Carbon Dioxide Sequestration in Concrete in Different Curing Environments

by

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Reduce, reuse, and recycle for sustainable developments.

Minimize use of manufactured materials.

Maximize environmental benefits: clean air, clean water, and resource conservation.
Carbon Dioxide (CO$_2$) Emission

• Carbon dioxide (CO$_2$) emissions are one of the most serious concerns among all greenhouse gas emissions, along with water vapor and methane.

• CO$_2$ and water vapor emissions can be affected by combustion of fuels and by respiration. Also, decaying organic matter generate CO$_2$ and methane.

• Oil- or coal-burning power plants and cement-producing industries account for a large amount of CO$_2$ emissions.
Need to Reduce CO$_2$ Emissions from Cement Clinker Production

• More efficient cement clinker production
• Reduce the production of cement clinker
  – Increased use of other cementitious materials (OCM)
  – Increased use of organic admixtures
  – Increased carbonation
CO$_2$ Sequestration

• There exists an urgent need for a reduction in CO$_2$ emissions and recycling of CO$_2$.

• An effective method for the reduction of CO$_2$ in the environment is to sequester it in lime- or cement-based (alkali-rich) products via the process of carbonation.
Carbonation of Concrete

(1) $ \text{CO}_2$ diffusion in the cement paste matrix.

(2) $\text{CO}_2$ dissolution in the pore solution for formation of *carbonic acid* ($\text{H}_2\text{CO}_3$) and reaction with calcium hydroxide:

$$\text{Ca(OH)}_2 + \text{CO}_2 \rightarrow \text{CaCO}_3 + \text{H}_2\text{O}$$

$$[\text{Ca}^{2+} + \text{CO}_3^{2-} \rightarrow \text{CaCO}_3]$$
(3) Reaction with silicates and aluminates:
- \(3\text{CaO} \cdot 2\text{SiO}_2 \cdot 3\text{H}_2\text{O} + 3\text{CO}_2 \rightarrow 3\text{CaCO}_3 + 2\text{SiO}_2 + 3\text{H}_2\text{O}\)
- \(4\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 13\text{H}_2\text{O} + 4\text{CO}_2 \rightarrow 4\text{CaCO}_3 + 2\text{Al(OH)}_3 + 10\text{H}_2\text{O}\)
Effects of Carbonation on Concrete

- Consumption of CO₂
- Pore refinement/densification due to precipitation of CaCO₃ inside the pores of the cement paste matrix
- Increase in weight
- Increase in strength
- Improved surface hardness
- Reduction in pH (reinforcing steel can become vulnerable to corrosion)
Factors Affecting Carbonation

• Pore structure
• Availability of Ca(OH)$_2$ and other products of hydration
• Moisture condition of the specimen and Curing environment
  – Relative humidity (Optimum: 50% to 70%)
  – CO$_2$ concentration
  – Temperature
• Use of mineral admixtures
Factors Affecting Carbonation (cont’d)

• Concrete with high internal moisture shows a low rate of carbonation because the diffusion of CO$_2$ becomes difficult when pores are saturated with water.

• Carbonation rate also reduces at a low internal moisture level due to insufficient water in the pores.
# Mixture Designations

<table>
<thead>
<tr>
<th>Fly ash / cementitious materials (%)</th>
<th>Curing condition</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Moist-curing room</td>
<td>Drying room</td>
</tr>
<tr>
<td></td>
<td>100% RH &amp; 0.15% CO₂</td>
<td>50% RH &amp; 0.15% CO₂</td>
</tr>
<tr>
<td></td>
<td>CO₂ chamber</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>50% RH &amp; 5% CO₂</td>
</tr>
<tr>
<td>Fly ash / cementitious materials (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>F0-M</td>
<td>F0-D</td>
</tr>
<tr>
<td>18</td>
<td>F18-M</td>
<td>F18-D</td>
</tr>
<tr>
<td>35</td>
<td>F35-M</td>
<td>F35-D</td>
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</table>
## Mixture Proportions and Fresh Properties of Concrete

<table>
<thead>
<tr>
<th>Mixture designation</th>
<th>F0-M</th>
<th>F0-D</th>
<th>F0-C</th>
<th>F18-M</th>
<th>F18-D</th>
<th>F18-C</th>
<th>F35-M</th>
<th>F35-D</th>
<th>F35-C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement (kg/m³)</td>
<td>297</td>
<td>301</td>
<td>298</td>
<td>253</td>
<td>253</td>
<td>252</td>
<td>211</td>
<td>210</td>
<td>209</td>
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<tr>
<td>Fly ash (kg/m³)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>56</td>
<td>56</td>
<td>56</td>
<td>113</td>
<td>113</td>
<td>112</td>
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<tr>
<td>Sand (kg/m³)</td>
<td>884</td>
<td>899</td>
<td>893</td>
<td>902</td>
<td>902</td>
<td>899</td>
<td>904</td>
<td>902</td>
<td>899</td>
</tr>
<tr>
<td>Co. agg., 19-mm max. (kg/m³)</td>
<td>1040</td>
<td>1060</td>
<td>1050</td>
<td>1050</td>
<td>1050</td>
<td>1040</td>
<td>1050</td>
<td>1050</td>
<td>1040</td>
</tr>
<tr>
<td>Water (kg/m³)</td>
<td>157</td>
<td>157</td>
<td>154</td>
<td>160</td>
<td>160</td>
<td>160</td>
<td>153</td>
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<tr>
<td>W/Cm</td>
<td>0.53</td>
<td>0.52</td>
<td>0.52</td>
<td>0.52</td>
<td>0.52</td>
<td>0.52</td>
<td>0.47</td>
<td>0.47</td>
<td>0.47</td>
</tr>
<tr>
<td>Slump (mm)</td>
<td>75</td>
<td>70</td>
<td>50</td>
<td>70</td>
<td>65</td>
<td>75</td>
<td>75</td>
<td>90</td>
<td>95</td>
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<tr>
<td>Air content (%)</td>
<td>2.2</td>
<td>2.6</td>
<td>1.7</td>
<td>1.5</td>
<td>1.5</td>
<td>1.2</td>
<td>1.2</td>
<td>1.4</td>
<td>1.6</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>2380</td>
<td>2410</td>
<td>2400</td>
<td>2420</td>
<td>2420</td>
<td>2410</td>
<td>2430</td>
<td>2430</td>
<td>2420</td>
</tr>
</tbody>
</table>
Mixture Proportions

- **Class C fly ash** was used as a partial replacement of cement. For 1 kg of cement being replaced, 1.25 kg of fly ash was added.

- The concrete mixtures were **not air entrained**.
Strength and Abrasion Tests

- Compressive strength: 100 × 200 mm cylinders
- Splitting tensile strength: 100 × 200 mm cylinders
- Flexural strength: 100 × 75 × 300 mm beams
- Abrasion resistance: ASTM C 944 using 45-mm thick disks saw-cut from the top of 150 × 300 mm cylinders
Depth of Carbonation Test

- RILEM CPC-18 using split halves obtained from splitting tensile tests.
- A pH-indicator solution (1% phenolphthalein in a 70% ethyl alcohol solution) was sprayed on the fractured surface of concrete specimens.
Demolding and Curing

• Approximately 24 hours after casting, specimens were removed from molds.
• Immediately, they were put in three types of curing environment
  – Moist-curing room: 100% RH & 0.15% CO₂
  – Drying room: 50% RH & 0.15% CO₂
  – CO₂ chamber: 50% RH & 5% CO₂.
CO₂ Chamber

- CO₂ concentration: 5 ± 1.25%
- Relative humidity: 50 ± 4%
- Temperature: 21 ± 1.5°C.
- A fan was provided in the chamber to circulate the CO₂ within the chamber.
Testing for Compressive Strength
Testing for Splitting Tensile Strength
Testing for Flexural Strength
Strength

• The concrete specimens cured in the drying room developed the lowest strength. In the drying room, there was little or no gain in compressive strength after the 28-day age; and, the concrete containing 35% fly ash showed the lowest compressive strength in this environment.

• The CO$_2$ chamber was as effective as the moist-curing room in developing the compressive strength of concrete containing 0% to 35% fly ash.
Abrasion testing: using rotating cutters for six minutes under a load of 197 N
Mass Loss Due to Abrasion

• The concrete cured in the moist-curing room showed the least mass loss upon abrasion (highest abrasion resistance).
• The concrete cured in the drying room showed the highest abrasion mass-loss, which worsened with age.
• The abrasion mass-loss of the concrete cured in the CO$_2$ chamber was lower than that of the concrete cured in the drying room, but higher than that of moist-cured concrete.
Mass Loss Due to Abrasion (cont’d)

In both the moist-curing room and the CO₂ chamber, the abrasion resistance concrete improved with age.
Testing for Depth of Carbonation of Concrete

Pink: considered non-carbonated.
No discoloration: considered carbonated.
Depth of carbonation of concrete mixtures containing 35% fly ash, measured at 28 days
Depth of Carbonation

• Concrete made with or without fly ash, cured in the moist-curing room (100% RH and 0.15% CO₂) did not show carbonation at 3, 7, 28, and 91 days.

• In the drying room (50% RH and 0.15% CO₂), concrete carbonated to some extent.

• Concrete cured in the CO₂ chamber showed much higher carbonation than the concrete cured in the drying room.
CONCLUSIONS

• Compared to moist-cured concrete, the concrete cured in the CO₂ chamber showed approximately the same strength and a similar or slightly lower abrasion resistance (higher mass-loss).

• The concrete cured in the drying room without enough carbonation showed the lowest strength and least abrasion resistance (highest mass-loss).
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