

EPFL



Advanced cementitious materials, MSE 420

Lecture 3: Sustainable Concrete design

Dr. Beatrice Malchiodi
24 September 2025

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	Presentation 1	
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	Presentation 2	
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	Presentation 3	
14	17/12/2025	Precast concrete 3D printing	Stef Maas Prof. Nicolas Roussel

Please refer to MSE-322
for basic knowledge of concrete

Learning objectives

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

- **Define** how concrete is made and which parameters affect its property.
- **Identify** the main desired and required properties of concrete.
- **Identify** the main factors that enable a reduction of the carbon footprint in concrete.
- **Establish** mix design strategies to meet the specified requirements for concrete with the lowest amount of embodied CO₂.

■ Please refer to MSE-322
for basic knowledge of concrete

Background and Carbon footprint

■

Concrete is everywhere around us



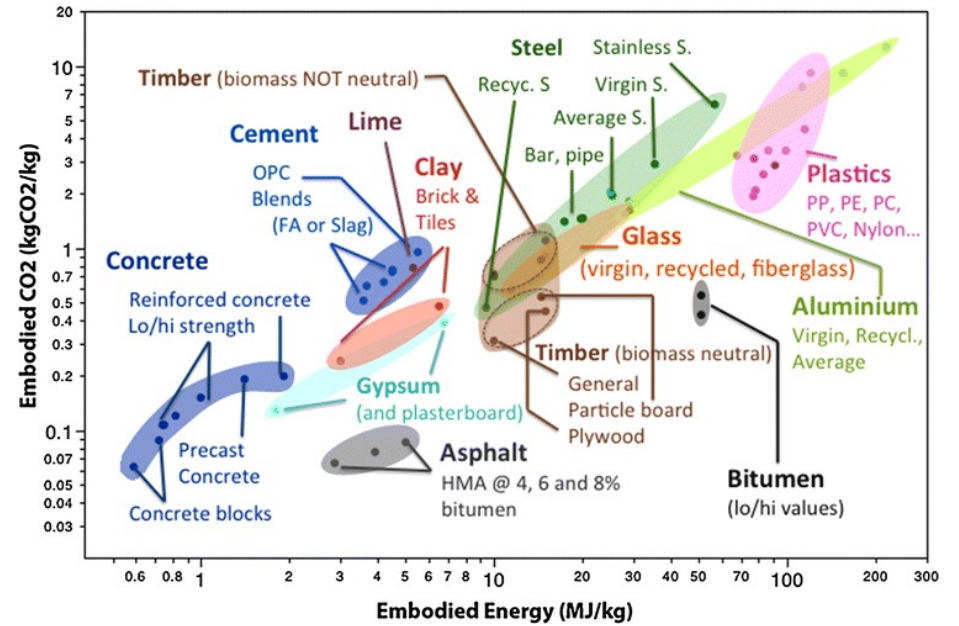
Sustainable energy technologies



Why do we use concrete as a construction material?



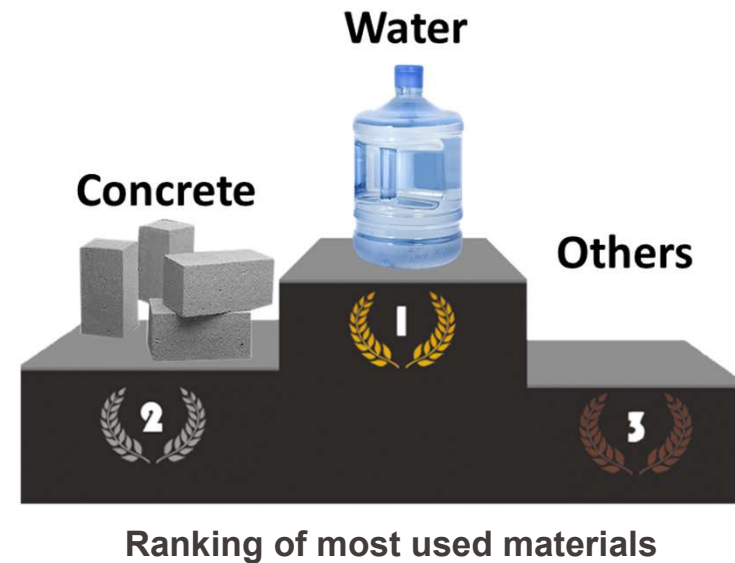
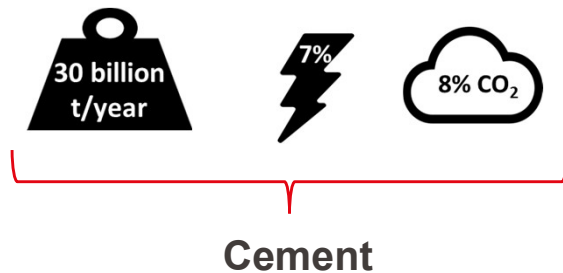
- ✓ Low-cost
- ✓ Availability
- ✓ Easy to use
- ✓ Versatility



Barcelo, L., Kline, J., Walenta, G. et al. Cement and carbon emissions. *Mater Struct* 47, 1055–1065 (2014).

As a consequence...

- We use a lot of it -> that is why it has a high environmental impact despite its relatively low environmental impact.
- There is still significant space for improvement in terms of embodied CO₂ content.

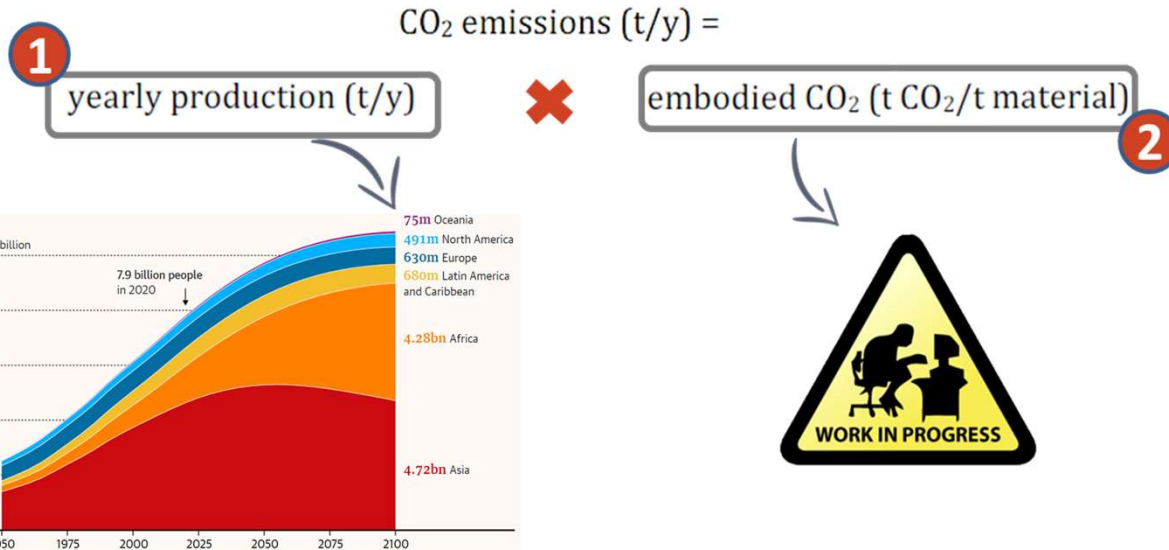


Why reducing carbon emissions?

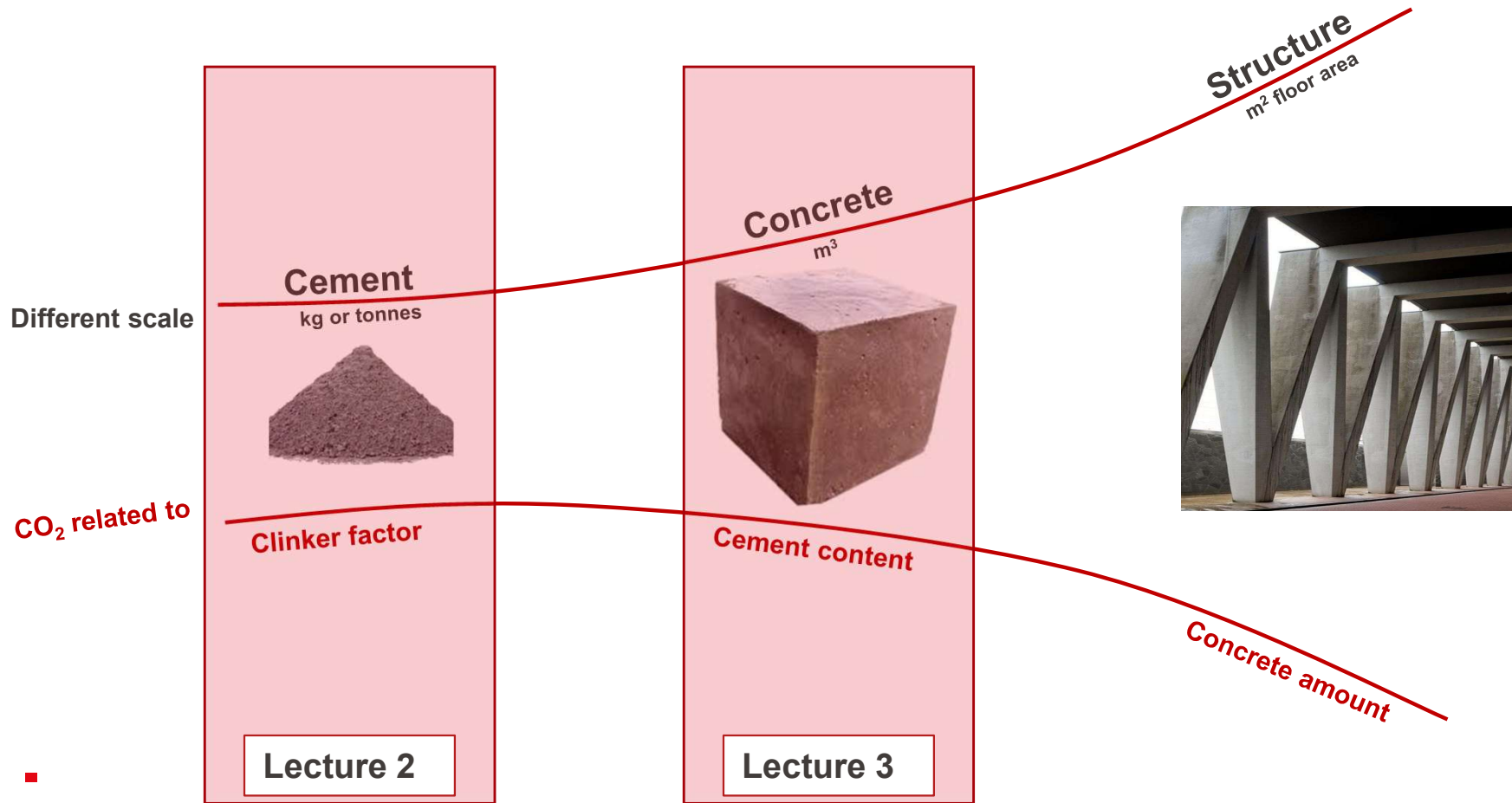
Paris Agreement, 2015:
Keep global warming below 2°C, targeting 1.5°C

Actual global warming = 2.4°C

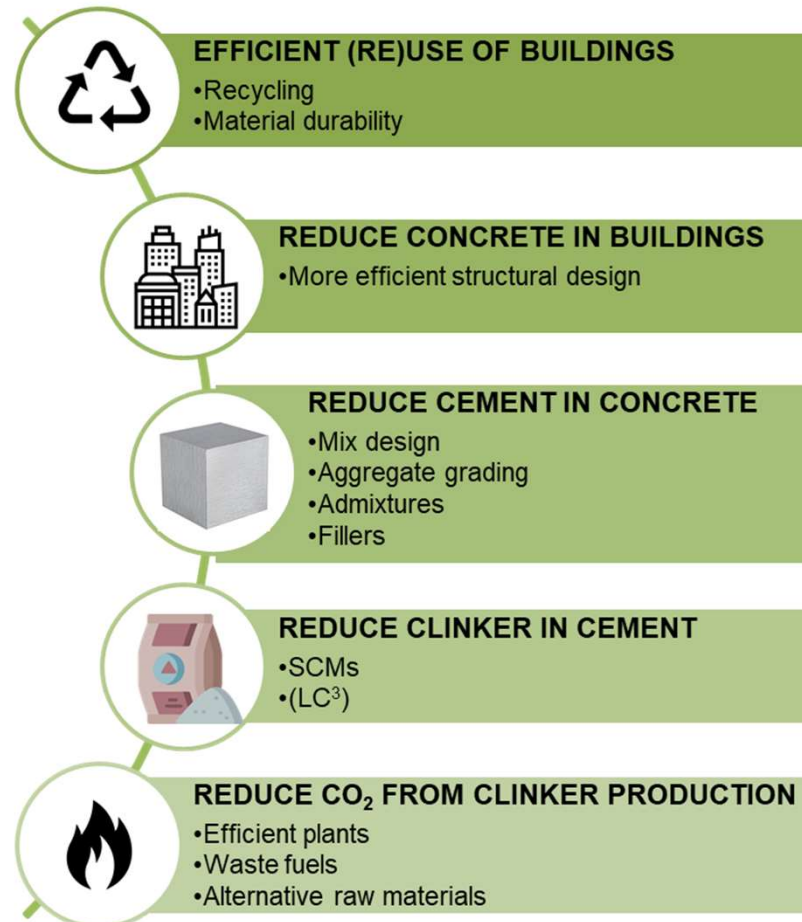
Intergovernmental Panel on Climate Change, 2018 and COP27:
Halving CO₂ emissions by 2030, carbon neutrality by 2050



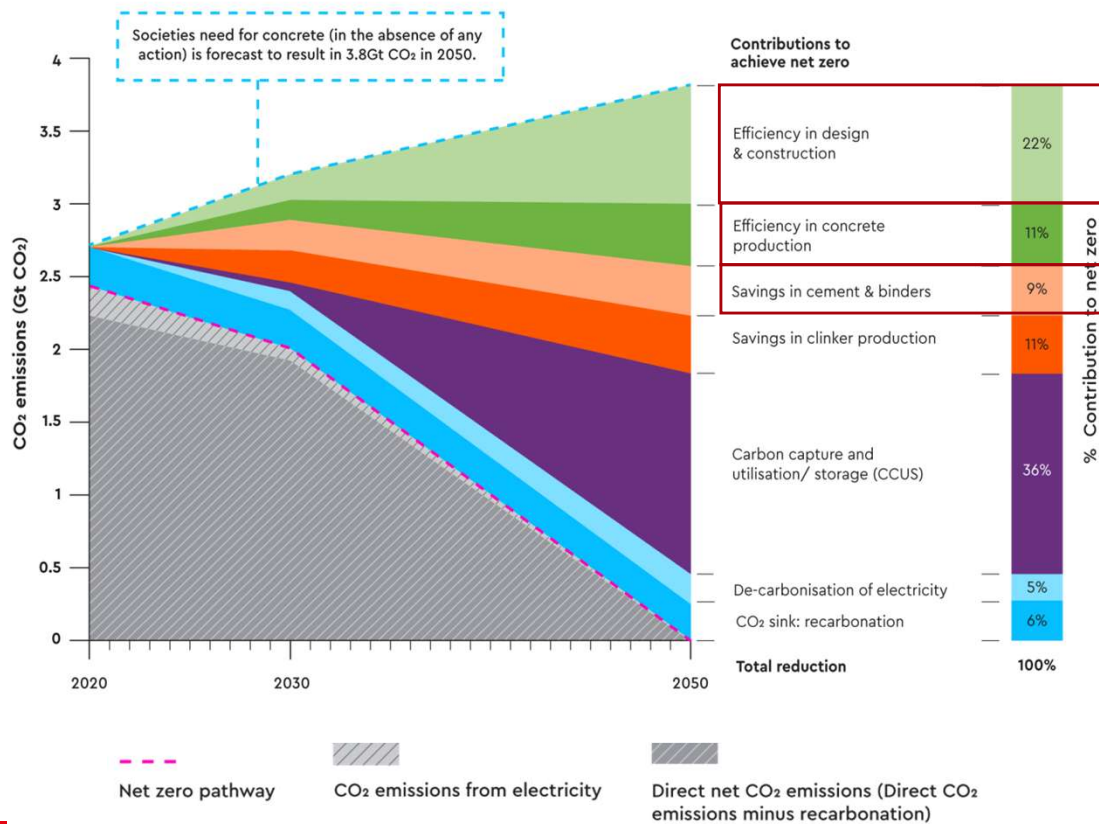
Embodied carbon at different scales



A multidimensional approach



A multidimensional approach - GCCA Roadmap



Structure

Concrete

Cement

Global Cement and Concrete Association (GCCA)

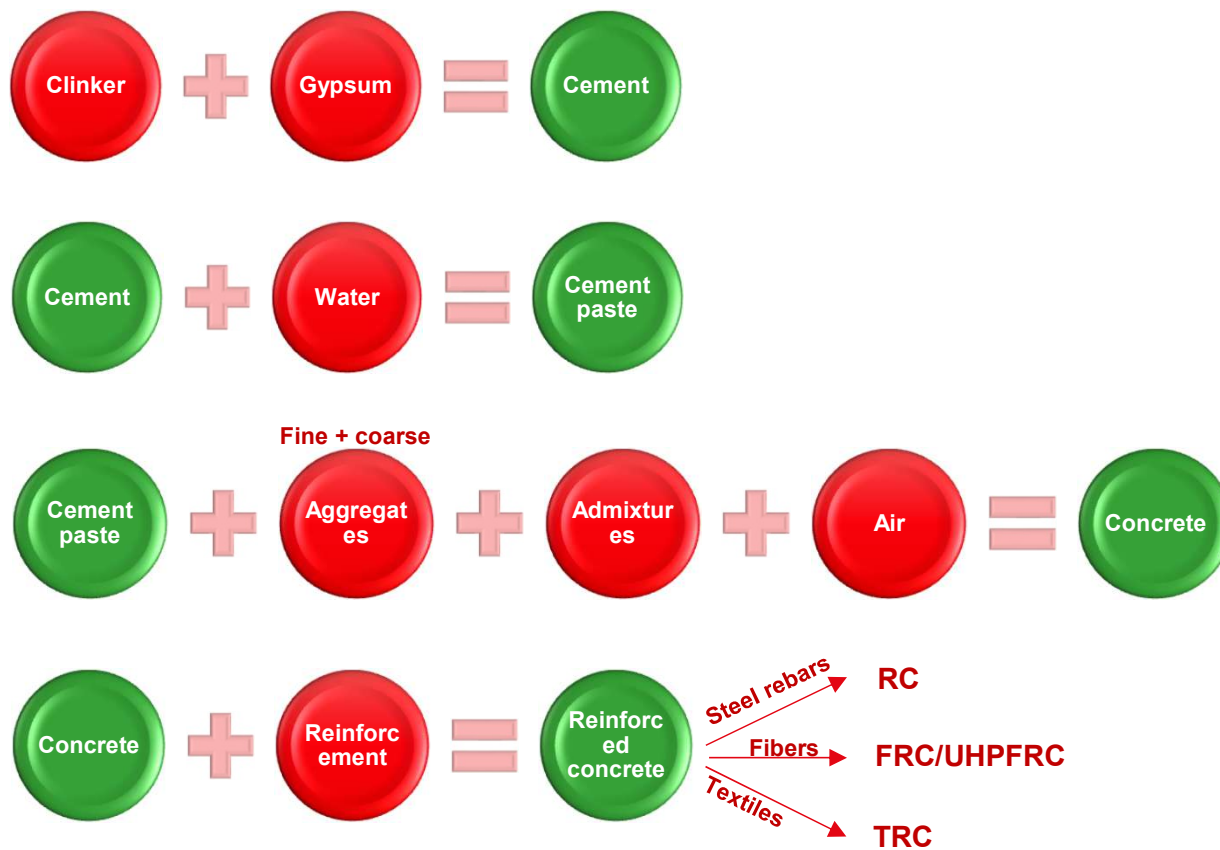
*“The GCCA 2050 Net Zero Roadmap sets out in detail how collectively, in collaboration with built environment stakeholders and policymakers, we will fully decarbonize the cement and concrete industry and provide **net zero concrete** for the world.”*

<https://gccassociation.org/concretefuture/>

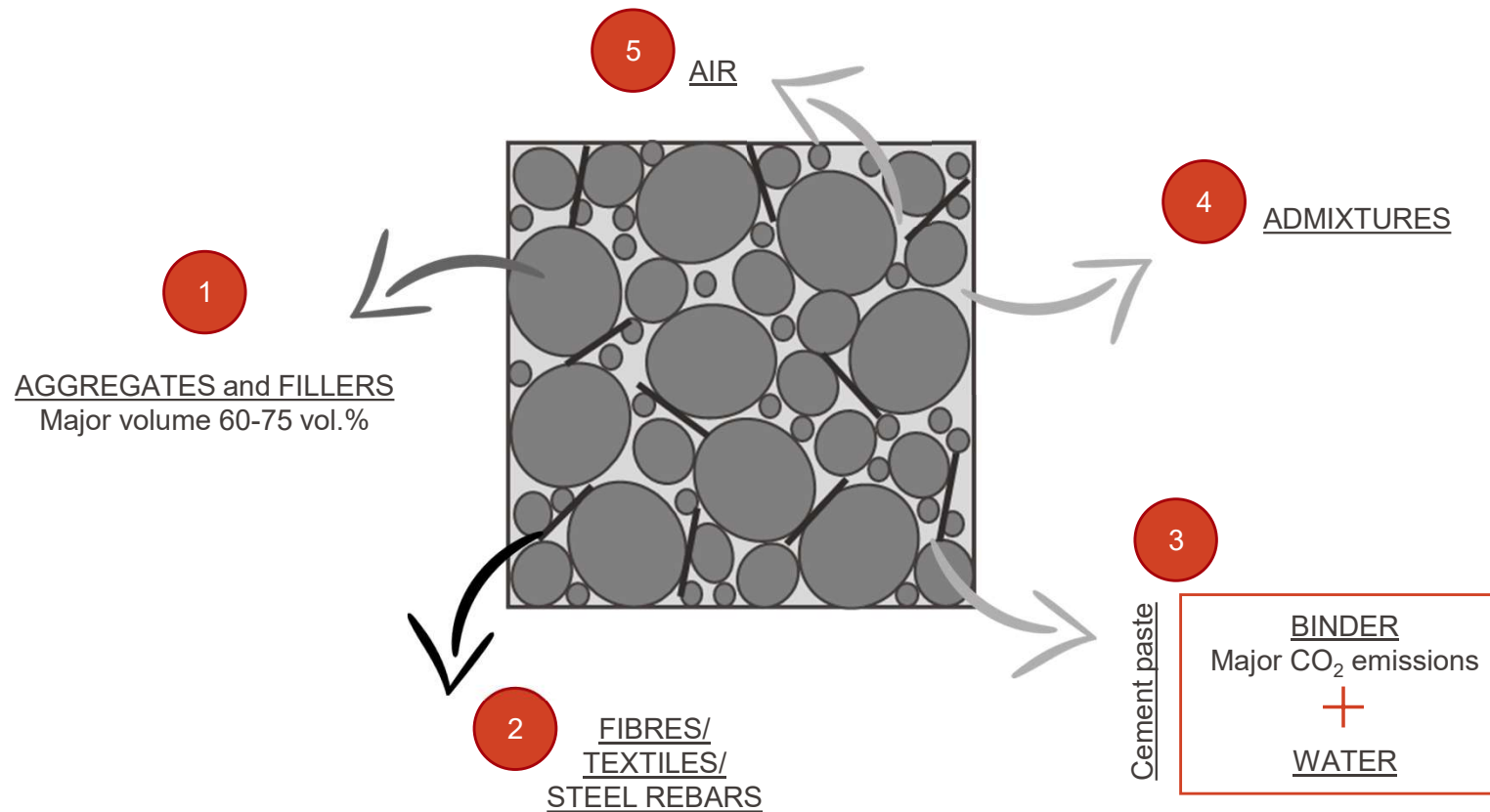
Concrete design

■

Review of basic definitions



Review of reinforced concrete components



Concrete design

“The ingredients of good concrete are very simple: water, cement, sand, aggregates, mineral additions and chemical admixtures. However, the ingredients of bad concrete are essentially the same. The difference lies in the know-how and the understanding”.

Neville, properties of concrete, 1996



1 Aggregates

Function:

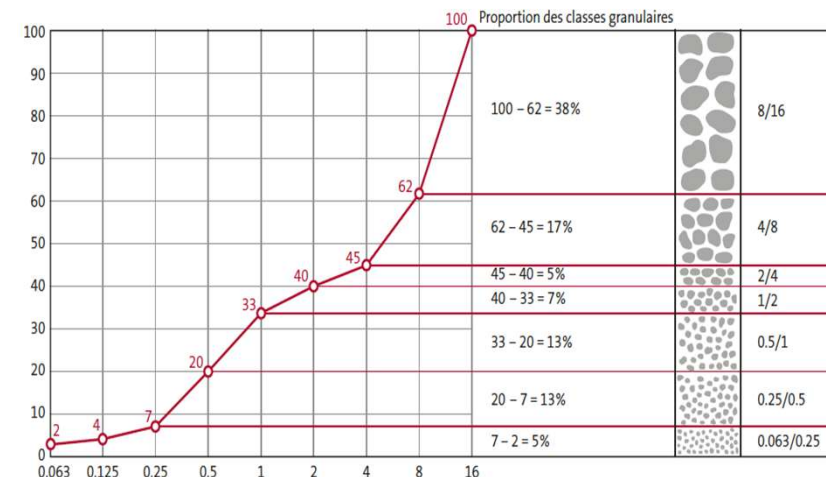
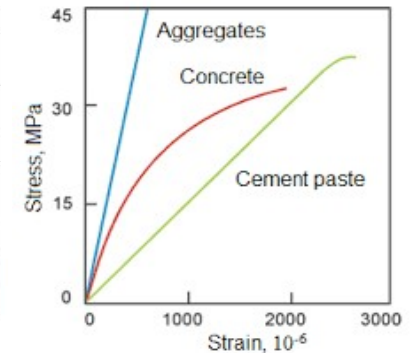
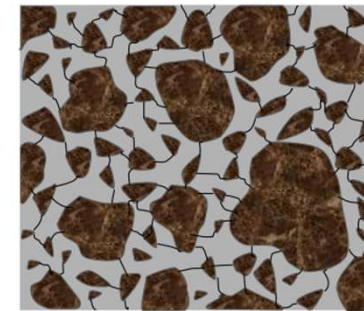
- Skeleton (60-75 vol.%),
- Reduce price (x5 less than cement)
- Reduce cement content (packing)
- Limit cracks and shrinkage

Requirements:

EN 12620

Properties:

- Nature (natural / recycled)
- Origin (river, lake, quarry, recycled concrete aggregates, ..)
- Mineralogy of the rock (sedimentary, metamorphic, volcanic..)
- Shape (round/cubic)
- Shape index
- Flakiness index
- Texture (smooth/rough)
- Size and fractions 0/4, 4/8, 8/16, 16/32, 32/64, 64/128 mm
- Impurities (should be clean!)



1

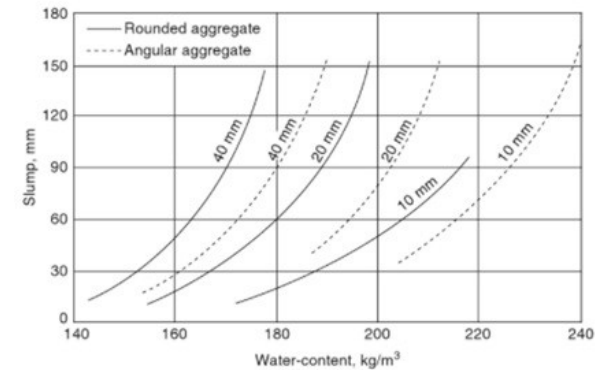
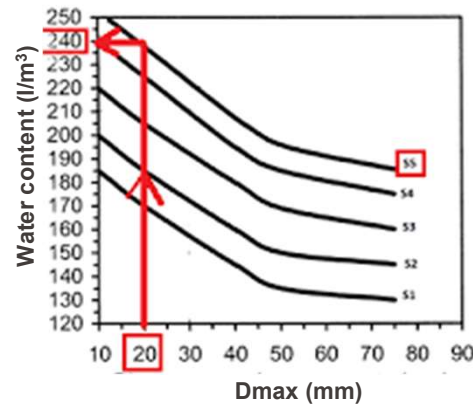
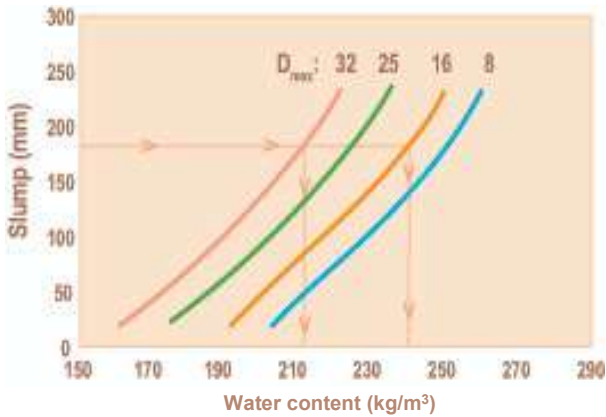
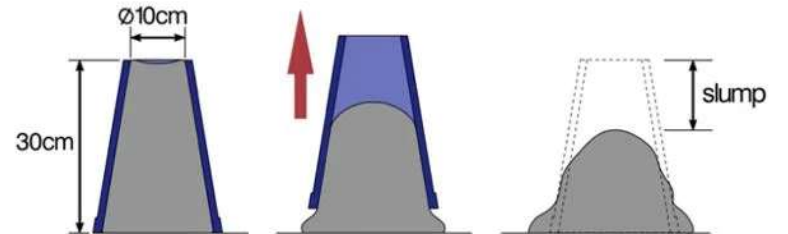
Aggregates

Aggregate size and shape:

Affect concrete workability (Slump)

Affect water content

Slump test - Workability



1 Aggregates

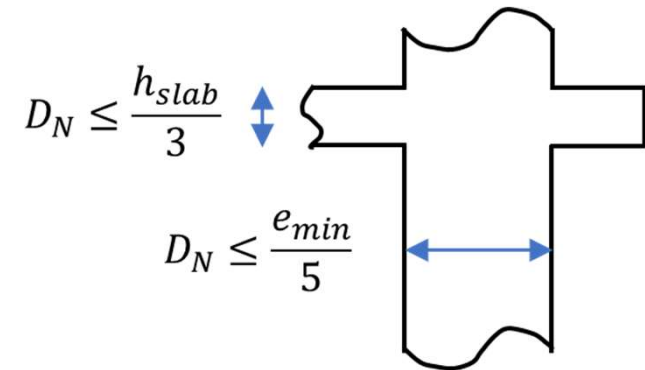
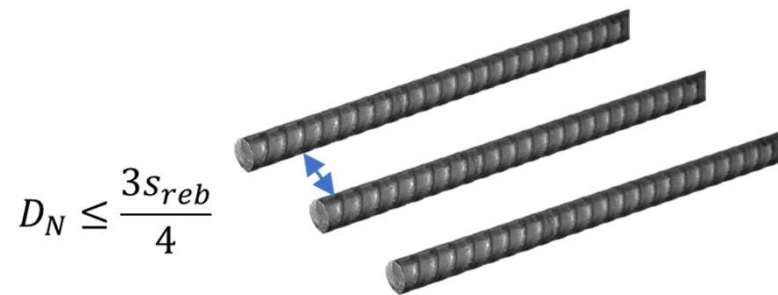
Choice of the maximum size of aggregate (D_N).

D_N is limited by:

Size of the element

Spacing between rebars

Min spacing between stirrups and formwork



FIBERS / TEXTILE / STEEL REBARS

2

If we see reinforced concrete as a composite material:

- Concrete is the matrix
- Fibers/fabrics/rebars-stirrups are the reinforcement

Function:

Provide tensile and shear, so bending strength
 Post-pone the failure
 Ductile failure mode
 Redistribution of stresses and cracks

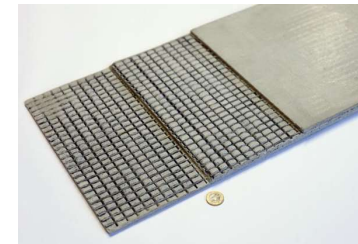
Properties:

Diameter/mesh size (μm to cm)
 Material (steel, PP, carbon, glass, ..)
 Texture (smooth, rough, improved adhesion)

Fibres



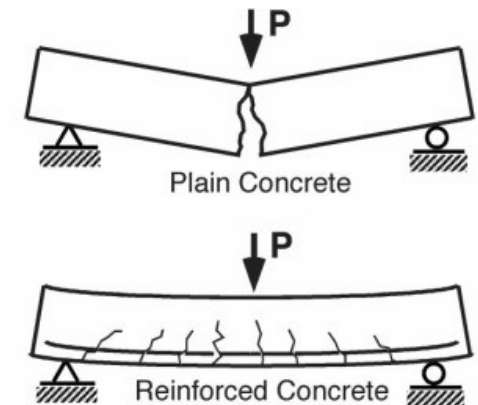
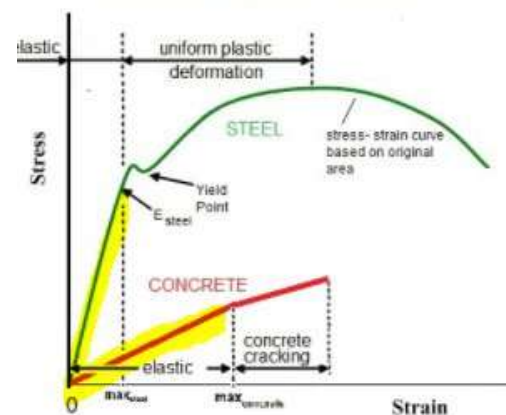
Fabric



Rebars+stirrups



Stress-strain diagram for steel and concrete



CEMENT PASTE (BINDER+WATER)

3

EN 197-1

Function:

- Bonding aggregates (around 30 vol.%)
- Develop hydration (chemical prop.)
- Develop mechanical resistance (mechanical prop.)
- Provide workability at fresh state (rheology prop.)

Requirements:

Cement type and SCMs– EN 197-1

Properties:

- Reactivity and heat of hydration
- Particle size distribution
- Cost
- Microstructure, permeability (durability)
- Content (w/b ratio, workability, bleeding, segregation, compaction)

Main types	Notation of the 27 products (types of common cement)		Composition (percentage by mass ^a)										Minor additional constituents		
			Main constituents												
			Clinker	Blast-furnace slag	Silica fume	Pozzolana		Fly ash		Burnt shale	Limestone				
						natural	natural calcined	siliceous	calcareous		L	LL			
K	S	D ^b	P	Q	V	W	T	L	LL						
CEM I	Portland cement	CEM I	95-100	–	–	–	–	–	–	–	–	–	–	–	0-5
CEM II	Portland-slag cement	CEM II/A-S	80-94	6-20	–	–	–	–	–	–	–	–	–	–	0-5
		CEM II/B-S	65-79	21-35	–	–	–	–	–	–	–	–	–	–	0-5
	Portland-silica fume cement	CEM II/A-D	90-94	–	6-10	–	–	–	–	–	–	–	–	–	0-5
		CEM II/A-P	80-94	–	–	6-20	–	–	–	–	–	–	–	–	0-5
	Portland-pozzolana cement	CEM II/B-P	65-79	–	–	21-35	–	–	–	–	–	–	–	–	0-5
		CEM II/A-Q	80-94	–	–	–	6-20	–	–	–	–	–	–	–	0-5
		CEM II/B-Q	65-79	–	–	–	21-35	–	–	–	–	–	–	–	0-5
		CEM II/A-V	80-94	–	–	–	–	6-20	–	–	–	–	–	–	0-5
	Portland-fly ash cement	CEM II/B-V	65-79	–	–	–	–	21-35	–	–	–	–	–	–	0-5
		CEM II/A-W	80-94	–	–	–	–	–	6-20	–	–	–	–	–	0-5
		CEM II/B-W	65-79	–	–	–	–	–	21-35	–	–	–	–	–	0-5
	Portland-burnt shale cement	CEM II/A-T	80-94	–	–	–	–	–	–	–	6-20	–	–	–	0-5
		CEM II/B-T	65-79	–	–	–	–	–	–	–	21-35	–	–	–	0-5
	Portland-limestone cement	CEM II/A-L	80-94	–	–	–	–	–	–	–	–	6-20	–	–	0-5
CEM II/B-L		65-79	–	–	–	–	–	–	–	–	21-35	–	–	0-5	
CEM II/A-LL		80-94	–	–	–	–	–	–	–	–	–	6-20	–	0-5	
CEM II/B-LL		65-79	–	–	–	–	–	–	–	–	–	–	21-35	0-5	
Portland-composite cement ^c	CEM II/A-M	80-88	←-----12-20-----→										0-5		
	CEM II/B-M	65-79	←-----21-35-----→												
CEM III	Blast furnace cement	CEM III/A	35-64	36-65	–	–	–	–	–	–	–	–	–	–	0-5
		CEM III/B	20-34	66-80	–	–	–	–	–	–	–	–	–	–	0-5
		CEM III/C	5-19	81-95	–	–	–	–	–	–	–	–	–	–	0-5
CEM IV	Pozzolanic cement ^c	CEM IV/A	65-89	–	←-----11-35-----→										0-5
		CEM IV/B	45-64	–	←-----36-55-----→										0-5
CEM V	Composite cement ^c	CEM V/A	40-64	18-30	–	←-----18-30-----→				–	–	–	–	–	0-5
		CEM V/B	20-38	31-49	–	←-----31-49-----→				–	–	–	–	–	0-5

CEMENT PASTE (BINDER+WATER)

3

Function of water:

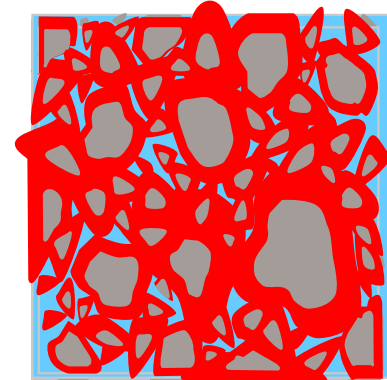
- Hydration (it continues until water is available)
- Development of strength over time
- Workability and consistency

Concrete does not dry, it becomes hydrated!

(chemical reaction between cement and water which forms hydrates).

Water is combined in hydrates (1 vol. solids -> 2 vol. hydrates)

Hydrates fill the space
Cement grains dissolve
Cement + water (after mixing)



CEMENT PASTE (BINDER+WATER)

3

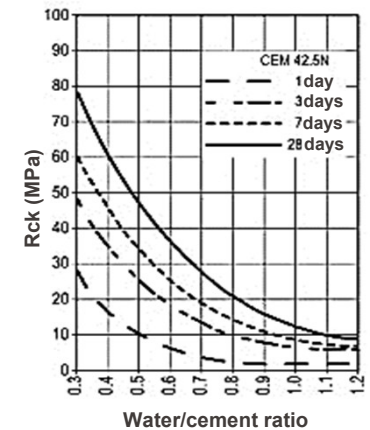
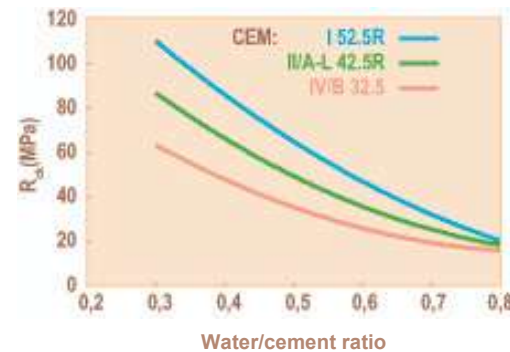
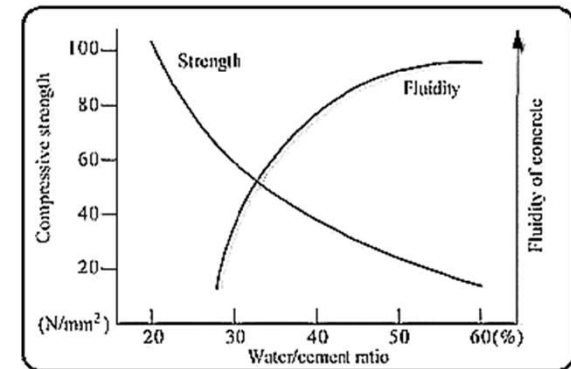


Higher water content or w/c ratio:

- Better workability
- Easier casting/compaction
- Higher porosity
- Risk of segregation/bleeding
- Lower strength

Lower water content or w/c ratio:

- Poorer workability
- More difficult casting/compaction
- Lower porosity
- Lower risk of segregation/bleeding
- Higher strength



CHEMICAL ADMIXTURES

4

Different function (as from ASTM 494/C494M-17):

- Water reducing admixtures
- Retarding admixtures
- Accelerating admixtures
- Water-reducing and retarding admixtures
- Water-reducing and accelerating admixtures
- Water-reducing, high-range admixtures
- Water-reducing, high-range, and retarding admixtures
- Specific performance admixtures

Different chemical composition

Most important use in concrete:

- control workability
- without increasing w/c ratio
- while keeping performances



■

CHEMICAL ADMIXTURES

Plasticisers / super plasticisers

Why plasticising?

Impacts on real applications



CHEMICAL ADMIXTURES

Plasticisers / super plasticisers

Real problem:

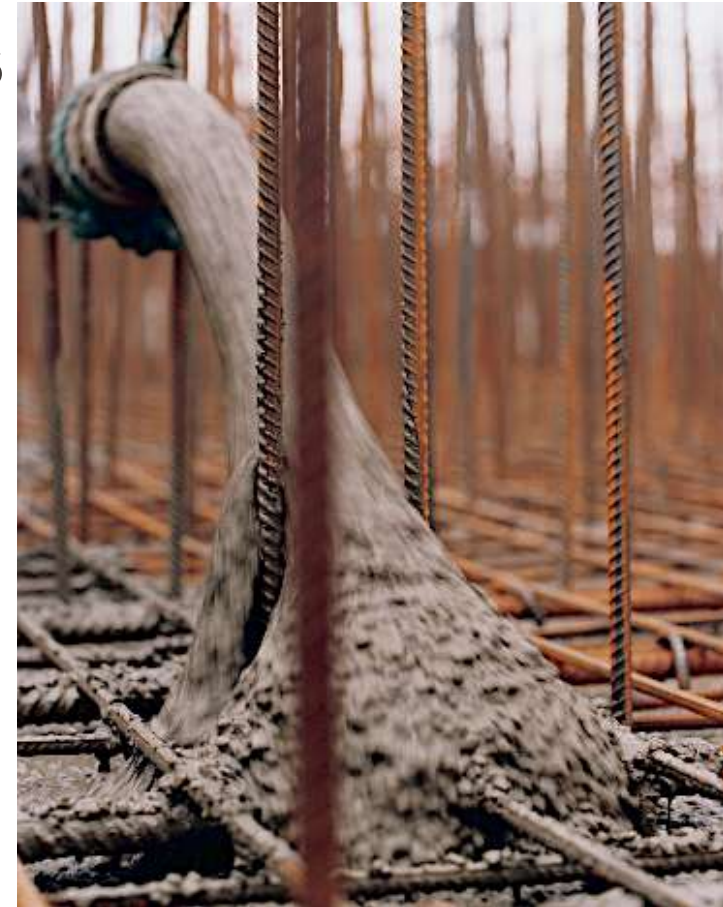
Need for workability during casting
without losing mechanical properties
and/or durability

Respect Standards EN 206

→ Remember: water addition
increases capillary porosity!

Solution :

Addition of plasticisers or
superplasticisers (dosage 0.1-1%)



CHEMICAL ADMIXTURES

Plasticisers / super plasticisers

Recent developments of concrete technologies:
→ Organic admixtures and mineral additions

High Performance
Concrete

Ultra High Performance
Fiber Reinforced Concrete



Shotcrete



Self compacting
concrete



CHEMICAL ADMIXTURES

Plasticisers / super plasticisers

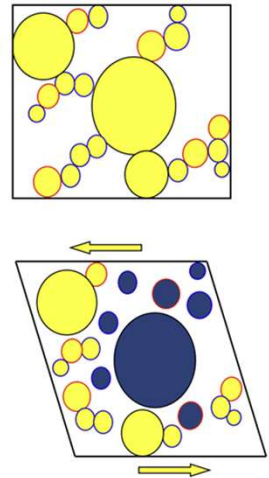
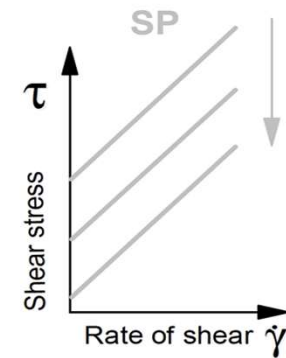
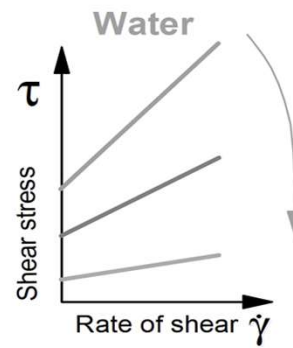
Fluidification

OR

Increase of w/c ratio
(durability - resistance)

OR

Increase of cement content



Wallevik, 2020

History of plasticisers / super plasticisers and composition

1930
1940
1950
1960
1970
1980
1990
2000
2010

Ligninsulphonates

Carbohydrates

$$\begin{array}{c}
 \text{COOM} \\
 | \\
 \text{H}-\text{C}-\text{OH} \\
 | \\
 \text{HO}-\text{C}-\text{H} \\
 | \\
 \text{H}-\text{C}-\text{OH} \\
 | \\
 \text{H}-\text{C}-\text{OH} \\
 | \\
 \text{CH}_2\text{OH}
 \end{array}$$

Naphthalinsulphonate

Melaminsulphonate

Vinyl Copolymer

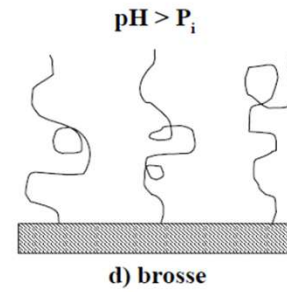
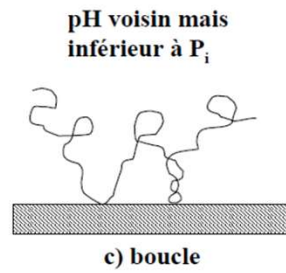
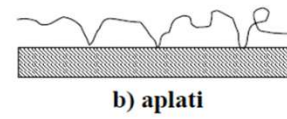
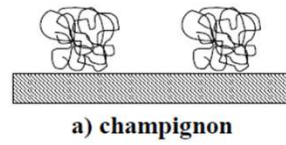
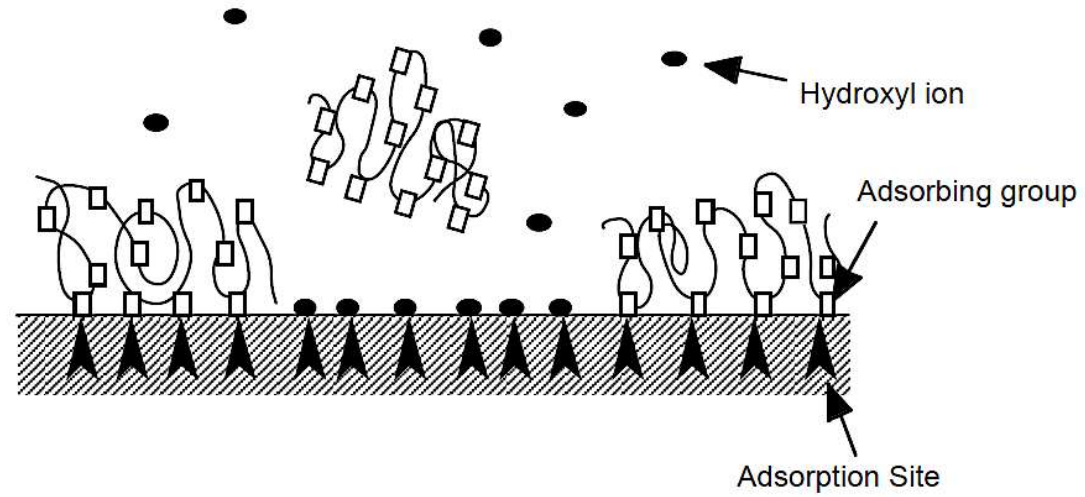
Poly-Carboxylate-Ether (PCE)

Stabilisation électro-statique (ancien)

Stabilisation stérique

Chemical structures shown include:
 - Ligninsulphonates: A polymer chain with a methoxy-substituted benzene ring and a sulfonate group (SO₃Na) attached to a carbon atom.
 - Carbohydrates: A Fischer projection of a sugar molecule with a COOM group at the top and a CH₂OH group at the bottom.
 - Naphthalinsulphonate: A naphthalene ring system with a sulfonate group (SO₃Na) attached to one of the rings.
 - Melaminsulphonate: A melamine ring system with a sulfonate group (CH₂SO₃Na) attached to one of the nitrogen atoms.
 - Vinyl Copolymer: A general structure for a vinyl copolymer with various side groups (NR¹R², COONa, H₂C, R³, R⁴).
 - Poly-Carboxylate-Ether (PCE): A copolymer structure with two repeating units: one with a carboxylic acid group (COOH) and another with an ether-linked side chain (CO-X-(CH₂CHRO-), R).

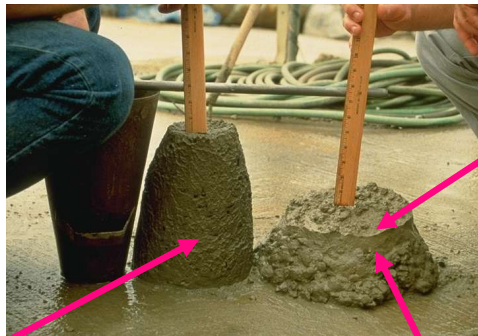
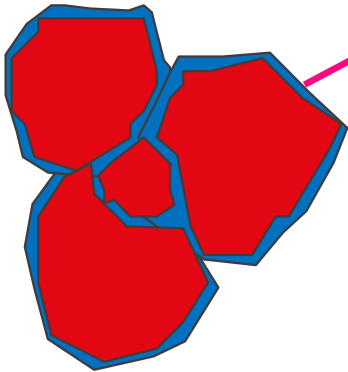
Mechanism:



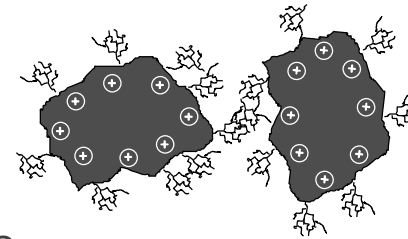
[Flatt, 1999]
[Perche, 2004]

Mechanism:

Van der Waals forces
(attractive)

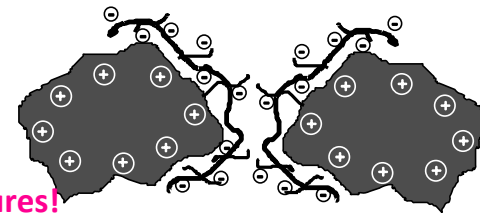


Sterique repulsion



Or:

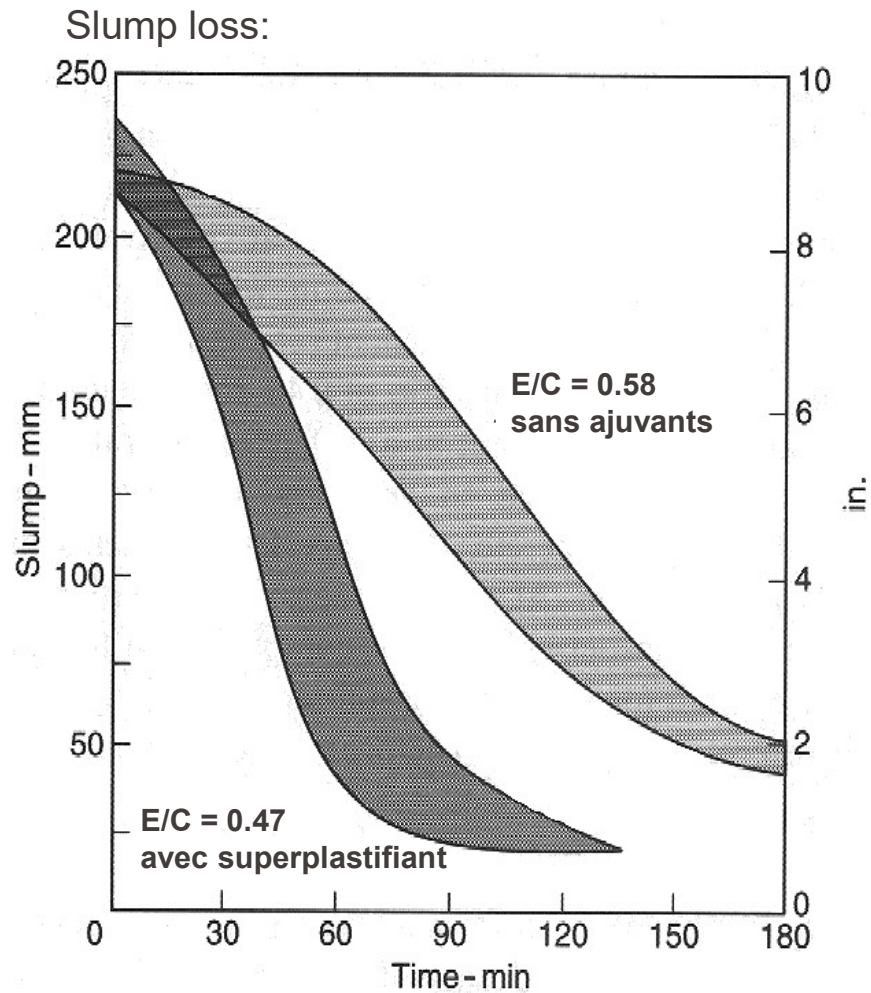
(Electrostatic repulsion)



The specific surface of the particles influences the effect of admixtures!

→ Importance of the fines





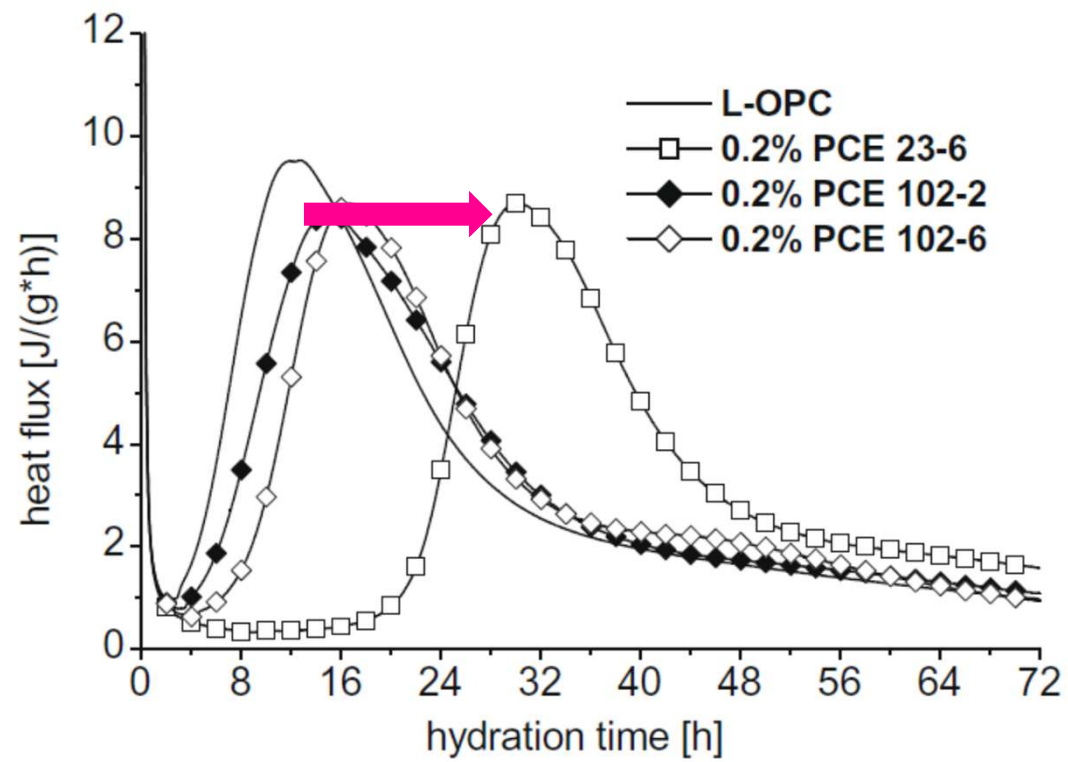
The effect of SPs is limited in time:
They are absorbed by hydration products.

The efficiency loss depends on:

- C_3A , SO_3 , alkalis
- temperature
- fineness

The efficiency loss can be minimised by
retarding the admixture addition
(on construction site)

Attention to the effect of PCE:
Certain have a retarder effect



[Zingg et al., 2009]

Concrete design

“The ingredients of good concrete are very simple: water, cement, sand, aggregates, mineral additions and chemical admixtures. However, the ingredients of bad concrete are essentially the same. The difference lies in the know-how and the understanding”.

Neville, properties of concrete, 1996

HOW DOES CONCRETE MIX DESIGN WORK ? AND HOW TO DESIGN LOW CARBON CONCRETE?

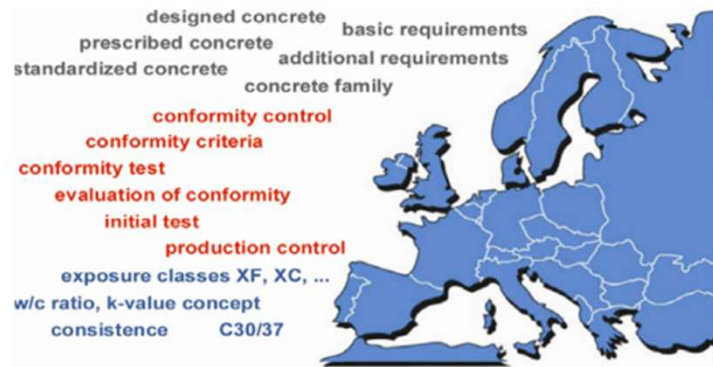
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STANDARD PRESCRIPTIONS

Every single component in concrete must meet some requirements prescribed by standards.

Here is the total set of European standards in concrete construction which takes into consideration **the interfaces between design and construction, concrete composition and manufacture, as well as the execution of concrete structures.**

Different standardization levels.



Concrete structure		
EN 1992 (EC 2) Design of concrete structures	EN 206-1 Concrete	ENV 13670-1 Execution of concrete structures
EN 12350 Testing fresh concrete	EN 197 Cement	
EN 12390 Testing hardened concrete	EN 450 Fly ash	
EN 13791 Assessment of concrete strength in structures	EN 13263 Silica fume	
EN 12504 Testing concrete in structures	EN 934-2 Admixtures for concrete	
	EN 12620 Aggregates for concrete	
	EN 13055-1 Light-weight aggregates	
	EN 1008 Mixing water for concrete	
	EN 12878 Pigments	

C. Müller 2012, Use of cement in concrete according to European standard EN 206-1

STANDARD PRESCRIPTIONS

At the concrete and structural level, for a given exposure class Standards prescribe:

- Minimum strength class,
- Minimum water/cement (w/c) or water/binder (w/b) ratio,
- Minimum cement content
- Minimum cover depth

*Guide for the concrete mix design!
High safety factors, safe design.
But also a limitation to CO₂
emission (see later)*

Requirements for carbonation exposures in various standards.

Standard	Exposure Class	Exposure	Minimum 28 day Strength MPa	Max. w/(c + k(SCM)) or w/(c + SCM)	Min. Cement Content kg/m ³	Minimum Curing Period days	Minimum cover depth mm
EN206	XC1	Dry or permanently wet	C20/25	0.65	260	^a	25 ^c
	XC2	Wet, rarely dry	C25/C30	0.60	280	^a	35 ^c
	XC3	Moderate humidity	C30/C37	0.55	280	^a	35 ^c
	XC4	Cyclic wet and dry	C30/C37	0.50	300	^a	40 ^c
ACI 318	Not Covered	If also exposed to freezing, unsaturated	27.6	0.55	-	7	50
CSA A23.1	Not Covered	If also exposed to freezing, unsaturated	25	0.55	-	3	40 ^d
AS3600 ^b	A2	Moderate Humidity	25	-	-	3	45
	B1	Tropical	32	-	-	7	40
	B1	Cyclic wet and dry	32	-	-	7	40
GB/T50476 (China) 50 y design life	I-A	Indoor, Dry < 60% rh	25	0.60	260	3	20
	I-B	Sheltered, Outdoor or Indoor, humid	30	0.55	280	3	20
	I-C	Outdoor, exposed to Rain	35	0.50	300	3	30 ^{***}

R. Douglas Hooton 2019, Future directions for design, specification, testing, and construction of durable concrete structures

CONCRETE DESIGN

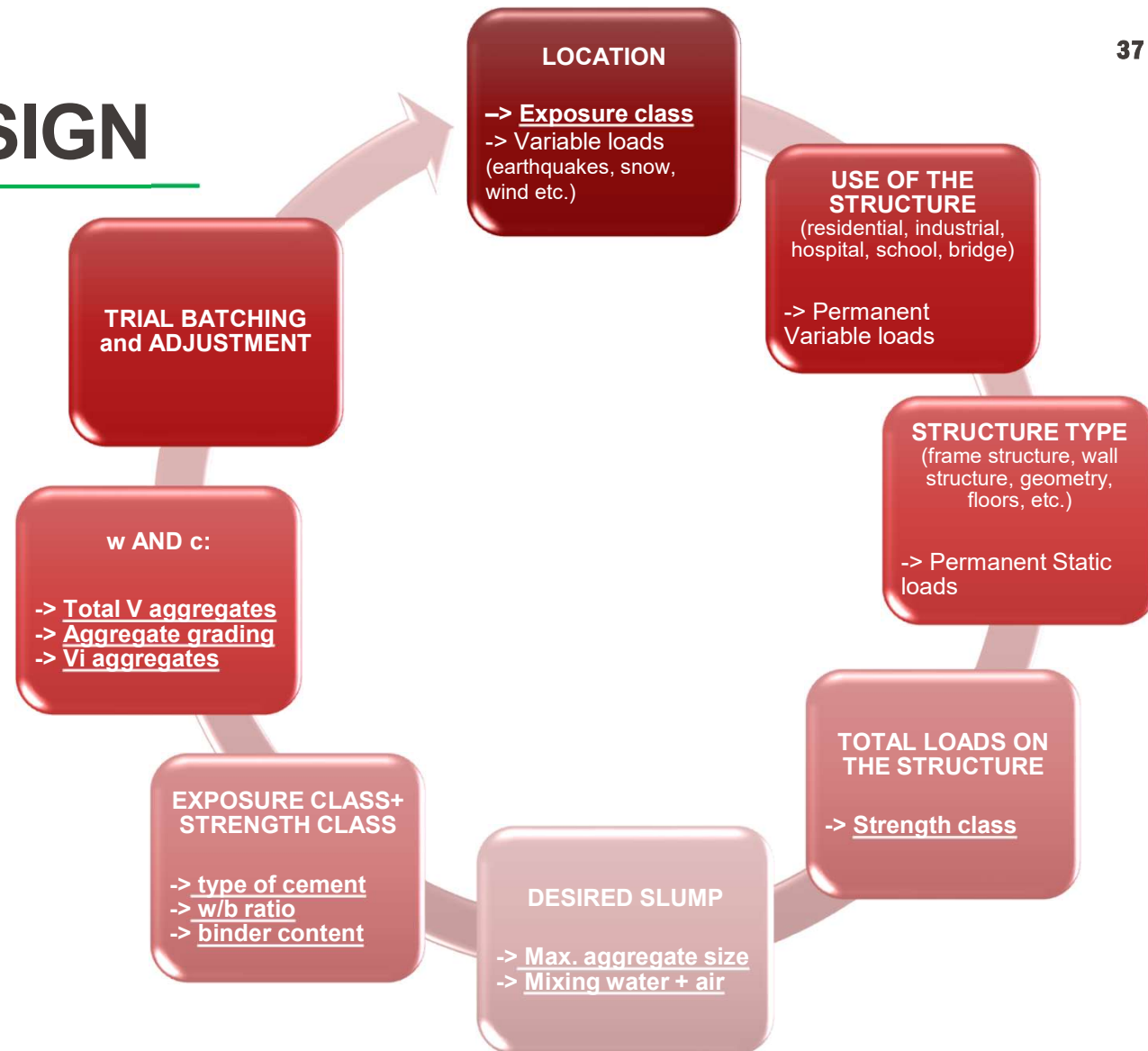
Structural design and concrete design affect each other.

Iterative workflow.

Decision-making process.

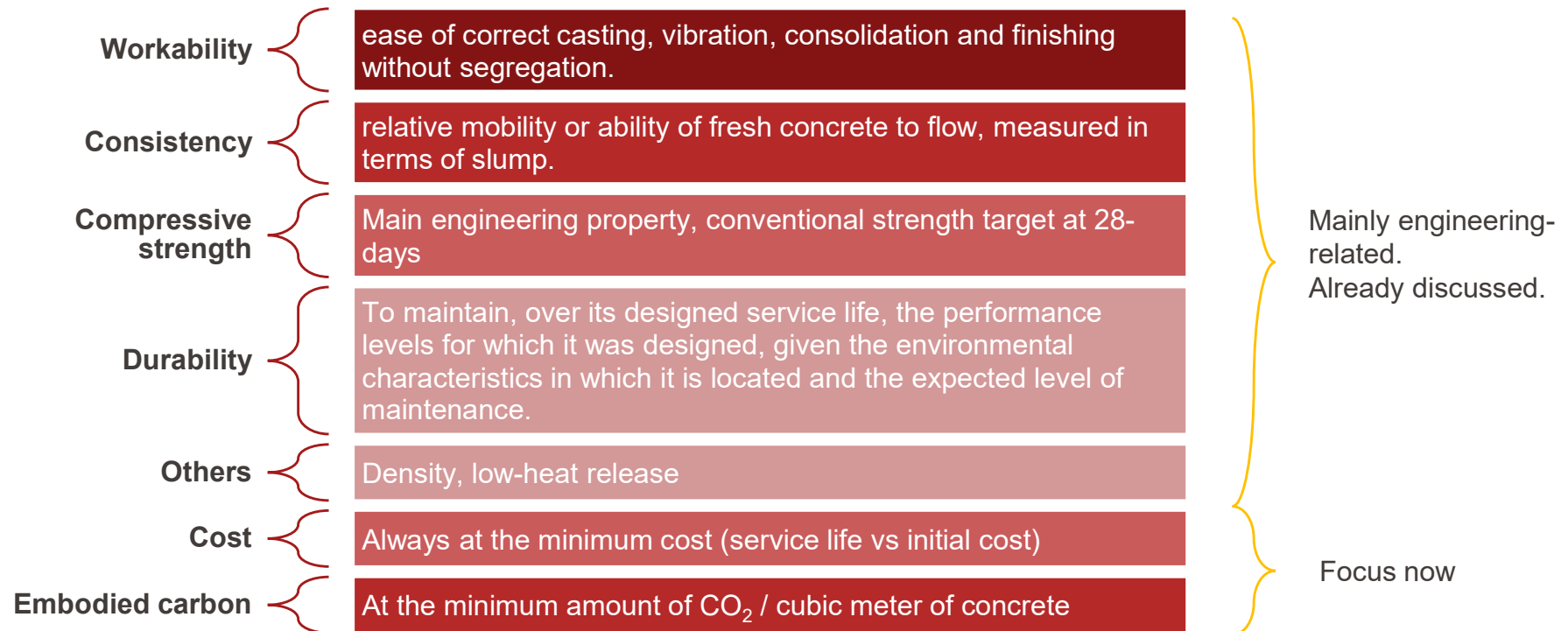
Standards-driven process but with a margin of choice.

The mix design of concrete is strictly dependent on structural design. (Location, exposure, strength class required, required slump).



CONCRETE DESIGN - GOALS

The main goal of concrete mix design is to provide certain properties of interest:

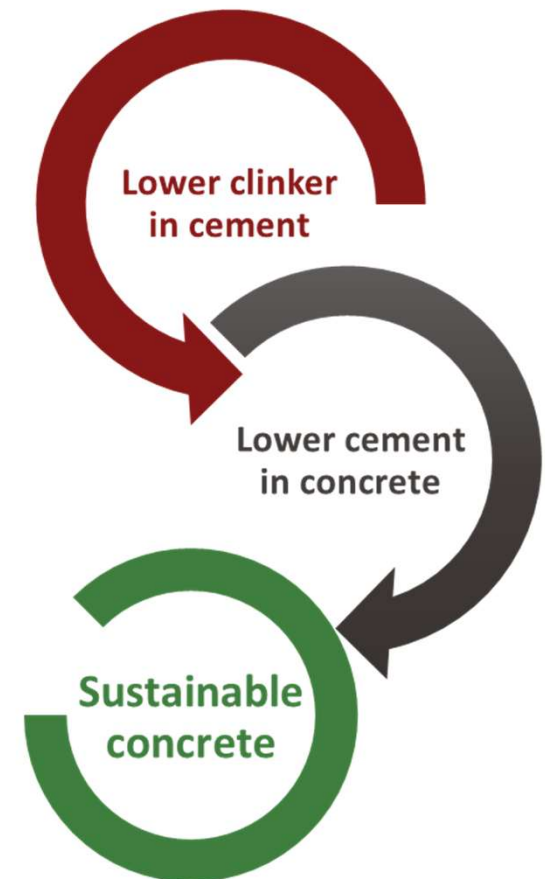


SUSTAINABILITY CONSIDERATIONS

Embodied CO₂ of concrete comes from clinker
(850 kg CO₂ / ton of clinker)!

How to reduce the clinker content in concrete, thus making
concrete more sustainable???

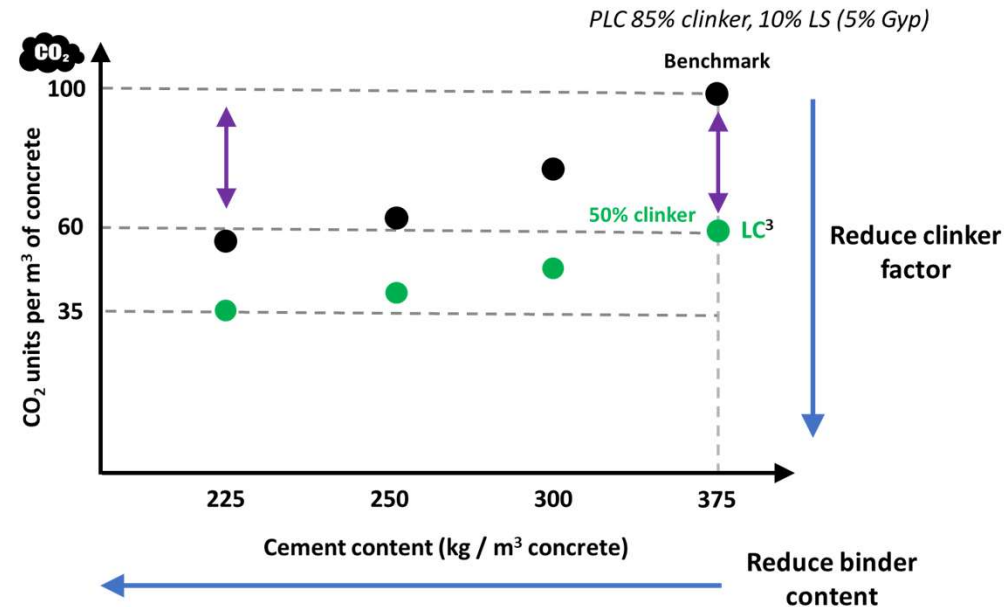
1. **Reduce the amount of clinker in cement by incorporating SCMs** (use blended cements), while retaining or improving performance.
2. Reduce the amount of cement per cubic meter of concrete, while retaining workability, strength and durability.



SUSTAINABILITY CONSIDERATIONS

How to reduce the clinker content in concrete, thus making concrete more sustainable???

1. **Reduce the amount of clinker in cement by incorporating SCMs** (use blended cements).
2. Reduce the amount of cement per cubic meter of concrete



SUSTAINABILITY CONSIDERATIONS

Only achievable if the concrete mix is designed correctly.

Technological and engineering approach.

Some useful parameters to control to achieve sustainability:

1. **Select the slump**
2. **Select the max. size of aggregate and aggregate grading**
3. **Select the mixing water and air**
4. **Select w/b**
5. **Select binder type (blended cements)**

Aggregates



Chemical admixtures

Use of SCMs

■

1. LOWEST SLUMP

The slump is specified by the contractor/field engineer and measured by ASTM C143-143M-20.
If not specified, ACI 211.1-91 provides reference values.

Requirement: Concrete needs to flow and fill the spaces between rebars (without segregating).

Lower slump -> lower water dosage -> lower binder content (at constant w/b).

Solution for sustainable concrete: **Use the lowest slump possible that meets the requirements of the project!**

*can be increased using admixtures

Type of construction	Slump (mm)	
	Max.*	Min.
Foundations (reinforced)	75	25
Foundations (plain)	75	25
Beams and walls	100	25
Columns	100	25
Pavement and slabs	75	25



Placing issues
(honeycomb)

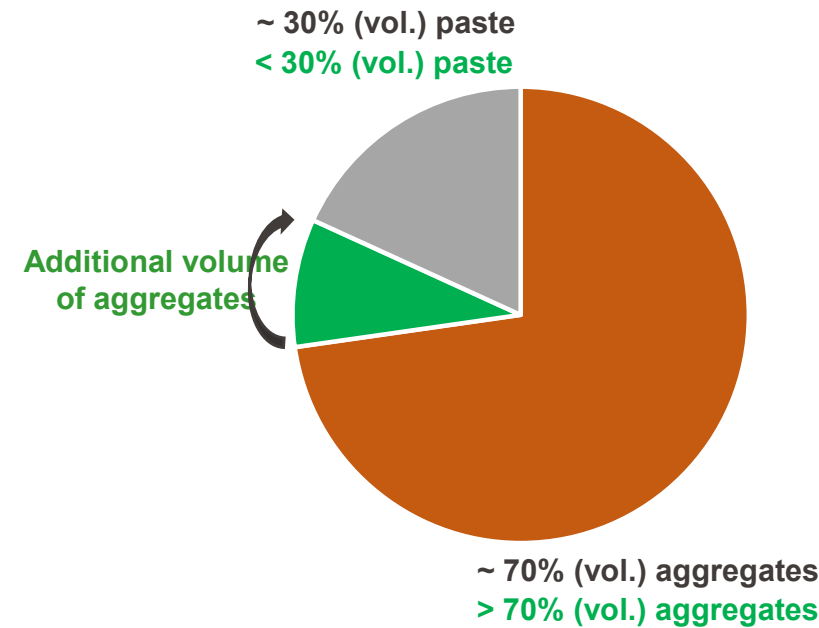
2. BEST GRADATION and LARGEST D_N

Cement paste is a lubricant between aggregates enabling flow. It coats and separates aggregates.

Increase the volume of aggregate -> reduce paste volume as much as possible.

Possible by:

- 1. Optimizing the aggregate gradation**
- 2. Increasing the maximum size of aggregates**



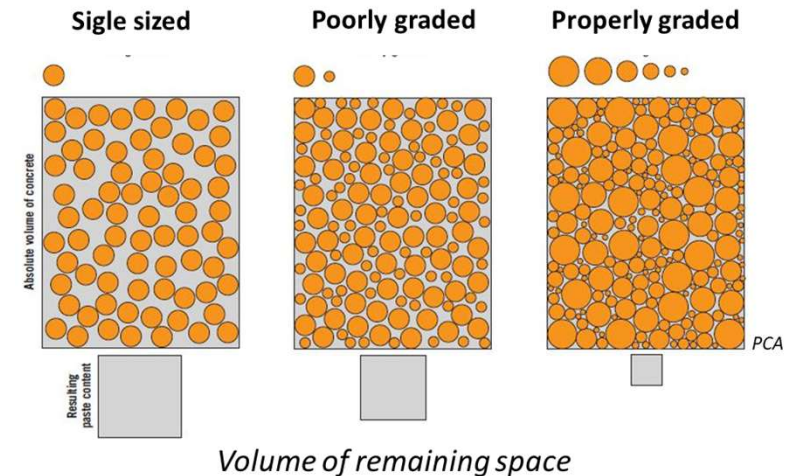
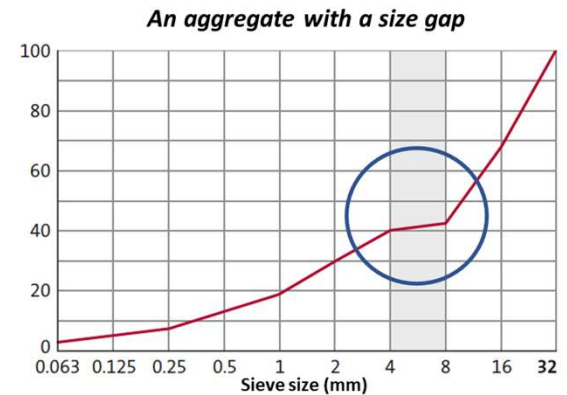
2. BEST GRADATION and LARGEST D_N

Optimizing the gradation of aggregates provide:

- Smooth and no-gaps- granulometric curve (packing density or void content of combined aggregate fractions).
- Filling the space between large aggregates with fine aggregates (fillers).
->Only the small gaps that cannot be taken by fine aggregates remain to be filled with cement paste.

Solution for sustainable concrete:

Use the best gradation possible to lower voids!



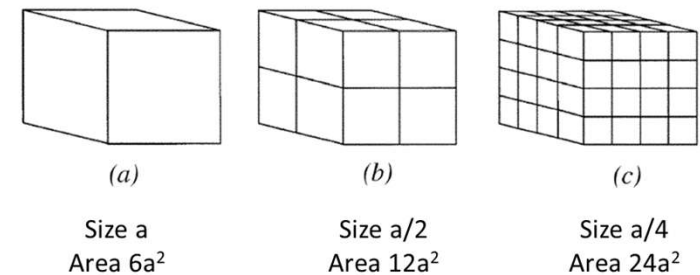
2. BEST GRADATION and LARGEST D_N

Increasing the maximum size of aggregates D_N :

- Reduces surface/volume ratio -> lower amount of paste (binder) to coat the surface of aggregates.
- Reduces the void content between aggregates -> lower amount of paste (binder) required to fill the voids.

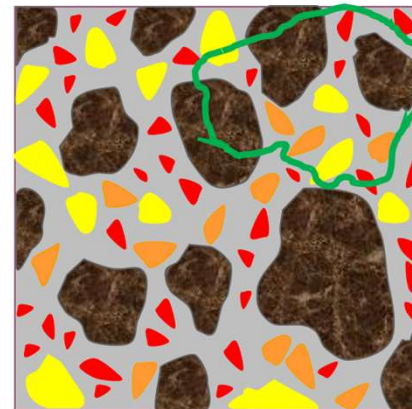
Solution for sustainable concrete: **Use the largest D_N available that is technically/economically feasible.**

Size effect on surface area (at constant volume)

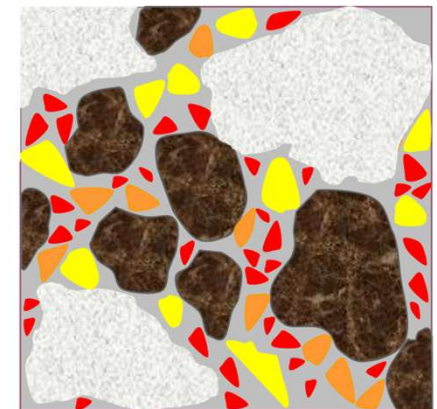


ACI E1-07

Well graded, D_N 12.5 mm



Well graded, D_N 25 mm



3. MIXING WATER

At constant w/b ratio, water content is directly proportional to cement content.

Higher slump -> higher mixing water dosage
(at constant binder content - higher w/b
at constant w/b – higher cement content)

Higher D_N -> lower mixing water dosage at
constant slump (and lower entrapped air)

Solution for sustainable concrete: **Reduce the water content to reduce cement content.**

-> **Larger aggregates**

-> **Admixtures**

Table A1.5.3.3 (ACI 211.1-91, for well-graded angular aggregates)

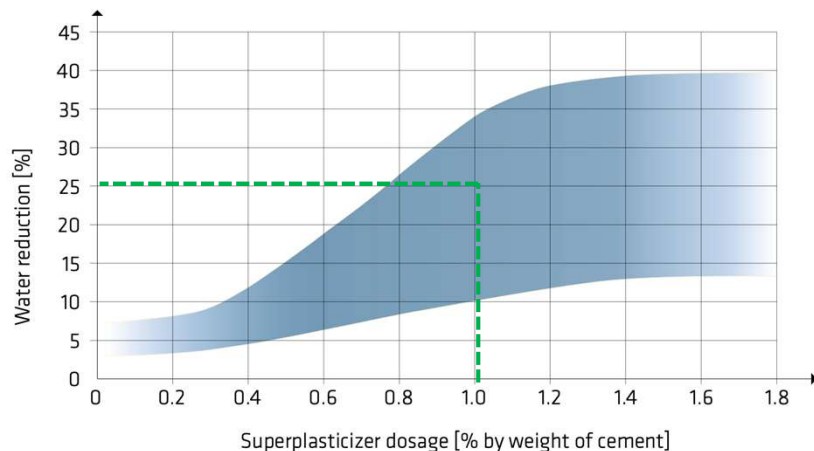
Slump, mm	Water, kg/m ³ of concrete for indicated nominal maximum sizes of agg				
	9.5 mm*	12.5 mm*	19 mm*	25 mm*	37.5 mm*
Non-air-entrained concrete					
25 to 50	207	199	190	179	166
75 to 100	228	216	205	193	181
150 to 175	243	228	216	202	190
Approximate amount of entrapped air in non-air-entrained concrete, percent	3	2.5	2	1.5	1

3. MIXING WATER

Chemical admixtures can enable to achieve certain properties (slump, early-age strength, shrinkage) and reduce the embodied CO₂ content.

Use chemical admixtures in the form and dosage recommended by the manufacturer

Solution for sustainable concrete: **Use chemical admixtures to reduce water demand (reduce w/b) and so cement content.**



Reducing CO₂ by using SP, exercise:

Hypothesis:

Water demand: 200 kg/m³

CO_{2,eq} PC = 0.82

CO_{2,eq} SP = 1.88 (EFCA EPD)

Cost PC = CAD 150 / ton (Statista, 2020 value)

Cost SP = CAD 13 / m³ (Canadian building materials, pricelist 2021)

<u>No SP</u>	<u>1% SP</u>
Water = 200 kg /m ³	Water = 150 kg /m ³
w/c = 0.45	w/c = 0.45
PC = 444 kg /m ³	PC = 333 kg /m ³
	SP = 3.3 kg /m ³ (2.1 L/m ³)
Binder = \$ 54.6	Binder = \$ 53.9
CO _{2EQ} PC = 364 kg/m ³	CO _{2EQ} PC = 273 kg/m ³
	CO _{2EQ} SP = 6.2 kg/m ³
	CO_{2EQ} = 279.2 kg/m³

-23% ! →

4. WATER/BINDER RATIO

Max w/b is prescribed by Standards and depends on:

- Min. strength class to achieve
- Exposure class (durability)

Max w/b vs compressive strength depends on cement type! (Slide 22) ->

Same strength target – different cement types – different w/b ratios

Solution for sustainable concrete:

Not always obvious which w/b allows for more sustainable concrete. Depends on strength and durability requirements!

Reducing CO₂ by using different w/b ratios, **exercise:**

Hypothesis:

Target slump: 100 mm

Two target strengths:

- 25 MPa
- 45 MPa

Two cement types:

- General use, 70% clinker
- High strength, 80% clinker

Water for D_N 25 mm = 193 kg/m³

Slump, mm	Water, kg/m ³ of concrete for indicated nominal maximum sizes of agg				
	9.5 mm'	12.5 mm'	19 mm'	25 mm'	37.5 mm'
	Non-air-entrained concrete				
25 to 50	207	199	190	179	166
75 to 100	228	216	205	193	181
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Approximate amount of entrapped air in non-air-entrained concrete, percent	3	2.5	2	1.5	1

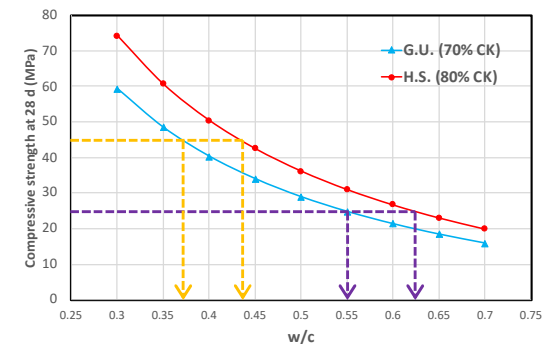
Clinker content (cement content)?

Case 1, 25MPa

Cement type	w/b	Clinker (kg/m ³)	CO ₂ (kg/m ³)
GU	0.55	246	202
HS	0.62	248	203

Case 2, 45MPa

Cement type	w/b	Clinker (kg/m ³)	CO ₂ (kg/m ³)
GU	0.37	365	299
HS	0.43	357	292



5. SCMs

Solution for sustainable concrete: **Use of SCMs to reduce clinker in the binder.**

$$(\text{Cement} + \text{SCMs}) = \frac{\text{water}}{w/b}$$

Warning: SCMs have lower densities than OPC

Portland cement ($3.0 < \rho < 3.1$)

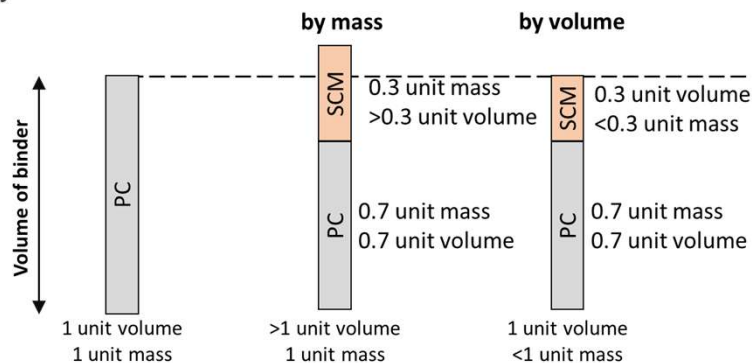
Fly ash ($2.0 < \rho < 2.6$)

Natural pozzolans ($2.4 < \rho < 2.7$)

Calcined clays ($2.2 < \rho < 2.6$)

GGBFS ($2.7 < \rho < 2.9$)

-> Be aware of the proportioning approach! by mass vs by volume



Proportioning of LC³-50 (55% OPC, 30%CC, 15%LS), exercise:

by mass:

$$\rho_{PC} = 3.0$$

$$\rho_{CC} = 2.5$$

$$\rho_{LS} = 2.7$$

$$\text{Tot. mass} = 100\text{kg}$$

$$V_{100PC} = \frac{100}{\rho_{PC}} = 33.3 \text{ lt}$$

$$V_{LC^350} = \frac{55}{\rho_{PC}} + \frac{30}{\rho_{CC}} + \frac{15}{\rho_{LS}} = 35.9 \text{ lt}$$

$$\Delta V = \frac{35.9}{33.3} = 1.08 \rightarrow +8\%$$

Same w/b (by mass)

But more vol. paste

Less vol. water to coat all the particles – workability issues -> use SPs

by volume:

$$\rho_{PC} = 3.0$$

$$\rho_{CC} = 2.5$$

$$\rho_{LS} = 2.7$$

$$\text{Tot. volume} = 1 \text{ lt}$$

$$M_{100PC} = \rho_{PC} \times 1 = 3\text{kg}$$

$$M_{LC^350} = (\rho_{PC} \times 0.55) + (\rho_{CC} \times 0.30) + (\rho_{LS} \times 0.15) = 2.80\text{Kg}$$

$$\Delta M = \frac{2.8}{3} = 0.93 \rightarrow -7\%$$

$$\frac{\Delta w}{b} = \frac{w}{0.93 b} = +7\%$$

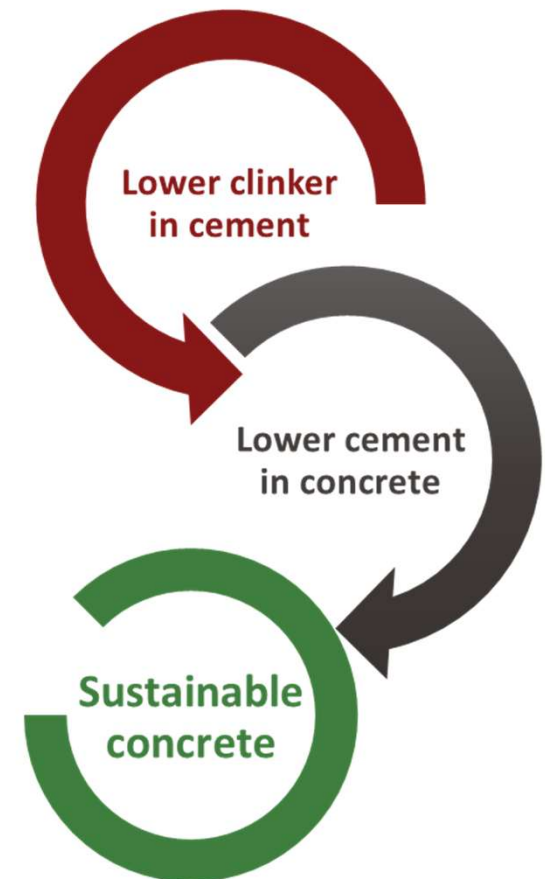
Same cement paste (by volume)

But higher w/b

RECAP ON SUSTAINABILITY

The golden rule is to develop (blended) cements with the least amount of embodied CO₂ that have sufficient performance to enable their use without a significant increase in binder content per m³

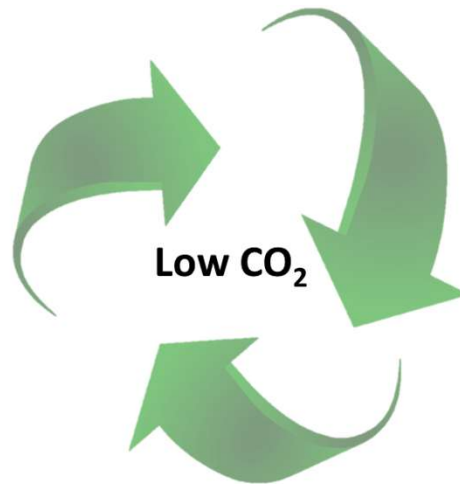
A sustainable concrete conceived this way is also cost-effective!



RECAP ON SUSTAINABILITY

Aggregates

- Get the **best (packed) aggregate gradation**
- Use the **largest D_N** feasible



Chemical admixtures

- Consider the **use of (super)plasticizers** to reduce the water demand (specially with some SCMs)

Use of SCMs

- Reduce the clinker factor of the binder
- Account for performance vs CO₂

RECAP ON SUSTAINABILITY

Avoiding the overdesign of concrete is another effective and necessary strategy to save CO₂:

1. Design for the **lowest slump** that is technically feasible for the application
2. **Do not over-specify strength** for applications where it is not needed
3. Be practical and realistic in assigning **exposure classes** to concrete

Final remarks that can be considered depending on the specific scenario:

1. Use **locally available SCMs**
2. **Optimize**, optimize, optimize. Even saving 10 kg/m³ of clinker makes a difference in a project with millions of cubic meters.



RECAP ON SUSTAINABILITY

The binder with the lowest amount of clinker will not always lead to the lowest embodied CO₂ content. Depends on:

- Strength vs w/b ratio (lower strength binder requires lower w/b to meet f'c)
For a given water content, lower w/b implies more cement per m³.
- Rheological performance of the binder (how much water do I need to achieve slump?)
If I'm forced to increase the water content, I need to increase the cement content to keep w/b. *Can I control it with admixtures?*
- Durability performance (can I meet the exposure class requirements?)
Some cements will not be allowed, or will lead to requirements of repair/replacement



Additional resources

- ACI PRC 211.1-91: Standard practice for selecting proportions for normal, heavyweight and mass concrete
- ACI Education Bulletin E1-07: Aggregates for concrete
- ACI 318M-19 *Chapter 19*: Concrete design and durability requirements
- UNEP Report "Eco-efficient cements: potential economically-viable solutions for a low-CO₂ cement-based materials industry", available at <https://wedocs.unep.org/handle/20.500.11822/25281>
- Cheung et al., Admixtures and sustainability, Cement and Concrete Research, V.114 (2018), pp. 79-89
- Featured RTL paper on "ultra-green concrete" (stay tuned during the year).

Learning objectives

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

- **Define** how concrete is made and which parameters affect its property.
- **Identify** the main desired and required properties of concrete.
- **Identify** the main factors that enable a reduction of the carbon footprint in concrete.
- **Establish** mix design strategies to meet the specified requirements for concrete with the lowest amount of embodied CO₂.

Always design in a durable and sustainable way!

■ Please refer to MSE-322
for basic knowledge of concrete

To learn more...

Sustainability – Design

Life cycle analysis for cement and concrete – Week 8

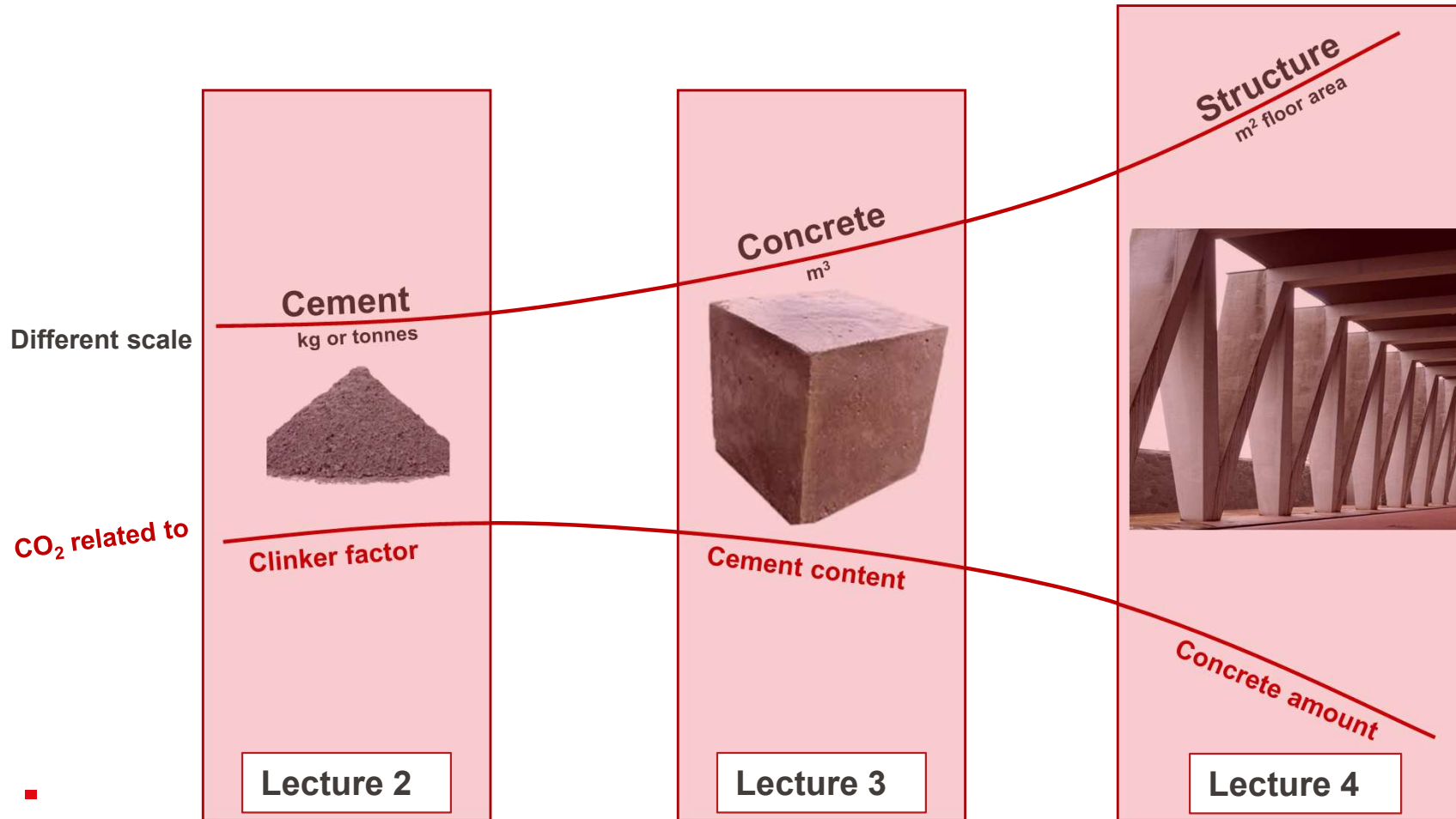
Concrete structures – Week 10

Chemical admixture use in concrete – Week 11

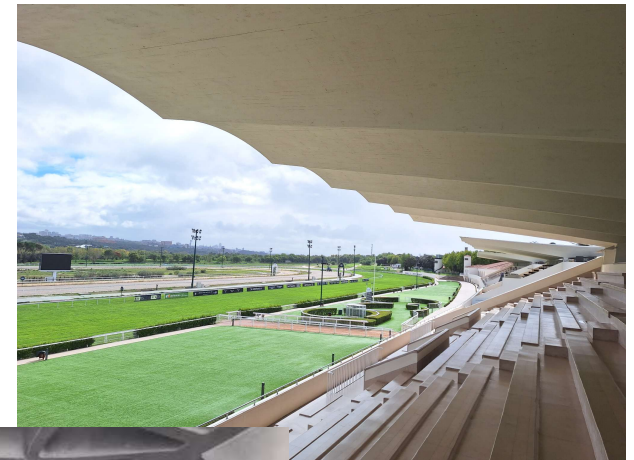
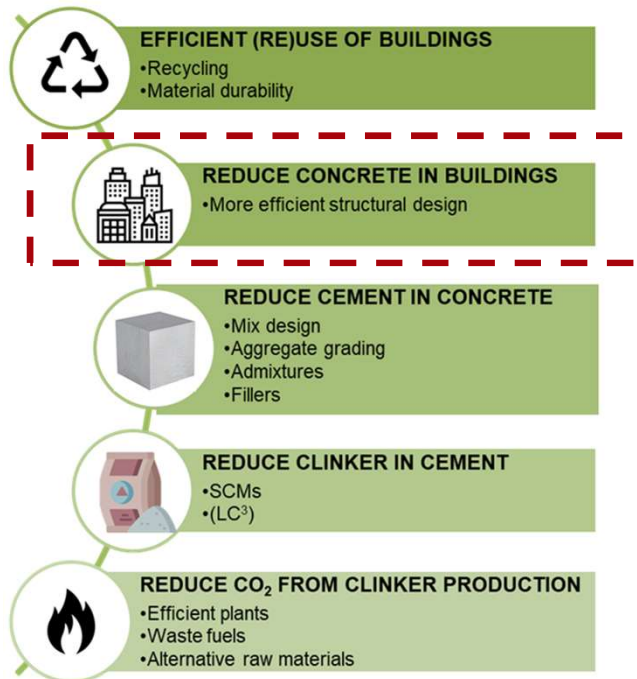
Don't miss it!



What's next? Embodied carbon at different scales



WHAT'S NEXT?



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	Presentation 1	
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	Presentation 2	
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	Presentation 3	
14	17/12/2025	Precast concrete 3D printing	Stef Maas Prof. Nicolas Roussel

Working groups

N°	Confirmed	First Name	Name	Scenario
1	✓	Benedicte Maria H��l��ne Anne	Lunven	Scenario 1 - concrete blocks. Housing Accra
2	✓	Ysaure Marie Donine	Landon	
3	✓	Bora	Bulut	
4	✓	Loris	Dubi	
6	✓	Eug��nie Perrine	Mazerand	Scenario 2 - Precast concrete. Tunnel lining Istanbul
7	✓	C��cile	Tran	
8	✓	Ludovic	Berchtold	
9	✓	No��	Paratte	
10		Dhruv Natwar	Mehta	
11	✓	Diane El��onore Marie	Meslin	Scenario 3 - UHPFRC concrete. Bridge deck Switzerland
12	✓	Natacha Helena Victoria	Kruzic	
13	✓	R��my Thibault Joseph	Grillet-Aubert	
14	✓	Samuel Jacques-Henri	Jaunin	
15	✓	Olivia Sophie	Rouiller	Scenario 4 - In situ reinforced concrete. Multi-storey building Thailand
16	✓	Lucie Julia	Caulier	
17	✓	Roman Claude Johann	Rechsteiner	
18	✓	Luis Adolfo	Del Barco Aguilar	
19	✓	Thomas	Artru	

EPFL



Questions?

**Advanced cementitious
materials, MSE 420**

**Lecture 3:
Sustainable Concrete
design**

**Dr. Beatrice Malchiodi
24 September 2025**