CarbonCure Technologies

Non-Confidential Final Report

K160002
Carbon Dioxide Utilization in Concrete

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Executive Summary

The economic opportunity for CO_2 Capture, Utilization, and Storage (CCUS) in the concrete sector is enormous - both at a global scale and for the Province of Alberta. CCUS for the concrete sector alone is estimated to be an annual $400 billion market opportunity and a CO_2 emissions reduction opportunity on the order of 3 gigatons annually with the correct policies in place (Source: Global CO_2 Initiative Report, 2016). CarbonCure's "made in Canada" portfolio of CCUS technologies has the potential to unlock over 7.2 MT annual CO_2 emission reductions in Canada and up to 786 MT of annual CO_2 emissions reductions across the globe based on current and project concrete production.

This project demonstrated the commercial viability of CarbonCure's technologies for the concrete sector through 1) further optimization and refinement of the technologies, business model, and value proposition to industry, 2) the introduction of new digital processes to enhance both efficiency and carbon reductions, and 3) demonstration of the technology at several concrete plants across Alberta. The deployment of CarbonCure's technologies, aided by the project funding, resulted in significant opportunities for key lessons to be learned, provided a use case for value-added carbon-based products, and positioned Alberta's concrete industry to transition to a lower carbon economy.

Several key lessons have been learned (see Outcomes and Learnings) which will be applied during Round 3 to accelerate future growth and adoption in the Province. Overall, the project has been successfully executed as planned per the components of the amended contract, schedule, and budget. All of the major deliverables have been met, and the project was on-time and on-budget.

CarbonCure Technologies would like to thank Emissions Reduction Alberta for its funding and guidance during this project, and the team looks forward to continuing to work together to achieve our joint mission of deploying business-friendly climate solutions in the Province during Round 3 of the Grand Challenge.

Project Description

Introduction and Background

The aim of this project was to transform Alberta's concrete, building construction, and infrastructure industries in order to establish a repeatable framework that will profitably reduce carbon dioxide (CO_2) emissions in Alberta and globally. Concrete is

the world's most abundant man-made material[1]. It is also an exceptionally valuable product for building low-emission new buildings due to its thermal mass properties and its unparalleled durability and resiliency attributes. Its high carbon intensity however is at odds with the rising demand for green building products and decarbonization trends. This project was designed to accelerate the commercialization of CarbonCure Technology's (CarbonCure) CO_2 utilization technology, which sequesters post-industrial CO_2 into concrete. Sequestration of CO_2 in concrete materials will enhance the sector's competitiveness by lowering the CO_2 footprint, and water intensity of concrete production. During this project, CarbonCure's commercialized ready mixed technology was installed and used in concrete plants located in Alberta. In addition, CarbonCure's latest innovation – beneficiating concrete reclaimed water with CO_2 – was also demonstrated during the project. Furthermore, CarbonCure introduced digital solutions to its portfolio, which have led to increased efficiency, remote maintenance and monitoring, and ultimately greater CO_2 reductions.

Technology Description

CarbonCure currently offers a suite of related CO_2 capture, utilization, and storage (CCUS) technologies for the concrete sector that involve introducing post-industrial carbon dioxide into concrete during production and is exploring additional applications of this technology. The introduced carbon dioxide reacts to form calcium carbonate ($CaCO_3$) which is locked into the concrete as a solid material. The method to integrate the carbon dioxide into the various production or treatment processes differs between the CCUS technologies, though the chemical reaction between CO_2 and cement is similar across the portfolio of CarbonCure CCUS technologies. In the masonry and ready mix applications the carbon dioxide reacts with freshly hydrating cement, while in the reclaimed water and recycled concrete applications the carbon dioxide reacts with hydrated cement. In each case the carbon dioxide is mineralized to form $CaCO_3$, using either a seeding or coating process. In both situations, the CO_2 is permanently locked within the concrete material in a solid form. See Figure 1 for an illustration of the chemical reaction that underpins the technology.

[1] Ashby, M. F. (2012). Materials and the Environment: Eco-informed Material Choice. Netherlands: Elsevier Science.

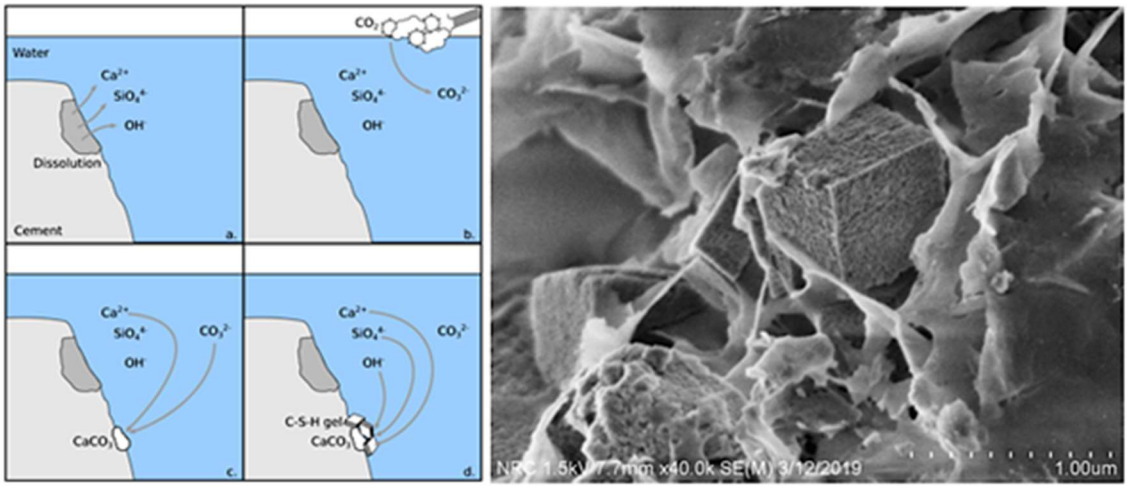

Figure 1: Schematic of masonry/ready mix/precast technology chemical reaction (left) where the addition of CO_2 results in the formation of nano-scale $CaCO_3$ (right).

The masonry technology targets a CO_2 dose to maximize carbon mineralization. In the masonry approach the intention is to maximize the amount of CO_2 injected, while minimizing losses (i.e. avoiding overdosing), avoiding increases to cycle times, avoiding incurred excessive costs, and achieving an equivalent performance. The resulting carbonated blocks are produced with a reduced carbon impact.

Alternatively, the ready mix technology targets an optimal dose to unlock *performance benefits.* The intention of the ready mix technology is to use an optimal amount of CO_2 that provides a concrete performance (i.e. compressive strength) benefit. An improved performance can allow for less cement to be used during production, and thereby save lifecycle CO_2 emissions that are associated with the displaced cement. Moreover, the reduction in cement unlocks production cost savings, thereby providing an economic benefit to the concrete producer. The second generation ready mix technology builds upon lessons learned from commercializing the first generation of the technology.

The reclaimed water treatment technology involves the injection of CO_2 into an agitated slurry of common on-site waste reclaimed water. The reclaimed water application relates to treating the water that is produced at a ready mix concrete plant as a by-product of concrete production (see Figure 2 and Figure 3). The water, which comes from washing the equipment (concrete mixers, trucks, etc.), can be a heavy economic, environmental, material and logistical burden since it can only be reused in the production with great difficulty and at high dilution rates. It is typically discarded at a significant cost to the producer (and environmental risk). CarbonCure's reclaimed water application involves treating the water with CO_2 which reduces or eliminates the barriers to recycling the slurry as mix water in a new batch of concrete. Beyond the economic benefit,

the process significantly reduces the amount of fresh water required to produce concrete and provides an additional viable opportunity for beneficial reuse of post-industrial CO_2.

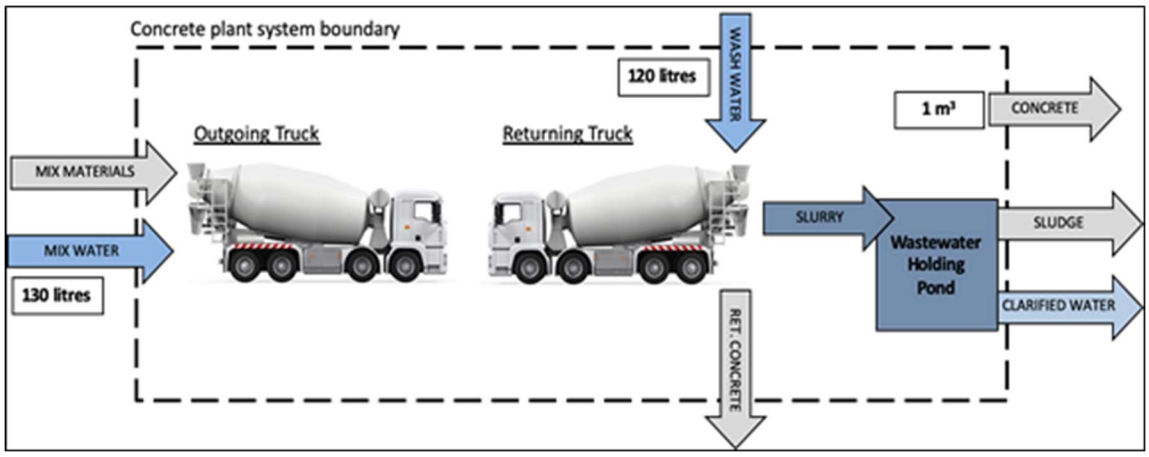

Figure 2: Schematic of business as usual reclaimed water production and handling

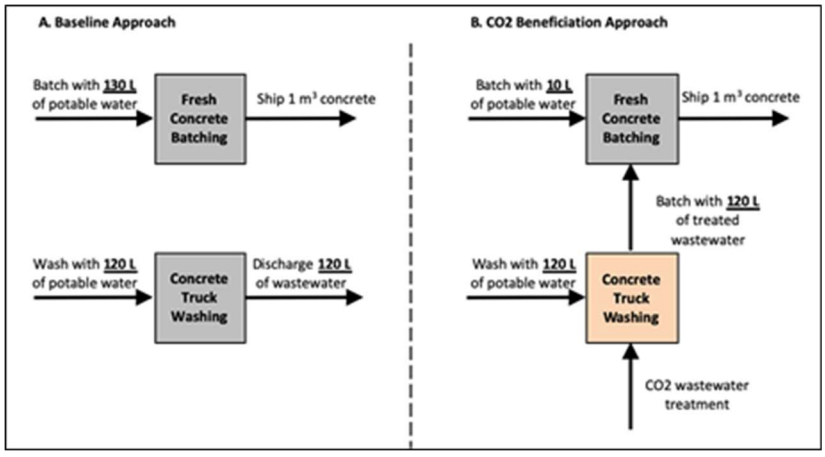

Figure 3: Reclaimed water recycling using Carbon Dioxide

Project Goals

The main objective of the project was to optimize, demonstrate and ultimately scale CarbonCure's CO_2-utilization technologies to demonstrate the ability to achieve at least 1 Megatonne of GHG reductions in the future. Specifically, the goals of the project were to:

- Identify and remove all remaining technical and market barriers for the CO_2 utilization technology application in ready mixed concrete
- Optimize the commercialized technology to increase amount of CO_2 injected
- Test and commercialize the CO_2 utilization technology application in reclaimed water, which is expected to increase both the CO_2 and water reduction benefits
- Demonstrate the integration of CarbonCure's technology with an innovative carbon capture system
- Determine whether reduced purity CO_2 is acceptable and would help to further improve the technology economics.

Ultimately, the goal of the project was for CarbonCure's technology to be fully commercialized and be ready for full deployment across Alberta. At the end of the project, all of the project goals and objectives were met, and key lessons were learned (described in following section) which will be applied to Round 3 of the program. The key lessons fall into the categories of optimizing the technology for enhanced performance and CO_2 reductions, expanding the value proposition and enhancing the business model, expanding the applications across the value chain, and removing market barriers to accelerate future adoption of the technologies.

Outcomes and Learnings

There were several important lessons learned during the project that resulted from both laboratory and field work, which fall into the following categories:

- Improvements to the technology hardware and software
- Improvements to the installation and commissioning processes to remove technical barriers to adoption by customers
- Expanded value proposition and business model modifications
- Expanded value chain applications
- Impact of market development lessons related to removing market barriers

Improvements to technology hardware and software, installation and commissioning

Since the beginning of the project several improvements have been made to the mixer technology equipment to make it easier to install and maintain, and also more accurate for the range of temperatures and pressures that the system is subjected to in field conditions. New software was developed to monitor installed CO_2 injection systems in the field to detect anomalies and system alarms which has resulted in an improvement to system uptime across the entire network of CarbonCure installations. System uptime now regularly registers at more

than 99%. A customer facing web portal, myCarbonCure, was also developed to give CarbonCure customers access to valuable resources to help them sell and promote the use of CarbonCure concrete. The system also provides operations staff with access to real-time data and metrics for concrete volumes treated with CO_2 and the environmental impact each customer has achieved since adopting the technology. The myCarbonCure platform continues to be a tool that CarbonCure's customers use to monitor production data and trends, create communications documentation that supports product submittals, quantify the reduced carbon intensity of their mix designs, monitor production trends, and overall share the message that concrete production can be a sustainable building material.

Expanded value proposition and business model modifications

Production data collected in Alberta contributed to a greater understanding of a potential value proposition that had not been previously considered. The technology has been demonstrated to increase the compressive strength of concrete and thereby allow for a more efficient use of cement. Some of the results obtained in Alberta during this project demonstrated that the concrete produced using carbon dioxide had reduced variability.

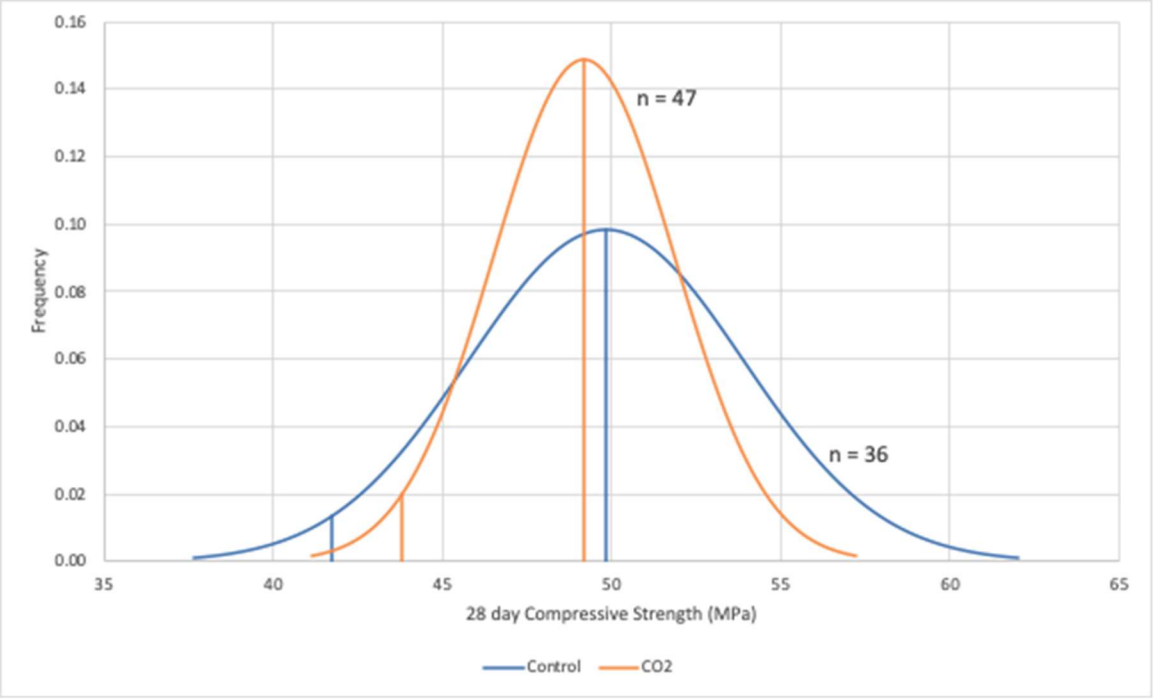

Figure 4: Reduction of variability due to CO_2 addition

The reduction in variability offers a different performance enhancement that would also support a reduction in cement. Where concrete is not defined so much by the strength of an individual batch but more suitably by the range of performance of a mix design produced over time. The data from the Alberta project validated that the safety factor could be increased even if the strength was not changed. The alternative value proposition was subsequently examined with other producers and validated.

Furthermore, during the demonstrations and through customer interviews and analysis, CarbonCure gathered feedback and experimented with various aspects of the business model, including contract structure and pricing. Ultimately, the business model was refined such that the economic value proposition to the customer is enhanced. Changes made include the removal of barriers related to upfront fees, and offering a blended fixed/variable pricing fee structure where customers pay more when they use the technology (i.e. during their busy season), and less when they do not (i.e. during winter). This modification has been well received by customers.

Expanded value chain applications

During the project, alternate upstream sources of CO_2 were investigated to demonstrate the impact on integration of CarbonCure's technology with an innovative carbon capture system. We also set out to understand whether reduced purity CO_2 would be acceptable and would help to further improve the technology economics. The project demonstrated a turn-key solution for the cement and concrete industries that could create an opportunity to profitably capture and convert cement production CO2 emissions into value-added concrete for construction projects.

Downstream, the use of the CarbonCure concrete at a project at the Calgary International Airport represented the first ever use of concrete in a paving application. Application of concrete in air-side paving projects is one of the most restrictive and regulated uses of concrete. This case study bolsters confidence in the use of carbon dioxide in concrete and the expansion of verified applications of the ready mixed concrete technology has been an important part of growing the usage base of the technology. The work at the airport stands as an important reference project that can drive value for CarbonCure now and in the future.

Figure 5: Work underway at Calgary International Airport using CarbonCure concrete

Impact of market development lessons related to removing market barriers

Awareness around embodied carbon (the carbon impact of building materials) was relatively low when the project initiated in 2017, but has grown exponentially in recent years. It was determined that challenges from a design perspective are: outdated concrete specification practices that limit innovative products, a complex specification/purchasing process that results in disaggregated responsibilities across the supply chain, and lack of effective communication methods across the supply chain. End user interest is most effective when concrete suppliers have had the opportunities to fully validate the CarbonCure technology and are actively promoting its use and submitting concrete bids with CarbonCure. Throughout the project, we learned that the above challenges can be mitigated when a building project owner is motivated to make a strong requirement for CarbonCure and effectively leverages its position to secure stakeholder alignment. Furthermore, driving specifications can be harder when the champion is a designer, not an owner, as specifications are typically not as strong (example: allowing CarbonCure as compared to requiring CarbonCure) in order to protect competitive bidding interests. In markets with low producer traction, strong specification signals from the private sector, and public agency regulatory bodies are powerful. Without clear specifications, concrete producers and contractors are not incentivized to change the supply status quo.

Greenhouse Gas and Non-GHG Impacts

CarbonCure reduces greenhouse gases through two avenues: 1) direct CO_2 mineralization into concrete products and reclaimed water, and 2) indirect CO_2 reductions achieved through cement reduction.

The ready mixed technology GHG benefits that are associated with mineralized CO_2 can provide an increased strength and enable a reduction in the amount of cement used. There were eight ready mixed concrete producers active during the project timeline. The Calgary Airport location was a temporary location established to serve a dedicated project and is excluded from forward-looking calculations. A total of 473 tonnes of GHG benefit were realized during the project. About 50.5 tonnes of CO_2 were utilized and an estimated 425 tonnes of cement were avoided across 70,535 m^3 of concrete that was produced. The Alberta market contains 131 ready mix concrete plants. Use of the ready mix concrete technology at average production levels and cement reductions at these plants over ten years represents an opportunity to use 8.3 Mt of CO_2 to produce 22 million m^3 of concrete and save 354 Mt of CO_2 emissions. Over 25 years the numbers rise to 21 Mt of CO_2, 55 million m^3 of concrete and 884 Mt of CO_2 emissions saved.

The reclaimed water technology was extensively studied and developed at the firm's own facilities and was piloted at one Alberta location in July 2019 before the first permanent installation. The technology offers the potential to reach 48 kg CO_2 benefit/m^3 concrete (combination of mineralized CO_2 and reduced emissions from avoided cement). If Alberta produces about 4.5 million m^3 of concrete per year, then the opportunity totals 108 Mt of CO_2 benefit per year. Over ten years the benefit could be 1080 Mt of CO_2.

Communications Plan

Communicating the value of CarbonCure's CCU technologies to both concrete producers and end users is critical to transforming the industry to encourage adoption of lower carbon processes. By removing market barriers to adoption, Alberta will be able to more quickly transition to a low-carbon economy, and more broadly the pathway will be accelerated towards reaching our target of 500 million tonnes of CO2 annually globally by the year 2030.

Between May 2017 and December 2019, CarbonCure built out a suite of communications documentation and educational resources that now form the basis for engagement with prospect customers, design and construction professionals, and interested end users. Key materials that were developed during the duration of this project phase included::

- A new www.carboncure.com website was launched June 2018
- A series of FAQs, summary informational sheets, and dedicated brochures intended for Architects, Engineers, Designers, and Contractors
- Specialized marketing material targeted toward the green building (e.g. LEED) market

- Continuing-education credit presentations for architects and engineers were developed and presented for CarbonCure's two product lines (ready mix concrete and concrete masonry units)
- A brochure, one pager and powerpoint presentation targeted at selling CarbonCure to concrete producers
- A product data sheet and corresponding technical material to support concrete partner's construction submittal packages

Since the project was completed, we have been developing new communications material targeted to Alberta's concrete industry and end users. Examples of such content includes:

- Specification Considerations for Engineers
- Introduction to CarbonCure for Contractors
- Introduction to CarbonCure for Designers

Overall Conclusions + Next Steps

The project contributed significantly to CarbonCure's understanding and development of the technologies designed to significantly transform Alberta's concrete, building construction and infrastructure industries. Funding obtained was instrumental in accelerating innovation as well as removing future barriers to commercializing additional technologies that lower the carbon footprint of Alberta's concrete industry. In addition to improving and optimizing CarbonCure's technologies, advances were made related to business model innovation, expanding the technology's value proposition, identifying expanded value chain applications, and removing market barriers for stakeholders. CarbonCure looks forward to continuing its collaboration with ERA in Round 3 of the Grand Challenge, to draw closer to our collective goal of significant CO_2 reductions in the Province.

Following up the Round 2 project for CarbonCure is the ERA Grand Challenge Round 3 program where CarbonCure intends on establishing concrete made with CO_2 as a new standard for concrete in Alberta. The goal is to transition Alberta to a low-carbon economy to help meet its climate goals, while increasing industry competitiveness and enhancing the economy.

Specifically, the Round 3 project scope will include additional efforts to integrate approaches across the value chain, broadly deploy five next-generation CCU technology applications for all concrete types across the province, and downstream installation of concrete made with CarbonCure's suite of five CCU technologies across a variety of reference construction projects in the built environment to overcome market adoption barriers and demonstrate market acceptance of the product. Demonstrations will occur in a range of construction projects (urban/rural, roads, commercial/residential buildings, low-rise/high-rise, prescriptive/performance mixes, etc.) to showcase the use of the concrete in all major project applications. Technical reports, case studies and workshops will be offered to showcase the technical, economic and environmental benefits of concrete made with CO_2.

Appendix A - Communications Plan Materials

- CarbonCure's Path to the Decarbonization of Concrete
- Introduction to CarbonCure for Ready Mix Producers
- Specification Considerations for Engineers
- Introduction to CarbonCure for Contractors
- Introduction to CarbonCure for Designers
- CarbonCure’s Impact on the GWP of Concrete