Proportioning of a sustainable concrete mixture

Franco Zunino
franco.zunino@epfl.ch

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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\textsubscript{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

Concrete is everywhere around us
And it's also part of our sustainable development strategies

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\textsubscript{2} content
Review of concrete components

- Cement paste
- Aggregates
- Admixtures
- Air

CONCRETE

EN 197-1

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!

Concrete proportioning workflow

Inputs
- Design (f'$_c$) or mean (f'$_{cr}$) strength
- Maximum nominal aggregate size (D$_N$)
- Durability requirements (exposure classes)
- Other properties of interest

Mixture proportioning is done for 1 m$^3$ 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
9. Trial batching
10. Yield of the batch
Unit weight (vs theoretical unit weight)
Observed workability / strength

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!

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
**Sustainability considerations**

Where is the embodied CO$_2$ of concrete coming from?

- **PLC 85% clinker; 10% LS (5% Gyp)**
- **Benchmark**
- **Cement content (kg / m$^3$ concrete)**
  - 100
  - 375
  - 60
  - 300
  - 250
  - 225
  - 15

<table>
<thead>
<tr>
<th>CO$_2$ units per m$^3$ of concrete</th>
<th>Reduce clinker factor</th>
<th>Reduce binder content</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>PLC 85% clinker; 10% LS (5% Gyp)</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>Benchmark</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td></td>
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<tr>
<td>15</td>
<td></td>
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</tbody>
</table>

**Technological approaches to low CO$_2$ concrete mixtures**

- **Aggregates**
- **Chemical admixtures**
- **Use of SCMs**

**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 C143-14/8M-20)**

<table>
<thead>
<tr>
<th>Type of construction</th>
<th>Slump (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foundations (reinforced)</td>
<td>75, 25</td>
</tr>
<tr>
<td>Foundations (plain)</td>
<td>75, 25</td>
</tr>
<tr>
<td>Beams and walls</td>
<td>100, 25</td>
</tr>
<tr>
<td>Columns</td>
<td>100, 25</td>
</tr>
<tr>
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<td>75, 25</td>
</tr>
<tr>
<td>Mass concrete</td>
<td>75, 25</td>
</tr>
</tbody>
</table>

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

- **Type of construction**
  - **Maximum**
  - **Minimum**

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</tr>
<tr>
<td>Pavement and slabs</td>
<td>75</td>
<td>25</td>
</tr>
<tr>
<td>Mass concrete</td>
<td>75</td>
<td>25</td>
</tr>
</tbody>
</table>

**Slump test**

*Values can be increased using admixtures.

**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.

- Use lowest slump possible that meets the requirements of the project

$D_N \leq \frac{3h_{	ext{max}}}{4} \leq \frac{\text{Max}}{5}$
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

- Additional volume of aggregates
  - $\approx 30\%$ (vol.) paste
  - $< 30\%$ (vol.) paste
  - $> 70\%$ (vol.) 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)

- Single sized
- Poorly graded
- Properly graded

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)

- A good graded aggregate
- An aggregate with a size gap

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
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.

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).

| Mixing water (kg/m$^3$) for different $D_N$ values |  
|-----------------|-----------------|-----------------|-----------------|-----------------|
| $D_N$ | No SP | 1% SP | No SP | 1% SP | No SP | 1% SP |
| Hydraulic cement | Water = 200 kg /m$^3$ | Water = 150 kg /m$^3$ | Water = 444 kg /m$^3$ | Water = 444 kg /m$^3$ |
| | PC = 364 kg/m$^3$ | PC = 333 kg/m$^3$ | PC = 333 kg/m$^3$ (2.1 L/m$^3$) | PC = 333 kg/m$^3$ |
| | CO$_2$PC = 273 kg/m$^3$ | CO$_2$PC = 273 kg/m$^3$ | CO$_2$PC = 273 kg/m$^3$ (2.1 L/m$^3$) | CO$_2$PC = 273 kg/m$^3$ |
| | Binder = $54.6$ | Binder = $53.9$ | Binder = $54.6$ | Binder = $53.9$ |
| | CO$_2$SP = 0.82 | CO$_2$SP = 0.82 | CO$_2$SP = 0.82 | CO$_2$SP = 0.82 |

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 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)

Choosing the most sustainable solution is not obvious.
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. (70% CK)  
H.S. (80% CK)

25 MPa w/cm: 0.55, 0.62
45 MPa w/cm: 0.37, 0.43

Assuming Dn = 25 mm, the water dosage is 193 kg/m³.

We can then compute the cement contents for each type of cement:

<table>
<thead>
<tr>
<th>Strength</th>
<th>G.U.</th>
<th>H.S.</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 MPa</td>
<td>353 kg/m³, 310 kg/m³ in terms of clinker / m³</td>
<td>246 kg/m³, 248 kg/m³</td>
</tr>
<tr>
<td>45 MPa</td>
<td>522 kg/m³, 446 kg/m³ in terms of clinker / m³</td>
<td>365 kg/m³, 357 kg/m³</td>
</tr>
</tbody>
</table>

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).

Identify the conditions the structure will endure

<table>
<thead>
<tr>
<th>Exposure class</th>
<th>Maximum w/cm</th>
<th>Minimum specified strength</th>
<th>Requirement to use air entraining admixtures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freeze-thaw</td>
<td>0.40</td>
<td>35 MPa</td>
<td>6% total air for F3 (6%)</td>
</tr>
</tbody>
</table>

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 CO₂).

Step 5: Binder proportioning

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

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

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

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

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

Mass replacement of 30%  
Volume replacement of 30%

PC  
SCM  
Volume of binder

-0.3 unit mass  
0.3 unit volume

-0.3 unit volume  
0.3 unit mass

PC  
SCM  
Volume of binder

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.

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

Volume occupied by 100% of PC  
Volume occupied by 30% calcined clay  
Volume occupied by 15% limestone

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,  

Volume occupied by calcined clay :  
Volume occupied by limestone :

We can add up these values with the volume of 55% OPC remaining,  

The increase in volume is then  

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

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

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

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$^3$

A sustainable concrete conceived this way is also cost effective!

Avoiding overdesign of concrete is another effective and 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 it 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
- Optimise, optimise, optimise. 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
- Cheung et al., Admixtures and sustainability, Cement and Concrete Research, V.114 (2018), pp. 79-89