Concrete – the carbon sink for a climate neutral Switzerland?

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CCS and the Industry of Carbon-Based Resources – FS2020
Outline

1. The emission problem of the cement & concrete industry
2. The physics of concrete carbonation
3. Piloting concrete as a carbon sink in Bern
4. Pathways towards a net-zero CO₂ concrete
The Net-Zero GHG Challenge

- Current rate of global warming due to human activities
- Paris agreement $\rightarrow$ 2°C is an acceptable level of global warming
- Temperature goal is equivalent to a limited carbon budget
- From 40Gt CO$_2$ to Net Zero in 30 years
- CCS a key technology to decarbonize the industrial sector and to create negative emissions
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The global cement industry – some key numbers

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement plants</td>
<td>~8000</td>
</tr>
<tr>
<td>Global cement production</td>
<td>~4000 Mt/a</td>
</tr>
<tr>
<td>CO₂ Emissions</td>
<td>~2250 Mt/a</td>
</tr>
<tr>
<td>Cement import/export</td>
<td>~5%</td>
</tr>
</tbody>
</table>
Figure 4: Cement production by region

Note: See Annex for regional definitions.

The cement manufacturing process

Calcination reaction: $\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2$

- Clinker globally a standard product
- Clinker blended with supplementary cementitious materials $\rightarrow$ cement

*limestone, gypsum, fly ash, clays, blast furnace slag

Note: A dry-process kiln is shown with a precalciner and multistage cyclone preheater, which is considered state-of-the-art technology. The modeling results used for the analysis in this roadmap include steps 3-10 of the above figure.

Cement sustainability initiative – climate strategy I

Figure 5: Global direct CO\textsubscript{2} emissions in cement production by scenario

*KEY MESSAGE:* The B2DS would require the cement industry to increase by about 45% the cumulative carbon emissions reductions effort compared to the 2DS, which is the reference carbon emissions reduction scenario for this roadmap’s vision.
Cement sustainability initiative – climate strategy II

Table 2: Key indicators for the global cement industry in the RTS and the roadmap vision (2DS)

<table>
<thead>
<tr>
<th></th>
<th>2014</th>
<th>RTS Low-variability case</th>
<th>Roadmap vision (2DS) Low-variability case</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2030</td>
<td>2040</td>
</tr>
<tr>
<td>Cement production (Mt/yr)</td>
<td>4.17</td>
<td>4.25</td>
<td>4.42</td>
</tr>
<tr>
<td>Clinker to cement ratio</td>
<td>0.65</td>
<td>0.66</td>
<td>0.67</td>
</tr>
<tr>
<td>Thermal energy intensity of clinker (GJ/t clinker)</td>
<td>3.5</td>
<td>3.4</td>
<td>3.3</td>
</tr>
<tr>
<td>Electricity intensity of cement (kWh/t cement)</td>
<td>91</td>
<td>89</td>
<td>86</td>
</tr>
<tr>
<td>Alternative fuel use (percentage of thermal energy consumption)</td>
<td>5.6</td>
<td>10.9</td>
<td>14.4</td>
</tr>
<tr>
<td>CO₂ captured and stored (MtCO₂/yr)</td>
<td>-</td>
<td>7</td>
<td>65</td>
</tr>
<tr>
<td>Direct process CO₂ intensity of cement (tCO₂/t cement)</td>
<td>0.34</td>
<td>0.34</td>
<td>0.34</td>
</tr>
<tr>
<td>Direct energy-related CO₂ intensity of cement (tCO₂/t cement)</td>
<td>0.20</td>
<td>0.19</td>
<td>0.18</td>
</tr>
</tbody>
</table>

Notes: Thermal energy intensity of clinker does not include any impact related to other carbon mitigation levers beyond improving energy efficiency (e.g., carbon capture). Electricity intensity of cement production does not include reduction in purchased electricity demand from the use of waste heat recovery equipment or any impact related to other carbon mitigation levers beyond improving energy efficiency (e.g., carbon capture). Alternative fuel use includes biomass, and biogenic and non-biogenic waste. Direct CO₂ intensity refers to net CO₂ emissions, after carbon capture.

Figure 7: Global cumulative CO₂ emissions reductions by applying the roadmap vision (2DS) compared to the RTS

2020-2050: The cement sector forecasts cumulative savings of 7.5 Gt CO₂ while they emit about 70 Gt CO₂. Investments in CCS are delayed.
# Emission reduction potential along the cement manufacturing value chain

## Performance improvement potential

<table>
<thead>
<tr>
<th>Lever</th>
<th>Measure</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unit</td>
<td>Current</td>
</tr>
<tr>
<td><strong>Thermal efficiency</strong></td>
<td>Upgrade to modern dry precalcer preheater kilns</td>
<td>MJ/t clinker</td>
</tr>
<tr>
<td><strong>Alternative fuels</strong></td>
<td>Increase the thermal substitution rate</td>
<td>%</td>
</tr>
<tr>
<td><strong>Electrical efficiency</strong></td>
<td>Replace ball mills with vertical roller mills…</td>
<td>kWh/t cement</td>
</tr>
<tr>
<td><strong>Waste heat recovery</strong></td>
<td>Install in all plants</td>
<td>kWh/t cement</td>
</tr>
<tr>
<td><strong>Clinker substitution</strong></td>
<td>Reduce the clinker-to-cement ratio with SCMs</td>
<td>Clinker content in %</td>
</tr>
<tr>
<td><strong>Low carbon cement</strong></td>
<td>Product innovation</td>
<td>Market share of low carbon cements %</td>
</tr>
</tbody>
</table>

CSI/GNR database (values for EU28), ECRA Technology papers (2017)

## CO₂ reduction potential

- **Actual CO₂**: 671
- **Thermal**: 28
- **AF**: 19
- **Power**: 8
- **WHR**: 6
- **Clinker factor**: 41
- **New clinker**: 0
- **Consolidation**: 6
- **CO₂ G9**: 563

Estimates D. Wiodarczak
Alternative binders

Material properties

- OPC
- OPC - quartz
- OPC - fly ash 1
- OPC - fly ash 2
- OPC - fly ash 1 + 5% limestone


Resources for alternative binders

- silica fume
- waste glass
- biomass ashes
- natural pozzolans
- blast furnace slag
- fly ash
- Portland cement
- clays

Summary

- Annual GHG emissions have to go to net-zero until 2050 – and cumulative emissions should be minimized
- There is very limited potential to save GHG emissions along the cement manufacturing process
- There are no alternatives to Portland cement
- CCS still needs 1) a business case 2) transport and storage infrastructure

→ What can be done right now to reduce emissions?
Outline

1. The emission problem of the cement & concrete industry
2. The physics of concrete carbonation
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4. Pathways towards a net-zero CO₂ concrete
Physics behind carbonation of concrete

Concrete Carbonation

Solid cement minerals

Liquid aqueous solution

\[
3\text{CaO} \cdot 2\text{SiO}_2 \cdot 3\text{H}_2\text{O} \leftrightarrow 3\text{Ca}^{2+} + 6\text{OH}^- + 2 \text{SiO}_2
\]

\[
\text{Ca(OH)}_2 \leftrightarrow \text{Ca}^{2+} + 2\text{OH}^-
\]

\[
\text{Ca}^{2+} + \text{CO}_3^{2-} \leftrightarrow \text{CaCO}_3(s)
\]

\[
\text{CO}_2 + \text{OH}^- \leftrightarrow \text{HCO}_3^-
\]

\[
\text{HCO}_3^- + \text{OH}^- \leftrightarrow \text{CO}_3^{2-} + \text{H}_2\text{O}
\]

\[
\text{H}_2\text{O} \leftrightarrow \text{H}_2\text{O}
\]

Air (400 ppm CO₂)

Ca(OH)₂(s) + CO₂(g) ⇌ CaCO₃(s) + H₂O(l)
Carbonation of concrete – state of the art

Modelling

Diffusion with reaction

\[
\frac{\partial c_{CO_2}}{\partial t} = \frac{\partial}{\partial x}\left(D_{CO_2}\frac{\partial c_{CO_2}}{\partial x}\right) - r_{CaCO_3}
\]

Carbonation depth

\[
x_c = \sqrt{\frac{2p_{CO_2}D_{CO_2}t}{c_{Ca(OH)_2}^0 + c_{CSH}^0}}
\]

Natural carbonation

Model validation

Accelerated carbonation

Model validation

Indoor exposure

\[
\frac{\partial c_{CO_2}}{\partial t} = \frac{\partial}{\partial x}\left(D_{CO_2}\frac{\partial c_{CO_2}}{\partial x}\right) - r_{CaCO_3}
\]

Natural carbonation

Accelerated carbonation

20% CO\textsubscript{2} / 52% RH / 20°C / W/C 0.4 - 0.6

Carbonation depth

10 mm

10 years

10 mm

1 month
Outline

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Bundesrat will bis 2050 eine klimaneutrale Schweiz


5% of CH CO₂ emissions have to be addressed by sinks.
CO₂ SINK CONCRETE
CO$_2$ SINK DEMOLITION CONCRETE

Demolition concrete

CO$_2$

Concrete recycling plant

Concrete batching

Recycling concrete

- cement + RC-fraction

RECARB
Compressive strength after 28 days

Beton SN EN 206; C 25/30; XC2; Cl 0.1; 0/32; F3; Kran

Effect of particle size

<table>
<thead>
<tr>
<th></th>
<th>Effect</th>
<th>60% RC</th>
<th>290 kg CEM II</th>
</tr>
</thead>
<tbody>
<tr>
<td>REF</td>
<td>40% RC 16/32</td>
<td>40% RC 4/32</td>
<td>40% RC 0/32</td>
</tr>
<tr>
<td>40% RC 4/32</td>
<td>40% RC 0/32</td>
<td>60% RC 4/32</td>
<td>60% RC 0/32</td>
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<td>40% RC 4/32</td>
<td>40% RC 0/32</td>
</tr>
</tbody>
</table>
Carbonation resistance

E-Module

Fresh properties of concrete

Carb. Resistance, spreading properties & E-Module

Carbonation resistance

- Increasing from 4.9 to 4.3 mm/y^{0.5}

- Remained at about 35 MPa

Spreading properties, entrained air, density remained within norm
CO₂ infrastructure:
• CO₂ liquefaction installed (until 5.2021)
• CO₂ transport organized (until 5.2021)

Engineering, construction and testing of pilot
• Pilot plant installed (until 8.2020)
• Pilot plant tested in operation at the Kästli concrete plant

Material handling and material tests
• Material will be filled into conventional silos
• Kästli will mix concrete with their large scale concrete mixer
• Fresh properties of concrete as well as properties of hardened concrete will be analyzed

CO₂ accounting program
1. The emission problem of the cement & concrete industry
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Cement and concrete value chain

**Centralized cement manufacturing**
- Cement plant
  - Kiln
    - CaCO$_3$ + SiO$_2$ → 1.6 Mt
  - Clinker
    - 0.55 Mt CO$_2$
  - Fuel
  - Air
  - Additions
  - Mill
    - 0.29 Mt CO$_2$
    - 1 Mt

**Accelerated carbonation**
- Mineral Carbonation
  - Sand
  - CaCO$_3$ → CO$_2$
- Concrete fines

**Concrete recycling**
- Iron
  - Crushing
  - Iron removal
  - Classification

**Decentralized concrete recycling**
- Concrete fines

**Decentralized concrete manufacturing**
- Concrete plants
  - Concrete
  - Infrastructure
  - Gravel
  - Sand
  - Water
  - 0.05 Mt CO$_2$

**Centralized cement manufacturing**
- Cement plant
  - 0.84 Mt CO$_2$

**Additions**
- CaCO$_3$ + SiO$_2$ → 1.6 Mt

**Infrastructure**
- 0.05 Mt CO$_2$
The technology

1. Concrete fines are suspended in an aqueous solution – the calcium of the cement phases is selectively leached.
2. The particles of the suspension are removed by filtration. These particles can be reused as sand.
3. The calcium rich solution is pumped to a carbonation reactor. Pure or flue gas CO$_2$ is bubbled through the aqueous solution, CaCO$_3$ precipitates.
4. The CaCO$_3$ is removed by filtration and the aqueous solution can be recycled.
Project outline

Work packages
1. Lab scale demonstration
2. Model based process design
3. Material use in construction sector
4. Material use in other than construction
5. Techno-economical feasibility of centralized recycling
6. Techno-economical feasibility of decentralized recycling
7. Environmental & economical performance of the value chain
1. We could operate the system in a continuous, reproducible manner – the flue gas outlet composition, flow rate, particle size distribution, CaCO3 yield and particle morphology.
Validation of process flow sheet and modification of particle size and shape
Estimation of CO₂ uptake potential

Data Source: Carbon Dioxide Information Analysis Centre, Oak Ridge National Laboratory
Vision of a net-zero emission concrete

### Emissions for 1 m³ concrete

<table>
<thead>
<tr>
<th>Component</th>
<th>CO₂ Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clinker</td>
<td>143 kg</td>
</tr>
<tr>
<td>Cabonated concrete aggregate</td>
<td>-18 kg</td>
</tr>
<tr>
<td>CaCO₃ in cement</td>
<td>-43 kg</td>
</tr>
<tr>
<td>CaCO₃ as fine sand</td>
<td>-82 kg</td>
</tr>
<tr>
<td><strong>Balance</strong></td>
<td><strong>0 kg</strong></td>
</tr>
</tbody>
</table>
Summary & conclusion

- The cement manufacturing process accounts for 2.25 Gt CO$_2$/y. CCS is the only option to cut emissions drastically, since processes are highly efficient.
- However, CCS still has to turn into a business case and required CO$_2$ transport infrastructure needs to be developed.
- Early on, by mineralizing CO$_2$ in demolition concrete 1) CO$_2$ can be stored, 2) the material can be upcycled – yielding a business case.
- Within RECARB, Neustark’s technology generation 1 will be scaled to pre-commercial level until 2021.
- Within an Innosuisse project, technology generation 2 will be developed.
- Swiss Concrete can offer a CO$_2$ storage capacity of 1 Mt CO$_2$/y in 2050.
- In principle, both technologies should allow to manufacture net-zero concrete in the future.