Abstract
The CarbonCure ready-mix technology produced concrete with a binder system comprising 80% Type IL cement and 20% Class F fly ash. The mix was produced with CO₂ which was added like an admixture. The added CO₂ enabled the use of less cement content without compromising the strength properties of the mix while achieving an increase in compressive strength of 8% over a reference mix.

Introduction
CarbonCure Technologies (CCT) has developed a carbon dioxide (CO₂) utilization approach that injects CO₂ into fresh ready-mix concrete similar to introducing any other chemical admixture. The CO₂ reacts with the calcium silicate phases present in the cement to form calcite nanoparticles that can enhance the compressive strength by improving the cement hydration efficiency of concrete [1] without compromising durability [2]. This allows for the optimization of any concrete mix design by safely reducing cement content and lowering the carbon footprint of concrete with no impact on quality or performance. The technology can be applied to a wide range of ready-mix concrete designs.

Case Study
The trial considered two conditions: 1) a reference concrete mixture using 80% Type IL cement and 20% Class F Fly Ash designed to have a 28-day compressive strength of 21 MPa (3,000 psi), and 2) a concrete mixture incorporating CO₂ addition as an admixture (referred herein as the CarbonCure mix). The proportions for the two mix variations are presented in Table 1. The data set comprises 26 samples for the reference mix and 13 samples for the CarbonCure mix. Both mixes also included a high-range water-reducing admixture. The reference cement content of 237 kg/m³ (400 lb/yd³) was adjusted to 230 kg/m³ (388 lb/yd³) for the CarbonCure mix to leverage a strength increase demonstrated in technology commissioning. The total cementitious reduction of 3% was accompanied by a 1% increase in the fine aggregate to maintain yield. The water-to-cementitious materials ratio (w/cm) increased slightly as a result of the mix adjustment.
Type IL Cement and Class F Fly Ash

Table 1: Mix design details for the reference and CarbonCure mixtures.

<table>
<thead>
<tr>
<th>Component</th>
<th>Unit</th>
<th>Reference</th>
<th>CarbonCure</th>
<th>Adjustment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type IL Cement</td>
<td>kg/m³ (lb/yd³)</td>
<td>237 (400)</td>
<td>230 (388)</td>
<td>-3.0%</td>
</tr>
<tr>
<td>Class F Fly Ash</td>
<td>kg/m³ (lb/yd³)</td>
<td>59 (100)</td>
<td>58 (97)</td>
<td>-3.0%</td>
</tr>
<tr>
<td>Coarse Aggregate</td>
<td>kg/m³ (lb/yd³)</td>
<td>1,098 (1,850)</td>
<td>1,098 (1,850)</td>
<td></td>
</tr>
<tr>
<td>Fine Aggregate</td>
<td>kg/m³ (lb/yd³)</td>
<td>825 (1,390)</td>
<td>833 (1,405)</td>
<td>+1.0%</td>
</tr>
<tr>
<td>Water</td>
<td>L/m³ (gal/yd³)</td>
<td>168 (34)</td>
<td>168 (34)</td>
<td></td>
</tr>
<tr>
<td>High-Range Water Reducer</td>
<td>mL/m³ (oz/yd³)</td>
<td>773 (20)</td>
<td>773 (20)</td>
<td></td>
</tr>
<tr>
<td>CO₂</td>
<td>mL/m³ (oz/yd³)</td>
<td>-</td>
<td>1,203 (31.1)</td>
<td></td>
</tr>
<tr>
<td>w/cm</td>
<td></td>
<td>0.57</td>
<td>0.58</td>
<td>+1.7%</td>
</tr>
</tbody>
</table>

Results

CO₂ Effect on Field Fresh Properties
The slump results are shown in Figure 1 for the reference and CarbonCure mixes. The slump for the reference mix design averaged 175 millimetres (7.0 inches) while the slump for the CarbonCure mix averaged 110 millimetres (4.25 inches).

CO₂ Effect on Field Compressive Strength
Table 2 and Figure 1 show compressive strength data for both the reference and CarbonCure mixes at 7- and 28-day age intervals. The average compressive strength at 28 days was 25.2 MPa (3,657 psi) for the reference mix and 27.1 MPa (3,935 psi) for the CarbonCure mix. The CarbonCure mix with 3% less cement had an 8% higher average 28-day compressive strength than the reference mix.

Table 2: Strength performance details for reference and CarbonCure mixtures.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Unit</th>
<th>Reference</th>
<th>CarbonCure</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample Count</td>
<td></td>
<td>26</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>Average 7-day strength</td>
<td>MPa (psi)</td>
<td>17.5 (2,532)</td>
<td>17.4 (2,529)</td>
<td>+0%</td>
</tr>
<tr>
<td>St. Dev of 7-day</td>
<td>MPa (psi)</td>
<td>2.5 (361)</td>
<td>3.4 (491)</td>
<td>+36%</td>
</tr>
<tr>
<td>Average of 28-day</td>
<td>MPa (psi)</td>
<td>25.2 (3,657)</td>
<td>27.1 (3,935)</td>
<td>+8%</td>
</tr>
<tr>
<td>St. Dev of 28-day</td>
<td>MPa (psi)</td>
<td>3.3 (481)</td>
<td>4.0 (579)</td>
<td>+20%</td>
</tr>
</tbody>
</table>
Mix Performance

The performance of the two mix designs in terms of cement efficiency is outlined in Table 3 below. The cement efficiency is calculated using Equation 1:

\[
\text{cement efficiency} = \frac{\text{compressive strength}}{\text{cement mass per unit of concrete}}
\]  

(1)

The reference mix design demonstrates a 28-day cement efficiency of 0.106 MPa\(\cdot\)kg\(^{-1}\)\(\cdot\)m\(^3\) (9.14 psi\(\cdot\)lb\(^{-1}\)\(\cdot\)yd\(^3\)), while the CarbonCure mix demonstrates a cement efficiency of 0.118 MPa\(\cdot\)kg\(^{-1}\)\(\cdot\)m\(^3\) (10.14 psi\(\cdot\)lb\(^{-1}\)\(\cdot\)yd\(^3\)), an increase of 11%. A similar calculation of cementitious efficiency, using the mass of cementitious instead, shows 0.085 MPa\(\cdot\)kg\(^{-1}\)\(\cdot\)m\(^3\) (7.31 psi\(\cdot\)lb\(^{-1}\)\(\cdot\)yd\(^3\)) cementitious for the reference mix and 0.094 MPa\(\cdot\)kg\(^{-1}\)\(\cdot\)m\(^3\) (8.11 psi\(\cdot\)lb\(^{-1}\)\(\cdot\)yd\(^3\)) cementitious for the CarbonCure mix.

<table>
<thead>
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<th>CarbonCure</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Cement Efficiency</td>
<td>MPa(\cdot)kg(^{-1})(\cdot)m(^3) (psi(\cdot)lb(^{-1})(\cdot)yd(^3))</td>
<td>0.106 (9.14)</td>
<td>0.118 (10.14)</td>
<td>+11%</td>
</tr>
<tr>
<td>Average Cementitious Efficiency</td>
<td>MPa(\cdot)kg(^{-1})(\cdot)m(^3) (psi(\cdot)lb(^{-1})(\cdot)yd(^3))</td>
<td>0.085 (7.31)</td>
<td>0.094 (8.11)</td>
<td>+11%</td>
</tr>
</tbody>
</table>

Concluding Remarks

This case study showed the feasibility of using the CarbonCure ready-mix technology in a 21 MPa (3,000 psi) commercially available concrete mixture with 80% Type IL cement and 20% Class F fly ash as the binder system. The addition of CO\(_2\) as an admixture into the fresh concrete allowed for a 3% reduction in the cement content of the CarbonCure mixture while achieving a compressive strength increase of 8% over a reference concrete mixture without CO\(_2\). The addition of CO\(_2\) has been demonstrated to cause additional cement hydration reactions attributed to the formation of calcite nanoparticles which increase the compressive strength of concrete by reducing porosity and providing additional nucleation sites for the
cement hydration reaction. This is translated into a better cement hydration efficiency in the optimized CarbonCure mixture.

**References**
