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Abstract

The construction sector is increasingly focused on improving energy and material efficiency to reduce its environmental impact. One promising approach gaining traction is the shift from a traditional linear economic model (extract, make, use, discard) to a circular model. In a circular economy (CE), materials are designed to have lower environmental impacts and are retained in the economy for as long as possible, thereby reducing resource depletion, environmental impact, and waste generation, while creating new business opportunities and jobs. Concrete, a widely used construction material, is a significant contributor to CO_2 emissions due to cement production. Efforts are underway to transition the cement and concrete industries to a CE. Strategies include infrastructure design to optimize concrete use and enable repair and reuse, as well as advanced material design such as the use of alternative cementitious materials, improved energy efficiency in production, and carbon capture from production and sequestration in concrete. However, challenges hinder the transition to a CE, including the industry's established technologies and supply chains, the need for demonstrated reliability of new materials, and lack of a trained workforce capable of designing and constructing with low-carbon materials. To overcome these challenges requires a collaborative, systems-level approach, with clear goals, harmonized metrics, robust assessment tools, standards development, workforce training, and coordinated regulatory efforts. The U.S. National Institute of Standards and Technology (NIST) can support the transition to a CE by advancing measurement science, developing data resources and modeling tools, participating in standards development, and convening necessary stakeholders to facilitate collaborative engagement.

Keywords

Circular Economy, Carbon Capture and Sequestration, Low-Carbon Cement and Concrete; Circular Built Environment.

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List of Acronyms

C&D	Construction and demolition
CE	Circular economy
CMU	Concrete masonry units
CO_2	Carbon dioxide, generally referred to as ‘carbon’ throughout this report
CCS	Carbon capture and storage
EoL	End of life
EPD	Environmental Product Declaration
Gt	Gigatonnes
GHG	Greenhouse gases
GPP	Green Public Procurement
LCA	Life Cycle Assessment
PCR	Product category rules
RCA	Recycled concrete aggregate
SCM	Supplementary Cementitious Materials

Executive Summary

Momentum is increasing to improve the energy and material efficiency of our built environment and ultimately reduce the environmental impact of the construction sector. One approach gaining traction is the transition away from the traditional linear – extract, make, use, discard – economic model toward a more circular model where materials entering the economy have lower environmental impacts than their traditional counterparts and are retained in the economy for as long as possible. A circular economy (CE) thereby preserves natural resources, reduces environmental impacts of production, lessens demand for landfills, and creates value, new business opportunities, and new jobs.

Concrete is the predominant construction material used globally due to its many beneficial properties and availability. However, the production of concrete, particularly the cement binder, is a major generator of CO_2 emissions. Due to the enormous volume produced annually, cement production is the largest single industrial emitter of CO_2, estimated to account for approximately 8 % to 10 % of total global anthropogenic CO_2 emissions [1, 2, 3]. As a result, there is expanding interest and effort aimed at transitioning to a CE for cement and concrete. Various opportunities for innovation exist that will hasten this transition, as depicted in the hierarchy shown in Figure ES-1. Changing how we design materials and infrastructure has the greatest potential impact on reducing the embodied carbon (i.e., the total carbon dioxide emissions released throughout the life cycle of the material or structure) and facilitating a CE. The carbon content of new concrete can be reduced by a number of strategies: a) lowering the cement content by using alternative and supplementary cementitious materials (SCMs); b) improving the energy efficiency of cement production (e.g., electrification using renewable energy sources); and c) capturing carbon emissions from cement production and utilizing it (along with other industrial CO_2) in concrete. The embodied carbon of new infrastructure can also be reduced through optimized design that reduces the demand for concrete, achieves improved service life, and enables repair, reuse, and recycling.

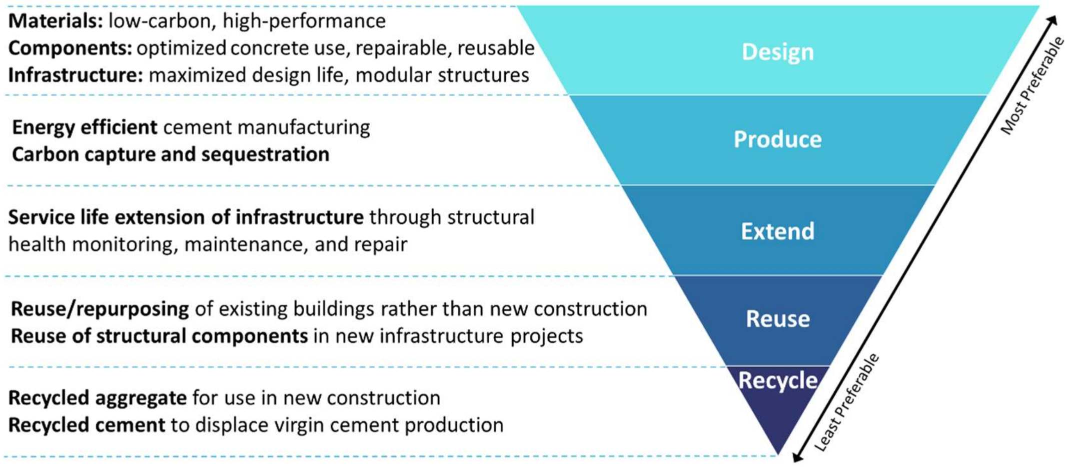

Figure ES-1: Circular economy hierarchy prioritizing most to least favorable pathways to extend the life of materials and infrastructure and reduce embodied carbon.

The cement and concrete industries have invested significant resources into evaluating approaches to enable the transition to a CE. Key among these are efforts focused on carbon capture and sequestration in concrete, and advancing the recovery and recycling of deconstructed concrete for use in new structural applications. In June 2022 the National Institute of Standards and Technology

(NIST) held a virtual workshop convening industry, research, and government stakeholders to discuss the state of practice and science in the areas of low-carbon and circular cements and concrete infrastructure, and identify challenges facing their advancement, what is needed to overcome barriers, and potential NIST action items that could help move to a CE for cement and concrete.

Challenges facing the advancement of a CE for cement and concrete range from technical, cultural, and political. Key challenges identified in the workshop include:

- The construction industry is well-established with capital intensive technologies with long lifetimes, established supply chains, and relatively low profit margins. It is therefore technically and economically challenging to deploy new formulations and processes.
- It is difficult to bring new materials and processes into the marketplace until they have fully demonstrated comparable or better reliability and durability relative to incumbents.
- Current standards and procurement policies (often) preclude the adoption of new materials, or inclusion of recycled concrete.
- Lack of a trained workforce capable of designing and constructing infrastructure using novel low-carbon materials as well as deconstructing and reusing existing infrastructure.
- The sequestration of carbon in concrete lacks the quality-assured measurements to verify how much CO_2 is reliably captured through both natural and accelerated carbonation.
- Biomineralization (i.e., use of microorganisms) of carbon in concrete is challenged by limited in situ measurement and characterization techniques as well as understanding of the long-term viability and survival of microorganisms in concrete (e.g., for self-healing concrete applications and totally new materials).
- The recycling of concrete for use in new structural applications is limited by a lack of established methods to identify and remove deleterious contaminants as well as concerns about the potential reduction of mechanical properties of concrete materials made with recycled content.

To address these challenges and improve the circularity of the cement and concrete industry requires a harmonized, systems-level, collaborative approach. Several opportunities for advancement include the following:

- Establish clear, prioritized technological, environmental, social, and economic goals for reducing the embodied carbon of concrete and transitioning towards a circular economy.
- Harmonize terms, metrics, methods, measures, and data to support a decision strategy framework.
- Advance robust, uniform, and transparent assessment tools such as life cycle assessment.
- Develop voluntary, consensus-based standards to support the adoption of low-carbon cements and concrete, including design standards and the use of recycled concrete.
- Coordinate regulatory and market levers to scale new technologies.
- Advance measurement methods to characterize and quantify carbon uptake mechanisms and pathways.
- Provide education and training of the labor force to the use of new and recycled concrete materials.

CE pathways can also be applied to other common construction materials such as gypsum, steel, asphalt, glass, and wood. While these materials may have unique challenges associated with improving their circularity, they also face many of the same industry-wide barriers as cement and concrete. NIST could support many of the needs and opportunities identified in the workshop: the development and hosting of data registries and repositories; advancement of traceability, assessment, and modeling tools; supporting the development of standards, specifications, and guidelines; as well as applied research including characterization and measurement methods for novel and recycled concrete materials. Furthermore, NIST is well-suited to serve as a convener of the wide range of stakeholders included in the construction sector, both private and public, and across the social and technical disciplines.

1. Introduction

1.1. Motivation

Interests and efforts to transition toward more climate-neutral construction materials and practices have risen significantly in recent years. Constructing and using the built environment, which includes buildings, roadways, bridges and other physical infrastructure, accounts for a significant portion of global energy demand and associated greenhouse gas (GHG) emissions. In addition, decommissioned infrastructure is a significant source of solid waste.

Through advances in materials science, improved manufacturing approaches, and modified construction methods, a more sustainable vision of the future can become reality. A future in which construction materials are environmentally benign with as good or even better performance; where construction production, quality, and throughput are more efficient and have lower environmental impacts; and the components of the built environment are maintained and reused at the end of their service life rather than discarded. For instance, fast setting carbon-neutral concretes can be formulated to be 3D-printed into structural elements that can be manufactured in large-scale robotic fabrication systems and undergo modular construction such that they can be deconstructed for reuse in the future. This circular, low-carbon vision can be reached; however, significant work is needed to make it a reality.

Reducing the environmental impacts of construction materials necessitates transitioning toward a more circular economy (CE) – that is, an economy in which atoms and molecules are retained in the economy and out of unwanted sinks, such as the environment and landfills. This includes carbon atoms, which must be kept within the economy by reducing CO_2 emissions, extending the life of existing infrastructure and materials, and capturing and sequestering CO_2 emissions generated. A few materials are responsible for the majority of emissions generated by the construction sector, and cements/concretes are top among them, particularly due to the significant volume of concrete manufactured annually. In fact, concrete is the second most used substance in the world after water, and concrete construction comprises a substantial proportion of the built environment, and its use will continue to increase along with population growth and global development [1]. However, its production, particularly the calcination of limestone in the cement production process, renders it the largest single industrial generator of CO_2 due to the significant volume produced annually [1, 2, 3]. The need thus exists to improve the circularity of concrete by extending the life of components through increased durability, reuse, and recycling; lowering the embodied carbon of cement and concrete production; and sequestering carbon in concrete through carbon mineralization.

The U.S. National Institute of Standards and Technology (NIST) has extensive experience in several areas that can contribute toward this effort. NIST can help to advance the metrology, materials science, reference material development, data registries and repositories, standards development, and life cycle assessment tools needed to facilitate a CE for construction materials generally, and cements/concretes in particular. To better understand barriers facing this effort and a potential role for NIST to help overcome them, NIST held a virtual workshop entitled “Fostering a Circular Economy and Carbon Sequestration for Construction Materials” in June 2022.

1.2. Workshop Overview

The one-day virtual workshop included 12 expert speakers from academia, national labs, and industry, and brought together ≈230 participants similarly associated with the construction industry. While the workshop primarily focused on the circularity of concrete including decarbonization and mineralization, some content focused on gypsum. Speakers in each session presented the state of research and/or practice on the session topic as well as persistent challenges. Recordings of the presentations with permission by the speakers are available online [4]. The session topics included the following:

Session Topics
- Carbon Sequestration and Concrete - Advances in Carbon Mineralization - Reuse of Concrete Materials - Circular Economy for Building Materials

In addition to the speaker presentations, attendee participation was garnered through the Slido polling application. The following poll questions were posed to all participants as well as speakers:

1. What are the main challenges facing carbon sequestration and mineralization in concrete and how can standards help?
2. What measurement science is needed to support standards for reducing the embodied carbon of concrete?
3. What measurement science is needed to support standards for concrete reuse and recycling?
4. What are the main challenges facing the use of recycled aggregate and cement in new concrete and how can standards help?
5. How should NIST prioritize near-term measurement science needs that support standardization efforts in supporting a circular economy and reducing the embodied carbon of concrete?

This report summarizes the key takeaways from the workshop including the state of research/industry, as well as persistent challenges and potential NIST action items.[1] Section 2 provides a background on the production, use, and environmental impacts of cement and concrete as well as drivers for and a description of a proposed CE for these materials and products. Section 3 dives into current efforts underway to facilitate a CE for cement and concrete, including carbon capture and sequestration in concrete through carbonation and biomineralization as well as concrete reuse and recycling. Challenges facing these pathways are described along with needs to overcome those barriers. Section 4 then offers potential action

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[1] The viewpoint of the experts attending the workshop are presented, however, they may not reflect the views of the broader community or NIST.

items NIST could partake in to help address challenges. Section 5 looks beyond concrete, using gypsum as an example of other common construction materials with great need for increased circularity yet with its own series of challenges and opportunities. A series of Appendices offers more detailed content including the workshop agenda (Appendix A), overviews of session presentations (B), workshop poll responses in Slido (C), description of recycled concrete aggregate (RCA) properties, performance, and resources for use (D), the state of science and practice for carbon sequestration via carbonation (E) and biomineralization (F), as well as the production and circularity of gypsum building materials (G).

2. Cement and Concrete: Use, Impacts, and Drivers for Change

Concrete is the 2nd most used material on earth, led only by potable water. There are many reasons for this as concrete has many advantages as a building material, including:

- **Availability:** raw materials such as limestone and clay are geographically available across the world
- **Durability:** well-constructed concrete structures can last for decades with minimal maintenance
- **Fire resistance:** concrete does not emit toxic fumes, smoke or drip molten particles when exposed to fire
- **Resilience:** concrete structures can withstand a multititle of hazards (e.g., fire, wind, water, mold, insects) and disasters
- **Versatility:** concrete can be molded or formed into any shape when newly mixed
- **Thermal properties:** Concrete has a high thermal mass and thus can absorb heat from the atmosphere in warm weather and release it during cooler periods

Because of these properties, concrete has been used as a building material in every region of the world since ancient times. As populations continue to increase, so too does the development of infrastructure such as roads, bridges, buildings, and water treatment plants, most of which utilize concrete. In 2020, an estimated 14 billion cubic meters (m^3) of concrete was utilized in new construction globally, with more than 40% of that used in residential infrastructure [5]. Today about 55 % of the world's population live in cities, where residential units compose vertically constructed, multi-family structures, predominantly made with concrete. Projections estimate that by 2050 closer to 70 % of the population will live in urban centers, suggesting the demand for concrete will continue to increase [5]. At present, no other material can replace concrete at the same scale.

While demand for new concrete construction is increasing, so is the rate of demolition. In cities such as Los Angeles, California, the building stock turns over once every 30 to 40 years [6]. The reason for this is not necessarily due to structural deficiency, but rather because the buildings are at the end of their designed use or function. As such, a significant volume of concrete is demolished from structures that theoretically retains their designed functionality and integrity.

The American Society of Civil Engineers (ASCE) grades civil infrastructure on an A-F scale (A representing exceptional, fit for the future and F failing/critical, unfit for purpose) based on condition, capacity, resilience, and other factors. According to their assessment, America's infrastructure scores an overall C- score. Dams, levees, and roads all scored a D, while bridges scored a C [7]. That said, according to U.S. Federal Highway Administration's (FHWA) National Bridge Inventory [8], currently more than 40 % of America's roughly 620,000 bridges are over 50 years old, and about 43,000, or roughly 7 % of the nation's bridge inventory, are considered structurally deficient. Concrete is the primary material of bridge construction, whether for substructure, superstructure, or deck. This suggests that many U.S. bridges may need to be replaced in the relatively near future, which will result in the significant generation of concrete debris as well as the need for new concrete in the construction of replacement infrastructure.

2.1. Environmental Impacts

Traditionally, concrete elements or structures follow a linear – take, make, use, discard – path. As depicted in Figure 1, each stage of life for concrete has environmental inputs and outputs, and, therefore, environmental impacts. The extraction of the raw materials, including limestone and clay as well as high-quality sands and aggregates, has an effect on the environment and is energy and water intensive. Further, local consumption of these materials can lead to local resource shortages [9]. Cement manufacturing relies on high energy demands and is a major source of GHG emissions. The construction of concrete elements also requires formwork and reinforcing steel, which have their own environmental costs, namely resource use and energy consumption. Well-constructed concrete elements tend not to require significant maintenance. The demolition and end-of-life (EoL) management of concrete elements is also energy intensive and results in the mass generation of solid waste. Naturally, each of these stages requires transportation, which can come at a high environmental cost due to the immense mass and volume considered.

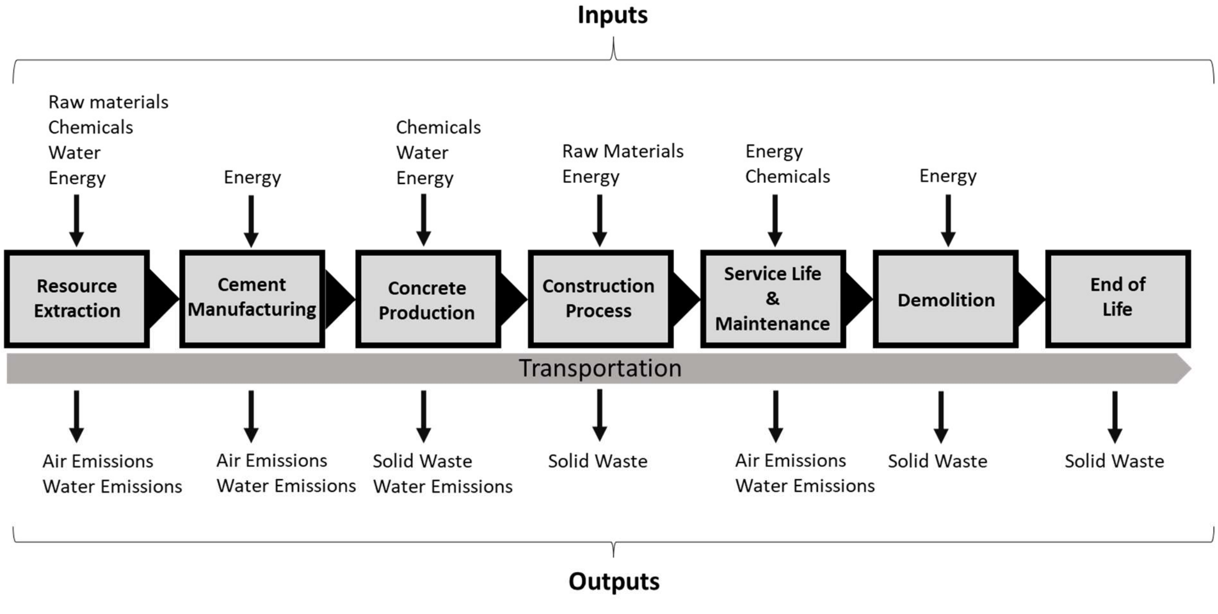

Figure 1: Environmental impacts of concrete

But perhaps the most recognized environmental impact of concrete is the carbon dioxide (CO_2) emissions resulting from the production of traditional Portland cement clinker, a component of cement. In this process, calcium carbonate (i.e., limestone) along with a silica source is heated in a rotary kiln up to 1,450 °C (~2,642 °F) to induce a series of complex chemical reactions ultimately resulting in the production of calcium silicate clinker nodules, with CO_2 released as a by-product [3]. Not only does this process result in the direct emission of CO_2, but the process itself necessitates a heavy use of fossil fuels to reach the necessary temperatures in the kiln. Fossil fuel combustion is estimated to be responsible for about 40 % of total CO_2 emissions in cement production, some of which is for grinding the clinker into powder, while limestone decomposition during calcination is responsible for the remaining 60 % [1]. On average, about 900 kilograms (kg) of CO_2 is emitted for every 1,000 kg of cement produced [10]. In 2020, roughly 4.2 billion tonnes of cement were produced, therefore amounting to the emission of about 3.8 billion tonnes of CO_2 [5]. As such, due to the enormous volume produced annually, cement production is considered the largest single industrial emitter of CO_2 and is now estimated to account for approximately 8 % to 10 % of total anthropogenic CO_2 emissions [1, 2, 3]. The total amount of CO_2 emitted is anticipated to rise steadily as global demand for concrete increases [11]. Furthermore, this value increases somewhat when the full production of concrete is considered such as aggregate extraction and processing, transport and placing, and the production and use of reinforcement steel.

Concrete structures are continuously decommissioned, generating a significant amount of waste. According to the U.S. Environmental Protection Agency (US EPA) [12], in 2018 roughly 600 million tons of construction and demolition (C&D) debris were generated in the U.S. from construction, renovation, and demolition activities for buildings, roads, bridges, and other structures. More than 90 % of the C&D debris generated in 2018 was the result of demolition activities alone, the remainder generated by construction waste. As depicted in Figure 2, C&D debris comprises a variety of materials, with concrete accounting for the largest portion at nearly 68 %.

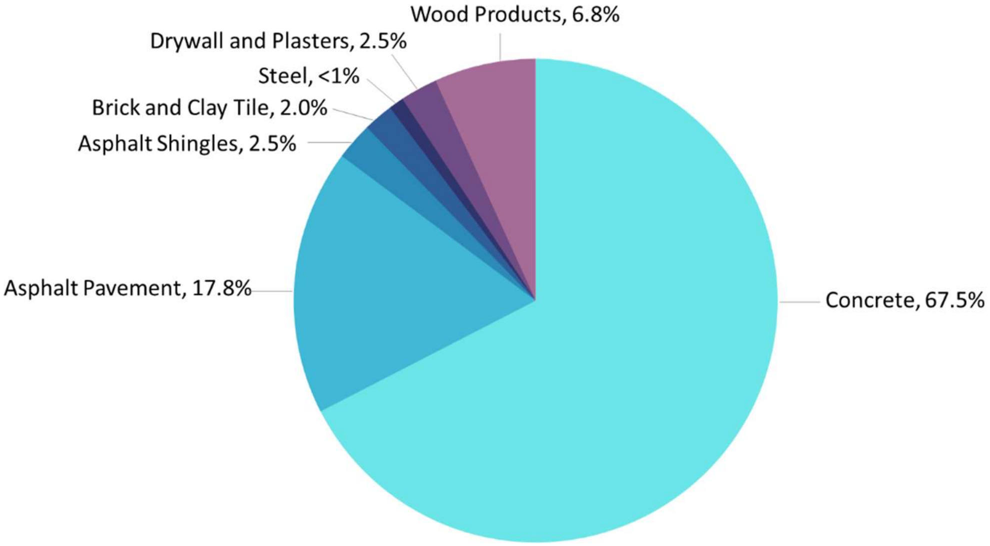

Figure 2: Material composition of the ~600 million tons of C&D debris generated in the U.S. in 2018 (per US EPA data, [12])

In the U.S., concrete debris is used as recycled concrete aggregate (RCA) in pavement subbase (i.e., road-base), non-structural backfill, or disposed of in landfills [12, 13, 14]. According to U.S. EPA data, in 2018, over 300 million tons of concrete C&D debris was utilized in some form, while 71 million tons was discarded in U.S. landfills [12]. As discussed further in Section 3.2.2, most RCA is not utilized in structural applications, and thereby is not used as an aggregate replacement in new concrete, which would have increased environmental benefits by reducing the demand for and transportation of virgin high-quality aggregates. Despite its potential, using RCA in new concrete is not yet common practice due to concerns over variation in mechanical properties and durability performance [13, 15, 16, 17].

2.2. Drivers for Change

Momentum is increasing to improve the energy and material efficiency of our built environment and ultimately lessen the environmental impact of the construction sector. Architects, designers, engineers, building owners (e.g., customers), policymakers, and users of civil infrastructure are increasingly calling for infrastructure constructed with the environment in mind, with reduced GHG emissions and improved recovery at the end of service life.

Economics are another factor driving a shift toward circularity. The easy availability of virgin materials, particularly virgin aggregates, close to urban areas is decreasing and thus the cost of these materials is rising, in particular the transportation costs. The New York Department of Transportation (DoT) reportedly spends $1.45 million every year to dispose of waste concrete [18]. Recycling this waste stream into new infrastructure not only saves on disposal costs, but also reduces the need for virgin materials.

Green Public Procurement (GPP) programs are also driving efforts to reduce the environmental impacts of concrete and to provide strong signal for market demand to help transition the industry. Public procurement is primarily carried out by local, state, and federal governments, which use GPPs in the pursuit of strategic objectives. In this sense, GPP initiatives utilize the purchasing power of public authorities to procure goods and services with reduced environmental impact, and may include measures to incentivize material efficiency, circular economy, and the use of low-carbon materials [19, 20]. The actual accurate measurement of “reduced environmental impact” is a current research question. This approach can stimulate the market for these materials by influencing the private sector and rewarding businesses that provide products or services with lower environmental impact [21]. In the construction sector, GPP measures can be at the *project* or the *product* level; the former incentivizing environmental impact reductions of the overall project – making them more complex to implement and validate – and the latter aimed at reducing the impact of individual components or materials. Life Cycle Assessment (LCA) is the most commonly used method to quantify environmental impacts, including embodied carbon emissions, and the results are generally reported in a standard format in Environmental Product Declarations (EPD) [20]. The EPDs follow guidelines specific to certain products called product category rules (PCRs), and these rules specify the unit of measurement, system boundaries, and assumptions to be made that aim to make EPDs transparent and comparable.

For instance, GPPs often require a product-specific Type III EPD that is third party verified to ensure that the procured product meets reduced impact requirements (e.g., [22]). This type of EPD generally relies upon the ISO14025 standard that outlines the third-party verification requirements [23]. Three U.S. states have legislated GPP policies (California, Colorado, and Oregon) and three others have considered GPP legislation in past two years (Washington, Minnesota, and New York). Several local authorities have also implemented GPP policies, such as Portland, Oregon’s low carbon concrete initiative [22]. Activity of this nature is also taking place at the federal level. Specifically, Executive Order 14057 on “Catalyzing Clean Energy Industries and Jobs Through Federal Sustainability” includes measures aimed at net-zero emissions from Federal procurement, including a Buy Clean policy to promote use of construction materials with lower embodied emissions [24].

In addition to industry and academia, many national laboratories and government agencies have programs aimed at reducing the environmental impact of our built environment. Oak Ridge National Laboratory (ORNL), US Army Corps of Engineers Engineer Research and Development Center (USACE-ERDC), and the Federal Highway Administration within the Department of Transportation (FHWA/DOT) are a few examples of labs that have active programs in this area. These organizations are currently working on efforts to quantify decarbonization and carbon reduction methods for building materials, as well as efforts to reduce the embodied energy in existing infrastructure. There are lifetime extension efforts as well, for if the concrete used in new construction has a much longer lifetime, there will be a reduction over time in the concrete that needs to be made. These programs have aims to address circularity in concrete and pavement materials through design and applications such as precast and three-dimensional concrete printing (3DCP), alternative materials and additives, CO_2 injection, and accelerated carbonation.

2.3. Cement and Concrete in a Circular Economy

As previously stated, the current life of concrete predominantly follows a linear model in which raw materials are extracted, processed, and used before being discarded or reused in sub-structural applications at EoL. A more circular economic model aims to decouple materials demand from environmental degradation and resource depletion, keeping materials cycling through the economy for as long as feasibly possible. Further, unlike the linear economy, a CE aims to reduce waste and emissions by designing processes, products, and infrastructure that are efficient, durable, reusable, and repairable while producing materials that can be recovered and recycled at the EoL. A circular economic model thereby preserves natural resources, reduces environmental impacts of production, lessens demand for landfills, and creates value, new business opportunities, and new jobs. Figure 3 represents a circular economic model for cement and concrete, emphasizing the use of low-carbon cementitious materials as well as different mechanisms that can extend and close the life cycle of concrete components.

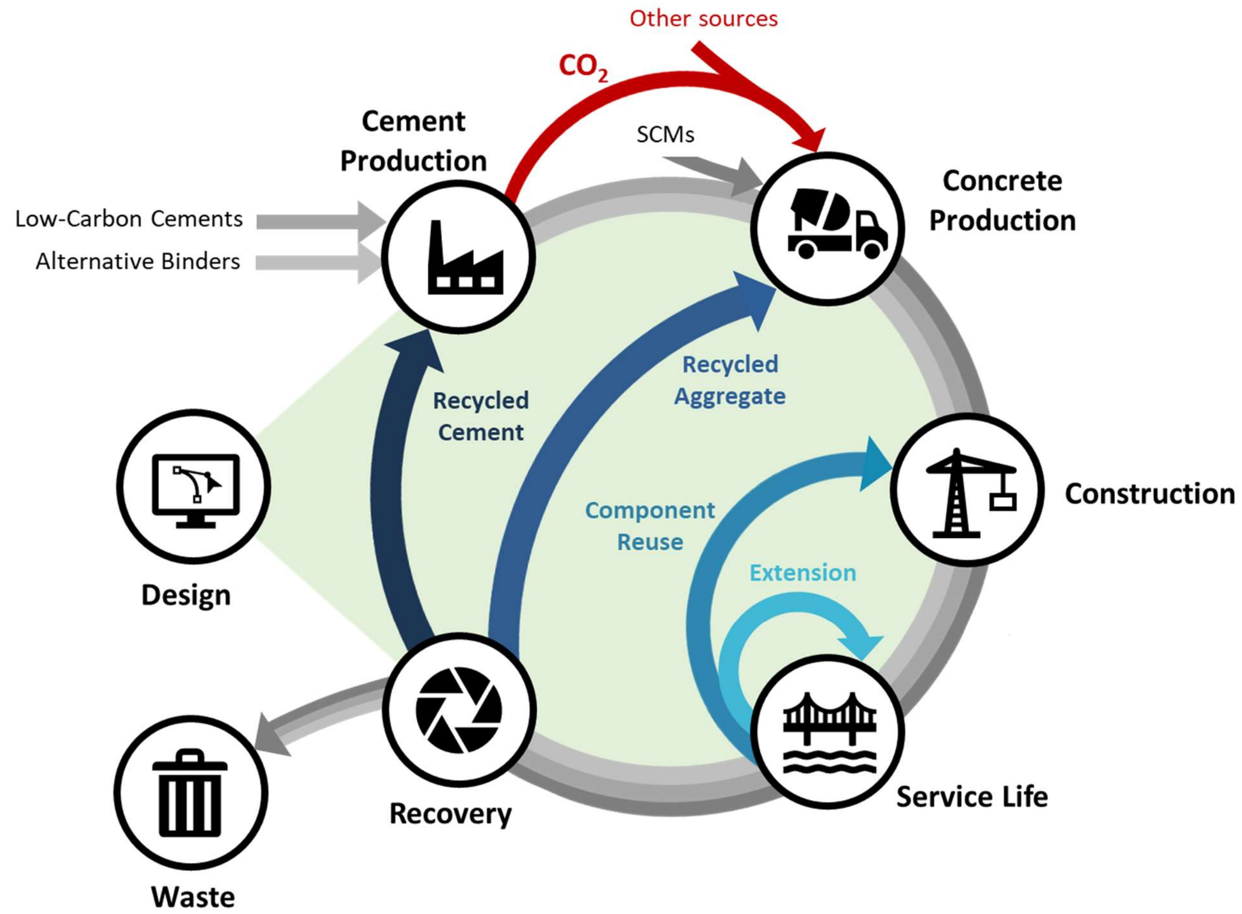

Figure 3: Circular economy system diagram highlighting low-carbon cementitious materials and mechanisms to close the life cycle and reduce the carbon impact of concrete materials and products; (SCM: Supplementary Cementitious Materials)

Changing how we design buildings and infrastructure may have the greatest potential impact on realizing a CE. This entails designing infrastructure with a focus not just on service and risk, but also design for circularity with consideration for low-carbon, high-performance materials; service life extension through monitoring, maintenance, and repair; as well as dismantling and reuse. Design for modular construction is one such approach that is estimated to reduce construction time and cost, as well as the capability for disassembly and reuse [6, 25]. However, changing our approach to design calls for proactive businesses and a trained workforce. Further, it necessitates changes in codes, standards, and policies to align with the shift in how projects are designed and delivered.

Key to the CE is the reduction of embodied carbon in the production of new cements and concrete infrastructure. Three predominant mechanisms to reduce carbon emissions from cement production include:

1) Improve the energy efficiency of cement production
2) Lower the cement content in concrete
3) Capture carbon emissions from cement production and utilize it (along with other industrial CO_2) in concrete

Energy efficiency improvements, renewable energy alternatives, as well as electrochemical and other alternative processes for cement production are being considered to reduce generated emissions. However, given that emissions from the fossil fuel heating sources only account for ≈40 % of the total CO_2 emissions, increasing energy efficiency has only partial impact on the total emissions associated with clinker production [1]. The use of Supplementary Cementitious Materials (SCMs) reduces cement production per cubic meter of concrete and is an active area of research. But cement replacement by traditional SCMs such as fly ash and blast furnace slag has limits beyond which mechanical or durability properties are compromised, and their availability will likely decrease with the ongoing departure from coal-fired power plants and reduced demand for pig iron in mature markets. Alternative SCMs such as limestone or calcined clay have the potential to provide sufficient volumes, although cement replacement by these materials may also be limited by performance and compositional constraints (e.g., impairment of early strength) [26, 11, 27]. Efforts are underway to develop alternative binders that produce lower or no process emissions during production (e.g., belite-rich Portland cement, magnesium silicate cement, and alkali-activated binders [28, 29]).

Carbon capture of the CO_2 released during the clinker production is an approach to reduce CO_2 emissions to the atmosphere. While efforts are underway to sequester captured carbon in geological formations, significant research is also taking place aimed at carbon sequestration in concrete. CO_2 can react with hydrated cement phases in the concrete, forming carbonates (such as limestone) [30]. This process, referred to as mineral carbonation, or mineralization, takes place naturally over the lifetime of concrete as atmospheric carbon is slowly taken up by hydrating cement. However, the process can be accelerated by the infusion of CO_2 early in the curing process and by using a binder that can almost be cured totally by CO_2. Carbonation depends on several environmental factors and on the microstructural features of the concrete. CO_2 can also be biologically mineralized in concrete with the help of microorganisms, a process known as biomineralization.

In addition to reducing the carbon impact of new concrete, a CE for cement and concrete includes preserving existing infrastructure, reuse of structural components, and structural recycling at end of service life. Through structural health monitoring, maintenance, and repair the life of buildings and infrastructure can be extended, thereby reducing the need for new construction. If infrastructure must be decommissioned, then reuse of structural components should be considered to the maximum extent possible. Ideally, recycling is only considered when structural components cannot continue in service and for recovery of production scrap and defective components. Recycled concrete should be prioritized for use as RCA in new concrete, while its use in backfill, pavement subbase, and other similar applications should be the last resort. The grinding and distribution of waste cement/concrete may be an additional CO_2 capture opportunity. Landfilling should be minimized to keep materials in the economy.

Through these mechanisms, a CE for concrete will not only reduce the waste generated through the demolition of buildings and other infrastructure, but also decrease the carbon impact associated with the production of new concrete. However, many challenges persist.

3. Current Circular Economy Efforts, Challenges, and Opportunities for Concrete

This section describes current efforts aimed at fostering a CE for cement and concrete, as described by workshop speakers and participants. The presentations focused on carbon capture and sequestration in concrete, including carbonation and biomineralization, as well as the reuse and recycling of concrete. Challenges facing these approaches are discussed followed by needs to overcome barriers. The section concludes with a list of potential measurement science action items that may help address the identified barriers.

3.1. Carbon Capture and Sequestration in Concrete

Significant research and development have focused on carbon mineralization through carbonation as well as biomineralization in concrete. Several workshop speakers presented ongoing efforts in this space, which are briefly summarized in Appendix B. Additionally, detailed information about the science and state of carbonation and biomineralization are provided in Appendices E and F, respectively. This section summarizes these efforts, as discussed in the workshop, beginning with carbon mineralization through carbonation. Biomineralization is then discussed with examples of its application in the construction industry.

3.1.1. Carbon Sequestration through Carbonation

Growing concrete demand combined with the uptake of carbon during curing suggests there is potential to sequester CO_2 in new concrete infrastructure. CO_2 captured from industrial flue gases and/or directly captured from the air (e.g., through direct air capture), can be embedded, or mineralized, into new concrete components. As depicted in Figure 4, under high temperatures limestone ($CaCO_3$) is calcinated into lime (CaO), releasing CO_2 as a byproduct. When lime is hydrated with water, a process called slaking, it forms a stable compound called calcium hydroxide, or hydrated lime (also referred to as portlandite). This hydrated lime then converts into calcium carbonate through carbonation, i.e., the re-absorption of CO_2 and evaporation of H_2O. Portland cement also contains calcium and magnesium silicates, oxides, and hydroxides, including lime, which similarly harden when hydrated and, under the right conditions, react with CO_2 to form carbonates [31]. Carbonation takes place naturally – i.e., atmospheric CO_2 is absorbed by curing concrete – and occurs at ambient temperature and pressure and continues over many years. However, the process can be accelerated by increasing the concentration of CO_2 and manipulating the moisture content and pressure regimes of the carbonation process [31]. Carbonation is a thermodynamically favorable reaction mechanism as it requires little, if any, extrinsic energy. Additionally, the carbonates formed are generally stable enough to outlast the life of the structure – i.e., representing the permanent capture of CO_2 [6].

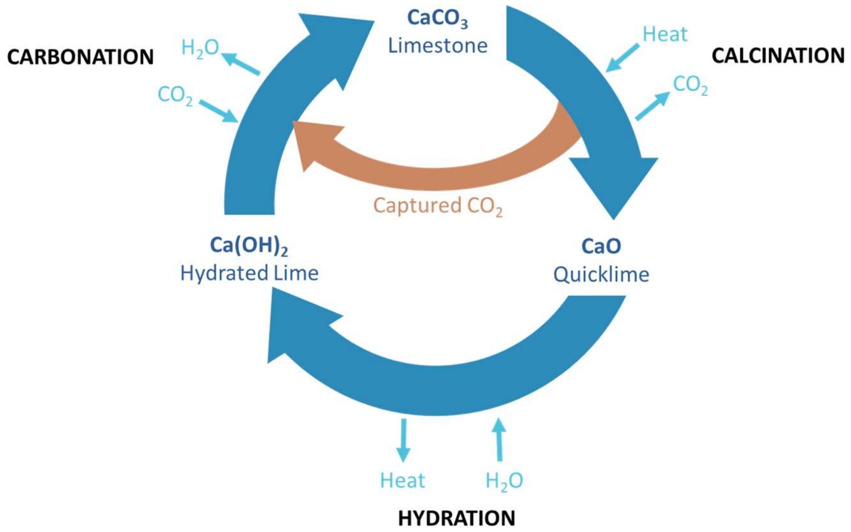

Figure 4: Lime cycle with carbonation form CO_2 capture (adapted from [6])

CO_2 captured from flue stacks (e.g., industrial emissions) may be advantageous relative to other sources [6]. For example, emission streams generated by the burning of landfill methane contains between 8-9 % CO_2, 80-90 % of which could reportedly be captured in concrete [6]. Carbonation in concrete is also generally insensitive to impurities such as sulfur and nitrogen oxides (SO_x and NO_x) that are often present with CO_2 in industrial emissions. The rate of carbonation relies on many factors such as the pore space, humidity, temperature, and exposed CO_2 concentration, all of which can be regulated on an industrial scale. The process may be accelerated by increasing the CO_2 concentration and manipulating the moisture content and pressure regimes of the carbonation process. Several companies are actively developing processes to capture carbon from flue gas streams (e.g., from powerplants) and utilize it in new concrete (see Appendix B for examples).

3.1.2. Biomineralization in Concrete

Under the right circumstances, biomineralization can also be a form of carbon capture. This approach utilizes microorganisms in concrete to mineralize CO_2 into calcium carbonate deposits. Theoretically, it is estimated that for every 1 kg of calcium carbonate formed, approximately 0.44 kg of CO_2 is sequestered [32]. While biomineralization occurs through multiple pathways, the three principal mechanisms include urea hydrolysis, photosynthesis, and sulfate reduction. Details about these mechanisms, including process reactions, are provided in Appendix F.

Microbial biomineralization can be used widely in construction applications, several of which are highlighted in Table 1. The most transformative application in terms of carbon-emissions reductions is likely self-healing concrete. This is not necessarily because of the quantity of CO_2 taken up, but rather because this application aims to produce more durable, and therefore longer lasting concrete. The premise of self-healing concrete is that when ureolytic microorganisms are added to fresh concrete – either directly or by encapsulating them in a hydrogel or other vascularized system –then the microorganisms resurrect upon damage (e.g., cracking) and enable sealing. The intent is to heal the concrete and fully recover mechanical integrity through biomineralization [32]. Challenges remain pertaining to the long-term viability and the long-term of survival of microorganisms in concrete. As such, this application requires further research prior to use in the field.

Applications of biomineralization in living building materials leverage microbes to engineer biological (limestone-based) concretes. Researchers are now able to produce large-scale biological concretes with the use of photosynthetic organisms and commercialization is underway (e.g., [32] [33]). The theory behind the biogenic limestone used for Portland cement and clinker production pertains to the natural limestone quarries that were developed in the past by photosynthetic biomineralizing organisms. Scientifically recreating that process could eliminate the calcination emissions of cement production by simply leveraging the natural ability of these microorganisms to produce and fix CO_2 in calcium carbonate.

Table 1: Construction applications of microbial biomineralization [32]

Construction Application	Description
Bio-deposition for Historic Preservation:	Microorganisms conserve stone by depositing calcium carbonate on the surface as a method of rehabilitation due to the weathering and dissolution caused by mildly acid rain [34]
Soil Stabilization and Biogeotechnics:	Use of microbial induced crystallization of calcium carbonate to improve the geotechnical properties of soil [35].
Self-Healing Concrete:	Addition of urealitic microorganisms to fresh concrete that become revitalize upon damage (e.g., cracking) to act as sealing agent [36]
Living Building Materials:	Use biomineralizing organisms to “grow” strong, tough biological concretes [37]
Biogenic Limestone for Portland cement and Clinker Production:	Effectively growing CO_2 storing limestone quarries using photosynthesis

3.2. Closing Material Loops through Reuse and Recycling

Current efforts aimed at closing the material cycles of cement and concrete predominantly focus on reuse and recycling. Reuse efforts commonly apply to concrete masonry units (CMUs) and less so to major structural components. Recycling efforts focus on CMUs as well as RCA for use in new concrete and for backfill and roadway applications. The following is a deeper dive into current reuse and recycling efforts and challenges encountered, as discussed in the workshop.

3.2.1. CMU Reuse and Recycling

The modular, segmental characteristics of dry-cast manufactured CMU products are uniquely suited for adaptive reuse. Depending on designer intent at the initial stage of design, CMUs can go together and come apart easily. Commonly, owners utilize CMUs when they are going to own a system for a long time (e.g., a century or more) and the system will need to be expanded at some point. A specific example is a landfill, which tends to be owned by local or jurisdictional governments and have 100-to-200-year lifespans. CMUs are utilized in initial design and construction and intended to be moved 40-to-50 years later as needed to expand the landfill footprint [38]. The reuse of interlocking pavers around trees and pathways has also proven beneficial. Challenges to reuse arise when CMUs are used in structural applications as mortar, grout, and rebar make it difficult to separate the units. That said, efforts are underway to utilize CMUs in load-bearing applications without the use of grout or mortar [38].

CMUs that cannot be reused, as well as units broken during production or handling, are ground and recycled into aggregates for use in new CMU production. However, the amount of this ‘regrind’ used can change the aesthetics and overall physical properties of new units. Below about 10 % by mass replacement of aggregate has little impact on overall color of finished product, while 10 % to 20 % can present unwanted shapes and colors within blocks. Regrind substitution above 40 % to 50 % by mass starts to deleteriously affect the physical properties of the CMU [38].

3.2.2. Recycled Concrete Aggregates

While this section provides a general overview of RCA, Appendix D includes detailed information about the production, use, and properties of RCA as well as guidance documents and the state of codes and standards relative to RCA use.

More than 400 million tons of RCA are generated annually in the U.S., 6 % of which is construction waste and the remainder demolition waste [39]. Construction waste has a higher potential for recycling, as it tends to have less variability and come from a known source where it likely met a specification of some type. Demolition waste, on the other hand, is often produced from mixed supplies containing various sources and materials.

As displayed in Figure 5, RCA is utilized in bound and unbound applications in the U.S. RCA is used as a fill material, filter material, and drainage layer as well as in unbound stabilized and unstabilized subbases. Additionally, RCA has been used in various pavement applications including in single and two-lift Portland cement concrete pavements as well as hot-mix asphalt pavements.

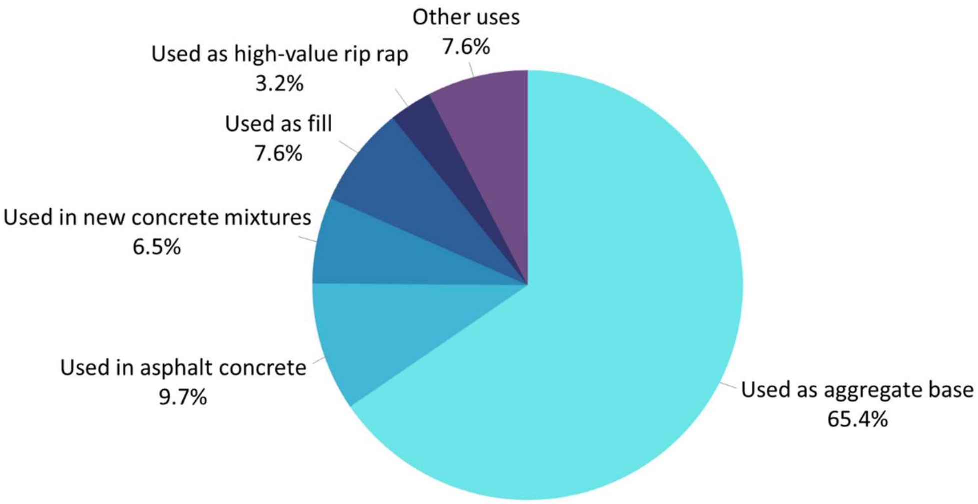

Figure 5: Current end uses of RCA (adapted from [39])

The utilization of RCA is of particular interest for urban areas, due to the fact that most development (especially with concrete) takes place in urban areas. Thus, RCA can be more readily available than natural aggregates and possibly cheaper due to the high transportation costs associated with hauling waste to landfill and virgin aggregates to job sites [18]. That said, the production emissions resulting from RCA compared to natural aggregate are comparable – 0.0012 kilograms and 0.0037 kilograms of GHG are emitted per kilogram of RCA and crushed aggregate produced, respectively [18]. The small difference in processing emissions suggests that embodied CO_2 benefits are dependent on transportation reductions. Additionally, the use of RCA can reduce project cost and schedule as well as potentially improve pavement performance when utilized in concrete paving projects [39].

3.3. Challenges Facing a CE for Cement and Concrete

Several challenges facing circular pathways were brought to light through the workshop. As depicted in Table 2, speakers and participants identified barriers facing a CE generally, challenges specific to carbon mineralization via carbonation and biomineralization, as well as challenges facing concrete reuse and recycling.

Table 2: Challenges facing a CE for cement and concrete generally, and specific to carbonation, biomineralization, and reuse and recycling pathways

General
- Established industry and existing manufacturing infrastructure - Insufficient policies and standards to accelerate adoption of low-carbon cements and concretes - Unclear how to compare concrete reduction pathways - Undetermined and unstandardized formulation and performance requirements of low-carbon cement and concrete - Lack of defined terms and measurable data for LCA modeling - Lack of tangible offtake agreements between owners and cement producers - Lack of knowledge of how to handle new/recycled materials
Carbon Sequestration via Carbonation
- Lack of understanding of CO_2 capture mechanisms and pathways limits technology advancement - Uncertainty regarding: 1. Scalability of CO_2 injection technology – a critical factor to adoption, and 2. The potential for additional benefits from improved performance optimization - Nascent measurement methods to quantify CO_2 uptake - Distinguishing between natural and accelerated carbonation
Biomineralization
- Limited ability to perform in situ polymorph characterization (i.e., of calcite, vaterite, aragonite) - Lack of viability measurements within concrete and other biomineralized building materials - Uncertainty regarding the type and quantity of embedded in situ biominerals - Lack of standards for characterization and durability testing of new phenotype of biomineralized building materials - Lack of prototyping and demonstration testbeds thwarts commercialization
Concrete Reuse and Recycling
- Design standards and practices do not currently support reuse and/or recycling at EoL - Lack of understanding and training for infrastructure decommissioning in support of component reuse - Lack of characterization/quantification of contaminants in RCA and their impact in new concretes - Concerns about adhered mortar in RCA and its influence on mechanical properties of new concretes

Challenges facing carbon sequestration in concrete

Many of the challenges facing carbon sequestration in concrete (irrespective of approach) stem from the liability risk created by the adoption of new technologies in the building sector. Changes to methods and/or materials could create perceived vulnerabilities and, hence, there is a significant need to prove long-term material performance and durability before new materials will be accepted.

Additionally, construction is a long-established industry with mature technologies, established supply chains, capital investments with long lifetimes, and relatively low profit margins. As a result, it is technically and economically challenging to deploy new formulations. Many businesses over the past few decades have shifted to a low-risk financial management model – away from a more innovation-driven model – and thus there is limited willingness among industry to explore new materials and approaches. New policies such as the Federal Buy Clean Initiative [40] are providing incentives, yet the challenge remains of creating an infrastructure that fosters adoption of novel technologies.

The current approach to procurement further challenges the adoption of novel materials and approaches due to the lack of tangible offtake agreements between infrastructure owners and cement producers. For instance, in public procurement situations, government agencies procure through design-build contracts in which multiple layers of intermediaries (e.g., contractors, subcontractors, ready-mix companies, and cement plants) are involved. This structure tends to leave contractors broad autonomy for implementation and results in high variability of demand by project.

Many existing policies and standards inhibit the advancement and development of carbon sequestration strategies in concrete. Current building codes and standards have evolved over the past ≈100 years and, for logical reasons, have explicitly favored safety and risk minimization at the expense of new technology and innovation. As a result, until novel (e.g., low carbon) materials are economically competitive and demonstrate reliably similar (or better) performance and durability, the incumbent will continue to be favored.

Challenges also stem from the very narrative of embodied carbon reduction efforts. Effectively and rapidly decarbonizing concrete requires carefully ascertaining whether efforts should be aimed at promoting CO_2 avoidance and/or utilization, or neither [6]. Until the underlying narrative is decided, building momentum and gaining support for modifying traditional construction practices will be difficult. Developing consensus on definitions, accounting, tradeoffs, and available data is necessary to determine a framework or structure for choosing the right strategies. For example, the amount of total carbon sequestration in concrete is a function of the calcium hydroxide content. However, significant efforts are underway to minimize the use of calcium hydroxide in concrete altogether (e.g., lower paste contents, higher replacement of SCMs, lower clinker content in cements). These two efforts both aim to reduce the carbon footprint of concrete; however, they compete with one another. It is currently unclear how to directly compare the various carbon reduction approaches, and even the different utilization pathways. This supports the point that consensus on the measures, data, and frameworks for decisions and strategies need to be developed to determine the best path(s) forward. This effort should also consider differentiation between local, national, and international considerations and circumstances.

The sequestration of carbon in concrete through carbonation is inhibited by persistent measurement and technology-related challenges. The most suitable concentration of CO_2 injected into concrete is yet to be fully determined. This is inhibited, in part, by measurement-related challenges that hinder the ability to detect how much CO_2 is reliably captured. It is also difficult to distinguish between natural and accelerated carbonation. As such, the most effective strategy for capturing CO_2 in materials is yet to be fully understood.

Biomineralization is challenged by limited in-situ polymorph characterization, which is needed to determine what polymorphs (e.g., calcite, vaterite, aragonite) are precipitated in the reactions. It is also difficult to measure the number of bacteria that are in a solid system. While Raman Spectroscopy is currently utilized to characterize the type and quantity of embedded in-situ biominerals, this approach is limited in its ability to do this in a rapid throughput state or at large scale. In addition, no standards currently exist regarding the characterization and durability testing of biomineralized building materials. Concrete standards are currently relied upon, although they do not necessarily adequately fit this new type of building material. Additionally, accelerating the commercialization of these new technologies requires prototyping and standardized demonstration testbeds, as well as standard reference materials and process calibrations, which do not yet exist.

Challenges facing Concrete Reuse and Recycling

Current design and construction practices do not necessarily support the reuse of infrastructure and building components upon deconstruction, nor do they promote material recycling at the end of service life. Furthermore, those working in the construction/demolition industry are not trained on how to deconstruct with salvage in mind. Nor are reverse logistics systems (such as dedicated collection bins) commonly in place to capture reusable or recyclable materials during deconstruction.

Several technical barriers prevent the increased utilization of RCA. As previously mentioned, the majority of RCA is derived from demolition waste, which generally comes from a combination of sources. As a result, RCA may be contaminated by other materials such as asphalt, brick, gypsum, glass, or metals. These contaminants can lead to air entrainment problems as well as have other negative impacts [39]. Some level of contamination is tolerable in certain applications such as unstabilized subbases and backfill, but characterization and removal may be necessary in structural applications.

Due to the attachment of mortar or cement paste in RCA, new concrete utilizing this material requires additional cement to offset the increased water absorption due to the porosity of the remaining paste (as much as 6 - 8 %) [41, 9]. In paving applications, concerns arise regarding the water demand and premature stiffening. These can be addressed by limiting or eliminating fine RCA, presoaking the RCA, and applying mineral admixtures. However, characterization of the RCA is necessary to determine the appropriate adjustments. Additionally, the increased porosity could render RCA concretes more vulnerable to freeze-thaw degradation. Due to the impact on fresh and hardened properties of concrete, RCA is increasingly reserved for where there is a lower load requirement. In effect, RCA currently needs to be treated as an "engineered material" and mixes and structural designs must be modified accordingly [39].

Combatting the negative side effects of adhered mortar is a current research question. Some approaches include modifying the RCA surface by coating RCA with polyvinyl alcohol, sodium silicates, silica fume, nano silica, and even cement slurries. Such treatments are designed to fill the pores of the adhered mortar and improve the bond strength at the interfacial transition zone (ITZ) between new and existing concrete but may suffer from added cost [41]. It can be advantageous to remove as much of the old cement paste as possible rather than applying additional treatment methods. Some companies are actively working in this space to develop technologies and processes to remove adhered cement paste from pre-crushed demolition waste and recover clean aggregate for reuse (see Appendix B for examples).

Several non-technical barriers also hinder the increased utilization of RCA in practice, including economics, knowledge transfer, and logistics. The economics associated with recycling concrete into aggregate are not well publicized, thereby hindering practitioners' adoption of the practice. More publicly available data are needed on the cost of start-up and equipment as well as examples of successful implementations from an economic standpoint. Knowledge transfer is another hurdle, as published literature is not necessarily made available to, or read by, stakeholders that need it. Industry needs to create new information materials and distribute them to a broader audience, in particular the smaller concrete operations that may not have time and/or funding to develop new materials and new knowledge. Logistically, the space necessary to incorporate RCA processing equipment and materials can be a setback as many concrete plants, particularly in urban environments, cannot accommodate more and varied streams of aggregates. Similarly to the adoption of low-carbon cements and concrete, the risks and liability associated with utilizing RCA is another barrier. Unknowns regarding the variability and long-term durability of this material limit its use in the field, particularly in loadbearing applications. It is not clear at present who bears the risk for a new material.

3.4. Needs to Overcome Challenges for Advancing Circularity

The above challenges are possibly resolvable but necessitate further research, advances in assessment tools, technological development, and new standards. Table 3 presents a collation of necessary actions to facilitate circularity generally, as well as to advance carbonation and biomineralization, specifically.

Table 3: Needs to Advance a CE for Cement and Concrete based on Workshop Findings

Needs to Advance a CE for Cement and Concrete
- Agreed upon narrative for reducing embodied carbon of concrete - Consensus on terms, accounting metrics, and available data to determine a decision strategy framework - Uniform, robust, and transparent assessment tools (e.g., life cycle assessment (LCA)) - Standardization of low carbon cement and concrete (e.g., formulation requirements, performance specifications) - Education and training of the labor force on how to design with and handle new materials - Coordinated regulatory and/or market pull and investment in rapid technology scaling - Identification of carbon-related structural metrics - Development of metrics and benchmarks for CO_2 uptake - Identification of additional benefits from improved performance optimization - Development of measurement methods to: 1. Understand CO_2 capture mechanisms and pathways 2. Distinguish between natural and accelerated carbonation 3. Quantify CO_2 uptake under different scenarios and input stream carbon concentrations 4. Advance in situ polymorph characterization and quantification of biominerals

Assessment tools such as uniform, robust, comprehensive, and transparent life cycle assessments (LCA) are needed to help identify the leading implications associated with carbon sequestration or mitigation and therefore to help dictate a common narrative and unified path forward. However, the inputs to LCAs must be soundly based on measurement science.

Advances in measurement methods aimed at quantification and validation of carbonation are also necessary to propel this sector forward. Such efforts should focus on distinguishing between natural and accelerated carbonation as well as quantifying carbonation at various stages of the life cycle. This necessitates developing metrics and benchmarks for carbon uptake. Quantitative microstructural and structural characterization can be advanced to validate model predictions and/or claims for carbonation, which would be particularly useful for standards.

In addition, appropriate structural metrics are needed relative to carbon metrics. For example, metrics such as CO_2 per ton or m^3 are often seen but associating carbon metrics with structural components (e.g., columns) such as CO_2 per unit of load capacity or per unit of height might have significant implications for driving change. Alternatively, collating structural metrics with LCA of the material could similarly be used to support the inclusion of carbon accounting in infrastructure design. In this sense, having more appropriate metrics would be helpful for designers and architects looking to optimize whole building designs. Similarly, advances are needed to more reliably link metrics of environmental performance (such as EPDs) to a particular concrete mixture. Current approaches focus on mix design, but alternative methods are needed to "fingerprint" the concrete to ensure traceability.

Consensus-based standards are needed to provide harmonized terminology, metrics, measures, and benchmarks, as well as to specify formulation and performance requirements of novel concrete materials. Standardized methods are also needed to enable reliable comparison of the various carbon reduction technologies and pathways. LCA modeling tools are one approach to this, however, they tend to not be transparent, repeatable, or verifiable. Existing LCA standards such as ISO 14040 [42] and 14044 [43] can be a good start for LCA. However, they are open to interpretation and face challenges when including 'wastes' such as CO_2 or fly ash. Standardized methods to quantify carbonation at various stages of the life cycle are also necessary to unify measurement methods and processes. In addition, standards are needed to provide guidance to suppliers and contractors regarding how to provide good quality construction as well as ways for engineers to assess construction quality. This will play an important role in giving engineers confidence in the performance of these materials and lead to their increased adoption. It is important that standards be performance-based to allow new, innovative technologies to come to market and be readily adopted in specifications.

Some of the non-technical issues facing the increased use of RCA could be addressed with policy actions, but at present there is little political will to increase the use of RCA. Current policy momentum is aimed at improving the embodied carbon in concrete such as resolutions promoting the use of concrete carbon storage technologies and GPP policies requiring the disclosure of carbon impact in public projects through EPDs [18]. These efforts are focused heavily on carbon reduction; however, as previously mentioned, RCA does not necessarily reduce the carbon impact of concrete and thus policies need to include other sustainability aspects beyond carbon reduction to include RCA.

4. Potential NIST Action Items to Facilitate a Circular Economy for Concrete

NIST could play an important role in addressing many of the challenges and needs described above. Specifically, NIST could contribute to measurement science; data, traceability, and modeling tools; standards development; education/training; and convening necessary stakeholders in workshops and consortia; and supporting the development of a circular economy roadmap.

4.1. Measurement science

NIST, with industry, has the capability to advance the measurement science needs identified in the workshop. NIST could perform pre-competitive research that can provide a foundation and help move the whole industry forward. Examples of measurement science that NIST could perform, or support include:

Measurement Science

- Development of measurement methods for CO_2 uptake assessment
- Rheology control of 3D printing slurries
- In situ polymorph characterization of biominerals
- Characterization of the type and quantity of embedded in situ biominerals
- Standardized demonstration testbeds for biomineralized materials
- Characterization of RCA properties including mortar phase and aggregate phase as well as contaminants
- Identification of the influence of contaminant variability on the properties and durability of RCA concrete products
- Measurement tools for variability within a stockpile of RCA
- Performance and property (e.g., strength) measurements to prove integrity of RCA
- Real-time rheology of hydration behavior for cement and concrete
- Large-scale applicability and longevity studies of recycled products use

4.2. Standards Development

NIST could support the development of standardization protocols and standards necessary to support consistency and reliability in the industry. Standards development requires verification methods that rely on extensive metrology and benchmarking, tasks in which NIST has experience. Examples of standards NIST could help develop include the following:

Standards Development

- Guidelines for LCA modeling including the utilization of ‘wastes’ (e.g., fly ash, CO_2) in concrete and comparing low carbon pathways,
- Standardization of low carbon cement and concrete
- Characterization of biomineralized building materials
- Durability testing of biomineralized building materials
- Performance metrics for biomineralized construction products
- Standard reference materials (SRMs), reference materials (RMs) and process calibrations
- Guides for design-for-circularity: e.g., circular material design, design for deconstruction, modular design, etc.
- Standards for testing of RCA stockpiles: i.e., standard sampling techniques to select test specimens
- Certification of recycled concrete materials based on quality/grades
- Standardized documentation for the traceability of concrete
- Alternative aggregate standard applicable to RCA or caveats into e.g., ASTM C33 to show that RCA is an engineered material and not just any other aggregate
- Guides on deconstruction for circularity

4.3. Data, Traceability, and Modeling Tools

NIST could provide data repositories and registries following FAIR data principles (Findable, Accessible, Interoperable, and Reusable). All data infrastructure should be publicly accessible and interpretable by all stakeholders. Where data exists, NIST could aggregate the data and make it accessible through comprehensive data registries and repositories. In this way, NIST could help make available the following data:

Data, Traceability, and Modeling Tools

- LCA inventory data
- Material characteristics of carbon-mineralized concretes
- Material characteristics of biomineralized concretes and other biomineralized construction products
- Public database of industrial carbon emission sources
- Public database of carbon capture and sequestration service providers
- Digitization of building products into accessible databases for future use/reuse
- Prediction of impacts of RCA on long term durability of concrete, based on mix design and quality of materials to determine which applications and exposure conditions may or may not be suitable
- Data inventory expansion and availability to advance and compare LCA modeling of circular concrete and gypsum
- Comparison measurements for sustainability related back to CO_2 so that CO_2/embodied carbon is not the only measurement of environmental impact
- Traceability tools to track concrete through the value chain; including materials, provenance, service locations, etc., to help identify how RCA and gypsum debris could be used in the CE rather than putting it in the lowest risk case possible
- Economic assessments of the processing and utilization of RCA, including capital expenditures and return on investment

4.4. Education/Training

NIST can also support education and training of the current and future workforce. Educational program development should aim to strengthen the technical and practical skills of a workforce prepared to extend beyond the status quo. Training programs should promote the development of a skilled and distributed workforce capable of incorporating innovative materials into the construction of new infrastructure. NIST can support such efforts with a specific focus on the following topics:

Education/Training

- Design and engineering support utilizing low-carbon concretes and RCA
- Internship opportunities for innovating and testing new materials
- Support for academic curricula incorporating CE principles
- Guides for deconstruction in a CE

4.5. Convener

NIST often fosters collaboration towards common industry sector goals, such as circularity, by serving as a convenor of industry, government, and non-profit organizations. Substantial efforts are already underway in multiple regions of the country and sectors of the industry, and NIST could help ensure these efforts are performed in collaboration and promote the exchange of knowledge and information. NIST continues to look for ways to bring stakeholders together to talk about approaches and strategies to support circularity.

4.6. Roadmap Development

A Roadmap for a Circular Economy for Concrete and/or Gypsum could provide a clear plan mapping out the timeline and path to transition to a CE. Such a roadmap would identify opportunities across the value chain related to how waste can be minimized and how infrastructure and associated materials can be repaired, reused, or recycled. It can further identify new technologies, products, services, and industries needed for, or emerging from, circularity as well as stakeholder roles and necessary collaborations. The roadmap can also outline how C&D waste will be tracked and measured, including how and where it is collected and how much of the collected volume is recycled versus discarded. The roadmap could outline the timeline of strategy implementation, including technology development and deployment, standards development, and policy design and enactment.

NIST could be a partner in supporting completion of a roadmap of this nature. For example, NIST's Office of Advanced Manufacturing (OAM) periodically releases funding opportunities for roadmap development, such as the Manufacturing USA Technology Roadmap Program [44]. This program in particular aims to establish new or strengthen existing (e.g., [45]) industry-driven consortia that address high-priority challenges and increase U.S. competitiveness and innovation in manufacturing. Roadmaps developed through programs such as this have the potential to influence significant future funding opportunities across the federal government.

5. Beyond Concrete

The CE pathways for cement and concrete can also be applied to other construction materials. Steel, asphalt, glass, wood, plastics, and gypsum are examples of other commonly used materials in the built environment with unique environmental impacts, most of which could be lessened through a CE. Gypsum, in particular, was discussed in the workshop as a construction material that is capable of increased circularity if barriers are addressed. Gypsum is a common raw material for manufacturing various construction products including plasters, drywall (wall board or plasterboard), ceiling tiles, partitions, and wall blocks and is even used in the portland cement industry as a retarder to help control flash (I.e., very early age) setting of cement. Gypsum wall board is the most common indoor building material in the U.S., which means that, like concrete, the environmental impacts result from its mass production as well as waste generation at end of service life of a building [46]. Many of these environmental impacts could be lessened with increased circularity. Appendix G dives deeper in the production, use, environmental impacts, and circularity of gypsum, as discussed in the workshop.

Recovering gypsum products for reuse or recycling necessitates the careful demolition of plasterboards and panels, which requires additional time, labor, and resources (e.g., dedicated on-site collection container) compared to standard practice. Upon demolition, current practice includes mixing wallboard scraps with other debris that are then hauled either to landfills or to processors for use in agricultural applications (e.g., as a fertilizer or for soil amendment) [47]. Similarly, recycling of these products also requires either dedicated collection systems on-site (i.e., separate from other C&D debris) or a system of separation from comingled C&D debris. The removal of potential contaminant, such as nails, screws, trim, and paint, is also necessary. Safety is a concern due to the potential for materials introduced to the gypsum during its service (e.g., lead paint, asbestos, unknown additives) as well as from unknown sources of gypsum products (e.g., imported from other countries) that may have unknown properties. Many of these challenges also are present in other construction materials.

These obstacles can be overcome through material handling and feeding adjustments, process modifications, and significant investment in research and development. Implementing reuse or recycling of gypsum and other building products at scale necessitates changing the current practice of deconstruction. Therefore, modification and development of codes and standards may also be useful to drive the deconstruction industry toward more circular practices. However, the role of design cannot go overlooked. Architects, designers, and engineers play a key role in ensuring all building components and materials are capable of and suitable for recovery at EoL.

Cement and concrete and other building materials like gypsum are foundational to the present and future world economy. But we need to abandon the linear economy that has defined the use of these materials. A decarbonized and circular economy for construction materials is necessary to reduce the significant environmental impacts caused by the industry, while providing essential structures to a large and growing American population and sustaining the high quality of life associated with our Nation. This is a challenge and an opportunity for the current generation and beyond.

Technologies to facilitate circularity and reduce the embodied carbon in concrete exist and continue to be developed. However, this is an industry that is conservative, commoditized, and price sensitive. NIST can help by utilizing its many capabilities to advance measurement science, support standards development, and enhance the data systems and tools needed to expedite the transition to a low-carbon, circular economy in construction.

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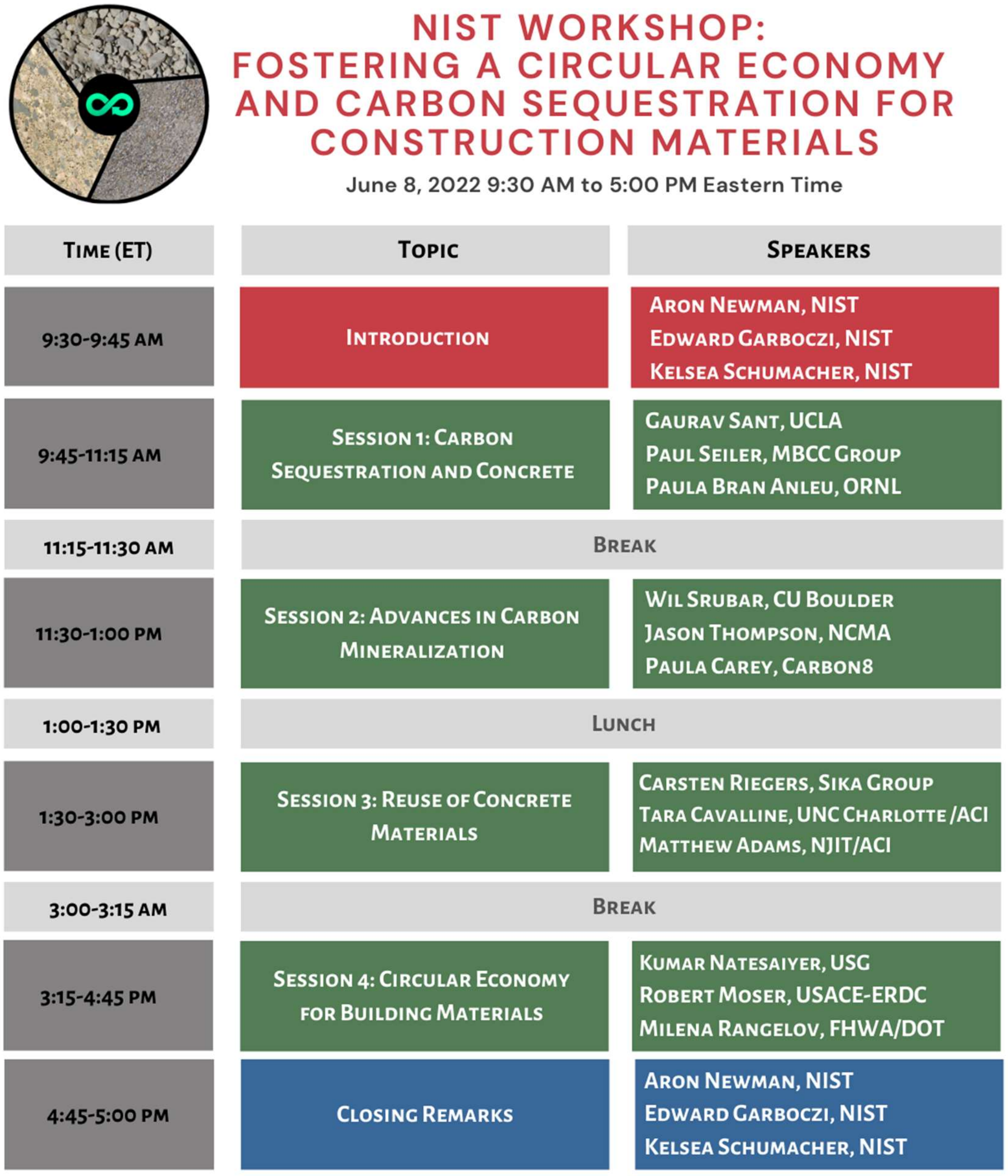
Appendix A. Workshop Agenda and Speakers



NIST WORKSHOP:
FOSTERING A CIRCULAR ECONOMY
AND CARBON SEQUESTRATION FOR
CONSTRUCTION MATERIALS

June 8, 2022 9:30 AM to 5:00 PM Eastern Time

TIME (ET)	TOPIC	SPEAKERS
9:30-9:45 AM	INTRODUCTION	ARON NEWMAN, NIST EDWARD GARBOCZI, NIST KELSEA SCHUMACHER, NIST
9:45-11:15 AM	SESSION 1: CARBON SEQUESTRATION AND CONCRETE	GAURAV SANT, UCLA PAUL SEILER, MBCC GROUP PAULA BRAN ANLEU, ORNL
11:15-11:30 AM	BREAK	
11:30-1:00 PM	SESSION 2: ADVANCES IN CARBON MINERALIZATION	WIL SRUBAR, CU BOULDER JASON THOMPSON, NCMA PAULA CAREY, CARBON8
1:00-1:30 PM	LUNCH	
1:30-3:00 PM	SESSION 3: REUSE OF CONCRETE MATERIALS	CARSTEN RIEGERS, SIKA GROUP TARA CAVALLINE, UNC CHARLOTTE /ACI MATTHEW ADAMS, NJIT/ACI
3:00-3:15 AM	BREAK	
3:15-4:45 PM	SESSION 4: CIRCULAR ECONOMY FOR BUILDING MATERIALS	KUMAR NATESAIYER, USG ROBERT MOSER, USACE-ERDC MILENA RANGELOV, FHWA/DOT
4:45-5:00 PM	CLOSING REMARKS	ARON NEWMAN, NIST EDWARD GARBOCZI, NIST KELSEA SCHUMACHER, NIST

Appendix B. Summary of Invited Talks

Session 1: Carbon Sequestration and Concrete

Gaurav N. Sant, Professor of Civil Engineering and Materials Science and Engineering, Pritzker Endowed Chair in Sustainability, and Institute of Carbon Management Director, University of California, Los Angeles (UCLA): "CO_2 mineralization and UltraFAST solidification: Pathways for decarbonizing concrete construction"

Prof. Sant's talk dealt with circularity in construction focused on CO_2-cured new materials. The big picture involved: (1) gathering CO_2 from industrial flue gas sources, (2) forming concrete masonry units (CMU) and curing them with the flue gas CO_2, and (3) constructing with such prefabricated components to enable rapid construction and rapid, easier reuse. He then stepped back to argue why calcium-based cements will remain in our future, because of their abundance in the earth's crust and ease of processing. He developed the system of using/reusing CO_2 by: trapping the gas that comes from the production of calcium hydroxide (portlandite) and then using it to cure the portlandite-based concrete, for a net-zero release of CO_2 into the atmosphere. The key parts of this technology were demonstrated at the pilot scale in Wyoming and at the National Carbon Capture Center in Alabama and are under commercial development from the CarbonBuilt company spun-off from Prof. Sant's research. This kind of material is especially well-suited for robotic 3D-printing of structures, which vastly increases design space and enables construction of optimal structures. A new technology called UltraFAST solidification that Prof. Sant is working on will greatly help in this area. Finally, Prof. Sant discussed the need for clarification in the LCA space between carbon avoidance and carbon utilization and between natural and accelerated carbonation, with the development of standard measurement methods for CO_2 uptake.

Paul Seiler, Director of Technology, Master Builders Solutions, MBCC Group, "Carbon Sequestration and Concrete"

Dr. Seiler gave an overview of the various ways lowering carbon use can be considered in the concrete construction industry, from the point of view of Master Builders Solutions, which is a developer and manufacturer of chemical additives that are aimed at solving many of the problems in concrete. While concrete has many great qualities, including availability, durability, fire resistance, strength, resilience, versatility, place-ability, thermal properties, and carbonization over time, regular cement production is CO_2-intensive. Reducing the carbon footprint of concrete involves using recycled aggregates, using supplementary cementitious materials to partially replace and lower the use of cement, and using chemical admixtures to lower the use of the cement as far as it can go in highly optimized mix designs. Several examples of these kind of mix designs were shown for large, completed construction projects. Absorbing CO_2 during production and/or curing can also be beneficial but there are differences between mixing and curing usage. Further industrialization, along with co-location of CO_2 sources with CO_2 usage facilities in pre-cast sites, can help in lowering the carbon use in the concrete construction industry.

Paula Bran Anleu, Associate Technical Professional, Nuclear Structures and Construction, Oak Ridge National Laboratory (ORNL): "Overview of ORNL activities on developing low-CO_2 emission building materials"

Dr. Anleu focused on what ORNL, a US Department of Energy laboratory, is doing in the broad space of developing low-CO_2 emission building materials. As an introduction, Dr. Anleu mentioned that while cement and concrete has one of the lowest carbon footprints per mass, the vast volume used every year worldwide makes them one of the highest carbon emitters in construction materials. In the ORNL Building Technologies Research and Integration Center, research is being pursued over many length scales of building technologies. One area is using biobased, fully renewable polymer feedstocks to: (1) produce foam insulation that is simple to recycle, (2) develop low-carbon sealants for prefabricated components, and (3) produce 3D printed construction molds that are cheaper and easier to reuse than regular polymer molds. ORNL is developing databases for the critical properties that are needed to promote the use of biobased materials for building envelopes. There is work on converting coal, a national resource of carbon, into value-added products. There is research on harvesting the tremendous amount of coal-ash stored in ponds, using it to simultaneously lower carbon footprints in concrete construction and reducing the environmental risk of coal-ash storage ponds. Finally, there is work on carbon mineralization for concrete alternatives, focusing at present (at the pilot scale) on large pre-cast panels and additive manufacturing applications using carbon dioxide-cured slaked lime slurries.

Session 2: Advances in Carbon Mineralization

Wil Srubar, Associate Professor, Department of Civil, Environmental, and Architectural Engineering, Materials Science and Engineering Program, University of Colorado Boulder: "Advances in Biomineralized Building Materials"

An alternate path to using CO_2 to cure building materials is through biological means using microbes. There are several paths to doing this, which fall into either biologically-induced or biologically-controlled mineralization. Different crystal structures and properties of the mineralized calcium carbonate can be produced, depending on microbe metabolism. Areas of application include biodeposition for historic preservation, soil stabilization and biogeotechnics, self-healing concrete, and what is probably of most relevance to this workshop, growing strong, tough biological concrete and biogenic limestone for Portland limestone cement and clinker production. Two start-up companies called Prometheus Materials and Minus Materials have been formed to commercialize these technologies. There are workshop attendees from Biomason, a company developing biologically-cured concrete masonry units.

Jason Thompson, VP Engineering, National Concrete Masonry Association (NCMA): "Carbonation and Circular Economy – Through the Lens of Manufactured Dry-Cast Concrete"

What is currently called “concrete masonry units (CMU),” prefabricated blocks composing thousands of products that can be built into large structures, in the past were known as the humble “cinder block.” They are currently made in what is termed “dry-casting”, low water-cement ratio material compressed into molds at a manufacturing plant. They are of relevance to the themes of this workshop in (at least) two ways. New CMUs can incorporate a large amount of “regrind”, which is waste material from the manufacturing process or demolition process. Their modular structure makes for easier reuse after demolition, which is a measure of CMU circularity. However, the presence of old mortar and steel rebar in more structural applications complicates reuse. Because of their porous structure, CMUs can absorb atmospheric CO_2 much faster than regular poured or pre-cast concrete. Today, the dry-cast concrete products industry is starting to integrate constituent materials, segmental products, production flexibility, and accelerated and natural carbonation to improve the circular economic and low-carbon aspects of CMUs.

Paula Carey, Chief Technical Officer, Carbon8 Systems: "Carbonation of Alkaline Residues in the Manufacture of Lightweight Aggregate”

Dr. Carey’s talk covered carbonation and mineralization, the history of Carbon8 Systems, products from carbonation, CO_2 capture capacity, and how value is generated in this process/business. The focus of Carbon8 is on industrial thermal residues, such as steel slags, various ashes from Energy-from-Waste power plants, and cement production residues, to permanently capture CO_2 without using large amounts of energy. Carbon8 uses semi-dry carbonation, at atmospheric temperature and pressure conditions and commercialized this technology in 2010. Currently, there are three plants treating air pollution control residues in the UK using pure CO_2 and the company is developing technology to use CO_2 directly from flue gas. There were two demonstration deployments in Ontario (2018) and in the UK (2019), with the first commercial deployment in 2021 with the Vicat Cement Group in France. Carbon8 has recently developed The CO_2ntainer – Carbon Capture in a Box, which is a Plug ‘n Play carbon capture, utilization, and storage (CCUS) solution that is retrofittable into any existing industrial plant. Finally, a current focus of the company is carbonating by-pass dust produced in the cement manufacturing process (primarily a result of a change to alternative fuels) to produce light-weight aggregates.

Session 3: Reuse of Concrete Materials

Carsten Riegers, Sika Group: "reCO$_2$ver - From Urban Mining to CO_2-Sequestration"

Sika wanted to address the issue of downcycling – where demolished concrete is mainly not used structurally but rather for lower-end applications such as fill or road-base material. These applications are usually end-use and are not capable of contributing to the circular economy concept in concrete. The basis, therefore, of the reCO$_2$ver process is taking concrete demolition waste (CDW), pre-crushing it, exposing the aggregates that are covered with mortar to CO_2, which carbonates the mortar. Due to mechanical impact during this carbonation process, the aggregates separate from the carbonated mortar, with the outcome of the process being cleaned aggregates in separated fractions and the carbonated mortar as powder that can both be reused in new cement and concrete. The main drawback to current recycled aggregates is excessive water absorption due to adhered mortar. Sika has shown that the aggregates coming out of this process have almost the same water absorption properties as virgin aggregates. Chemical admixtures are used in this process to improve the quality of the output materials. This process has been demonstrated successfully at the pilot scale and should contribute to a more circular economy for concrete by making it more possible to use (and reuse) recycled concrete in structural materials.

Tara Cavalline, Associate Professor, Civil Engineering Technology & Construction Management, University of North Carolina at Charlotte: "Recycled Concrete Aggregates: Current Practice, Implementation Challenges and New Guidance"

The focus of Prof. Cavalline's talk was how the use of recycled concrete aggregates (RCA) can increase pavement sustainability and circularity. Increased use of RCA in bound and unbound applications in concrete paving projects can address challenges such as dwindling landfill space and increased disposal costs, increased demand for aggregates, and reduced availability and longer hauls for virgin aggregates. Use of RCA provides reduced environmental impacts due to conservation of materials, reduced emissions associated with production of virgin aggregates and hauling, and reduced construction traffic. Prof. Cavalline discussed statistics on the availability of RCA, current usage, intrinsic properties vs. virgin aggregates, and properties of concrete incorporating various amounts of RCA. She gave several examples of actual use of RCA in various pavement projects and pointed the audience toward many technical guidance documents, some of which she contributed to, which can help users evaluate and successfully use RCA in a wide extent of applications. Prof. Cavalline concluded that RCA, if it is treated as an engineered material, not just a blind substitution for virgin aggregate, can be used in many more structural projects than is the current practice, which will then contribute to improving the circularity of concrete.

Matthew Adams, Associate Professor of Civil and Environmental Engineering, New Jersey Institute of Technology: "State of Circular Economy for Demolished Concrete as an Aggregate in New Concrete"

Prof. Adams focused on the issues of policy, economics, knowledge transfer, and standards that form barriers to the increased use of recycled aggregate (RCA), building on the technical information that Prof. Cavalline presented in the previous talk. The use of RCA is really a sustainability and environmental issue, not so much a direct carbon-reduction issue. Low-carbon political policies do not include sustainability considerations of RCA but they should. A cost analysis study in New York showed that there was a cost benefit for buying the equipment for making RCA and saving disposal costs vs. simple disposal. These kind of cost studies need to be more widely available and promoted. A related issue is resource efficiency – aggregate needs for a local area can be more than aggregate availability from local quarries, driving the need for increased RCA use. The knowledge transfer issues involve getting the available literature (ACI 555 is developing new, up-to-date guidance documents for RCA) to the small companies that do most of the concrete demolition/disposal work. A related barrier would be that not all concrete plants have space for storing RCA aggregates. NIST can help: develop new standards and measurement tools for stockpile variability testing, develop standardized documentation for history of waste concrete (composition, environmental exposure), and develop alternative aggregate standards to ASTM C33 that are more applicable to RCA, which treat RCA as an engineered material.

Session 4: Circular Economy for Building Materials

Kumar Natesaiyer, Vice President, Corporate Innovation Center, US Gypsum (USG): "Circular Economy for building materials"

Dr. Natesaiyer’s talk focused on the gypsum industry and in particular USG, his company (115+ years old), which is the leading producer of gypsum wallboard in the US, which is itself the most highly-used indoor building material in the US. Sustainability and the circular economy have long been important to USG. The circularity of gypsum wallboard material depends on recycling demolished gypsum wallboard and using recycled gypsum to produce new wallboard. Currently much of demolition waste goes to a landfill, due to the difficulty of extracting clean waste, which can be reused in the manufacturing process, from many demolition site contaminants, including paper facing from the old wallboard. About half of new gypsum wallboard produced used synthetic gypsum, which is recovered as a by-product from coal-fired power plants, which adds to circularity and reduces the need for mining gypsum. Dr. Natesaiyer’s conclusion was that though there is already much recycling in the gypsum wallboard industry, more needs to be made possible, which will require significant investment in research and development, potential process adjustments, material handling and feeding adjustments, and better demolition practices to ensure a cleaner, more usable waste that can be more readily incorporated back into the manufacturing process.

Robert Moser, Senior Scientific Technical Manager, Materials and Structures, Geotechnical and Structures Laboratory, US Army Engineer Research and Development Center, US Army Corps of Engineers (USACE-ERDC): "Reducing Lifecycle GHG Emissions of Construction Materials"

Dr. Moser’s talk focused on reducing lifecycle greenhouse gas (GHG) emissions in the construction materials used by the Defense Department, which has a very large stock of buildings and infrastructure. These include over 560,000 facilities located at over 800 bases. These mainly concrete and steel structures include warehouses, offices, barracks, bunkers, bridges, wharfs, airfields, rail systems, and roads, and are located in a broad range of climates. Sustainability and climate change (e.g., low carbon) drivers include the burden of aging infrastructure, a strong emphasis on 100+ year reliable service lives, and lowering GHG emissions over these lifetimes. Dr. Moser described research and development initiatives in nature-based solutions, multi-hazard resilience, integrating design, materials, and manufacturing, advanced materials-by-design, and new looks at manufacturing and construction processes. He closed with these thoughts: government construction often relies on commodity products and needs to move to performance specifications; materials and lifecycle design must go together in order to improve circularity; and professions such as researchers, engineers, policymakers, manufacturers, contractors, and labor must work together to achieve circularity/sustainability goals.

Milena Rangelov, Research Engineer FHWA/DOT and currently VP of Research, VitalMetrics: "Sustainability and Resilience of Concrete Pavements"

Dr. Rangelov, from the point of view of the US Federal government, examined Green Public Purchasing Initiatives, especially the Executive Order on Federal Sustainability: EO 14057-

Catalyzing Clean Energy Industries and Jobs Through Federal Sustainability. Section 102 (a)(v) of this order calls for net-zero emissions from Federal procurement. Section 303 of this order calls on the Buy Clean Task Force to provide recommendations to the Chair of the Council on Environmental Quality (CEQ) and the Director of the Office of Management and Budget (OMB) on policies and procedures to expand consideration of embodied emissions and pollutants of construction materials in Federal procurement and federally funded projects. There is a trend across the US for Green Public Procurement (GPP). GPP is the practice of selecting products with lower environmental impacts than commonly procured products. Public procurement is the primary economic activity of government and is used by government for the pursuit of strategic objectives. GPP influences the private sector market. Dr. Rangelov described a detailed research study on paving concrete carried out by the FHWA. This was a collaborative study between the Sustainable Pavements Program and the Mobile Concrete Technology Center. The objectives of the study were: evaluate the state of practice for paving concrete, identify the opportunities for improvement, and identify strategies for pavement agencies to achieve greenhouse gas savings for concrete pavements. She concluded with a closer examination of Environmental Product Declarations.

Appendix C. Slido Poll Responses

Question 1) What are the main challenges facing carbon sequestration and mineralization in concrete and how can standards help?

- Lack of standardization of low carbon cement and concrete. How can an end-user buy low-carbon concrete?
- Essential is breaking up the cement industry oligopoly. They had a decade to get going and have embraced greenwashing instead. There is insufficient innovation
- Lack of knowledge in the labor force of how to handle and construct these new materials and processes; particularly hard from scalability point of view to shift all the local markets and teach all the suppliers/contractors/engineers
- How industry relies on status quo and primary motivation is cost and schedule. Owners may be able to exert some influence if embodied carbon is also considered when awarding bids Reports that give engineers confidence in the performance of these materials/processes to specify them and standards that provide guidance to suppliers/contractors for how to provide good quality construction as well as ways for engineers to assess construction quality will play an important role. Reports/standards will need to vary based on construction application.
- Technology related issues – capture of CO_2 in materials, scale-up of processes, determining needed concentration of CO_2 etc. - Measurement related issues – how to determine how much CO_2 is captured reliably, how to determine whether a material is carbon negative for part or all of its life cycle, allocation/scope issues to resolve in LCA (CO_2 source dependent) to ensure comparisons are sensible and fair. - Policy related issues - what sort of support is needed to help development of the industry Standards should focus primarily towards measurement & communication of benefits. ISO 14040 & 14044 are a good start for LCA, but are open for interpretation and this can get particularly messy when using 'wastes' such as CO_2 or fly ash, clinker dust etc.
- Industry trust and embrace. Implementation will be key, and all stakeholders need to be engaged early.
- The issue is volumes of CO_2 you can sequester. Using methods such as Carbon Cure or Solidia (in principle similar to Carbon built) is that you can only deposit small quantities of CO_2 per cubic yard of concrete. Hence these approaches are good "supporting" role in our toolbox but can not provide large enough CO_2 sequestration quantities that would move the needle. Alternative approach of carbonizing CO_2 into aggregate seems more promising. To give you an idea of scale, to move the needle you should be able to absorb - say 1 MTA of CO_2. If you go with existing CO_2-to-stone technologies, you can theoretically sequester more than 9 MTA of CO_2 in yearly concert production only in Houston. In all of these cases the biggest challenge is how to scale the technologies to the 1MTA CO_2 "watermark". What is needed is coordinated regulatory or market pull and investment in rapid technology scaling
- Complacency - many businesses over the past few decades have shifted to a low risk, financial management model as opposed to innovation driven. They are content with letting others do the development work, only to adopt a technology if it becomes financially viable or necessary. Standards and policy must be performance based to allow new, innovative technologies to come to market and be readily adopted in specifications.
- carbon sequestration in concrete is a function of CH content.... but we try to minimize the CH content. E.g., lower paste contents, higher replacement of SCMs, lower clinker contents in our cements. These two techniques towards lower carbon footprints seem to be in competition with each other.
- Regulations

- It is unclear how to directly compare 1-to-1 the various technologies. We need standardized methods (perhaps LCA tools?) to be able to compare.
- Carbon sequestration's problem is it is in adequate and unpredictable. Reducing the energy footprint of the overall process as well as enhancing mineralization effectively is the most likely path to commercial and scalable outcomes.
- Focus on performance.
- The technology is mostly hidden behind patent walls and secretive startup companies, making it difficult for the industry at large to try it.

Question 2) What measurement science is needed to support standards for reducing the embodied carbon of concrete?

- Metrics, benchmarks, and standards for CO_2 uptake (either upfront or in situ) versus CO_2 emissions (upfront), since carbonation processes only reclaim a small fraction of upfront emissions.
- Appropriate structural metrics – for example, we often see CO_2 per t or m3, but perhaps something like structural columns should look at CO_2 per unit of load capacity per unit of height. Having more appropriate metrics would be helpful for designers and architects looking to optimize whole building designs
- Such a NIST question! Quantifying carbonation at various stages of the life cycle in a standardized way.
- quantification and validation
- Quantitative microstructural and structural characterization using Xray and neutron scattering, diffraction and imaging (including tomography) to validate model predictions and/or claims for carbonation, hence derived standards.
- Something that is apples to apples. Currently legislation is working to enforce EPDs
- for produced products. That for concrete has short comings since it is only based on the A1-A3 portions of LCA. Concrete, with its advantages in durability, natural sequestration, and re-use potential needs to have those attributes accounted for.
- how can directly link a metric of environmental performance (EPD for example) to a particular concrete mixture? Right now, I think we do it by mix design. Is there another way to "fingerprint" the concrete to make sure it's what the paper really says?
- amount of CO_2 uptake

Question 3) What measurement science is needed to support standards for concrete reuse and recycling?

- Standardized modules, measurements and tests for grout-less conventional masonry, and new, low-CO_2 masonry products. "Recertification" methods and standards for solid concrete products to be directly reused in new buildings. Digitization of building products into accessible databases for future use/reuse.
- The biggest issue as I see it, is from a risk management perspective. A prediction of impacts of recycled agg/concrete on long term durability would be helpful, based on mix design and quality of materials to determine which applications and exposure conditions may or may not be suitable.
- Perhaps some means of quantifying the reuse potential of new construction. Modular elements that could be deconstructed rather than demolished would score higher
- certifying recycled concrete materials for quality.

- Quality/grades of the recycled content and quality/grades of new materials with XX% of recycled content
- Ultimately, performance and property (e.g., strength) measurement to prove integrity of new material. Real-time rheology of hydration behavior may also be needed for cement and concrete re-use construction standards.
- Large scale applicability and longevity studies of recycled products use.
- usability classification

Question 4) What are the main challenges facing the use of recycled aggregate and cement in new concrete and how can standards help?

- Codes and standards should allow it. Currently, ACI 318 requires performance equivalence. Better to incorporate RCA in ASTM C33
- Addressing the recycling potential at the Design and construction phase.
- Help by showing state DOTs the max amounts of RAC that can be used in concrete and the performance of such new mixes. Adoption can be slow and data from a credible source helps decision-making.
- Long term durability concerns and management and control over recycled materials (quality and consistency) to select appropriate amounts per application
- Regional aggregate dependency. Needing to have a system on site for the process as
- rotating RCA in ready mix drums seems to promote particle breakdown.

Question 5) How should NIST prioritize near-term measurement science needs that support standardization efforts in supporting a circular economy and reducing the embodied carbon of concrete?

- Help develop performance tests and criteria to replace prescriptive specs like cement contents, limits on SCM contents, maximum w/cm when it is not needed which drives more binder etc.
- Good methods for measuring CO_2 entrainment in products
- Work on the appropriate metrics by which recycled materials should be evaluated and appropriate thresholds, although these will vary by application
- Circular economy involves more than just product carbon reduction. Support efforts would be welcome in advocating for initiatives, standards, specifications, and legislations that look at sustainability holistically.
- Measurement reporting and verification standards. How will this look like at scale?

Appendix D. Recycled Concrete Aggregates

RCA Production and Use

National production of RCA and RCA fines in comparison to select other construction byproducts is displayed in Table D1. More than 400 million tons of RCA are generated annually in the U.S., 6 % of which is construction waste and the remainder being demolition waste. Construction waste has a higher potential for recycling, as it tends to have less variability and comes from a known source. Demolition waste is often produced from mixed components, containing various slabs, columns, foundations, pavements, and roadways, and is often produced in municipal plants with a varying stream of material. Depending on the crushing process, about 25 to 40 % of RCA become RCA fines [39].

Table D1: National production, beneficial use, and disposal of select construction byproducts (adapted from [39])

Construction Byproduct	Production	Beneficial Reuse	Disposal
Recycled asphalt pavement (RAP)	107 million tons	102.1 million tons	4.9 million tons
Recycled concrete aggregates (RCA)	405.2 million tons - 6 % construction waste - 94 % demolition waste	334.0 million tons	71.2 million tons
Quarry fines	484 million tons	N/A	N/A

In the U.S., RCA is used in bound applications, such as a fill material, filter material, and drainage layer as well as in unbound stabilized and unstabilized subbases. Additionally, RCA has been used in various pavement applications including in single and two-lift portland cement concrete pavements as well as hot-mix asphalt pavements. In Europe, RCA is commonly used in the lower lift of two-lift concrete pavements. More RCA is now used in new asphalt than in new concrete mixtures [39]. As of 2017, 44 States use RCA, where unstabilized subbases/backfill is the most common application.

RCA often has cement paste or mortar attached to aggregate, which alters the properties of the material. Table D2 compares select properties of RCA to those of virgin aggregate. Two key differences of RCA are the higher absorption capacity and the lower specific gravity, which impact the fresh properties of concrete containing RCA. For instance, when coarse and/or fine RCA are utilized in concrete the workability decreases, the finishability is more difficult, there is less water bleeding, the air content is slightly higher, and the water demand is greater [39].

Table D2: Properties of Virgin Aggregate and RCA (adapted from [39])

Properties	Virgin Aggregate	RCA
Shape and Texture	Well-rounded, smooth to angular/rough	Angular with rough surface
Absorption Capacity	0.8 % – 3.7 %	3.7 % – 8.7 %
Specific Gravity	2.4 – 2.9	2.1 – 2.4
L.A Abrasion	15 % – 30 %	20 % – 45 %
Sodium Sulphate	7 % – 21 %	18 % – 59 %
Magnesium Sulfate	4 % – 7 %	1 % – 9 %
Chloride Content	0 – 2 lb/yd^3	1 – 12 lb/yd^3

Table D3 shows the properties of hardened concrete containing RCA as coarse aggregate as well as coarse and fine aggregate. Potential adjustments are also included that can help to mitigate negative impacts. Utilizing coarse and/or fine RCA has the potential to reduce both the compressive and tensile strength of hardened concrete as well as increase the permeability. These impacts could be mitigated by reducing the water-to-cement ratio.

Table D3: Properties of Hardened Concrete containing RCA (adapted from [39])

Property	RCA used as Coarse Aggregate	RCA used as Coarse and Fine Aggregate	Potential Adjustments
Compressive strength	0 % to 24 % less	15 % to 40 % less	Reduce w/cm ratio
Tensile strength	0 % to 10 % less	10 % to 20 % less	Reduce w/cm ratio
Strength variation	Slightly greater	Slightly greater	Increase average strength compared to specified strength
Modulus of elasticity	10 % to 33 % less	25 % to 40 % less	This may be considered a benefit regarding cracking of slabs on grade
Specific gravity	0 % to 10 % lower	5 % to 15 % lower	None recommended
Coefficient of Thermal Expansion	0 % to 30 % greater	0 % to 30 % greater	Reduce panel sizes
Drying shrinkage	20 % to 50 % greater	70 % to 100 % greater	Reduce panel sizes
Creep	30 % to 60 % greater	30 % to 60 % greater	Typically not an issue in pavement applications
Bond strength	Similar to conventional concrete, or slightly less		None recommended
Permeability	0 % to 500 % greater	0 % to 500 % greater	Reduce w/cm ratio

RCA Guidance

Several guidance documents have been published or are in development aiming to support the increased use of RCA, as displayed in Table D4. Recent advances have been made in RCA characterization, some of which have been performed through the American Concrete Institute Concrete Research Council (ACI CRC). Technical guidance on the use of RCA in pavement applications have also been published by the National Concrete Pavement Technology Center at Iowa State University and the Federal Highway Administration (FHWA).

Table D4: Recent and forthcoming guidance documents for use of RCA

Title *Publisher*	**Description**	**Reference**
ACI CRC 2019 P0027: **Effective Characterization of RCA for Concrete Applications** *American Concrete Institute Concrete Research Council (ACI CRC)*	Improved existing tests and developed new tests: - Modified residual mortar content (RMC) test o Improved thermal shock method - Modified Aggregate crushing value (ACV) test o Strength characterization - Aggregate freeze-thaw test o Able to differentiate the air-entrainment level of parent concrete - Portable handheld XRF o Can be used for chemical characterization and residual mortar determination	[48]
Recycling Concrete Pavement Materials: A Practitioner's Reference Guide *National Concrete Pavement Technology Center, Iowa State University, Ames*	92 pages of useful technical information including many case studies and up-to-date implementation guidance	[49]
FHWA-HIF-22-020: **Tech Brief: Use of RCA in Concrete Paving Mixtures** *US DOT Federal Highway Administration*	- Updated guidance to build upon 2018 Practitioner's Reference Guide - Guidance for: o Characterizing RCA o Influence of RCA on concrete properties o Mixture design approaches o Production and use considerations o Example projects	[50]

Tech Brief: Use of construction byproducts in concrete paving mixtures *US DOT Federal Highway Administration*	- Characteristics of byproducts - Provides information on handling and processing needed for reuse - Recommends how to evaluate construction byproducts for reuse in bound and unbound applications - Describes potential impacts of reusing each byproduct in specific applications - Presents a protocol for characterizing and assessing byproducts for reuse - Provides recommendations for qualification-, preconstruction- and construction-phase tests for the byproduct materials and applications (bound/unbound bases, fills, concrete mixtures) - Describes design and construction considerations and ways to protect the environment	Forthcoming; [51]

Current state of codes and standards

Significant activity is taking place to include RCA in codes and standards. ACI’s Building Code Requirements for Structural Concrete (ACI 318) introduced the use of RCA in new concrete for the first time in the most recent code with the caveat RCA must be specifically approved for a particular project by the designer and must undergo a rigorous testing program [52].

ASTM C33, the Standard Specification for Concrete Aggregates allows the use of RCA, but the RCA must meet all requirements for natural aggregates listed in C33 [53]. However, not all the tests in C33 are indicative of the performance acquired with RCA. For example, the LA abrasion tests in C33 are not appropriate for RCA because it is a test of the abrasion of aggregate and not mortar. Therefore, the system was not designed to test for the abrasion of mortar, which is destroyed in the abrasion machine. Additionally, C33 provides standard sampling requirements that may not capture the variability of RCA materials. Natural aggregate stockpiles generally come from the same quarry where variability is well defined and studied. In RCA stockpiles, on the other hand, material comes from many different sources, and may have different exposure conditions and different parent concrete properties. Understanding of this variability and how to sample RCA stockpiles is uncertain.

The ACI 555 Concrete with Recycled Materials committee is also actively supporting the use of RCA. This committee is currently developing a new guidance document that aims to replace ACI PRC-555.01: Removal and Reuse of Hardened Concrete [54] with three new documents, which will include design tools, guidance on RCA assessment, and demolition guidance for preparation in making RCA [18]. Additionally, the committee is supporting research into the use of RCA through three projects funded by the ACI Foundation. They are collaborating with outside stakeholders to identify research needs and support technology transfer, as well as working with other ACI and ASTM committees to harmonize codes and standards efforts.

Appendix E. The Science and State of Carbon Mineralization in Concrete

Insights into the mineral carbonation reaction are provided in the text box below. As calcium hydroxide carbonates it releases water and the release of water autocatalyzes the reaction itself. This is key, because as water is released it motivates a hydroxyl (OH^-) for carbonate (CO_3^{2-}) exchange reaction. Herein, the rate of transport (intrusion) of carbonate appears to be rate limiting. Because the reaction is dissolution-precipitation controlled, the release of water helps autocatalyze the reaction. The release of water reduces the thermodynamic energy demand of the reaction by nearly 30 % [6].

Mineral Carbonation Reaction Insights [6]

- Instantaneous surface nucleation
- Solid reactant separated from fluid by boundary layer; process switches to diffusion-control
- Reaction proceeds by OH^--for-CO_3^{2-} exchange (carbonate intrusion appears to be rate limiting)
- OH^- recombines with H^+ resulting in formation of water – which in turn "catalyzes" the process
- 32 % reduction in energy (ΔG) confirmed by DFT calculation

According to Paula Carey [31], two conditions of carbonation include the following:

1. Water to solid ratio greater than one (water: solids ratio >1:1): alkaline water leads to precipitation of carbonate in the water; and
2. Semi-dry or thin film: Carbonate nucleates on the grains or replaces the grains of the residue and can help bind the grains together.

Effectively, alkalinity is induced following the dissolution of alkaline calcium or magnesium species – which also facilitates the precipitation of carbonate mineral. These reactions occur at atmospheric temperatures and pressures or at a range of elevated temperatures and pressures up to super critical CO_2 conditions (e.g., using autoclaves or curing chambers). Elevated temperatures and pressures may result in the absorption of more CO_2, but at the penalty of greatly increased energy requirements and additional complexity of the engineering needed for commercial plants.

Carbonation during mixing vs curing

CO_2 can be introduced in a concrete either during mixing (i.e., in a mixer) or during the curing process. CO_2 added during mixing relies on the capture, compression, storage, and transportation of CO_2 prior to introducing it to the mix. Very short contact time is available between the CO_2 and the concrete in a mixer, and thus a portion of the CO_2 tends to be lost to the atmosphere. When CO_2 is combined with a liquid the solubility is dictated by the pH of the system. Based on this, only a limited amount of CO_2 can be absorbed in atmospheric environments like a mixer, essentially Henry's law, and the remainder may be lost. That said, when added during mixing, the CO_2 can form nanoscale calcite that may have a positive impact on strength development [8]. When added during curing, CO_2 that would generally be released to the atmosphere can be redirected through a carbonation chamber. This process allows for a longer period of contact between concrete and CO_2 and contributes to the strength development. Another factor in the above analysis is that the amount of dissolved calcium species present in the concrete, which are the main absorbers of CO_2, also increase during curing and are present only in very limited amounts during mixing.

Carbon Mineralization in Pre-cast vs. Cast-in-place Concrete

Pre-cast concrete components are poured into a mold and cured off-site whereas cast-in-place (also called ready-mix) concrete is poured and cured onsite in the concrete's finished position. Benefits to pre-cast includes its ability to be performed year-round during any season, and as an industrial process it brings increased control and thus increased optimization of material usage (i.e., greater efficiencies) and the ability to complete carbonation in a matter of a few hours. Carbon mineralization is more effective and extensive in pre-cast concrete, due to the controlled environment and the ability to cure components in the pressure and temperatures most beneficial for effective carbon uptake.

Carbon Mineralization in Dry-cast vs Wet-cast Concrete

Dry cast concrete is another potential avenue for carbon mineralization. Concrete masonry units (CMUs) are perhaps the most common form of dry cast concrete, which incorporate only fine aggregates (coarse: <10mm) and the moisture content is kept very low. CMUs are generally manufactured in an industrial process where they are steam-cured in a controlled environment (e.g., the temperature, humidity, and pressure are managed).

Wet-cast and dry-cast concrete carbonate at vastly different rates due to the increased porosity of the pore structure of dry-cast products. As a result, dry-cast products are better able to sequester carbon [38]. Porosity, water-to-cement ratio, relative humidity, and CO_2 diffusivity all affect the carbonation in hydrated cement [55]. A recent study involved the collection of CMUs from across the U.S. and Canada that were allowed to naturally carbonate prior to TGA analysis to measure carbon uptake. The net carbon uptake of the CMUs averaged 21 kg/m^3, higher than what one would expect with wet-cast concrete [38].

Carbon Mineralization and the Risk of Carbonation-Induced Corrosion

Corrosion of steel reinforcement in concrete can occur due to either the intrusion of chloride (Cl^-) ions (e.g., from exposure to deicing salts or seawater) or from advanced carbonation or a combination of both. The question thus arises whether carbon sequestration in concrete poses an increased risk of carbonation-induced corrosion. Experts in the field argue that the system must be designed such that not all alkalinity should be consumed [6, 56, 57]. By strategically designing carbonation sequences some calcium hydroxide can be left in the system, thereby leaving a residual buffer that maintains a sufficiently high alkaline pH near the reinforcement to hinder corrosion. An alternative is to use reinforcements that do not corrode (e.g., reinforced polymer rebars) while still providing the required mechanical properties for structural reinforced concrete.

Carbon Mineralization and 3D printed Concrete

Efforts are underway combining the idea of CO_2 mineralization and 3D printing of concrete. Calcium hydroxide is an optimum base material for this effort due to its CO_2 uptake and the ability to produce products with a compressive strength of at least 35 MPa. In general, more than 90 % of all concrete produced globally has a strength equal to or lower than 35 MPa [6]. While the mineralization reaction is straightforward (same as the carbonation reaction of Figure 4), the release of water is of key importance, which may impact rheological properties during printing that allows for scalability in both layer heights, stackability, and printing time for each layer. The challenge remains how to accurately control the process and materials properties, e.g., to yield solidification in seconds and produce MPa-level strength in minutes [6]. Researchers at UCLA are actively investigating this, aiming to achieve ultrafast stiffening, a prerequisite attribute for 3D manufacturing [58]. Researchers at the Oak Ridge National Laboratory are also active in this space, and have successfully demonstrated the printability and the carbonation potential of polymer-enhanced $Ca(OH)_2$ slurries using a lab-scale printer [58] [56]. Continued investigations include evaluating different polymers and slurry formulations as well as testing CO_2 injection during mixing.

Appendix F. Biomineralization in Concrete

The three principal mechanisms of $CaCO_3$ biomineralization include urea hydrolysis, photosynthesis, and sulfate reduction. Table F1 provides the process reactions and general advantages and disadvantages of each mechanism. Other less common mechanisms include denitrification and organic compound conversion.

Urea hydrolysis is the most studied and best understood pathway and efforts toward self-healing concrete and Bio-mason products typically use this approach [38]. Urea hydrolysis requires urea as the principal carbon source. Microorganisms, through their normal metabolic activity (mainly by the production of the urease enzyme), decompose urea into carbonic acid and ammonia and through additional bio-chemical reactions these microorganisms produce calcium carbonate. This mechanism is known for its efficient and fast production of $CaCO_3$ in the laboratory scale. Ureolytic microorganisms are also highly resilient, and many are spore-forming, which may allow them to survive longer in harsh environments such as the pore solution of concrete. However, these microorganisms are also heterotrophic and require both urea and organic carbon (e.g., yeast extract) to mineralize $CaCO_3$. This pathway requires an external source of Calcium, but there are many sources in nature including seawater and brackish water. An additional disadvantage of this pathway is the production of ammonia as a byproduct, which is considered an environmental contaminant and may hinder the efficiency of biomineralization.

Biomineralization through photosynthesis is less studied and rarely applied to concrete materials research. A myriad of photosynthetic micro- and macro-organisms exist that can pull CO_2 into water through the production of carbonic anhydrase (CA) to produce carbonic acid. The carbonic acid can then dissociate into bicarbonate and hydrogen and in the presence of calcium the microorganisms again through normal metabolic activity will nucleate calcium carbonate [32]. This is a natural process, and simply relies on sunlight, water, and CO_2.

Biomineralization through sulfate reduction is the least studied of the three mechanisms, particularly in the field of construction research. This process requires calcium sulfate (gypsum) and formaldehyde (CH_2O) and through the metabolic activity of the organism calcium carbonate can be precipitated. An alternative, but similar mechanism, requires gypsum and formaldehyde that can result in precipitation of calcium carbonate, which follows a different chemical reaction. Unlike ureolytic microorganisms, sulfate-reducing organisms are anaerobic and therefore do not require continuous access to oxygen. This trait may make them better suited for certain construction applications. A significant disadvantage of sulfate reduction is the production of toxic hydrogen sulfide (H_2S).

Table F1: Advantages and disadvantages of biomineralization mechanisms (adapted from [32])

	Urea hydrolysis	Photosynthesis	Sulfate reduction
Process Reactions	$CO(NH_2)_2 + 2H_2O \xrightarrow{Urease\ Enzyme} \mathrm{H_2CO_3} + 2NH_3$ $H_2CO_3 \leftrightarrow HCO_3^- + H^+$ $2NH_3 + 2H_2O \leftrightarrow 2NH_4^+ + 2OH^-$ $HCO_3^- + OH^- \leftrightarrow CO_3^{2-} + H_2O$ $Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3$	$CO_2 + H_2O \xrightarrow{CA\ Enzyme} \mathrm{H_2}CO_3$ $H_2CO_3 \leftrightarrow HCO_3^- + H^+$ $Ca^{2+} + HCO_3^- \rightarrow CaCO_3 + H^+$	$CaSO_4 \cdot 2H_2O \rightarrow Ca^{2+} + SO_4^{2-} + 2H_2O$ $2CH_2O + SO_4^{2-} \rightarrow H_2S + 2HCO_3^- + CO_2 + H_2O$ $Ca^{2+} + HCO_3^- \rightarrow CaCO_3 + H^+$ Or $CaSO_4 + 2CH_2O \rightarrow \mathrm{CaS} + 2CO_2 + 2H_2O$ $\mathrm{CaS} + 2H_2O \rightarrow Ca(OH)_2 + H_2S$ $CO_2 + H_2O \rightarrow H_2CO_3$ $Ca(OH)_2 + H_2CO_3 \rightarrow CaCO_3 + 2H_2O$
Advantages	- Well-studied and well-applied - Prolific quantities of $CaCO_3$ - Spore-forming microorganisms - Genetic modification of urease gene cluster	- Natural, photosynthetic process - Robust micro- and microorganisms - Direct CO_2 capture in permanent mineral form - Minerals are controllable by template proteins - High and low quantities of $CaCO_3$ depending on species (advantage & disadvantage)	- Microorganisms are anaerobic; do not necessitate continuous access to oxygen
Disadvantages	- Production of ammonia - Requires urea and organic carbon - Microorganisms are aerobic: require continuous access to oxygen - Requires external source of Calcium	- Less studied and applied - Requires external source of Calcium - High and low quantities of $CaCO_3$ depending on species	- Not well studied - Production of toxic hydrogen sulfide (H_2S) - Requires gypsum and formaldehyde - Does not fix atmospheric CO_2

In addition to the different mechanisms of biomineralization, biomineralization can be either biologically induced or biological controlled. In biologically induced mineralization, the mineralization is extra-cellular; i.e., it occurs outside of the cell. Microorganisms secrete hydroxide ions that spike the pH, which is the biocatalytic activity that causes the extracellular nucleation precipitation of calcium carbonate. This pathway results in calcium carbonate that displays a variety of polymorphs, either calcite, vaterite, aragonite, or amorphous calcium carbonate. Biologically induced mineralization typically produces minerals with disordered morphologies (e.g., vaterite) on the order of short time scales. These minerals thermodynamically transition over time to more stable forms (e.g., calcite) at ambient temperatures and pressures. During biologically controlled mineralization, the microorganisms produce the calcium carbonate intracellularly and transport that calcium carbonate from cellular compartments to the cell surface. This can result in very stable polymorphs, typically calcite, and very intricate and controlled morphologies [32].

Appendix G. A Circular Economy for Gypsum

Gypsum is a common raw material for manufacturing various construction products including plasters, drywall (wall board or plasterboard), ceiling tiles, partitions, and wall blocks. Additionally, about 4 to 5 % of gypsum is used in the Portland cement industry as a retarder to help regulate the early-age flash set of aluminate components of the cement [59]. Gypsum slurries have excellent workability in the fresh state, fast setting and hardening, and excellent finishing properties. In addition, gypsum-based construction products have many advantageous characteristics including light weight, thermal insulation, acoustic absorption, fire proofing, and white coloring.

Gypsum raw materials come either from natural sources (i.e., from natural gypsum stone), or synthetic sources. Both have the same chemical composition, $CaSO_4 \bullet 2H_2O$. Synthetic gypsum is typically generated as a byproduct of the process used to remove pollutants from the exhaust created by the burning of fossil fuels for power generation [46]. It is estimated that roughly 45 % of the gypsum used by U.S. manufacturers in 2010 was of the synthetic variety [46]. The use of synthetic gypsum can reduce some environmental impacts, most notably the demand for the extraction of natural gypsum stone. However, the availability of synthetic gypsum may decrease in the future as power generation transitions away from fossil fuels.

Gypsum processing includes fine grinding followed by calcination (i.e., dehydration) to produce a powder with uniform chemical and physical properties that will set with added water. Calcination temperatures of between 120° to 150°C (250° to 300° F) are needed to drive off this water [47]. To produce the range of gypsum products (e.g., walling, heat insulating, acoustic, and decorative) requires different processing techniques, including pressing for blocks, rolling and extrusion for panels and boards, and casting for decorative elements and foam products [60]. Perhaps the most common gypsum building product is wall board (also known by its proprietary names Drywall and Sheetrock), which is a gypsum plaster panel that is glued between two sheets of paperboard or cardboard. This gypsum board is the most common indoor building material in the U.S., and it is estimated that domestic construction uses roughly 30 billion square feet of the material per year [46]. According to the U.S. Geological Survey (USGS), domestic consumption of gypsum (natural + synthetic) amounted to roughly 41 million metric tons in 2020 [61].

The carbon footprint for gypsum building production comes from the fossil-fuel sources used [60]. This suggests that relying on synthetic gypsum sources does not fully mitigate the environmental impacts of these building materials.

Waste generation of gypsum building products is another source of environmental impact. The EPA estimates that drywall and plasters make up roughly 2.5 % of C&D debris generated in the U.S., amounting to 15.2 million tons in 2018 [12]. Landfills were the primary destination for this debris. Disposal of gypsum products has become an issue, in part because of the massive volume, but also because they still contain various substances such as organic matter (paper and wood), drywall (made mainly of paper lining and gypsum), and potentially heavy metals (particularly for synthetic gypsum). As such, the wastes are regarded as a major contributor to hydrogen sulfide (H_2S) generation in landfills [62].

Circular Gypsum Building Products – Challenges and Opportunities

The CE for gypsum building products is akin to concrete in which component maintenance, repair, and reuse would ideally be prioritized above recycling. However, the current standard of practice for used gypsum building products includes mixing wallboard scraps with other debris upon demolition that are then hauled either to landfills or to processors for use in agricultural applications (e.g., as a fertilizer or for soil amendment) [47]. As such, while the direct reuse of gypsum products is technically feasible it is not common practice.

Recovering gypsum products for reuse or recycling necessitates the careful demolition of plasterboards and panels, which requires additional time, labor, and resources compared to standard practice. Specifically, recycling of these products requires either dedicated collection systems on-site (i.e., separate from other C&D debris) or a system to separate gypsum product waste from aggregated C&D debris. The removal of potential contaminants is also necessary, such as nails, screws, trim, and paint. Implementing reuse or recycling of gypsum building products at scale therefore necessitates changing the current practice of deconstruction.

Concern about material product safety is a key challenge facing the circularity of gypsum. These concerns arise from materials introduced to the gypsum during its service life such as lead paint, as well as from unknown sources of gypsum products (e.g., imported from other countries) that may have unknown properties. Asbestos contamination is also a common concern as are additives carried over from recycled dry wall waste. The inconsistency of gypsum supply is a hinderance as dry wall waste collection and processing is erratic and varies according to job site and location.

Technical challenges arise from the inability to fully separate the fibrous layer (e.g., cardboard or paper) from the gypsum board. Despite current removal approaches, a significant amount of paper is carried with the gypsum. This paper is mechanically and chemically bonded to the gypsum slurry during manufacturing, which may impact the integrity of products made with recycled gypsum board [47].

These obstacles can all be overcome through material handling and feeding adjustments, process modifications, and significant investment in research and development. Modification and development of codes and standards may also be useful to drive the deconstruction industry toward more circular practices.