclic wet and dry	Parts of bridges exposed to spray containing chlorides. Pavements. Car park slabs

Chlorides no sea

# Exposure classes – Classification 2/2

## 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)

XS1	Exposed to airborne salt but not in direct contact with sea water	Structures near to on the coast
XS2	Permanently submerged	Parts of marine structures
XS3	Tidal, splash and spray zones	Parts of marine structures

Chlorides from sea

## 5 Freeze/thaw attack with or without de-icing salts

(Where concrete is exposed to significant attack from freeze-thaw cycles whilst wet)

XF1	Moderate water saturation, without de-icing agents	Vertical concrete surfaces exposed to rain and freezing
XF2	Moderate water saturation, with de-icing agents	Vertical concrete surfaces of road structures exposed to freezing and airborne de-icing agents
XF3	High water saturation, without de-icing agents	Horizontal concrete surfaces exposed to rain and freezing
XF4	High water saturation, with de-icing agent or sea water	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

Freeze -Thaw

## 6 Chemical attack

XA1	Slightly aggressive chemical environment according to Table 2*	
XA2	Moderately aggressive chemical environment according to Table 2*	
XA3	Highly aggressive environment according to Table 2*	

Chemical attack

Table 2 (of EN 206-1:2000) provides limiting values of  $SO_4$ ,  $pH$ ,  $CO_2$ ,  $NH_4$ ,  $Mg$  for ground water and  $SO_4$  and acidity of natural soil for XA1,

**Table 2. Environmental exposure conditions**

Environment	Exposure conditions
Mild	Concrete surfaces protected against weather or aggressive conditions, except those situated in coastal areas
Moderate	Concrete surface sheltered from severe rain or freezing whilst wet; concrete exposed to condensation and rain concrete continuously under water; concrete in contact or buried under non-aggressive soil/ground water; concrete surfaces sheltered from saturated salt air in coastal area
Severe	Concrete surfaces exposed to severe rain, alternate wetting and drying or occasional freezing whilst wet or severe condensation; concrete completely immersed in sea water; concrete exposed to coastal environment
Very severe	Concrete surfaces exposed to sea water spray, corrosive fumes or severe freezing conditions whilst wet; concrete in contact with or buried under aggressive sub-soil/ground water
Extreme	Surface of members in tidal zone; members in direct contact with liquid/solid aggressive chemicals

Source: Table 3 of IS 456:2000

# Prescriptions vs Classification of exposure class

Table A.9 Limiting values for composition and properties of concrete to resist freezing and thawing (XF exposures)

Exposure class	Min. strength class	Max. w/c ratio	Min. air content <sup>A)</sup> and min. cement or combination content (kg/m <sup>3</sup> ) for max. aggregate size				Other requirements
			32 mm or 40 mm	20 mm	14 mm	10 mm	
XF1	C25/30	0.60	4.0 260	4.5 280	5.5 300	6.5 320	—
	C28/35 or LC28/31	0.60	— 260	— 280	— 300	— 320	—
XF2	C25/30	0.60	4.0 260	4.5 280	5.5 300	6.5 320	—
	C32/40 or LC32/35	0.55	— 280	— 300	— 320	— 340	—
XF3	C25/30	0.60	4.0 260	4.5 280	5.5 300	6.5 320	Freeze-thaw resisting aggregates <sup>B)</sup>
	C40/50 or LC40/44	0.45	— 320	— 340	— 360	— 360	
XF4	C28/35	0.55	4.0 280	4.5 300	5.5 320	6.5 340	Freeze-thaw resisting aggregates <sup>B)</sup>
	C40/50 or LC40/44	0.45	— 320	— 340	— 360	— 360	



# Prescriptions vs Severity of exposure class

## nominal concrete cover for different exposure conditions specified in IS 456:2000

Exposure	Minimum cement content#, kg/m <sup>3</sup>	Maximum free w-c ratio	Minimum grade of concrete	Minimum nominal concrete cover,* mm
Mild	300	0.55	M 20	20**
Moderate	300	0.50	M 25	30
Severe	320	0.45	M 30	45***
Very severe	340	0.45	M 35	50***
Extreme	360	0.40	M 40	75

Source: Table 5 of IS 456:2000.

Notes:

\* for a longitudinal reinforcing bar in a column, nominal cover shall not be less than 40 mm, nor less than the diameter of such bar;

\*\* for reinforcement upto 12 mm dia. bar for mild exposure, the nominal cover may be reduced by 5 mm;

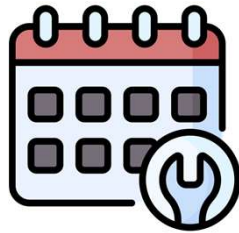
\*\*\* for exposure conditions severe and very severe, reduction of 5 mm may be made, where concrete grade is M 35 and above. The actual concrete cover should not deviate from the required nominal cover by +10 mm.

# Cement content mentioned in the code is irrespective of the grades of cement and it is inclusive of the additions (fly ash, GGBS, silica fume, high reactive metakaolin, rice husk ash, etc.) mentioned in clause 5.2 of IS 456.

# Why taking durability into consideration?



Structural design  
(exposure class, %air,  
w/b, concrete cover)



Maintenance  
(Predict and  
avoid damages)



Cost-effective  
(Maintenance vs  
Restoring)



Safety  
(Structure collapse,  
human life)



Sustainability  
(5-10% GWP,  
LCA lecture)

Now, at the end of this class, you are able to...

- **Define** durability, and **interpret** its significance for concrete and concrete structures.
- **Describe** the main degradation processes affecting concrete and concrete structures, and **identify** the parameters influencing them.
- **Suggest** mitigation and prevention solutions for the major degradation processes affecting concrete and concrete structures.
- **Relate** concrete durability to the sustainability of real concrete structures.

Always design in a durable and sustainable way!

▪

# Course Schedule

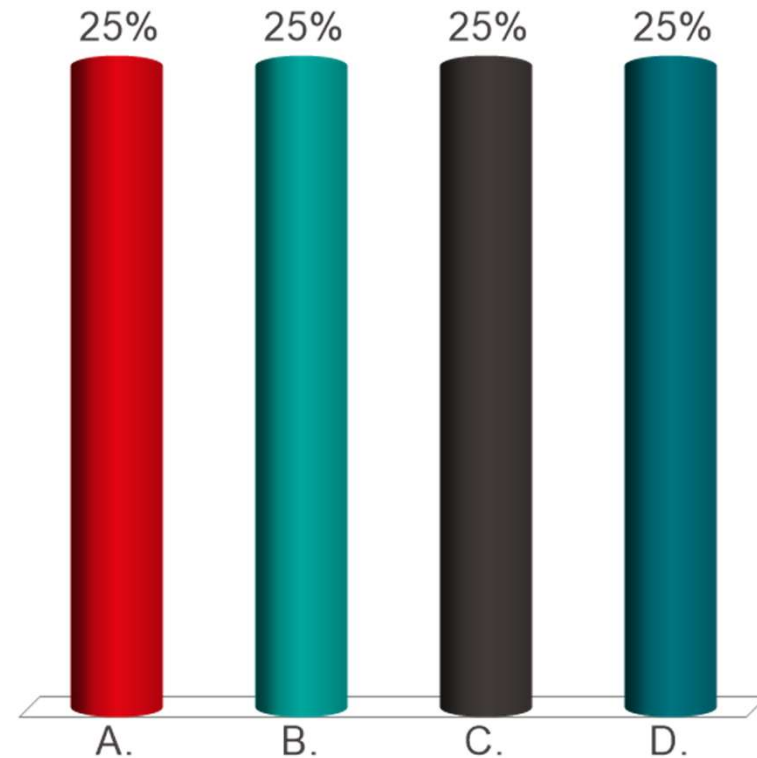
Wk #	Class date	Title	Teacher
1	10/09/2025	Introduction Guidelines for Literature review	Prof. Karen Scrivener Dr. Alastair Marsh
2	17/09/2025	SCMs and LC3 - Limestone Calcined Clay Cement	Dr. Mehnaz Dhar
3	24/09/2025	Sustainable Concrete design	Dr. Beatrice Malchiodi
4	01/10/2025	Material saving through a better concrete structural design	Prof. David Ruggiero
5	08/10/2025	LCA - Life Cycle Analysis	Dr. Alastair Marsh
6	15/10/2025	<b>Presentation 1</b>	
7	29/10/2025	Analytical characterisation techniques for cementitious materials	Dr. Antonina Goncharov
8	05/11/2025	Durability of cementitious materials	Dr. Beatrice Malchiodi
9	12/11/2025	<b>Presentation 2</b>	
10	19/11/2025	Cement hydration	Prof. Karen Scrivener
11	26/11/2025	GBDI Informal sector	Dr. Nicole di Santo Dr. Ruvimbo Munemo
12	03/12/2025	Low-carbon clinker production and CCUS Study session	Dr. Maciej Zajac- Heidelberg LMC Team
13	10/12/2025	<b>Presentation 3</b>	
14	17/12/2025	Precast concrete 3D printing	Stef Maas Prof. Nicolas Roussel

# The chemical degradation processes...

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- A. involve chemical reactions at the surface of the material/structure. Surface degradation.
- B. Are activated by chemicals.
- C. Can be generated from the core of concrete.
- D. Depend on the permeability of concrete – porosity.



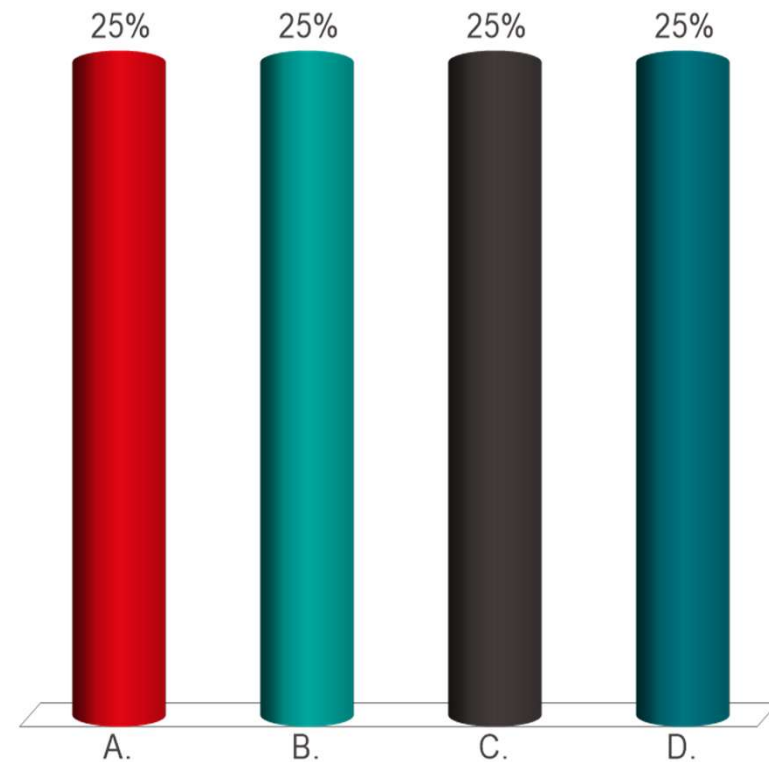
Response  
Counter

# How did you overall find the presentation?

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- A. The concepts were explained clearly and at the right speed
- B. The concepts were explained clearly but too fast
- C. The concepts were explained clearly but too slowly
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Response  
Counter

**EPFL**



# Questions?

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**Advanced cementitious  
materials, MSE 420**

**Lecture 2: Durability of  
cementitious materials**

**Dr. Beatrice Malchiodi  
beatrice.malchiodi@epfl.ch  
5 November 2025**