Application of Carbon Capture and Sequestration Technologies in Transportation Infrastructure Construction Materials

Requested by
Jacquelyn Wong, Office of Structural Materials

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Table of Contents

Executive Summary

Background

The use of carbon capture and sequestration (CCS) technologies to produce industrial materials, such as concrete and asphalt aggregate, has the potential to reduce greenhouse gas emissions related to transportation infrastructure construction activities. The CCS technologies of interest to Caltrans use CO_2 as a raw material for making carbonate rocks that are used in place of natural aggregate or inject liquefied CO_2 into construction material. Caltrans' interest in this project does not extend to carbonation-cured concrete or the use of fly ash and slag to produce construction materials. These construction materials and methods are currently being explored by Caltrans in other projects and are outside the scope of this Preliminary Investigation.

Caltrans is interested in exploring the commercial options for use of these CCS technologies, and the availability of CCS-based materials to complete large-scale transportation infrastructure projects. Also of interest are the environmental impacts of these materials, and their cost and performance as compared to traditional construction materials. To gather this information, CTC & Associates reviewed published research and research in progress, consulted with representatives from technology companies and concrete producers, and surveyed departments of transportation (DOTs) to identify agencies with practical experience with these materials applied in the field.

Summary of Findings

Our research identified commercial and research efforts that have produced the types of CCS-based construction materials of interest to Caltrans. However, at the time of publication, we found no reported applications of these materials on large-scale transportation infrastructure projects in the field. However, this type of use appears to be on the horizon. Findings are summarized in the topic areas below:

- CCS-based companies and research groups.
- Other related resources.
- Survey of state practice.

CCS-Based Companies and Research Groups

Below is a summary of the CCS-based companies and research groups described in more detail in this Preliminary Investigation.

Blue Planet Ltd.

Using unpurified CO_2 absorbed directly from power plant flue gas or other industrial CO_2 emission sources, California-based Blue Planet's technology combines that captured CO_2 with metal oxide(s) like calcium oxide sourced from industrial/construction waste material(s) to form carbonate minerals (limestone). A substrate is then coated with this limestone to produce a CO_2-sequestered construction aggregate for use in concrete. The limestone coating is 44 percent by mass permanently sequestered CO_2 waste.

Blue Planet's technology can produce a range of ASTM-compliant products, including lightweight, standard weight and high-strength limestone-coated aggregates; supplementary cementitious materials; and remediated recycled concrete aggregates. Small batches of material are being produced in the company's lab-based pilot line. The company is developing a larger production facility in the San Francisco Bay Area that will automate production of up to 70,000 tons per year of coated lightweight aggregate and up to 500,000 tons per year of remediated recycled concrete aggregates (coarse and fine). This facility is scheduled to break ground in several months. Blue Planet's limestone-coated lightweight aggregates were used in a commercial placement of lightweight concrete at San Francisco International Airport in 2016.

CarbonCure Technologies Inc.

CarbonCure, a Canadian company, uses CO_2 captured from emissions that has been purified and liquefied, and delivered to partner concrete producer plants in pressurized tanks. CarbonCure technology injects the recycled CO_2 into wet concrete while it's being mixed. The company's primary products are masonry blocks and ready-mixed materials. The ready-mixed product is a poured—not precast—concrete.

In January 2018, CarbonCure was nearing completion of its 100th concrete plant retrofit in North America. Two California concrete producers—Central Concrete Supply Company Inc. and Outback Materials—are working with CarbonCure to retrofit production facilities that can provide CarbonCure ready-mixed materials. Outback Materials has contracted to provide CarbonCure materials for the California High-Speed Rail (CHSR) project. Central Concrete will use materials for smaller-batch projects in the near term as it scales up its CarbonCure process; larger-scale projects are expected next year. CarbonCure's marketing and communications director noted that the company has had discussions with interested parties in the Midwest that might lead to the use of CarbonCure ready-mixed materials in transportation infrastructure projects.

Mineral Carbonation International

Mineral Carbonation International (MCi) has developed a process that "reacts captured CO_2 with quarried low-grade minerals in a continuous industrial process." The company recently launched a pilot plant in Australia to develop "new low-carbon building materials with partners globally." The company is primarily focused on developing carbonate-based products using CO_2 and low-grade minerals and wastes as feedstock. MCi's development efforts are moving its technology toward "industrial demonstration."

Calera Corporation

Calera's production process removes the CO_2 and a calcium source from flue gas from power plants and burning coal to form "a special calcium carbonate product that is then dried to a free-flowing powder. This powder can then be used to make products, like boards, because of the special cementing nature of the calcium carbonate." Products made with Calera's calcium carbonate cement include decorative concrete products such as countertops, plant holders and benches, and fiber cement board sheets.

Note: The two groups described below are finalists for the Carbon XPRIZE, a $20 million global competition that "challenges teams to transform the way the world addresses carbon dioxide (CO_2) emissions through breakthrough circular carbon technologies that convert carbon dioxide emissions from power plants into valuable products." CarbonCure Technologies Inc. is also among the 10 finalists for the Carbon XPRIZE.

See page 16 of this Preliminary Investigation for more information about the Carbon XPRIZE competition.

Carbon Upcycling UCLA

Carbon Upcycling UCLA, a University of California, Los Angeles research group, uses carbon upcycling to fabricate CO_2NCRETE, a near CO_2-neutral construction material. The process uses flue gas exhausted from power plants or cement plants "by efficiently recovering waste heat and enriching CO_2 present in the gas stream. A novel binder system based on calcium hydroxide (hydrated lime) is mixed with aggregates and admixtures to form a shape-stabilized CO_2NCRETE building element. The final and key step lies in combining the captured CO_2 with CO_2NCRETE element via a carbonation reaction (i.e., CO_2-mineralization) to form a solid building component."

The project team is seeking funds to support the lab-scale proof of concept, which is expected to be completed in approximately 18 months. After completing the proof of concept, the technology could be commercialized over the following five to seven years.

Carbon Capture Machine

Carbon Capture Machine markets a proprietary technology developed at the University of Aberdeen (Scotland) that "dissolves combustion CO_2 from any source in dilute alkali, converting it to carbonate ions with efficiency approaching 100%. The carbonate solution is reacted with readily and abundantly available calcium (Ca++) and magnesium (Mg++) brines to selectively precipitate $CaCO_3$ (Precipitated Calcium Carbonate, PCC) and MgCO3·3H2O (Precipitated Magnesium Carbonate, PMC)." A multistage precipitation technology is used to separate and produce nearly insoluble Ca and Mg carbonate minerals that have useful properties. The resulting conversion products are "carbon negative, high value feedstocks that are in demand across many industries," and are currently used in papermaking, plastics, paints and adhesives; future applications in cement and concrete are under development.

Other Related Resources

We provide a small sample of recent publications that consider the use of CCS technologies to produce carbonate rocks or the use of CO_2 in the production of construction materials. (Many more publications are available that examine CCS-related processes that are not the focus of this Preliminary Investigation.) White papers and journal articles produced by CarbonCure staff members describe the company's research and case study results. Other publications examine carbon capture technologies more generally, reviewing the leading CO_2 capture technologies and assessing their maturity, and consider specific processes such as mineralization and use of alkaline industrial wastes.

Survey of State Practice

An online survey distributed to members of the AASHTO Committee on Construction sought to identify agencies with practical experience with CCS-based materials applied in the field. None of the 13 state DOTs responding to the survey reported on experience with or are considering the use of CCS-based construction materials.

Gaps in Findings

The technology needed to produce CCS-based materials is maturing, and in several cases research processes have been commercialized. At this time, however, use of these materials in transportation infrastructure applications appears to be quite limited. For some companies, CCS-based materials are not yet available in sufficient quantity for large-scale projects, though a new production facility is planned for later this year (Blue Planet), while for others, CCS-based materials are expected to be used for a current project (CarbonCure materials will be used on the CHSR project).

It appears that more time is needed for commercially available CCS-based materials to be used in larger quantities and with greater frequency in the field. Once larger-scale use is more common, data can be collected on the cost, performance and environmental impact of CCS-based materials to allow for a comparison with traditional construction materials.

Next Steps

Moving forward in the short term, Caltrans could consider:

- Consulting with the leaders of the companies and research groups described in this Preliminary Investigation to learn more about each technology and plans for use of the CCS-based materials in the field. Related inquiries might address:
    - Blue Planet's new production facility and the availability of its carbon-coated lightweight aggregate for large-scale projects.
    - CarbonCure's contacts with concrete producers and transportation agencies in connection with use of its ready-mixed product on larger-scale transportation infrastructure projects.
- Contacting Outback Materials to learn more about the company's plans to install CarbonCure materials on the CHSR construction project.

In connection with a longer-term assessment, Caltrans could consider:

- Contacting the Carbon Upcycling UCLA research group to discuss the group's plans for a proof of concept and long-term commercialization efforts.
- Consulting with Central Concrete Supply Company to learn more about the company's expected use of smaller-batch CarbonCure materials and expectations for larger-scale projects that will use CarbonCure materials in 2019.
- Following the progress of the Carbon XPRIZE competition to track the latest developments in "circular carbon technologies that convert carbon dioxide emissions from power plants into valuable products."

Detailed Findings

Background

The use of carbon capture and sequestration (CCS) technologies to produce industrial materials, such as concrete and asphalt aggregate, has the potential to reduce greenhouse gas emissions related to transportation infrastructure construction activities. For this Preliminary Investigation, the CCS technologies of interest to Caltrans use CO_2 as a raw material for making carbonate rocks that are used in place of natural aggregate or inject liquefied CO_2 into construction material. Caltrans' interest does not extend to carbonation-cured concrete or the use of fly ash and slag to produce construction materials. These materials and methods are under review by Caltrans in other projects.

Caltrans is interested in exploring the environmental benefits of these CCS technologies and commercial options for their use. Caltrans is also interested in determining whether CCS-based construction materials can be produced in the quantities necessary for large-scale transportation infrastructure projects, as well as their cost and performance relative to conventional construction materials.

To gather information for this Preliminary Investigation, CTC & Associates consulted with private sector contacts who have experience with CCS-based construction materials, reviewed research on the CCS technologies used to produce construction materials that could be used in transportation infrastructure projects, and conducted a survey of state departments of transportation (DOTs) to identify agencies that have experience with construction materials produced using CCS technologies. Findings are summarized below in four topic areas:

- Selected CCS-based technology companies.
- Carbon XPRIZE competitors. (The Carbon XPRIZE global competition incentivizes research that "develop[s] breakthrough technologies that will convert CO_2 emissions from power plants and industrial facilities into valuable products like building materials, alternative fuels and other items that we use every day.")
- Other related resources.
- Survey of state practice. (None of the 13 state DOTS responding to the survey reported experience with or are considering use of CCS-based materials.)

Selected CCS-Based Technology Companies

Below are brief case studies of selected companies developing technology to produce CCS-based materials:

- Blue Planet Ltd.
- CarbonCure Technologies Inc.
- Mineral Carbonation International.
- Calera Corporation.

When available, the results of interviews with company representatives and other individuals familiar with the companies' products and processes supplement the information gathered using publicly available sources.

Blue Planet Ltd.

We spoke with Ken Hines, Blue Planet's vice president of business development and licensing, to learn more about the company's products, business model and plans for the future. We also contacted representatives from Central Concrete Supply Company Inc. and San Francisco International Airport (SFO) to learn more about a placement of concrete using Blue Planet material that was installed at the airport in May 2016.

Product Description

Blue Planet's technology can produce a range of products:

Limestone-coated aggregate. Blue Planet takes CO_2 from power plant flue gas or other industrial CO_2 emission sources and combines that captured CO_2 with metal oxide(s) (for example, calcium oxide) sourced from industrial/construction waste materials (for example, demolished or returned concrete) to form carbonate minerals (limestone). A substrate is then coated with this limestone to produce CO_2-sequestered construction aggregates, which are used in a wide range of minor, structural and lightweight concrete mix designs. Unlike other carbon capture and use technologies, Blue Planet captures the CO_2 in dilute form and does not need to purify the CO_2 used in its production process. The company's limestone coating is 44 percent by mass sequestered CO_2 waste. The aggregates meet ASTM specifications for lightweight or standard weight aggregates (based on the substrate type used) and can be produced in sizes ranging from sand-sized to gravel-sized, along with a range of coating thicknesses. The company's web site indicates that "the use of Blue Planet coated aggregates is the most effective way to achieve carbon neutral and carbon negative concrete."

Remediated recycled concrete. Blue Planet's process uses common rock waste and/or other industrial waste materials that contain the alkalinity and calcium oxides needed to produce its coated products. One readily available waste material is returned concrete (left over from a batch delivery) from ready-mix concrete suppliers or demolished concrete from construction demolition. Using this as a waste material input generates two products—the primary product, using the calcium oxide for the limestone-coated aggregate(s), and a remediated concrete aggregate.

Current Practices

Blue Planet is using a low-volume, semiautomated pilot line in its Los Gatos, California, facility to produce small batches of carbon-coated material using bottled CO_2 as well as remediated recycled concrete aggregates. Hines reported on plans to break ground in the next several months to build a larger facility in Pittsburg, California (located in the East Bay region of the San Francisco Bay Area), that will significantly scale up material production. Initial material production is expected in late 2018 with full-capacity operation, capable of producing up to 70,000 tons per year of coated lightweight aggregate and up to 500,000 tons per year of remediated recycled concrete aggregates (coarse and fine), in mid-2019.

Hines noted that coated lightweight aggregate can be shipped farther to market at a lower cost than the heavier remediated recycled concrete aggregates. Given shipping costs, recycled material may have a greater appeal and competitive costs in local markets (in close proximity to a Blue Planet plant) as opposed to the coated lightweight aggregates that may travel farther. The remediated recycled concrete produced as a by-product is currently undergoing extensive testing to determine its usefulness beyond minor concrete mixes in replacing virgin aggregates in structural applications. Testing also continues to determine the optimal concrete mix designs using various products.

Business Model

Blue Planet intends to license its technology on a worldwide basis into a wide range of Blue Planet plant ownership structures and does not necessarily intend to own and operate most production facilities (other than the facility soon to be constructed). Instead, Blue Planet will facilitate the efforts of concrete producers, among other construction material companies, to develop and own their plants at a given location(s). Those parties interested in owning/operating a plant can work with Blue Planet to identify the ideal location, including the source for the CO_2 and the waste material (for example, demolished concrete) that will be used to extract the metal oxide(s) needed to produce the limestone coating and products to be produced. The owner/operator will license Blue Planet’s patented technology and can also retain the services of Blue Planet to assist with development of the production facility and the desired product from Blue Planet’s menu of products:

- Lightweight and/or standard weight coated aggregates (properties of the aggregate can vary based on substrate used, as can the amount of coating).
- Remediated recycled concrete. *Note*: If another waste material other than returned or demolished concrete is used as the source of metal oxide(s), the remediated product may possibly be used as a supplementary cementitious material (SCM) or other construction filler material.
- Carbonate precipitate (similar to interground limestone, this is the material that didn’t stick to the aggregate during the coating process) may be used as a CO_2-sequestered SCM.

Once a producer’s plant begins operations, the plant owner will pay a royalty on all Blue Planet product sales.

Field Application: San Francisco International Airport Project (Central Concrete Supply Company Inc.)

In May 2016, working in collaboration with the primary contractor, Turner Construction Company, Central Concrete Supply Company Inc. provided the concrete for installation of 40 total yards (the original quote specified 90 yards) of concrete to construct an atrium deck for pedestrians at SFO, where Blue Planet's carbon-sequestered, lightweight carbon-coated aggregate was specified by SFO architects and engineers at 5 percent minimum of the overall coarse aggregate used in the concrete mix (617 pounds of noncoated coarse aggregate and 32 pounds of coated aggregate per yard of concrete). The lightweight carbon-coated material was soaked in water prior to application.

To date, the SFO placement is the only field application of Blue Planet's lightweight carbon-coated aggregate. SFO's planning director is unaware of the project and unable to provide any details of the concrete installation or its durability over time.

Field Application: Future Uses (Central Concrete Supply Company Inc.)

Juan Gonzalez, Central Concrete's sustainability manager, indicated interest in using Blue Planet's coated aggregate, but the company is waiting for completion of the Blue Planet production facility to assess use of the product in the field. Gonzalez also reported interest in Blue Planet's recycled concrete by-product, though noted that completion of the proof of concept, including industry certification, is needed to use Blue Planet's recycled material as a substitute for virgin aggregate. Central Concrete and other concrete producers could also provide the waste returned concrete material Blue Planet needs for its carbonate production process.

Related Resources

Technology, *Blue Planet: Economically Sustainable Carbon Capture*, Blue Planet Ltd., 2015.
http://www.blueplanet-ltd.com/#technology
From the web site:

> **Unique, Efficient & Low-cost Carbon Capture Method**
> Blue Planet's technology uses CO_2 as a raw material for making carbonate rocks. The carbonate rocks produced are used in place of natural limestone rock mined from quarries, which is the principal component of concrete. CO_2 from flue gas is converted to carbonate (or CO3=) by contacting CO_2 containing gas with a water-based capture solutions. This differentiates Blue Planet from most CO_2 capture methods because the captured CO_2 does not require a purification step, which is an energy and capital intensive process. As a result Blue Planet's capture method is extremely efficient, and results in a lower cost than traditional methods of CO_2 capture.

"Turning CO_2 Into Concrete," Jeff O'Heir, *Mechanical Engineering: The Journal of the American Society of Mechanical Engineers*, Vol. 138, No. 8, page 24, August 2016.
Article excerpt at https://www.highbeam.com/doc/1P3-4233226621.html
This article provides a brief description of the May 2016 SFO test patch that used Blue Planet material.

Contacts

Ken Hines, Vice President, Business Development and Licensing, Blue Planet Ltd., 650-823-8355, khines@blueplanet-ltd.com.

John Bergener, Airport Planning Director, San Francisco International Airport, 650-821-7867, john.bergener@flysfo.com.

Juan (Johnny) Gonzalez, Sustainability Manager, Operations, Central Concrete Supply Company Inc., 408-771-6261, jgonzalez@us-concrete.com.

CarbonCure Technologies Inc.

We spoke with Alanna Komisar, CarbonCure's director of marketing and communications, about the company's technology and products. (Komisar was no longer with CarbonCure at the time of publication. Contact information for Christie Gamble, CarbonCure's current director of marketing, is provided on page 13.) We also spoke with Juan Gonzalez to learn more about Central Concrete Supply Company Inc.'s plans to produce CarbonCure ready-mixed materials.

Product Description

CarbonCure's process uses CO_2 captured from emissions that has been purified and liquefied and delivered to partner concrete producer plants in pressurized tanks. As the company's web site indicates, the "CarbonCure technology precisely injects the recycled CO_2 into wet concrete while it's being mixed. Once injected, the CO_2 becomes chemically converted into a solid mineral and permanently captured within the concrete."

The company's primary products are masonry blocks and ready-mixed materials. CarbonCure's masonry blocks have been used to construct commercial buildings and schools and for residential construction. The ready-mixed product is a poured—not precast—concrete.

An online FAQ (see http://carboncure.com/faq/#unique-identifier7) indicates that "use of the CarbonCure system can result in an offset of roughly 5% of the carbon emissions associated with concrete's manufacture. This benefit is gained by introducing a small amount of CO_2 in concrete to increase the materials' early strength, which creates an opportunity for producers to optimize their concrete mixes—this may include reducing the cement content, or increasing the use of cement alternatives such as fly ash or slag."

Current Practices

CarbonCure's initial focus was on the production of masonry blocks. In 2015, the company began using its technology to produce ready-mixed concrete that could be used in transportation infrastructure projects. Komisar noted that the company has had discussions with interested parties in the Midwest that might lead to use of CarbonCure ready-mixed materials in transportation infrastructure projects. In January 2018, the company was nearing completion of its 100th concrete plant retrofit in North America. Two California concrete producers—Central Concrete and Outback Materials—are working with CarbonCure to retrofit production facilities that can provide CarbonCure ready-mixed materials.

Business Model

CarbonCure provides customized solutions for small- and large-scale production facilities. Production costs will vary based on CO_2 prices. A recent CarbonCure press release (see http://info.carboncure.com/press/cleantech-top-100-2018) describes the company's business model:

> The proprietary CarbonCure technology is licensed without CAPEX [capital expenditure] to concrete producers to recycle waste carbon dioxide (CO_2) into concrete. The CO_2 is sourced from local industrial emitters and injected into concrete during production.

CarbonCure's technology system, its components and how the technology can be integrated into a production facility are addressed in a CarbonCure white paper available at http://info.carboncure.com/white-papers/ready-mixed-technology-system.

Field Application: California High-Speed Rail Project (Outback Materials)

CarbonCure is working with the California concrete supplier Outback Materials to provide carbon-coated concrete for the California High-Speed Rail (CHSR) project. CarbonCure provided the necessary equipment for installation in Outback Materials' Fresno plant to chemically sequester waste CO_2 in fresh concrete during the manufacturing process (an injection process is completed before the mix is loaded on trucks). Outback Materials is expected to provide ready-mixed concrete for the CHSR project's Construction Package 1.

Outback Materials was expected to supply 450,000 cubic yards of concrete for the first sections of the project, which is part of a 29-mile-long segment with 25 concrete structures. A November 2017 online news article describing plans for the use of CarbonCure material on the CHSR project did not indicate what portion of the 450,000 cubic yards of concrete supplied by Outback Materials will be CarbonCure material, but did note that use of CarbonCure material is projected to offset more than 3,000 tons of CO_2 emissions across the Construction Package 1 concrete schedule. In a July 2017 press release, CarbonCure's chief executive officer, Robert Niven, said that "[i]f CarbonCure's technology were used to produce the concrete for the rest of the first construction package, spanning from Madera to Fresno, the carbon reductions would be equivalent to the amount of CO_2 consumed by 3,200 acres of American forest over a year."

Margaret Cederoth, sustainability manager for the CHSR project, indicated during a January 16, 2018, CHSR board meeting that Outback Materials "has been studying the use of CarbonCure" (see page 53 of the transcript of proceedings available at http://www.hsr.ca.gov/docs/brdmeetings/2018/brdmtg_011618_Board_Meeting_Transcript.pdf). At the time of publication, we were unable to connect with representatives from Outback Materials to learn more about the use of CarbonCure material on the CHSR job site.

Field Application: Future Uses (Central Concrete Supply Company Inc.)

Central Concrete has entered into a contract with CarbonCure to retrofit five or six of its wet ready-mixed concrete plants (also referred to as "wet concrete batch plants") with CarbonCure computers, tanks and other equipment needed to load and unload CO_2 into the plants' drum mixers. The CO_2-enriched mix will then be loaded onto delivery trucks. The company expects to complete smaller jobs using CarbonCure materials over the next six months as it scales up its CarbonCure work process. Larger-scale projects using CarbonCure materials are expected in 2019.

Related Resources

Technology, CarbonCure Technologies Inc., 2018.
http://carboncure.com/technology/
From the web site:

> **How does the CarbonCure technology work?**
> Carbon dioxide is captured from the emissions of local industrial polluters by gas suppliers across the country. This purified and liquefied CO_2 is delivered to CarbonCure's concrete producer partner's plants in pressurized tanks. The CarbonCure technology precisely injects the recycled CO_2 into wet concrete while it's being mixed. Once injected, the CO_2 becomes chemically converted into a solid mineral and permanently captured within the concrete. The technology is integrated with the producer's batching system and has no impact on normal operations ….

CarbonCure Ready Mixed Technology: Recycling CO_2 to Make Simply Better Concrete, CarbonCure Technologies Inc., 2016.
https://cdn2.hubspot.net/hubfs/725075/CARBONCURE%20SALES%20BROCHURE%20201702.pdf
While this brochure describing CarbonCure's ready-mixed technology focuses on the use of CarbonCure materials for buildings and structures rather than roadways, the data it presents may be of interest to Caltrans. *Excerpts from the brochure*:

> CarbonCure conducted concrete durability testing in collaboration with leading academics. The tests compared plastic, hardened and durability properties between a reference concrete batch and a batch subjected to CO_2 addition. Concrete durability test results indicated that the carbon dioxide process did not compromise the expected performance of the treated concrete.
>
> Batches of concrete were prepared for which the slump and air content were measured both before and after the addition of CO_2. It was found that the carbon dioxide had little to no effect on the air content and slump of the concrete. Producers using the technology can realize the compressive strength benefits without impacting fresh properties.
>
> When CO_2 is injected into wet concrete using the CarbonCure technology, the CO_2 reacts immediately with cement to form a solid calcium carbonate mineral. Calcium carbonate does not impact rebar corrosion. Research has shown that a CO_2 utilization process has a negligible effect on the pH of the pore solution of mature concrete, and therefore suggests no risk of rebar corrosion.

"Outback Materials Tracks Carbon Factor in 500,000-Yd. Rail Contract," *Concrete News*, Concrete Products, November 1, 2017.
http://concreteproducts.com/news/news-scope/10691-outback-materials-tracks-carbon-factor-in-500-000-yd-rail-contract.html#.WtYCAljrt9A
From the article:

> Fresno, Calif.-based Outback Materials has teamed with CarbonCure Technologies, a developer of carbon dioxide-sequestering processes, on one of the initial contracts for the high-speed rail project linking northern and southern California.
> ....
>
> A CarbonCure equipment installation at Fresno headquarters, he [Outback Materials owner Curtis Lovett] adds, will improve the environmental impact and overall integrity of the rail contract concrete. Through an injection process ahead of mixer truck loading, the technology chemically sequesters industrial process-derived CO_2 in fresh concrete. The gas

contributes to strength development and reduces finished concrete structures' carbon footprint.

"Outback Materials to Partner With CarbonCure for the California High Speed Rail Project," Press Release, CarbonCure Technologies Inc., July 11, 2017.
http://info.carboncure.com/press/outback-and-carboncure-partner-for-greener-high-speed-rail-opportunities
This press release includes comments from CarbonCure's chief executive officer about the impact CarbonCure materials could have on the CHSR project's Construction Package 1.

Note: See **Other Related Resources** on page 20 of this Preliminary Investigation for other publications related to the CarbonCure process and products.

Contacts

Christie Gamble, Director of Marketing, CarbonCure Technologies Inc., +1 902-220-9380, cgamble@carboncure.com.

Juan (Johnny) Gonzalez, Sustainability Manager, Operations, Central Concrete Supply Company Inc., 408-771-6261, jgonzalez@us-concrete.com.

Mineral Carbonation International

We contacted Marcus St. John Dawe, chief executive officer of Mineral Carbonation International (MCi), to learn more about the Australian company's activities in producing CCS-based materials.

Product Description

MCi's core process "reacts captured CO_2 with quarried low-grade minerals in a continuous industrial process." Dawe highlighted the company's newly launched pilot plant in Australia and its efforts to develop "new low-carbon building materials with partners globally," though noted that the company is "operating under commercial secrecy and generally do[es] not provide information to third parties except under nondisclosure." The company is primarily focused on developing carbonate-based products using CO_2 and low-grade minerals and wastes as feedstock. Dawe noted that MCi has developed its technology to a technology readiness level of 6 to 7 and is "progressing it towards industrial demonstration."

Note: The technology readiness level (TRL) index developed in the 1970s by NASA is used globally as a benchmarking tool to track progress of a specific technology. The TRL index begins with Level 1, when scientific research is beginning and results are being translated into future research and development, and ends with Level 9, when an actual system has been proven through successful operations. Described below are the TRLs cited by Dawe in connection with MCi's technology:

- TRL 6 involves a fully functional prototype.
- TRL 7 requires that the system prototype be demonstrated in an operational environment.

Related Resources

Mineral Carbonation International, Mineral Carbonation International, undated.
http://mineralcarbonation.com/
From the web site: Mineral Carbonation International (MCi) is an Australian based company which is developing technology for carbon ut[i]lisation (CU). Its priority is large scale transformation of CO_2 into valuable products through mineral carbonation processes. This would assist as a transition technology for the major emitting countries as they move away from carbon intensive power generation and industry to more sustainable energy mixes and decarbonized industrial processes.

….

MCi's core process reacts captured CO_2 with quarried low grade minerals in a continuous industrial process. This mimics but greatly speeds up the natural weathering by rainfall which produces common types of rocks over millions of years. It is anticipated that the MCi process will be economically viable even without a high carbon price as markets are substituted with these carbon trapped products.

Technology Readiness Levels for Renewable Energy Sectors, Australian Renewable Energy Agency, Commonwealth of Australia, February 2014.
https://arena.gov.au/assets/2014/02/Technology-Readiness-Levels.pdf
This publication describing TRLs recommends their use by the renewable energy sector "as a tool that project proponents may want to use when considering their projects." The agency uses the index "to measure the technical readiness of renewable energy solutions."

Contact

Marcus St. John Dawe, Chief Executive Officer, Mineral Carbonation International, marcus.dawe@mineralcarbonation.com.

Calera Corporation

Note: Calera Corporation's current emphasis is on developing products used for purposes other than the transportation infrastructure projects of interest to Caltrans. We did not seek additional information from company representatives to supplement the publicly available information presented below.

Product Description

Calera Corporation's production process removes the CO_2 and a calcium source from flue gas from power plants and burning coal to form "a special calcium carbonate product that is then dried to a free-flowing powder. This powder can then be used to make products, like boards, because of the special cementing nature of the calcium carbonate." Products made with Calera's calcium carbonate cement include decorative concrete products such as countertops, plant holders and benches, and fiber cement board sheets.

Related Resource

The Process, Calera Corporation, 2018.
http://www.calera.com/beneficial-reuse-of-co2/process.html
From the web site: Calera's process for CO_2 reduction involves the capture of CO_2 gas from industrial emitting sources and converting the CO_2 into a novel calcium carbonate cement system that's used to make a variety of valuable products. Calera concentrates on the manufacture of building materials, particularly focusing on innovative board products from Calera's novel cement system. Calera's process removes CO_2 from emitting sources by converting the gas into a solid form of calcium carbonate thereby permanently sequestering the CO_2. The Calera process is unique with a CO_2 capture and conversion technology that transforms CO_2 into a profitable feedstock. Calera's CO_2 solution couples environmental sustainability with economic sustainability.

Contact

Contact information for Ryan Gilliam, Calera's chief executive officer, is not readily available. See the company's Contact page at http://www.calera.com/company/contact.html for a form that can be completed to submit an inquiry.

Carbon XPRIZE Competitors

The nonprofit XPRIZE Foundation designs and implements competitions geared to solving "the world's greatest challenges." Among the global competitions in process is the Carbon XPRIZE, described in an April 2018 XPRIZE press release announcing the 10 teams advancing to the finals of the $20 million competition:

> This four-and-a-half-year global competition challenges teams to transform the way the world addresses carbon dioxide (CO_2) emissions through breakthrough circular carbon technologies that convert carbon dioxide emissions from power plants into valuable products.

Two parallel tracks will demonstrate conversion of CO_2 emissions from coal-fired and natural gas-fired power plants. The 10 finalist teams were each awarded an equal share of a $5 million milestone prize and are now tasked with demonstrating their technologies "at a scale that is at least 10 times greater than the semifinals requirements at one of two purpose-built industrial test sites." The two test sites are a coal-fired power plant in Gillette, Wyoming, and a natural gas-fired power plant in Alberta, Canada.

Below are brief descriptions of the Carbon XPRIZE finalists' technologies that relate to Caltrans' interest in CCS-based construction materials:

- Carbon Upcycling UCLA (U.S.). Building materials that absorb CO_2 during the production process to replace concrete.
- Carbon Capture Machine (Scotland). Solid carbonates with applications to building materials.

The Canadian company CarbonCure Technologies Inc. is also among the 10 Carbon XPRIZE finalists; see page 10 of this Preliminary Investigation for more information about CarbonCure.

Related Resources:

"Ten Teams From Five Countries Advance to Finals of $20M NRG COSIA Carbon XPRIZE: Finalists Reimagine Carbon and Will Demonstrate CO_2 Conversion Tech Under Real-World Conditions," Press Release, XPRIZE Foundation, April 9, 2018.
https://carbon.xprize.org/press-release/ten-teams-five-countries-advance-finals-of-20m-nrg-cosia-carbon-xprize
This press release announces the 10 finalists advancing to the final round of the Carbon XPRIZE competition.

Carbon Conversion Landscape Analysis, XPRIZE Foundation, December 2014.
http://www.xprize.org/sites/default/files/carbon_conversion_landscape_analysis_2014.pdf
From the document:

> This report is a landscape analysis of carbon conversion technologies that was created as part of a formal prize design process for a Carbon XPRIZE. This report summarizes the primary and secondary research and analysis conducted during the prize design with the goal of informing the development of a prize competition that would incentivize innovations around converting CO_2 into valuable products.

See page 16 of the document for a root cause analysis and discussion of "seven critical market failures that have slowed development of CO_2 conversion technologies":

1. Investment in reducing emissions from power plants and other industrial sources has focused primarily on CCS rather than CO_2 conversion.
2. CO_2 conversion processes compete with very mature, high-volume manufacturing.
3. The universe of CO_2 conversion technologies is highly diverse, and it is difficult to compare performance and benefits across different types of processes and products.
4. The economic benefits of CO_2 conversion have not been quantified.
5. The environmental benefits of CO_2 conversion are not well understood.
6. The energy industry is risk averse and hesitant to demonstrate or deploy first-of-its-kind technology.
7. Lack of regulation of CO_2 from power plants and other industrial sources in most countries around the world has resulted in stunted demand for technologies to reduce CO_2 emissions.

Carbon Upcycling UCLA

The Technology

The UCLA project team's web site describes its carbon upcycling process:

> *Carbon upcycling* is based on the integration of several technologies into a closed-loop, to fabricate CO_2NCRETE, a near CO_2-neutral construction material. The process is designed to efficiently utilize flue gas exhausted from point source emitters (e.g., power plants and cement plants) by efficiently recovering waste heat and enriching CO_2 present in the gas stream. A novel binder system based on calcium hydroxide (hydrated lime) is mixed with aggregates and admixtures to form a shape-stabilized CO_2NCRETE building element. The final and key step lies in combining the captured CO_2 with CO_2NCRETE element via a carbonation reaction (i.e., CO_2-mineralization) to form a solid building component. These elements can be used like Lego to rapidly assemble buildings, bridges and other infrastructure traditionally constructed with concrete.

What's Next

The project team is seeking funds to support the lab-scale proof of concept, which is expected to be completed in approximately 18 months. After completing the proof of concept, the technology could be commercialized over the following five to seven years.

Related Resources

Carbon Upcycling UCLA: Turning Carbon Dioxide into CO_2NCRETE, Luskin Center, University of California, Los Angeles, 2018.
http://www.co2upcycling.com/
From the web site:

> **Better building designs & lower construction costs**
> The future of construction needs advanced material systems to enable leaps forward in constructability, structural efficiency and resilience. As a material, CO_2NCRETE is designed to meet these goals with its adaptability to a wide array of forming and manufacturing techniques, rapid strength development and Lego-like assembly. While CO_2NCRETE may be hand-molded similar to traditional concrete, its unique reaction mechanism makes it readily adaptable to additive manufacturing techniques (i.e., 3D printing). The accelerated

> strength gain by carbonation, coupled with the tight quality controls and efficiency of the CO_2NCRETE prefabrication paradigm will accelerate construction timelines, while reducing labor intensity.

"Reimagining CO_2: UCLA Team Advances to Carbon XPRIZE Finals," News Article, Luskin School of Public Affairs, University of California, Los Angeles, April 9, 2018.
https://luskin.ucla.edu/reimagining-co2-ucla-team-advances-to-carbon-xprize-finals/
From the article: Traditional forms of cement are formed from anhydrous calcium silicate, while CO_2NCRETE is composed from hydrated lime that is able to absorb carbon dioxide quickly into its composition. As a result, producing CO_2NCRETE generates between 50 to 70 percent less carbon dioxide than its traditional counterpart.

The unique "lime mortar-like" composition also helps reduce the nearly 9 percent of global carbon dioxide emitted from the production of ordinary portland cement, the binding agent used in traditional concrete.

The most compelling advantage CO_2NCRETE offers when compared to other carbon capture and utilization technologies, Sant said, is that the carbon dioxide stream used in its production does not have to be processed before use. [Dr. Gaurav Sant is the principal investigator of UCLA's Laboratory for the Chemistry of Construction Materials.] The manufacturing process allows for carbon dioxide borne in the flue gas of power and industrial plants to be captured and converted at its source. This advantage creates a cost-competitive business model that avoids the expense of a carbon dioxide enrichment or treatment facility.

Contacts

J.R. DeShazo, Director, Luskin Center for Innovation, University of California, Los Angeles, 310-593-1198, deshazo@ucla.edu.

Gaurav Sant, Principal Investigator of the Laboratory for the Chemistry of Construction Materials; Associate Professor and Henry Samueli Fellow, Department of Civil and Environmental Engineering, University of California, Los Angeles, 310-206-3084, gsant@ucla.edu.

Carbon Capture Machine

The Technology

Carbon Capture Machine (CCM) was developed at the University of Aberdeen (Scotland) and is being further developed and marketed by Carbon Capture Machine (UK) Ltd. The company's patented technology is described on its web site (emphasis added):

> Proprietary CCM technology dissolves combustion CO_2 from any source in dilute alkali, converting it to carbonate ions with efficiency approaching 100%. The carbonate solution is reacted with readily and abundantly available calcium (Ca++) and magnesium (Mg++) brines to selectively precipitate CaCO3 (Precipitated Calcium Carbonate, PCC) and MgCO3·3H2O (Precipitated Magnesium Carbonate, PMC).
>
> These conversion products are carbon negative, high value feedstocks that are in demand across many industries. PCCs are currently used in paper making, plastics, paints, adhesives, and **future applications in cement and concrete are under development**.

Cementised PMC is an entirely new product that can be cast into final shape and thermally cured at low temperature. As a consequence, the solid undergoes spontaneous reaction bonding to form rigid solids (blocks, panels, tiles, etc.).

Related Resources

The Carbon Capture Machine, Carbon Capture Machine (UK) Ltd., 2018.
https://ccmuk.com/
This web site describes the team and its technology (see https://ccmuk.com/technology for more details of the team's proprietary technology).

Technical Summary: Carbon Capture Machine, University of Aberdeen, undated.
https://www.abdn.ac.uk/ccm-carbon-xprize/technical-summary/index.php
From the web site: The CCMs [carbon capture machines] that will be demonstrated and commercialised through the competition dissolve CO_2 flue gas directly into slightly alkaline water …. A novel multi-stage precipitation technology will be used to separate and produce nearly insoluble Ca and Mg carbonate minerals that have useful properties, and hence commercial value in existing established and new markets. NaCl, if present, is easily excluded from the final products.

The simplicity and reliability of our process, its superiority compared to other CCU [carbon capture and utilisation] processes, its ability to use standard, off-the-shelf components, and low capital investment needs make this technology peerless.

Carbon XPRIZE Teams: Carbon Capture Machine, XPRIZE Foundation, 2018.
https://carbon.xprize.org/teams/carbon-capture-machine
This Carbon XPRIZE web page provides an overview of the Carbon Capture Machine team and its technology.

Contacts

Mohammed Imbabi, Founding Director, Carbon Capture Machine (UK) Ltd.; Senior Lecturer, School of Engineering, University of Aberdeen, 44 (0)1224 272506, m.s.imbabi@abdn.ac.uk.

Fredrik Glasser, Founding Director, Carbon Capture Machine (UK) Ltd.; Emeritus Professor, School of Natural and Computing Sciences, University of Aberdeen, 44 (0)1224 272906, f.p.glasser@abdn.ac.uk.

Zoe Morrison, Founding Director, Carbon Capture Machine (UK) Ltd.; previously Senior Lecturer, Management Studies, School of Business, University of Aberdeen.

Other Related Resources

Below is a sampling of recent publications that consider the use of CCS technologies to produce carbonate rocks or the use of CO_2 in the production of construction materials. Many more publications are available that examine CCS-related processes that are not the focus of this Preliminary Investigation.

"On Carbon Dioxide Utilization as a Means to Improve the Sustainability of Ready-Mixed Concrete," Sean Monkman and Mark MacDonald, *Journal of Cleaner Production*, Vol. 167, pages 365-375, November 2017.
Citation at https://doi.org/10.1016/j.jclepro.2017.08.194
From the abstract: Carbon dioxide utilization in the production of ready mixed concrete was investigated through the injection of an optimal amount of CO_2 during batching and mixing. The carbon dioxide improved the concrete compressive strength with minimal impact on fresh air content or workability. Three-way comparisons between a reference batch, reduced binder batch and reduced binder batch with CO_2 addition, confirmed that the carbon dioxide could allow for a 5–8% reduction in binder loading without compromising strength. A model case shows that integrating a CO_2 utilization step into conventional concrete production can, net of process emissions, reduce the carbon footprint of the concrete by 4.6%. The direct utilization is amplified to attain a carbon footprint improvement that is more than 35 times larger than the amount of carbon dioxide required. One year production at a medium sized producer would use about 24 tonnes of carbon dioxide to achieve nearly 897 tonnes of CO_2 absorbed and avoided.

"Properties and Durability of Concrete Produced Using CO_2 as an Accelerating Admixture," Sean Monkman, Mark MacDonald, R. Doug Hooton and Paul Sandberg*, Cement and Concrete Composites*, Vol. 74, pages 218-224, 2016.
Full-text article available at http://info.carboncure.com/white-papers/properties-and-durability-of-concrete-produced-using-co-2-as-an-accelerating-admixture (click on "Download CarbonCure White Paper")
From the abstract: Carbon dioxide was investigated for use as a beneficial admixture to concrete as it was truck mixed. The reaction between the CO_2 and the hydrating cement creates finely distributed calcium carbonate reaction products that thereby influence the subsequent hydration. Comparisons of the fresh, hardened and durability properties were made between a reference concrete batch, a batch that contained a conventional accelerating admixture, and three batches subjected to a carbon dioxide addition. The optimum dose of carbon dioxide was found to reduce the time to initial set by 40% and increase the one and three day compressive strengths by 14% and 10% respectively. In comparison to the CO_2 batch, the conventional accelerator provided greater reductions in set time but lower early strength. Concrete durability test results indicated that the carbon dioxide process did not compromise the expected durability performance of the treated concrete. Carbon dioxide is a viable admixture to improve concrete performance.

"Carbon Capture in the Cement Industry: Technologies, Progress and Retrofitting," Thomas Hills, Duncan Leeson, Nicholas Florin and Paul Fennell, *Environmental Science and Technology*, Vol. 50, No. 1, pages 368-377, 2016.
https://pubs.acs.org/doi/pdf/10.1021/acs.est.5b03508
From the abstract: Several different carbon-capture technologies have been proposed for use in the cement industry. This paper reviews their attributes, the progress that has been made toward their commercialization, and the major challenges facing their retrofitting to existing cement plants. A technology readiness level (TRL) scale for carbon capture in the cement industry is developed. For application at cement plants, partial oxy-fuel combustion, amine

scrubbing and calcium looping are the most developed (TRL 6 being the pilot system demonstrated in relevant environment), followed by direct capture (TRL 4–5 being the component and system validation at lab-scale in a relevant environment) and full oxy-fuel combustion (TRL 4 being the component and system validation at lab-scale in a lab environment). Our review suggests that advancing to TRL 7 (demonstration in plant environment) seems to be a challenge for the industry, representing a major step up from TRL 6. The important attributes that a cement plant must have to be "carbon-capture ready" for each capture technology selection is evaluated. Common requirements are space around the preheater and precalciner section, access to CO_2 transport infrastructure, and a retrofittable preheater tower. Evidence from the electricity generation sector suggests that carbon capture readiness is not always cost-effective. The similar durations of cement-plant renovation and capture-plant construction suggests that synchronizing these two actions may save considerable time and money.

Note: The following two citations are a sampling of the white papers available on CarbonCure's web site. Other CarbonCure white papers are available at http://info.carboncure.com/white-papers.

White Paper: Ready Mixed Technology Case Study: CO_2 Utilization in Concrete Mix Design Optimization, Sean Monkman and Mark MacDonald, CarbonCure Technologies Inc., December 2016.
White paper available at http://info.carboncure.com/white-papers/ready-mixed-technology-case-study
From the executive summary: The CarbonCure Ready Mixed Concrete Technology is being implemented by concrete producers across the United States and Canada to improve the compressive strength and environmental footprint of their concrete products. This case study examines data provided by a CarbonCure producer partner who installed the CarbonCure technology and used the system to produce concrete with an optimized dosage of CO_2. Concrete prepared using the CO_2 injection system was shown to deliver comparable compressive strength performance with a 5–8% reduction in binder loading while having a neutral impact on fresh proper ties, including air, slump and temperature. Roughly 45,000 yd of concrete were produced over an 8 month period using a 5% binder reduction in conjunction with an optimized dose of CO_2. The estimated cement savings exceeded 450 tons and more than 400 tons of CO_2 emissions were avoided. The use of the technology did not impact the producer's cycle time; all operations continued as normal throughout this assessment.

White Paper: Ready Mixed Technology Trial Results, Sean Monkman, CarbonCure Technologies Inc., November 2016.
White paper available at http://info.carboncure.com/white-papers/ready-mixed-technology-trial-results-white-paper
From the executive summary: The CarbonCure Technologies ready mixed concrete system is commercially available as of April 2015. Industrial pilot testing results of the carbonated ready mixed concrete are presented in this white paper. The process created nanocrystalline carbonate reaction products that positively [a]ffected the early hydration and the compressive strength. The carbonated concrete was as much as 20% stronger than the control concrete without any compromise in pore solution pH or risk for chloride penetrability.

"Bioinspired Concrete," Brent R. Constantz, Mark A. Bewernitz, Christopher L. Camiré, Seung-Hee Kang, Jacob Schneider and Richard R. Wade II, *Biotechnologies and Biomimetics for Civil Engineering*, pages 297-308, Springer International Publishing, 2015.
Citation at https://doi.org/10.1007/978-3-319-09287-4_13
From the chapter abstract: New bioinspired cement can be used to form artificial limestone aggregate for concrete, as well as cement for the binding phase of concrete. Amorphous calcium carbonate precursors were first used in combination with unstable calcium phosphates to form high strength, rapid setting carbonated calcium phosphate cements, similar to the mineral phase of bone. Later, these amorphous calcium carbonate precursors and other unstable polymorphs of calcium carbonate were used in combination to form calcium carbonate cements with high strength and other advantageous properties. In the last decade, mechanisms to use the carbon dioxide from the combustion of fossil fuels were developed, allowing very large quantities of calcium carbonate cementing precursor materials to be formed, making it a foreseeable reality that new concrete mixes comprising calcium carbonate, both as the aggregate component and the cementing phase of concrete can be establish broadly on a worldwide basis. Calcium carbonate concrete compositions enable a sustainable pathway for concrete as a construction material.

"Carbon Capture and Storage Update," Matthew E. Boot-Handford, Juan C. Abanades, Edward J. Anthony, Martin J. Blunt, Stefano Brandani, Niall Mac Dowell, José R. Fernández, Maria-Chiara Ferrari, Robert Gross, Jason P. Hallett, R. Stuart Haszeldine, Philip Heptonstall, Anders Lyngfelt, Zen Makuch, Enzo Mangano, Richard T.J. Porter, Mohamed Pourkashanian, Gary T. Rochelle, Nilay Shah, Joseph G. Yao and Paul S. Fennell, *Energy and Environmental Science*, Vol. 7, pages 130-189, 2014.
http://pubs.rsc.org/-/content/articlehtml/2014/ee/c3ee42350f
From the abstract: Here, we review the leading CO_2 capture technologies, available in the short and long term, and their technological maturity, before discussing CO_2 transport and storage. Current pilot plants and demonstrations are highlighted, as is the importance of optimising the CCS system as a whole. Other topics briefly discussed include the viability of both the capture of CO_2 from the air and CO_2 reutilisation as climate change mitigation strategies. Finally, we discuss the economic and legal aspects of CCS.

"Waste Materials for Carbon Capture and Storage by Mineralisation (CCSM)—A UK Perspective," Aimaro Sanna, Marco Dri, Matthew R. Hall and Mercedes Maroto-Valer, *Applied Energy*, Vol. 99, pages 545-554, November 2012.
Citation at https://doi.org/10.1016/j.apenergy.2012.06.049
From the abstract: This work reviews the advantages and disadvantages of using mineral wastes for CCS and their potential in CO_2 abatement, highlighting the potential applications and scenarios. This study indicates that a variety of inorganic waste materials such as pulverised fuel ash, municipal solid waste ash, cement kiln dust, biomass and paper sludge ash and sewage sludge ash are available feedstocks for Carbon Capture and Storage by Mineralisation (CCSM) in the UK. The high variability of both the waste amounts and chemical composition represent a major obstacle to the deployment of these materials in CCSM. Currently, mineral waste resources for mineral carbonation have the theoretical potential to capture about 1 Mt [1 metric megaton (unit of mass) is equal to 1,000,000 metric tons]/year CO_2 in the UK, considering only the materials not recycled that are currently sent to landfill. Moreover, inorganic waste as a CCSM resource is in many ways more complex than the use of natural minerals due to uncertainty on future availability and high chemical variability and might be viable only in niche applications. For example, the use of inorganic wastes (concrete waste and steel slag) and buffer solutions in spray trickle bed systems (able to sequester 50% of the CO_2 entering the system) was estimated to have costs competitive with geological storage.

"Carbon Capture and Storage Using Alkaline Industrial Wastes," Erin R. Bobicki, Qingxia Liu, Zhenghe Xu and Hongbo Zeng, *Progress in Energy and Combustion Science*, Vol. 38, No. 2, pages 302-320, April 2012.
Citation at https://doi.org/10.1016/j.pecs.2011.11.002
From the abstract: Mineral carbon sequestration is the only known form of permanent carbon storage and has the potential to capture and store CO_2 in a single step. It is based on the geologic process of natural rock weathering where CO_2 dissolved in rain water reacts with alkaline rocks to form carbonate minerals. While the reactions are thermodynamically favourable, in nature the process occurs over thousands of years. The challenge of mineral carbon sequestration is to accelerate carbonation and exploit the heat of reaction with minimal energy and material losses. Minerals commonly selected for carbonation include calcium and magnesium silicates. These minerals require energy-intensive pre-treatments, such as fine grinding, heat treatment and chemical activation with strong acids, to provide adequate conversions and reaction kinetics. Industrial waste residues present alternative sources of mineral alkalinity that are more reactive than primary minerals and are readily and cheaply available close to CO_2 sources. In addition, the carbonation of waste residues often improves their environmental stability. This paper provides an overview of the types of industrials wastes that can be used for mineral carbon sequestration and the process routes available.

Survey of State Practice

An online survey distributed to members of the AASHTO Committee on Construction received responses from 13 state DOTs:

- Arizona.
- Arkansas.
- Indiana.
- Maine.
- Massachusetts.
- Michigan.
- New Hampshire.
- Oklahoma.
- Pennsylvania.
- Rhode Island.
- South Carolina.
- Tennessee.
- Utah.

None of these agencies reported on experience with or are considering the use of CCS-based construction materials.

Appendix A provides the full text of the survey questions. Contact information for the individuals responding to the survey appears on page 24.

Contacts

The individuals below participated in an online survey that sought information for this Preliminary Investigation. Contact information for other individuals we contacted for this project appears throughout the Preliminary Investigation.

State Agencies

Arizona

Julie Kliewer
State Construction and Materials Engineer
Arizona Department of Transportation
602-712-7323, jkliewer@azdot.gov

Arkansas

Dwayne Cale
Staff Construction Engineer
Arkansas Department of Transportation
501-569-2116, dwayne.cale@ardot.gov

Indiana

Greg Pankow
Construction Management/State Construction Engineer
Indiana Department of Transportation
317-232-5502, gpankow@indot.in.gov

Maine

Dale Peabody
Director, Transportation Research
Maine Department of Transportation
207-624-3305, dale.peabody@maine.gov

Massachusetts

John Grieco
Director, Research and Materials
Office of Construction
Massachusetts Department of Transportation
857-368-3410, john.grieco@dot.state.ma.us

Michigan

John F. Staton
Construction Field Services/Concrete Operations and Materials Engineer
Michigan Department of Transportation
517-322-5701, statonj@michigan.gov

New Hampshire

Charles Dusseault
Administrator, Materials and Research
New Hampshire Department of Transportation
603-271-3151, chuck.dusseault@dot.nh.gov

Oklahoma

Kenny Seward
Assistant Materials Engineer
Oklahoma Department of Transportation
405-521-2677, kseward@odot.org

Pennsylvania

Joseph S. Robinson
Chief Materials Engineer
Pennsylvania Department of Transportation
717-705-3841, josrobinso@pa.gov

Rhode Island

Michael D. Sock
Principal Civil Engineer
Rhode Island Department of Transportation
401-222-3030, michael.sock@dot.ri.gov

South Carolina

Merrill Zwanka
Materials and Research Engineer
South Carolina Department of Transportation
803-737-6681, zwankame@scdot.org

Tennessee

Laura Chandler
Construction Division/Specification Engineer
Tennessee Department of Transportation
615-741-0786, laura.chandler@tn.gov

Utah

Rob Wight
Director, Construction and Materials
Utah Department of Transportation
801-965-4869, rwight@utah.gov

Appendix A: Survey Questions

The following survey was distributed to members of the AASHTO Committee on Construction.

Survey Introduction

The carbon capture and sequestration (CCS) technologies of interest to Caltrans are those that apply a carbonate mineral coating to aggregates or other construction materials or pressurize CO_2 to liquefy it and inject it into construction material.

1. Does your agency have experience with the use of construction materials produced using the CCS technologies described above?
2. Is your agency considering the use of construction materials produced using the CCS technologies of interest to Caltrans, or related CCS technologies? If yes, please describe your agency's interest in the use of CCS-based construction materials.

The following questions were presented to agencies responding "Yes" to Question 1 above.

Description and Use of CCS-Based Materials

1. Please describe the CCS-based construction material(s) your agency has used and name the vendor(s) supplying the material.
2. What CCS technology was used to produce the construction material(s)? Select all that apply.
    - Addition of CO_2 as a coating for a structural material such as aggregate.
    - Injection of liquefied CO_2 into construction material.
    - Other (please describe).
3. Please describe the project or projects that used CCS-based construction material.
4. Please compare your agency's experience with CCS-based construction materials with the use of conventional construction materials in terms of:
    - Constructability.
    - Cost.
    - Performance.
5. Has your agency found that the CCS-based construction materials are available in the quantities necessary for large-scale transportation infrastructure projects? If yes, please describe the quantities used for your agency's project(s).
6. When applied, are the CCS-based construction materials carbon neutral or carbon negative? Please base your answer on actual work completed using CCS-based construction materials.
7. If your agency has found that the application of CCS-based materials is carbon neutral or carbon negative, is this determined by a cradle-to-gate or cradle-to-grave assessment?

Special Considerations

8. Please describe any special considerations required for environmental conditions such as weather and moisture when applying CCS-based construction material.
9. Please describe any special considerations required for maintenance-related activities (for example, concrete surface grinding, material disposal or chemical deicing treatments) associated with CCS-based construction material.

Data, Research and Documentation

10. Does your agency have any data (or know of any research) relevant to the constructability, cost and performance of CCS-based construction materials?
11. Does your agency have any data (or know of any research) that quantifies the environmental impacts of the use of these materials? If yes, please describe the data or research.
12. If available, please provide links below to documents such as project specifications or other guidance that describe your agency's use of CCS-based construction materials. Send any files not available online by email to chris.kline@ctcandassociates.com.

Completing the Survey

Please use this space to provide any comments or additional information about your answers above.