Removing Barriers to Rapid Adoption of Carbon Reduction in Concrete

EXECUTIVE SUMMARY

Breakthrough Energy Foundation
PO Box 563
Kirkland, WA 98083

April 2023

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1885 S. Arlington Ave, Ste 111
Reno, NV 89509
NCE Project No. 1163.01.25

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Prepared for:

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List of Associations and Organizations

The United States and Canadian cement and concrete industry is large and decentralized, with 156,000 people employed in cement, concrete, lime, and gypsum manufacturing in 2021[1]. It consists of producers and suppliers, manufacturers, contractors, and designers and is represented by numerous organizations and associations, some of which are listed below.

Acronym	Organization	Website
AASHTO	American Association of State Highway and Transportation Officials	https://www.transportation.org/
ABC	Associated Builders & Contractors	https://www.abc.org/
ACAA	American Coal Ash Association	https://acaa-usa.org/
ACEC	American Council of Engineering Companies	https://www.acec.org/
ACI	American Concrete Institute	https://www.concrete.org/
ACI Foundation	ACI Foundation	https://www.acifoundation.org/
ACI NEU	NEU – An ACI Center of Excellence for Carbon Neutral Concrete	https://www.neuconcrete.org/
ACPA (Pavement)	American Concrete Pavement Association	https://www.acpa.org/
ACPA (Pipe)	American Concrete Pipe Association	https://www.concretepipe.org/
ACPA (Pumping)	American Concrete Pumping Association	https://www.concretepumpers.com/
ACPPA	American Concrete Pressure Pipe Association	https://acppa.org/
AGC	Associated General Contractors	https://www.agc.org/

[1] https://www.bls.gov/cps/cpsaat18.htm

Acronym	Organization	Website
APA	Architectural Precast Association	https://www.archprecast.org/
API	American Petroleum Institute	https://www.api.org/
APWA	American Public Works Association	https://www.apwa.net/
AREMA	American Railway Engineering and Maintenance-of-Way Association	https://www.arema.org
ARTBA	American Road & Transportation Builders Association	https://www.artba.org/
ASA	American Shotcrete Association	https://shotcrete.org/
ASBI	American Segmental Bridge Institute	https://www.asbi-assoc.org/
ASCC	American Society of Concrete Contractors	https://ascconline.org/
ASCE	American Society of Civil Engineers	https://www.asce.org/
ASTM	American Society for Testing and Materials	https://www.astm.org/
CAC	Cement Association of Canada	https://cement.ca/
Cembreau	European Cement Association	https://www.cembureau.eu/
CFA	Concrete Foundations Association	https://www.cfaconcretepros.org/
CPCI	Canadian Precast/Prestressed Concrete Institute	https://www.cpci.ca/
CPG	Concrete Promotional Group	https://www.concretepromotion.com/
CRMCA	Canadian Ready Mixed Concrete Association	https://www.crmca.ca/
CRSI	Concrete Reinforcing Steel Institute	https://www.crsi.org/

Acronym	Organization	Website
CSA	Canadian Standards Association	https://www.csagroup.org/
CSDA	Concrete Sawing and Drilling Association	https://csda.org/
CSI	Construction Specifications Institute	https://www.csiresources.org/home
ESCSI	Expanded Shale, Clay, and Slate Institute	https://www.escsi.org/
FAA	Federal Aviation Administration	https://www.faa.gov/
FHWA	Federal Highway Administration	https://highways.dot.gov/
GCCA	Global Cement and Concrete Association	https://gccassociation.org/
ICFA	Insulating Concrete Forms Manufacturer's Association	https://icf-ma.org/
ICPI	Interlocking Concrete Pavement Institute	https://icpi.org/
ICRI	International Concrete Repair Institute	https://www.icri.org/
IGGA	International Grooving and Grinding Association	https://www.igga.net/
NAHB	National Association of Home Builders	https://www.nahb.org/
NCMA	National Concrete Masonry Association	https://ncma.org/
NPA	Natural Pozzolan Association	https://pozzolan.org/
NPCA	National Precast Concrete Association	https://precast.org/
NRMCA	National Ready Mixed Concrete Association	https://www.nrmca.org/
NSSGA	National Stone, Sand & Gravel Association	https://www.nssga.org/

Acronym	Organization	Website
NUCA	National Utility Contractors Association	https://www.nuca.com/
PCA	Portland Cement Association	https://www.cement.org/
PCI	Precast/Prestressed Concrete Institute	https://www.pci.org/
PTI	Post-Tensioning Institute	https://www.post-tensioning.org/
RCCPC	Roller Compacted Concrete Pavement Council	https://www.rccpavementcouncil.org/
SCA	Slag Cement Association	https://www.slagcement.org/
SUDAS	Statewide Urban Design and Specifications	https://iowasudas.org/
TCA	Tilt-Up Concrete Association	https://www.tilt-up.org/
TMS	The Masonry Society	https://masonrysociety.org/
USGS	United States Geological Survey	https://www.usgs.gov/
WRI	Wire Reinforcement Institute	https://www.wirereinforcementinstitute.org/

List of Acronyms

Acronym	Definition
AASHTO	American Association of State Highway and Transportation Officials
ACAA	American Coal Ash Association
ACI	American Concrete Institute
ACM	Alternative Cementitious Material
ACPA	American Concrete Pavement Association
AIA	American Institute of Architects
AREMA	American Railway Engineering and Maintenance-of-Way Association
ARTBA	American Road & Transportation Builders Association
ASCM	Alternative supplementary cementitious material
ASR	Alkali-silica reaction
ASTM	ASTM International
CAC	Calcium aluminate cement
CAC	Cement Association of Canada
CAGR	Compound annual growth rate
CCUS	Carbon capture, utilization, and storage
CLSM	Controlled Low Strength Material
CMU	Concrete masonry unit
CSA	Calcium sulfoaluminate
CSI	Construction Specification Institute
CTAC	Concrete Testing Adherence Collaboration
DOT	Department of Transportation
EAF	Electric arc furnace
EPD	Environmental product declaration
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration

Acronym	Definition
GCCA	Global Cement and Concrete Association
GHG	Greenhouse Gas
GU	General Use
GWP	Global warming potential
HE	High Early Strength
HQ AFCEC	Head Quarters - Air Force Civil Engineer Center
HS	High Sulfate Resistance
IBC	International Building Code
ICC-ES	International Code Council Evaluation Service
ICC	International Code Council
IRBC	International Residential Building Code
LC3	Limestone-calcined clay-cement
LDP	Licensed design professional
LH	Low Heat of Hydration
MH	Moderate Heat of Hydration
MnDOT	Minnesota Department of Transportation
MRD	Materials-related distress
MRF	Municipal waste materials recovery facility
MS	Moderate Sulfate Resistance
NACE	National Association of County Engineers
NASA	National Aeronautics and Space Administration
NAVFAC	Naval Facilities Engineering Systems Command
NBCC	National Building Code of Canada
NEU	ACI Center of Excellence for Carbon Neutral Concrete
NPA	Natural Pozzolan Association
NRMCA	National Concrete Ready Mixed Association

Acronym	Definition
NRRA	National Road Research Alliance
NTPEP	National Transportation Product Evaluation Program
PCA	Portland Cement Association
PCC	Portland Cement Concrete
PLC	Portland-limestone cement
RCA	Recycled concrete aggregate
RCC	Reactive Calcium Carbonate™
RCM	Reclaimed Concrete Material
RHC	Returned Hardened Concrete
SCM	Supplementary Cementitious Material
SDO	Standards developing organization
U.S.	United States
UFGS	Unified Facilities Guide Specifications
USACE	U.S. Army Corp of Engineers
USGS	United States Geological Survey

Abstract

The cement and concrete industries are committed to being net carbon neutral by 2050 and various roadmaps to achieve that goal have been published. These roadmaps share common elements that address the carbon footprint across the entire concrete value chain. The greenhouse gas (GHG) emissions associated with concrete are almost 90% due to the process of producing portland cement clinker. Therefore, reducing the clinker content in concrete is the best near-term method for reducing the carbon footprint of concrete and must occur across the concrete value chain.

It is important to understand that concrete is not a single product. It is tens of thousands of products made from a wide range of local materials and mixture proportions, each product being designed to have specific fresh, hardened, and durability properties. This means to innovate and reduce the clinker content, solutions must be tailored for the specific concrete mixture and application; one size does not fit all. That said, strategies to reduce clinker content fall into two general approaches. The first is avoidance, which is achieved by reducing the total cementitious content of a given volume of concrete. The second strategy is substitution, meaning partial or full replacement of portland cement in concrete with one or more other cementitious material(s). Avoidance is an approach that can be implemented through training and technology transfer. For example, implementing mixture optimization that maintains the concrete's fresh and hardened properties while increasing aggregate volume and decreasing cementitious materials content can make a significant impact. Substitution is where innovation is required through increased use of supplementary cementitious materials (SCMs), alternative cements (ACMs) and alternative SCMs (ASCMs).

Concrete materials innovation is commonly shunned by stakeholders in the construction industry due to a strong risk-aversion. Owners, contractors, and material providers all avoid risk, both real and perceived, meaning they turn to the same materials and methodologies that were used on previous successful projects. on The primary risk is life-safety, which is not negotiable. The risks to be addressed comprise a very wide range of economic factors and engineering considerations. Regardless of the specific concern, without a fair distribution of the risk of innovation, new materials and methodologies cannot proceed. And without a clear understanding of the true nature of the risk, that equitable distribution cannot occur.

In the near-term, any new cementitious material, whether an ACM or ASCM, must conform to the existing cement and SCM distribution infrastructure, must be compatible with existing concrete batching and delivery equipment, must be able to be handled and placed on site by contractors using existing means, must be robust and specified and tested like existing concrete, and be cost competitive.

Portland cement is the predominate type of cement currently used in concrete and is also the main component of most blended cements currently produced. A portland cement blended with only ground limestone is referred to as portland-limestone cement (PLC). A recent success in reducing embodied carbon by the concrete industry has been the accelerated acceptance of PLC throughout much of the United States and Canada, although minor implementation difficulties have emerged in a few markets. Modern concrete is commonly made with SCMs, but SCM use is not increasing and supplies of key materials, like coal fly ash, are in question. Harvested coal ash will fill the need for SCMs long term, as will new materials like calcined clay and other ASCMs. But increasing the overall use of SCMs is the primary challenge. This applies to existing and alternative materials. Education and training of the existing workforce as well as educating college-level engineering students is a near-term need to increase SCM usage in all concrete. Following the industry roadmaps, SCM use needs to approximately double from its present use to achieve carbon neutral concrete by 2050.

Codes and specifications play an important role in implementing new materials. In some cases, existing codes and specifications hinder use by imposing minimum cement contents, or maximum SCM limits. Changing codes and specifications takes time and requires commitment and expertise that many companies marketing new materials do not have. Developing new specifications provides pathways for new materials into the industry and ultimately into building codes. But again, the standards development process is slow and pedantic. Nonetheless, continued efforts in the codes and specifications areas are needed to move new materials forward. Sustainability codes are emerging and are causing ready mixed concrete producers to pursue carbon reduction technologies along with standard tools such as environmental product declarations (EPDs) and life cycle assessments (LCAs). Unfortunately, some technologies are being brought forward that claim carbon reductions that cannot be substantiated. Means of identifying these "green washing" claims is important to provide owners and ready mixed concrete producers confidence in the innovations they pursue, and to reduce the perceived risk.

To identify the most promising tasks needed to reach carbon reduction goals, it is important to look at where cement is being used and what the hurdles to change are in those use categories. Approximately 75% of the concrete in the United States is produced in approximately 6,800 ready mixed concrete plants nationwide. In 2021, 106 million metric tons (117 tons) of portland cement were used in the United States. Approximately 54% of portland cement was used in the building construction sector and 43% used in the public works sector. Both building construction and public works represents similar volumes of cement use and therefore offer similar opportunities for carbon reduction. Each sector, however, provides unique barriers to carbon reduction and given the stakeholders and contracting environments involved, the potential for near-term impact varies. Focusing on progress in public sector construction offers the best opportunity for making meaningful carbon reductions in the near term given the number of applications that are not tied to code compliance and life safety.

The need for education varies between stakeholder groups and therefore requires multiple thrusts tailored to each group.

Existing Workforce - There is an immediate need to work with organizations and associations that serve tradespeople and professionals that are working in the cement and concrete industry, providing them with training in carbon reduction strategies. Given the size and diversity of the concrete-industry workforce, a train-the-trainer approach is required, aiding in preparing and delivering continuing education curriculum. More difficult to accomplish, an approach to training owners is required including guidance on selecting carbon reduction strategies. Technology transfer training is also required, which is more technical and specific to identified applications.

College-level Engineering Students - Students in university engineering programs do not receive adequate education on sustainability or specifically, carbon reduction in concrete. There is a need first and foremost for train-the-trainer activities for college-level as well. In the case of universities, summer workshops for faculty are needed and undergraduate and graduate college students would be incentivized through scholarships tied to engaging in a minor or a certificate program centered on carbon reduction in construction.

Policy Makers –There is significant activity on the policy side of the carbon issue. There is a need for technical information, delivered at the appropriate technical level, to educate policy makers so that laws and regulations are developed that are practical and implementable.

There is also a need for demonstration projects. In the construction industry, the performance risk associated with adopting a new technology is the single largest barrier other than real or perceived increased cost (i.e., the green premium). Even if a technology comes with no increase in cost, few if any are willing to be the first adopter. To address this, it is necessary to conduct demonstration projects where innovative materials or technologies are put into practice under real-world conditions in a demonstration project that is underwritten by a third party or taken on by an owner knowing that a risk of failure exists. This process requires a significant commitment of resources over and above those required simply for the conventional construction. The project needs to not be trivial and yet must not pose a risk of life safety if failure occurs. Without real-world demonstration of a new technology, adoption by the risk-adverse construction community will be slow.

Other actions needed to achieve innovation include a process to vet claims of carbon reduction to minimize the green washing effect, create specification paths to allow for innovation in materials that will be a predecessor to changes in building codes, and providing start-up companies with technical support on specifications and other aspects of integration into the industry.

Executive Summary

INTRODUCTION

This report summarizes the conditions that prevail in the cement and concrete industry with respect to available and emerging materials, materials procurement, and logistics, and identifies barriers to further reduction in the carbon footprint of concrete production and utilization.

The cement and concrete industries are committed to being net carbon neutral by 2050 and various roadmaps to achieve that goal have been published. These roadmaps share common elements that address the carbon footprint across the entire concrete value chain. In the near term, meaning the next 5-10 years, industry road maps project that significant progress must be achieved through enhancements in concrete production and use.

THE CARBON FOOTPRINT OF PORTLAND CEMENT

Concrete is humankind's most widely used material. On a unit mass basis, concrete has one of the lowest carbon footprints and embodied energy of all manufactured materials. The enormous use of concrete, however, acts as a multiplier and causes concrete to be one of the largest single sources of anthropogenic greenhouse gas (GHG) emissions. The GHG emissions associated with concrete are almost 90% due to the process of producing portland cement.

The cement clinker production process is the largest contributor to the carbon footprint of portland cement. The combination of fuel combustion and calcination result in a global warming potential[1] (GWP) of approximately 0.9 kg $CO_{2\ eq}$/kg cement, for portland cement produced in the United States and Canada. For the United States, the production of portland cement is responsible for approximately 0.7% of the total U.S. greenhouse gas emissions in 2020[2] while globally, portland cement production accounts for approximately 7% of the total GHG emissions worldwide[3].

USES OF CONCRETE

It is important to understand that concrete is not a single product. It is tens of thousands of products made from a wide range of local materials and mixture proportions and designed to have a wide range of fresh, hardened, and durability properties.

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[1] The global-warming potential (GWP) of various greenhouse gases are equated to the equivalent effect of CO_2 and expressed in terms of the embodied carbon dioxide equivalent ($CO_{2\ eq}$).

[2] EPA, 2020. FastFacts-1990-2020 National-Level Green House Gas Inventory, US Environmental Protection Agency, https://www.epa.gov/system/files/documents/2022-04/fastfacts-1990-2020.pdf.

[3] Canadian Government, 2022. ROADMAP TO NET-ZERO CARBON CONCRETE BY 2050, Report by Innovation, Science and Economic Development Canada, https://ised-isde.canada.ca/site/clean-growth-hub/sites/default/files/documents/2022-11/roadmap-net-zero-carbon-concrete-2050_0.pdf.

It is common to use the term “end users” to describe those that purchase a product. In the case of portland cement, use follows a chain of ownership. From the time it is purchased from the cement manufacturer, portland cement will pass through the hands of multiple entities as it moves towards its final placement in concrete. Each entity imparts added value along the way, and each share in the risk associated with the concrete placement and use. When analyzing how decisions are made regarding cement and concrete procurement and use, it is more informative to not think of an end user but rather, think about who holds the risk if that concrete fails to perform in service.

RISK IN CONCRETE CONSTRUCTION

Risk can be broadly organized into two categories: life-safety risk and the very broad category of economic risk. Life safety is not negotiable and is a primary focus of a structural building code. A catastrophic failure due to non-compliance with a building code can lead to death and property loss and thereby lead to criminal charges. Knowingly assuming this type of risk is completely avoided by all stakeholders.

Economic risk is more nuanced, resulting from several different situations that can impact use of alternative materials. Examples of economic risks to suppliers of concrete products include construction delays incurred if the new material is more sensitive to ambient weather conditions or uncertainty in achieving specified pay items (e.g., strength, permeability, floor flatness) with an unfamiliar material.

For the concrete supplier concerns include how to store and handle new materials at their existing plant, whether they mix and deliver the concrete using their existing equipment and be able to discharge it at the construction site with the required fresh properties for placement.

From the owner’s perspective, economic risk occurs if a concrete product is not performing due to inadequate material properties, resulting in a loss of functionality and/or increased maintenance cost. In extreme cases, a material may fail prematurely, requiring early removal and costly replacement of the affected structure (e.g., cost of replacement, loss of productivity, loss of business).

Outside of cost (i.e., the green premium), risk is the largest barrier to implementing new technologies within the construction sector. Adoption of new concrete materials technologies can only be advanced if the risk is assessed and shared. A non-equitable distribution of risk can result in overdesign and may completely derail the implementation of a new technology.

At the end of a project, the owner expects to receive a structure that will perform over the intended service life for the price agreed upon at the start. While owners may want to use lower carbon concrete, that desire may recede if the risk of failure is too high. Contractors simply want to be paid for what they agreed to provide and using materials they are familiar with provides them with the lowest risk of failure.

MATERIALS PRODUCTION AND OTHER CONSIDERATIONS

In the near-term (i.e., next 5-10 years), any new cementitious product introduced to replace portland cement, partially or fully, must easily integrate into the existing infrastructure of the cement, concrete, and construction industries. In general, the product must:

- Fit within the existing storage and shipping infrastructure of the cement and concrete industry,
- Allow concrete producers to use the new material in existing concrete production facilities and transport the concrete using existing means, and
- Be competitive in cost to portland cement.

To achieve industry-wide carbon reduction goals, changes are needed beyond simply changing the cement. Increased use of supplementary cementitious materials (SCMs), use of alternative supplementary cementitious materials (ASCMs), reduced cementitious contents in concrete, and reduced use of concrete itself, are all necessary changes to be implemented. As changes are made to concrete and concrete-making materials, those changes must be supported by the required training and code/specification modifications and must:

- Allow concrete designers to specify and design using the new concrete materials or mixtures, as they specify concrete today,
- Allow concrete contractors to convey, place, finish, and cure the resulting concrete in a similar way as they use concrete today, and
- Be competitive in cost to portland cement concrete.

CONCRETE

Concrete is a very robust material, produced using several different approaches depending on the specific application, and placed under an extreme range of environments and conditions. The robustness, or "forgiveness", of concrete, owing to the simplicity of portland cement, is one reason why concrete is so widely used world-wide. New materials and mixtures must be similarly robust if they are to be successfully used in most concrete applications.

PRODUCTION & LOGISTICS

Approximately 75% of the concrete in the United States is produced in ready mixed concrete plants. Ready mixed concrete applications are shown Table E1. Historical ready mixed production is shown in Figure E1.

Table E1. Reported uses of ready mixed concrete as a percentage of total use. (NRMCA, 2021)

Application	Reported Use (percent total)
Commercial Structure	40.7%.
Residential Structure	32.5%.
Parking Lots	
New Construction	3.8%.
Reconstruction	1.2%.
Streets/Local Roads	
New Construction	6.8%.
Reconstruction	2.4%.
Public Works Structure	9.7%.
Pervious Concrete	0.2%.
Roller Compacted Concrete	0.1%.
Flowable-Fill	2.5%.

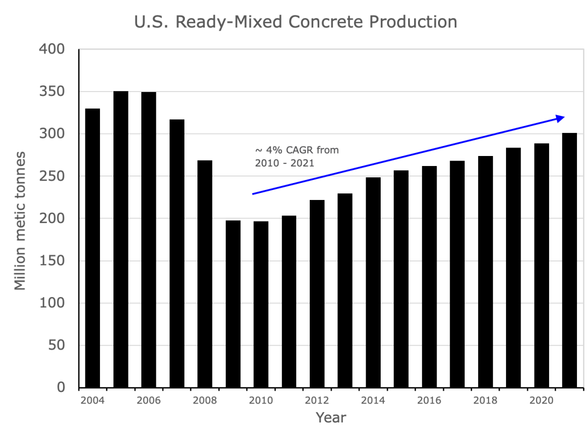

Figure E1. Ready mixed concrete production 2004 – 2021. Data shows a compound annual growth rate (CAGR) of approximately 4% since 2009. (Source: National Ready Mixed Concrete Association.)

CARBON REDUCTION STRATEGIES

Concrete is a mixture of aggregates, cement, SCMs, chemical admixtures, and water. Modern concrete mixtures typically contain SCMs that are used in addition to, or as a partial replacement of, portland cement in the concrete. The use of SCMs lowers the GWP of the concrete mixture but historically SCMs have been used to reduce cost and improve durability. Examples of SCMs include fly ash, bottom ash, and harvested ash, collectively known as coal ash, other by-product materials such as slag cement, recycled materials such as ground glass, as well as natural pozzolans[4]. In addition to portland cement, blended cements are used, which are a portland cement blended with an SCM or ground limestone at the cement production facility rather than mixing at the ready mixed concrete plant. For the purposes of this report, the term concrete refers to that produced with either portland cement or blended cement.

[4] A pozzolan is a finely-divided siliceous or siliceous and aluminous material that will not react chemically with water, but will react with calcium hydroxide and water at ordinary temperatures to form compounds possessing cementitious properties. (Source: ASTM C 125 *Standard Terminology Relating to Concrete and Concrete Aggregates*). When portland cement hydrates, calcium hydroxide is produced. That calcium hydroxide reacts with the pozzolan to form cementitious compounds.

Although portland cement comprises approximately 15% of the concrete by mass and 10% by volume, it is responsible for approximately 90% of the embodied carbon in conventional portland cement concrete. For this reason, the focus on reducing the carbon footprint of concrete is largely centered on reducing the amount of portland cement in the concrete. Two broad strategies are currently used to reduce the carbon footprint of concrete.

The first is avoidance, which is achieved by reducing the total cementitious materials content of a given volume of concrete through mixture optimization. The second strategy is substitution, meaning partial or full replacement of portland cement in concrete with one or more other cementitious material(s).

For full replacement of portland cement, several types of alternative cementitious materials (ACMs) are emerging or are under development that have a lower GWP than portland cement, thereby providing a significant reduction in the carbon footprint of concrete. Adoption of new ACMs is hindered by either a lack of standard specifications and test methods, or by existing specifications and codes precluding their use. Also, current ACM technologies lack sufficient production output to meet the demand of the concrete industry and often lack the robustness of portland cement for a broad range of environmental conditions encountered during placement.

PLACEMENT

Concrete is the only construction material that is manufactured at the job site. The act of placing fresh concrete is an important consideration when discussing barriers to new material technologies. Changes made to concrete for the purposes of carbon reduction may result in changes to setting times, finishing times, or other considerations such as curing and timing of joint sawing. With new materials such as ACMs and ASCMs, special handling or curing approaches may be needed. In some cases, using the same methods suitable for conventional concrete may lead to failure. It is therefore imperative that education and technology transfer efforts extend to the level of the trades workers who will be placing and finishing these new materials. Given the large number of employers and workers in this industry, this will come at a cost that needs to be included in the costs of implementing new technologies.

CONCRETE TESTING AND ACCEPTANCE

Concrete acceptance testing conducted during placement is currently a concern for the concrete industry that, if resolved, would result in a measurable reduction in portland cement use. The most common testing requirement is for a minimum strength (e.g., compressive strength at 28 days.) The problem facing the industry is that often the handling and testing of the concrete samples (e.g., cylinders, beams) is not performed correctly and concrete meeting the specifications is erroneously rejected. Because strength is an acceptance pay item, concrete suppliers routinely add excess portland cement to the concrete mixture to overcome deficiencies in specimen handling and testing and to ensure the required minimum strength is met, thereby avoiding monetary penalties.

Solutions to this issue include requiring all concrete field and laboratory testing technicians to be ACI certified, that concrete specimens molded in properly handled and cured, and that testing laboratories meet prequalification requirements for each test in annual performance test programs, adopting the Concrete Testing Adherence Collaboration (CTAC)[5] approach. Implementing use of embedded sensors in the concrete structure or in test samples may also help. These sensors need to be developed and vetted through research and demonstration projects and standardized to ensure uniform and reproducible results.

Further, rejection of the in-place concrete due to low strength should be exercised in cases where strength critical to performance is not achieved. In other applications, such as curb and gutter, sidewalks, and many pavements, durability tests would be more appropriate.

PORTLAND CEMENT AND BLENDED CEMENT

PRODUCTION

Portland cement is the predominate type of cement used in concrete and is also the main component of most blended cements currently produced. Portland cement consists of portland cement clinker interground with a source of calcium sulfate (e.g., gypsum), less than 5% raw limestone, and up to 5% other processing additions. Portland cement is a hydraulic cement, meaning that it chemically reacts with water to form a hardened cement paste and will harden underwater.

Blended cement production can involve additional steps of intergrinding materials such as additional raw limestone with the clinker and gypsum, or simply blending the ground portland cement separately with SCMs such as coal ash, natural pozzolan, and/or slag cement. The blending of a limestone, pozzolan, or slag cement reduces the clinker factor[6] of the blended cement.

A portland cement blended with only ground limestone is referred to as portland-limestone cement (PLC). A recent success in reducing embodied carbon by the concrete industry has been the accelerated acceptance of PLC throughout much of the United States and Canada. The use of PLC in place of ASTM C150 Type I or Type I/II portland cement results in an approximate 8-10% reduction in $CO_{2\ eq}$ without the need to modify current concrete mixture designs or construction practices.

[5] https://www.concretetac.com

[6] Clinker factor is the term used to quantify the amount of clinker in a unit mass of portland cement. As an example, a clinker factor of 0.90 indicates the final portland cement is 90% clinker, 10% other materials.

LOGISTICS

Introducing new materials requires them to be integrated into the existing materials storage and distribution network that currently supports the concrete industry. Most cement plants produce only one type of clinker and in most cases only one type of cement (e.g., ASTM C150 Type I). Portland cement plants are almost always sited near large deposits of limestone since it is the primary raw material. Where possible cement plants are located adjacent to navigable water access providing a low-cost and low-energy method to transport clinker and cement products to terminals and customers. If not near water, then rail access is needed to meet shipping demands and to do so in a manner that minimizes cost. Storage of clinker and cement is an important component of the production process and storage capacity is limited, designed to buffer fluctuations in the manufacturing process and temporal fluctuations in the market demand.

Because of this centralized production and the need to serve a decentralized market, storage and distribution becomes one of the most important aspects of portland cement production.

Cement production is extremely capital intensive, requiring specialized equipment for material handling and processing, pyro-processing, grinding, and storage. Portland and blended cements are commodity products that sell for pennies per pound and cement plants are designed for a long operating life to amortize the high capital costs and produce a product at a market acceptable price. As a result, changes to produce different types of products in any given cement plant, even for a brief production run, requires significant process changes that add cost and reduce production capacity.

Given limited flexibility in a cement plant's unit operations, and limited storage capacity along the distribution network, a cement manufacturer cannot produce a new material on speculation.

SUPPLEMENTARY CEMENTITIOUS MATERIALS

The production and supply of SCMs is an important factor that will impact the drive to carbon neutral concrete. Every concrete industry roadmap for carbon reduction relies on increasing the use of SCMs to reduce the clinker component of cement. As one example, the Portland Cement Association (PCA) *Roadmap to Carbon Neutrality* estimates the current clinker factor to be ~0.90, calling for a clinker factor of 0.85 by 2030, 0.80 by 2040, and 0.75 by 2050. Widespread adoption of PLC can bring the clinker factor down to ~0.80-0.85 and further reductions will be met largely by using higher levels of SCMs in blended cements.

HISTORY OF SCM USE

Historically, the primary reason for using SCMs has been cost reduction by partially replacing portland cement, the most expensive component of the mixture. Over the past 50 years, however, the body of research has demonstrated that durable concrete almost always requires the use of an SCM in some quantity to reduce permeability and mitigate deleterious chemical reactions.

The benefits of SCMs are known by engineers working with concrete but many still specify SCMs cautiously and many codes and specifications still place limits on the maximum allowable SCM content in concrete mixtures. These maximum limits are a significant barrier to increased SCM use, which has been constant or decreasing over the past 15 years. To illustrate this, coal fly ash is the most common SCM used in concrete, yet its use appears to be decreasing since 2015. On an absolute basis, the average use from 2004 to present has not changed appreciably (i.e., 14.4 ± 3.3 million Mt, 15.9 ± 3.3 million short tons), while the use of ready mixed concrete has increased at a compound annual growth of approximately 4%.

In addition to coal fly ash, other SCMs are used including slag cement, natural pozzolans, and ground glass. Each of these have regional impact but do not have the broad use of coal fly ash. Slag cement is the next most used SCM, with shipments of approximately 4 million metric tons (4.4 million short tons) in 2021, about ¼ of coal fly ash. Natural pozzolans are currently only commercially available in the western United States, although clay suitable for calcining, an emerging technology, has reserves distributed across the United States. According to the Natural Pozzolan Association (NPA), natural pozzolan use in 2021 was approximately 0.86 million metric tons (0.95 short tons) and is expected to increase by approximately 25% in 2022. Ground glass pozzolan, from recovered municipal waste glass, is relatively new as a pozzolan and currently only available in relatively small quantities in a few local markets. ASTM passed the standard specification ASTM C1866 in 2020 which has helped move ground glass forward in selected markets but the overall impact to date has been small. Ground glass producers seek to expand but are limited given the small number of municipal waste materials recovery facilities (MRFs) that separate glass.

PRODUCTION & LOGISTICS

Production of conventional SCMs varies with SCM type. Starting with coal fly ash, production has dropped to less than half of its recent maximum in 2008 and as more coal-fired power plants close the supply of freshly produced fly ash will continue to decline.

However, the coal ash industry is actively moving towards use of harvested coal ash, which are materials that have been placed in landfills or disposal ponds and are now being mined for use in concrete. Recently, ASTM has changed the specification for coal fly ash (ASTM C618) to allow for broader use of coal ash (i.e., coal fly ash, coal bottom ash and harvested ash). The ACAA estimates that in 2022, 2.7 million metric tons (3 million short tons) of harvested ash was produced in the United States.

Coal fly ash, fresh or harvested, still has distribution challenges. Unlike portland cement plants that are sited to facilitate low-cost bulk transfer, power plants are more distributed and as power plants close or convert to gas, it is increasingly necessary to transport ash long distances, adding cost and negatively impacting the GWP benefits of using ash. Another barrier to increased harvested ash production is reluctance by power companies to pursue harvesting, especially for landfills or impoundments that have already been closed.

According to the NPA, current raw natural pozzolan capacity is estimated to be 1.35 million metric tons per year (1.5 million short tons per year) while calcined clay is estimated to be approximately 45,000 – 90,000 metric tons (50,000 – 100,00 short tons) in 2021. Between now and 2025 the NPA predicts rapid and significant growth in the production of calcined clays given their broader availability across the United States.

In 2018, the most recent data available from the EPA, 11.2 million metric tons (12.3 million short tons) of container glass were produced, which is the largest single source of recycled glass. Very little of the recycled glass made its way into concrete given the lack of processing centers that separate glass and the even smaller number of ground glass pozzolan producers; currently there are only 2 producers in the United States and one in Canada. The estimated annual production is on the order of 35,000 metric tons (40,000 short tons) with another production plant expected to be added in 2023.

LC3 CEMENTS

Two of the most widely available materials in the earth’s crust are limestone and various clay minerals that interestingly comprise the same elements found in raw materials used to produce portland cement. By calcining kaolinite clay, water is released from the clay mineral structure creating an amorphous calcium silicate that is a highly reactive pozzolan. Calcining clay does not release CO_2, as happens with calcining limestone. And because lower temperatures are required as compared to clinker production, fuel-related CO_2 emissions are also reduced. Calcined clay can be blended or interground together with limestone to make a blended SCM. While extensive research results over more than 12 years have been very promising, including field trials of LC3 cements, no major cement producer in Europe or North America is currently producing LC3, except in limited trials.

CHALLENGES FOR ADOPTING LC3 AND OTHER ALTERNATIVE CEMENT SYSTEMS

Challenges for ACMs like LC3 fall into three categories. The first is risk. Simply put, these are new cements with limited field experience. When the proposition is to fully replace portland cement in a concrete mixture with an unknown material, it is a risk most owners and contractors are currently not willing to take.

The second challenge is the specification environment. For the most part in the United States and Canada, all cement is specified using ASTM, AASHTO, or CSA standards, regardless of the project type or scope. Currently these standards are prescriptive and only cover hydraulic cement.

The third challenge is the size and breadth of the market that ACMs need to operate in. Currently, there is no alternative cement, including LC3, that can be produced in quantities large enough to significantly displace portland cement from the market.

For these reasons, alternative cements will evolve slowly. The best-case scenario is that relatively soon, specifications will be developed removing that barrier. From there, each technology will need to find a niche, or an early adopter, and demonstrate their performance.

ALTERNATIVE SUPPLEMENTARY CEMENTITIOUS MATERIALS

Alternative supplementary cementitious materials (ASCMs) are entering the marketplace and will play a significant role in achieving carbon neutrality given the current pressures on coal fly ash supplies and limited quantities of other SCMs. These materials offer several advantages that will assist. First, many are manufactured, meaning the production facility can be located near the point of use, or navigable waterway. Second, a factor causing ready mixed concrete producers to limit fly ash use is inconsistency in the product. Coal fly ash is a waste product, and its characteristics change as the operation of the power plant changes. Being manufactured, an ASCM can be more consistent and allow for larger, predictable substitution levels in concrete mixtures. An additional benefit of ASCMs is that some are being manufactured with carbon sequestration as part of the process or a benefit of their use. The result is the material being used as an ASCM also provides the ability to sequester carbon in the concrete mixture.

CHALLENGES FOR ALTERNATIVE SUPPLEMENTARY CEMENTITIOUS SYSTEMS

The path to implementation for an ASCM is less challenging than is the case for an ACM. This is because in most cases, the resulting cementitious system is still largely portland cement based. If performance of the ASCM can be demonstrated to be equal to a conventional SCM, acceptance is not unrealistic to expect. A key remaining barrier is developing a national specification that can be used for these materials. At ASTM, a general specification for SCMs is under development that will be applicable to most emerging SCMs.

CODES, SPECIFICATIONS, AND STANDARDS

BACKGROUND ON CODES

Both codes and specifications provide direction on how a structure will be designed or constructed, what materials may be used, or a wide range of other types of requirements. Codes are enacted by a legally established body having a defined jurisdiction and authority, and failure to comply could have legal repercussions including civil charges, criminal charges, or both.

It should be noted that Codes only provide minimum requirements, and they can be exceeded. Adding sustainability into structural code documents like ACI 318 is not seen as necessary for life-safety and creates a concern that reduced embodied carbon options could result in an increased risk of failure.

BACKGROUND ON SPECIFICATIONS

Specifications are the written portion of a construction contract; plans and drawings comprise the remainder of the contract. Specifications may be enforced as part of a contract but are not statutorily enforced and may be superseded by independent action taken by the owner, or through mutual agreement between the owner and the contractor, assuming said action still meets any applicable code. Normally in such discussions, the licensed design professional (LDP) or a construction manager is the owner's representative.

A specification may be prescriptive or performance based. Often specifications provide both a performance requirement and a prescriptive "deemed to comply" requirement and meeting either requirement demonstrates compliance.

BACKGROUND ON STANDARDS

Standards are, in general, documents written with the intent of providing uniformity to the construction and contracting processes. There are numerous types of standards referenced in construction documents. Standards are intended to provide a uniform approach and therefore, in some cases, have the ancillary effect of limiting innovation by making every project the same, regardless of the project scope, stifling innovation.

DEVELOPMENT OF CODES, SPECIFICATIONS, AND STANDARDS

Code language is drafted and approved by code writing bodies such as the American Concrete Institute (ACI) and that language is then approved for inclusion in the International Building Code (IBC), which is a model building code developed by the International Code Council (ICC). Local jurisdictions (e.g., cities, counties, states) adopt the IBC as the applicable building code, sometimes with modifications to accommodate local needs, and those local jurisdictions are responsible for enforcement.

Specifications may be standard specifications written by consensus organizations such as ACI or ASTM, or they may be drafted independently by the owner or an LDP working on behalf of the owner. For example, all state DOTs write their own specifications for road and bridge construction, drawing on standard specifications but also developing their own specification language. Many develop their own standard tests, which may also reference national standards but with modification. State DOT material specifications serve as the default minimum requirements in most markets because state materials specifications are generally more restrictive than standard material specifications, and a ready mixed concrete producer needs to meet the requirements for most jobs. As a result, state DOT material specifications strongly impact the materials available from a ready mixed concrete producer.

There are general standard specifications that are packaged into contract-ready form allowing the specifier the convenience of having lengthy construction contract documents partially prepared in advance. This can and does result in specifiers assembling contract documents without investing the time to research new products or consider carbon reduction options that may be appropriate for a given project. A common example of these pre-packaged specifications is MasterSpec®, which was developed by the American Institute of Architects (AIA) and is based on the Construction Specification Institute (CSI) MasterFormat®. A MasterFormat® document can be used to specify any work, but standard language included refers to code-related requirements, which may not be required on the project being specified. This can result in over specification and imposition of requirements that are counter to carbon reduction.

CEMENT SPECIFICATIONS

The portland cement types commonly used in the United States and Canada are ASTM C150 (AASHTO M 85) and CSA A3001. Different types of cement are produced under each specification, each having unique properties and applications. The general classifications of these types are general use, moderate sulfate resistance, high sulfate resistance, high early strength, and low heat of hydration. Blended cements in the United States are specified under ASTM C595 (AASHTO M 240) and in Canada under CSA A3001. In the United States, hydraulic cements for construction may also be specified under ASTM C1157, which is a performance specification for hydraulic cements. Note that ACMs that are not hydraulic are not covered under this specification. To date, this performance-based cement specification has not gained wide acceptance in the United States or Canadian construction industries.

OTHER CONCRETE-MAKING MATERIALS SPECIFICATIONS

COAL FLY ASH, NATURAL POZZOLANS OTHER SCMS

Coal fly ash and natural pozzolans are specified under ASTM C618 (AASHTO M295). ASTM C618 was recently changed to specify coal ash rather than coal fly ash, where coal ash is defined as either coal fly ash, coal bottom ash, harvested coal ash, or combinations thereof. Note that harvested ash will generally be a blend of coal fly and bottom ash. Slag cement, silica fume, and ground glass all have standard specifications in both U.S. and Canadian specifications.

CONCRETE SPECIFICATIONS

READY MIXED CONCRETE

In the United States, the standard specification for ready mixed concrete is ASTM C94. The AASHTO equivalent is AASHTO M 157. This specification covers ready mixed concrete manufactured and delivered to a purchaser in a freshly mixed and unhardened state. It is essentially a specification governing quality; it does not address mixture design or expected performance in the hardened state. Acceptable materials are specified and therefore any new material needs to be included in the specification, which means any new material requires a specification that can be referenced by ASTM C94 (AASHTO M 157). This specification does not cover the placement, consolidation, curing, or protection of the concrete after delivery to the purchaser. ACI 301-20 *Specifications for Concrete Construction* is a reference specification covering the general requirements for concrete construction. The LDP for a project involving concrete construction applies this document by reference in the project specifications.

It is common for the purchaser of concrete to have their own requirements beyond those specified in the standard specifications and under those conditions, the purchaser's specification governs. Two common specification barriers to reducing the carbon footprint of concrete observed in purchaser's specifications are (1) minimum cement (or cementitious materials) content, and (2) maximum allowable replacement levels of cement with SCMs.

PRECAST/PRESTRESSED CONCRETE

Codes and specifications for precast/prestressed concrete are currently more fragmented than is the case for cast-in-place structural concrete. The Precast/Prestressed Concrete Institute (PCI) publishes a series of guide specifications[7] covering structural, architectural, and other applications. For its part, ACI addresses precast and prestressed as part of ACI 318 as well as in other codes such as ACI 350 for environmental structures. Two new ACI code committees have been formed and are writing code language for Precast Structural Concrete (ACI 319) and Post-Tensioned Structural Concrete (ACI 320). Both of those code language documents are under development and are intended to consolidate code requirements for structural precast/pre-stressed concrete.

BUILDING CODES

ACI 318/INTERNATIONAL BUILDING CODE

The American Concrete Institute is responsible for publishing ACI 318 Building Code Requirements for Structural Concrete. The document is written in mandatory language and is included in the IBC by reference. The document has a singular purpose and that is to provide the minimum requirements for structural concrete to ensure life safety. In the current version (i.e., ACI 318-19) published in 2019, sustainability is not addressed and arguably it is not impacting the singular mission of the code. ACI 318 does impart some barriers to implementing sustainable solutions but as data becomes available, particularly performance data, ACI 318 has adopted changes to allow for alternative materials to be used. For the next edition of the 318 Code, subcommittee 318-N on sustainability was established in 2019. Proposed changes include addition of GWP limits for concrete mixtures of different strength, but to date, none of the balloted items have passed, and it is not yet clear that such changes will make the 2025 edition of the Code.

Changing ACI 318 requires a long lead time. ACI code documents are revised over a 5-year cycle. After approval within ACI, it takes a few more years before the

[7] https://www.pci.org/GuideSpecifications

latest version of ACI 318 is adopted into the IBC model code and finally into local building codes in the United States Similarly.

SUSTAINABILITY CODES

MARIN COUNTY

The Marin County Low-Carbon Concrete Code[8], adopted by Marin County, California is the first code addressing carbon reduction in concrete construction. It establishes a maximum portland or blended cement content for different strength concretes as well as maximum limits on embodied carbon. Cement contents can be increased by up to 30% where high-early strength is required. The limits for maximum embodied carbon are based on industry average EPDs and are provided within the code.

GENERAL SERVICES ADMINISTRATION

In March 2022, the General Services Administration (GSA) adopted Low Embodied Carbon Concrete Standards for all GSA Projects. This requires the contractor to provide a product-specific cradle-to-gate Type III environmental product declaration (EPD) for each concrete mix design specified in the contract and used at the project. Maximum GWP limits are listed for six different strength classes for each of standard, high-early strength, and light-weight concrete mixtures. These limits reflect a 20% reduction from GWP (CO_2e) limits in proposed code language[9].

[8] Low-Carbon Concrete Code Chapter 19.07.50 (accessed Jan. 5, 2023) https://library.municode.com/ca/marin_county/codes/municipal_code?nodeId=TIT19MACOBUCO_CH19.07CACORE

[9] "Lifecycle GHG Impacts in Building Codes" by the New Buildings Institute, January 2022. https://newbuildings.org/wp-content/uploads/2022/02/NBI_LI1.pdf

PORTLAND, OREGON

In May 2022, Portland, Oregon adopted a project-based embodied carbon limit for concrete. This provides flexibility to the contractor to use different types of concrete for different structural elements while meeting a total embodied carbon limit for the project. So higher GWP mixtures can be used where needed to meet design requirements or construction schedules, and be traded off against lower GWP mixtures that have less impact on construction schedules while still meeting minimum design requirements.

PCA STATE AND MARKET REPORT

The PCA State and Market Report is released twice a year and summarizes annual estimates for cement consumption across 46 market classes for 56 State and partial-state geographic areas. The breakdown of these market classes, based on the currently available 2022 Report, is shown in Figure E2. In total, 106,003,000 metric tons (~116,850,000 tons) of portland cement were used in 2021, with 39% of that cement being used in the construction of residential buildings. This use for residential construction is a 5% increase from 2019. Almost 30% of portland cement was used for street and highway construction, and roughly 10% each for commercial buildings and for water and wastewater management.

UNITED STATES GEOLOGICAL SURVEY

The 2021 data shows that 92 million metric tons (101 million tons) of portland and masonry cement were produced in the United States including cement made with imported clinker. Domestic clinker production clinker production for 2021 was estimated to be 79 million metric tons (87 million tons). Imports of cement, excluding clinker imports, accounted for another 19 million metric tons (21 million tons). With cement exports included, the net apparent consumption in the United States was 109 million metric tons (120 million tons).

The average price per ton in 2021 is estimated to be $125 USD. The compound annual growth in price from 2018 to 2021 was 1.1%. The report provides information on imports that indicates the net reliance on imports, including cement and clinker, was 18% in 2021, up from 15% in 2020. The compound annual growth in import reliance from 2018 to 2021 was 6.5%. For the period 2017-2020, the prominent import sources were Canada (32%), Turkey, (20%), Greece (13%), and China (8%).

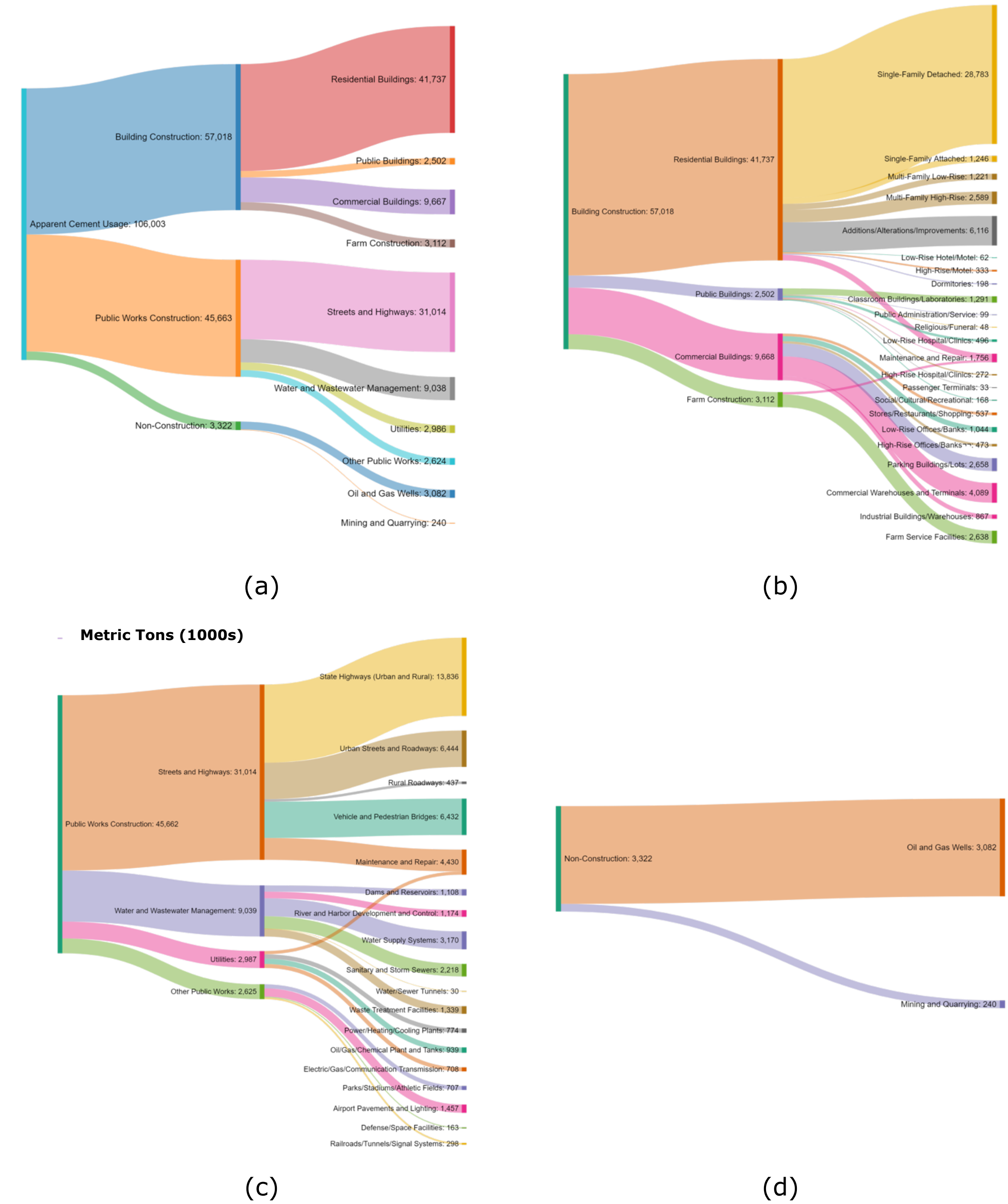

Figure E2. Apparent use of portland cement in the United States in 2021 for a) specific markets, b) building construction, c) public works construction, d) non-construction (Source: PCA, 2022).

DISCUSSION AND ACTION PLAN

DISCUSSION

The barriers related to materials innovations can be placed into three general categories 1) related to the existing materials production and logistics infrastructure, 2) related to cement and concrete use, which includes how the industry specifies, tests, and accepts concrete and designs concrete structures, and 3) related to adopting new technologies in a risk-adverse industry. Given the existing infrastructure for manufacturing, delivery and installation of concrete, and the massive capital investment that would be required to change it, advancements in carbon reduction must be made within this infrastructure. This leaves changing how we use cement and concrete, and mitigating the risk of new technologies, as the key areas to address to affect carbon reduction in the next 5-10 years.

Regarding concrete use, there are many reasons why carbon reduction solutions have not been implemented, including:

- Education is required across the industry, for all stakeholder groups,
- Fact-based technical information to facilitate the use of a new technology is lacking,
- Initial higher costs (i.e., the green premium) continue to be a barrier to implementation, and
- In some cases, the availability of low carbon technologies or material supplies are limited geographically.

Outside of cost, the risk associated with adoption of a new technology, real and perceived, is one of the largest barriers to implementing new technologies within the construction sector. As new technologies are adopted, the risk must be assessed and shared. Anon-equitable distribution of risk can result in overdesign and may completely derail the implementation of a new technology.

ACTION PLAN

Based on the analysis of portland and blended cement use, and based on input from key industry stakeholder groups, it is estimated that 70 - 75% of portland and blended cement use in the United States is in ready mixed concrete. Approximately 54% of portland cement is used in the building construction sector and 43% towards the public works sector. It is assumed that blended cements distribute in similar proportions. The four largest uses are in:

1. residential buildings (~39%),
2. streets and highways (~29%),
3. commercial and public buildings (~9%), and
4. water and wastewater management (~9%).

Focusing on either building construction or public works represents similar volumes of cement use and therefore similar opportunities for carbon reduction. Each sector, however, provides unique barriers to carbon reduction and given the stakeholders and contracting environments involved, the potential for near-term impact varies.

The opportunities for action are shaped by the following points.

- Adoption of carbon-reducing technologies in the building sector will be slowed by the need for specific design information to meet building code requirements.
- Implementation in the streets and highways sector does not have the restrictions imposed by building codes.
- Public sector improvements can be approached on a push-pull basis from both the technology/engineering side and the policy/legislation side.
- Although public works is the smaller use, requirements for public works projects are the lowest common denominator for concrete producers and in most regions, are often being dictated by state DOT specifications.
- Cross support between policy/legislation teams and technical teams will have the largest impact in public sector projects.

For these reasons, focusing on progress in public sector construction offers the best opportunity for making meaningful carbon reductions in the near term. To do so will require action in the areas briefly discussed below.

EDUCATION

The need for education varies between stakeholder groups and therefore requires multiple thrusts tailored to key stakeholder groups.

Existing Workforce - There is an immediate need to work with organizations and associations that serve trades people and professionals that are working in the cement and concrete industry, providing them with training in carbon reduction strategies. A train-the-trainer approach is required, aiding in preparing and delivering continuing education curriculum. Immediate attention should be given to designers, engineers, and architects, followed by contractors and trades people. More difficult to accomplish, an approach to training owners is required. Training for public owners needs to be delivered to elected and non-elected officials but for elected officials a different scope of training activities will be required. In the transportation sector, groups such as the National Center for Concrete Pavement Technology Center (CP Tech Center) at Iowa State University, AASHTO, and the American Road & Transportation Builders Association (ARTBA) are possible partners. At the municipal level groups such as the National Association of County Engineers (NACE) and the American Public Works Association (APWA) can be important allies in providing opportunities to present and train at their annual meetings. Also, ACI has a vast network of local chapters and harnessing those groups to deliver carbon reduction training could reach multiple audiences.

College-level Engineering Students - Students in university engineering programs do not receive adequate training on sustainability or specifically, carbon reduction in concrete. Most curricula are limited by time and required credits, making addition of new material difficult. The students, however, are very aware and motivated to learn about carbon reduction and seek an opportunity to be better informed and prepared to engage in carbon reduction when beginning their post-education career.

There is a need first and foremost for train-the-trainer activities for faculty. In the case of universities, summer workshops for faculty are needed to provide the background they need to lecture effectively. Applicable reference material needs to be organized and provided in a format that can be readily disseminated in their classroom. Model curricula and syllabi need to be provided to launch the programs. Also, a cadre of guest lecturers needs to be developed that can be made available to visit individual schools and jump-start programs. Most universities have options for minors or certificate programs that focus on a specific subject and encourage study in one specific area. These need to be developed for carbon reduction in construction materials.

For college students, undergraduate and graduate scholarships need to be made available. In the former case the support should be tied to engaging in a minor or a certificate program centered on carbon reduction in construction materials or completing a graduate degree with that focus. Several universities now offer summer programs that are one-two week intensive study of a specific subject, such as materials. The faculty need to be incentivized to offer those programs and the students need financial support to attend. These summer programs can be very important in both training young engineers but also training future faculty (i.e., graduate students) and preparing them to deliver instruction on carbon reduction once they receive their academic appointment.

Policy Makers – Government Officials – There is significant activity on the policy side of the carbon issue and clearly, without policies to create demand for low carbon technologies, progress will be slow. However, policies are often made in a technical vacuum. Those making polices and laws, and approving public funding for carbon reduction initiatives, invariably do not fully understand the complexity of the problem. There is a need for technical information, delivered at the appropriate technical level, to educate policy makers so that as laws and regulations are developed, they are also practical and implementable.

Technology Transfer/Training - To move forward on carbon reduction, all stakeholders need to be aware of strategies, understand why certain aspects of their job may be changing, and understand the impact of continuing business as usual. That is delivered in an educational program. Also needed is technology transfer where specific technical knowledge is provided. This is directed initially to architects, engineers, and others on the design team. Technology training is also needed for contractors and the trades people working with new technologies in the field. Resources to accomplish technology transfer need to be focused through state

DOTs, federal agencies, engineering and design firms, trade organizations and industry associations, as well as through union halls and trade schools.

TECHNOLOGY VALIDATION

So called "green washing" is when a company or sponsor makes incomplete or false claims about a technology and implies or states that certain carbon reduction goals can be achieved by use of their technology. This practice is a barrier to new technologies if left unchecked. This plays into the issue of risk. If a stakeholder (i.e., owner, designer, contractor) adopts a technology only to discover it has little or no carbon reduction value, they will be much more hesitant about trying another technology on a project. There needs to be a process to vet claims of carbon reduction to minimize the green washing effect.

DEMONSTRATION PROJECTS

In the construction industry, risk is the single largest barrier other than cost. And even if a technology comes with no increase in cost, few if any are willing to be the first adopter.

To address this, it is necessary to conduct demonstration projects where innovative materials or technologies are put into practice under real-world conditions. The construction of a demonstration project needs to utilize existing equipment and concrete production facilities and the project requires exposure to normal or rigorous use. This process requires a significant commitment of resources over and above those required simply for the construction, and the project needs to be significant but not one that poses a risk of life safety if failure occurs. Public works projects offer a lower risk of entry, as compared to commercial or residential construction, and through recent legislation, public funds are available to support these types of projects. It is unrealistic to expect rapid implementation of even the most benign changes in concrete construction without demonstration projects to provide confidence of success.

SPECIFICATION AND CODE DEVELOPMENT

Specifications and codes are often considered to be barriers to innovation and historically that may be true. Without a specification, it is difficult to move forward with innovation because there is no apparent path to market. Creating a specification path removed a barrier to innovation and allowed for the development of PLC. To allow for innovation more broadly, a performance-based specification for ASCMs is required as well as specifications for ACMs and other low-carbon technologies. In general, it is imperative for key influencers within ASTM, AASHTO, and CSA to keep working within those organizations to ensure that a specification path is available for innovative materials.

Code changes will come more slowly and cannot be expected to move quickly given a) the code writing process, and b) the need for protecting life safety, which is at the heart of a structural concrete design code. That said, it is important to keep bringing new technologies forward to code writing bodies. Invariably, those charged with writing the codes will require published, peer-reviewed research as well as the results from field testing (i.e., demonstration projects). With data to support their decisions, code writing bodies can be swayed but the process will be slow and will be a continual barrier.

ONBOARDING NEW TECHNOLOGY COMPANIES

Most new materials being introduced into concrete construction are being promoted by small startup companies that often have little to no experience in the construction industry. For these companies with innovative ideas, their inexperience and lack of knowledge regarding the existing concrete production and placement infrastructure is a significant barrier to their success. Start-up companies need to work with independent experts in the industry, enlist those individuals as champions, and draw from their experience to guide the company’s entrance into the industry.