Using Carbon Dioxide as a Beneficial Admixture in Ready-Mixed Concrete

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Cement Production And CO$_2$ Emissions

- **Combustion**: 1.13 t Raw Material, 0.1 t coal
- **Calcination**: 0.65 t CO$_2$, 60% 40% changes
- **Clinker**: 0.75 t, Specific CO$_2$ emissions: 865 kg CO$_2e$ / t
- **Cement**: 0.75 t, 0.25 t additions, 650 kg CO$_2e$ / t
Carbonation Of Freshly Hydrating Cement

\[
\begin{align*}
\text{Dissolution} \\
(\text{Ca}^{2+} \text{ Supply})
\end{align*}
\]

\[
\begin{align*}
\text{Precipitation} \\
(\text{CO}_2 \text{ Storage})
\end{align*}
\]

\[
\begin{align*}
\text{C}_3\text{S}_{(\text{alite})} + 3\text{H}_2\text{O} & \iff 3\text{Ca}^{2+} + \text{SiO}_2^0 + 6\text{OH}^- \\
\text{C}_2\text{S}_{(\text{belite})} + 2\text{H}_2\text{O} & \iff 2\text{Ca}^{2+} + \text{SiO}_2^0 + 4\text{OH}^- \\
\text{Ca(OH)}_2 + \text{H}_2\text{O} & \iff \text{Ca}^{2+} + 2\text{OH}^- + \text{H}_2\text{O}
\end{align*}
\]

\[
\begin{align*}
\text{CO}_2 (\text{g}) & \iff \text{CO}_2 (\text{aq}) \\
\text{CO}_2 (\text{aq}) + \text{H}_2\text{O} & \iff \text{H}_2\text{CO}_3 (\text{aq}) \\
\text{H}_2\text{CO}_3 (\text{aq}) & \iff \text{HCO}_3^- (\text{aq}) + \text{H}^+ \\
\text{HCO}_3^- (\text{aq}) & \iff \text{CO}_3^{2-} (\text{aq}) + \text{H}^+
\end{align*}
\]

\[
\begin{align*}
\text{Ca}^{2+} (\text{aq}) + \text{CO}_3^{2-} (\text{aq}) & \iff \text{CaCO}_3 (\text{s})
\end{align*}
\]
Schematic Of Gas Delivery System Integration With Ready-mix Truck

1 - Truck
2 - Mixing drum
3 - CO₂ tubing or water line
4 - Connection to gas supply
5 - Gas manifold
6 - Control box
7 - Telemetry
8 - CO₂ supply
Trial summary

• Trial one
  o One truck
  o CO₂ applied at the wash rack, three doses.

• Trial two
  o Two trucks
  o CO₂ during batching and at the wash rack

• Testing
  o Slump, temperature, isothermal calorimetry
  o Compressive strength (1, 3, 7, 28, 56, 91 days)
  o Resistivity
Metrix – Mix Design (kg/m$^3$)

- Sand, 959, 42%
- Stone, 1080, 47%
- Cement, 212, 9%
- Slag, 53, 2%

- 25 MPa plain mix
- 20 mm aggregate
- 20% slag
Trial 1 outline

<table>
<thead>
<tr>
<th>Sample Code</th>
<th>Condition</th>
<th>Age at injection (min)</th>
<th>CO₂ Dose (%bwc)</th>
<th>Slump (inches)</th>
<th>Mix Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1401</td>
<td>Control</td>
<td>-</td>
<td>-</td>
<td>3.5</td>
<td>23.9</td>
</tr>
<tr>
<td>1402</td>
<td>CO₂</td>
<td>42</td>
<td>0.10</td>
<td>3.0</td>
<td>-</td>
</tr>
<tr>
<td>1403</td>
<td>CO₂</td>
<td>56</td>
<td>0.30</td>
<td>3.0</td>
<td>25.6</td>
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<tr>
<td>1404</td>
<td>CO₂</td>
<td>71</td>
<td>0.60</td>
<td>2.0</td>
<td>26.5</td>
</tr>
</tbody>
</table>

- One truck, sequential dosing of CO₂ after the control specimen was taken.
- Slump was decreasing, temperature was increasing
Trial 1 Calorimetry - Power

Normalized Power (a.u.)

Time After Mixing (hours)

- Control 1401
- CO2 1402
- CO2 1403
- CO2 1404
Trial 1 Calorimetry - Energy

![Graph showing energy (J/g cement) over time after mixing (hours) for different conditions: Control 1401, CO2 1402, CO2 1403, CO2 1404. The graph illustrates the increase in energy over time for each condition.](image-url)
Trial 1 - Early compressive strength

- **Control**
- **CO2-1**: 106% increase
- **CO2-2**: 115% increase
- **CO2-3**: 122% increase

<table>
<thead>
<tr>
<th>Time</th>
<th>Compressive Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>106%</td>
</tr>
<tr>
<td>1 day</td>
<td>109%</td>
</tr>
<tr>
<td>3 day</td>
<td>117%</td>
</tr>
<tr>
<td>7 day</td>
<td>122%</td>
</tr>
</tbody>
</table>

Compressive Strength (psi)

- **Control**
- **CO2-1**: 115% increase
- **CO2-2**: 126% increase
- **CO2-3**: 116% increase

<table>
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<th>Time</th>
<th>Compressive Strength (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>106%</td>
</tr>
<tr>
<td>1 day</td>
<td>109%</td>
</tr>
<tr>
<td>3 day</td>
<td>117%</td>
</tr>
<tr>
<td>7 day</td>
<td>122%</td>
</tr>
</tbody>
</table>
Trial 1 - Later compressive strength

Compressive strength (MPa)

Control

CO2-1

CO2-2

CO2-3

Compressive Strength (psi)

28 day

59 day

108%

97%

105%

103%

115%

121%
Bulk Resistivity ($\Omega \cdot m$) and Chloride Penetration Risk

<table>
<thead>
<tr>
<th>Batch</th>
<th>Test Age (days)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>28</td>
<td>59</td>
</tr>
<tr>
<td>1401 Control</td>
<td>78.7</td>
<td>106.5</td>
</tr>
<tr>
<td>1402 CO2</td>
<td>74.1</td>
<td>112.0</td>
</tr>
<tr>
<td>1403 CO2</td>
<td>67.1</td>
<td>97.7</td>
</tr>
<tr>
<td>1404 CO2</td>
<td>70.2</td>
<td>101.8</td>
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</tbody>
</table>

The resistivity ranges as relating to chloride ion penetrability levels described in ASTM C1202 suggest there was no change in the risk of chloride penetration.
Strength benefit conclusions

<table>
<thead>
<tr>
<th>Age (days)</th>
<th>1</th>
<th>3</th>
<th>7</th>
<th>28</th>
<th>59</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg Control</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>1402 0.10% CO2</td>
<td>106%</td>
<td>109%</td>
<td>107%</td>
<td>108%</td>
<td>97%</td>
</tr>
<tr>
<td>1403 0.30% CO2</td>
<td>115%</td>
<td>117%</td>
<td>112%</td>
<td>105%</td>
<td>103%</td>
</tr>
<tr>
<td>1404 0.60% CO2</td>
<td>122%</td>
<td>126%</td>
<td>116%</td>
<td>115%</td>
<td>121%</td>
</tr>
</tbody>
</table>

- Strength benefit of last condition was maintained across the test period.
- Can the results be repeated? Is there more industrially viable approach?
### Trial 2 outline

<table>
<thead>
<tr>
<th>Sample Code</th>
<th>Condition</th>
<th>Age at injection (min)</th>
<th>CO(_2) Dose (%bwc)</th>
<th>Slump (inches)</th>
<th>Mix Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>801</td>
<td>Control</td>
<td></td>
<td>-</td>
<td>3.5</td>
<td>22.4</td>
</tr>
<tr>
<td>802</td>
<td>CO(_2)</td>
<td>27</td>
<td>0.10</td>
<td>3.0</td>
<td>24.0</td>
</tr>
<tr>
<td>803</td>
<td>CO(_2)</td>
<td>43</td>
<td>0.30</td>
<td>2.5</td>
<td>24.7</td>
</tr>
<tr>
<td>804</td>
<td>CO(_2)</td>
<td>52</td>
<td>0.60</td>
<td>1.5</td>
<td>27.3</td>
</tr>
<tr>
<td>805</td>
<td>CO(_2)</td>
<td>0</td>
<td>0.30</td>
<td>3.0</td>
<td>23.3</td>
</tr>
</tbody>
</table>

- Sequential dosing of CO\(_2\) after the control was taken in first truck, dosing during batching in second truck.
- Slump was decreasing, temperature was increasing
Trial 2 Calorimetry - Power
Trial 2 Calorimetry - Energy
Strength - CO2 during batching

![Graph showing compressive strength (MPa) and psi at different test ages with percentage increases]
Trial 2 - Early compressive strength

The chart shows the compressive strength of different batches of concrete. The compressive strength is expressed in MPa and psi. The percentages indicate the increase compared to the control batch.

- **Control Batch**: 99%
- **CO2 - 1 Batch**: 107%
- **CO2 - 2 Batch**: 106%
- **CO2 - 3 Batch**:
  - 1 day: 108%
  - 3 day: 109%
  - 7 day: 115%
Trial 2 - Late compressive strength

Compressive Strength (MPa) vs. Batch:
- Control: 35 MPa (104%)
- CO2 - 1: 30 MPa (85%)
- CO2 - 2: 35 MPa (110%)
- CO2 - 3: 35 MPa (116%), 28 day (110%), 56 day (107%), 91 day (111%)

Compressive Strength (psi):
- 0 to 6000 psi

Batch:
- Control
- CO2 - 1
- CO2 - 2
- CO2 - 3
### Strength benefit conclusions

<table>
<thead>
<tr>
<th>Age (days)</th>
<th>1</th>
<th>3</th>
<th>7</th>
<th>28</th>
<th>56</th>
<th>91</th>
</tr>
</thead>
<tbody>
<tr>
<td>0801 Control</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>0802 0.10% CO2</td>
<td>99%</td>
<td>107%</td>
<td>106%</td>
<td>104%</td>
<td>85%</td>
<td>103%</td>
</tr>
<tr>
<td>0803 0.30% CO2</td>
<td>106%</td>
<td>112%</td>
<td>111%</td>
<td>110%</td>
<td>116%</td>
<td>106%</td>
</tr>
<tr>
<td>0804 0.6% CO2</td>
<td>108%</td>
<td>109%</td>
<td>115%</td>
<td>107%</td>
<td>111%</td>
<td>107%</td>
</tr>
<tr>
<td>0805 0.30% CO2</td>
<td>114%</td>
<td>126%</td>
<td>121%</td>
<td>115%</td>
<td>118%</td>
<td>115%</td>
</tr>
</tbody>
</table>

- Best results from CO2 during batching
- Resistivity results and chloride risk conclusions were reinforced
Mechanism

• Strength benefit associated with nano-CaCO$_3$ formation.
• Acceleration in calorimetry associated with nucleation
• Like an admixture, there are cement sensitivities
• Subject of further investigation
Environmental Impact

- CO₂ utilization is modest, doses are small
- However a consistent strength benefit can
  - Allow a price premium on a stronger mix
  - Allow mix design optimization
- If the mix design is reformulated for increased SCM usage then the carbon footprint of the mix is decreased.
Durability Study Commenced Oct 2014

• Strength
  – Compressive and flexural

• Exposure
  – Freeze-thaw durability, salt scaling
  – Chloride Permeability
  – RCPT, bulk diffusion test

• Shrinkage

• Service life carbonation testing

• Abrasion testing
Durability Study

Pore Solution Chemistry - pH

- Paste samples made specifically for pore solution expression.
- Carbonation had essentially no impact on pH.
- We do not necessarily expect increased corrosion potential due to CO$_2$ addition, even at 1.7% bwc.
Ready-mix pilot program
Trial Feb 2015
Design: 3000 psi @ 24 hrs and 6000 psi @ 28 days
Thank You

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