Final Report to Climate Change Emissions Management (CCEMC) Corporation

CCEMC Project ID: K130084

Title of project:
Use of Carbon Dioxide in Making Carbonate-Bond Precast Concrete Products

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Completion date of the project:
2016-05-30

Total CCEMC funds received and amount of hold back
Total CCEMC funds received: $350,000
Total holdback: $150,000

Confidentiality period
2016-06-01 to 2018-05-30

Submission date
2016-05-30

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Final outcomes report (Non-confidential)

1. Executive Summary

This project is to explore the possibility of using the existing precast concrete production for carbon capture, utilization and storage (CCUS) in Alberta. The target of carbon dioxide utilization is 1 million ton per year. To maximize the carbon uses in concrete production, both cement matrix and aggregates are examined for their reactivity with carbon dioxide and carbon storage capacities. Artificial aggregates are manufactured using calcium-rich industry wastes and activated by carbon dioxide on site where the wastes and CO2 are produced. The manufactured aggregates will replace natural sand and stones for concrete production. The making of artificial aggregates serves not only as the carbon storage. It also reduces waste landfill, promotes waste utilization, reduces natural resource consumption and performs heavy metal sequestration. The carbonate aggregates are then shipped to precast concrete plant to mix with cement binder to make concrete through secondary carbonation of cement matrix. In order to prepare for commercial production, the standard industry mixture proportion and product forming procedure are strictly followed so that the results can be applied to commercial production immediately. The main change is that the conventional steam curing will be replaced by carbon dioxide curing at precast plants. The final products have demonstrated a unique carbonate bond. The carbonated precast has shown mechanical performance comparable to the conventional products by steam curing and demonstrated much improved resistance to freeze-thaw cycling, chloride penetration, and efflorescence formation. This is attributed to the formation of carbonate precipitation and the refinement of pore structure due to carbonate bond. It is expected that the carbonated precast products can have a longer service life. This project also involves the development of carbon capture and separation technology for producing low cost and high purity carbon dioxide for concrete utilization. Without low cost CO_2, it is impossible to implement the production in full scale. With the innovative self-concentrating absorption technique and residual heat utilization in an integrated system, the high purity CO_2 can be produced with energy consumption of 1-1.2 GJ/t CO_2 and at a cost about $10-20/t CO_2, making carbonation process competitive to steam.

2. Project Description

Unlike the steam curing that accelerates the formation of calcium silicate hydrate (CSH) bond, carbon dioxide curing produces calcium carbonates. The formation of carbonate bond requires the candidate materials be rich in calcium silicate compounds in any polymorph forms. The reactions of tri-calcium silicates and di-calcium silicates with carbon dioxide are given in Eqs (1-2). The final products are hybrid of calcium-silicate-hydrates (CSH) and calcium carbonates ($CaCO_3$). The increase in carbonation degree will increase the percent of carbonates and decrease the calcium to silica ratio in CSH.

$$2\,(3CaO\cdot SiO_2)+3CO_2+3H_2O\rightarrow 3CaO\cdot 2SiO_2\cdot 3H_2O+3CaCO_3 \qquad (1)$$

$$2\,(2CaO\cdot SiO_2)+CO_2+3H_2O\rightarrow 3CaO\cdot 2SiO_2\cdot 3H_2O+CaCO_3 \qquad (2)$$

The carbonate bond can also be achieved from carbonation of hydration products such as calcium silicate hydrates and calcium hydroxide as given by Eqs (3-4):

$$Ca(OH)_2+CO_2\rightarrow CaCO_3+H_2O \qquad (3)$$

$$3CaO\cdot 2SiO_2\cdot 3H_2O+3CO_2\rightarrow 3CaCO_3+2SiO_2+3H_2O \qquad (4)$$

It is clear that carbonation reaction of calcium silicates and hydration products is a CO_2 sequestration process. Carbon dioxide will be converted to thermodynamically stable calcium carbonates and can be permanently stored in concrete products. To maximize the carbon sequestration in concrete, both cement binder and aggregate filler are considered as reactants to uptake carbon dioxide and produce carbonate bond construction products. Aggregates count for 80% by mass in a concrete. Natural aggregates are not carbon reactive. However many industry wastes contain calcium silicate that can be activated by carbon dioxide to develop strength and make artificial carbonate aggregates. Concrete is the most used man-made material. If both binder and filler in concrete can store carbon dioxide, the carbon utilization capacity of concrete can be significantly enhanced. On the other side, concrete is sensitive to the price change. Because of the quantity used in a project, small increase in production cost due to the carbon utilization will lead to a jump in total cost. Therefore production of low cost CO_2 is crucial to the carbon utilization in concrete. The final cost involving carbon utilization shall be comparable to conventional process such as steam curing.

The project has two objectives: 1) to maximize the carbon uptake in concrete products by carbonation of both artificial aggregates and their concretes and 2) to produce low cost carbon dioxide from flue gas for concrete utilization. The ultimate goal is to develop a process that can consume 1 Mt CO_2/year in Alberta using the existing precast concrete products. This project is special in that the process developed is an integrated and self-sustained system including carbon capture and utilization. Without a low cost CO_2, utilization in concrete is not feasible.

Three tasks are carried out:

- Task 1 is to promote carbon uptake in cement to 20-30% on a dry cement basis to form a carbonate bond in a variety of precast concrete products;
- Task 2 is to promote carbon uptake by calcium silicate wastes to 10-30% by mass for making carbonate aggregates out of industry wastes for concrete uses;
- Task 3 is to produce low cost CO_2 using 3H self-concentration absorption technology and develop a capture-utilization integrated system for carbonate aggregate production.

3. Outcomes and Learnings

3.1. Task 1 on carbonation curing of concrete products

3.1.1. Survey on Alberta precast concrete industry

Survey on Alberta precast concrete industry was performed. Precast products produced in Alberta include the unreinforced products and the reinforced products.

Unreinforced products include masonry blocks, paving stones and retaining walls. They have no steel inside and can be carbonated to a high degree of carbon uptake. The precast products are mass produced, cured by steam and excellent candidates to receive carbonation for fast curing and carbon storage. There are approximately 10 producers in Alberta that are making those unreinforced products. Based on the annual market report by Canadian Concrete Masonry Producers Association (CCMPA), western Canada produces 6 million units of equivalent dimension of 20-cm as hollow blocks. Alberta is the bulk producer. Its annual capacity is about 5 million units. In average, Alberta block industry consumes 0.009 million ton (Mt) of cement per year and 0.072 million ton (Mt) of aggregates per year.

The **reinforced precast products** are structural concretes reinforced by steel. The typical products used in Alberta include the concrete pipes, piles, hollow core panels, sandwich panels, benches, barriers, manholes, fire walls, septic tanks, culverts, concrete fence, and architectural components. Because of the steel reinforcement, the reinforced products have to be processed under a controlled carbonation to avoid accelerated corrosion. Precast products are mass produced and usually require steam curing after casting. They are excellent candidates for carbon utilization through the carbonation curing in place of steam curing. Alberta annul cement production is about 2 Mt by two major producers: Lafarge and Lehigh Hanson. Approximately 25% of the cement is used in precast products. It is about 0.5 Mt cement per year. The corresponding concrete will reach 3.3 Mt for precast products with 15% cement content (assuming the typical ratio of cement:aggregate:water = 1:5:0.5). The aggregates needed for precast concrete is about 2.5 Mt.

3.1.2. Technology development and experimental procedure.

A unique process has been developed to promote carbon uptake by Portland cement binder to make carbonate-bond concretes using the existing process and the well-developed market. It involves hydration-carbonation-rehydration. After precast concretes are cast formed by vibration, the products are preconditioned in an open air for preset hydration to remove part of free water and create capillary space for gas diffusion and carbonate precipitation. After preset, the products are placed into a carbonation chamber for curing. After carbonation curing, precast products will be sealed for subsequent rehydration.

3.1.3 Unreinforced products: concrete blocks with 100% Portland cement.

Prototype production of 20-cm blocks using carbonation process was carried out at commercial block plant. A small scale carbonation curing chamber was set next to the production line. Both commercial normal weight and lightweight 20-cm blocks were produced from the production line. Ten for each were cured in carbonation chamber and the rest of the batch was cured in an autoclave by high pressure steam. The compressive strengths of the blocks were tested using both carbonated and steamed blocks as comparison. The normal weight blocks with granite aggregates weigh 16.8 kg each and lightweight blocks with expanded lightweight aggregates weigh 14.5 kg each. The normal weight block has shown a higher carbon uptake than the lightweight blocks based on the cement content. The corresponding average carbon dioxide mass is 304 g in each normal weight block and 315 g of CO_2 in each lightweight block. The absolute carbon take is higher in lightweight block since each lightweight block contains more cement (1.94 kg each) than normal weight block (1.63 kg each). The carbon uptake is measured by comparing the mass of the blocks before and after carbonation. With the reference to the cement content, the carbon uptake is 18.6% in normal weight concrete and 16.1% in lightweight concrete. It is challenging to carbonate the full-size blocks through the thickness. The teste results had shown that the carbonated blocks have higher compressive strength than the autoclaved blocks. The difference is more apparent in normal weight concrete. This prototype demonstration is an important milestone for the project to promote full scale production.

3.1.4 Unreinforced products: concrete blocks with 75% cement and 25% SCM (fly ash/iron slag).

Second small scale carbonation test was performed on concrete blocks with fly ash or slag. Modern concrete is always made with supplementary cementitious materials (SCM), such as fly ash or iron slag, to reduce the cement content and improve the durability. SCM is a pozzolanic material, requiring calcium hydroxide (CH) to activate the pozzolanic reaction. The conventional hydration is CH producing reaction which is beneficial for the use of SCM. However carbonation is CH consuming which could be contradictory to pozzolanic reaction. A study was carried out to examine the relationship between the pozzolanic and carbonation reactions and to address the concern if concrete with SCM can be treated by carbonation.

Two commercial SCM materials were employed. They are Lafarge Newcem and NewcemPlus. The Newcem is composed of 100% GGBF (ground granulated blast furnace) slag and NewcemPLus is composed of 50% GGBF slag and 50% fly ash. Three concrete batches are investigated:

A: 100% OPC concrete with hydration and carbonation
B: 75% OPC + 25% Newcem concrete with hydration and carbonation
C: 75% OPC + 25% NewcemPlus concrete with hydration and carbonation

For each concrete, both hydration and carbonation curing were applied. Degree of carbonation was slightly decreased due to the addition of SCM since Newcem and NewcemPlus were not carbon reactive as comparison to OPC. Based on total cementitious binder, the carbon uptake was 18.1% in OPC, 17.7% in concrete with 25% Newcem and 15.7% in concrete with 25% NewcemPLus. They are calculated based on dry cement used in the product. The increase in 90-day strength by hydration in Batch B and Batch C in comparison to Batch A is indicative of pozzolanic reaction. Carbonation has doubled the 1-day concrete strength in all three batches, but reduced the 90-day strength in Batches B and C by 10% due to the decreased pozzolanic reaction in subsequent hydration. It is clear that pozzolanic reaction after carbonation can still proceed. The reaction degree can be affected by carbonation. However carbonation can have added value to durability enhancement in addition to carbon utilization.

After laboratory investigation, the full-size 20-cm blocks with 25% fly ash or GGBF slag as additive are also carbonation produced. Each block can uptake about 0.2 kg CO_2 which is lower than 0.3 kg in the blocks made from 100% Portland cement. This is because only 75% Portland cement is used in binder. However the 28-day strength has reached 35 MPa which is comparable to blocks with 100% Portland cement. It is evident that blocks can be made with 25% supplemental cementitious materials (SCM) with carbonation treatment. It will significantly reduce the carbon emission by using less cement and storing more carbon dioxide in comparison to steam-produced blocks.

3.1.5 Unreinforced products: Full scale pilot carbonation tests.

Full scale pilot tests were performed at commercial block plant in fall 2015. The carbonation chamber has the capacity to do carbonation curing of 4200 units with 20-cm standard size blocks per kiln. On average, the normal weight 20-cm blocks can uptake about 426 to 444 g per block and gain a strength of 34 to 39 MPa. The normal weight 20-cm blocks with 25% SCM performed as well as the block with 100% Portland cement. Its CO_2 uptake has reached 410 g/block and the strength 35.5 MPa, comparable to reference blocks with no SCM. High strength blocks have shown highest uptake (460g CO_2/block) and highest strength (57.4 MPa). The carbonated blocks are stronger than traditional autoclave products. The first of its kind full scale pilot tests have demonstrated that high uptake and high strength blocks can be produced with carbon dioxide. Therefore it is possible to replace steam process with benefits.

3.1.6 Reinforced products: concrete pipes, concrete slabs and concrete railway crossties.

The second product group to be explored for carbon utilization is the steel reinforced products such as concrete pipes, slabs and crossties. They are mass produced and popularly used in different systems. They are the majority of recast products. The challenge for this task is that degree of carbon shall be controlled to avoid the significant reduction of pH value in concrete pore solution which will induce corrosion of steel. Durability is an issue. A systematic study is carried out: (1) to develop a special process for reinforced product carbonation (2) to examine the effect of carbonation on pore structure and freeze-thaw damage (3) to study the effect of carbonation curing on efflorescence formation (4) effect of early carbonation curing on service weathering carbonation.

Special process for carbonation curing of precast reinforced concrete. Carbonation is usually considered detrimental to reinforced concrete because of the carbonation-induced corrosion of steel. However if carbonation is performed at early age through curing, the process can be beneficial. A unique process has been developed for early age carbonation curing of precast reinforced concrete to maximize the performance improvement and the carbon storage capacity. The process includes vibration casting, in-mold curing, demold conditioning, carbonation curing and subsequent hydration. It was found that a carbon uptake of 16% based on the cement content could reduce concrete pH to 9.2 on the surface and maintain pH of 13.0 at core immediately after 12 h carbonation. The subsequent hydration was able to increase the pH on surface over 12.3 which was comparable to hydration reference. The carbonated concrete had shown more resistance to permeation by having a higher electrical resistivity on surface and was not more vulnerable to weathering carbonation. The demold conditioning in open air caused no shrinkage cracking because of the controlled evaporation rate. The process makes concrete a sandwich structure with carbonate-rich surface.

Two types of concretes with different water to cement ratio were investigated. Concrete A has cement content of 450 kg/m3 with a water to cement ratio of 0.4 and concrete B has a cement content of 526 kg/m3 with a water to cement ratio of 0.3. Carbonation can make low cement concrete (batch A) directly comparable to high cement concrete (batch B). The carbon uptake is 16% in concrete A and 11% in concrete B. Surface layer (0-20mm) of concrete is heavily carbonated with pH reduced to 9.2. However, after 28 days rehydration, pH is increased to 12.3, comparable to hydration reference. Carbonation depth disappears. Therefore the early carbonation is suited to reinforced concrete curing without causing carbonation corrosion.

The ***pore structure*** of ordinary Portland cement (OPC) pastes subject to carbonation curing is characterized by Mercury Intrusion Porosimetry (MIP) technique. The permeability performance of corresponding concretes was assessed by surface resistivity and freeze-thaw scaling resistance. It was found that early carbonation could significantly reduce porosity and pore size at both early and late ages. The process had the capacity to reduce large capillary pores and create more gel pores and ink-bottle pores. As a result, concrete porosity is reduced, surface electrical resistivity is enhanced and freeze-thaw resistance is improved.

- It is conclusive that total pore volume is significantly reduced by carbonation curing in comparison to hydration references. Right after carbonation, the pore volume reduction was 22% in OPC pastes. After 1 year subsequent hydration, this reduction became 40%. The precipitated calcium carbonate due to carbonation has enhanced the early strength and is responsible for pore structure refinement in late hydration.
- The pore size is significantly reduced by carbonation curing as well. Critical pore diameter was decreased by approximately 10 times in OPC paste at the age of 1 day. After 1 year subsequent hydration, carbonation curing reduced critical pore diameter to half of that in hydration reference. Pore shape was also changed by carbonation curing. More ink-bottle pores smaller than 10 nm were formed in carbonation. The pore structure is considerably refined in carbonated pastes.
- Although carbonation curing occurred at early age and in a short period of time, it also had the effect on subsequent hydration. The carbonated OPC concrete had shown higher strength and much refined pore structure at late age in comparison to hydration-only reference. It was evident that precipitated calcium carbonates not only accelerated early strength but also served as precipitation sites for late hydration.
- The refinement of pore structure in paste due to carbonation has played a critical role in improving concrete strength and durability. The carbonated concrete is stronger and more durable because of the reduced porosity, reduced permeability and enhanced freeze-thaw resistance. The pH value of carbonated concrete is comparable to hydration reference after subsequent hydration, making the early carbonation curing process suitable for reinforced concrete production.

Effect of carbonation curing on efflorescence formation. Efflorescence is a salt deposit which is formed on or near the surface of a porous material such as Portland cement concrete. Although efflorescence is not an indication of internal damage, it alters the aesthetic quality of the product. The primary goal of this work was to investigate whether early-age carbonation can help reduce, or altogether eliminate, the efflorescence formation on concrete paver blocks. It has significantly economic benefit. The carbon uptake reaches 10.4% based on cement content. The carbonated pavers are evaluated by a newly developed test method to visualize efflorescence formation. It is modified from wicking test and is proven effective for the accelerated formation of efflorescence. A MATLAB-assisted image-analysis technique is used to quantify efflorescence severity. It was found that early age carbonation curing successfully eliminated the formation of efflorescence on the top exposure surface compared to extensive white deposits precipitated on the service surface of reference hydration pavers. Carbonation curing seems to prevent the pore solution from migrating up to the service surface, and instead of precipitating on the top surface, a line of white deposits on each side was observed on the lower portion of the paver. Since the efflorescence is considered as an aesthetic problem only, carbonation curing is a feasible technique to prevent efflorescence by keeping it out of sight. Lower absorption and calcium hydroxide consumption are considered as the two reasons that carbonation curing has the capability to resist efflorescence formation. It is well known that the carbonation curing is a CH consumption process, and CH is the essential chemical component causing carbonate based efflorescence. With the penetration of carbon dioxide during the curing process, more and more calcium carbonate fills the pores, and resulting in decrease in permeability, porosity and absorption. Semi and fully immersed absorption test were conducted to prove that the absorption and permeable voids volume of carbonated paver were lower than that of hydrated reference. And the water migration in the concrete is the leading cause of degradation. Therefore, the carbonated concrete has a better resistance to the weathering.

In principle, early age carbonation curing is able to prevent all kinds of efflorescence regardless of the chemical compositions and sources, since all of those types have the same forming mechanism. Carbonation curing provides a new efflorescence prevention solution for the concrete industry. Unlike the existing removal and prevention methods, this technique can eliminate the salt deposits on the visible service surface without damage or alter the desired texture and color. Furthermore, manufactures could benefit from the higher early age strength to reduce the production cycle. In addition, carbonation curing is an environmental friendly process, large amount of carbon dioxide will be consumed if the technique can be adopted by the industry.

Effect of early age carbonation curing on weathering carbonation for precast reinforced concrete. The effect of early carbonation of concrete with different water to cement ratios on carbonation depth during the weathering carbonation in service was studied. Weathering carbonation is the reaction between atmospheric carbon dioxide and hardened concrete in service, leading to carbonation corrosion. Therefore carbonation depth shall be limited. Concrete samples of 10 x 10 x 10 cm were cast, using two water to cement ratio: w/c = 0.65 and w/c = 0.40. Specimens were de-molded after 5 hours, upon which they were subject to 7 hours of air-drying and finally carbonated for durations of 2 and 12 hours at 5 bar using pure CO_2. CO_2 uptake was calculated using mass-gain method. Hydrated reference samples were also cast for each batch. After completing the prescribed processing conditions, all batches underwent subsequent hydration for 28 days in a moisture room (100% RH). The 1-day and 28-day strength was recorded as baseline. Weathering carbonation was simulated in an air-tight apparatus with the following conditions: 20% CO_2, 75% relative humidity (RH), and 23 ^{0}C. Carbonation depth was measured by phenolphthalein after exposed to simulated atmospheric carbonation at 4, 8, 12, and 16 weeks. The following conclusions can be drawn:

- After 12 hours of carbonation curing, the concrete with w/c = 0.65 measured a CO_2 uptake of 20% by cement mass and a penetration depth of 12.1 mm; while the samples prepared using w/c = 0.40 recorded a CO_2 uptake of 10 % and a depth of 2.6 mm. The concrete with high w/c ratio is more vulnerable to CO_2 permeation, creating larger carbonation depth. After 28 days subsequent hydration, the carbonation depth in high w/c concrete remained while the carbonation depth in low w/c concrete disappeared.
- After 16 weeks of weathering carbonation of concrete with high w/c ratio of 0.65, the hydrated reference samples experience a higher rate of carbonation penetration (12.2 mm) than the 12-hour early-age carbonated samples (5.2 mm). Carbonation treated concrete is more resistant to weathering carbonation.
- Early-age carbonated concrete using low w/c = 0.4 displayed more resistance to CO_2 penetration. Total carbonation depth was much smaller due to weathering. It is conclusive that concrete with high w/c ratio is not good candidate product for carbonation curing. This is because the carbonation depth

is large. It is recommended that carbonation cured products use low water to cement ratio to avoid large carbonation depth.

3.2 Task 2 on carbonate-bond aggregates and their concrete products

3.2.1 Carbonate aggregates produced from steel slag by carbonation activation

In typical concrete mix design, Portland cement counts for 10-20% by mass and the aggregate 75 to 85%. Aggregates comprises of the majority of the body. If aggregates can also be used to store carbon dioxide, the carbon utilization capacity by concrete products will be considerably enhanced. The making of artificial aggregates from industry wastes by carbonation is thus examined. It is found that steel slag, once ground fine, is reactive with carbon dioxide and can be an ideal material to make artificial aggregates for concrete. The as-received slag was passed through a sieve to remove large metallic fragments and other impurities and ensure homogeneity. The steel slag fine was then mixed with water and compact formed into cylinders, which were carbonated by carbon dioxide. The immediate strength gain was over 80 MPa with a carbon uptake of 14% by mass. This was the result of primary carbonation. The carbonated cylinder was then crushed by a controlled force to make granular aggregates, which were further treated by secondary carbonation. This process was critically important to carbonate the freshly exposed crushed surface and promote more carbon uptake in granules. The carbon uptake by secondary carbonation of the crushed granules was 3% by mass which was indicative that most reaction had occurred in primary carbonation. The granules were sieved to different size and mixed to gain a desired gradation curve based on concrete block requirement. Finally concrete cubes were produced using Portland cement as binder and carbonate aggregates as filler. Tertiary carbonation was performed on the 5-cm block cubes as concrete product. In this third time carbonation, the carbon uptake was about 20% based on cement content, slightly higher than that obtained from full-size block carbonation (16-18%), possibly due to the presence of carbonate aggregates in concrete was also beneficial for more carbon uptake.

The compressive strength tests of 5-cm masonry concrete cubes with granite aggregates, lightweight expanded slag aggregates and artificial carbonate aggregates were conducted. Both hydration strength and carbonation strength were compared. For 24h hydration strength, carbonate aggregate concrete was comparable to commercial lightweight concrete but weaker than granite concrete. At 28 days, hydration strength of carbonate aggregate concrete was of close to that of granite concrete and stronger than the lightweight concrete. The carbonation curing had significantly increased the 24 h strength by more than 4 times. Relatively the strength of carbonate aggregate concrete is slightly lower than the granite but higher than the lightweight concrete. The similar trend was observed at 28 days after carbonation curing. It is conclusive that concrete with carbonate aggregates can have performance comparable to granite concrete which is the best structural concrete reference. The compressive strengths of all three concretes exceed the minimum requirement of 17 MPa for block application.

Based on laboratory tests, the breakdown of carbon uptake for a full size 20-cm block weighing 17.9kg each is calculated. The carbon uptake will be 0.46 kg by cement and 2.47 kg by carbonate aggregates, leading to a total carbon uptake of 2.93 kg by each 20-cm block. Assuming the annual production of masonry blocks in Alberta is 50 million units, the corresponding carbon dioxide consumption by block production will reach 0.146 million tonnes every year.

3.2.2. Carbonate aggregates with other materials and the use of nodulizer.

The granulation method was developed in making crushed aggregates. The aggregates so made is similar to crushed stone. However the process is time consuming. Although it can be automated, the process involves many steps and should be simplified. Therefore nodulization process is investigated. Nodulization makes aggregates by rotating the powder on a pan at an angle and certain speed. The aggregates are basically spherical. This is commonly used in making expanded clay aggregates and cement clinker nodules. More calcium silicate waste materials are also examined for making carbonate aggregates. They are EAF steel slag, ladle steel slag, and waste cement collected from recycling of cement based bead-board.

The industry wastes were sieved and nodulized on a pan. For each batch, a few aggregates in a size of about 5 mm in diameter were selected and tested by direct crushing in an MTS machine. The reference aggregates included granite aggregates (natural stone), expanded shale (manufactural lightweight aggregates), LECA (manufactured expanded clay lightweight aggregates) together with carbonate aggregates.

The granite aggregates had the highest strength, followed by expanded shale. Carbonate aggregates from EAF steel slag and ladle steel slag seemed to have performed well. They were comparable to expanded shale and better than expanded clay (LECA). Carbonate aggregates from waste cement was also comparable to expanded clay.

Carbon uptakes by carbonate aggregates were also tested. EAF slag had shown lower carbon reactivity. However its strength was relatively higher. Carbon uptake by ladle slag, and waste cement were in the same order of magnitude. Ladle slag had higher load capacity than waste cement. It was interesting to notice that the load capacity of the nodules was not proportional to carbonation reactivity. The strength development was based on the calcium silicate compound. Upon exposure to carbon dioxide, di-calcium silicates will produce stronger solid than calcium hydroxide although the latter may absorb more carbon. This mechanism is worth of an in-depth study.

Waste cement collected from recycling of cement boards had demonstrated its potential for carbonate aggregate application since cement boards had high residual cement content. It is the calcium silicate hydrate and calcium hydroxide in hydrated cement that react with CO_2 and produce solid. If cement boards can be collected for recycling after service, this could be an excellent source for carbon use. The challenge is if this powder cement can be collected from recycled concrete. Effort was made to separate the fine powder from recycled concrete collected from the field. The result was not satisfactory. Ten buckets of recycled concrete were obtained from the concrete recycling plant in Montreal. The fine powder was sieved passing 100 microns and tested. They were mostly fine sand. The lack of cement in the finer powder did not provide reactive component for carbonation. There was no strength after carbonation of those powder nodules. The use of cement powder from recycled concrete is not feasible. Concrete uses much less cement (15% by mass) than cement boards (more than 50% by mass). Unless special scrubbing process is used to separate cement paste from aggregates, the fine powder produced by crushing of concrete is not carbon reactive.

3.2.3 *Carbonate aggregates produced from APC residue by carbonation activation*

Air pollution control (APC) residue, from municipal solid waste (MSW) incineration, is rich in lime and has the potential to make a granular aggregate for concrete. The processing involves the use of a rotary nodulizer for the formation of granules and their subsequent carbonation. These aggregates are then used to cast 5-cm concrete cubes, and compared to reference concrete samples made using commercial granite and Lafarge expanded slag. APC residue was processed into differently shaped and sized granules using a rotary nodulizer. Granules were carbonated by multiple carbonation steps to produce carbonate aggregates. Overall average CO_2 uptake of APC granules as carbonate aggregates is about 20 % by mass.

To test the dynamic resilience of the APC granules, individual grains were hand selected and subjected to compressive strength. A handful of granules, ranging between 5 – 10 mm in diameter, from each material, granite, expanded slag and APC carbonate aggregates, were tested. A minimum of 5 granules were tested per material, with each granule crushed individually and then averaged. In general, commercial aggregates such as granite and expanded slag are more consistent with less deviation. The APC carbonate aggregates however had shown large deviation. Some of the aggregates were very strong and comparable to commercial products. Nevertheless, some of them were very weak. The carbonate aggregate was not uniform. The process shall be modified for uniformity.

Concrete with APC carbonate aggregates was tested too. The APC-based concrete displayed the lowest 1-day compressive strength of 4.9 MPa, compared to 31.4 MPa for granite and 28.4 MPa for expanded slag. It also displayed the lowest uptake (7 wt. % cement versus 10.3 wt. % for granite-concrete and 23.7 wt. % for expanded-slag-concrete). The low strength and CO_2 uptake values are believed to be mainly attributed to the granules' high affinity to water and inhomogeneous physical stability. In terms of bulk weight, the APC-concrete demonstrated its ability to store 16.5 % of its weight in CO_2, which translates to 396 kg CO2 per cubic meter of concrete so produced because of the large carbon uptake by APC aggregates. More work is needed to improve the strength of APC carbonate aggregates.

3.2.4 Carbonate aggregates produced from lime sludge

Lime sludge (LS) is the by-product from oil production and is investigated by its capacity to react with carbon dioxide to make carbonate aggregates. The two sludge materials, LS1 (labelled CLS) and LS2 (labelled WLS), are studied. The X-ray diffraction analysis has shown that LS1 sludge has 93% calcite and 7% amorphous phase while LS2 sludge has 30% calcite, 70% amorphous phase. The CaO content is also different. LS1 sludge has shown 47% CaO and LS2 only 16%. The chemical composition indicates that LS1 will be more carbon reactive than LS2.

Small cylinders were fabricated to evaluate the carbon reactivity and strength development of sludge materials. The as-received sludge was dried, pulverized and mixed with water at water to powder ratio of 0.15 to make small cylinder of 15 mm in diameter and 30 mm in height. The cylinders were then carbonated by 12 hours at 3 bar with pure gas. For LS1 sludge, the carbon uptake was 3.9% based on dry powder mass and compressive strength was 6 MPa. For LS2 sludge, the reaction was nearly zero. There is no carbon uptake and no strength gain. To enhance LS1 reactivity, 25% ordinary Portland cement (OPC) was added to LS1 powder. Cylinders made by 25% OPC and 75% LS1 sludge had gained a carbon uptake of 5% based on dry powder and a strength of 10.2 MPa. It is conclusive that LS1 lime sludge can be activated by carbon dioxide. However its reactivity is much weaker than all other materials studied in this project. With addition of OPC, the reactivity of LS1 is improved but not to a great extent. More innovative process shall be developed to make LS1 suitable to aggregate application. LS2 sludge is not carbon reactive at all.

3.3 Task 3 on production of low cost CO2 using 3H self-concentration absorption technology

Production of low cost CO_2 plays a critical role in marketing the carbon products. It is especially important for concrete products which are used in large volume and sold by low price in comparison to other carbon products. In Task 3, the work performed includes (1) Carbon capture plant design and integration of the carbon capture plant into the supercritical pulverized coal fired plant; (2) Generating the additional experimental data for design and cost analysis needed; (3) Performing an economic assessment with the plant performance and cost estimating results; (4) Comparing the cost result of 3H self-concentration absorption carbon capture technology with US DOE Baseline Case.

3.3.1 Optimization of self-concentrating absorption process

The self-concentrating absorption process is different from the conventional amine-based processes. It uses amine as activated agent, which when mixed with a special solvent forms a special self-concentrating absorbent for CO_2 capture. The absorbent, after absorbing CO_2 from flue gas in an absorber, flows into a settler where it separates into two phases: a CO2-rich phase and a CO_2-lean phase. The solvent in the CO_2-rich phase settles at the bottom of the settler, while the solvent in the CO_2-lean phase occupies the upper part of the settler. The CO_2-rich solvent is then processed in a regenerator for separating CO_2 and regenerating the absorbent. After regeneration, the effluent CO_2-lean solvent is mixed with the previously separated CO_2-lean solvent to re-combine the two CO_2-lean solvents and complete the cycle. The absorbent is characterized as self-concentrating absorbent due to its natural ability to separate the concentrated CO_2-rich phase from CO_2-lean phase. It is noted that the process is similar to a conventional MEA process with the exception of the addition of a settler for separating the two phases.

The approach used to develop the assessment of the 3H CO_2 capture technology includes:

- Modelling of the capture systems and power generation facility using the 3H pilot testing data to determine the performance of the 3H Phase Transitional Absorption system;
- Determining the equipment size of the power plant and the scale-up of 3H Company CO_2 capture system;
- Developing the capital, operational and maintenance (O&M) cost estimates based on the performance modelling;
- Performing an economic assessment with the plant performance and cost estimation results. The economic assessment is determined based on:
    - Cost of electricity (COE)
    - Levelized cost of electricity (LCOE=1.268 x COE)
    - Cost of CO_2 captured
    - Cost of CO_2 avoided
    - Increase in COE with capture over non-capture case.

The capture costs of 3H technology in DOE case 11 (without capture) and DOE case 12 (with capture using amine process) are compared. 3H technology has the advantages over Flour's technology (DOE Case 12):

- COE (cost of electricity) with capture is \$35.7/MWh less, a 24.7% reduction
- Cost of CO_2 captured is \$31.0/tonne CO_2 less, a 48.6% reduction
- Cost of CO_2 avoided is \$53.93/tonne CO_2 less, a 58.6% reduction.

With US DOE Cost Analysis Baseline, results show that 3H's carbon capture technology meets DOE's goal that requires capture cost be less than \$40 per ton CO_2 with 90% carbon capture from post combustion.

It is noted that in this comparison, the calculation of cost of electricity (COE) includes transportation, compression and monitoring (TS&M), fuel cost, variable cost (consumables, waste disposal and material maintenance), fixed cost (labour, administrative, properties, insurance) and capital cost (plant, preproduction, chemicals, land, finance). With all factors considered, the CO_2 cost is \$32.8/tCO_2 including compression, transportation, storage and monitoring.

In Subtask 3.2, 3H Company has performed parameter study on various conditions. The purpose is to determine the carbon capture system performance change with the change of the operation conditions, and/or absorbents. The parameters include CO_2 loading, CO_2 retention, and different types of amine. In conclusion, changes in several deciding factors such as CO_2 loading after absorption, CO_2 retention in lean phase after regeneration, enthalpy of reaction between Amine and CO_2, can greatly affect COE. The higher the loading of CO_2 after absorption, the lower the cost. On contrary, the high enthalpy of reaction and high CO_2 retention usually lead to high cost.

3.3.2. Full scale pilot tests of carbon capture

This parametric study is necessary for integrated system to reduce the cost of the operation. Hopefully in Phase II, there will be a chance to setup the integrated system next to the steel mill or power plant to produce aggregate nodules and their concrete products. In scale-up of the full production, the high purity CO_2 produced from 3H regenerator will be pumped into a storage tank which will be further injected into pressure tube to make aggregate nodules and the concrete products. For pure gas, static carbonation is sufficient to promote carbon uptake and strength development with minimum input energy. The integrated system eliminates the cost of gas compression, leading to a lower operation cost. Further energy reduction for integrated system is still possible by using residual heat from the system. The results can be obtained from simulation.

To prepare for the integrated system, 3H Company has performed carbon capture experiment using self-concentrating absorption technology to recover CO_2 from simulated flue gas of 15% concentration. One of the important components of this experiment is to examine if the self-concentrating absorption technology can reduce the carbon capture cost below DOE benchmark, \$40/tCO_2.

A laboratory pilot scale CO_2 capture looping system is fabricated in order to test the overall system performance of the chemical and mechanical workability and to evaluate 3H Phase Transition Absorption through small scale continuous operation of the absorption and regeneration functions. This bench scale CO_2 capture looping system will give us a better understanding technically and economically of the technology, and better prepare for a full scale working model.

Results. A bench scale CO_2 capture looping system has been built in order to test the overall system performance for post combustion CO_2 capture. 3H researchers are conducting the tests to meet the DOE (US Department of Energy) goal that 90% CO_2 captured with less than 35% cost of electricity increase. To meet DOE goal, one of the most important cost saving is in the reduction of operation energy consumption.

The captured CO_2 concentration is highly related to the condensation temperature of the gas released from regeneration cell since the gas from regeneration cell is the mixture of CO_2 and moisture. When the condensation temperature is 25 ^oC, the CO_2 concentration can reach about 97% balanced by H_2O. If the condensation temperature can be reduced below 10 ^oC, CO_2 concentration of over 99% can be obtained. Therefore the use of commercial gas with 99.5% purity can simulate the recovered carbon dioxide produced by 3H technology.

3.3.3 Integrated system and use of residual heat to cut cost

In Part III, 3H conducted the techno-economic analysis for the flue gas which will integrate 3H process into carbon utilization through concrete and/or aggregates production. The conditions of the flue gas are provided by McGill University. 3H Company has performed the integrated system process design, conducted energy and material balances, and performed the process flow modeling of the capture system. The utility (steam, electricity, and cooling water) requirements for the system and the related equipment list and sizes based on its pilot testing data are presented and the cost of the integrated system with the capacity of 2 ton CO_2/day are analyzed. The size and daily capacity of CO_2 capture are selected based on phase II project budget.

Three cases were studied in order to minimize the energy consumption. The condition for each step is given as follows.

Flue Gas Inlet Conditions. In the Process as described by McGill University team, the flue gas exits from the FGD at the temperature of 200°C. CO_2 molar concentration is around 14.80%. The total amount of flue gas exiting is 389.36 kg/h.

Cooling of the flue gas. The hot 200°C flue gas enters a heat exchanger where it will be cooled down to 60°C in order to recover the heat from flue gas. After that, the flue gas enters a direct contact cooler and exists at 33.45°C saturated.

Flue Gas Blower. Flue gas from direct cooler enters blowers and exists at 42°C, unsaturated.

CO_2 Absorption. The absorption section operation used the non-aqueous, phase-separating technology. The flue gas enters at the bottom of the column and reacts with the countercurrent solvent liquid flow. The reaction is exothermic. The solvent is the mixture of amine and solvent. After absorption, the absorbent separates into two phase, CO_2 rich phase and CO_2 lean phase.

CO_2 Regeneration. The outlet CO_2-rich phase from the column is cross exchanged in a plate and frame heat exchanger with the inlet hot flue gas of 200°C. The rich phase is then pre-heated again in a plate and frame heat exchanger with regenerated amine. The temperature of the phase will increase nearly to the regeneration temperature. The hot phase will be then passed to another heat exchanger, where the phase temperature will be brought to regeneration temperature and pressure. The regeneration process operates and produces very little amount of liquid vaporization, mainly water.

Mixing and Cooling. The CO_2 lean phase from absorption column and the lean amine enter the mixer. The components are mixed with medium agitation. The outlet mixed absorbent leaves the tank at 46°C. Then it will be cooled down to 40°C in a plate and frame heat exchanger with cold water and pumped back to the top of the absorption column.

Integrated with CO_2 Utilization Plant. The CO_2 gas is then enter air blower and has it pressure increase from 1 atm to 2 atm to cure the concrete.

Based on the above listed conditions, the energy consumption and equipment cost to capture 2 ton CO_2/day is estimated. From the system analysis, it can be concluded that 3H technology has more advantages compared to Ecoamine technology. The total amount of CO_2 gas the system can capture is 78. 25 kg/hour. For a day, the system can capture 1,878 kg. The total cost of equipment is estimated at around $300,000. The results of steam requirement for the integrated system is 1 – 1.2 GJ/ton CO_2 captured, which is much lower than 1.5-1.6 GJ/tCO_2 that claimed by other processes. CO_2 retention in lean phase after regeneration, enthalpy of reaction between Amine and CO_2, and water retention in lean phase after absorption can greatly affect the size of the equipment, hence the cost of the equipment, the cost of the installation, and finally the total cost. The higher the loading of CO_2 after absorption, the lower the total cost. In contrary, the higher the water retention, the enthalpy of reaction and the CO_2 retention are, the higher the total cost is.

4. Greenhouse Gas and NON GHG Impacts

4.1 GHG benefits

Summary. The carbon utilization capacity by cement binder is different depending on types of concretes. For concrete blocks, its uptake is in the range between 15 to 25% based on cement mass, equivalent to a CO_2 content of 40 kg/m^3 concrete. For reinforced precast concrete products, such as pipes and slabs, it is about 11 to 16%, equivalent to a CO_2 content of 72 kg/m^3 concrete. Obviously CO_2 per m^3 concrete is higher in reinforced concrete products than in blocks because the blocks have only 10-13% cement while the precast reinforced concretes use up to 20% cement. Reinforced precast concrete products have the capacity to utilize more carbon dioxide.

The carbon utilization capacity by aggregates in concretes is dependent on the material. It is assumed that normal weight concrete has the density of 2200 kg/m^3 and contains 80% aggregates by mass of concrete. The carbon uptake was 17% in KOBM slag, 10% in waste cement, 20% in APC residue and 5% in lime sludge. The equivalent CO_2 content per unit volume of concrete was respectively 300, 183, 352 and 88 kg/m^3 concrete. Aggregates have much higher capacity to store carbon dioxide than the cement binder. The challenge is that not all aggregates are strong enough to serve as structural materials and that not enough carbon-reactive raw feedstock is readily available for this type of application.

Immediate benefit for GHG reduction can be gained from block production. Assuming annual block production in Alberta is 5 million units. The standard block has a dimension of 20x10x10 cm (20-cm block or 8" block) and has a mass of 18 kg. It contains 10% cement binder and 80% aggregates. Based on laboratory tests, each block can uptake 2.93 kg of CO2 including 0.46 kg in cement binder and 2.47 kg of CO2 in aggregates. It is obvious that aggregates play more critical role in maximizing the carbon utilization capacity in blocks. The total carbon utilization by Alberta block industry is about 14650 t CO2 per year. The concrete block market in Alberta is not large enough to consume 1 Mt CO_2/year. However this is the immediate GHG benefit and can be implemented right after the phase I project.

Benefit in next ten years. More precast concrete products shall be considered for carbon use and storage. Assuming 25% cement will be used by precast products, it is about 0.5 Mt cement per year. Since Alberta block industry has used 0.009 Mt cement, the remaining of 0.491 Mt cement will be available for other precast products such as concrete paving stones, veneers, bricks and retaining wall systems. Other precast products such as concrete pipes, piles, hollow core slabs, and railway ties are also readily available to accept carbonation process. Moreover general precast for precast structures can also be carbon treated. For 0.491 Mt cement per year, it will produce 3.27 Mt concrete that requires 2.62 Mt aggregates, assuming the typical ratio of concrete is cement : aggregate : water = 1:5:0.5. The cement counts 15% and aggregates 80% by mass. (1) If the 0.491 Mt of cement in precast products can absorb CO_2 at 20% uptake rate based on cement mass, concrete carbonation can take 0.098 Mt CO_2/year. (2) If carbonate aggregates in concretes is also used to take CO_2, the 2.62 Mt aggregates will consume 0.52 Mt CO_2/year at 20% uptake rate by aggregate mass. The contribution to carbon utilization is much higher by aggregates than by cement matrix because the mass ratio of aggregates in concrete is higher. The total carbon dioxide consumption by both blocks and other precast is 0.015 Mt + 0.098 Mt +0.52 Mt = 0.633Mt per year. This is the contribution by the Alberta precast concrete industry and is expected to happen in next 10 years period.

Benefit in future. With all precast used for utilization, it is still not enough to reach the target of 1 million ton CO_2 per year. The extra 0.4 Mt CO_2 needs to be considered. It can be accomplished through the aggregate carbonation for general ready mix concrete application. The Alberta ready mix concrete consumes 1.5 Mt cement. Its corresponding concrete mass is about 10 Mt per year (assuming cement mass counts 15% of concrete mass) and the corresponding aggregate mass is about 8 Mt. To achieve carbon utilization of 0.4 Mt, it only requires 2 Mt aggregates to be manufactured from calcium rich industry wastes at 20% carbon uptake rate.

4.2 Non-GHG benefits

- Concrete products can be made cheaper by using carbon dioxide curing in comparison to steam curing with the low cost CO_2.
- Concrete products produced by carbon dioxide curing can have much improved resistance to sulfate attack, chloride penetration, water permeation, freeze thaw damage, efflorescence formation, weathering carbonation. Carbonated concrete products have shown better durability and longer service life.

5. Overall Conclusions

It is challenging to develop a commercial product that can consume 1 Mt CO_2 per year. Concrete is the most used man-made material on the Earth and is an excellent candidate product for carbon capture and utilization. No other materials can compete with concrete by mass. It is proven that both aggregate and concrete can be carbonation treated to store carbon dioxide as carbonate bond materials. Carbonated concretes have shown higher early strength, better durability, and can be made cheaper using low cost carbon capture technology. Since aggregates count more than 80% by mass in concrete, the contribution by aggregate carbonation is more significant than that by concrete carbonation through cement binder.

Concrete blocks are readily available for carbonation process. Since there is no steel reinforcement, degree of carbonation can be maximized with no detrimental effect. Based on laboratory and full scale tests, one standard 20-cm block can uptake 0.46kg CO_2 by cement binder and 2.47 kg CO_2 by artificial aggregates, totaling a carbon uptake of 2.93 k per unit. Alberta block industry can consume 14650 t CO_2 (=0.0146 Mt CO_2) every year.

All other precast concrete products can also be carbonation processed. Concrete carbonation shall be controlled within 10-20% carbon uptake to avoid carbonation corrosion. Relatively aggregates play more critical roles in carbon utilization capacity. This precast product sector can take 0.618 Mt CO_2 per year.

Even all precast products are considered, there are still not enough concrete products to consume 1 Mt carbon dioxide per year. Ready mix concrete has to be used. In this case, carbonate aggregates will be fully employed to store carbon dioxide for ready mix concrete.

We have successfully made carbonate aggregates out of steel slag. Carbonate aggregates so made are strong and durable for both precast and ready mix concretes. The challenge is Alberta doesn't have enough steel slag for this application. It has to be imported from other provinces and states.

Laboratory tests have shown that waste cement powder from cement building product (such as cement board and cement fiber board) recycling can be good candidate for making aggregates by carbonation. However in concrete recycling business, there is no such waste cement powder for the use. Recycled concrete was examined for it capacity. The fine powder collected from recycled concrete is basically sand which is not reactive with carbon.

Air pollution control (APC) residue from municipal solid waste (MSW) incineration is a lime-rich waste material, and can be used to make aggregates. Lightweight APC aggregates were successfully made with carbon uptake capacity of 20% by mass. The individual aggregate can have comparable load capacity as commercial products. However its concrete was weak. It was indicative that the aggregates produced were not uniform. Some of them were strong and some weak. More work is necessary to develop innovative mix design to improve the strength of the APC aggregates. Although there is no MSW incinerator in Alberta right now, a few of them are in planning. One on-going project is run by Southern Alberta Energy from Waste Association (SAEFWA). They are planning an incinerator of 366,000 ton per year. At least 36,000 ton of APC will be produced and can be used for aggregates for carbon storage.

Lime sludge was tested for its capacity to store carbon dioxide and make structural aggregates. In one facility, annual production is about 18,000 ton. Currently they are landfilled. The results had shown that lime sludge with high CaO content was carbon reactive and could develop strength. However the reactivity was weak and the strength was not enough for structural aggregate application. Innovative process is needed to make lime sludge more reactive.

This project is special in that carbon capture is also included. 40% budget was used to develop low cost carbon dioxide for concrete uses. Although it is not required by this Round One innovative carbon uses project, it is believed that low cost CO_2 is essential for carbon utilization in concrete production. 3H self-concentrating absorption technology was optimized to reduce the energy cost including the utilization of residual heat from hot flue gas for regeneration. The energy consumption for 3H technology is in the range of 1-1.2 GJ/t CO_2 captured. It is lower than 1.5-1.6 GJ/t CO_2 which was claimed by other company. Using the same calculation method by other company, 3H technology can recover high purity CO_2 at about $10-20 per ton. For $20/ton CO_2, it is equivalent to $0.02/kg. If one 20-cm block can uptake 0.4 kg CO_2 by carbonation curing of cement binder, the cost is about $0.008 per block, which is much cheaper than the steam curing ($0.05-0.1/block).

An integrated system was designed and cost analysis was performed by 3H Company. Integrated system will connect CO_2 capture to CO_2 utilization on the same site so that the compression and transportation of gas can be avoided. With residual heat utilization, the capital cost for the equipment was only $300,000 for daily capacity of 2 ton CO_2. This is an excellent case study for CCEMC Round Two pilot tests.

6. Scientific Achievements

Peer review journal publications:

1. Zhang, Duo and Shao, Y. (2016), "Early age carbonation curing for precast reinforced concretes", Construction and Building Materials, 113, 134-143
2. Zhang, Duo, Cai, X and Shao, Y. (2016), "Carbonation curing of precast fly ash concrete", ASCE J of Materials in Civil Engineering, accepted, DOI: 10.1061/(ASCE)MT.1943-15 5533.0001649.
3. Zhang, Duo and Shao, Y. (2016), "Effect of early carbonation curing on chloride penetration and weathering carbonation in concrete", submitted to Construction and Building Materials, March.
4. Zhang, Duo and Shao, Y. (2016), "Pore structure of cementitious pastes subject to carbonation curing and its effect on concrete performance", submitted to Cement and Concrete Research, February
5. Zhang, S., Ghouleh, Z. and shao Y. (2016), "Effect of carbonation cuing on efflorescence formation in concrete", to be submitted to Journal of Materials in Civil Engineering.
6. Lerigoleur, E., Ghouleh, Z. and Shao, Y. (2016), "Carbonation reaction vs pozzolanic reaction in concrete masonry blocks", to be submitted to ACI Materials Journal.
7. Liu, T., Zhang, D. and Shao, Y. (2016), "Effect of early carbonation on carbonation depth in concrete subject to weathering carbonation", to be submitted to Construction and Building Materials

Patent on steel slag carbonation

- Shao, Y, Mahoutian, M., Ghouleh, Z. (2015) "Carbonate-bonded construction products from steel-making residues and method for making the same", US Provisional patent 61/968,991, and Patent Cooperation Treaty (PCT) international patent application, date filed: March 23, 2015.

Thesis:

1. Zhang, S. (2016), M. Eng. Thesis, Effect of carbonation curing on the efflorescence formation in concrete
2. Liu, T. (2016), M Eng. thesis, Effect of early carbonation on concrete resistance to weathering carbonation
3. Zhang, D. (2016), PhD thesis, Performance Evaluation of Precast Reinforced Concrete after Early-Age Carbonation Curing

7. Next Steps

The team is working with Lehigh-Hanson cement plant in Edmonton, Alberta, to set up pilot test using the integrated system. Lehigh-Hanson plant is a perfect site for this pilot test. The company produces cement and at the same time makes concrete pipes. We will setup the carbon capture device at cement kiln to capture 2 ton CO_2 a day and use it in concrete pipe production. The results produced from this phase I project on reinforced concrete can be applied to this case. Currently the concrete pipes are produced using steam curing. With low cost CO_2, the carbonation curing will be very competitive. In addition, carbonated concrete pipes can have comparable strength and better durability. The concrete resistance to thaumasite sulfate attack and freeze-thaw cycling damage will be significantly enhanced by carbonation.

More research is needed to convert more calcium rich wastes into construction products. The team will do its best to make the lime sludge collected from oil refinery process a value- added aggregate product. The team is still searching for new calcium based waste materials for aggregate applications. The cost analysis will be performed to examine the economic feasibility of carbonate aggregates. Since natural aggregates are cheap, it is challenging if carbonate aggregates can be made economically competitive. It is also crucial for reaching the target of 1 Mt CO_2 a year. Without aggregates, the maximum carbon uptake in concrete carbonation is about 0.1 Mt (=0.5 Mt cement/year x 20% CO_2 uptake), only one tenth of the target. More calcium-rich waste-driven feedstocks will be needed in Alberta.

8. Communication Plans

We are talking with interesting partners on the collaboration. Lehigh-Hanson cement is excellent partner for Round Two pilot project. Sludge lime company (name is confidential) is interested if the carbonation process can make their waste material a useful product to avoid landfill. We did not do presentation at any public conferences.