Proportioning of a sustainable concrete mixture

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Laboratory of Construction Materials, EPFL

Franco Zunino
franco.zunino@epfl.ch

EPFL

At the end of this lecture you will be able to:

- Identify the main factors that enable a reduction of the carbon footprint of a concrete mixture
- Establish mixture design strategies to meet the specified requirements for concrete with the lowest amount of embodied CO_2 based on the ACI PRC 211.1-91 procedure

Main reference

ACI PRC 211.1-91: Standard practice for selecting proportions for normal, heavyweight and mass concrete

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Concrete is everywhere around us

And its also part of our sustainable development strategies

Cerro Dominador, Chile

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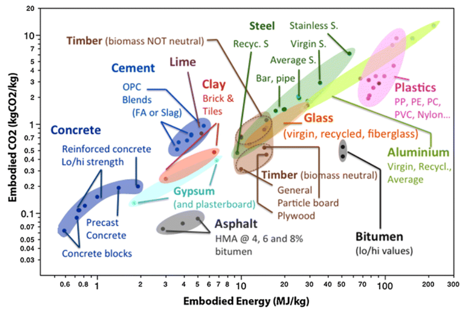
Concrete is sustainable



- We use a lot of it
- Despite the relative low environmental impact of concrete compared to other materials, there is still significant space for improvement in terms of embodied CO_2 content

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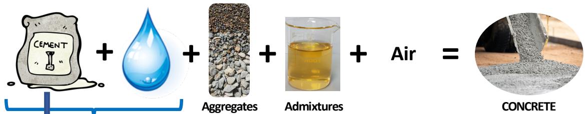
Review of concrete components



cement paste

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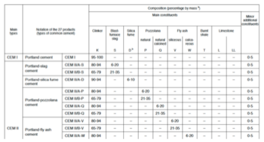

Supplementary cementitious materials (SCMs)

+ Fly ash
Natural pozzolan (uncalcined and calcined)
Ground granulated blast-furnace slag
Silica fume
Glass powder

Binder

- Cost
- Specific properties required (heat, late-age strength, durability)
- **Reduce CO_2 footprint!**

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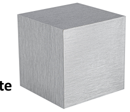
Concrete proportioning iterative workflow

Inputs
Design (f'c) or mean (f'cr) strength
Required slump (mm)
Maximum nom. aggregate size (D_N)

Durability requirements (exposure classes)
Other properties of interest



Mixture proportioning is done for 1 m³ of concrete

Opportunities to reduce embodied CO_2

1. Choice of slump → 2. Choice of maximum aggregate size → 3. Mixing water content + air → 4. Choice of w/cm → 5. Binder proportioning

→ 6. Coarse aggregate content → 7. Fine aggregate content → 8. Adjustment for agg. moisture → **Trial batching**

Adjust:
Yield of the batch
Unit weight (vs theoretical unit weight)
Observed workability / strength

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Concrete proportioning goals

Components and proportions are selected to provide certain qualities of interest:

Workability : concrete can be placed, consolidated and finished properly without segregation

Consistency : relative mobility of the concrete (how it flows), measured in terms of **slump**

Compressive strength : main engineering property, conventionally the value at 28 days is considered (**f'_{cr}**)

Durability : to endure the expected exposure conditions without compromising serviceability

Others (density, low-heat release)

At the minimum cost **At the minimum amount of CO_2 / cubic meter of concrete!**

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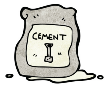
Sustainability considerations

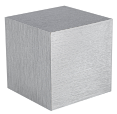
Where is the embodied CO_2 of concrete coming from?



Approximately 850 kg CO_2 / ton clinker are emitted

Best strategy is to **reduce the amount of clinker by incorporating SCMs** (use blended cements)

BUT… the construction material is concrete, not cement paste



We have to **think in terms of total binder content** (cement + SCMs) per cubic meter of concrete →

- Slump requirement
- Aggregate max. size
- Aggregate grading
- Choice of w/cm (cement type, durability)
- Chemical admixtures

Strategies and concepts to keep in mind to achieve a more sustainable concrete mixture design will be highlighted in green in the next slides

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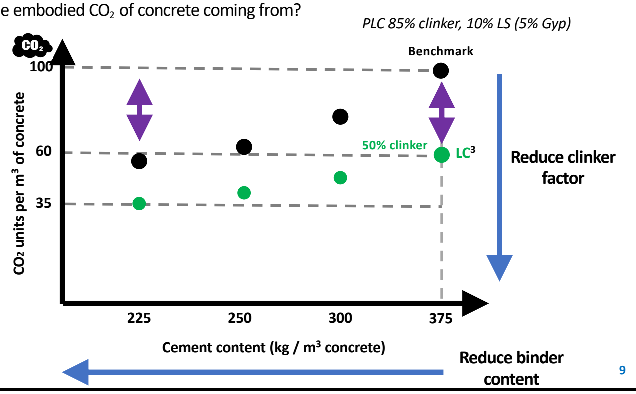
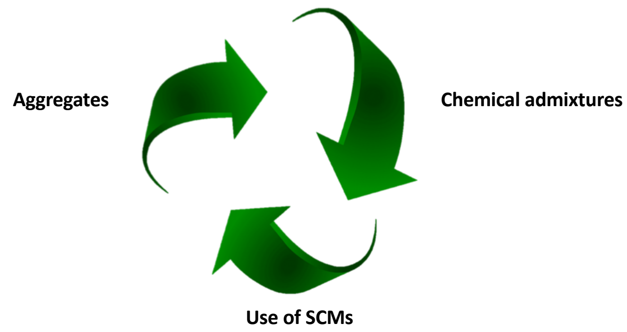
Sustainability considerations

Where is the embodied CO_2 of concrete coming from?



Sustainability considerations

Technological approaches to low-CO_2 concrete mixtures



Step 1: Choice of slump

Normally, this value **will be specified** by the contractor/field engineer

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

Slump test (ASTM C143-143M-20)

Placing issues
(honeycomb)

If slump is not specified, ACI 211.1-91 provides a reference value to start (*vibrated concrete*):

Type of construction	Slump (mm)	
	Maximum*	Minimum
Foundations (reinforced)	75	25
Foundations (plain)	75	25
Beams and walls	100	25
Columns	100	25
Pavement and slabs	75	25
Mass concrete	75	25

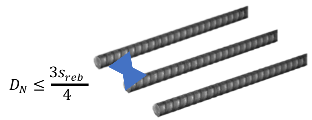
*Values can be increased using admixtures

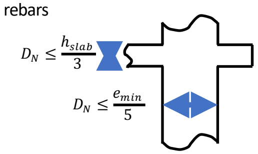
Higher slump → higher water dosage → higher binder content (at constant w/cm)

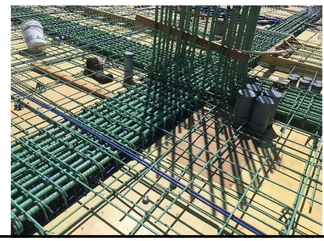
Use lowest slump possible that meets the requirements of the project

Step 2: Choice of maximum size of aggregate (D_N)

D_N is limited by the size of the element and the spacing between rebars



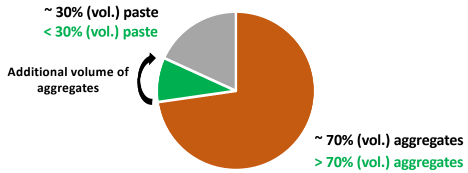


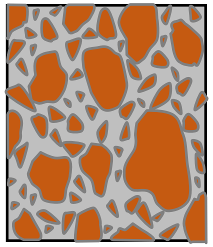


Step 2: Choice of maximum size of aggregate (D_N)

Aggregates form the main backbone of concrete

Cement paste fill the spaces between the aggregates





Cement paste acts as a lubricant between aggregate particles enabling flow → we require a **certain amount of cement paste to coat and separate the aggregates**

We want this amount to be as low as possible!

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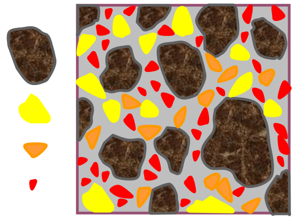
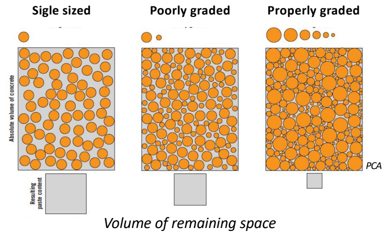
Step 2: Choice of maximum size of aggregate (D_N)

Good grading of aggregates reduce the spaces between particles (**lower amount of paste required**)





Fine aggregates fill the spaces between coarser particles

By properly grading the aggregate fraction, only the small gaps that cannot be taken by aggregate particles remain to be filled with cement paste.

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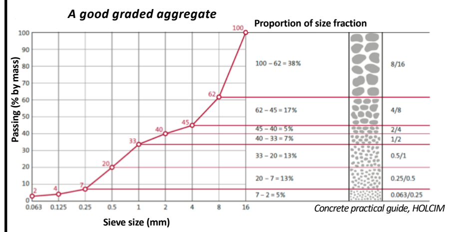
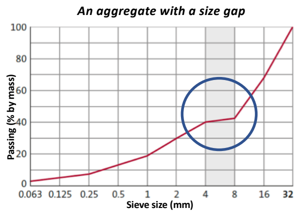
Step 2: Choice of maximum size of aggregate (D_N)

Good grading of aggregates reduce the spaces between particles (**lower amount of paste required**)





Granulometric curves of well-graded aggregates look smooth and without gaps

Grading can be done separately for coarse and fine aggregate, but **what matters is the packing density (void content) of the combined aggregate fractions**

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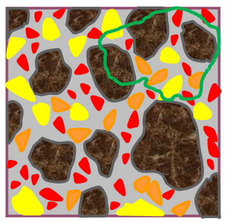
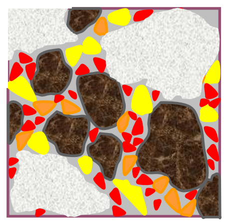
Step 2: Choice of maximum size of aggregate (D_N)

Increasing the maximum size of aggregate reduces the amount of paste required

Well graded, D_N 12.5 mm



Well graded, D_N 25 mm



Increasing D_N reduces the void content between aggregates (a number of small particles are replaced by a single large one)

Use the largest D_N available that is technically/economically feasible

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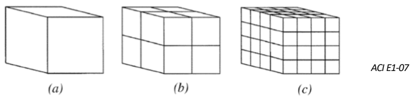
Step 2: Choice of maximum size of aggregate (D_N)

Larger aggregates have a **smaller surface / volume ratio** → lower amount of paste required for coating the surface of aggregates

Size effect on surface area (at constant volume)



Size a, Area $6a^2$ — Size a/2, Area $12a^2$ — Size a/4, Area $24a^2$

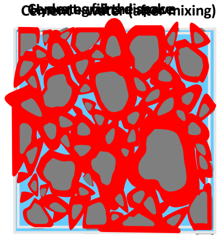
In summary, the sustainable strategies related to aggregate size/grading are:

1. Use a properly graded aggregate mixture to **reduce the amount of voids**
2. Use maximum D_N possible to further **reduce the amount of voids and surface**

Less voids ↓ **Less paste** ↓ **Less cement**

Step 3: Mixing water (and air) content

Water is an essential element in concrete
- Hydration
- Development of strength over time
- Workability and consistency



Concrete does not **dry**, it becomes **hydrated** (a chemical reaction leading to the formation of hydrates)

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

Slump, mm	Mixing water (kg/m³) for different D_N values: 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

Higher slump → higher mixing water dosage
Higher D_N → lower mixing water dosage at constant slump (and lower entrapped air)

The amount of mixing water is directly proportional to the cement demand at constant w/cm

Step 3: Mixing water (and air) content

The use of **chemical admixtures** can enable to achieve certain properties (slump, early-age strength, shrinkage) beyond the envelope of non-admixed concrete and **reduce the embodied CO_2 content**

Water demand for slump = 200 kg /m³

No SP

Water = 200 kg /m³
w/c = 0.45
PC = 444 kg /m³

CO_{2EQ} PC = 364 kg/m³

Binder = $ 54.6

1% SP

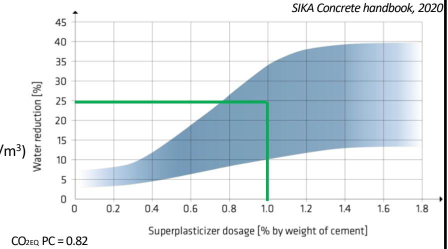
Water = 150 kg /m³
w/c = 0.45
PC = 333 kg /m³
SP = 3.3 kg /m³ (2.1 L/m³)

CO_{2EQ} PC = 273 kg/m³
CO_{2EQ} SP = 6.2 kg/m³
279.2 kg/m³

-23% CO_{2EQ} / m³

Binder = $ 53.9

SIKA Concrete handbook, 2020



CO_{2EQ} PC = 0.82
CO_{2EQ} SP = 1.88 (EFCA EPD)

Cost PC = CAD 150 / ton (Statista, 2020 value)
Cost SP = CAD 13 / m³ (Canadian building materials, pricelist 2021)

Chemical admixtures **should be used in the form and dosages recommended by the manufacturer.**

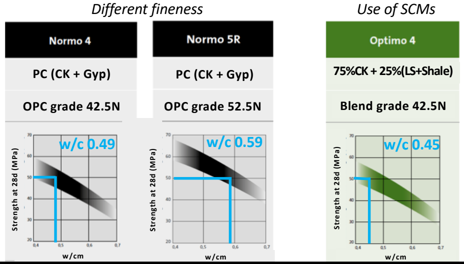
Step 4: Selection of w/cm

w / cm = water-to-cementitious materials ratio (by mass)
- Highly correlated with strength of concrete
- Also limited by durability considerations

The w/cm versus strength relationship depends on the particular cement (or cement + SCMs) used (and temperature, curing conditions)

Different fineness — *Use of SCMs*

50 MPa



Choosing the most sustainable solution is not obvious

HOLCIM Switzerland

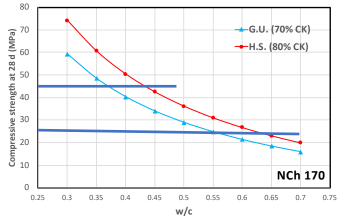
Step 4: Selection of w/cm

Example: pozzolanic (nat. pozzolan) cements from the Chilean market (general use and high strength grades)

General Use (G.U.) 70% clinker content
High strength (H.S.) 80% clinker content

Preliminary design of concrete with 100 mm slump and strength of 25 or 45 MPa

	G.U.	H.S.
25 MPa w/c	0.55	0.62
45 MPa w/c	0.37	0.43



Assuming D_N = 25 mm, the water dosage is 193 kg/m³.
We can then compute the cement contents for each type of cement,

	G.U.	H.S.	In terms of clinker / m³	G.U. (70% CK)	H.S. (80% CK)
25 MPa	353 kg/m³	310 kg/m³		**246 kg/m³**	248 kg/m³
45 MPa	522 kg/m³	446 kg/m³		365 kg/m³	**357 kg/m³**

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Step 4: Selection of w/cm

Exposure classes can limit the maximum w/cm below the value determined by strength requirements

Example: Freeze-thaw exposure (***F***, according to ACI 318M-19, Chapter 19).
Exterior pavement (20 MPa req), frequently moist, deicing salts used in winter to prevent sliding

Identify the conditions the structure will endure

Table 19.3.1.1—Exposure categories and classes

Category	Class	Condition
Freezing and thawing (F)	F0	Concrete not exposed to freezing-and-thawing cycles
	F1	Concrete exposed to freezing-and-thawing cycles with limited exposure to water
	F2	Concrete exposed to freezing-and-thawing cycles with frequent exposure to water
	F3	Concrete exposed to freezing-and-thawing cycles with frequent exposure to water and exposure to deicing chemicals

Table 19.3.2.1—Requirements for concrete by exposure class

Exposure class	Maximum w/cm[1,2]	Minimum f_c', MPa	Additional requirements: Air content	Limits on cementitious materials
F0	N/A	17	N/A	N/A
F1	0.55	24	Table 19.3.3.1 for concrete or Table 19.3.3.3 for shotcrete	N/A
F2	0.45	31	Table 19.3.3.1 for concrete or Table 19.3.3.3 for shotcrete	N/A
F3	0.40[3]	35[3]	Table 19.3.3.1 for concrete or Table 19.3.3.3 for shotcrete	26.4.2.2(b)

Maximum w/cm to use **0.40**
Minimum specified strength **35 MPa**
Requirement to use air entraining admixtures (6% total air for F3)

Very important to consider durability of the material, but care should be taken to avoid overspecification (and the consequent limitation of our ability to reduce embodied CO_2)

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Step 5: Binder proportioning

Cement + SCMs content = water demand / (w/cm)

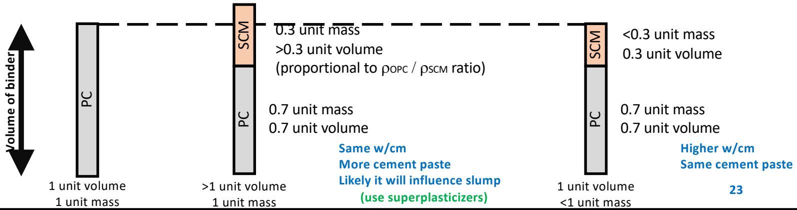
Except if higher limit is given by specification

If **supplementary cementitious materials (SCMs)** are used, there is two proportioning approaches

SCMs have lower densities than Portland cement (3.0 < ρ < 3.1)

Fly ash (2.0 < ρ < 2.6)
Natural pozzolans (2.4 < ρ < 2.7)
Calcined clays (2.2 < ρ < 2.6)
GGBFS (2.7 < ρ < 2.9)

Replacement of PC by SCMs can be computed on mass or volume basis:



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Step 5: Binder proportioning

Exercise: Consider a system where 45% of PC was replaced by 30% calcined clay and 15% limestone on a mass basis. Determine the increase in binder volume.

PC ρ_{PC} = 3.0
Calcined clay ρ_{CC} = 2.5
Limestone ρ_{LS} = 2.7

Let's assume for simplicity that we will prepare 100 kg of blended cement

Volume occupied by 100% of PC $V_{PC} = \dfrac{100}{\rho_{PC}} = 33.3\ lt$

As the replacement is done on a mass basis, we can compute the volume that 30% calcined and 15% limestone will occupy in the blend,

$$V_{30CC} = \frac{30}{\rho_{CC}} = 12\ lt \qquad V_{15LS} = \frac{15}{\rho_{LS}} = 5.6\ lt$$

We can add up these values with the volume of 55% OPC remaining, $V_{BLEND} = \dfrac{55}{\rho_{PC}} + 12 + 5.6 = 35.9\ lt$

The increase in volume is then $\Delta V = \dfrac{35.9}{33.3} = 1.08 \rightarrow 8\%$

Independent work: what are the proportions (in mass) for a design on a volume basis? How much is w/cm affected? 24

Remarks and considerations on proportioning

We want to design a mixture with the lowest embodied CO_2 per cubic meter of concrete.

The cement (binder) with the lowest amount of clinker will **not** always lead to the concrete mixture with the lowest embodied CO_2 content.

Depends on:

- **Strength vs w/cm relationship** *(lower strength binder requires lower w/cm to meet f'_c)*

  For a given water content, lower w/cm implies more cement per m^3

- **Rheological performance** of the binder *(how much water do I need to achieve slump?)*

  Can I control it with admixtures? If I'm forced to increase the water content, I need to increase cement content to keep w/cm

- **Durability performance** *(can I meet the exposure class requirements?)*

  Some cements will not be allowed, or will lead to requirements of repair/replacement

Remarks and considerations on proportioning

The golden rule is to develop and use (blended) cements with the least amount of embodied CO_2 that have sufficient performance to enable their use without a significant increase of binder content per m^3

CO_2 of cement
(reduce clinker, retain or improve performance)

Two-fold strategy

CO_2 of concrete
(reduce paste content while still workable, strong and durable)

A sustainable concrete conceived this way is also cost effective!

Remarks and considerations on proportioning

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 CO_2

Remarks and considerations on proportioning

Avoiding overdesign of concrete is another effective an necessary strategy to save CO_2:

- Design for **lowest slump that is technically feasible** for the application
- **Do not over specify strength** for applications where is not needed
- Be practical and **realistic to assign exposure classes** to concrete

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

- Use locally available SCMs
- **Optimize, optimize, optimize**. Even saving 10 kg/m^3 of clinker make a difference in a project where millions of cubic meters are poured.

Additional resources

- ASTM standards referred throughout the lecture
- 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-CO_2 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

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