NRG COSIA Carbon XPRIZE: carbon-dioxide mineralization in recycled concrete wash water

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Abstract

Wash water is generated as a waste stream from ready-mixed-concrete production. Reuse of the water as mixture water is limited, in practice, by the negative material performance impacts associated with the water chemistry and properties; the effects are intensified with increasing content of suspended solids and age. However, this waste material can be used as a beneficial additive to concrete by profiting from the cementitious properties of the suspended solids, if variability can be reduced. A method of stabilizing this material is through CO$_2$ treatment. The added CO$_2$ is mineralized through a reaction with the calcium from the cement particles. This provides a calcium-carbonate coating that prevents further cement hydration, making the material predictable. This has been shown to alleviate concerns with set acceleration and inconsistencies in compressive strength. A method of CO$_2$ treatment was tested as part of the NRG COSIA Carbon XPRIZE at a site in Calgary, Alberta. The slurry for the treatment was provided by a local concrete plant and had a specific gravity of 1.15. The simulated wash water was treated in 1000-L quantities with each treatment mineralizing an average of 40 kg of CO$_2$. The system ran for 1600 hours of operation over 127 treatment cycles and converted 14.5 tonnes of CO$_2$ at an average mineralization efficiency of 80%. The treated slurry was used as an additive in >300 batches of concrete where the concrete met the necessary requirements for fresh properties and setting time, while achieving a strength benefit. Replacement of 5% and 10% of batch water with treated slurry (9.4 and 18.8 kg slurry/m$^3$ concrete) showed a strength benefit of 3% and 6% compared to a reference. The technology was selected as the winner of the NRG COSIA Carbon XPRIZE (Track B: Natural Gas) in April 2021.
Introduction

CarbonCure Technologies participated in the NRG COSIA Carbon XPRIZE competition in Calgary, Alberta, Canada. Teams were tasked with converting carbon dioxide (CO₂) into high-value products. The competitive element weighted the amount of CO₂ converted, the efficiency of the CO₂ capture and conversion, the value of the product made and the total market size of CO₂ contained within the product [1].

The CarbonCure team demonstrated a concrete wash-water beneficiation strategy whereupon CO₂ was mineralized through a reaction with waste Portland cement as contained within a simulated wash-water slurry. The CO₂ was permanently locked as CaCO₃ into the treated slurry, which in turn was used as a component in a concrete mix. The reuse of the slurry, like an admixture, as part of concrete mixes demonstrated a scalable method of CO₂ removal and a sustainable recycling of industrial waste. The work is part of a growing body of research to develop CO₂-utilization solutions for the creation of concrete products [2–5].

The technology implementation was shaped by competitive operational constraints. The teams were required to operate their respective technology demonstrations on-site at the Alberta Carbon Conversion Tech Center (ACCTC), using CO₂ from the flue gas stream generated from the Shepard Energy Centre, a natural-gas-fired power plant. In satisfaction of the competition requirements, CarbonCure implemented a stand-alone operation on-site at the ACCTC that emulated a downscaled industrial concrete wash-water management system using CO₂ delivered from a capture system at the test centre.

Novel CO₂-utilization technologies offer pathways for turning CO₂ into useful products and to achieve value-added CO₂ reductions [6]. A review of six potential markets for CO₂-utilization technologies found that the building-products segment was at the most advanced stage of development and had the greatest addressable market size and the highest potential for CO₂ mitigation [8]. Further noted was that mineralization is thermodynamically favoured, thus offering permanence and a lower energy requirement than other CCU pathways.

Implementation and widespread adoption of such technologies rest upon developing solutions that are commercially viable and scalable. The XPRIZE served as a catalyst to numerous CO₂-capture and -conversion technologies. The CarbonCure entry was selected as the winning entry in the Calgary Track of the NRG COSIA Carbon XPRIZE [9].

The account herein serves as a technical case study of the participation of CarbonCure in the competition. The prototyping and preliminary testing of the conversion process are described. The upscaling of the technology for the competition and the execution at the ACCTC is detailed. A technology assessment is offered; a Life Cycle Assessment (LCA) of the process was calculated as part of the XPRIZE competition while a techno-economic analysis (TEA) has been completed.

1 Technology background

1.1 Waste flows at a concrete producer

The handling and discharge of process wash water are onerous operational burdens for concrete producers and carry substantial environmental impacts. It is produced through the periodic cleaning of equipment such as concrete trucks and mixers. The wash water comprises the water used in the cleaning process and materials removed by the washing, particularly fine particles of sand and suspended solids (binder, hydrating cement and hydration products). The National Ready Mixed Concrete
Association (NRMCA) estimates that a typical concrete plant in the USA produces an equivalent of 114 L of wash water per m³ of concrete produced [10]. This compares to a use of 181 L of mix water/m³ concrete produced (Fig. 1). (While the NRMCA survey compiled feedback from 489 concrete plants, it is worth further noting that published estimates of wash-water output can vary widely, with one citation identifying a range of 13–500 kg wash water/m³ concrete [11].) Wash water commonly has a specific gravity (suspended solids content) that is three or more times greater than the recommended ASTM limit for concrete mixing water (50 000 ppm) [12–14]. The volume of water produced requires appropriate management strategies.

1.2 Management of wash water

A concrete producer assumes an ongoing economic and logistical burden if choosing to dispose of the waste slurry. The slurry would typically be separated into clarified water and retained solids. The water must be neutralized before it can be disposed of, while the separated solids are typically collected and landfilled. On the other hand, technical challenges arise if a producer chooses to recycle the slurry back into the process. Traditionally, using wash-water slurry (particularly high-solids slurry) as mix water in concrete results in performance compromises such as increased water demand, decreased workability, decreased time to set and decreased compressive strength [12, 15, 16]. Typically, the recycling of wash-water slurry into concrete production relies on clarification and/or dilution, most commonly to a specific gravity of 1.03 or lower [17], and may not eliminate the landfilling of waste solids.

1.3 CO₂-mineralization technology

A technology has been developed to treat concrete wash water with CO₂ to allow the treated slurry to be more readily reused in concrete mixes (Fig. 2). Wash water is produced during normal plant operations; the concrete mixer and returning concrete trucks are washed intermittently. The resulting cement-laden slurry can be collected in a treatment vessel. The technology mineralizes CO₂ through a chemical reaction with the suspended cementitious phases contained within the waste slurry. The slurry is converted into a stable form (reduced or eliminated evolution with time [18]) that is more readily recycled as a mix component in concrete. Doing so provides value-added performance and environmental benefits, and eliminates the operational burden and costs of disposing of this harmful waste. Wash-water-mineralization technology represents a paradigm shift by harvesting this waste material as a CO₂-removal feedstock and to beneficially recycle it in concrete production with improved economics, consistency of quality and environmental performance.

1.3.1 Reaction mechanism

An industrial wash-water slurry contains suspended solids related to the concrete batch associated with the washing event. The solids will largely be in the binder phase of the
concrete (e.g. cement, fly ash, slag) with possibly some small proportion of the finest fractions of the fine aggregate (sand) in the mix. The cement and the hydration products of cement contain the phases that are reactive with CO₂.

Portland cement includes hydraulic calcium silicates and aluminates. The major phases of Portland cement are tricalcium silicate (C₃S in cement chemistry notation), dicalcium silicate (C₂S), tricalcium aluminate (C₃A), tetracalcium aluminoferrite (C₄AF), calcium-sulphate phases (e.g. gypsum) and limestone.

The silicate phases will readily react with CO₂ to form calcium carbonate and a silicate hydrate gel [19]:

\[
3\text{CaO} \cdot \text{SiO}_2 + 3\text{CO}_2 + y\text{H}_2\text{O} \rightarrow \text{SiO}_3 \cdot y\text{H}_2\text{O} + 3\text{CaCO}_3 + 347 \text{kJ/mol}
\]

\[
2\text{CaO} \cdot \text{SiO}_2 + 2\text{CO}_2 + y\text{H}_2\text{O} \rightarrow \text{SiO}_3 \cdot y\text{H}_2\text{O} + 2\text{CaCO}_3 + 184 \text{kJ/mol}
\]

Additionally, certain hydration phases (calcium hydroxide and calcium silicate hydrate gel, the latter considered herein as tobermorite and as jennite) can react with CO₂ to form calcium carbonate, a silica gel and water:

\[
\text{Ca(OH)}_2 + \text{CO}_2 \rightarrow \text{CaCO}_3 + \text{H}_2\text{O} + 74 \text{kJ/mol}
\]

\[
0.83\text{CaO} \cdot \text{SiO}_2 \cdot 1.3 \text{H}_2\text{O} + 0.17 \text{Ca(OH)}_2 + \text{CO}_2 \rightarrow \text{CaCO}_3 + \text{SiO}_2 + 1.4 \text{H}_2\text{O} + 33\text{kJ/mol}
\]

\[
1.67\text{CaO} \cdot \text{SiO}_2 \cdot 2.1 \text{H}_2\text{O} + 0.33 \text{Ca(OH)}_2 + 2\text{CO}_2 \rightarrow 2\text{CaCO}_3 + \text{SiO}_2 + 2.44 \text{H}_2\text{O} + 179 \text{kJ/mol}
\]

Each of these mineralization reactions is thermodynamically favoured and represents a lower energy state for the CO₂ molecule [20]. Mineralization is the only form of practical and permanent carbon removal and offers a distinct climate advantage over temporary and energy-intensive CO₂-conversion options such as chemical and fuel production.

A wash-water slurry is generated from a truck or mixer that had earlier contained a freshly generated concrete mix. The washing will have occurred at a time, e.g. from <5 minutes later to >3 hours later, after the contained concrete mix or mixes were initially batched and the hydration of the cement started (Fig. 3a). Once the cement starts to hydrate, cement-hydration products form (e.g. calcium hydroxide, ettringite and calcium silicate hydrate gel) and encompass the reacting anhydrous cement (Fig. 3b). The pH of the solution phase rapidly increases to a highly alkaline level, e.g. 12.5. The injection of CO₂ gas into a concrete wash-water slurry (Fig. 3c) sees the formation of carbonate ions (CO₃²⁻) that will react with calcium ions (Ca²⁺) generated from one of the anhydrous cement phases or one of the hydration phases that may be present. A solid product of CaCO₃ forms and can coat the cement substrate (Fig. 3d). Eventually, the cement particles can be covered by a mixture of the reaction products (CaCO₃ and silica gel) as the reactive hydration products are consumed and some of the anhydrous phases react. Provided enough CO₂ has been added to the system, the solution phase will acidify, e.g. to a pH of 7.

1.3.2 Recycling beneficiated slurry
Lab testing has shown that a CO₂-beneficiated wash-water slurry can be used as a replacement for mix water and...
impacts performance benefits relative to untreated wash water [18]. It was verified that the treated solids can act as a direct replacement for virgin cement. The application of CO₂ treatment to the wash water can reduce the scale of the negative properties associated with wash-water reuse to the point at which they may be easily managed by Quality Assurance/Control personnel at elevated specific gravity and ages via conventional strategies. The treated slurry can result in concrete with improved compressive strength and a reduced demand for fresh water. When leveraged to reduce virgin-cement usage, the costs of production can be lowered. The concept of mineralizing CO₂, reducing cement usage, reducing fresh-water consumption and reducing on-site wastes aligns strongly with the industry aims to produce more sustainable concrete [21].

As a retrofit to existing concrete plants, the concept requires very low energy, capital expense (CAPEX) and landfootprint requirements. Combining the low barriers to adoption and value-added attributes of the process yields an immediately scalable CO₂-utilization solution that addresses water and solid wastes from concrete production. The CarbonCure team chose to demonstrate this technology as part of the Carbon XPRIZE due to the permanent CO₂-sequestration potential impact on a global scale. In addition to the CO₂ benefits, the demonstrated technology offers concrete producers with an enhanced solution for reducing waste in the form of returned cementitious materials and water. This results in both environmental benefits as well as operational cost savings, leading to an economically viable and scalable method for permanently sequestering large quantities of CO₂.

It is estimated that the technology has a potential net global impact of 295 Mt of CO₂ including 55 Mt of net mineralized CO₂ and 240 Mt CO₂ reductions associated with reduced cement usage. Details of this estimate are included as an Appendix.

2 Technology development and implementation

2.1 Scoring constraints

The competitive nature of the work was defined by common scoring criteria that each team was assessed against. There were two components of the scoring: the conversion score (C) and the net value (NV).

C was based upon the fraction of CO₂ converted (F), which was a mass ratio of the CO₂ input and the CO₂ output embodied in products, and a scale penalty (P) that reduced C by ≤25% if <2000 kg of CO₂ was converted per day.
where the team scale (S) is in kg of CO₂ converted per day. F is determined as a combination of both the capture and conversion subprocesses, if appropriate:

\[ C = F - P \]  
\[ C = F - \left( \frac{(2000 - S)}{2000} \times 25\% \right) \]  

The NV was based upon the product value (p) in $ per tonne of product as defined in the competition Standard Data Set (SDS), the cost of inputs (c) in $ per tonne of product and the product market size (M) in Mt of CO₂ embodied in saleable products per year:

\[ NV = (p - c) \log(M) \]  

The competition incentivized high conversion efficiency (more so than an increased scale) and the generation of products with large markets and low costs relative to price. The competition further directed teams to have an overall technology operation of ≥1200 hours including a continuous operating period of 720 hours (30 days at 24 hour/day) demonstrating an operational availability of ≥80%.

### 2.2 Product definition

The competition required teams to create a product that fits under a definition outlined within, or was otherwise added to, the SDS. Since the technology benefitted a waste product to be used as a component of a concrete mix and since the treated slurry comprised a solid suspension within a liquid phase, it was determined that the treated slurry would be considered a concrete admixture (examples of which are chemicals, often suspensions of active component solids within liquids, that are added to concrete to modify its performance). Since the slurry would not fit the performance definition of one of the typical concrete admixtures (e.g. air entrainers, set accelerators), it was considered as an ASTM C494 Type S admixture of specified performance [22]. Preceding work on the technology had identified the potential to use the beneficiated wash water as a replacement for mix water that would increase the compressive strength of the concrete so produced [18], which is a performance claim of several commercially available Type S admixtures. The work also established that the treated wash-water solids were a viable cement replacement by allowing cement reduction in proportion to the quantity of solids contained within the mix water.

Whereas the greatest environmental benefit per unit of concrete may have been realized by maximizing the amount of slurry used in the concrete (and thereby maximizing the amount of CO₂ mineralized solids incorporated into the concrete), the identification of the slurry as analogous to a concrete admixture meant following competition scoring that incorporated a performance assessment. The market size and price (for NV purposes) of a strength-enhancing concrete admixture was described by the following simplified relationships defined by XPRIZE:

\[ \text{Admixture Market Size} = 5,290,869,565 \times \text{Dosage Rate} \]  
\[ \text{Strength Enhancing Admixture Price} = 35.2 \times \left( \frac{S}{S_0} \text{ team} \right) \]  

where S and S₀ are the strengths of the concrete with the admixture and the reference concrete without the admixture, respectively, and the team dosage was in tonnes of admix/m³ concrete. In the interest of maximizing both the market size and the price, a balance had to be reached on the dosage; an increased dosage would increase the market size but decrease the price. This led to the target of smaller admixture dosages where compressive-strength benefits were of secondary importance.

### 2.3 Initial validation

A prototype was initially operated at the CarbonCure laboratory. It consisted of a single treatment cell (a 1000-L vessel as adapted from a liquid admixture tote) retrofitted with CO₂-injection hardware and circulating pumps (Fig. 4). The validation examined the robustness of the engineering design, process variations, the impacts of CO₂ flow rates, CO₂-uptake efficiency and concrete performance. Testing used laboratory-grade pressurized CO₂ gas.

The vessel was filled with 1000 L of simulated concrete wash water at a specific gravity of 1.15 (a slurry comprising 930 kg of water and 220 kg of cement). The slurry was recirculated through an ~20-m-long and 75-mm-internal-diameter external piping system. The slurry was driven by a submersible pump placed at the bottom of the slurry-mixing vessel, and the slurry was circulated at a flow rate of 450 LPM. Carbon-dioxide gas was injected in-line into the slurry conduit at a gas-flow rate of 100 LPM. An 8-m-length of gas-diffuser hose (12.5-mm inside diameter) was situated within the slurry conduit, with the CO₂ gas fed directly into the gas-diffuser hose to deliver a stream of micro-bubbles across the entire length of the diffuser hose. The set-up time meant that the simulated waste cement had been hydrating for 15–20 minutes before the addition of CO₂. The CO₂-aerated slurry would then continue flowing through the external piping system and subsequently return to the slurry-mixing vessel through a downcomer pipe where it was driven to the bottom of the vessel. The temperature, solution pH and proportion of CO₂ mineralized in the cement solids were monitored.

Mineralized CO₂ was quantified using an ELTRA CS 800 infrared absorption combustion analyser. An increase in mineralized CO₂ was quantified as the net difference in the percentage of carbonate between the starting condition and the post-treatment condition, normalized for the starting condition. Testing was repeated in triplicate. The mineralized CO₂ is reported as a percentage with respect to the units of cement that it has bound to (percentage by weight of cement). The physico-chemical nature of the
CaCO₃ mineral product has been investigated in a previous study [18]. The treated slurry was used to produce concrete with differing amounts of slurry added. An investigation of the performance sensitivity to the dosage of slurry was completed. The concrete fresh properties (slump and air content) and the compressive strength were measured.

2.4 Preliminary results and conclusions

2.4.1 Treatment

In an example treatment, across a 6.5-hour treatment time, the temperature of the slurry increased from 14.3°C to 56.2°C (a gain of 41.9°C). The pH decreased from 12.9 to 9.3. The CO₂ content of the solids showed a net increase of 25.6% by weight of the original cement. The evolution of the observed characteristics over the treatment time is shown in Fig. 5.

The original slurry mass of 930 kg of water and 220 kg of cement was treated with CO₂. Sampling and analysis of the suspended solids reveal that the gas was mineralized to add 56 kg of CO₂ to the slurry (26% by weight of the cement). The slurry product in this case would be 4.7% CO₂ by mass (56 kg out of 1206 kg).

2.4.2 Concrete properties

The slurries were used to manufacture 31 batches of concrete (mix design in units of kg/m³: 311 cement, 776 sand, 1089 stone, 172 water). As per analysis of the scoring rubric, the effort considered a replacement of mix water with treated wash water that was optimized for scoring rather than maximum environmental benefit. The testing examined treated wash water as a replacement for the mix water ranging at levels from 11 to 92 kg of product per m³ of concrete (6–53% of the mix water). Replacement is determined as a 1:1 substitution of mix water by the water subfraction of the slurry (thereby incorporating the suspended solids as net new mass in the mix design that can thereby lead to a reduction in workability as the solids loading increases). The average 28-day compressive strength for the reference concrete (potable water as mix water) was 31.4 MPa (see Fig. 6). Strength benefits as high as 20% were observed in the concrete produced with the wash water. The fresh properties (air and workability) were acceptable for all batches produced with wash water.

2.4.3 Conversion efficiency

The second aspect of the preliminary study considered maximizing the conversion efficiency. It was discovered that, in use of the prototype, the efficiency could decrease as the carbon uptake increased. Trade-offs of efficiency would be realized if targeting a higher CO₂ proportion in the solids. Consideration that the solubility of CO₂ in water decreases as the solution temperature increases directed effort to examine the impact of starting the treatment with a lower-temperature slurry.

A comparison was made of two tests otherwise performed the same except for chilling one slurry to start at 5.8°C vs 12.9°C. The results (Fig. 7) showed that a decreased starting temperature improved the efficiency.

The temperature of the chilled slurry rose in parallel with that of the unchilled slurry and remained ~6°C lower for a similar level of uptake at the conclusion of the test. The mineralization rate within the chilled slurry was greater with the treated solids, reaching 26.9% CO₂ by weight of cement in 360 minutes vs 26.6% in 420 minutes for the reference slurry. Finally, the process efficiency of the reference treatment declined over the duration of the test from ~95% over the first 150 minutes to 79% at the test conclusion. The cooling of the solution increased the efficiency to 90% at the conclusion of the test and the efficiency was stable during the treatment. It was decided that
the final version of the technology would include a cooling element to target increased efficiency.

2.4.4 Preliminary scoring estimate

Preliminary conclusions were made based upon the limited data sets. For example, at a dose of 11 kg/m$^3$, the average strength benefit was 6%. Taking the admix as 4.6% CO$_2$ by mass, the market size is calculated as 2.7 Mt of CO$_2$ and the product price as $3378/tonne. At 22, 33 and 44 kg admix/m$^3$ concrete, the strength benefit was 11%, 13% and 12%, respectively. Across this dosage range, the calculated market size increased from 5.4 to 10.6 Mt CO$_2$ while the
calculated price decreased from $1752 to $901 per tonne. Mineralization-conversion efficiency at 90% or greater was demonstrated.

3 XPRIZE participation

The XPRIZE competition required Track B teams to demonstrate their technologies at the ACCTC adjoining a natural-gas combined cycle power plant. Flue gas from the plant served as a CO₂ source for the teams. CarbonCure created a wash-water-treatment set-up to operate within the test-centre environs. A purpose-built stand-alone reactor loop was built to simulate an industrial retrofit to a concrete producer’s operations. Team CarbonCure selected a modular outdoor design that was capable of emulating and treating a downscaled daily inflow of concrete wash water for a typical ready-mixed-concrete plant. The one-cell prototype version was expanded to six 1000-L treatment cells.

The redundant operational design featured separate treatment vessels to receive and treat wash-water slurry inputs. The vessels consisted of a treatment volume that was continuously agitated. The CO₂ injection was incorporated into the slurry agitation through circulation conduits. The modular design meant that continuous operations could be maintained while the select capacity was offline during maintenance or refilling. A process flow diagram of the operation is provided in Fig. 8.

3.1 Simulating an industrial process

An industrial-scale embodiment of the technology would be installed as a retrofit on-site at a ready-mixed-concrete plant, where the wash water is both generated and managed as part of the full spectrum of concrete production and ancillary site operations. Operation of the technology in a commercial setting would see, subject to the economics and scale of material transport, that the CO₂ would be compressed and transported from the CO₂-capture site to the conversion technology located at the concrete plant (liquefaction of the CO₂ would be required for cost-effective transportation). The feedstock of post-industrial CO₂ would be sourced from the merchant market [23], which offers a mature supply chain for post-industrial CO₂. While the mineralization of CO₂ from flue gas is feasible, scaling the technology commercially with merchant-market CO₂ reflects the logistical sensibility of transporting a small amount of purified CO₂ to many concrete plants to treat large quantities of wash water as opposed to transporting large quantities of wash water to centralized collection and treatment facilities that are created and operating at CO₂ point sources. Further, the LCA of industrial CO₂ (including emissions from energy for capture and transport) sourced as a by-product of hydrogen, ammonia and ethylene-oxide production suggests that a process emission can be modest, e.g. currently in the order of 60 kg CO₂ emitted/tonne CO₂ produced [24].

The CarbonCure XPRIZE demonstration used the CO₂ supplied from the on-site CO₂-capture system installed at the ACCTC. A compressor and buffer tank were added to receive CO₂ at the desired conditions. The CO₂-conversion system received a simulated wash-water slurry that was prepared at a concrete plant and transported to the ACCTC. This slurry was transferred into the series of six treatment vessels that were equally distributed on two load cells (three per load cell). Each treatment vessel had a dedicated recirculation pump and in-line carbonation piping loop. Each of these cells constituted a treatment system capable of generating 1.25–1.35 tonnes of treated slurry for a cumulative total (across the six cells) of 7.5–8 tonnes of product per production cycle. The system processed up to two batches per day, depending on the desired CO₂ loading in the product.
Each circulating loop had a CO₂-injection port, where compressed CO₂ (80–100 psig) was injected into the slurry as it recirculated through the system. When treatment was complete (i.e. when the target CO₂ delivery was achieved, e.g. after 6–8 hours, depending on the carbonation level), the finished product was transferred out of the treatment vessels and into a series of holding vessels, and subsequently transported back to the concrete plant where it was available for dosing into freshly produced concrete.

Fig. 7: Treatment data with unchilled vs chilled starting slurry temperature

Slurry temperature, CO₂ uptake (by weight of cement) in the solids and efficiency of mineralization monitored with time.
that the simulated waste cement was hydrating for 60–90 minutes prior to the start of the CO₂ treatment.

Pre-cooling of the slurry had been identified in pre-deployment optimization trials as a means to maintain highly efficient CO₂-conversion efficiency at higher CO₂ loading concentrations in the product. For the purposes of the industrial process simulation, ice was used during the slurry-batching process to achieve the desired slurry temperature prior to it being supplied to the CO₂-conversion system. The melted ice (water) was part of the slurry (material feedstock) and was included in the design of the slurry (e.g. 80% city water, 20% water from ice) so as to maintain a consistent input slurry specific gravity. The ice addition was reflected in the competitive scoring evaluation as both an energy input and operational cost, but not as a water-consumption metric, as water would otherwise be part of the as-received slurry while the cooling effect of ice, if desirable, would be replaced by appropriate heat-exchanging equipment in a commercial implementation.

The cooling strategy was modified prior to the continuous data-collection period. An ice-making unit was installed on-site to provide cooling during the treatment of the slurry in the CO₂-conversion system, thus obviating the need for ice addition during the slurry-batching process at the nearby concrete plant. The first-of-a-kind industrial implementation of the technology was commissioned, during the XPRIZE competition, in Victoria, British Columbia, Canada. The commercial implementation of this technology does not use ice or cooling, but, in contrast, is operating semi-continuously rather than as a batch process.

3.2 Competition outcomes

3.2.1 Carbon-conversion metrics

Slurry samples were collected and dewatered/dried to isolate the dry-solids fraction, which was then analysed using the infrared absorption combustion analyser. Inbound and outbound slurry was sampled six times for each batch (one sample from each of the six treatment vessels) and carbon analysis was performed in triplicate on each of these six samples. The measured weight percentage of carbon for the solids fraction of inbound/outbound slurries was based upon 18 separate chemical analyses and built a high level of confidence in the carbon quantification.

Carbon conversion was characterized daily (Fig. 9) in terms of efficiency (proportion of CO₂ delivered to the treatment that was mineralized), scale (total amount of CO₂ mineralized) and mass fraction of CO₂ in the final product (treated slurry). The operational period can be divided into two phases: an initial optimization period...
and the final continuous period. Greater variability in scale and efficiency was observed in the optimization period. Miscellaneous equipment failures were observed during the initial optimization period as the operational demands increased. The redundant design of the demonstration system (six treatment subsystems) allowed rolling maintenance activities to take place without losing full continuous operation. The bulk of the issues encountered

Fig. 9: Conversion efficiency, amount of CO₂ converted and mass % CO₂ in the product
Solid lines identify averages during the continuous period (orange points) and the dotted line identifies the average during the high-CO₂-product phase.
were related to the site-specific temporary equipment required to operate this demonstration at the test site and are irrelevant to a full-scale retrofit installation of the technology at a concrete plant.

The operation consisted of 127 mineralization treatment cycles (88 in the optimization period and 39 in the continuous period). The pilot converted 14.5 tonnes of CO₂ across 66 days of activity (over >1600 hours of operation). The mineralization was 8.8 tonnes over the 30 days of the continuous period (~1400 operating hours).

The average daily mineralization was 219 kg CO₂ overall with a higher scale of 293 kg achieved during the continuous period. The conversion efficiency varied and was lower than observed in the preliminary technology development. The overall efficiency was 70% with an increased efficiency of 75% during the continuous period. The CO₂ per unit of product (treated slurry) was 2.7% overall and 3.2% during the continuous period.

Preliminary results and early results during the continuous period pursued two treatment cycles per operating day. The initial-period target CO₂ uptake in the solids was 10–12% by weight of the cement, resulting in a content of 2.32% CO₂ by mass of the final product. A strategic change was implemented partway through the continuous period to confine operations to one treatment cycle per day but with a higher conversion target of 20–22% CO₂ by weight of cement. In this high-conversion period, a content of 3.8% CO₂ by mass of final product was achieved.

3.2.2 Concrete-performance metrics

More than 300 batches of concrete were produced during the competition (mix design in units of kg/m³: 325 cement, 776 sand, 1067 stone, 188 water). The preliminary work directed effort towards replicating the strength improvements observed in the preliminary lab testing at low quantities of slurry product/m³ concrete. Test specimens were made at water-replacement levels of 20%, 30% and 40% but most of the attention was devoted towards validating concrete performance when the slurry replaced 5% or 10% of the mix water (9.4 and 18.8 kg of slurry/m³ concrete). The data can be considered in two phases, where the CO₂ uptake per unit of suspended cement solids was either low (during initial operations) or high (as during the conclusion of the work).

The fresh properties of the concrete mixes were measured as part of assessing whether the concrete with the slurry addition was acceptable (Fig. 10). The average slump of the reference concrete was 195 mm. In the cases of the low CO₂-uptake slurry, the slump was relatively unaffected by the use of the slurry at ≤30% replacement of the water with a decline to an average of 168 mm at 40% replacement. In the high CO₂-uptake slurry trials, the average slump reduced slightly to 173 mm in the 5% replacement and 166 mm in the 10% replacement cases. Air content was not affected by the slurry.

The compressive-strength results (Fig. 11) showed that for the lower CO₂ level, the strength response was neutral. Once the operations shifted to a higher CO₂ uptake in a single cycle, the concrete compressive strength increased. The 28-day compressive-strength benefits were increased +3% and +6% for the 9.4 kg (5% replacement) and 18.8 kg (10% replacement of mix water) admixture levels, respectively. That the scale of the strength response was not as significant as it had been in the preliminary testing reflects both a sensitivity of the feedstock (cement chemistry) and, given the improved results observed late in the operations, that the outcomes could have been improved with additional site-specific optimization time.

Additional concrete testing was completed to measure the setting time, density, flexural strength and length change as compared to a reference. All additional testing was within the acceptable range set forth by ASTM C494.
3.2.3 Life-cycle analysis

As part of the competition, LCA was completed by the University of Calgary. It was evaluated whether (i) the team demonstrated a carbon-neutral process (an absolute reduction) or (ii) the teams demonstrated a carbon-avoiding process (a relative reduction compared to existing processes for producing the product(s) in question) or (iii) if neither (i) nor (ii) is true today, the conditions under which the company could demonstrate a carbon-negative, carbon-neutral or carbon-avoiding process in future to conclusions.

The CarbonCure entry used the on-site capture unit to provide purified CO₂ to the conversion technology. The LCA considered the consumption of electricity, natural gas and monoethanolamine (MEA) and the unconverted CO₂ for the capture and conversion operations.

The competition case of the technology, as installed in Alberta with an electrical grid emissions intensity of 0.695 kg CO₂/kWh, resulted in a net emission of 0.99 units of CO₂ per unit of CO₂ converted. On the basis of 1 tonne of CO₂ converted, this sum is due to an input of −1.274 t CO₂, and outputs from the operating the capture (+0.88 t CO₂) and conversion (+1.11 t CO₂) stages, and the CO₂ that was fed but not converted (+0.274 t CO₂). This is highlighted as point A in Fig. 12. The competition-based stand-alone simulated CO₂ treatment involved equipment (e.g. pumps)

![Figure 12](https://example.com/fig12.png)

**Fig. 12:** LCA net process emissions as a function of the electrical grid CO₂ emissions rate in the competition and full-scale retrofit cases

Dotted lines represent the grid emissions in Alberta (ACCTC) and British Columbia (first industrial installation) where A represents the competition case at ACCTC, B a case of a full-scale installation at ACCTC and C the full-scale industrial installation in British Columbia. Adapted from an in-competition report issued by the University of Calgary.
and inputs (e.g. natural gas) that are used in the scaled-down operations but are already present, or not necessary, in an industrial retrofit case.

The full-scale industrial case would change the CO₂ source from the small-scale capture of CO₂ out of a dilute power-plant flue gas to merchant-market CO₂ that involves higher purity by-product streams with much lower energy demands and thereby much lower CO₂ impacts. For example, at an industrial capture power demand of 200 kWh/tonne liquid CO₂ [25], the capture impact would be 0.139 kg CO₂/kg CO₂ captured or an 80% reduction in the value of the ACCTC capture system. It would be a further 98% lower if the industrial capture took place within the much cleaner energy grid in the British Columbia (12.8 g CO₂/kg CO₂ as reported by [26]) site of the first industrial-scale installation of the technology.

The electrical grid sensitivity analysis (Fig. 12) suggested that the test-centre implementation would be carbon-negative if the carbon intensity of the power was <89 g CO₂/kWh. If the full-scale industrial retrofit case could have been demonstrated at the ACCTC instead of the stand-alone demonstration, further efficiencies would be realized related to more efficient hardware and a net 0.320 kg CO₂ could be removed per kg converted (point B). The first-of-a-kind full-scale industrial installation has a modelled benefit (point C) of a net 0.711 kg CO₂ removed per kg converted.

Where the technology can leverage a strength improvement to achieve reduced cement loading in the concrete mix, then the environmental benefit could readily exceed a ratio of 1 unit benefit per unit converted. For example, at a high specific gravity (1.15, solids fraction of 20 wt%) and a CO₂ uptake of 20% by unit of untreated cement, cement at 81% of the suspended solids and a high replacement rate of mix water with slurry (80 kg/m³ concrete, as demonstrated in the pre-competition validation, ~44% of the overall mix water as outlined in Fig. 1), there would be 16 kg of solids reacting with 2.6 kg of CO₂ to create 18.6 kg of treated solids. Upon addition to the concrete mix, the resulting compressive-strength improvement could support a 1:1 replacement of virgin cement with treated solids. Where the cement has a specific greenhouse gas (GHG) impact of 0.922 kg CO₂/kg cement (in the USA [27]), then the reduced cement has an impact of 17.1 kg CO₂. With a net mineralization at 1.9 kg CO₂, the total carbon reduction of 19.0 kg CO₂/m³ concrete would be achieved where the net mineralization represents 10% and the reduction 90% of the total. In this pathway, 1 tonne of CO₂ mineralized creates a total benefit of 7.3 tonnes of CO₂.

This exceeds the unit benefit of modelled mineralization concepts that have been analysed for environmental benefits, such as a state-of-the-art continuously stirred tank reactor using serpentine at a net 1.14 tonnes of CO₂ benefit per tonne of CO₂ stored [7]. The increased unit benefit in the present scenario is attributable to not requiring slurry feedstock processing (mining and transport), not requiring pretreatment of the feedstock (mechanical, thermal or chemical activation prior to carbonation), not requiring mineralization at elevated temperature and pressure, and a greater substitution of cement per unit of CO₂ mineralized.

### 3.2.4 TEA

The successful commercialization and scaling of the concrete wash-water CO₂-conversion technology rests on not only the associated environmental benefits, but also the economic viability of the technology in the concrete

| Table 1: TEA assumptions |
|--------------------------|------------------|------------------|
| Factor                    | Value            | Note             |
| Cement cost (USD/tonne)   | $121             | XPRIZE SDS       |
| Cost of disposal (incl. haulage) (USD/tonne) | $30 | Representative industry communication |
| CO₂ cost (USD/tonne)      | $250             | Generic US commodity price |
| CO₂ offset credit value (USD/tonne) | $250 | Representative price [28] |
| CO₂ emissions/kg cement produced | 0.922 | USA [27] |
| Rate of returned concrete (% of production) | 5% | [29] |
| Plant size (annual production, m³) | 75 000 | Nominal value, large plant |
| Addressable production with technology (% of production) | 80% | Generic assumption |
| Mix design cementitious content, average (kg/m³ concrete produced) | 345 | [10] |
| CO₂ uptake (wt% CO₂ by weight cement in wash-water slurry) | 20% | As per XPRIZE demonstration |
| Proportion of cement in binder portion of concrete (wt% by weight of binder) | 82% | [10] |
| Cement in wash-water slurry-solids portion (wt% by weight of total solids) | 72% | Slurry solids are assumed to be 10% sand [18] |
| Maximum specific gravity for blended mix water (slurry and potable water) | 1.07 | Communication with first industrial user |
| Cement replacement factor (units of cement removed per unit of suspended solids included) | 0.8 | Conservative, present case assumption |
industry today. A TEA of the concrete wash-water technology, as applied in a commercial setting, is heretofore presented.

Fundamentally, any new technology must provide reasonable evidence of an economically viable implementation in a commercial setting for it to be considered for further commercialization. In addition to this, the estimation of incremental costs and operational savings associated with implementation of the technology should not rely on speculative indicators, but rather should be based on current market data. The core assumptions associated with the TEA as presented are listed in Table 1. A summary of the economic impacts, as presented in Fig. 13, shows the net savings that a concrete producer would realize in using the wash-water-conversion technology.

![Fig. 13: Model economic impacts for commercial implementation of CO2-conversion technology](https://academic.oup.com/ce/article-abstract/5/4/553/6406686)

**Table 2: Material and energy inputs for the capture and conversion processes**

| Input                  | Value  | Unit     |
|------------------------|--------|----------|
| CO₂                    | 391.65 | kg/day   |
| Waste water            | 9084.38| kg/day   |
| Industrial water       | 0.16   | m³/day   |
| Industrial electric power | 652.74 | kWh/day |
| Natural gas            | 3.00   | 1000 ft³/day |

**Table 3: Product definition**

| Aspect                  | Value  | Unit       |
|-------------------------|--------|------------|
| Dose rate               | 0.02156| metric tonne admix/m³ concrete |
| Cement replacement factor | 1      |            |
| Strength-enhancement factor | 1.02563|            |
| Calculated price        | 1674.5 | USD/metric tonne product |
| Calculated market       | 114 071 148 | metric tonne product/year |
| Flue-gas CO₂ input      | 485.76 | kg/day |
| Capture unit efficiency | 80.63% | CO₂ out/CO₂ in |
| Conversion unit efficiency | 74.68% | CO₂ out/CO₂ in |
| CO₂ in product stream   | 391.65 | kg CO₂/day |

**Table 4: Scoring results**

| Metric                              | Value  | Unit       |
|-------------------------------------|--------|------------|
| Output of product                   | 9532.7 | kg/day    |
| Carbon content of product           | 0.010297 | Kg C/kg product |
| F (conversion efficiency)           | 60.21% |            |
| Csp (CO₂ embodied in saleable product) | 292.47 | kg CO₂/day |
| Scale penalty (P)                   | 0.21   |            |
| C (conversion efficiency + scale penalty) | 38.86% |            |
| p–c (across all products)           | 1671.83 | $/day    |
| M (metric tons CO₂ per year)        | 3 499 776 | tonne CO₂/year |
| NV (net value)                      | 909.54 | (unitless) |

In commercial implementation, this technology is installed as a ‘bolt-on’ module requiring significantly less equipment with a much lower cost, footprint and energy consumption than observed at the ACCTC. While the hardware and operational costs are not included in the TEA, they are expected to be negligible within the context of an industrial concrete plant setting. Additional indirect costs
(e.g. one-time equipment installation, periodic maintenance) are also intentionally omitted from the TEA, as the costs are more site-specific but small in comparison to the expected lifespan and total operations of the equipment.

The model economic impacts of combining the cement savings, disposal savings and CO₂ costs suggests an opportunity to save $1.48 per m³ of concrete. To put this into perspective, the XPRIZE Standards Data Set used a concrete price of $53.06/tonne (or $116.73/m³ if assuming a density of 2200 kg/m³) against an estimated cost of $41.32/tonne (as calculated using inputs collected during Round 2 of the XPRIZE). If the mineralized and reduced CO₂ can be verified for sale on the offset market at USD $250/tonne [28] (herein credited at 50% as per being shared equally between the concrete producer and the technology provider), then the business case for commercialization of the technology is enhanced. The savings would increase to $3.51/m³ concrete.

The technology can be deployed commercially at a typical concrete plant with extremely low CAPEX, energy consumption and footprint. In the first-of-a-kind industrial deployment, the technology has used ≤700 kg of CO₂ per day while demonstrating cement reductions in proportion to the solids reintroduced into the concrete mixes. The solution could scale to >100 000 addressable concrete plants globally and fit within their existing supply chains and concrete plants.

3.2.5 Scoring

The outcomes of the competition are summarized. Table 2 shows the data relevant to the material and energy inputs germane to the conversion efficiency F (Section 2.1). Table 3 shows the data relevant to the calculation of the product (Section 2.2). Table 4 summarizes the scoring results. The competition demonstrated an overall efficiency (capture + conversion) of 60.21%, adjusted to a final conversion of 38.83% due to the scale of the conversion. The market was determined to be 3 499 776 tonnes CO₂/year and the NV score was calculated to be 909.54.

4 Conclusion

This study, as part of the NRG COSIA Carbon XPRIZE, investigated the treatment of concrete wash water with CO₂ to transform it from an onerous waste product into a beneficial concrete additive. It concluded that:

- Preliminary testing showed that the treated wash water could reach 25% uptake by weight of cement at 90% mineralization efficiency and provide compressive-strength benefits of 20% versus a control with potable mix water. The strength benefit produced by the treated wash water offers the potential to reduce virgin cement from the concrete mixes.

- Within the XPRIZE competition, the technology demonstrated an uptake of 20–22% by weight of cement with a mineralization efficiency of 75%. The CO₂-treated wash water did not have any negative effects on the concrete fresh properties and was able to provide a 3–6% benefit in compressive strength as compared to a reference.

- Across all operations, a total of 14.5 tonnes of CO₂ were mineralized including 8.8 tonnes during the 30-day continuous-operation period.

- An LCA of the competition process suggested that it emitted 0.99 units of CO₂ per unit of CO₂ converted. However, if the process was operated using electrical power with emissions of <0.089 kg CO₂/kWh, it would have resulted in a net carbon benefit. Importantly, implementing the technology as a full-scale retrofit would reduce the electrical consumption of the process and allow carbon-negative operation. Using the technology to achieve savings of virgin cement in the concrete so produced would increase the net environmental benefit even further. An estimated benefit of 7.3 tonnes of CO₂ per tonne of CO₂ mineralized is feasible.

- The TEA estimated that there is a savings potential of $1.48/m³ concrete so produced, which suggests that the technology could be better than cost-neutral. Where the carbon offsets can be monetized at $100/tonne, the benefit can increase to $3.51 saved per m³ concrete.

- The scoring concluded a C of 0.3886, an annual market of 3.5 Mt of CO₂ and an NV score of 909.54. Outside of the definitions of the competition, the opportunity is estimated at 65 Mt of CO₂ mineralized and an additional 230 Mt of carbon reductions through cement savings.

The foregoing account was the basis of the CarbonCure final submission to XPRIZE in December 2020. CarbonCure was selected as the winner of the NRG COSIA Carbon XPRIZE (Track B: Natural Gas) in April 2021.

Acknowledgements

The authors wish to recognize the technology development support from the National Research Council’s Industrial Research Assistance Program (NRC-IRAP Project 872578 and NRC-IRAP Project 932406). The local concrete partner was Lafarge, Calgary East plant. Sylvia Sleep and Dr Joule Bergerson of the University of Calgary completed the LCA as part of the XPRIZE assessment. The professionalism and thoroughness of the verifiers from 350 Solutions, Tim Hansen, Kevin McCabe and Bill Chatterton, ensured that the competition was fair and equitable. The staff at the ACCTC, Alvin Heck (Site Supervisor) and Aref Najafi (Site Manager), made sure that the competition ran smoothly considering a myriad of challenges. The hard work of the XPRIZE Foundation is highlighted: Marcus Ettavour, Michael Leitch, Nikki Batchelor, James Burbridge and their erstwhile colleagues Roopa Dandamundi and Paul Bunje. The efforts of CarbonCure technicians Geoff Arbuckle, Adam Meade, Almas Ikhsanov and Varun Sharma, and the project technicians (Olailekan Idowu, Tyler Little and Quentin Bellroy) were critical to the execution of the demonstration. Finally, at CarbonCure, Team lead Jennifer Wagner and Engineering lead Dean Forgeron were pivotal to the planning, leadership and overall success of the team. The time, constructive comments and critical suggestions of the anonymous Journal reviewers are recognized for their contribution towards strengthening the manuscript.

Conflict of Interest

None declared.
Appendix: Global market and CO₂ impact potential calculation

An estimate of the global potential opportunity for wash-water recycling was developed with respect to the industry in 2030 (Table 5). This differs from the in-competition market size and carbon opportunity, since it is tied to the industry itself rather than to SDS-defined products and competitive scoring. The model starts with an estimate of the overall size of the industry. There were 4050 Mt of cement produced in 2018 [30] and the industry forecasts that this will rise to 4481 Mt by 2030 [31]. (Note: the increase that was forecasted in the International Energy Agency/World Business Council for Sustainable Development (IEA/WBCSD) model was a growth from 2014 (4180 Mt cement) to 2050 of between 12% and 23%. A growth scenario at the midpoint of the forecasted range (a 17.5% increase) projects to 4912 Mt of cement in 2050 at a compound annual growth rate (CAGR) of 0.45%. Application of this growth rate from 2014 results in a projected cement production of 4481 Mt in 2030.)

The World Business Council for Sustainable Development Cement Sustainability Initiative estimated that the production of one unit of Portland cement in 2015 resulted in the emission of about 0.88 units of CO₂. Their 2DS roadmap (2-degree warming scenario) suggested improvements in cement manufacturing would decrease the emissions factor to 0.85 units by 2030. (Analysis based upon the IEA and WBCSD model where the roadmap estimated the direct CO₂ emissions from cement production would improve from 0.54 to 0.52 t CO₂/t cement by 2030, including a 0.003 t CO₂/t cement reduction from deployment of cement-industry carbon capture and storage. The CO₂ emissions from the process are projected to improve from 0.34 in 2015 t CO₂/t cement to 0.33 in 2030. The total emissions factor is 0.88 in the 2015 reference scenario and 0.85 in 2030 of the 2DS.)

The largest fraction of cement is directed to ready-mixed-concrete production. An average of 300 kg of cement are used for a cubic metre (m³) of concrete [32] (a more globally generic number than reported in the NRMCA survey). A generic concrete mix is assumed to contain 345 kg of binder and have a water-to-cement ratio of 0.525 (as per the baseline 4000 psi (28 MPa) mix reported in the 2019 NRMCA benchmark report [10], a strength class selected given the previous survey in 2016 [33] reported that 49% of concrete produced in the USA was at a strength class of 3500 psi (24.1 MPa) or lower and 94% was at a strength class of 5000 psi (34.5 MPa) or lower). The average cement fraction in the binder is then assumed to be 87% (300 kg cement within 345 kg of binder).

A model projection that 50% of cement is currently used in ready-mixed-concrete production would mean that in 2018 the 4050 Mt of cement (at a binder loading of 345 kg binder/m³ concrete and a cement fraction in the binder of 87%) would have been used to make ~6750 million m³ of ready-mixed concrete. (According to the European Ready-Mixed Concrete Organization (ERMCO) Ready-Mixed Concrete Industry Statistics Year 2018 [34], the proportion of cement used in ready-mixed concrete is ~53% in Russia, 55% in the EU, 70% in Japan and 75% in the USA. Estimates for cement use in ready-mixed concrete in China vary but it is commonly estimated to be between 40% and 50%.)

If the ready-mixed-concrete output grows with a CAGR of 4%, then by 2030 there would be an estimated 10 800

Table 5: Ready-mixed-concrete industry growth model

| Year       | 2018     | 2030     |
|------------|----------|----------|
| Global cement output | 4050     | 4481     |
| Cement growth in 2018–30 | +10.6%   |
| Ready-mixed (RM) CAGR | 4.0%     |
| Emissions factor of cement (global) | 0.880    | 0.850    |
| Proportion of cement used in RM | 50%      | 67%      |
| Total cement used in RM | 2025     | 2981     |
| RM binder loading | 345      | 345      |
| Proportion of cement in binder | 87%      | 80%      |
| Cement loading | 300      | 276      |
| Total RM concrete production | 6747     | 10 802   |

Table 6: Model of wash-water generation

| Year       | 2018     | 2030     |
|------------|----------|----------|
| Concrete water-to-binder ratio | 0.525    | 0.525    |
| Binder loading | 345      | 345      |
| Mixing water | 181      | 181      |
| Global mixing water used | 1222     | 1956     |
| Improvement in washing efficiency | +10%     |
| Ratio: wash water vs mix water | 63%      | 57%      |
| Unit wash water produced | 114      | 103      |
| Global wash water generated | 769      | 1109     |
| L water/m³ concrete    |          |
| kg cement/m³ concrete  |          |
| billion L water        |          |
| L wash water/m³ concrete|          |
| billion litres         |          |
million m$^3$ produced that consumes 67% of the cement. For context, one published market research analysis [35] projects the ready-mixed-concrete industry to have a revenue-based CAGR of 5.5% from 2019 to 2026. A more conservative annual growth of 4% is used in the model to account for inflation increasing ready-mix revenue faster than ready-mix output.

The growth of the ready-mixed-concrete outputs, both in unit terms and as a proportion of cement, is to be expected given that most of the growth in cement consumption is forecasted to take place in emerging markets. Cement used in bulk formats (e.g. suitable for ready-mix and precast applications) as opposed to that which is bagged (small-scale, lightly industrial production) is known to increase with increasing GDP per capita [36]. Currently, ~42% of cement that is produced globally is solid in bags [37]. This proportion will decrease as developing economies improve their infrastructure.

Building upon the industry size is an estimate of the amount of concrete wash water produced as a waste stream from concrete production (Table 6). According to the NRMCA values of 114 L of wash water per 181 L of mix water, per m$^3$ of concrete [10], the ratio is wash water at 63% of the mix water. Across the model 2018 global production, there would be 1221 billion litres of mix water used and 770 billion litres of wash water produced. In 2030, with an increase in the amount of concrete output alongside an improved washing efficiency (modelling a 10% decrease in the amount of wash water produced per unit of concrete), the total mix water is 1956 million litres and the wash water is 1109 million litres.

The cement content of the wash water can be modelled. The quantity of solids in a wash-water slurry depends upon composition of the suspended solids and the specific gravity of the slurry. The characteristics of a model slurry are outlined in Table 7. The model uses a specific gravity of 1.10, which is more conservative than that used in the XPRIZE demonstration (1.15). The 2018 case assumes that the suspended solids in the wash water are in the same subcomponent proportions as the binder in the generic model concrete being composed of 87% cement and the remainder equal portions of fly ash and slag. In 2030, the binder proportions of the concrete are modelled with an ~50% increase in the amount of cement replaced by secondary cementitious materials (SCMs) to be 80% cement and 20% SCMs. Again, the SCMs are equal parts fly ash and slag and, while the future case may include other binder components such as limestone and calcined clay, the model is centred upon identifying the quantity of waste cement. The modelled increase in cement replacement by 2030 is likely greater than what is currently expected given the already high utilization rates of clinker substitute sources [37]. Herein it provides a conservative overall estimate to the amount of cement contained within the wash-water waste stream.

The mass fractions of the suspended binder and the specific gravity of the binder can be used to determine the blended specific gravity of the suspended binder solids. The masses of water and suspended solids can be calculated from the slurry specific gravity and the density of the comprising fractions (water and the suspended solids). The mass of cement is then determined from the mass of solids. In an example, in the 2030 case, 1000 L of slurry at a specific gravity of 1.10 (mass 1100 kg) comprises 949 kg of water and 151 kg of suspended solids that contain 121 kg of cement. The solids are modelled to be 15.9% by the mass of the water. Where 1109 billion litres of water would be used for washing, in 2030, there would be an estimated 168 million tonnes of cement contained within the produced slurry.

| Table 7: Model wash-water slurry properties |
|-------------------|---|---|
| Year | 2018 | 2030 |
| Slurry specific gravity | 1.10 | 1.10 | 1.10 |
| Volume of slurry | 1000 | 1000 | 190.7 |
| Mass of slurry | 1100 | 1100 | 209.8 |
| Density of water | 1 | 1 | 1 |
| Density of cement | 3.15 | 3.15 | 3.15 |
| Density of fly ash | 2.2 | 2.2 | 2.2 |
| Density of slag | 2.2 | 2.2 | 2.2 |
| % mass cement in wash-water solids | 87.0% | 80% | 80% |
| % mass fly ash in wash-water solids | 6.5% | 10% | 10% |
| % mass slag in wash-water solids | 6.5% | 10% | 10% |
| Blended density of solids | 3.0265 | 2.96 | 2.96 |
| Mass water in slurry | 950.7 | 949.0 | 181.0 |
| Mass of solids in slurry | 149.3 | 151.0 | 28.8 |
| Mass of cement in slurry | 129.9 | 120.8 | 23.0 |
| Volume of water in slurry | 950.7 | 949.0 | 181.0 |
| Volume of solids in slurry | 49.3 | 51.0 | 9.7 |
| Mass % solids to slurry | 13.6% | 13.7% | 13.7% |
| Mass % solids to water | 15.7% | 15.9% | 15.9% |
The environmental impact of the CO₂ utilization is dependent upon the quantity of CO₂ mineralized and the amount of cement that can be replaced by the treated solids Table 8. The mineralization of CO₂ with the cement contained within the wash-water slurry is modelled at a rate of 35% by mass of the cement. While this level of uptake was not demonstrated in the presented work, it has been observed in lab trials [38] and is used as a ceiling on uptake using the technology. As a comparison, the CO₂-binding capacity of anhydrous cement can be determined by its chemical composition [39] and is typically ~50% by mass of cement.

The scale of the wash-water production means that, in the 2030 projection, the slurry can replace 57% of the global mix water. If the slurry is used to replace all the mix water on a batch of concrete, then 57% of concrete could be produced in this way. Where a generic concrete mix contains 181 L mix water/m³ concrete and this quantity of water was instead supplied by the CO₂-treated wash water, then 209.8 kg of untreated slurry (comprising 181.0 kg of water and 28.8 kg of wash-water solids) would be used. The slurry solids would include 23.0 kg of waste cement which would increase by mass 8.1 kg after the CO₂-mineralization treatment. On a global scale, the estimated capacity in 2030 is 59 million tonnes of CO₂ mineralized to create 269 million tonnes of treated solids.

The use of the treated slurry, or reclaimed water, as mix water can provide compressive-strength improvements. Results suggest a strength improvement [38, 40] where the treated solids could potentially replace slightly more than an equivalent amount of cement by mass, herein incorporated into the model as 1.05 units of cement reduced per incorporation of 1.0 unit of treated solids. The 36.9 kg of treated solids could replace 38.7 kg of cement/m³ concrete. Globally, it is estimated to be 282 million tonnes of cement with a 2030 CO₂ impact of 240 million tonnes of CO₂ reduced.

The net benefit must include the process emissions associated with the CO₂ capture, CO₂ transport and operations (Table 9). It can be considered in terms of 1 tonne of CO₂ utilized. Industrially sourced CO₂ with a capture energy demand of 200 kWh/tonne liquid CO₂ have emissions dependent upon the electrical grid. If, as per the IEA [41], the carbon intensity of industrial energy consumption in 2018 was 51.8 g CO₂/MJ (186 g CO₂/kWh), then the emissions to capture and process 1 tonne of CO₂ are 0.037 tonnes. The IEA further predicts [42] 2030 industrial energy consumption carbon intensities of 48.4 g CO₂/MJ in the reference scenario and 44.9 g CO₂/MJ in the 2°C scenario.

Table 8: CO₂ impact of wash-water beneficiation and reuse

| Year    | 2018  | 2030  | Unit               |
|---------|-------|-------|--------------------|
| CO₂-uptake rate | 35%   | 35%   | per unit mass of cement |
| Global mass of wash-water (WW) solids | 143  | 210  | million tonnes WW solids |
| Global mass of cement in WW | 124 | 168 | million tonnes cement |
| Potential CO₂ converted | 44  | 59  | million tonnes CO₂ |
| Mineralization efficiency | 90% | 90% | CO₂ converted per utilized |
| Potential CO₂ utilized | 49  | 65  | million tonnes |
| Total net solids | 187 | 269 | million tonnes WW solids |
| Cement replacement factor | 1.05 | 1.05 | units cement/unit WW solids |
| Reduced cement through WW solids | 196 | 282 | million tonnes cement |
| CO₂ impact of reduced cement | 173 | 240 | million tonnes CO₂ |

Table 9: Estimated CO₂-process emissions

| Year    | 2018  | 2030  | Unit               |
|---------|-------|-------|--------------------|
| Units of CO₂ utilized | 1.000 | 1.000 | tonne |
| Capture energy | 200 | 200 | kWh/tonne |
| Energy emissions rate | 186 | 162 | g CO₂/kWh |
| Emissions from CO₂ capture | 0.037 | 0.032 | tonnes CO₂ emitted |
| Transport distance | 200 | 200 | km |
| Transport emissions rate | 99 | 89 | g CO₂/ton.km |
| Emissions from freight transport | 0.020 | 0.018 | tonnes CO₂ emitted |
| Utilization energy demand | 37 | 33.3 | kWh/tonne CO₂ |
| Emissions from utilization operation | 0.007 | 0.005 | tonnes CO₂ emitted |
| Total process emissions | 0.064 | 0.056 | tonnes CO₂ emitted |
| Process emissions rate vs utilized | 6.4% | 5.6% | |
| Mineralization efficiency | 90% | 90% | CO₂ converted per utilized |
| Total CO₂ mineralized | -0.900 | -0.900 | tonnes CO₂ removed |
| Net total CO₂ mineralized | -0.836 | -0.844 | tonnes CO₂ removed |
If employing the latter, then a 13.3% improvement is expected (162 g CO₂/kWh) and the emissions to capture and process 1 tonne of CO₂ are 0.032 tonnes.

A generic freight transport distance of 200 km was used along with an emissions rate derived from Taptich et al. in 2016 [43]. Median emissions rates for heavy-duty truck freight among a series of regionally calculated values were selected from data reported for 2010 (105 g CO₂/tonne-km) and projected for 2030 (89 g CO₂/tonne-km); a proportionally determined value in 2018 was estimated (99 g CO₂/tonne-km). The transport emissions in 2030 are estimated to be 0.018 tonnes of CO₂.

The energy to run the injection hardware is modelled against a similar commercial technology where an estimated 37 kWh of energy are associated with the injection of a tonne of CO₂. The 2030 case projects a conservative 10% improvement in the energy requirement. The operational emissions are estimated to be 0.005 tonnes.

The total process emissions are then estimated to be 0.056 tonnes of CO₂ or 5.6% of the amount utilized. For 1 tonne of CO₂ utilized, it is estimated that 900 kg of CO₂ are mineralized and 56 kg of CO₂ are emitted. The net mineralization is estimated to be 844 kg or 84% of the utilized amount.

The overall summary of the estimated potential global impacts is reported in Table 10. Scaled across the washwater output of 1109 billion litres, there is a potential to utilize 65 million tonnes of CO₂ and achieve a net mineralization/removal of 55 million tonnes of CO₂. The technology can potentially support the saving of 282 million tonnes of cement and remove an associated 240 million tonnes of CO₂. The total net environmental impact is 295 million tonnes of CO₂, or 27.3 kg/m³ of concrete (alternately 48.1 kg/m³ in the fraction of batches made with full mix-water replacement).

Table 10: Summary of impacts

| Year | 2018 | 2030 |
|------|------|------|
| Potential total utilized CO₂ | 49   | 65   |
| Potential total mineralized CO₂ | 44   | 59   |
| Potential total net mineralized CO₂ | 41   | 55   |
| Potential cement savings | 197  | 282  |
| Potential CO₂ reduction from cement | 173  | 240  |
| Cumulative net potential benefit | 214  | 295  |

If employing the latter, then a 13.3% improvement is expected (162 g CO₂/kWh) and the emissions to capture and process 1 tonne of CO₂ are 0.032 tonnes.

A generic freight transport distance of 200 km was used along with an emissions rate derived from Taptich et al. in 2016 [43]. Median emissions rates for heavy-duty truck freight among a series of regionally calculated values were selected from data reported for 2010 (105 g CO₂/tonne-km) and projected for 2030 (89 g CO₂/tonne-km); a proportionally determined value in 2018 was estimated (99 g CO₂/tonne-km). The transport emissions in 2030 are estimated to be 0.018 tonnes of CO₂.

The energy to run the injection hardware is modelled against a similar commercial technology where an estimated 37 kWh of energy are associated with the injection of a tonne of CO₂. The 2030 case projects a conservative 10% improvement in the energy requirement. The operational emissions are estimated to be 0.005 tonnes.

The total process emissions are then estimated to be 0.056 tonnes of CO₂ or 5.6% of the amount utilized. For 1 tonne of CO₂ utilized, it is estimated that 900 kg of CO₂ are mineralized and 56 kg of CO₂ are emitted. The net mineralization is estimated to be 844 kg or 84% of the utilized amount.

The overall summary of the estimated potential global impacts is reported in Table 10. Scaled across the washwater output of 1109 billion litres, there is a potential to utilize 65 million tonnes of CO₂ and achieve a net mineralization/removal of 55 million tonnes of CO₂. The technology can potentially support the saving of 282 million tonnes of cement and remove an associated 240 million tonnes of CO₂. The total net environmental impact is 295 million tonnes of CO₂, or 27.3 kg/m³ of concrete (alternately 48.1 kg/m³ in the fraction of batches made with full mix-water replacement).

Table 10: Summary of impacts

| Year | 2018 | 2030 |
|------|------|------|
| Potential total utilized CO₂ | 49   | 65   |
| Potential total mineralized CO₂ | 44   | 59   |
| Potential total net mineralized CO₂ | 41   | 55   |
| Potential cement savings | 197  | 282  |
| Potential CO₂ reduction from cement | 173  | 240  |
| Cumulative net potential benefit | 214  | 295  |

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