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Curing concrete with carbon

The construction industry is under constant pressure to reduce their environmental impact and introduce sustainable measures. A new low-lime cement product that can produce concrete using CO_2 to cure instead of water could be the next-generation solution to which the sector is looking.

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Over 30 billion tonnes of concrete, containing approximately 3 billion tonnes of Portland cement, are manufactured and used every year. According to a 2005 study by the World Resources Institute(1) on greenhouse gas emissions by major industries, the cement industry is responsible for 3.8% of the total global greenhouse gas emissions, which is equivalent to 5–7% of industrial CO_2 emissions.

The International Energy Agency (IEA) has created a roadmap to guide the long-term sustainability efforts of the cement industry, which stipulates that the industry must reduce its total CO_2 emissions from 2.0Gt in 2007 to 1.55Gt by 2050(2). Over this same period, cement production is projected to grow from 2.6 to 4.4Gt. This recommendation to reduce carbon emissions is a daunting challenge to the industry.

Solidia Technologies has introduced a solution that helps the building materials and construction industries meet the IEA's CO_2 emissions goal by using CO_2 to create new materials, with minimal requirements for new supply chains and capital investment(3).

Currently in commercialisation, the company's patented technology starts with Solidia Cement, a sustainable, low-lime product that can be made from the same raw materials and in the same rotary kilns as Portland cement (PC). Manufacturing the cement in place of PC will allow companies to reduce both fossil fuel consumption and CO_2 emissions by 30%.

Solidia Concrete, made with Solidia Cement, can be mixed and formed into desired shapes in the same manner and using the same equipment as PC-based concretes. The concrete differs from its PC-based counterpart in that it cures by reacting with CO_2 instead of water. When the reduced CO_2 emissions, made possible by the production of the new cement, are coupled with the CO_2 captured during the curing of the concrete, the carbon footprint associated with cement production and use can be reduced by up to 70%.

Chemistry

The cement is a low-lime alternative to PC. Its primary mineral constituents are $CaO{\cdot}SiO_2$ (wollastonite), $3CaO{\cdot}2SiO_2$ (rankinite), and an amorphous phase. It also contains a series of complex Ca-Al-Si-O-based melilite phases.

By contrast, PC consists primarily of $3CaO{\cdot}SiO_2$ (alite) and $2CaO{\cdot}SiO_2$ (belite) plus $3CaO{\cdot}Al_2O_3$ (tricalcium aluminate), $4CaO{\cdot}Al_2O_3{\cdot}Fe_2O_3$ (tetracalcium aluminium ferrite) and $CaSO_4{\cdot}2H_2O$ (gypsum).

Both cement chemistries rely on limestone as a source of lime (CaO) and sand, shale or clay as a source of silica (SiO_2), albeit in different proportions. To create the binder, a raw materials mix is selected that will yield a cement containing 40–45 wt % CaO. PC, which contains high-lime phases and will require raw materials mixes that yield 61–67 wt % CaO.

Depending on the purities of the raw materials available at the manufacturing site, PC production may require additions of bauxite as a source of alumina and laterite as a source of iron oxide. The simple, low-lime chemistry of Solidia Cement does not require those additions and may also permit the use of low-grade limestone in cement formulation. These factors allow significant flexibility and raw material cost reduction opportunities in the manufacture of the clinker.

The low-lime content of the clinker also enables two separate opportunities to reduce the CO_2 emissions during cement production. The first involves the chemical decomposition of the calcium carbonate in limestone. The CO_2 released will be reduced from 540kg per tonne of PC clinker to about 375kg per tonne of Solidia Cement clinker.

The second opportunity rests with the cement's ability to react lime and silica at a kiln temperature of 1200°C, which is 250°C lower than the temperature required for PC clinker formation. During the production, the CO_2 emissions associated with the burning of fossil fuel to heat the kiln are calculated to be 190kg per tonne of clinker, compared with 270kg per tonne of PC clinker. Clinker production thus reduces the overall CO_2 emissions from cement kilns by approximately 30%, from 810kg per tonne of PC clinker to 565kg per tonne of Solidia Cement clinker(3,4).

Figure 1: Raw meal fed into the 0.3m inner-diameter, 7.6m-long rotary kiln at IBU-tec.

The synthesis of the cement in rotary kilns was first demonstrated at IBU-tec (Weimar, Germany) in a series of trials conducted between May and July 2012. The raw meal for these trials was prepared from limestone-clay and limestone-clay–sand mixtures that were co-ground, wet-granulated and fed directly into a natural gas-fired, 0.3m-diameter, 7m-long rotary kiln heated to 1200°C (Figure 1). Over 500kg of clinker was produced in these trials at a rate of about 20kg/hr. The clinker was ground into a cement powder form and used to produce concrete objects, as described below. Ongoing cement trials are also being conducted with Lafarge.

Concrete

Solidia Concrete uses a proprietary CO_2 curing process that can be readily deployed in any traditional concrete facility. Concrete can be produced in standard mixers and formed into the final part shape by the same equipment used for PC-based concretes. The concretes differ only in the chemical process by which they cure.

Unlike PC, the new cement does not hydrate when exposed to water during the concrete mixing and forming processes. Concrete components will not cure until they are simultaneously exposed to water and gaseous CO_2. The curing is a mildly exothermic reaction in which the low-lime components react with CO_2 in the presence of water to produce calcite ($CaCO_3$) and silica (SiO_2). The formation of these reaction products gives the concrete its hardness and durability in much the same way that calcium-silicate-hydrates strengthen PC-based concrete.

After the concrete is formed, the pores within the structure are partially filled with water, enabling the water to facilitate the reaction between the cement and CO_2. The water gradually evaporates as that reaction progresses and can be collected and recycled. CO_2 diffuses into the concrete through any exposed surfaces and through the partially filled pores.

The chemistry of the cement also allows for extremely short curing times. Concrete products typically reach target strength within 24 hours; by contrast, PC-based concrete products may take up to 28 days to fully harden.

Curing times are dependent on the thickness of the concrete part, which limits the rate at which gaseous CO_2 can permeate through the porous concrete structure. For example, thin concrete products such as wet-cast tiles (thickness ~10mm) can reach target strength within six hours. Thicker concrete products such as railroad ties (thickness ~250mm) can reach target strength within 24 hours.

Water conservation and CO_2 storage

The fast curing times offer the concrete manufacturer greater flexibility in equipment usage, inventory management and production planning. It also offers the opportunity to significantly reduce the water usage in concrete manufacturing.

One cubic metre of a typical Solidia Concrete structure requires about 127kg of water to provide the required flow characteristics. However, as the concrete cures via a reaction with CO_2, no water is chemically bound within and no additional water is needed to compensate for evaporation. The short curing time will allow as much as 80% of the water evaporating from the concrete structure to be condensed and recycled(5).

The ability of the cement to cure via CO_2 also opens up the possibility for the permanent capture and storage of carbon dioxide in the cured concrete structure. The curing process enables products to contain between 250 and 300kg of CO_2 per tonne of cement used. Depending on the amount of cement in the mix, the final component may contain between about 3 and 7 wt % of sequestered carbon dioxide.

When the reduced CO_2 emissions are coupled with the carbon captured in the curing, the CO_2 footprint can be reduced from 810kg per tonne of PC to as little as 265kg per tonne of Solidia Cement, representing a reduction of almost 70%(3).

Table 1 – Properties for precast made with 400kg/m^3 of Solidia Cement and 0.30 water:cement ratio

Property	ASTM test reference	Solidia Concrete
Compressive strength	C39	10,100psi (70MPa)
Split tensile strength	C496	1150psi (8MPa)
Flexural strength	C78	> 850psi (>5.9MPa)
Young's modulus	C469	5100ksi (35GPa)
Poisson's ratio	C469	0.150
Coefficient of thermal expansion	CRD-C39	~7 to 9 × 10^{-6}/°C
Abrasion resistance	C770	< 1mm
Durability factor after 350 freeze/thaw cycles	C666 Procedure A	88%

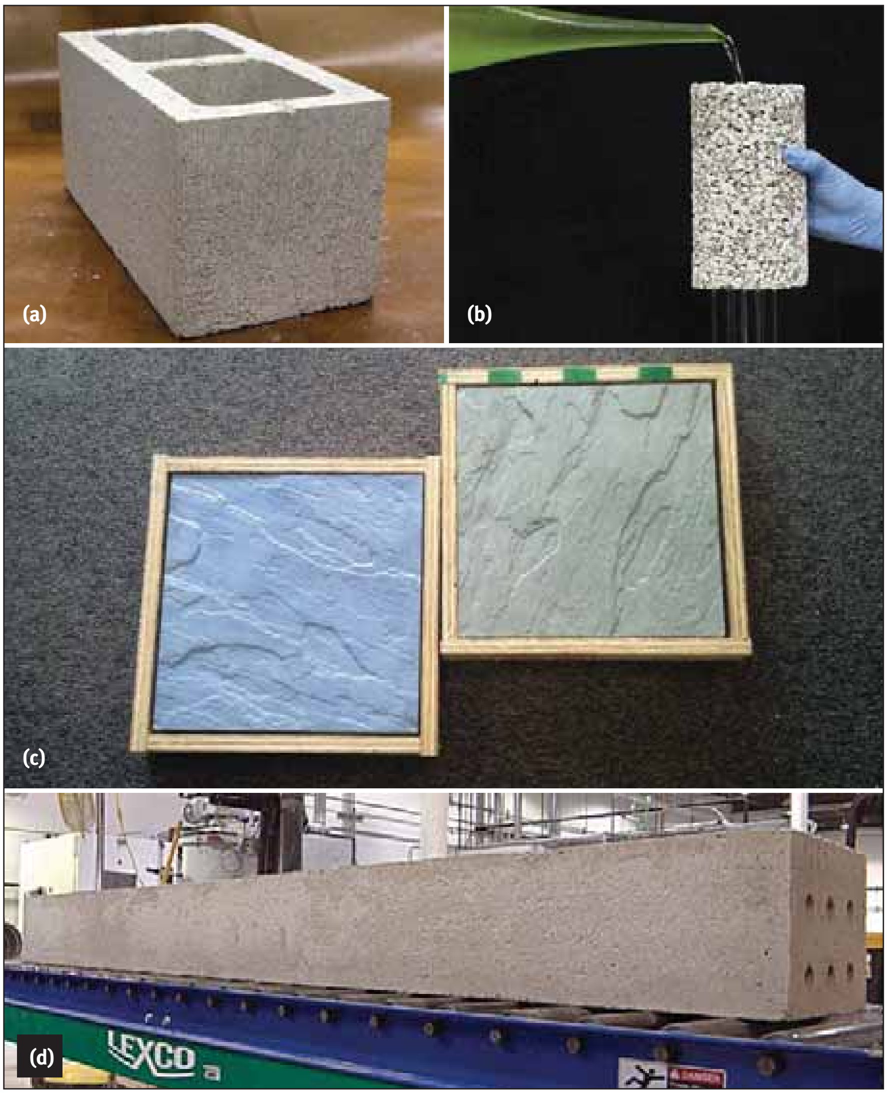

Figure 2: (a) concrete block; (b) pervious concrete; (c) wet-cast concrete tiles; and (d) concrete railroad tie.

Properties

Solidia Concrete shares all of the favourable characteristics of traditional concretes, including strength, damage and mould resistance, low-thermal conductivity, affordability and versatility. Thus, it can be designed for and used in virtually any precast concrete application.

As shown in Table 1 above, compressive strengths of 70MPa (>10,000psi) and flexural strengths of 8MPa (>1100psi) have been measured. These results demonstrate similar or superior properties when compared with PC-based concrete.

Table 1 includes outstanding performance for both abrasion resistance and freeze/thaw durability. In addition, the concrete exhibits excellent scaling resistance (not included in Table 1). Data for acid and sulfate attack are currently being measured.

Reinforcement matters

The main parameter that impacts the corrosion of reinforcement in a concrete matrix is the pH of the system. The presence of ions such as chloride, the ionic binding capacity of the matrix and the permeability of the matrix will also impact reinforcement corrosion.

Solidia Concrete will exhibit a pH of approximately 12 before CO_2 curing, decreas-

Figure 3: Internal shot of the kiln feed.

ing to between 9.5 and 10 after carbonation. By contrast, PC-based concrete has a pH between 13.0 and 13.5. Although the concrete is expected to be less tolerant of corrosive environments than PC-based concrete, its pH is sufficiently high to inhibit reinforcement corrosion during CO_2 curing and during service in high humidity/water immersion environments. It is expected that concrete reinforced with plain carbon–steel can be used in environments where it is not exposed to Cl$^-$ levels above 10-5M. Experiments are underway with a US university to confirm this. Solidia Technologies is also working in an institute at another US university on a novel approach to addressing reinforcement corrosion.

Figure 2 shows some examples of concrete products. Concrete blocks, with compressive strengths of 17.2MPa (2500psi), exceed the requirement specified by ASTM C90(6). Pervious concrete, with a relatively high proportion of large-sized pores as per the *Report on Pervious Concrete*(7), allows for the rapid drainage of water. Wet-cast tiles for outdoor landscaping contain multiple colour-type gels to achieve a desired colour. Concrete railroad ties, with compressive strength of 80MPa (11,600psi) and abrasion index of 23.85min/mm (606min/in), exceed the application requirements as per the *Manual for Railway Engineering*(8) and ASTM C779(9).

Conclusion

The Solidia Cement and Concrete production technologies make it easy and profitable to use CO_2 to create superior building materials. Taken together, they can reduce the carbon footprint associated with cement production and use by up to 70%, allow the recycling of up to 80% of the water used in concrete production, fully cure concrete parts within 24 hours, and provide durable and sustainable end-products with comparable or superior properties to traditional concrete. These capabilities equate into significant savings of energy, water, time and money. ■

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