EXECUTIVE SUMMARY

The CarbonCure Ready Mix Concrete Technology is being implemented by concrete producers across the United States and Canada to improve the compressive strength and environmental footprint of their concrete products. This case study examines data provided by a CarbonCure producer partner who installed the CarbonCure technology and used the system to produce concrete with an optimized dosage of CO₂.

Concrete prepared using the CO₂ injection system was shown to deliver comparable compressive strength performance with a 5-8% reduction in binder loading while having a neutral impact on fresh properties, including air, slump, and temperature. Roughly 45 000 yd³ of concrete were produced over an 10 month period using a 5% binder reduction in conjunction with an optimized dose of CO₂. The estimated cement savings exceeded 600 tons and more than 550 tons of CO₂ emissions were avoided. The use of the technology did not impact the producer’s cycle time; all operations continued as normal throughout this assessment.

The action of the CO₂ is discussed in terms of nanomaterial impacts. The injection of carbon dioxide into the concrete mix forms well dispersed calcium carbonate nanoparticles, which allows concrete producers to realize the understood benefits of nanoparticle additions while avoiding common technical or economic barriers. The technology delivers value to the concrete producer while reducing the concrete’s environmental impact.
Introduction

This case study analyzes data collected by a CarbonCure producer utilizing the CarbonCure Ready Mix Technology to inject CO$_2$ during normal concrete operations. The CarbonCure technology controlled the carbon dioxide delivery into the ready mix concrete truck during the initial batching and mixing. The carbon dioxide was bound as solid and stable carbonate reaction products in the cement matrix and provided a positive impact on the concrete properties.

Methods

The fresh concrete was assessed via on-site measurement of slump, temperature, air content and unit weight. The concrete was then cast into 4" x 8" cylinders for compressive strength testing at 7, 14 and 28 days after batching. All concrete specimens were prepared and tested in accordance with the relevant ASTM and ACI standards.

The CarbonCure Ready Mix Technology controlled the delivery of CO$_2$ into the concrete. In a process that resembles the introduction of a chemical admixture, a tank of liquid CO$_2$ was connected to the CarbonCure injection system. The liquid was metered to deliver an optimum dose of CO$_2$ into the drum of the ready mix truck at the same time as the concrete was loaded. Upon entering the mixing drum, the liquid carbon dioxide converted into a mixture of CO$_2$ gas and solid carbon dioxide snow whereupon it reacted with the hydrating cement to form solid calcium carbonate particles. The concrete was then subjected to assessment and testing.

All samples were collected from trucks carrying 9 yd$^3$ of a residential mix with design strength of 3000 psi. The concrete mix design used a ternary binder system of Portland cement, class F fly ash and slag.

To illustrate the potential of CO$_2$ in mix design optimization, a three-way comparison was conducted between a standard mix, a mix with reduced binder content, and a reduced binder mix that used an optimized dose of CO$_2$. Two mix designs, including/excluding air entrainment admixtures, were examined. The relevant binder loadings for the mix designs are summarised in Table 1. Small adjustments of fine aggregate loadings were also included to ensure that yield was maintained following a reduction in binder loading.

The binder reduction leads to a decrease in paste volume, but can also serve to slightly increase the water to cementitious ratio and admix loading per unit of binder. The former is expected to have a negative impact on strength development while the latter is expected to have a neutral impact.

Strength Enhancement Results

An overview of the fresh properties for the loads produced during the production run is presented in Table 2.

<table>
<thead>
<tr>
<th>Mix Type</th>
<th>Type</th>
<th>Cement (lbs/yd$^3$)</th>
<th>Class F Fly Ash (lbs/yd$^3$)</th>
<th>Slag (lbs/yd$^3$)</th>
<th>Total Binder (lbs/yd$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Mix</td>
<td>Reduced Binder</td>
<td>258</td>
<td>132</td>
<td>149</td>
<td>539</td>
</tr>
<tr>
<td>Non Air</td>
<td>Mix Relative</td>
<td>249</td>
<td>132</td>
<td>119</td>
<td>500</td>
</tr>
<tr>
<td>Entrained</td>
<td>Change</td>
<td>-4%</td>
<td>n/a</td>
<td>-20%</td>
<td>-7%</td>
</tr>
<tr>
<td>Air Entrained</td>
<td>Reduced Binder</td>
<td>281</td>
<td>109</td>
<td>151</td>
<td>540</td>
</tr>
<tr>
<td></td>
<td>Mix Relative</td>
<td>248</td>
<td>129</td>
<td>119</td>
<td>496</td>
</tr>
<tr>
<td></td>
<td>Change</td>
<td>-12%</td>
<td>+18%</td>
<td>-21%</td>
<td>-8%</td>
</tr>
</tbody>
</table>
Table 2: Production variables, CO₂ settings and fresh results.

<table>
<thead>
<tr>
<th>Mix</th>
<th>Type</th>
<th>Slump (in)</th>
<th>Air (%)</th>
<th>Unit Wt (lbs/ft³)</th>
<th>Temp (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non Air Entrained</td>
<td>Reduced Binder</td>
<td>5</td>
<td>2.5</td>
<td>146.6</td>
<td>84</td>
</tr>
<tr>
<td></td>
<td>Reduced Binder with CO₂</td>
<td>4</td>
<td>2.5</td>
<td>147.2</td>
<td>84</td>
</tr>
<tr>
<td></td>
<td>CO₂ Standard Mix</td>
<td>4</td>
<td>2.5</td>
<td>147.2</td>
<td>84</td>
</tr>
<tr>
<td>Air Entrained</td>
<td>Reduced Binder</td>
<td>6</td>
<td>4.2</td>
<td>144.4</td>
<td>84</td>
</tr>
<tr>
<td></td>
<td>Reduced Binder with CO₂</td>
<td>5</td>
<td>3.4</td>
<td>147.2</td>
<td>81</td>
</tr>
<tr>
<td></td>
<td>CO₂ Standard Mix</td>
<td>6</td>
<td>3.5</td>
<td>146.0</td>
<td>84</td>
</tr>
</tbody>
</table>

The average compressive strength measured for each batch at three test ages is summarized in Figure 1.

The binder modification in the non-air entrained batch lead a strength reduction at all ages including a 17% drop in 28 day compressive strength. However, when the carbon dioxide was added the strength of the reduced binder batch improved to be within 4% of the reference at 28 days. The trial represented the first attempt at an optimized mix design and it was observed that further tweaks of the modified mix design and/or CO₂ dose should establish that the CO₂ addition can result in at least equivalent performance at all ages. The 28 day data suggested that a CO₂ injection in conjunction with a binder reduction on the order of 7% can create concrete without compromising performance.

The binder reduction in the air entrained batch lead to an 11-13% drop in compressive strength across the three test ages.

Figure 1: Compressive strength development of non air entrained (A) and air entrained (B) concrete test loads. For each mix the customer compared 3 cases: A standard mix (dark blue), the standard mix with a reduction in binder loading (light blue), and the standard mix with a reduction in binder loading that further incorporated the addition of an optimized dose of CO₂ (orange). The binder reductions were 8% and 7% for the non air entrained and air entrained variations respectively.
However, when the carbon dioxide was added the strength of the reduced binder batch improved to be equivalent to the standard mix.

The strength benefit results confirmed two major outcomes:

1) A reduction in the binder loading leads to a reduction in the compressive strength
2) The strength reduction could be offset through the introduction of CO\textsubscript{2} into the concrete mix during batching

The conclusion was examined in extended production.

**Extended Production Results**

Three mix designs were selected for expanded testing to assess the performance enhancement of CO\textsubscript{2} across a range of concrete strength classes. The compressive strength development of mixes with 28 day design strengths of 3000, 5500 and 8000 psi were assessed when using CO\textsubscript{2} alongside reductions in binder loading of 4.5%, 4.4% and 3.1% respectively. The 7 and 28 day compressive strength results for each mix design are plotted in Figures 2-4 against graphical ranges of historical data representing the average, 10\textsuperscript{th} percentile and 90\textsuperscript{th} percentile results for the unmodified mix.

In each case the addition of an optimized dosage of CO\textsubscript{2} was shown to bring the performance of the concrete mix design with a reduced binder loading within the expected performance range based on historical data. The average and the variation of the reduced binder CO\textsubscript{2} batches were consistent with the historical data of the unmodified mix. The acceptable production of batches using the CO\textsubscript{2} and a reduced binder loading across a range of strength classes was assured.

The success of these two assessments encouraged the ready mix concrete producer to apply the CarbonCure Ready Mix Concrete Technology across their concrete production. Over a 10-month period, spanning March to December, CO\textsubscript{2} was injected into roughly 56,000 yd\textsuperscript{3} of concrete with an average cement reduction of 5%. The extended implementation of the technology resulted in 600 tons of cement savings and, according to emissions information specific to the cement, 530 tons of avoided CO\textsubscript{2} emissions (Figure 5).

![Figure 2](Image1): Compressive strength development of a 3000 psi air entrained mix. The blue boxes represent the historical compressive strength performance range (10\textsuperscript{th} to 90\textsuperscript{th} percentile) while the orange circles represent the compressive strengths of loads of the mix prepared with a 4.3% reduction in binder content (5.7% reduction in cement content) and an optimized dose of CO\textsubscript{2}. Whiskers indicate the historical data maximum and minimums.
Figure 3: Compressive strength development of a 5500 psi mix designed for high early strength applications. The blue boxes represent the historical compressive strength performance range (10th to 90th percentile) while the orange circles represent the compressive strengths of loads of the mix prepared with a 4.4% reduction in binder content (4.4% reduction in cement content) and an optimized dose of CO₂. Whiskers indicate the historical data maximum and minimums.

Figure 4: Compressive strength development of a 8000 psi mix. The blue boxes represent the historical compressive strength performance range (10th to 90th percentile) while the orange circles represent the compressive strengths of loads of the mix prepared with a 3.1% reduction in binder content (6.0% reduction in cement content) and an optimized dose of CO₂. Whiskers indicate the historical data maximum and minimums.
Figure 5: Cumulative cement savings (orange) and avoided CO\textsubscript{2} emissions (gray) for a producer using the CarbonCure Ready Mix Technology in conjunction with a 5% cement reduction over an 10 month period. These reductions were totalled through the production of approximately 56 000 yd\textsuperscript{3} of concrete.

This customer data provides verification that producers can leverage the strength enhancing effect of the CO\textsubscript{2} to achieve binder adjustments with diverse motivations:

- **Economic** – reducing the overall amount of binder can save money. The reduction of the most expensive components can be prioritized.

- **Performance** – durability benefits related to increased binder proportioning of slag and/or fly ash can be targeted while not compromising on the early strength development.

- **Environmental** – reducing cement usage directly leads to avoiding CO\textsubscript{2} emissions thereby allowing for a reduction in the carbon footprint of the mix.

**Mechanism**

When liquefied CO\textsubscript{2} is injected into wet concrete the CO\textsubscript{2} chemically reacts with calcium ions released from cement to form solid, nano-sized calcium carbonate particles that become permanently bound within the concrete.

The main cement phases, tricalcium silicate and dicalcium silicate, are known to react with carbon dioxide in the presence of water to form calcium carbonate\textsuperscript{1}. The reaction proceeds in the aqueous state when calcium ions from the cementitious phases meet carbonate ions from the applied CO\textsubscript{2}.

The reaction of carbon dioxide with hardened concrete is conventionally acknowledged to be a durability issue due to such effects such as shrinkage, reduced pore solution pH, and carbonation induced corrosion. In contrast, carbon dioxide utilization in concrete production reacts CO\textsubscript{2} with freshly hydrating cement, rather than the hydration phases present in mature concrete, and does not have the same effects. Consequently durability is not affected\textsuperscript{2}. By virtue of adding CO\textsubscript{2} to freshly mixing concrete the carbonate reaction products are formed within the concrete mix at the nano-scale and homogenously distributed. Figure 6 shows an example of a nano-scale reaction product formed following the introduction of CO\textsubscript{2} into a hydrating cement sample produced in an associated laboratory test.
While it is known that the addition of nano-sized calcium carbonate particles can be used to impact the hydration of cement, concrete producers attempting to add nanoparticles to a concrete mix often run into technical (e.g. difficulty achieving homogeneous dispersion), operational (e.g. availability and/or quality of supply) and economic (e.g. cost) barriers. The addition of liquefied $\text{CO}_2$ injected into the concrete mix enables concrete producers to manufacture nano-$\text{CaCO}_3$ within the concrete mixture at the time of production, thus permitting the producer to realize the benefits of nano-$\text{CaCO}_3$ while avoiding these common barriers.

Conclusions

Industrial scale integration of the CarbonCure ready mix concrete system into a concrete production environment has demonstrated the ability to leverage $\text{CO}_2$ as a new tool in mix design optimization. By combining the strength enhancing properties of an optimized dose of $\text{CO}_2$ with reduced binder loadings concrete producers are able to achieve equivalent 28-day compressive strength performance with a reduced environmental footprint.

References