CarbonCure’s 500 Megatonne CO$_2$ Reduction Technical Roadmap
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Introduction

In 2012, CarbonCure Technologies set out on a mission to decarbonize the concrete industry.

The first step on that mission was to align CarbonCure’s commercial goals with an environmental goal to reduce 500 megatonnes (Mt) of carbon dioxide (CO₂) annually from the concrete industry by 2030.

This technical roadmap outlines the methodologies, assumptions, and carbon reduction calculations used to determine the 500 Mt goal, which is outlined in detail in CarbonCure’s Path to the Decarbonization of Concrete ebook.
Industry Size

There were 4,050 Mt of cement produced in 2018\(^1\) and the industry forecasts that this will rise to 4,481 Mt by 2030\(^2\). The World Business Council for Sustainable Development (WBCSD) 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 CO\(_2\). Their 2DS roadmap suggested improvements in cement manufacturing would decrease the emissions factor to 0.85 units by 2030\(^3\).

The largest fraction of cement is directed to ready mix concrete production. An average of 300 kg of cement are used for a cubic meter (m\(^3\)) of concrete\(^4\). It can be projected that about 50% of cement is currently used in ready mix\(^5\) and with the 4,050 Mt of cement produced in 2018 there would have been about 6,750 million m\(^3\) of ready mix concrete produced\(^6\). If the ready mix concrete output grows with a Compound Annual Growth Rate (CAGR) of 4%\(^7\) then by 2030 there would be an estimated 10,800 million cubic meters produced which consumes 67% of the cement\(^8\).

Precast concrete is the second largest industrial market for cement. If an estimated 4% of cement production is used in precast concrete manufacturing then 162 million tonnes of cement would be used in 2018. If the generic cement loading of precast concrete is taken as 360 kg/m\(^3\) then there are 450 million m\(^3\) produced (6.7% as much as the ready mix concrete output). If the precast output grows with a CAGR of 5%\(^9\), then by 2030 the precast segment should be outputting over 800 million m\(^3\) (consuming 6.2% of the cement and growing to a ratio of 7.5% of the ready mix concrete output).

The growth of both the ready mix concrete and precast 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\(^10\). Currently about 42% of cement that is produced globally is solid in bags\(^11\). This proportion will decrease as developing economies improve their infrastructure.

Concrete wash water as a byproduct from concrete production is generated in a proportion that is about 63% of the amount of mix water used at the facility\(^12\). A generic concrete mix of 28 MPa typically has a water to binder

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\(^1\) USGS, Mineral Commodity Summaries, CEMENT, January 2020.
\(^2\) International Energy Agency (IEA) and WBCSD. Technology Roadmap: Low-Carbon Transition in the Cement Industry, OECD/IEA and WBCSD, Paris and Geneva (2018). An increase of 12 to 23% between 2014 (4,180 Mt cement) and 2050 was forecast. The median growth scenario projects 4,912 Mt of cement in 2050 at a compound annual growth rate (CAGR) of 0.45%. Application of this growth from 2014 results in a projected Mt cement) and 2050 was forecast. The median growth scenario projects 4,912 Mt of cement in 2050 at a compound annual growth rate (CAGR) of 0.45%. Application of this growth from 2014 results in a projected cement production of 4,481 Mt in 2030.

\(^3\) Analysis based on the IEA and WBCSD model where the roadmap estimated the direct CO\(_2\) emissions from cement production would improve from 0.54 to 0.52 t CO\(_2\)/t cement by 2030 (including a 0.003 t CO\(_2\)/t cement reduction from CCS deployment). The CO\(_2\) emissions from the process are projected to improve from 0.34 in 2015 t CO\(_2\)/t cement to 0.33 in 2030. The total emissions factor is 0.88 in the 2015 RIS and 0.85 in 2030 of the 2DS.

\(^4\) Figure identified in the LafargeHolcim Integrated Annual Report 2019. Allowing that LafargeHolcim has a global footprint for cement and concrete production it is taken that this is a reasonable figure to use on a global modeling basis.

\(^5\) According to the ERMCO Ready-Mixed Concrete Industry Statistics Year 2018; Proportions are about 55% in the European Union, 70% in Japan, and 75% in the United States. Non-ERMCO estimates for China estimates a proportion between 40 and 50%.

\(^6\) Binder loading 345 kg/m\(^3\) with cement at a proportion of 87% (300 kg/m\(^3\)) of the binder

\(^7\) For context, one published market research analysis projects the ready mixed concrete industry to have a revenue-based CAGR of 5.9% from 2015 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.

\(^8\) Binder loading 345 kg/m\(^3\) with cement at a proportion of 80% (276 kg/m\(^3\)) of the binder due to increased use of SCMs.

\(^9\) As an example, one published market research analysis projects the precast industry to have revenue-based CAGR of 6.3% over the period from 2016 to 2027. A more conservative annual growth of 5% is used in the model to account for inflation increasing ready mix revenue faster than ready mix output.


\(^12\) Athena Sustainable Materials Institute, 2019. NRMCA Member National and Regional Life Cycle Assessment Benchmark Industry Average Report – Version 3.0. Accessed 2020-03-14. Data suggests a 4000 psi mix design contains 305 lb/yd\(^3\) (181 L/m\(^3\)) mixing water and a concrete facility consumes 23.03 gal/yd\(^3\) (114 L/m\(^3\)) of water during operations. The water from operations was termed “washing water” in the Version 2.0 Benchmark Report that has since been superseded.
ratio of 0.525 and about 345 kg of binder/m$^3$. In the absence of the discussed technologies, a 28 MPa concrete mix can be modeled to use 181 L mix water/m$^3$ and produce 114 L wash water/m$^3$ concrete. Across the 2018 global production there would be 770 billion litres of wash water produced. In 2030, with an increase in the amount of concrete output alongside an improved washing efficiency (a 10% decrease in the amount of wash water produced per unit of concrete) the total wash water is 1,109 billion litres. A wash water slurry that contains suspended cementitious solids at a generic specific gravity of 1.10 has an expected solids content that adds an additional 15.9% by mass of the water$^{13}$. The 2030 global production of wash water would contain solids that include an estimated 168 million tonnes of cement.

Construction and demolition waste (CDW) is one of the heaviest and most voluminous of all waste types. Approximately 4,000 million tonnes are produced per year$^{14}$. Between 20 and 40% of CDW is concrete$^{15}$. If a median proportion of 30% is modeled then there would be 1,200 million tonnes of concrete CDW produced annually. Should the infrastructure renewal efforts see this waste stream grow at an annual rate of 5% then by 2030 there would be 2,155 million tonnes of concrete CDW suitable for processing as recycled concrete aggregate. By contrast, the global market for aggregates, estimated to be 47,500 million tonnes in 2018, is expected to reach 83,200 million tonnes in 2030$^{16}$.

$^{13}$ A model slurry at s.g. 1.10 would have a volume of 1000 litres and a mass of 1100 kg. If the suspended solids are a mixture of binder components in proportion to the binder usage at a facility then it would be something like 87% cement with a density of 3.15 g/ml, 6.5% fly ash at 2.2 g/ml and 6.5% slag at 2.2 g/ml. Thus for 1100 kg of mass the blend would be 950.7 kg water and 149.3 kg solids including 129.9 kg cement. The proportion of the solids to slurry is 13.7% while the proportion of solids to water is 15.7%. If, by 2030, the proportion of SCMs increases to 20% then the blend becomes 949.0 kg water, 151.0 kg solids including 120.8 kg cement where solids are at 15.9% by weight of the water.


$^{15}$ Adapted from a published market research analysis projection that suggests global demand for construction aggregates will have a CAGR of 4.8% over the period from 2016 to 2024 provided a growth from 43,300 million tonnes in 2016 to 62,900 million tonnes in 2024. CAGR for this period is used to determine aggregate demand in 2018 and 2030.
CarbonCure for Ready Mix and Precast

Ready mix concrete is a mixture of aggregates (graded stones and sand), binder (Portland cement possibly along with one or more SCMS or fillers, such as fly ash, blast furnace slag, silica fume, and/or limestone), and water. Chemical admixtures are often included to provide specific performance benefits such as workability, set control, air entrainment, etc.

CO$_2$ can be added to ready-mixed and precast concrete, like an admixture, to provide an improvement to the concrete properties. The injection of an optimized dose of waste CO$_2$ into concrete while batching promotes in-situ nanoscale calcium carbonate seeding$^{17}$ that can improve the compressive strength of the mix$^{18}$. The increased cement efficiency allows the concrete to be produced with less cement thereby realizing a greenhouse gas benefit through both the mineralization of waste CO$_2$ and the avoided cement CO$_2$ emissions. Cement reductions have typically been around 5%$^{19}$. The concrete so-produced maintains the required durability$^{20}$.

CarbonCure for Reclaimed Water

Concrete wash water is a byproduct of the concrete industry. This water, which may contain suspended solids in the form of sand, aggregate and/or cementitious materials, is generated by the washing-out of concrete mixers and trucks following the production and delivery of concrete. This water is alkaline in nature and requires specialized treatment, handling and disposal.

While this water can be suitable for reuse in the production of concrete, it has been documented that negative impacts to the concrete properties can arise. Wash water is mainly a mixture of cement and, in many cases, supplementary cementitious materials (SCMs) in water. The cement hydrates with time and changes the chemistry of the water. The evolution of the water, along with the hydration products, can cause a host of issues when the water is used as mix water including set acceleration, increased water demand, and reduced 7-day strength$^{21,22}$. These issues generally worsen as the amount of cement in the water increases, and/or the water ages.

A CO$_2$ treatment of the wash water slurry can allow it to be beneficially reused as concrete mix water. The CO$_2$ is mineralized in a reaction with the waste cement suspended in the slurry to create calcium carbonate$^{23}$. The carbonate mineral makes the slurry solids more stable with age allowing the performance outcomes of the concrete produced with the slurry to be more predictable. Set acceleration can be reduced or eliminated. The treated or reclaimed slurry can more readily be used as mix water in a new concrete batch. The performance benefit of using the recycled slurry, in particular the cementitious nature of the treated wash water solids, allows for a cement replacement.

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CarbonCure for Recycled Aggregate

Recycled concrete can be processed and reused as aggregates in new concrete production. Concrete made with recycled concrete aggregates (RCA) typically is weaker than concrete made with natural (virgin) aggregates. The RCA can be less dense, have a higher water absorption and a lower crushing value than natural aggregates\(^{24}\). The concrete so-produced can have a significantly increased drying shrinkage and chloride ion diffusion coefficient thereby creating durability concerns.

Treatment of the recycled concrete aggregates with CO\(_2\) can serve to mineralize the CO\(_2\) while also improving the properties of the aggregates and the concrete produced with the aggregates\(^{25}\). The CO\(_2\) reacts with the hydrated cement paste component of the crushed concrete to form calcium carbonate.

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CarbonCure’s CO₂ Utilization Technologies

The CO₂ utilization approaches mineralizes CO₂ through reaction with hydrating cement (ready mix and precast), waste hydrating cement (reclaimed water) and hydrated cement paste (recycled concrete aggregate). In each approach a mineralization efficiency can be assumed where a vast majority (90%) of the utilized CO₂ is fixed as a calcium carbonate reaction product.

The implementation of the technologies is accompanied by net new power consumption and transport emissions. CO₂ supplied by the merchant market would have an energy consumption of about 200 kWh/tonne liquid CO₂ produced. The CO₂ emissions rate from industrial energy consumption is estimated at 52.7 g CO₂/MJ or 189.7 g CO₂/kWh. The energy emissions associated with the capture, compression, and liquefaction of one tonne of liquid CO₂ results in about 0.038 tonnes CO₂ emitted. A 10% improvement in the carbon impact of energy by 2030 would lower the impact to 0.034 tonnes.

The transport of the CO₂ to the locations of utilization will be associated with a CO₂ emission. A representative rate of CO₂ emissions for freight transport would be 97 g CO₂/tonne-km of freight. Moving one tonne of liquid CO₂ 200 km from the point source emitter to the utilization site would result in emissions of 0.019 tonnes CO₂. By 2030 the rate would improve to 89 g CO₂/tonne-km and reduce the emissions to 0.018 tonnes CO₂.

Additionally, the operation of the injection equipment is associated with an energy consumption (estimated at 0.037 kWh/kg CO₂ injected) for an emissions of 0.007 tonnes of CO₂. A 10% improvement in the energy consumption rate by 2030 would reduce the emission to 0.006 tonnes CO₂. The other factors related to CO₂ utilization (e.g. the production and transport of the injection equipment) are minimal compared to the gas processing, gas transport and equipment operation. The overall impacts of the capture, transport and injection of CO₂ can be determined per tonne of CO₂ utilized. The compiled results are summarized in Table 1 and show that the process emissions in 2030 are about 5.8% of the total utilization.

### TABLE 1: Estimated process emissions impact of CO₂ utilization in 2020 and 2030

<table>
<thead>
<tr>
<th>Aspect</th>
<th>2020</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total CO₂ utilized (tonne)</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td>CO₂ capture emissions (tonne)</td>
<td>0.038</td>
<td>0.034</td>
</tr>
<tr>
<td>Freight transport emissions (tonne)</td>
<td>0.019</td>
<td>0.018</td>
</tr>
<tr>
<td>Utilization operation emissions (tonne)</td>
<td>0.007</td>
<td>0.006</td>
</tr>
<tr>
<td>Total process emissions (tonne)</td>
<td>0.064</td>
<td>0.058</td>
</tr>
<tr>
<td>Total CO₂ mineralized (tonne)</td>
<td>0.900</td>
<td>0.900</td>
</tr>
<tr>
<td>Net total CO₂ mineralized (tonne)</td>
<td>0.836</td>
<td>0.842</td>
</tr>
<tr>
<td>Process emissions rate vs utilization</td>
<td>6.4%</td>
<td>5.8%</td>
</tr>
</tbody>
</table>

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Carbon Impacts

The potential carbon impacts of the four technologies are assessed with respect to the concrete industry in 2030 where there are 10,802 million m³ of ready mix concrete concrete, 168 million tonnes of cement contained within concrete wash water, 808 million m³ of precast concrete, 2,155 million tonnes of concrete construction demolition waste processed into 862 million tonnes of coarse and 1,293 million tonnes of fine recycled concrete aggregate.

CarbonCure for Ready Mix

CO₂ is added at a rate of 0.15% by weight of cement to ready mix concrete with a binder loading of 345 kg/m³ and a 2030 cement loading of 276 kg/m³. The addition of CO₂ increases the cement efficiency and compressive strength and thereby allows for the cement loading to be reduced by 5% without any compromise in performance. There are 14 kg/m³ of cement avoided in the modified concrete mix. The injection of CO₂ at 0.393 kg/m³ results in 0.354 kg of mineralized CO₂/m³. Taking into account the process emissions, the net mineralization is 0.331 kg CO₂ mineralized/m³ concrete. An additional 11.7 kg CO₂/m³ concrete is attributable to the avoided cement.

Scaled across the concrete output of 10,802 million cubic metres means that 4.2 million tonnes of CO₂ are utilized, a net 3.6 million tonnes are mineralized, 149.1 million tonnes of cement are avoided for with a carbon impact of 126.7 million tonnes of CO₂. The total environmental impact is 130.3 million tonnes of CO₂ or 12.1 kg/m³ of concrete.

CarbonCure for Reclaimed Water

The wash water slurry is treated with CO₂ whereupon it is reclaimed, as the CO₂ mineralizes at a proportion of 35% by weight of the cement. The global content of cement in wash water, 168 million tonnes, is then able to mineralize 58.8 million tonnes of CO₂ to create 268.7 million tonnes of solids. The slurry can replace 57% of the global mix water. If the slurry is used to replace all of the mix water on a batch of concrete, then 57% of concrete could be produced in this way. A generic concrete mix contains 181 L mix water/m³ concrete. If 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 of 23.0 kg of waste cement which increase by mass 8.1 kg after the CO₂ mineralization treatment.

The use of the treated slurry, or reclaimed water, as mix water can provide compressive strength improvements. Results suggest that 1.05 units of cement can be 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.

Scaled across the wash water output of 1,109 billion litres means that 65.3 million tonnes of CO₂ are utilized, a net 55.0 million tonnes are mineralized, 282.2 million tonnes of cement are avoided with a carbon impact of 239.8 million tonnes of CO₂. The total environmental impact is 294.9 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).

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21 2020 binder loading taken as 345 kg binder at 87% cement and 13% SCMs. 2030 binder loading taken as 345 kg binder at 80% cement and 20% SCMs.

22 Initial suspended solids total 200.6 million tonnes including 160.5 million tonnes of cement and 40.1 million tonnes of SCMs.


24 Wash water solids represent this binder proportions in the concrete, or 80% cement in 2030.
CarbonCure for Precast

CO₂ is added at a rate of 0.15% by weight of cement to precast concrete with a cement loading of 360 kg/m³. An increased cement efficiency and compressive strength improvement allows for the cement loading to be reduced by 5% without any compromise in performance. There are 18 kg of cement avoided in the modified concrete mix. The injection of CO₂ at 0.513 kg/m³ results in 0.462 kg of CO₂ mineralized/m³ concrete. Taking into account the process emissions, the net mineralization is 0.432 kg CO₂ mineralized/m³. An additional 15.3 kg CO₂/m³ is attributable to the avoided cement.

Scaled across the concrete output of 808 million cubic metres means that 0.41 million tonnes of CO₂ are utilized, a net 0.35 million tonnes are mineralized, 14.6 million tonnes of cement are avoided for with a carbon impact of 12.4 million tonnes of CO₂. The total environmental impact is 12.7 million tonnes of CO₂ or 15.7 kg/m³ of precast concrete.

CarbonCure for Recycled Aggregate

If 2,155 million tonnes of concrete demolition wastes are converted into recycled concrete aggregates (RCA) beneficiated with CO₂, then the carbon benefit is sensitive to the particle size. Where processing (e.g. crushing) may favour the production of fine aggregate over coarse aggregate the size fractions are modeled as 60% fine and 40% coarse. The carbon uptake of the coarse fraction is 2.5% by weight, while the carbon uptake of the fine fraction is 5.0% by weight³⁵.

Scaling the concrete demolition output of 2,155 million tonnes means that 95.8 million tonnes of CO₂ are utilized, and a net 86.2 million tonnes are mineralized. The treated aggregates could be used in small percentage replacements of virgin aggregates given that that RCA would be widely distributed geographically and the cumulative amount relative to the market for aggregates would be less than 3%. Thereby, complete consumption of the supply of treated RCA could be achieved by a 3% replacement rate of virgin aggregates by treated aggregates while respecting limitations on the amount of recycled concrete aggregate permitted by regulations and specifications and the possible challenges associated with fine fraction RCA.

Cumulative Impact

<table>
<thead>
<tr>
<th>Aspect</th>
<th>CO₂ Utilized (Mt)</th>
<th>Net Impact (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CarbonCure for Ready Mix</td>
<td>4.2</td>
<td>130.3</td>
</tr>
<tr>
<td>CarbonCure for Reclaimed Water</td>
<td>65.3</td>
<td>294.9</td>
</tr>
<tr>
<td>CarbonCure for Precast</td>
<td>0.4</td>
<td>12.7</td>
</tr>
<tr>
<td>CarbonCure for Recycled Aggregate</td>
<td>95.8</td>
<td>80.7</td>
</tr>
<tr>
<td>Cumulative Total</td>
<td>165.7</td>
<td>518.6</td>
</tr>
</tbody>
</table>

³⁵Approximate uptake rates taken from published sources.

For more information on CarbonCure’s mission, read CarbonCure’s Path to the Decarbonization of Concrete.