INTEGRATION OF CARBON DIOXIDE CURING INTO PRECAST CONCRETE PRODUCTION

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Carbonation curing of precast concrete, an alternative to steam curing, is being pursued by Carbon Sense Solutions as a means of lowering the costs of unit production, achieving equivalent or improved material performance, charging a "green" premium for the cured products and reducing greenhouse gas emissions for the concrete industry. The approach exposes fresh precast concrete to carbon dioxide gas from flue gas, which then reacts to form thermodynamically stable carbonate microstructures. Material benefits (improved freeze/thaw durability, reduced water absorption), process enhancements (accelerated strength development) and significant carbon absorption have been demonstrated in lab tests and the approach is being adapted for industry use. The scope of the carbon reductions realized by widespread implementation of carbonation curing is estimated at several million tonnes per year, with the reductions achieved at a single average plant retrofit roughly equivalent to the annual emissions of 700 cars.

INTRODUCTION

Combating the effects of climate change by mitigating greenhouse gas (GHG) emissions and implementing adaptive measures is of paramount concern to the global community (IPCC, 2007; Ministry of Foreign Affairs of Japan, 2008). Despite concerted international action to limit emissions, GHG levels have risen by 24% to 49 Gt CO_2-eq from 1990 to 2004 (IPCC, 2007). Climate models demand that GHG emissions stabilize, and begin to decline, within the next decade to avoid irreversible climate change effects (IPCC, 2007). Fossil fuel use for power generation and transportation accounts for the overwhelming majority of CO_2 emissions, the primary GHG. Cement production is the second largest industrial source and contributes 5% of global CO_2 emissions (Damtoft et al., 2008). The cement industry recognizes the magnitude of its emissions profile and as a consequence has taken voluntary GHG accounting and reporting actions and invested heavily in new technical innovations (Damtoft et al., 2008; Scrivener and Kirkpatrick, 2008, WBCSD, 2009). The industry, however, is faced with unique and mostly process related technical barriers to lower its greenhouse gas emissions that will prove to be insurmountable using current technologies and practices. The concrete industry faces somewhat dissimilar greenhouse gas management drivers. While the market effects of a price on carbon upon the cement sector will be passed on to concrete producers, the industry is exposed to increasingly meaningful green building code, procurement policy and supply chain pressures. Fortunately, unlike cement, concrete producers have larger gains available to improve energy efficiency by adopting technology and service solutions that improve competitiveness by lowering energy costs and subsequently lowering greenhouse gas emissions. In a commodity market, inconsistent carbon constraints and market pressures between jurisdictions further motivates both the cement and concrete sectors to maintain their competitiveness by adopting new low-carbon and low-cost technologies and practices.

Carbon Management

Carbon management refers broadly to the process of measuring emissions at the process or company level, through internationally recognized standards like ISO 14064, and managing emissions, through both low-carbon technologies and operational adjustments. Typically, carbon management solutions achieve co-benefits of lower energy consumption, leaner manufacturing and consumer preferences. Thankfully, as regulations tighten, mandatory and voluntary carbon markets emerge, and supply-chains become increasingly carbon-conscious (Deloitte, 2010; Europa, 2010; Maestri, N., 2010), the cement and concrete sectors now have a suite of technology options and best practices to respond to these pressures.

There have been a number of potentially transformational developments in low-carbon concrete and cement technologies in recent years. For instance, California-based Calera operates two demonstration plants that produce carbon-negative aggregates and cementitious materials by using converting carbon emissions from coal- and natural-gas-fired combustion into saleable mineral products (Calera, 2010a; Calera, 2010b). In Nova Scotia, numerous ambitious carbon management activities are underway. Lafarge is conducting its own projects at its Brookfield facilities that include limestone substitution and biofuel switching. Furthermore, VJ Rice Concrete Ltd., limits its greenhouse gas footprint by reducing fleet idling practices and fuel switching to biomass.

The effectiveness of low carbon technologies can be maximized if their implementation is complemented with capacity-building, internal expertise, and a sophisticated understanding of organizational emissions. Competently assessing the efficacy of low-carbon technologies relies on the expertise to transparently and verifiably quantify reductions (Gotlieb, 2010). As such, investments in such technology should be coupled with similar investments in internal capacity-building in carbon accounting; where a sophisticated understanding of organizational carbon emissions may have once set leading companies apart, it is becoming a common point of engagement, often initiated by buyers with great purchasing power (for example, IBM, n.d.).

Companies that seek to manage emissions will face a global patchwork of carbon legislation, protocols for accounting for company-wide emissions versus low-carbon-project emissions, and both legitimate and dubious options to monetize emission reductions (Pew Center on Global Climate Change, n.d., CSA Standards, 2009, Business for Social Responsibility, 2007). Similar to the Generally Accepted Accounting Principles that guide financial accounting (WBCSD & WRI, 2005), the field of carbon management now benefits from similar oversight and assurances through new professional certifications. The Canadian Standards Association (CSA), the Greenhouse Gas Management Institute, and the American National Standards Institute offer designation programs to carbon-management professionals (CSA Standards, 2010; GHG Management Institute, 2010, ANSICA, 2010). In addition to transparency and credibility, certified professionals provide similar assurance to financial accounting support in the level of detail and familiarity with such undertakings.

As the industrial carbon management field develops, the suite of both products and services available to concrete producers is both growing and diversifying. Waiting for complete regulatory certainty will likely prove a costly gamble. Investing in both technical innovations and specialized support can mitigate the risks of costly upgrades and skills shortages should competitors take action first or legislation mandates rapid changes.

Concrete

Concrete is the world's most widely used building material and is manufactured at a rate of about one cubic meter per person on earth per year, equating to 2600 Mt of cement produced in 2007 alone (van Oss, 2007). Annual Canadian production is on the order of 14 Mt. Nearly three quarters of concrete is used for ready-mix applications in North America. The balance is made up of a broad array of products including precast/prestressed, brick and block, building materials and oil and gas well drilling. The principal sources of direct emissions from concrete production will vary depending on the product type and the assignment of assessment boundaries. Typically, the transportation fleet and steam generation for curing and heating are the highest emitting and energy intensive process steps.

Cement is the active component of concrete, and is responsible for the majority of concrete's embodied or indirect greenhouse gas emissions. A 2009 report commissioned by the WBCSD estimated that 800 kg of CO_2 are released during the production of 1 tonne of cement on a global average basis (WBCSD, 2009). Cement consumption is expected to rise to between 3700 to 4400 Mt by 2050 with the growth largely attributed to soaring cement demand in developing countries, namely China. While overall cement production may increase, the global cement industry is attempting to reduce their carbon emissions intensity by supplementing feedstocks and fuel types with low carbon alternatives and raising process efficiencies (Van Oss and Padovani, 2003; Rehan and Nehdi, 2005; Damtoft et al., 2008; WBCSD, 2009). The cement manufacturing process involves two significant CO_2 emitting steps: (1) limestone calcination and (2) fossil fuel combustion to heat cement kilns in order to drive the heavily endothermic calcination reactions. Calcination is the fundamental chemical reaction in cement production and. as shown in equation 1. releases one mole of CO_2 for every mole of calcium oxide produced (Van Oss and Padovani, 2003). Collectively these two processes account for about 90% of the industry emissions. The remaining 10% is attributed to electricity generation for processing and fossil fuel use for transport (Rehan and Nehdi, 2005).

$$CaCO_{3(s)} + heat \rightarrow CaO_{(s)} + CO_{2(g)} \quad (1)$$

As mentioned above, 90% of emissions in cement production are related to limestone calcination and fossil fuel use for kilns. The range of CO_2 emission factors for the calcination and combustion steps are between 0.31 to 0.6 kg CO_2 / kg clinker for fossil fuel use and 0.51-0.53 kg CO_2 / kg clinker for calcination (Van Oss and Padovani, 2003; Damtoft et al., 2008). Clinker is the product of calcination and precursor to cement prior to grinding and blending of additives. There is minimal variation in calcination emission factors due to the homogeneity of limestone and clinker. The broad range of combustion emission factors is related to advances in kiln design and fossil fuel variability. Under optimal conditions, the minimum emission factor using fossil fuels is 0.29 kg CO_2/ kg clinker; only 0.02 kg CO_2 less than modern cement plants (Damtoft et al., 2008). It is perceived that very little can be done to lower the calcination emissions (0.53 kg CO_2/ kg clinker) due to the process thermodynamics and the lack of available low-carbon supplementary cementitious materials (SCMs). Apart from modest gains achieved from cement substitutes and experimentation with alternative low carbon fuels such as biofuels, the cement industry has limited options to sustain its aggressive trend of lowering the production based intensity targets for CO_2 emissions.

Similar to the situation of the oil sands in Canada, the cement industry is facing record global production expectations, mounting regulatory pressure and limited GHG mitigation options. As regulatory and market pressures mount, cement will face new compliance costs that will eventually be passed onto the concrete sector. It is understandable why these industries are promoting a sectoral intensity based approach to CO_2 mitigation (Rehan and Nehdi, 2005; Alberta Environment, 2008). Regardless of whether the cement industry is regulated with a sectoral approach; in order to remain competitive it will require sustainable technical breakthroughs to lower CO_2 emissions and energy demand (Rehan and Nehdi, 2005; Sathre and Gustavsson, 2007; Damtoft et al., 2008; Scrivener and Kirkpatrick, 2008). Nonetheless, commercialization of innovations is inhibited by barriers related to structural testing and certification; scales of production; and overcoming institutional resistance to change.

Industry associations (WBCSD, 2009) and Scrivener (2008) advocates that sustainability is a main driver for innovation for the cement industry in the 21st century. Although not explicitly stated, sustainability must incorporate environmental as well as societal, economic and product performance considerations. Industry adoption of new practices and technologies will undoubtedly accelerate if a strong economic, and to a lesser extent, material performance improvements can be irrefutably demonstrated. New scientific and engineering approaches based in such disciplines as nanotechnology and green chemistry and often simple changes to operating practices are called upon to achieve these breakthroughs (Damtoft et al., 2008; Scrivener and Kirkpatrick, 2008). Recent products of aggressive R&D initiatives include self-consolidating concrete admixtures (SCC), new cement and aggregate products (Calera) and ultra-high performance concrete blends. These breakthroughs represent the type of sustainable innovation that was prescribed by Scrivener (2008).

This paper aims to review the concepts and report upon the commercialization developments of a new low-cost and high-performance green concrete technology, CO_2 Accelerated Concrete Curing. The industrial pilot study has been operating since 2008 at a precast concrete plant in Nova Scotia, Canada will build upon the preliminary physiochemical research and material testing with the purpose of optimizing process conditions and demonstrating its full-scale effectiveness (Logan, 2006; Monkman and Shao, 2006; Niven, 2006; Shao et al., 2006; Shao et al., 2007).

PROCESS OVERVIEW

CO_2 Accelerated Concrete Curing was designed to replace steam curing of precast concrete products. The block diagrams, shown in figure 1, contrast the typical steam curing process and the proposed carbonation curing method. Of note is that steam curing consumes energy and releases the resulting CO_2 to the atmosphere, whereas the CO_2 Accelerated Concrete Curing process consumes the CO_2 released from an external fossil fuel combustion source. This relationship is an example of the industrial symbiosis that may emerge from the consumption of CO_2 rich waste emissions from nearby large stationary emitters for the improvement of precast production.

The process is intended as a bolt-on solution to existing or new precast concrete plants that will complement standard process equipment and minimize retrofit costs. Precast concrete products are those which are manufactured in an industrial setting, typically using highly mechanized processes and energy and water intensive curing. Examples of products include blocks, paving stones, panels, pipes and barriers. The reactor design and standard concrete properties facilitate ambient operating conditions (atmospheric pressure and room temperature) and require no additional chemical additives or substantive energy inputs. If proven to be commercially viable, the process will be a significant improvement over conventional steam curing and GHG mitigation options.

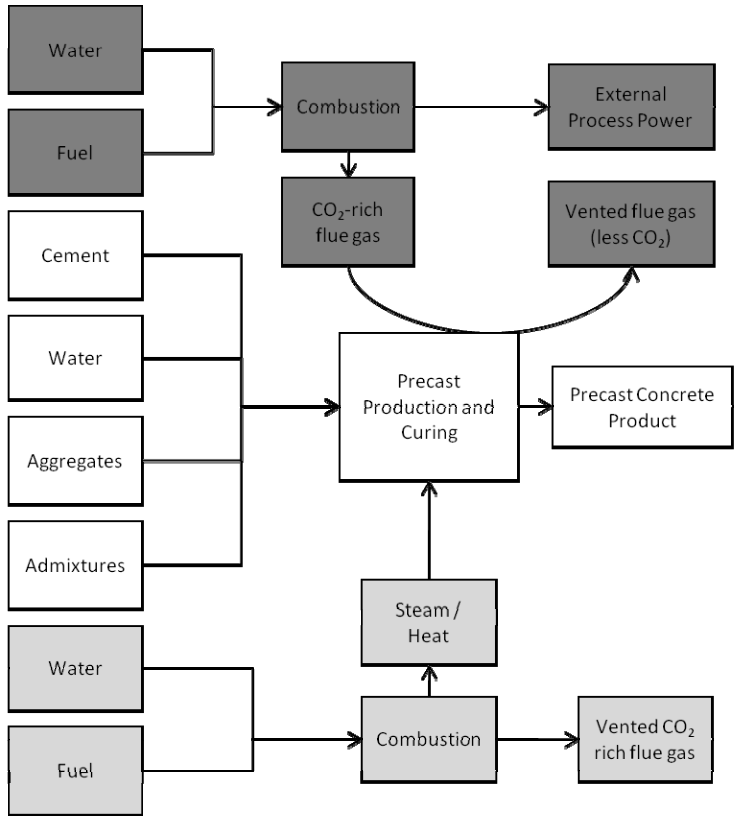

Figure 1. Block diagrams of the CO_2 Accelerated Concrete Curing process (top, hatched) and conventional steam curing process (bottom, dark). Both processes share the common concrete production process (middle, no fill).

Physiochemical Mechanisms

Interrelated physical and chemical reactions govern the CO_2 sequestration potential and material properties of carbonated products (Young et al., 1974; Papadakis et al., 1989; Fernandez Bertos et al., 2004). Cement is the reactive component of the concrete mixture. CO_2, the corresponding reactive agent, is introduced in a gaseous form at a specified concentration and pressure. The calcium in the cement reacts, in solution, with carbonate ions. The activity of the carbonate and mineral ions is affected by chemical (pH, temperature) and physical (relative humidity, surface area, permeability) factors (Fernandez Bertos et al., 2004; Chen et al., 2006). The overall reaction is exothermic and the final product is solid calcium carbonate (equation 2). The deposition greatly affects the material properties and reaction kinetics (Fernandez Bertos et al., 2004). The calcite product morphology of calcium carbonate was identified as the primary carbonated product (Monkman and Shao, 2006). An amorphous calcium-poor silicate hydrate gel is also created.

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3 \qquad (2)$$

Material Performance

In the past, concrete carbonation has been investigated to successfully reduce the occurrence of shrinkage cracking in steam cured concrete (Shideler, 1955; Steinour, 1959; Toennies, 1960). The development of a carbonation curing approach has developed over time with recent emphasis being placed upon the possibility of using it as a means of carbon sequestration while improving the properties of concrete. (Young et al., 1974; Sorochkin 1975; Fernandez Bertos et al., 2004; Monkman and Shao, 2006; Shao et al., 2006; Shao et al., 2007). The early strength, late strength, weathering carbonation shrinkage, freeze/thaw durability, water absorption, and pH of carbonation cured concrete has been found to be generally comparable, or superior, to that of the hydrated concrete (Monkman and Shao, 2010a).

Environmental Performance

The GHG mitigating potential is the primary environmental incentive of the process. Reductions in water consumption, cement requirements, air particulate matter and NO_x and SO_x emissions are also achieved. Two pathways account for the CO_2 reductions: (1) carbonation of calcium silicate and hydroxide minerals of cement and (2) reduction of fuel consumption for precast concrete manufacturing (Niven, 2006; Shao et al., 2007). In total the process reduces CO_2 emissions by an average of 120 kg/ t concrete. The estimate assumes theoretical sequestration limits are achieved and that data from a recent PCA lifecycle study is representative (Marceau et al., 2007). Laboratory experiments achieved between 20 - 80% of the theoretical limit (Niven, 2006). The industrial trials will provide more accurate projected GHG reduction figures.

A representative elemental analysis of type 10 Portland cement by XRF is reported in Niven (2006) and Monkman and Shao (2006). The CO_2 uptake according to equation 8 and the standard chemical composition type 10 Portland cement was 49.6% w/w of cement. The cement content of a representative precast mixture, as listed in table 1, is 220 kg/ t concrete. Therefore the resulting estimated CO_2 sequestration potential of a ton of concrete is 110 kg, approximately half the weight of cement contained within the concrete. From a GHG accounting perspective, it is noteworthy that the emission reductions from this mechanism are equivalent to the CO_2 emissions from limestone calcination. Limestone calcination is in fact the reverse reaction.

The second mechanism for CO_2 reduction is the reduction of fossil fuel use due to the elimination of steam curing. The PCA reports that on average steam curing consumes 155 MJ/ t concrete (Marceau et al., 2007), equivalent to 9.81 kg CO_2/ t concrete. Collectively both mechanisms combine to reduce CO_2 emissions by 120 kg CO_2 / t concrete.

Table 1. Process inputs for precast concrete manufacturing. [Modified from (Marceau, 2007)]

Production Inputs	**Intensity based consumption figures (t concrete)$^{-1}$**
Total Energy	353 MJ
Steam Curing	155 MJ
Other	198 MJ
Total Water*	369 L
Steam Curing	14_2 L
Disposal	217 L
Recycled	10 L
Concrete Mixture†	
Coarse Aggregate	458 kg
Fine Aggregate	242 kg
Batch Water	78 kg
Cement	220 kg
Admixture‡	-

* Excludes batch water for concrete

† Mix design achieves a 50 MPa 28-day compressive strength rating

‡ Negligible contribution to mass

A total analysis of the energy and emissions associated with a carbonation curing process has estimated that the overall ratio of carbon sequestered to carbon emitted would exceed 9 to 1 (Monkman and Shao, 2010b).

Economic Performance

The primary economic incentives for adopting the process are reduced precast plant operating costs from lower energy (44%) and water (39%) consumption achievable through a low cost retrofit of existing plant equipment. Plants may lower other operational expenses associated with faster production, less inventory handling and fewer shrinkage defects. Operators may also earn potential carbon tax relief and/or credits associated with any certifiable CO_2 emission reductions of the process estimated to be 120 kg CO_2/ to concrete. Furthermore, consumer preference and building codes are gradually demanding environmentally friendly products. Precast concrete products are already recognized as green building materials (Holton, 2008). Carbonated precast products, however, will offer even greater consumer appeal to satisfy sustainable building practices and as such may realize a market premium, which along with lower production costs, further increases profit margins for the operator. The margin advantage will enable early adopters to realize a rapid return on investment. As adoption becomes more wide spread this technology may cause downward pressure on consumer prices, at which point accelerated curing processes will be required to remain competitive in regional markets where it is utilized.

Societal Performance

Global warming is widely considered the greatest threat affecting society (Ministry of Foreign Affairs of Japan, 2008). Reducing GHG emissions is critically important to lessening the effects of global warming. While still early in development, the CO_2 mitigation potential of the CO_2 Accelerated Concrete Curing process would be 283 Mt CO_2/ yr or 21.6% of the 2007 cement industry CO_2 emissions assuming that 20% of present day global cement supply is consumed for precast products and optimal process performance is achieved. The long-term international CO_2 reduction targets are likely to be a 50% reduction below 1990 levels to avoid irreversible effects of global warming (Ministry of Foreign Affairs of Japan, 2008). As discussed earlier, the target is not attainable by the cement sector due to the technical limitations imposed by the calcination step in cement production. CO_2 Accelerated Concrete Curing reverses the calcination reaction by sequestering CO_2 within precast products. The cement industry may achieve the long-term targets if it were to base a broad portfolio of other innovative technological solutions upon the deep CO_2 reduction potential and economic advantages of this process.

Sustainability

Sustainability is the maxim of the 21st century. Business as usual energy and consumer practices are under scrutiny in the wake of depleting natural resources and food shortages (Holton, 2008). Industry and environmental groups are aligned in prescribing sustainable solutions for the cement and concrete industry (Damtoft et al., 2008; Scrivener and Kirkpatrick, 2008; WBCSD, 2008). The aim of the CO_2 Accelerated Concrete Curing pilot study is to demonstrate its sustainability merits on the grounds of environmental, economic, material performance and societal factors. Each component should be satisfied to pass the increasingly stringent public and industry scrutiny for commercialization. The projected sustainability performance is discussed in the following sections.

PILOT PROJECT DESCRIPTION

The pilot project is managed by Carbon Sense Solutions Inc. and has been undertaken by a private-public joint venture consortium composed of private enterprises and academic institutions with support from the ecoNova Scotia program of the Province of Nova Scotia. The program was established to achieve the objectives set out by the provincial Vision 2020 plan and Bill 146, the Environmental Goals and Sustainable Prosperity Act.

Preliminary trials were conducted in the winter of 2008/09 at the precast and brick manufacturing facilities of project partner Shaw Group Ltd. (www.shawgroupltd.com) at Lantz, Nova Scotia. Local engineering firms, specialists and universities have performed key support services. A third party expert panel is assembled to review and validate the project findings.

Initial testing conducted at Shaw investigated precast pipe. Subsequent testing has investigated precast block. A prototype for block carbonation has been developed for industrial trials of a retrofit carbonation curing system at Shaw before the close of 2010. Air Liquide has provided support in the design of gas delivery infrastructure for the prototype trials.

The technical objectives are to demonstrate the industrial application of this process, identify optimal operating conditions, validate the CO_2 mitigation potential and extensively investigate the material property performance of carbonated products. A complementary economic assessment as part of a broader commercialization strategy will build upon the technical findings and provide early adopters of the technology with the necessary investment information. The societal objectives will be to develop the knowledge base for a material carbonation centre of excellence in Nova Scotia that will complement current geological CCS projects.

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