ERA Project ID: E0160684

Title of Project: CO2 Utilization in Concrete: A new circular economy model.

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Name of ERA Project Advisor: Vicki Lightbown

Start Date of the Project: 01/01/2020

Completion date of the Project: 11/29/2023

Technology Readiness Level (TRL) at Project Initiation: Level 9

TRL at Project completion: Level 9

Total actual ERA funds received: $2,373,997.83 ($2,136,598.04 received to date; $237,399.78 holdback)

Total actual Project costs, including a breakdown of total eligible and total ineligible costs: $4,482,190.41 (CarbonCure share: $2,108,192.59; ERA share: $2,373,997.83)

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.[1] CarbonCure Technologies' (CarbonCure) “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 production.

Building off CarbonCure’s previous Emissions Reduction Alberta projects, this project further explored the commercial viability of CarbonCure’s technologies for the concrete sector through further optimization and refinement of the technologies, business model and value proposition to industry and installation 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.

[1] Global Roadmap Study of CO2U Technologies, Global CO2 Initiative, 2016

Through the project's evolution, CarbonCure identified market-related difficulties which hindered adoption by the Province's concrete producers. Many producers based adoption decisions primarily on project specifications, and without sufficient end-user demand for lower-carbon concrete, producers were unlikely to adopt CarbonCure on a long-term basis. This limitation resulted in fewer installations and diminished reduction in GHG than originally anticipated over the course of the project. However, CarbonCure was able to incorporate lessons learned into its marketing, sales and communications strategies to better identify markets and situations favorable to long-term relationships with producers.

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 would like to thank Emissions Reduction Alberta for its funding and guidance during this project and for its on-going support of lowering GHG emissions across industries in Alberta.

Project Description

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. It is also an exceptionally valuable product for building low-emission new buildings due to its thermal mass properties and its durability and resiliency. Its high carbon intensity however is at odds with the rising demand for green building products and climate regulatory trends. This project was designed to accelerate the commercialization of CarbonCure's 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, water intensity, and cost of concrete production. During this project, CarbonCure's commercialized ready mix technology was installed and used in concrete plants located throughout Alberta. In addition, CarbonCure's latest innovation – beneficiating concrete wash 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.

Introduction

CarbonCure currently offers several CO_2 capture, utilization, and storage (CCUS) technologies for the concrete sector that involve introducing post-industrial carbon dioxide into concrete during production. The introduced CO_2 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, which includes CO2 injection into ready mix concrete, pre-cast concrete, concrete masonry units (CMU), concrete wash water and recycled concrete aggregate.

In the ready mix, pre-cast and CMU applications, the CO_2 reacts with freshly with cement while the cement is hydrating, the reaction in which cement forms chemical bonds with water molecules to harden the concrete, while in the wash water and recycled concrete applications the carbon dioxide reacts with hydrated (hardened) cement. In each case the CO_2 is mineralized to form $CaCO_3$, using either a seeding or coating process, and is permanently locked within the concrete material in a solid form. See Figure 1 for an illustration of the chemical reaction.

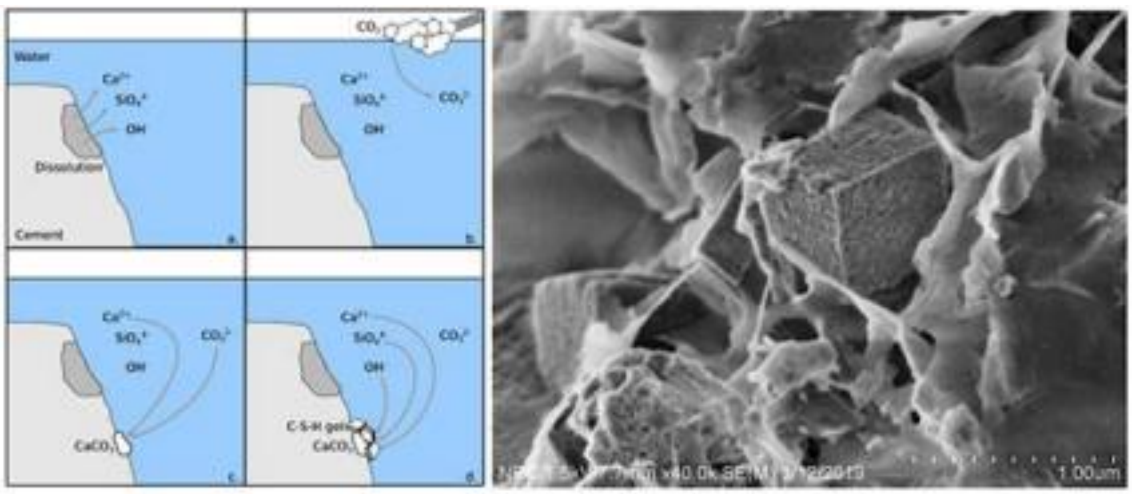

Figure 1: Schematic of masonry/ready mix/precast technology chemical reaction (left) where the addition of CO_2 results in the formation of nano-scale CaCO3 (right).

To mineralize CO_2 into CMU, CarbonCure technology injects dose of liquid CO_2 into the fresh concrete prior to molding the blocks 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 (see Figure 2).

Alternatively, the ready mix and pre-cast technologies inject an optimal dose of liquid CO_2 into the concrete ingredients (cement, water and gravel) at the point at which they begin mixing. The CO_2 reacts with the calcium oxide (lime) in the cement to form calcium carbonate (limestone). These limestone particles allow for more efficient hydration (hardening) of concrete, which enables the producer to use up to 10% less cement 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 (see Figure 2)

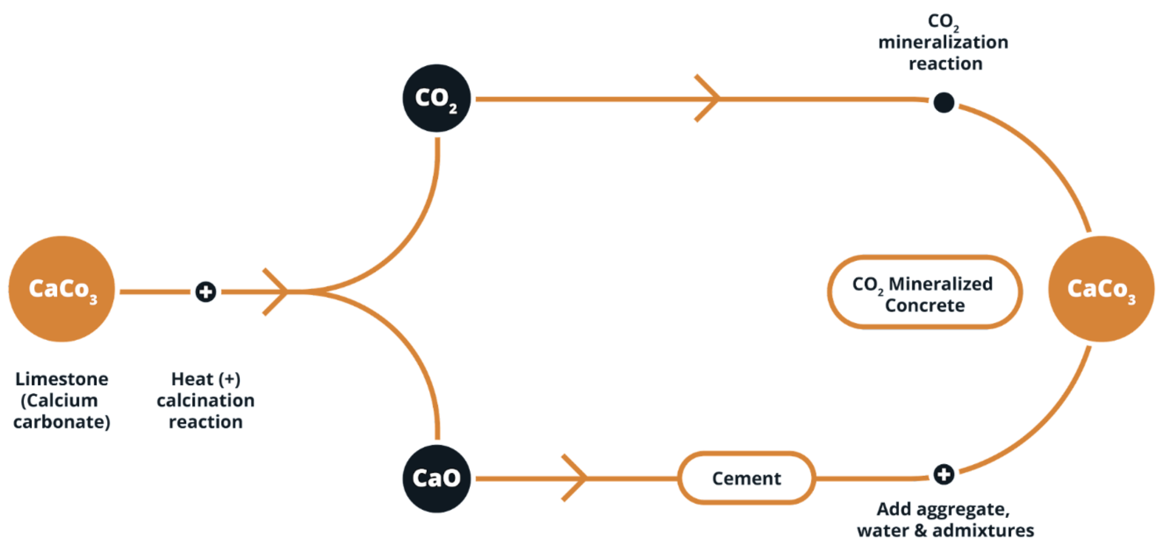

Figure 2: CO_2 Mineralization in Concrete (all applications)

The wash 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 3 and Figure 4). 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 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.

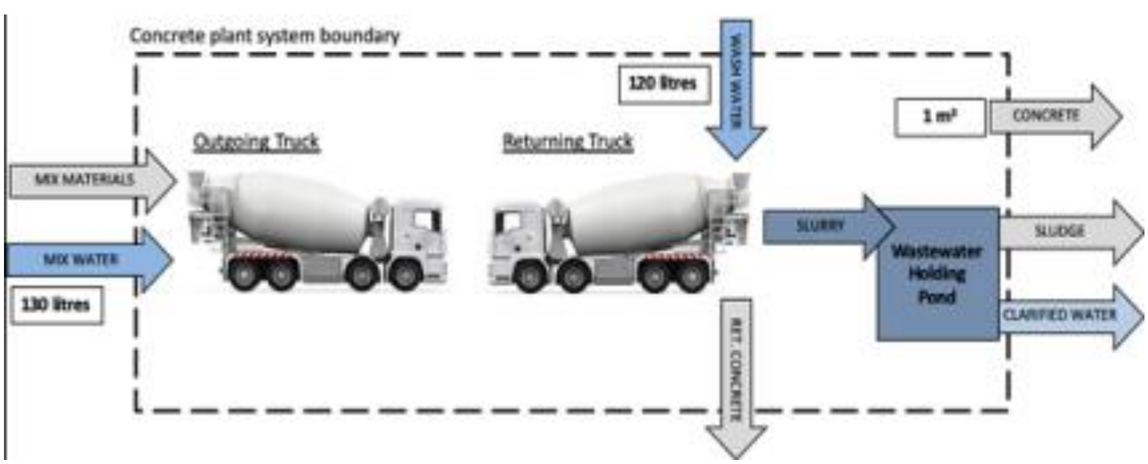

Figure 3: Schematic of business as usual wash water production and handling

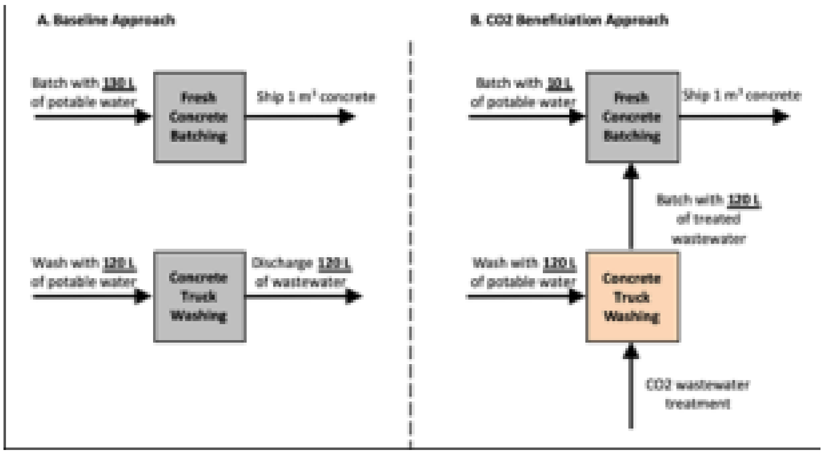

Figure 4: Wash water recycling using Carbon Dioxide

The project focused on establishing an advanced and integrated circular economy for the cement and concrete industry. The purpose of this project was to recycle waste streams to create value-added carbon-based products and to enable the province of Alberta to achieve more than 2 megatons of annual CO_2 reductions by the year 2050.

This project scope was applicable to project activities that capture waste CO_2, which would have otherwise been emitted into the atmosphere, and utilize that gas as a feedstock in the production of concrete in projects operating in Alberta. These project activities reduced GHG emissions by sequestering CO_2 via concrete production. This manufacturing process has the additional benefit of requiring less cement, which further reduces emissions because the cement production process is energy and carbon intensive. The project activity took place at the location where the concrete is first manufactured (mixed with cement, water, aggregates, etc.) in the province of Alberta.

While Round 2 of the project involved introducing CarbonCure's carbon utilization technologies with concrete producers, Round 3 focused on expanding the deployment of carbon utilization technologies with concrete producers, and broaden the project boundaries to include the downstream market conversion of the Alberta construction sector. Specifically, the Round 3 project scope included:

- Commercialization of four generations of carbon utilization technology applications for all concrete types across the province (CMU, ready mixed concrete, precast concrete, and concrete reclaimed water).
- Downstream installation of concrete made with CarbonCure's suite of carbon utilization 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 occurred 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.

The original success metrics detailed in the Contribution Agreement were as follows with revisions struck through and in bold:

Success Metric	**Commercialization target**	**Project target**	**Achievements to date**
Concrete meets quality, performance standards	Concrete meets all CSA/ASTM standards, such as CSA A23.1	Concrete meets all CSA/ASTM standards, such as CSA A23.1	To date, concrete has exceeded all required CSA/ASTM standards. **Unable to validate wash water and CRCA due to lack of market adoption of low-carbon technology, which may change as companies are required to decarbonize through regulation or public expectation.** ~~Impact of CarbonCure's wash water and CRCA technologies must be validated.~~
CO_2 injection rate - Masonry	2% by weight of cement (bwc)	1% bwc	0.5% bwc has been achieved in all cases, and in some cases exceeded.
CO_2 injection rate – Ready mix	0.5% bwc	0.3% bwc	**An average of** 0.3~~1~~% bwc has been achieved ~~in all cases, and in some cases exceeded~~.
CO_2 injection rate – Precast	0.5% bwc	0.3% bwc	0.1% bwc has been achieved in all cases, and in some cases exceeded.
CO_2 injection rate – Wash water	10% bwc	5% bwc	A range of 20-35% bwc has been demonstrated in early trials, although a cost-benefit analysis may identify a lower dose.

~~CO_2 injection rate – CRCA~~	~~8% per tonn CRCA~~	~~Avg 5% per tonne CRCA~~	~~CO_2 uptake demonstrated to be sensitive to many factors~~
Cement reduction	5%	3%	The minimum requirement of 5% cement reduction has been achieved and exceeded in some cases.
Average plant production	300 trucks per month (1,800 m^3)	250 trucks per month (1,500 m^3)	Demonstrated 200 trucks per month (1,200 m^3)

Reference to CarbonCure's carbonated recycled concrete aggregate (CRCA) technology was removed from the success metrics in an amendment to the Contribution Agreement as it was not deployed as part of the project.

During the course of the project, CarbonCure's carbonated recycled concrete aggregate (CRCA) technology was removed from the scope of the project due to its lack of technological readiness for commercial deployment.

Based on research of the current market conditions and technological capabilities of Alberta concrete producers, the number of system installations was amended to eliminate the installation of a specific number of masonry, precast and wash water and reduce the number of ready mix concrete installations to three (from twenty five). Targets were set for volume of concrete produced with the technologies. Resources were shifted to focus on creation of a marketing plan for CarbonCure's reclaimed water (wash water) technology and to perform sales and engineering activities to grow CarbonCure production in the market.

There were no changes to the corporate structure of CarbonCure since the commencement of the project.

Technology risks to the project included lack of ability to integrate CarbonCure's technology into existing concrete plants, as well as the risk of equipment degradation at concrete plants. Finally, there were technological risks associated with data telemetry from CarbonCure equipment, acquisition of CO2 injection data from concrete plant computer systems and data quality issues associated with the concrete plant data.

To mitigate the risks to equipment integrity or integration, CarbonCure employed staff to assist with installation and maintenance and provided education to concrete plant operators to perform self-service. Data-related risks were mitigated by CarbonCure's Digital team members, who worked with concrete plant operators to ensure proper data quality and controls.

The risks related to equipment integration and degradation manifested in a reduced ability to install carbonated recycled concrete aggregate (CRCA) technology and wash water technology, which caused CarbonCure to pivot away from deploying these technologies as part of the project.

While data-related risks were largely mitigated, CarbonCure's progression with carbon offset generation fell behind schedule due to unforeseen delays with the verification and audit processes.

Project Work Scope

Consistent with the Milestone Work Plan, CarbonCure engaged in the following activities:

- Successfully identified partners, secured CO2 supply and installed three ready mix systems throughout Alberta at the following concrete plants: Dufferin Concrete (Calgary International Airport), Inland Concrete (Fort McMurray) and Rolling Mix (Edmonton). Material testing was performed at all of these as well as Eagle Builders. Of these ready mix companies, Rolling Mix retained CarbonCure's technology, and produced an emissions reduction of 465 tonnes of CO_2 due to reduction of cement use, and injected 65 tonnes of CO_2 into concrete, across nearly 86,000 m^3 of concrete produced, which resulted in a reduction of 588 tonnes of cement. This concrete was poured at multiple sites, exceeding the Milestone work plan goal;
- Improved its carbon offset project plan development across the company to offer carbon credits through Verra, the carbon credit standards body, publishing a credit methodology,[2] and reducing the lag time between pouring of CarbonCure concrete and issuing and selling carbon credits. These improvements benefited Alberta customers by giving them faster access to carbon credit revenue if eligible;
- Designed and developed educational and training materials which were used to solicit interest from Alberta customers and conducted stakeholder a workshop leveraging this training collateral. Through this work, CarbonCure was able to identify hurdles to scaling deployment of ready mix, pre-cast and CMU technologies in Alberta; and
- Deployed and improved a cloud-based internal reporting dashboard and external user interface for CarbonCure customers across the company to show volume of concrete poured using CarbonCure. This benefited all Alberta producers by enhancing both customer support and the user experience. Because wash water and CRCA technologies were not deployed, reporting dashboards were not developed for wash water or solid waste reporting.

[2] https://verra.org/methodologies/methodology-for-co2-utilization-in-concrete-production/

In addition to the commercial installation of CarbonCure's ready mix technology at concrete plants, described below, the project also included exploration of the commercial readiness and viability of CarbonCure's wash water and CRCA technologies.

As documented above, the wash 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 above). 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 this water with CO_2 and incorporating it back into the concrete production process. To do this, CarbonCure works with the concrete plant to manage how water is processed through the plant's reclaimer to optimize, including controlling factors such as limits for cement replacement and average specific gravity. Beyond the economic benefit, the process has the potential to significantly reduce the amount of fresh water required to produce concrete and provides an additional viable opportunity for beneficial reuse of post-industrial CO_2.

Tests were conducted during the project to reduce equipment degradation caused by high concentrations of particulate matter within the wash water. Ultimately, CarbonCure concluded that more testing was required to fully overcome these issues before commercial deployment.

Likewise, during the course of the project, CarbonCure's CRCA technology was removed from the scope of the project due to its lack of technological readiness for commercial deployment.

Commercialization

CarbonCure successfully installed three ready mix systems throughout Alberta at the following concrete plants: Dufferin Concrete (Calgary International Airport), Inland Concrete (Fort McMurray) and Rolling Mix (Edmonton). During the project, CarbonCure saw its progress in Alberta and globally reach new heights. In April 2021, CarbonCure was named the winner of the Calgary stream of the NRG COSIA Carbon XPRIZE, which was integral to the development of CarbonCure's reclaimed water technology and brought CarbonCure considerable attention in the local market and beyond. Additionally, CarbonCure was specified for use in the two large projects, the YYC East Deicing Apron Phase II and the McMurray Métis Cultural Centre, with premier Canadian concrete producers, Dufferin Concrete and Inland Concrete, respectively. Lastly, Rolling Mix ramped up to utilize CarbonCure ready mix technology in ~45% of its production at its Edmonton plant. Technological readiness for our ready mix, pre-cast and CMU technology was and remained at TRL 9.

Through the project timeframe, CarbonCure's wash water technology was and remained at TRL 7 and CRCA remained at TRL 5. Pilots for both these technologies occurred in areas outside of

Alberta in conditions with optimal test environments. Through the outreach, marketing and customer feedback in Alberta, CarbonCure determined that these technologies both required additional testing before being deployed into the mainstream concrete industry in Alberta.

Lessons Learned

First, installation of systems was hindered because producers in the Alberta market base adoption decisions primarily on project specifications, meaning that end users will need to require CarbonCure or lower-carbon concrete in order for producers to install and use CarbonCure technology. This is an opportunity for adoption of provincial or local regulation that incentivizes use of lower-carbon or carbon-utilized concrete. This can be done through government procurement, changes to local building codes or creating incentives, such as tax credits or property tax abatements, for private sector actors to use lower-carbon or carbon-utilized concrete.

Second, carbon credit generation and issuance was delayed due to a delay in validation and audit of the underlying data. CarbonCure has since focused more resources within our digital team to engage with third-party credit validators and auditors to speed up response times and identify ways to improve CO_2 injection and concrete production data access and transfer. This work was conducted in Halifax at CarbonCure's headquarters, but the benefits all accrue to CarbonCure's Alberta-based customers.

Environmental Benefits

Emissions Reduction impact

Greenhouse Gas and Non-GHG Impacts

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

The ready mixed technology GHG benefits that are associated with mineralized CO_2 can enable a reduction in the amount of cement used. Of the three ready mixed concrete producers active during the project timeline only Rolling Mix in Edmonton provided data enabling CarbonCure to analyze GHG benefits (see table below) as a result of its ready mix technology. Rolling Mix reduced the cement required in CarbonCure-dosed mixes by an average of 2.5%, which, during the project period, resulted in an emissions reduction of 465 tonnes of CO_2 due to reduction of cement use and 65 tonnes of CO_2 injected into concrete, across nearly 86,000 m^3 of concrete produced, which resulted in a reduction of 588 tonnes of cement.

The installations of the technology represented 22 producer-months of activity. If the technology was used in the three Alberta locations consistent with Rolling Mix outcomes across the 22 installed months then an estimated 195 tonnes of CO_2 would have been used, 1,590 tonnes of

CO_2 benefit would have been created, 1,764 tonnes of cement avoided and 258,000 m^3 of concrete would have been 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 46 Mt of CO_2 to produce 61 million m^3 of concrete and save 375 Mt of CO_2 emissions. From now until 2050, the numbers rise to 115 Mt of CO_2, 152 million m^3 of concrete and 937 Mt of CO_2 emissions saved.

Because wash water technology was in a pilot phase during the project, no material GHG emissions reductions or CO_2 removals occurred.

Parameter	Rolling Rock							
Design mix 1...n (list each design mix separately)	12020	13010	13020	21020	22020	23010	23020	32020
Quantity of concrete produced by Design Mix 1…n over project period (m^3)	8113.27	18230.11	52064.25	150.32	156.25	7201.25	8.5	35
Quantity of emissions from CO2 transport and injection over project period (tonnes)	0.628	1.461	5.584	0.012	0.016	0.739	0.0001	0.004
Distance between site and CO2 source (miles)	30							
Quantity of CO2 from the flow meter (tonnes)	4.85	11.29	43.13	0.09	0.12	5.71	0.0009	0.03
Baseline emissions by mix design (tonnes)	1259.45	2741.08	10953.53	22.75	31.18	1447.89	0.33	7.79
Project emissions by mix design (tonnes)	1225.43	2666.76	10637.05	22.14	30.34	1408.73	0.32	7.58
Net Emissions Reduction by Mix Design (tonnes)	34.02	74.32	316.48	0.62	0.84	39.16	0.01	0.21
Emissions Reduction per m^3 of concrete poured by mix design (10^{-3})	4.19	4.08	6.08	4.12	5.38	5.44	1.18	6

Other Environmental impacts

Leveraging the work in the project to commercialize CarbonCure's reclaim water (wash water) technology in Alberta will help to deploy reclaimed water technology going forward, which will help to reduce concrete plant water consumption and wastewater output.

Economic and Social Impacts

Installation of CarbonCure systems, and the efforts of the project overall, have increased awareness in the province of low-carbon concrete options for decarbonizing construction, particularly at Calgary International Airport, which received local and trade press coverage when the concrete was poured. With the installation of each system, CarbonCure educated and trained staff at concrete producer plants on how to maintain the installed systems and read and analyze data outputs from the systems. This knowledge sharing helps make the Alberta workforce more competitive for climate and decarbonization jobs.

In addition, concrete producers which installed and operate systems, such as Rolling Rock, may have seen a cost savings from reduced cement consumption and will see carbon credit revenue generated over time.

Scientific Achievements

S. Monkman, T. Janke, A. Hanmore, NRG COSIA Carbon XPRIZE: carbon-dioxide mineralization in recycled concrete wash water, Clean Energy 5 (2021) 553–574. https://doi.org/10.1093/ce/zkab023.

S. Monkman, A. Hanmore, M. Thomas, Sustainability and durability of concrete produced with CO2 beneficiated reclaimed water, Materials and Structures (2022) 55:170

2022 Halifax Business Awards, Innovative Business of the Year

CleanTech Group's 2020 North American Company of the Year.

Overall Conclusions

The project contributed significantly to CarbonCure's understanding and development of the technologies designed to 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.

Next Steps

Going forward, CarbonCure plans to leverage the system installation performed during the project and the lessons learned to continue to help transition Alberta to a low-carbon economy to help meet its climate goals, while increasing industry competitiveness and enhancing the economy. This includes continuing to pour lower-carbon concrete using CarbonCure's installed system at Rolling Mix, generating carbon credits, which we share with Rolling Mix, and using Rolling Mix as a showcase for other Alberta producers interested in long-term relationships to reduce emissions in their concrete production.

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 2020 and August 2023, 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. This included an extensive series of webinars geared toward concrete producers, designers & builders and carbon credit buyers, specialized marketing material targeting carbon credit buyers and informational sheets, op-eds and presentations advocating for lower carbon concrete and carbon removal policies. Examples of key materials that were developed during the duration of this project phase included a suite of explainer videos for general audiences as well to explain concrete production as a carbon removal pathway.