Carbon Capture from cement production through mineralisation

Responsible for 8% of global greenhouse gas emissions and set to grow substantially, the cement sector is a key target for emissions reduction technologies. Stephen B. Harrison, sbh4 consulting, reviews some of the companies developing commercial carbon capture solutions.

Concrete is a composite material and the most frequently used building material worldwide. As a composite, it consists of three main components: cement, sand, and aggregate. The exact mixing ratio depends on the application and required strength, with a 'normal mix' being 1 part cement, 2 parts sand, and 4 parts aggregate (1:2:4). The annual global cement production in 2019 was 4.2 Giga Tonnes, of which 55% was produced in China.

Typically, concrete is produced locally and distributed within a 400 km radius. The fine and coarse aggregates are mined in local quarries and the sand must be of certain size and grain quality. Desert sands, for example those in the Sahara are not suitable. This has led to shortages in sand supply in some regions.

Up to 1 Tonne of CO2 is released into the atmosphere during the production of 1 Tonne of cement production. The raw material, mainly limestone, accounts for 65% of the emissions, and the fuel consumption of the production for the remaining 35%. Due to the large demand for concrete, the CO2 released from cement making accounts for 8% of global emissions – four times more than the global aviation industry.

Non-Hydraulic Cement

The most popular non-hydraulic cement in the past millennia was lime mortar, a mixture of lime, sand, and water. Limestone is burnt and decomposed into quicklime (carbon carbonate) and carbon dioxide above 900°C.

$$CaCO_3 \rightarrow CaO + CO_2$$

The quicklime is then mixed with water, and optionally sand, to form calcium hydroxide.

$$CaO + H_2O \rightarrow Ca(OH)_2$$

The lime mortar is then ready to use. After the excess water has evaporated, carbonation starts.

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$

This mineralisation takes carbon dioxide from the atmosphere but is very slow due to low partial pressure of CO2. In theory all CO2 which was released during limestone burning should eventually captured again at the end of the carbonation process.

Hydraulic Cement

Portland cement is the most common type of hydraulic cement. It has a higher strength than quicklime and is water resistant after curing is completed. Within the Portland cement production process limestone and clay, with a high silicon dioxide content, are mixed and preheated to 900°C where CO2 from the calcium carbonate is released as a gas. In the cement making rotary kiln, the components are sintered at temperatures of up to 1450°C into complex compounds such as tricalcium silicate.

$$3CaCO_3 + SiO_2 \rightarrow (CaO)_3 \cdot SiO_2 + 3CO_2$$

The concrete curing starts with the mixing of cement and water. Hydration occurs during curing with the forming of calcium-silicate hydrates.

$$2((CaO)_3 \cdot SiO_2) + 7H_2O \rightarrow 3(CaO) \cdot 2(SiO_2) \cdot 4(H_2O) + 3Ca(OH)_2$$

Under typical conditions it can take up to 28 days until 90% of the strength is reached. Over several decades atmospheric carbon dioxide diffuses into the concrete and converts the calcium hydroxide into calcium carbonate to further strengthen the concrete. However, the maximum theoretical carbon sequestration capacity is only 50% of the raw material CO2 emissions.

Carbon Cure – Carbon Dioxide Concrete Injection

The Canadian-based company Carbon Cure takes advantage of the sequestration capability of concrete by injecting an additional 1.5 kg of CO2 per Tonne of cement (or 0.482 kg CO2 per m^3 of concrete) during concrete preparation. This increases the strength of the concrete.

Since the strength increases, up to 16.9 kg of cement can be removed from each cubic metre of concrete and replaced with sand. Due to the high CO2 emissions of cement about 17 kg CO2 are saved per cubic metre of concrete. The cement avoidance accounts for 97.7% of total emissions reduction from this process, rather than the additional binding of CO2 to the cement.

The technology is readily available to reduce the CO2 emissions of concrete by 5% and can be scaled up immediately, as few changes are necessary in the concrete production process. Several reference projects exist in the US, with the Amazon HQ2 the largest project to date, achieving a net saving of 1,144 Tonnes of CO2.

Solidia – Alteration of the Cement Production

The US based company Solidia Technologies goes one step further and alters the cement production process itself. Instead of a 3:1 ratio of calcium carbonate to silica within Portland cement, the ratio was altered to a 1:1 and the burning temperature reduced to 1250°C instead of 1450°C. This creates synthetic calcium silicate (Wollastonite) instead of tricalcium silicate.

$$CaCO_3 + SiO_2 \rightarrow CaSiO_3 + CO_2$$

Hence, the CO2 emissions in cement manufacturing reduces by approximately 30% including both the emissions from limestone and the energy demand. The Solidia concrete is cured at 60°C and ambient pressure mainly by CO2 with just a minimal amount of water, instead of up to 50% water at Portland cement-based concrete. This makes Solidia concrete favourable for precast concrete producers.

Considering the CO2 sequestration during curing plus the CO2 emission avoidance in cement production, the CO2 footprint can be lowered to 550 kg of CO2 per tonne of cement, which is equal to a reduction of about 50%. The technology is currently offered by LafargeHolcim in the US to precast concrete producers.

The cement industry is responsible for 8% global GHG emissions

Blue Planet – Carbon Dioxide Sequestered Aggregates

The two technologies presented so far have a certain GHG reduction potential. Nevertheless, there are still dedicated CO2 emissions associated with them. To sequester anthropogenic CO2 emissions Blue Planet suggested a new mineralisation process. It uses recycled concrete as base material. The crushed concrete contains the aggregate and cement fraction. During the process, the aggregate is upcycled and can be reused as aggregate in new concrete. Whereas the old cement fractions are mineralised with CO2 to form a new layer of calcium carbonate around the old cement parts, which basically acts as an incubation seed.

The CO2-sequesterd aggregate is used in addition to the upcycled aggregate in newly mixed concrete. In a first reference project the aggregates were used at the Interim Boarding Area B at San Francisco International Airport in 2016.

To store the CO2 as calcium carbonate, a raw material with a high calcium hydroxide or calcium oxide content is necessary. One example for this is Portland cement where the included calcium hydroxide is used for CO2 storage, like the Carbon Cure approach. Whereas other raw materials are fly ash (CaO 10-40%, MgO 0-10%) and steel slag (CaO 40-50%, MgO 5-10%). These materials contain also other metal oxides in high concentration, for example MgO. These can be also utilised to sequester carbon dioxide by the formation of carbonates (for example MgO + CO2 ◊ MgCO3).

The Blue Planet process reduces CO2 emissions by 100 kg per Tonne of concrete. This equates to about 220 kg CO2 per m^3 concrete. Considering a cement content of 320 kg per m^3 of concrete, this results in a reduction of about 0.65 Tonnes of CO2 per Tonne of Portland cement, and would therefore compensate for the raw material CO2 emissions of the cement production.

SkyMine – Turning Flue Gas into Baking Soda

Some processes above require modifications to the concrete and cement production process. The company CarbonFree has developed a new process, where the CO2 capture and sequestration can be directly connected to standard cement kilns. The flue gas is directed into an absorber column where CO2 is stripped using an aqueous sodium hydroxide solution.

$CO_2 + 2\ NaOH \rightarrow Na_2CO_3 + H_2O$

In a second step the sodium hydroxide is reacted with additional flue gas to produce sodium hydrogen carbonate, commonly known as baking soda.

$Na_2CO_3 + H_2O + CO_2 \rightarrow 2\ NaHCO_3$

The sodium hydroxide is produced on a chloralkali electrolyser. This electrolysis is responsible for 87% of the total energy demand, which reads as 8.3 GJ per Tonne of captured CO2. This is very similar to state-of-the art Direct Air Capture processes such as CarboNEngineering or Climeworks. If the avoided energy requirement to produce the electrolysis by-products (HCl, NaClO, NaOH) is accounted for in the overall carbon footprint analysis, then the energy demand for the CO2 sequestration drops to 2.8 GJ per Tonne of captured CO2.

In a first demonstration of the SkyMine process, 90% of the CO2 from a slipstream at the San Antonia cement factory is being captured. It has operated since 2016 and captures 75,000 Tonnes of CO2 annually. Food-grade baking soda from the process is supplied into the consumer market. Ultimately, the captured CO2 is released into the atmosphere in ovens during the baking process.

Global imperative to maintain the pace of innovation

The cement industry is responsible for 8% global GHG emissions. The worldwide market is expected to grow by up to 25% until 2050. Due to the sheer size of the cement industry and the lack of affordable alternatives to cement, it remains a global imperative to reduce the impact of CO2 emissions from this sector. Several technologies may have the potential to alleviate the problem, but the field is still open to see which carbon capture technology will dominate within this sector.

More information

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