

## NRC Publications Archive Archives des publications du CNRC

### NRC-CAC Low Carbon Concrete Research and Development Workshops

Makar, Jon; Nkinamubanzi, Pierre-Claver; Cooney, Robert; Littlejohns, Jennifer; Shouvik, Dev; Butler, James

This publication could be one of several versions: author's original, accepted manuscript or the publisher's version. / La version de cette publication peut être l'une des suivantes : la version prépublication de l'auteur, la version acceptée du manuscrit ou la version de l'éditeur.

For the publisher's version, please access the DOI link below. / Pour consulter la version de l'éditeur, utilisez le lien DOI ci-dessous.

<https://doi.org/10.4224/40003952>

### NRC Publications Archive Record / Notice des Archives des publications du CNRC :

<https://nrc-publications.canada.ca/eng/view/object/?id=6fb960f3-e686-493d-b04c-926e7b31f3aa>

<https://publications-cnrc.canada.ca/fra/voir/objet/?id=6fb960f3-e686-493d-b04c-926e7b31f3aa>

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at

<https://nrc-publications.canada.ca/eng/copyright>

READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L'accès à ce site Web et l'utilisation de son contenu sont assujettis aux conditions présentées dans le site

<https://publications-cnrc.canada.ca/fra/droits>

LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D'UTILISER CE SITE WEB.

**Questions?** Contact the NRC Publications Archive team at

PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the first page of the publication for their contact information.

**Vous avez des questions?** Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n'arrivez pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.

**NRC-CMRC**

# **NRC-CAC Low Carbon Concrete Research and Development Workshops**

**Report Number:** A1-018683.1

**Date:** November 17, 2025

**Editor:** Jon Makar, Ph.D. P.Eng.

**Authors:** Jon Makar, Ph.D., P.Eng., Pierre-Claver Nkinamubanzi, Ph.D., Robert Cooney\*

Construction Research Centre

Jennifer Littlejohns, Ph.D., P.Eng.; Dev Shouvik, Ph.D., James Butler, Ph.D.

Clean Energy Innovation Research Centre

**CBI:** Construction Research Centre

\*Now at Cement Association of Canada



National Research  
Council Canada

Conseil national de  
recherches Canada

**Canada**<sup>1+1</sup>

---

## Executive Summary

The production of cement and concrete for use in construction is a major source of greenhouse gases (GHGs), with cement production alone being responsible for 1.5% of Canadian GHGs and as much as 8% of the world emissions. Reducing cement and concrete GHG emissions is therefore a key component to meeting Canada's 2030 and 2050 GHG reduction targets. As the world's cement industry has also prioritized reaching net-zero by 2050, developing new technologies to support that goal also offers a significant export opportunity for Canadian industries.

Reaching net-zero emissions from the concrete used in construction will require changes to industry practice as well as new materials and changes to cement production methods. Research, development and knowledge mobilization will be needed to support these changes. The National Research Council Canada (NRC) and the Cement Association of Canada (CAC) held a series of broadly based workshops at the end of 2021 to identify the key research needs that should be addressed by the Canadian construction industry. This document summarizes the results of those workshops.

The seven workshops covered a total of 20 different topics, many in more than one session. The workshop sessions covered technologies related to combustion at the kiln, clinker production, cement, concrete and carbon sequestration in concrete. Geological sequestration of CO<sub>2</sub> emissions from cement production was not addressed. A total of 75 different knowledge gaps were identified during the sessions, with 60 being related to cement and concrete and 15 to alternative fuels and cement production. Analysis showed that 54 of the knowledge gaps could be grouped into the categories of:

- Development or improvement of test methods;
- Concrete performance and durability;
- Assessing GHG emissions reductions benefits;
- Improvements to understanding of fundamentals
- Supply chain issues; and
- Changes to standards.

This grouping applied to both the cement and concrete and the alternative fuels sessions. The remaining 21 knowledge gaps were related to individual technologies.

The workshop sessions recommended research activities to address many of the knowledge gaps. Where possible, these recommendations were used as the basis to outline research pathways that would lead to the filling of the identified gaps. In some

---

cases, no recommendations were given and the research pathways were developed from the authors' knowledge of the topic.

The overall results from each session were assessed based on the likely impact on GHG emissions from the cement and concrete industry and the estimated ease of adoption of the technology. Eighteen recommendations for research, development and knowledge mobilization activities were given, with eleven to support meeting Canada's 2030 GHG emissions reductions targets and seven additional ones for further activities to support meeting the 2050 net-zero targets. Carbon capture, utilization and storage (CCUS) are likely to play a major role in the 2050 timeframe in particular, but the approaches described in this report will be critical for success in meeting the 2030 targets and important for minimizing the amount of carbon dioxide that needs to be captured once CCUS systems are fully in place.

It should be noted that recommendations are based on the workshops and identified industry needs. The report does not indicate who should undertake which activities, nor is it intended as a description of future NRC activities.

---

# Table of contents

Executive Summary .....	2
Table of contents .....	4
Figures.....	10
Tables.....	10
Acknowledgements.....	10
1 Introduction .....	11
2 Alternative approaches to design and construction.....	16
2.1 Introduction .....	16
2.2 Knowledge Gaps.....	18
2.2.1 Performance-based design approach.....	18
2.2.2 Design to minimize concrete material volumes.....	21
2.2.3 Approaches to optimize material reliability.....	23
2.2.4 Long term performance of structures made with low carbon intensity concrete .....	25
3 Alternative Sources of Standard Supplementary Cementing Materials (SCMs).....	28
3.1 Introduction .....	28
3.2 Knowledge Gaps.....	29
3.2.1 Availability of SCMs.....	29
3.2.2 Harvested Fly Ash .....	31
3.2.3 Container glass.....	33
4 Alternative supplementary cementitious materials (ASCMs).....	34
4.1 Introduction .....	34
4.2 Knowledge Gaps.....	34
4.2.1 Supply Chain / Commercial Viability .....	34
4.2.2 Qualification of ASCMs.....	36
4.2.3 Performance of ASCMs in Concrete.....	37
5 Increasing limestone content in Portland limestone cement (PLC) .....	39
5.1 Introduction .....	39
5.2 Research and Knowledge Gaps.....	40
5.2.1 Long term effect of high limestone content in GUL cements on concrete performance and durability.....	40

---

5.2.2	GHG reduction benefits of high limestone PLC .....	42
5.2.3	Need for Performance Based Standards .....	42
6	Coarse and fine recycled concrete aggregate.....	43
6.1	Introduction .....	43
6.2	Research and knowledge gaps .....	44
6.2.1	Performance of RCA concretes .....	44
6.2.2	Recycled concrete fines.....	47
6.2.3	RCA Supply .....	48
7	Alternative binders .....	50
7.1	Introduction .....	50
7.2	Research and knowledge gaps .....	51
7.2.1	Alternative binder supply .....	51
7.2.2	Environmental Impacts of Alternative Binders .....	52
7.2.3	Alternative binder performance.....	53
8	Residential Concrete.....	55
8.1	Introduction .....	55
8.2	Knowledge Gaps.....	55
8.2.1	Gap between research expertise and home builders .....	55
8.2.2	Research on low carbon concrete mixes for residential needs.....	56
8.2.3	LCA of homes, including concrete .....	57
8.2.4	Use of recycled materials in residential concrete.....	59
8.2.5	3D printing in residential concrete .....	60
8.2.6	Use of precast in residential construction .....	62
9	Precast concrete .....	63
9.1	Introduction .....	63
9.2	Knowledge Gaps.....	63
9.2.1	Inclusion of A4 and A5 in LCA calculations .....	63
9.2.2	High early strength PLC.....	65
9.2.3	Use of high volume SCM/ASCM mixes in precast concrete .....	66
9.2.4	Other approaches to low carbon precast concrete .....	68
9.2.5	Performance of novel low carbon materials in precast concrete.....	69
9.2.6	Natural carbonation of precast concrete .....	70

---

10	Low carbon high performance/ultra-high performance concrete (HPC/UHPC) ..	71
10.1	Introduction .....	71
10.2	Knowledge Gaps.....	72
10.2.1	Analysis of the potential for HPC/UHPC to reduce GHG emissions.....	72
10.2.2	Low Carbon HPC/UHPC mix design .....	73
10.2.3	Carbon sequestration in HPC/UHPC.....	75
10.2.4	Guidance on use/selection of HPC/UHPC .....	76
11	Nanomaterials .....	77
11.1.1	Introduction .....	77
11.2	Knowledge Gaps.....	78
11.2.1	Understanding of nanomaterials.....	78
11.2.2	Carbon reduction benefits of concrete containing nanomaterials .....	79
11.2.3	Performance benefits of nanomaterials in concrete .....	81
11.2.4	Safety of use .....	83
11.2.5	Supply .....	85
12	Biomaterials.....	86
12.1	Introduction .....	86
12.2	Knowledge Gaps.....	86
12.2.1	Improved understanding of biomaterials in concrete .....	86
12.2.2	Potential GHG benefits of using biomaterials .....	88
12.2.3	Testing protocols for concrete containing biomaterials.....	89
12.2.4	Supply .....	91
13	Natural Carbonation .....	92
13.1	Introduction .....	92
13.2	Knowledge Gaps.....	93
13.2.1	Quantification of carbonation of concrete structures .....	93
13.2.2	Effect of carbonation on long term performance .....	95
13.2.3	Quantification of carbonation of crushed concrete .....	96
14	Long term performance of concrete containing sequestered carbon dioxide ....	98
14.1	Introduction .....	98
14.2	Knowledge Gaps.....	99
14.2.1	New standardized tests for long term performance assessment.....	99

---

14.2.2	Long term performance, including field trials .....	100
14.2.3	Effect of different CO <sub>2</sub> sources on sequestration and concrete performance .....	102
15	Assessing/quantifying sequestration .....	104
15.1	Introduction .....	104
15.2	Knowledge Gaps.....	104
15.2.1	New standardized tests, including field tests .....	104
15.2.2	Including long term concrete behaviour in Life Cycle Assessments .....	106
15.2.3	Determination of factors affecting sequestration performance .....	108
16	Sequestration in high volume SCM and other specialized concrete mixes.....	109
16.1	Introduction .....	109
16.2	Knowledge Gaps.....	110
16.2.1	Ability of SCMs and ASCMs to sequester CO <sub>2</sub> .....	110
16.2.2	Effect on longterm performance .....	111
16.2.3	Guidance documents and standards.....	113
16.2.4	Quantification of CO <sub>2</sub> uptake .....	113
17	Guidance on sequestration use .....	114
17.1	Introduction .....	114
17.2	Knowledge Gaps.....	114
17.2.1	CSA standards for sequestration.....	114
17.2.2	Guidance on the inclusion of sequestration in analysis of global warming potential	116
17.2.3	Guidance for Decision Makers .....	116
18	Alternative Fuel Choices.....	117
18.1	Introduction .....	117
18.2	Knowledge Gaps.....	118
18.2.1	Supply Chain Security .....	118
18.2.2	Decision support for fuel selection.....	123
18.2.3	Hydrogen fuel in cement kilns .....	124
18.2.4	Research into the use of aluminum as a fuel source.....	126
19	Standardization of fuels to produce stable fuel performance .....	126
19.1	Introduction .....	126
19.2	Knowledge gaps .....	127

---

19.2.1	Applicability of Existing Standards.....	127
19.2.2	Performance of Standardized Fuels .....	129
19.2.3	Effects of Fuel Impurities on Cement .....	130
19.2.4	Storage and Handling of Low Carbon Fuels.....	131
20	Accessing waste streams .....	132
20.1	Introduction .....	132
20.2	Key Knowledge Gaps .....	133
20.2.1	Benefits of co-processing versus traditional disposal .....	133
20.2.2	Regional fuel availability .....	135
20.2.3	Impacts of current waste disposal policies on fuel availability .....	136
20.2.4	Engineering kilns for high levels of waste use .....	137
20.2.5	Research Pathways .....	137
21	Evidence in support of alternative fuel use regulation .....	138
21.1	Introduction .....	138
21.2	Key knowledge gaps.....	138
21.2.1	Alternative fuel standards.....	138
21.2.2	The effect of low carbon alternative fuels on air pollutants.....	139
21.2.3	Support for consistent fuel supply .....	141
22	Discussion .....	142
22.1	Knowledge Gap Categories .....	142
22.2	Cement and Concrete.....	146
22.2.1	Development or improvement of test methods .....	146
22.2.2	Concrete performance and durability .....	146
22.2.3	Assessing GHG emissions reductions benefits.....	147
22.2.4	Improvements to understanding of fundamentals.....	147
22.2.5	Supply Chain Issues.....	147
22.2.6	Changes to Standards.....	148
22.3	Alternative Fuels .....	148
22.4	Approaches to Technology Adoption by Cement and Concrete Users .....	148
22.5	Advantages and Disadvantages of Various Research Areas.....	149
23	Conclusions .....	154
23.1	Summary of Knowledge Gaps and Research Needs.....	154

---

23.2	Recommendations .....	155
23.2.1	Recommendations to support 2030 GHG emissions targets.....	156
23.2.2	Recommendations to support 2050 GHG emissions targets.....	158
24	References .....	159

---

## Figures

Figure 1 Multi-dimensional optimization of built assets, including carbon emissions ....	17
Figure 2 Optimization of carbon emissions a) current status; b) desired 2050 end state (total carbon offset for visibility) .....	18

## Tables

Table 1 – Workshops .....	13
Table 2 – Breakout Session Topics.....	14
Table 3 - Examples of fuels derived from waste streams (Murray & Price, 2008) .....	118
Table 4 Common Knowledge Gaps by type .....	142
Table 5 Knowledge Gaps Corresponding to Workshop Sessions/Report Chapters ....	143

## Acknowledgements

The authors wish to acknowledge the reviews and useful feedback provided by the following people, which resulted in a better report.

Tim J. Smith, P.Eng., MSc. Eng.  
Senior Technical Director, Infrastructure and Specifications  
Cement Association of Canada

Val Sylaj, P.Eng., Ph.D.  
President/Director of Technical Services  
Canadian Precast/Prestressed Concrete Institute

Ana Milena Rebellon  
Technical Services Engineer  
Heidelberg Materials

Galal Fares, Ph.D., P.Eng.  
Senior Research Officer  
Mitchell Greenis, P.Eng.  
Research Officer  
Runxiao Zhang, Ph.D.  
Research Officer  
National Research Council Canada

---

# 1 Introduction

Concrete made from Portland cement is the second most commonly used material in the world, following only water. It is the key material for many construction products and is widely used for buildings, bridges, sidewalks, pipes and many other structures. The Portland cement used in concrete is also one of the largest contributors to Canadian and global greenhouse gas (GHG) emissions. Approximately 1.6% of Canadian emissions (ECCC, 2025) and 8% of global emissions (World Economic Forum, 2024) are due to Portland cement production. Fuel sources, production efficiencies, relative amounts of cement production per capita and the impact of fossil fuel production on Canadian GHG emissions are responsible for the differences in relative cement emissions between Canada and the world averages.

Portland cement is manufactured in kilns where the raw ingredients, clay and limestone, are heated to over 1400 °C. While generating the necessary heat is responsible for some of the emissions, approximately 2/3 of the emissions comes from the thermal decomposition of the limestone into calcium oxide and carbon dioxide (CO<sub>2</sub>). While fuel switching can reduce the heat emissions, it will not impact those from the limestone. Multiple different routes will therefore be needed to decarbonize cement production and concrete.

In 2023, the Canadian cement industry released their action plan, [Concrete Zero](#) (Cement Association of Canada, 2023) to achieve emission reductions from a 2020 baseline of 40% by 2030, 59% by 2040, and net-zero by 2050 using today's technologies. This Action Plan is organized based on the cement and concrete value chain, identifying at each stage where emissions reductions will come from, which are described as the "5 C"s:

- Clinker;
- Cement;
- Concrete;
- Construction; and
- Carbon uptake

In addition, the industry is now adding a sixth "C": Carbon Capture, Utilization and Storage.

These routes are described (Cement Association of Canada, 2023) as:

**"Clinker** is the primary ingredient of cement. Clinker is produced by heating limestone, clay, and other minerals to about 1500°C-2000°C in a rotary kiln system. At these temperatures, the elements that comprise the raw minerals recombine to form crystalline minerals that dissolve and then harden when mixed with water. Clinker is the base binder material used to produce cements." Changes in combustion emissions,

---

furnace energy supply or raw materials can reduce the emissions associated with clinker.

“**Cement** is the active ingredient of concrete and typically comprises between 10 to 15% of the concrete’s mix by volume. It is manufactured by finely grinding clinker and gypsum together. Other materials can be added to produce cements with specific qualities, e.g., limestone is added to produce Portland-limestone cement.” Adding lower carbon materials such as limestone can reduce the embodied carbon in cement.

“**Concrete** refers to a castable, stone-like, composite building material that is composed of fine and coarse aggregates (i.e., sand and gravel) that are bound together with water and cement that hardens over time.” Changing concrete mix designs to reduce cement content is one route to reduce concrete emissions.

“**Construction** refers to the process of designing and building. Architects, engineers, and the construction industry are all users of concrete products, whether it’s in roads, buildings, or bridges. Finding efficiency in the way concrete is used, both in design and construction, can help reduce emissions.”

“**Carbon Uptake** refers to the potential of concrete to be a CO<sub>2</sub> sink. Over time, CO<sub>2</sub> in the atmosphere reacts with the calcium hydroxide in concrete to form calcium carbonate—a reversal of the chemical process that occurs when making the cement used in concrete. This reduces the whole-life CO<sub>2</sub> footprint of both the cement and the concrete for which it (the cement) is used.”

Finally, **Carbon Capture, Utilization and Storage** refers to the permanent storage of GHGs in either geological formations or mineral by-products and the utilization of CO<sub>2</sub> in the production of new commercial products. It is worth noting that Canada is a world leader in this approach. The first fully operational geological carbon sequestration project is under construction in Alberta (Heidelberg Materials, Edmonton) and several pilot scale projects are under way on carbon capture and mineralization technologies by companies such as Hyperion Global Energy Corp. (Lafarge, 2024) and Carbon Upcycling Technologies Inc. (Carbon Upcycling, 2024). Canadian companies such as CarbonCure Technologies Inc. (<https://www.carboncure.com/>) and CarbiCrete (<https://carbicrete.com/>) offer services and products related to carbon sequestration in concrete.

While there are many different approaches that can be taken to decarbonizing cement and concrete production, there are also many knowledge gaps that need to be filled in order to support uptake of the available technologies and develop new ones where needed. In some cases, the technologies are already available in other countries, but are not common in North America. In others, the basic knowledge is available, but standards, code requirements or user specifications prevent technology use. There are

also approaches that may be viable, but where more fundamental research is required to determine whether the technology can be successfully deployed.

In November and December of 2021, the National Research Council Canada (NRC) and the Cement Association of Canada (CAC) hosted a series of seven workshops to discuss the research and development needed to ensure the cement and concrete industries meet Canada’s 2030 and 2050 carbon emissions reduction goals. Canadian government GHG reduction policy had explicitly supported reductions in cement emissions, while the Global Cement and Concrete Association had set a target of net-zero emissions by 2050 for its members (GCCA, 2021).

Workshop session topics were selected in advance and then confirmed through a survey of potential participants. A total of seven different sessions were held (Table 1) with three of the sessions duplicated to allow different options for attendance. As part of the preliminary survey, recipients were asked to prioritize which topic breakout sessions they would prefer to attend. Recipients were then assigned breakout sessions based on their priorities. In most cases the first priority was assigned, with a few people being assigned their second priority in cases of timing conflicts or oversubscribed sessions. Participants were drawn from industry, academia and governments, with representation from across the country and the full range of the cement and concrete value chain. A total of 140 people attended the different workshops, with many attending three or four.

*Table 1 – Workshops*

Workshop
Lowering Carbon Content in Concrete Made Following Standard Practices (1)
Lowering Carbon Content in Concrete Made Following Standard Practices (2)
Developing New Approaches to Reducing Embodied Carbon in Concrete (1)
Developing New Approaches to Reducing Embodied Carbon in Concrete (2)
Carbon Sequestration in Concrete (1)
Carbon Sequestration in Concrete (2)
Alternative Fuels for Cement Kilns

Taken together, the topics discussed in the workshops covered all of the 6 Cs with the exception of carbon sequestration in geological formations. This topic was excluded primarily because it had been heavily researched in the past and was already moving into deployment at the time of the workshops. Specific breakout session topics for each workshop are shown in Table 2. The results of each session form one of the chapters in this report, although the text starts with the chapter on “Alternative Approaches to Design and Construction” before continuing with the topics from the first workshop.

*Table 2 – Breakout Session Topics*

Lowering Carbon Content in Concrete Made Following Standard Practices
<ul style="list-style-type: none"> <li>• Alternative sources for standard supplementary cementing materials (SCMs)</li> <li>• Alternative supplementary cement materials (ASCMs)</li> <li>• Increasing limestone content in Portland limestone cement (PLC)</li> <li>• Coarse and fine recycled concrete aggregate</li> <li>• Alternative binders</li> <li>• Residential concrete</li> </ul>
Developing New Approaches to Reducing Embodied Carbon in Concrete;
<ul style="list-style-type: none"> <li>• Low carbon high performance/ultrahigh performance concrete (HPC/UHPC)</li> <li>• Alternative approaches to design and construction</li> <li>• Nanomaterials</li> <li>• Precast concrete</li> <li>• Biomaterials</li> </ul>
Carbon Sequestration in Concrete
<ul style="list-style-type: none"> <li>• Natural carbonation</li> <li>• Long term performance of concrete containing sequestered carbon</li> <li>• Assessing/Quantifying sequestration</li> <li>• Sequestration in high volume supplementary cementing materials (SCM) and other specialized concrete mixes</li> </ul>
Alternative Fuels for Cement Kilns
<ul style="list-style-type: none"> <li>• Alternative fuel choices</li> <li>• Standardization of fuels to produce stable fuel performance</li> <li>• Accessing waste streams (to fuel kilns)</li> <li>• Evidence in support of regulation</li> </ul>

The workshops included two breakout sessions. During the first, workshop attendees were asked to identify key knowledge gaps for the breakout session topic. During the second, attendees were asked to provide potential actions to resolve those knowledge gaps. Results from each breakout session were reported back to subsequent plenary

---

sessions to allow cross-discussion and ensure that participants were aware of results from the sessions they were not attending.

Analysis of the workshop results involved combining the gaps identified in each duplicate workshop session by topic as in many cases the same gaps were identified in each case. The actions to resolve those gaps identified by the participants were also grouped together. They were then used as the basis for the report authors to develop sets of research, development and knowledge mobilization activities to address the knowledge gaps. The report chapters then provide introductory material on the subject matter of the breakout session, followed by a section on “Knowledge Gaps”. This section provides the gaps identified by the participants, followed by background information on those gaps.

The actions proposed by the participants are then described, followed by the research pathways developed from those actions. The chapters based on the first six sessions were written by experts from NRC’s Construction Research Centre, while those on alternative fuels were written by experts from NRC’s Clean Energy Research Centre. The input from the workshop participants is quoted as presented during the workshops. In general, the research pathways are deliberately designed to address the input from the participants, but in some cases the proposed actions were more appropriately covered in other chapters and are only mentioned for completeness.

It should be noted that the quotes from workshop participants on needs and actions have been italicized throughout the report. These quotes are presented verbatim for the record. As such, they are in some cases out of date or based on incomplete or inaccurate information. **No attempt has been made to edit the quoted material.** Instead, the introductory text and research pathways provide commentary where needed.

The report concludes with a discussion of commonalities across the topics and recommendations for next steps. Some significant changes have occurred since the workshops were completed, including the development of the Government of Canada/CAC Roadmap to Net-Zero Carbon Concrete by 2050 (ISED, 2022) and the launch of NRC’s Platform to Decarbonize the Construction Sector ([Platform to Decarbonize the Construction Sector at Scale - National Research Council Canada](#)). The impact of these activities and identification of areas where work has already taken place are also discussed in the Conclusions section.

---

## 2 Alternative approaches to design and construction

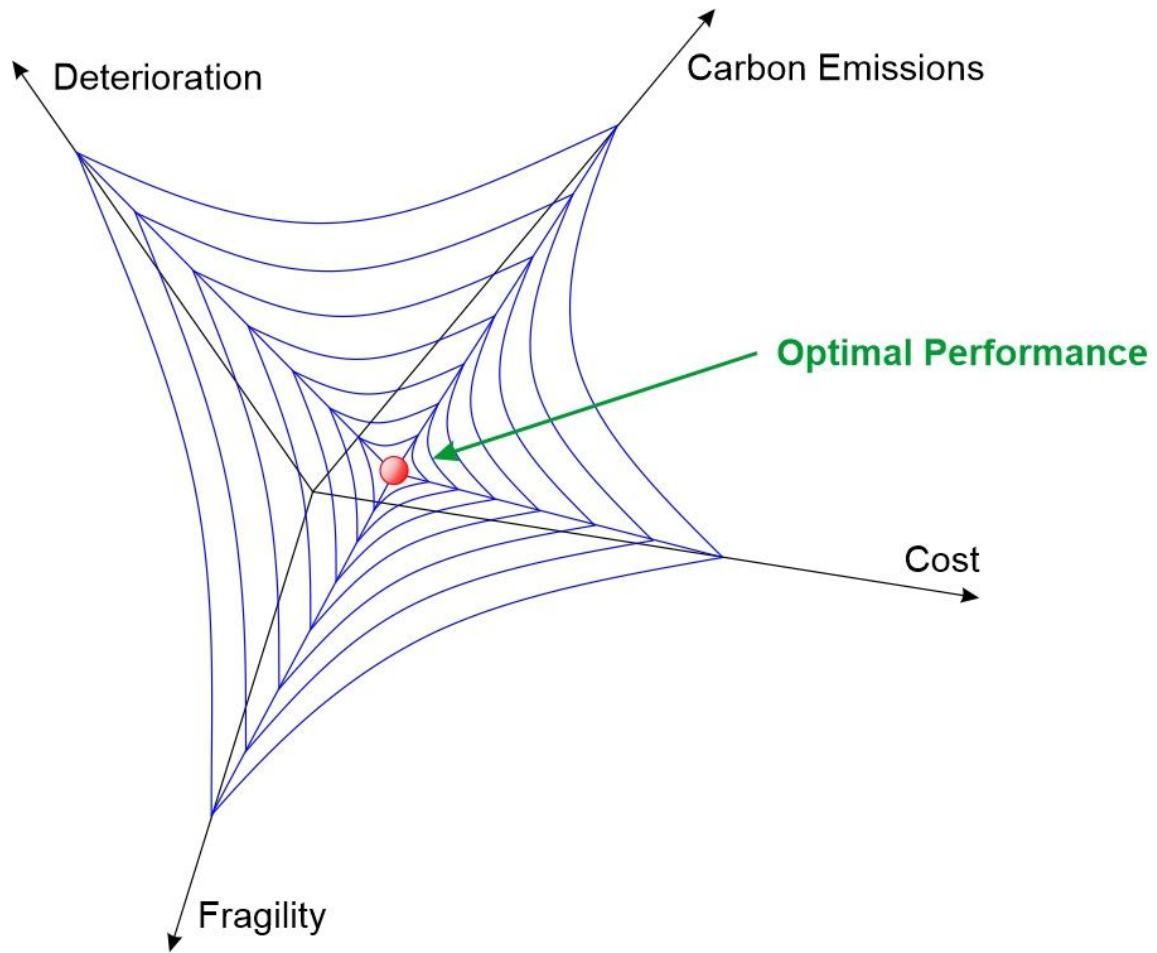
### 2.1 Introduction

Traditional concrete design practices tend to emphasize minimizing cost after structural performance requirements are met. Sometimes the cost is simply the upfront cost (including the cost of design), while more advanced practices consider lifecycle costing including such issue as durability and disaster resilience. Better design is, however, a key route to reducing the embodied carbon in buildings and infrastructure. Concrete beams, for example, are typically designed with the same cross-section through-out the beam, whether or not the pattern of stresses requires it. Using a varying cross-section that places concrete and reinforcing steel where it is needed to resist the actual loads can result in substantial materials savings.

Designing optimized structures that minimize embodied carbon may require additional expertise in areas such as life cycle assessment (LCA). In addition, providing the tools to carry out the required multi-dimensional optimization process (Figure 1) may require basic research and development and support for technology deployment. Note that the Figure shows a four dimensional optimization where the inverse to resilience (fragility) and durability (deterioration) are shown so that the problem is expressed as one that tries to find the minimum (optimal) solution.

Each of the optimization dimensions may actually represent a group of related dimensions that can either be optimized together to develop an input into the final optimization or that may need to be optimized individually in the design. As an example (Figure 2a), minimizing total carbon emissions from a concrete structure may initially involve examining embodied and operational carbon emissions and finding a solution in which neither embodied nor operational carbon are completely eliminated. As information becomes available, construction and end-of-life carbon emissions could be added into the process. By 2050, the goal would be to have a variety of solutions available that will give net-zero carbon emissions potentially with the requirement that the individual components of the problem to each have net-zero solutions (Figure 2b).

While the concept of optimizing designs to minimize carbon emissions is easy to express, actually carrying out the process will be much more complex. This chapter discusses knowledge gaps in four keys areas related to low carbon emissions designs that were identified during the three workshop sessions on the topic.



*Figure 1 Multi-dimensional optimization of built assets, including carbon emissions*

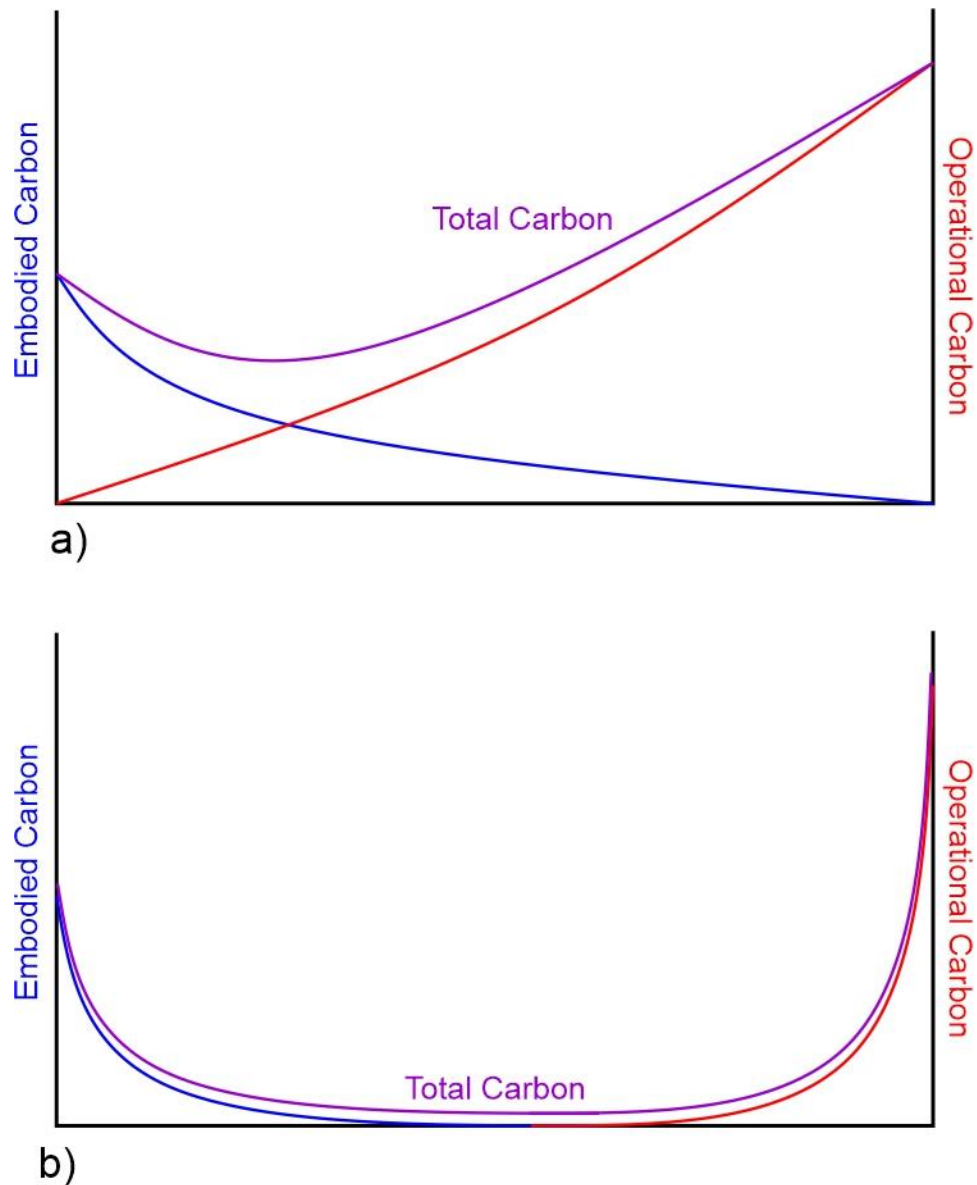


Figure 2 Optimization of carbon emissions a) current status; b) desired 2050 end state (total carbon offset for visibility)

## 2.2 Knowledge Gaps

### 2.2.1 Performance-based design approach

*“Performance-based design approach. There is a need to unlock the potential to allow for innovative design. A clear evaluation approach for alternatives which are not covered in the national building code and CSA standards.”*

---

*Consideration is required to design and specify concrete based on its global warming potential values*

Current Canadian design practice is largely prescriptive in nature, due to the need to meet the requirements of the National Building Code of Canada (NBC) (Canadian Commission on Building and Fire Codes, 2020), the provincial building codes and various CSA standards such as CSA S6 Canadian Highway Bridge Design Code (CSA Group, 2024a), CSA A3000 Cementitious Materials Compendium (CSA Group, 2023) CSA A23.3 Design of Concrete Structures (CSA Group, 2024b), and CSA A23.1 Concrete materials and methods of concrete construction (CSA Group, 2024c). The building codes are currently prescriptive, although the objectives of the sections of the code may be given to help building officials to evaluate alternative solutions. CSA A23.3 is also prescriptive. CSA S6 and A23.1 are hybrid documents, with some sections allowing performance based solutions, while others remain prescriptive.

The impact of prescriptive requirements on innovative, low carbon design is well understood in the building code system. Part of the work covered in NRC's Platform to Decarbonize the Construction Industry covers starting the process of moving the NBC to include provisions for performance based design. The initial focus is on seismic and fire related code provisions, which are expected to be included in the 2030 NBC update. The current goal is to complete the process for the 2035 update. At the time of writing, NRC is also working with CSA Group to update the relevant construction standards to include or expand performance based design provisions in the relevant construction standards.

These activities are taking place over a medium to long term time frame, which does not match the short term time frame anticipated by the workshop participants (see below). However, the process of moving to performance based codes and standards is more complex than it might first appear. In many cases the rationale for the existing provisions may be undocumented, so the first step is to undertake an analysis of the code or standard section to determine why it is the way it is currently written. Depending on the provision, the reasons may be obvious, obscure, or retained in detail only in the memories of current and past committee members, making the time required to investigate them highly variable. Once the reasons are known, performance based approaches than need to be developed to provide comparable results. These approaches may need to be tested in field trials and demonstration projects before codification. Finally, guidance documents that cover the new design principles will be needed for both designers and building officials.

### **2.2.1.1 Activities Recommended by Workshop Participants**

#### Short Term

- *“Develop performance-based requirements to revise current specifications and standards.”*

- 
- *“Legislation, third party verification, codes and standards.”*

#### Medium Term

- *“Develop standardized structural design procedures for structural members made of concrete using newer technologies such as HPC, UHPC, recycled materials, biomaterials, etc.”*
- *“Looking at alternative materials with lower global warming potential building on shorter-term research.”*

#### Long Term

- *“Design tests to monitor performance of structures in the field over time and couple with on-going climate and weather conditions.”*

### **2.2.1.2 Research Pathways**

#### Short Term

Code and standard provisions should be selected for assessment and modification. While initial areas of code conversion are likely to focus on seismic and fire related issues, performance based cement and concrete standards can and should address other significant topics related to decarbonization, including the use of novel low carbon materials, durability and resilience. It should be noted that provincial and territorial priorities will need to be taken into account in the decisions about which code provisions should be converted first. The National Master Specification should be revised in parallel with code and standard changes.

#### Medium Term

Selected code and standard provisions should be analyzed to determine their underlying rationale. Based on that rationale, performance based requirements that fulfil the same function should be developed and brought into the relevant code or standard documents. Performance oriented specifications for low carbon concrete should be developed as models for potential use by governments and other concrete end-users.

#### Long Term

Where necessary, trials of designs produced using the performance based requirements should be carried out to confirm their functionality. Guidance documents for designing using the new requirements should be produced to illustrate how they should be used and to speed their adoption. The guidance documents should give examples of traditional designs and their performance based equivalents so that the benefits of using performance based methodologies are clear to practitioners. At the same time, the process of conversion should be initiated for the next set of provisions.

---

## 2.2.2 Design to minimize concrete material volumes

*“Over-design structural elements have cascading effect on the required structural elements size. Research is needed to provide guidelines and requirements on the optimal design of structural elements with the focus on minimizing use of materials which would lead to reduced GHG emissions.”*

*“Consideration is required in terms of structural design optimization in order to avoid over-design of reinforced concrete sections.”*

Overdesign of concrete structures occurs when the cross-sections of those structures are greater in area than is actually required to meet structural performance requirements. It can occur for a number of reasons, such as:

- choice of material reliability factors;
- the design of members to simplify formwork, reinforcing steel, or casting;
- avoidance of reinforcing steel in basement walls and similar applications;
- specifications or standards that require high levels of concrete cover over rebar to reduce corrosion risks;
- lack of knowledge of how to minimize the mass of particular components such as floors or shear walls;
- the desire to speed the design process by duplicating successful designs from previous work; and
- a focus on low design costs rather than low materials and construction costs or low GHG emissions.

Other causes are also possible.

Material reliability factors are considered in a separate section of this chapter, with other issues addressed here. It should be noted that overdesign is the one area in this report where steel production GHG emissions are discussed. Overdesign of reinforced concrete structures may mean excessive reinforcement as well as excessive concrete volumes. Conversely, some measures to reduce concrete cover, such as the use of stainless steel rebar in bridge decks to prevent corrosion damage, rather than relying on the concrete cover alone, can increase the embodied carbon of the steel at the same time as reducing that of the concrete. Finally, in buildings that use both reinforced concrete and structural steel, decreasing one material may result in the need to increase the other, affecting the overall emissions benefits.

It is also possible that some approaches to reducing the concrete mass in a building in particular will impact the operational carbon emissions from the building. This is

---

particularly the case where the concrete mass in the structure is intended to act as a thermal sink, reducing the need for cooling in the summer and heating in the winter. If the goal is to minimize the life-cycle carbon emissions of a structure, integrated design approaches where the architect, structural engineer, LCA specialists and other professionals work as a team, are likely to provide optimum solutions.

Potential solutions to support design to minimize concrete and steel use depend on the root cause of the overdesign. They may include:

- Research to develop new design approaches or validate existing ones;
- Revisions to codes, standards and/or specifications to allow optimized designs;
- The development of design guidelines to support optimizing materials use;
- Demonstration projects that highlight design optimization, including cost/benefit analysis;
- Development of model specifications that can be used by project owners to ensure that the optimized designs are used in the project.

More solutions may be identified in a detailed analysis.

### **2.2.2.1 Activities Recommended by Workshop Participants**

#### Short Term

- *“Develop and/or refine a classification system for concrete grades and applications, as a basis for structural design research and pilot studies.”*

#### Long Term

- *“Standards and methods applied for predicting CO<sub>2</sub> emissions have not yet been included in international codes and standards. There has been no standard method for calculating CO<sub>2</sub> emissions from RC (reinforced concrete) buildings, although these structures are the primary source of CO<sub>2</sub> emissions.”*

### **2.2.2.2 Research Pathways**

#### Short Term

A framework for assessing major concrete elements (floors, columns, beams, shear walls, etc.) to determine impediments to low carbon design in each case should be developed, along with corresponding solutions. Once the framework is developed and validated, it should be applied to archetypal elements for both building and infrastructure applications to identify the key impediments for each one.

#### Medium and Long Term

Activities in medium and long term will vary depending on the impediments identified during the assessment process. If research is required to develop or validate better

---

designs, an appropriate research program should be developed and executed, which will likely be initiated in medium term, but may not be completed for 8 or more years. Model language for specifications can be developed relatively quickly after the need is identified, while demonstration projects and guideline writing could potentially be completed in the medium term as well. Changes to codes, standard and infrastructure specifications may require the results of these activities before changes can be made, although movement to performance based codes, standards and specifications may speed up the process. Guideline writing will need to provide direction for GHG emissions assessment based on LCA principles, potentially extending the time for their completion.

One approach to encouraging demonstration projects would be for outside agencies to contribute part or all of the additional costs associated with design optimization on one or more public projects. A maximum amount of funding could be set for any one project, with part of the requirements for receiving the funding being the documentation of the project in a form suitable for uptake by the broader construction industry.

### **2.2.3 Approaches to optimize material reliability**

*“Currently, the CSA A23.3 design standard sets the material resistance factor for concrete at 0.65, meaning only 65% of the concrete’s actual strength can be accounted for in structural design. Greater research and tighter construction tolerances could improve the reliability of concrete.”*

Limit state design uses material resistance factors to provide a margin of error in the design of structures. These factors are intended to account for any variability in the material and in the construction process itself. They are set in the relevant design standards, but are not necessarily consistent from standard to standard. In Canada, CSA A23.3 (CSA Group, 2024b) sets the resistance factor for concrete at 0.65 and the resistance factor for reinforcing steel at 0.85. The values in the Canadian Highway Bridge Design Code (CSA Group, 2024a) are 0.75 and 0.9 respectively. The reasons for the differences between the two documents are not clearly explained, but may be related to the levels of monitoring and quality control associated with the different types of construction.

A low material resistance factor means that a greater amount of material is needed to perform the same role in a structural design as a material with a higher resistance factor, in turn creating a higher level of CO<sub>2</sub> emissions. Increasing the materials resistance factor for concrete could therefore be a relatively direct way to lower the emissions associated with a structure without requiring changes in design approaches. A change from a 65% to a 75% resistance factor would lead to a greater than 10% reduction in concrete requirements and emissions, in addition to emissions reductions from reduced transportation.

---

Whether this approach is reasonable depends largely on how much concrete variability can be reduced without creating excessive costs. Industry practices may well have improved so that a higher materials resistance factor would now be appropriate. Suppliers to both the building and highway bridge industries are likely to be able to provide concrete to tight enough tolerances to justify using a 0.75 materials resistance factor without significant changes to their practices. Demonstrating the viability of making the change would, however, require significant research.

### **2.2.3.1 Activities Recommended by Workshop Participants**

#### Short Term

- *“Engage with the responsible CSA committees to determine rationale for the stated resistance factors.”*
- *“Build comfort with using tighter construction tolerances in the industry. Improve material resistance factor above 0.65 noted in CSA A23.3”*

### **2.2.3.2 Research Pathways**

#### Short Term

The rationale for the stated resistance factors in CSA A23.3 (CSA Group, 2024b) and CSA S6 (CSA Group, 2024a) should be investigated through discussions with the relevant technical committees, but also through investigation of past standards, practices in other jurisdictions and review of available technical literature. Key factors that led to the selection of current materials resistance factor values should be identified and research protocols developed to test the current status of those factors.

#### Medium term

Industry participants should be recruited to collect the data necessary to justify changing the materials resistance factors. It is likely that a large number of results from tests taken from a number of different participants located across the country will be necessary to provide sufficient data to justify a change. The same data should be used to examine whether current mix designs are consistently exceeding requested performance levels by a significant margin and to establish the degree of variability of the mixes. Overdesign of mixes to ensure a targeted strength or other performance criteria is another possible contributor to GHG emissions.

#### Long term

If the test program shows that changes in materials resistance factors are justified, appropriate changes should be made through the relevant CSA technical committees. Test structures designed using the current materials resistance factors and the proposed ones may need to be built and tested to demonstrate the validity of the new factors. It is possible that the findings would support changing the values for different classes of concrete or applications, with those found to be most consistent receiving

---

higher factors than those that are more variable. If mixes are found to be oversized, new design guidance should be issued. Practitioners could also specify a maximum allowed strength for their concrete as well as the minimum acceptable strength to reduce the GHG emissions associated with higher strength mix designs.

## **2.2.4 Long term performance of structures made with low carbon intensity concrete**

*“Combination of short- and long-term testing of structures using low carbon alternatives and/or recycled materials. Forward thinking should also be considered to develop additional testing not currently available for alternative concrete solution.”*

*“The relationship between utilizing sustainable concrete and its impact on the durability aspects of concrete.”*

*“Research needs to be done to optimize durability and extension of life including consideration of predictive models, accelerated test-methods and mix design for low carbon concrete.”*

The approaches to low carbon design for concrete structures described in this chapter all have the potential to reduce the amount of concrete used in a structure compared to current practices. Assuming that load capacity requirements are met, a second key requirement is that the resulting structures still have the same durability and service lives. Reductions in concrete cross-section or cover may affect these properties even when structural requirements are met. As an example, reducing the concrete cover on a bridge deck may allow more rapid penetration of chloride ions to the reinforcing steel without impacting immediate structural performance.

Most aspects of durability research are covered in other chapters of this report. However, including service life as part of a design optimization process requires robust predictive models that can be used for the design. This section of the report therefore primarily focuses on model development and validation, which is not covered elsewhere.

### **2.2.4.1 Activities Recommended by Workshop Participants**

Note: many of the recommended activities from this session are materials related, rather than design related. As such, they are covered in detail in later chapters of the report. They are included here for completeness, but research pathways are only outlined for the specific topics unique to this chapter.

#### Short Term

- *“Elaborate systematic research program for each major new material used to make concrete”*

- 
- *“In lieu of waiting decades for long term test results, perform testing on existing old concrete infrastructure. Concrete has changed since then but some results may be able to be applied to current concrete. Perhaps correlation factors could be determined to relate old concrete to new materials.”*
  - *“Continuing R&D on preparing new mixtures of cement for longer durability and maintaining a clear requirement for recycled materials such as a maximum percentage use of recycled aggregates in concrete.”*
  - *“Developing accelerated test methods and potentially AI-based predictive models for durability of new lower carbon mixes.”*
  - *“CSA and associated codes need to be updated to reflect more design optimization options through acceptable analysis rather than recipe book standards.”*

#### Medium Term

- *“Accelerated life cycle testing of alternative concrete formulations for durability and reuse of CO<sub>2</sub> from other industrial processes into cement production.”*
- *“Archetypal building modeling. Study the design, cost and LCA impacts of (alternative) concrete formulations. Consider software and artificial intelligence for design optimization. Could include machine learning or related to consider simulation or real data.”*
- *“Sustainable strengthening techniques for reinforced concrete structures that consider the cost/benefit ratio of CO<sub>2</sub> reductions etc”.*

#### Long Term

- *“Development of computer modelling that could use short term testing data to establish long-term performance.”*
- *“Consider supply availability risk.”*

### **2.2.4.2 Research Pathways**

#### Short term

Existing predictive models should be reviewed, classified by type and degree of use in practice, and analyzed to determine where the models would need to be updated or adapted to address low carbon concrete. Part of the review should include discussions with design firms to determine which models are used and the circumstances under which their use takes place.

Canadian environmental exposure sites should be established to enable validation of durability models.

---

### Medium term

Durability data for different low carbon concrete materials should be compiled and put into a form suitable for model use. Parameters needed for utilizing the models should be obtained from the test results and the results of the models validated against the available data. Drawing on the short term analysis and the model validation, modifications to the available models should be made if necessary to produce sufficiently conservative results to allow use in practice.

### Long term

The predictive ability of the models should be improved by longer term comparisons between model and actual results, which are likely to require measurements on samples in outdoor environmental exposure sites as well as longer term accelerated aging tests. Specialized accelerated aging testing, such as aging under load should be pursued to provide the data to further improve and validate the models. If necessary, new models should be developed if the research data shows that the existing ones do not apply to specific forms of low carbon concrete.

---

## 3 Alternative Sources of Standard Supplementary Cementing Materials (SCMs)

### 3.1 Introduction

Due to the implementation of environmental regulations and agreements for the sustainable development of green technologies in the construction industry, engineers, architects, concrete producers and contractors are increasingly required to adhere to these new sustainable building regulations by specifying appropriate concrete mix designs. The use of minimum binder content in concrete mixtures without compromising the performance is often the simplest way to meet this requirement. The concrete industry could achieve this goal by increasing the proportion of SCMs such as fly ash, slag, silica fume, metakaolin, rice husk ash and/or other natural pozzolans and ground limestone fillers.

The use of SCMs to replace part of the Portland cement in concrete is the most used strategy to lower the carbon footprint of the concrete. Since most SCMs are industrial by-products, their quality and abundance vary and may affect the performance and the concrete product which in turn may influence the type of applications that will comply with the use of such SCMs. The availability of high quality SCMs is becoming increasingly limited as coal powered electricity generation is reduced (ECCC, 2025) and blast furnace steel product replaced with direct reduction iron and electric arc furnaces (Chung, 2025). With the growing demands for concrete, new sources of SCMs should be considered to meet this growing need.

Assessment and development of new substitution materials for cement in concrete that will remain in abundant supply is of high importance. This will be achieved by finding alternative sources for current SCMs and improved methods for qualifying new SCMs. Rapid screening methods are required to evaluate the performance of new sources of SCMs, to be able to promote their implementation in the concrete industry.

It should be noted that the workshops had a strong emphasis on research on harvested fly ash, but relatively little discussion on calcined clays. Harvested fly ash is now more commonly used in Western Canada (Smith, 2025) and some issues identified in the workshops have been resolved. In contrast, there is growing interest in the potential of calcined clays as an SCM and more research is needed on that topic than was outlined in the workshops. The latter topic is included in the recommendations, but is not discussed in this chapter.

---

## 3.2 Knowledge Gaps

### 3.2.1 Availability of SCMs

*“A market analysis of the current and future regional availability of SCMs would be useful as foundational data to support optimization of their decarbonization potential in concrete.”*

*“Lack of surveys of known sources of SCMs”*

*“Lack of conversations between concrete community and other industries.”*

Ground granulated blast furnace slag (GGBFS), fly ash and silica fume are the most commonly used SCMs in Canada. All three are by-products from other industrial processes (blast furnace steel production, coal fueled power generation and silicon and ferrosilicon production, respectively). However, both GGBFS and fly ash are expected to be available in decreasing quantities in the future. Steel production in North America is moving to technologies such as direct iron reduction and electric arc furnaces, which do not produce GGBFS. Coal fueled power production is being phased out in Canada and is in decline in the United States. Alternative sources of new production of these products are likely to be from overseas locations such as India or China, resulting in added embodied carbon in the SCM due to transportation.

Other SCMs are, however, recognized in CSA A3001:23, Cementitious Materials for Use in Concrete (CSA Group, 2023a). They include natural pozzolans, calcined clays and ground glass. In addition, “harvested” fly ash recovered from landfill disposal can potentially be used in place of newly produced fly ash, provided that it meets the same performance requirements. Understanding how rapidly existing sources of SCMs will be depleted and the availability of alternatives is key to ensuring that the Canadian concrete industry can continue to use SCMs to meet desired concrete performance and reduce embodied carbon.

#### 3.2.1.1 Activities Recommended by Workshop Participants

##### Short Term

- *“Research on quality, traceability and consistency of imported SCMs and GHG impacts relative to domestic supply.”*
- *“Updated LCIs to quantify GHG burden of SCMs (based on source, local vs imports etc.)”*
- *“There is work to be done to establish partnerships on a low carbon concrete initiative with geological survey and mining associations.”*
- *“Consider the environmental extraction requirements. The previous survey was conducted in 2003.”*

---

## Medium Term

- *“Implementation of a research chair or other mechanism to ensure standard SCMs are advanced forward to support industry.”*

### **3.2.1.2 Research Pathways**

#### Short Term

While the decline in supply of GGBFS and fly ash is becoming known in the cement and concrete industry, there is little information available on how rapidly the decline will take place and extent of regional variations in its rate. This information is key to identifying future needs for imported SCMs and whether other SCMs can be developed in a timely fashion. At the same time, there is little information available on the extent of supplies of natural pozzolans and harvested fly ash. Ground glass is potentially readily available through recycling of commercial and consumer waste, but the mechanisms for collecting, sorting and processing it do not currently exist. Initial research in this area therefore needs to focus on providing quantified assessments on these issues, including:

- Potential volumes of harvested fly ash “deposits” available in Canada;
- Potential volumes of natural pozzolan deposits available in Canada, including clays suitable for calcining;
- Future availability of Canadian, North American and overseas sourced GGBFS, fly ash, and silica fume; and
- The economic and environmental feasibility of using these materials at the national level.

The recommendations here is evaluate availability at the national scale to determine overall feasibility of material use and inform government policy, rather than to determine the viability of individual material deposits. This information will be key to determining the need for development of alternative SCMs, but will also provide the necessary information for discussions between the cement industry and other industry sectors. It will also help to prioritize work to support the use of the newer standardized SCMs.

A second area of work would be to support the updating of key specification documents such as the National Master Specification to be updated to cover the usage of high-volume SCMs, newer SCMs and ASCMs. Such a change would immediately reduce the embodied carbon in concrete specified using these documents, but may speed the depletion of conventional SCM sources.

#### Medium term

Research pathways for harvested fly ash and container glass are covered separately in this chapter. In the case of natural pozzolans, extraction and processing methods are

---

likely to vary between deposits and will need to be developed on a case by case basis. Given that they will be most commercially viable when used near the source, local expertise in testing will need to be employed and possibly developed. Testing for pozzolanicity, consistency, effect on mix design and rheology, and short and long term performance will be needed for each developed pozzolan.

### Long term

Provincial and municipal governments are the most significant owners of concrete construction. Incorporation of natural pozzolans, harvested fly ash and ground glass in the CSA standards is necessary for adoption of these materials by those governments, but is generally not sufficient. Instead, they also need to be included in government specifications as acceptable materials, which may require independent testing, field trials and other work beyond that taken for inclusion in CSA A3001. This work is also best carried out by local academic and corporate experts, who may have already built relationships with government departments and will be familiar with local conditions and needs.

## **3.2.2 Harvested Fly Ash**

*“Harvested fly ash is a potentially very abundant supply to replace an expected diminishing supply of ‘live fly ash’ from coal-fired power plants as they shut down. There are some questions around additional testing and testing frequency to make sure that confidence can be built in the development of these materials.”*

As noted in the quote, “harvested” fly ash recovered from land fill has the potential to partially or fully replace existing sources of newly produced fly ash. Extent and duration of supply are critical questions that were addressed above, but there are also issues that need to be explored such as recovery methods; potential contamination of the material by bottom ash or other waste that may have been landfilled at the same time; and whether short and long term performance is the same as that of newly produced fly ash. In addition, CSA A3001 (CSA Group, 2023a) currently treats harvested fly ash in the same way as newly produced fly ash if it meets the standard criteria. Workshop participants indicated, however, that further work may be needed to develop standards in a variety of areas to support the production and use of the material.

### **3.2.2.1 Activities Recommended by Workshop Participants**

#### Short Term

- *“Local research to support the performance and GHG benefits of harvested fly ash. Support development of standards with respect to processing, handling and the use of harvested fly ash to meet performance requirements in a Canadian context and Canadian environment.”*
- *“Assess and inventory existing deposits.”*

- 
- *“Refining, understanding and helping communicate current CSA standards for surveying a deposit.”*

#### Medium Term

- *“Use of alternative binders to activate SCMs and optimize performance.”*

#### Long Term

- *“Testing protocol to qualify novel SCMs for use in specific concrete applications.”*

### **3.2.2.2 Research Pathways**

#### Short Term

Determination of the extent and composition of landfilled fly ash deposits is crucial for determining the economic viability of this approach to replacing current fly ash sources. The basic outline for the needed work at the national scale has been given in the previous section of this chapter on the availability of SCMs. For competitive reasons, more detailed analysis should be undertaken by the companies identifying and developing the deposits. In the case of harvested fly ash, some additional work may also be needed to address the best approaches for sampling material from landfills, including the identifying of and testing for possible contamination and its effect on performance.

Regional case studies demonstrating the use of harvested fly ash may be needed to support adoption by a broad range of users.

It should be noted that harvested fly ash was first included in CSA 3001 (CSA Group, 2023) in 2021. While some updates to that standard based on the case studies above may be required, most of the standards work recommended for harvested fly ash by the work shop participants has already been completed.

#### Medium term

Depending on the results of the contamination studies, additional work may be needed to determine how to beneficiate harvested fly ash if significant contamination is present in a given landfill. It is also possible that fly ash from multiple sources may need to be homogenized to provide consistent performance. It is currently unclear whether all markets would accept harvested fly ash as a direct substitute for newly produced fly ash. Some additional laboratory work or field testing may be needed to support product uptake.

Although workshop participants suggested the possibility of creating a new standard for harvested fly ash, such a standard appears unnecessary as the material is already covered by CSA 3001 (CSA Group, 2023a). New information about harvested fly ash could be incorporated in this standard if necessary.

---

### Long term

Work on such topics as the interaction of alternative binders with harvested fly ash and establishing the performance of the material in concrete would only be necessary if it showed significant chemical, physical or performance differences from newly produced fly ash. Otherwise, long term research activities are likely to focus on research to fill gaps in the existing body of knowledge of fly ash behaviour in concrete.

### **3.2.3 Container glass**

*“Lack of utilization of municipal recycling (container glass).”*

*“Understanding the effects of ground glass on durability and source constraints”* (raised under Alternative Binders discussion).

Unlike natural pozzolans or harvested fly ash, the source for container glass is known (municipal waste streams) and does not require excavation. Considerable recent research has also been carried out at the University of Sherbrooke (Medji et al., 2022) (Zidol, Tognovi, & Tagnit-Hamou, 2021) (Omran et al., 2018) on the use of ground glass in the Canadian context. The major constraints on the use of this material therefore appear to be related to the development of appropriate facilities for its production and ensuring product consistency and quality.

#### **3.2.3.1 Activities Recommended by Workshop Participants**

##### Long Term

- *“Testing protocol to qualify novel SCMs for use in specific concrete applications.”*

#### **3.2.3.2 Research Pathways**

##### Short term

A key step for market acceptance of this material will be field trials carried out in different locations across the country. These field trials would not only demonstrate the potential of ground glass as an SCM to the concrete industry but would also help municipalities and grinding facilities understand the market for the recycled material and make decisions to support any needed investments. Preparation for the field trials may need to include development of the grinding procedure, methods for selecting appropriate glass available at scale with consistent properties and trial mixes to ensure performance. Different mix designs should be explored during the field trials to help determine optimum replacement contents for different concrete applications. Addressing concerns about the potential for increased risk of alkali-silica reactions due to use of ground glass are critical for the success of the SCM and should be part of the field trials.

##### Medium and long term

---

Concrete produced during the field trials should be monitored as long as possible to provide long term durability data. Samples should also be included in an environmental exposure site if one is available. The potential for the use of high alkali glasses to be used as alkali activators for geopolymer cements should also be further explored.

## **4 Alternative supplementary cementitious materials (ASCMs)**

### **4.1 Introduction**

The use of SCMs in concrete reduces CO<sub>2</sub> emissions and saves non-renewable resources. Substituting SCMs for Portland cement minimizes industrial waste, enhances the properties of the concrete, and increases the service life of concrete structures.

The availability of quality SCMs has almost reached its limits and cannot offset the need for higher volumes of concrete required by developing markets and this fact will be exacerbated by the phase out of thermal plants that produce fly ash for use in concrete to replace part of the cement. The use of alternative supplementary cementitious materials (ASCMs), including off-spec products and less-investigated by-products can be a viable alternative. However, there are many obstacles and limitations which hinder the use of such products. These are related to the lack of long-term results related to mechanical and durability of concrete they are used in, the variability of their chemical composition and the presence of undesirable substances including heavy metals.

There is a wide range of materials that can be considered as ASCMs, such as cement kiln dust, electric arc dust, glass powder, biomass and vegetable ashes, municipal solid waste incineration ashes, and clay brick waste. These materials have a marginal and often localized availability, and a variable chemical composition as compared to conventional SCMs. All these materials generally comprise industrial, municipal, or agricultural wastes destined for landfills, but can be reused as a cementitious material for the manufacture of concrete. Efficient and rapid methods are necessary for evaluating their performance and reactivity in concrete materials. Thus, there is a need to characterize the chemical, physical, and mineralogical properties ASCMs that may have the potential to be used in concrete production.

### **4.2 Knowledge Gaps**

#### **4.2.1 Supply Chain / Commercial Viability**

*“We need to know more about where ASCMs are located in Canada to determine distributions. Distribution will be an issue in the future.”*

---

*“Work needs to be done to understand if ASCMs are commercially viable, sustainable beyond strictly carbon determination from a life cycle assessment (LCA) perspective, and what can be done in regards to locally sourced material that may only be available in small volumes.”*

*“If everyone starts mandating concretes with use of greater volumes of ASCMs and SCMs, is there a risk of running out?”*

The amount of ASCMs available and their ease of access is a critical factor for commercial viability for a number of reasons.

- Canadian cement production reached 13.6 million tonnes in 2019 (Statistics Canada, 2019), the last year data was available. In order for ASCMs to be substituted for ordinary Portland cement (OPC) or PLC on a wide spread basis, they will need to be available in hundreds of kilotonne quantities at a minimum.
- Qualification of ASCMs under CSA A3001 (CSA Group, 2023a) is time consuming and relatively expensive. Supplies need to be large enough to justify the expense.
- Supplies also need to be consistent enough that testing can be done at a similar frequency to that carried out for current SCMs.
- Purchasers of ASCMs must be assured that there is sufficient supply of the material that it is worth investing their time to understand how to use it.
- Cost and proximity of supply to major markets may be key to whether the ASCM truly provides GHG benefits.

In addition, the actual GHG benefits for ASCMs that by-products are likely to depend on how the environmental impacts of the industrial process are allocated between the primary product and the by-product. Current practice is typically to assign all of the impacts to the primary product, but future guidance from ISO or governmental bodies may require allocation on an economic value basis. LCAs that account for both approaches may need to be used to assess commercial potential.

#### **4.2.1.1 Activities Recommended by Workshop Participants**

##### Short Term

- *“Surveying Canadian availability of ASCMs and natural SCMs. This is a possible role for Canadian geological surveys but we need to determine how to capture availability of industrial by-products, recycled materials, etc.”*
- *“Looking at exactly how sustainable ASCMs would be (geographically, material availability, environmental) to determine if this is truly an environmental benefit.”*
- *“Develop a Canadian map for the availability of ASCMs or other known sources of materials that have not been used extensively in construction.”*

---

## 4.2.1.2 Research Pathways

### Short Term

A preliminary survey of potential industrial by-products that could be used as ASCMs is currently being carried out by NRC. Depending on the quality of data that is obtained, some of the recommendations above may be addressed by that project. It should be noted, however, that the precise environmental impacts produced by an LCA would need to be carried out on a case by case basis, rather than as part of a survey. Transportation emissions can be estimated based on distance to market, but production emissions may vary greatly depending on the raw material in the ASCM and the degree to which it needs to be valorized.

### Medium Term

While the survey described above may be useful for providing information on currently available ASCMs, detailed geological surveys are likely to be necessary to identify the full extent of ASCM deposits and availability. These surveys are likely to be carried out on a commercial and confidential basis, rather than as a public research activity. In addition, it is highly likely that potential new ASCMs will continue to be identified after the NRC survey has been completed and published. Developing guidelines for assessing the viability of ASCMs as they are proposed would allow proponents to focus time and effort on where the most benefit would be obtained.

## 4.2.2 Qualification of ASCMs

*“The establishment of a baseline SCM to compare emerging material against. Current testing compares new ASCMs against 100% OPC blends as opposed to against equal replacement with an established baseline SCM, such as fly ash.”*

*“Characterization and refinement of both ASCMs and natural SCMs i.e., their chemical, physical, mineralogical composition, but also how they behave in concrete.”*

As noted above, the current process for qualifying ASCMs in CSA A3001 (CSA Group, 2023a) is time consuming and expensive. This is partially due to requirements for long-term testing, but also due to the number of tests that are considered necessary to evaluate the performance of the ASCM in concrete. It is not clear, however, whether the full range of tests is needed for all ASCMs. As implied by the second quote above, it is possible that ASCMs may be able to be grouped according to their basic composition, allowing for a reduced, performance based set of tests to be made. If this grouping is possible, then the development of guidance for comparisons to existing standard SCMs as suggested by the first quote may become possible. As an example, silica fume is a by-product from the production of ferro-silicon. Other chemical processes may produce material that is similar in size, silicon content and reactivity, but

---

under current rules would need to undergo the full range of ASCM tests. A performance based approach would see it tested as a silica fume, with only the relevant follow tests required. If grinding is required or alkalis are present in the material, a comparison to ground glass might be more appropriate.

#### **4.2.2.1 Activities Recommended by Workshop Participants**

##### Medium term

- *“Develop fast-track characterization of ASCMs and natural SCMs as the current standard for qualifying is time consuming and expensive. Is there a minimal set of testing that can be used to reduce costs and allow faster adoption?”*

#### **4.2.2.2 Research Pathways**

##### Short Term

ASCMs are intended to replace OPC/PLC in concrete by taking part in one or more of the hydration reactions. They must therefore have the right composition and structure to allow for those reactions to take place. A system of categorization could therefore be developed based on composition, similarity to existing SCMs and the presence of any adverse chemical elements.

##### Medium Term

Carry out comparison tests between ASCMs and comparable standard SCMs to validate a performance based approach to ASCM testing, including using field tests.

##### Long Term

Update the CSA standards to permit performance based approaches to qualifying ASCMs for use in concrete.

#### **4.2.3 Performance of ASCMs in Concrete**

*“Lack of knowledge in long-term performance of strength and durability of ASCMs. This could potentially be resolved with accelerated testing but long-term performance in the field as well as the effect of climate must be considered.”*

*“On one hand is the materials and ASCM performance and on the other hand is the finished product’s performance (concrete) which depends on its raw materials (SCMs and cement) among other parameters such as mix design and production methods.”*

Uncertainty over how well ASCMs will perform compared to traditional SCMs in concrete is one of the key unknowns that may affect their acceptance by the industry. While the previous section of the report addresses speeding up the qualification

---

process, this section addresses the confidence building measures needed to demonstrate that any individual ASCM will perform as expected. It also addresses the possible need for guidance on issues such as workability and finishing that may not be covered by qualification testing.

#### **4.2.3.1 Activities Recommended by Workshop Participants**

##### Short term

- *“Develop a platform or protocol to qualify materials as safe. Removing the word “alternative” should also be considered as it may connote a perceived risk.”*

##### Medium term

- *“Trial with industry and major infrastructure owners to use materials in low-risk demonstration projects to help inform decision makers.”*

##### Long term

- *“Re-establishing a long-term durability field site for concrete materials.”*

#### **4.2.3.2 Research Pathways**

##### Short Term

The work to develop test methods described in Section 4.2.2 would be expected to develop quicker test protocols to establish basic information about long term performance for ASCMs. Additional work may, however, be needed to provide guidance on how to use a newly qualified ASCM. Amongst others, potential topics might include successful mix designs, effects on concrete rheology, appropriate finishing approaches or managing shrinkage. Results from these tests could be used to build a field performance database for guidance. This guidance would need to be developed for each ASCM and would likely require trials performed on a concrete plant and concrete trucks, rather than using smaller mixers. Standardized protocols for this work would need to be established.

##### Medium Term

Once application guidance has been developed, the field trials recommended by the workshop session participants should be carried out. They are essential for demonstrating that ASCMs can be used successfully in concrete and may, in addition, provide additional information to improve the guidance documents developed as short term work as described above.

##### Long Term

Laboratory concrete testing can carry out short and medium term testing (typically up to 3 years, although some universities may retain samples longer for research purposes), long term tests in outdoor exposure sites are the gold standard for evaluating concrete

---

durability. Unfortunately, while some existing long term exposure sites continue to be monitored, there are no Canadian sites where samples containing new ASCMs or alternative binders can be placed. Moreover, the existing site at Treat Island in the Bay of Fundy has recently been lost, while other sites are in locations where they are vulnerable to being removed by property owners no longer interested in concrete durability issues. Developing a secure long-term outdoor exposure site that can be accessed by Canadian industry and academics would support many of the research pathways described in this report.

## **5 Increasing limestone content in Portland limestone cement (PLC)**

### **5.1 Introduction**

Limestone is a common sedimentary rock consisting mostly of calcium carbonate,  $\text{CaCO}_3$ , used as a building stone and in the manufacture of lime, carbon dioxide, and cement. Portland-limestone cement (PLC) is a relatively new class of cement. PLC is produced by blending Portland cement and limestone or by inter-grinding Portland cement clinker and limestone, to which various forms of calcium sulphate, water, and processing additions may be added at the request of the manufacturer.

In Europe, limestone fillers have been used in concrete applications for many years (Tinnis, Thomas, Weiss, Farny, & Giannini, 2024) Different grades of blended cements where limestone is inter-ground with clinker have been produced. OPC containing up to 5% and blended cements grade with 5-20% of limestone and blended cements grade with 20-35% of limestone are frequently used. Limestone is also used in cast-in-place concrete as a substitution of a portion of the cement to improve the performance/packing density in concrete mixtures.

In contrast, PLC is relatively new to Canada, being first included in the 2008 edition of CSA A3000 Cementitious Materials Compendium Standards and first referenced in the 2010 National Building Code of Canada. The maximum allowed percentage of limestone in Canadian general use limestone (GUL) cements is 15%, with many manufacturers offering a product with a lower percentage of limestone. Increasing the allowed amount of limestone in GUL would further reduce GHG emissions. However, while higher percentages of limestone have been used in European cements, differences in environmental conditions and industry requirements mean research is needed to ensure higher limestone content cements are suitable for Canadian use.

---

## 5.2 Research and Knowledge Gaps

### 5.2.1 Long term effect of high limestone content in GUL cements on concrete performance and durability

*“A research gap exists in understanding the impacts of increasing limestone content beyond 15%. The impacts need to be considered in terms of durability, workability, and more specifically, ... the potential use of PLC in high early strength precast concrete.”*

*“Lack research to confirm the optimal percentage of PLC in the concrete mix for concrete products.”*

Although PLC was first adopted in the CSA Cementitious Materials Compendium in the 2008 edition, considerable work was carried out before hand to provide the technical information to allow the responsible CSA technical committee to evaluate the material's short and long term performance. This work included research at Canadian universities, but also field trials of the material. Based on the discussion in the workshops, participants expected that a similar amount of research and development would be necessary to deploy PLC with higher levels of limestone content.

One key issue is whether additional amounts of limestone can be added using the same grinding procedures as current forms of PLC or if the limestone and OPC will need to be ground more finely to maintain the same strength development. The latter approach would change the rates of reaction of secondary compounds as well as the primary hydration reaction that forms calcium silicate hydrates (C-S-H) and may therefore require additional testing. A second issue is that appropriate applications need to be identified for different levels of replacement with limestone. While Europe uses PLC with significantly higher limestone levels, where it can be used is limited based on expected concrete performance. In Canada, as an example, research might show that cements made with a 20% limestone content could be used in much the same fashion as current PLC, but cements made with a 40% limestone content could only be used for low strength applications such as basements.

#### 5.2.1.1 Activities Recommended by Workshop Participants

##### Short Term

- *“A literature review of current practices in Europe and worldwide where some countries already have standards which allow the use 20% or up to 35% of limestone content complimented by a research study on lessons learned.”*
- *“Research on durability (RCP [rapid chloride permeability], salt scaling), workability, effect on curing requirements (e.g., 28-day strength). Is there potential to develop a test program to look at testing different limestone*

---

*percentages to the applicable standards over a range of strengths and water / cement or GUL ratios?”*

- *“Field tests and research beside the labs in order to obtain more factual results.”*
- *“More research, collaboration and literature review to compare percentages of cement and its effect on design performance of products to come up with optimal number.”*

#### Medium Term

- *“Real world studies on the impact of increasing limestone percentages in different applications. (e.g., residential, infrastructure, tunnels). Take select projects and monitor them over time.”*

### **5.2.1.2 Research Pathways**

#### Short term

At the time of writing, a literature review and preliminary testing on high limestone PLC have already been carried out at two Canadian universities. As a first step in building acceptance of this class of products, early publication of that review either in an academic journal or a report accessible on-line would be helpful. A detailed research and development plan targeting specific grades or applications for high limestone PLC should be part of that review.

Short term experimental work would be needed in the areas of mix design, admixture compatibility, workability, and short term hardened concrete properties. This work will need to include issues such as water to cement ratio highlighted in the workshop recommendations, but also issues around finishing, shrinkage, creep, and the potential for use in applications such as ultrahigh performance and precast concrete.

#### Medium term

Selected mix designs will need to be assessed for medium and long term performance, with a particular focus on durability issues. Particular attention will need to be paid to forms of sulfate attack, particularly if the high limestone content PLC is ground very finely compared to current PLC products. Past work has shown that extremely high surface area limestone in cement can speed cement reactions (Makar, Beaudoin, Trischuk, Chan, & Torres, 2012) and care would be taken that performance is not affected. Selected field trials could begin at this stage, with a focus on low value, readily replaced applications.

#### Long term

Some durability tests may require long term examination. Results from earlier durability and other performance tests should be correlated with results of long term testing and field trials to ensure that accelerated aging methods are producing accurate performance guidance. Additional field trials with higher value applications should be

---

started once the initial field trials are completed. As with work on ASCMs, a long term exposure site would be useful to assess durability performance and expected concrete lifetimes.

## **5.2.2 GHG reduction benefits of high limestone PLC**

*“There is a need to assess the carbon impacts of increasing the limestone content in concrete.”*

Increasing levels of replacement of the clinker by limestone would be expected to reduce GHG emissions from cement production due to the reduced need for kiln operation for the same mass of product. More grinding, would, however, be needed, particularly if a finer material is required for the same performance. Very fine cement may also create a higher packing density in the concrete, potentially raising the need for higher cement contents or changes in aggregate grading to maintain the same cement content. While it is expected that high limestone content would reduce GHG emissions from cement, analysis of GHG benefits is needed to confirm that expectation before investments in the necessary R&D and production equipment are made.

### **5.2.2.1 Activities Recommended by Workshop Participants**

#### Short term

- *“As we increase the percentage of limestone in cement, we want to evaluate what we’re doing in terms of global warming potential. What is the breakeven point of increasing limestone percentage if we have to add cement powder content to get same properties?”*

### **5.2.2.2 Research Pathway**

#### Short term

A preliminary LCA should be carried out using estimated environmental inputs and outputs based on existing production data. This work could be carried out in a generic manner with some data provided by cement producers, or could be carried out by individual producers based on their own data with third party verification. The latter approach may be more appropriate if cost/benefit ratios and return on investment calculations will be included in the analysis. In either case, verified potential for reductions in GHG emissions would be beneficial in making the case to government and end-users to support the use of the new product.

## **5.2.3 Need for Performance Based Standards**

*“Lack of alignment between current prescriptive standards and a performance-based design approach.”*

---

ASTM currently offers two approaches to specifying cement – one with a prescriptive approach, ASTM C150 (ASTM International, 2024), and a second, ASTM C1157 (ASTM International, 2023) that supports performance based design. CSA A3000 (CSA Group, 2023) currently offers only the first option, although ASTM C1057 is recognized in the 2024 edition of CSA A23.1 (CSA Group, 2024c) as a first step to incorporating performance based design approaches into the standard in future editions. The goal in this case is to allow the end-user to specify performance requirements, rather than specific concrete mix classifications, allowing more flexibility in the choice of materials. This approach would be expected to make it easier to use alternative binders such as high limestone content PLC and, if extended to SCMs, would make it easier to use ASCMs as well.

### **5.2.3.1 Activities Recommended by Workshop Participants**

No activities on this topic were identified during the workshop sessions.

### **5.2.3.2 Research Pathway**

#### Short term

Field trials and demonstration projects will be needed to support the broad use of performance based approaches in specifications, standards and building codes. Other research activities that would support these approaches are outlined in Chapters 4 and 7 of this report. Part of this work should include developing guidance on how to specify performance based design approaches to get expected project outcomes.

#### Medium term

An analysis of comparable mix designs specified using prescriptive and performance based specifications and of projects built using performance and prescriptive based design approaches should be undertaken using LCA methods to show whether there are any differences in project GHG emissions between the two methods. An overall analysis of outcomes between prescriptive and performance based approaches would also be helpful in supporting the case for the latter methodology.

## **6 Coarse and fine recycled concrete aggregate**

### **6.1 Introduction**

The construction waste produced from building demolition is in hundreds million tons per year. Historically, the most common method of managing this material has been through disposal in landfills.

---

Concrete recycling gains importance because it protects natural resources and eliminates the need for disposal by using the readily available concrete as an aggregate source for new concrete or other applications such as road base.

Recycling concrete reduces the environmental impact of the construction industry by several different ways. In addition to the resource management aspect, recycled concrete aggregates absorb a large amount of carbon dioxide from the surrounding environment. The natural process of carbonation occurs in all concrete from the surface inward. In the process of crushing concrete to create recycled concrete aggregates (RCA), areas of the concrete that have not carbonated are exposed to atmospheric carbon dioxide, accelerating the overall carbonation of cement paste in concrete.

RCA can be produced from some types of construction waste by crushing and sorting particles into desired sizes. Recycled materials have been increasingly used with the aim of reducing the use of natural aggregates. In 2020, 89% of construction waste in the European Union was recycled, although much of that reuse was in lower value products than the original materials (Caro, 2024). Even industrial fibres in fibre reinforced concrete can be replaced with more sustainable alternatives, such as natural and recycled fibres.

Although recycling concrete seems to be a simple process, the quality of concrete with RCA is very dependent on the quality of the recycled material used. Reinforcing steel and other embedded items, if any, must be removed, and care must be taken to prevent contamination by other materials that can be troublesome, such as asphalt, soil and clay balls, chlorides, glass, gypsum board, sealants, paper, plaster, wood, and roofing materials. Unless well cleaned, recycled concrete aggregates contain not only the original aggregates, but also hydrated cement paste. This paste reduces the specific gravity and increases the porosity compared to virgin aggregates. Higher porosity of RCA leads to a higher absorption of mix water, potentially altering mix design requirements.

Based on the high variability of the quality of RCA from different sources, there is a need for sustained research work and testing to minimize the risks of decreasing the concrete durability made of RCA.

## **6.2 Research and knowledge gaps**

### **6.2.1 Performance of RCA concretes**

*“There is a lack of understanding in terms of the short- and long-term performance of concretes made with recycled aggregates.”*

---

*“A lack of understanding of the effect of introducing new types of aggregate on fresh and hardened concrete properties.”*

*“Research needs to be done to create a standard in order to de-risk concerns around the use of RCA.”*

*“A gap exists in terms of the materials’ quality consistency. The fluctuation of recycled materials’ quality makes it difficult for ready mix concrete use.”*

*“RCA beneficiation: lack of techniques and strategies to improve the physical property performance of RCA.”*

Although there is an extensive body of literature on RCA and a high degree of awareness of it amongst industry, participants in the workshop sessions believed that substantial additional work on RCA performance in concrete is needed to enable the approach to be broadly used. The use of RCA was considered to be higher risk than the use of new aggregate, due to the potential for contaminated or deleterious aggregate being supplied from demolition sites, and because RCA may retain hydrated cement paste after processing. The former issue raises the possibility that new concrete made with RCA will experience the same deterioration, while the latter suggests that concrete made with RCA may not have the same fresh or hardened properties as that made with new aggregate. Unit weight may also be affected, which may reduce potential applications. Overcoming this perception will require more research, field trials and standardization.

### **6.2.1.1 Activities Recommended by Workshop Participants**

#### Short Term

- *“Research to set and identify requirements and testing procedures in CSA A23.1 for use of RCA in concrete for various types of applications. (i.e., Sidewalks would require lesser requirements than structural applications).”*
- *“Short term performance should focus on understanding the effects of different types of RCA on concrete fresh properties (slump, air content, strength development, etc.), and durability properties (shrinkage, cracking, chloride diffusion and F/T).”*
- *“Re-carbonation - When concrete is crushed to produce RCA some amount of CO<sub>2</sub> is captured. Being able to quantify this amount of CO<sub>2</sub> will help with a better understanding the GWP of concrete produced using RCA.”*
- *“Assess the performance of recycled aggregate in concrete by conducting a literature review including national and global standards as well as published research. This can be used to guide full-scale structural testing under varying local climatic loads and environmental loads to assess dynamic structural behavior of RCA concrete. This will inform a guideline developed by a standardization body to define the RCA specific LCA. The research priorities and findings can be shared through a Centre of Excellence using a collaborative*

---

*approach with research organizations and industry. The results of these actions would be a database of the performance to be used to look at techniques and strategies to improve the physical performance of RCA.”*

- *“Establish an inventory of all sources and types of RCA to come up with a standard classification system; and then for each class, conduct performance testing.”*

### **6.2.1.2 Research Pathways**

#### Short Term

Given the amount of research that has been done on RCA and the apparent level of uncertainty in the industry over the potential for use of the material, an in-depth techno-economic analysis (TEA) should be carried out on this subject as an initial step. This analysis should:

- carry out an up to date literature review;
- look at other existing information available on RCA in both the global and Canadian contexts;
- consider the potential GHG reduction benefits of using RCA;
- consider whether the use of RCA in concrete is economically viable;
- identify if additional standardized test methods and changes to CSA A23.1/2 are needed;
- Alternatively, determine if a separate standard for RCA is needed to ensure product consistency;
- and identify where additional research is needed to fill the knowledge gaps outlined in this report.

The analysis should consider scenarios where recycled concrete fines can be used (see section 6.2.2 below) as well as those where only the coarse aggregate can be used. The degree of cleanness of the aggregate needed to obtain acceptable performance should also be examined. Completing this study would give direction on whether further investments on RCA research, development and deployment are warranted.

#### Medium Term

Assuming the TEA demonstrates that the use of RCA in concrete is worth pursuing, medium term research will need to fill the knowledge gaps identified here and in the TEA. If new test methods are required, they will also need to be developed during the medium term time frame.

#### Long Term

Field trials and demonstration projects will be needed to show the concrete industry that RCA can be successfully used. Multiple projects will be needed to support different applications with different performance requirements. Based on the previous work and these projects, standards for the use of RCA will need to be developed, along with guidelines for those interested in using the material. It is possible that the findings of the work would initially only permit the use of RCA in lower performance applications, which would require restrictions in the relevant standards and/or design codes.

---

## 6.2.2 Recycled concrete fines

*“Mix design methods for fine recycled concrete aggregate in Canada.”*

While considerable research effort has taken place to support the use of recycled coarse aggregate in concrete, less attention has been paid to the use of recycled concrete fines. This material includes both hydrated and crushed cement paste and the original fine aggregate, typically silica sand, used in the concrete.

In many ways, however, more benefits may potentially be obtained through the reuse of the fines than the coarse material. New coarse aggregate is produced through the excavation of gravel deposits or crushing of rock material from quarries. Since recycled coarse aggregate needs to also be crushed and cleaned before use, there may not be a substantial GHG benefit to its use compared to the new material. The benefits may instead come from improving the circularity of concrete production and reducing land fill use. Careful analysis of the environmental impacts of producing the different coarse aggregate materials would be needed to demonstrate the relative environmental benefits of using coarse recycled concrete.

In contrast, the hydrated cement paste in recycled concrete fines is responsible for approximately 90% of the embodied carbon in the concrete (The Concrete Centre, 2016). If it could be separated from the fine aggregate and reused in cement production, it has the potential to significantly lower the GHG emissions associated with cement production due to a reduction in the amount of limestone needed to produce the cement. At the same time, sources of good natural fine aggregates are becoming limited near large population centres (UNEP, 2022), while the production of artificial fine aggregates requires considerably more energy than that of needed to manufacture crushed stone coarse aggregates. The reuse of the fine aggregates would help to reduce reliance of new material, again potentially reducing GHG emissions. A final point to consider is that some of the drawbacks of using coarse recycled concrete aggregate may be minimized in recycled concrete fines during the production process. Production may be designed to minimize the presence of coarse aggregate material in the fines, while salts could potentially be more easily removed during the separation process in fine materials compared to coarse.

### 6.2.2.1.1 Activities Recommended by Workshop Participants

#### Short term

- *“The use of RCA in concrete production is most successful using coarse fraction. However, significant RCA fines are produced during crushing process. The high pH of the RCA fines can make this material difficult to handle and to add to other materials (i.e., road base, etc.). Research into the use of the fines fraction of RCA would be beneficial.”*

---

## 6.2.2.2 Research Pathways

### Short term

A literature review of existing research on recycled concrete fines should be undertaken as a first step. Building on that work, it is likely that two main streams of research will be necessary. The first will examine how to cost effectively separate the hydrated paste from the fine aggregate in this material. The second would demonstrate that the hydrated paste can be successfully incorporated into new cement production, including the potential for removal of contaminants. It might also be possible to develop methods of separating the C-S-H and calcium hydroxide in the recycled hydrated cement from other hydration products, improving the chemistry of the newly produced cement.

A third possibility to explore is whether the recycled concrete fines themselves can be used in cement production as an addition to the mix of raw materials in the kiln. Typically, the silica in OPC comes from clays, which are heated together with limestone to produce the reactive compounds in the cement. It is possible, although somewhat unlikely, that the silica in the sand might be able to substitute for the clay, which would simplify the recycling process. The literature review may help to determine if this research area is worth pursuing.

### Medium term

If the results from the short term work is promising, scaling up the separation procedure would be required. An initial goal would be to produce enough recycled aggregate to produce concrete for laboratory testing, with a second stage being the production of enough material for field trials. The same supply of recycled material could be used to produce larger quantities of recycled paste for new cement production, again with the goal of producing enough material for laboratory testing and then field trials.

### Long term

A final research stage would be the production of enough recycled hydrated cement paste to allow trial runs in a cement kiln to ensure that the material can be successfully used commercially. Commercial viability may also depend on the ability to reuse the recycled fine aggregate successfully.

## 6.2.3 RCA Supply

*“Dealing with regional lack of supply. Can we demolish existing structures better so we have the right quality material to use as RCA?”*

Once technical activities are completed, the use of RCA on a regular basis will depend on the available supply of the material. Most demolished concrete is currently either used in road base material or landfilled. Diversion of the material for recycling in concrete will be necessary, but techno-economic analysis to determine where recycling

---

is viable will also be necessary, as will guidance for recyclers, municipalities and land-fill operators.

### **6.2.3.1 Activities Recommended by Workshop Participants**

#### **Short Term**

- *“Development of deconstruction guidelines and best practices.”*

### **6.2.3.2 Research Pathways**

#### **Short Term**

The development of guidelines/best practices for building deconstruction to promote the efficient recovery of all construction materials is a crucial part of reducing construction waste from demolition in general. The best options for recovering concrete materials should be a key part of these guidelines. At the same time, research should be carried out to determine the best options for crushing, cleaning and grading the aggregate. One area for analysis would be to determine if the crushing is best done on site or at a centralized plant. The former approach may be more effective in terms of tracking aggregate sources and potential contamination, while the latter may be more cost effective.

#### **Medium Term**

The best practice guidelines developed as short term activity should be turned into a CSA standard. The standard should include guidance for municipalities and other landfill owners on when concrete should be diverted to recycling sites. Other guidance will be needed for specifiers on how much recycled concrete aggregate they should expect to be able to be used on the basis of both an individual project and across a portfolio of projects. Limits on an individual project would depend on the results of work on the performance of RCA concrete, since in some cases using 100% RCA may be viable, but in others only a percentage of the aggregate may be able to be replaced. Limits on a portfolio of projects are likely to be connected to expected levels of RCA supply.

#### **Long term**

If materials passport technology is sufficiently advanced, it could also be used to track to the source of RCA, helping to improve the supply chain and lower the risk of contaminated/deleterious aggregate being reused.

---

## 7 Alternative binders

### 7.1 Introduction

One of the innovative ways to reduce the emissions of CO<sub>2</sub> by the cement industry is the development of alternative binders that generate lower or no process emissions during production. Alternative binders for concrete form a new generation of construction materials that may constitute a sustainable and economical alternative to OPC. Several alternative binders have been available for almost as long as Portland cement, yet have not been extensively used, and new ones are being developed.

Mineral-based alternative binder systems include calcium sulfoaluminate cements, calcium aluminate cements, magnesium-based cements, alkali-activated systems, and blends of these materials (Hewlett & Liska, 2019) Some of these binders possess rapid setting and/or strength gain, making them attractive for repair or rapid construction.

Alternative binders have different physical and chemical properties compared to PLC or OPC. It is not certain whether the physical and chemical degradation models well-established for OPC based cements can explain microstructural changes of the alternative binders when exposed to aggressive environments. Unlike OPC, the experience with alternative binders is very recent, and their long-term behaviour (durability) cannot be judged based on exhaustive field tests. It has therefore become obvious that, in order to have some knowledge about their expected behaviour in Canadian environmental conditions, it is crucial to understand their degradation it is crucial to investigate their degradation both in the laboratory and the field.

While recent years have shown important improvements in the performance of alternative cementitious binders and an increased understanding of their chemistries, reaction mechanisms and property development, these binders continue to only be used in niche applications and have yet to see widespread use. The primary hindrances to the adoption of alternative binders are the higher costs compared to Portland cement and the prescriptive nature of specifications for binders in concrete. As performance-based specifications become more prevalent, it is likely that the use of alternative binders will increase. Establishing the broad use of alternative binders is then likely to depend on a combination of technical performance, economic viability and environmental benefits. These topics are addressed in the remainder of this chapter.

---

## 7.2 Research and knowledge gaps

### 7.2.1 Alternative binder supply

*“An understanding of what alternative binders are available in Canada, what the stage of their development is and how to identify their carbon footprint.”*

*“An understanding of what the market acceptance is for various alternative binders in Europe. Find a way to facilitate a faster acceptance program in Canada.”*

Many alternative binders are well described in the literature, including coverage in texts such as Lea’s Chemistry of Cement and Concrete (Hewlett & Liska, 2019) Depending on the binder, there may also be a track record of their use in general concreting, specialty applications, or related products such as the production of wallboard. Broad use in Canada will depend on technical performance issues, but also supply availability and the amount of investment needed to create production facilities or modify existing cement kilns to produce the alternatives. Some alternative binders, such as alkali activated materials and geopolymers, may require specific minerals for production, or may be based on materials such as blast furnace slag that will be in declining supply in the future. Understanding supply chain and economic issues related to alternative binders is therefore as important to determining whether they are worth developing for the Canadian market as information on technical issues such as workability, strength development or long term durability.

#### 7.2.1.1 Activities Recommended by Workshop Participants

##### Short term

- *“Develop a cost range of each alternative binder as well as a map, first in Canada and then worldwide, indicating availability of the alternative binders.”*
- *“Consider availability of resources for alternative binders including, for instance, studies on the impact of alternative binders coming from different regions or different countries.”*

##### Medium Term

- *“Determine which of the alternative binders have a sustainable supply and will be available long-term.”*
- *“Creation of a technical committee that is part of the CSA dealing with alternative binders. Work is being done on CSA standards to have a platform to develop criteria to qualify other types of cements not currently used in mainstream production. Alternative binder qualification can be streamlined through this performance-based criteria.”*

---

Long Term

- *“Determine whether any material identified in Canada has export potential.”*

### **7.2.1.2 Research Pathways**

#### Short Term

An overview of Canadian geology to identify potential volumes of alternative binders should be undertaken for policy purposes in order to help determine which binders are worth supporting for further development. A general assessment of economic viability and the success of binders in other countries could be undertaken based on existing data, but detailed assessments of Canadian costs and binder viability would need to be carried out commercially by companies interested in pursuing the development of these binders.

Such an assessment would be likely to include examination of the availability of the raw materials used to make the proposed alternative binders; estimation of the cost of building or modifying production facilities; considering how alternative binders could be deployed and estimating whether the return on investment would support industry investment. The results from these studies would then be used to support development decisions and to raise funding.

#### Medium Term

Assuming corporate analysis indicates that one or more alternative binders are technically, economically and environmentally feasible, support mechanisms such as a new CSA technical committee or a new subcommittee within the existing CSA structure should be pursued. It may be beneficial to initiate this activity before corporate investments are made to move forward with commercial development.

#### Long Term

If alternative binders are successfully deployed in Canada, the potential for export markets should be assessed, bearing in mind the need for long term supply for Canadian users.

### **7.2.2 Environmental Impacts of Alternative Binders**

*“Research on the environmental impacts of alternative binders. A full life cycle analysis including material transportation, water use, fuel requirements etc. would be useful.”*

A primary reason to consider using alternative binders in place of Portland cement based materials is the expectation that their environmental benefits will be high enough to offset the cost of transitioning to them. While LCA needs to be carried out on particular projects, an initial study to determine the benefits from adopting different

---

binders needs to be carried out as part of the work to determine which, if any, should be adopted.

### **7.2.2.1 Activities Recommended by Workshop Participants**

#### Short Term

- *“Carbon footprint study for each of the considered alternative binders. First step would be establishing an EPD [environmental product declaration] to account for carbon footprint in a meaningful way as well as developing test-methods that verify, validate and accurately measure the carbon reduction claims of these alternative binders.”*
- *“Investigate the full environmental impact of alternative binders beyond carbon footprint.”*

### **7.2.2.2 Research Pathways**

#### Short Term

An initial environmental impact/benefit study using information from the research literature should be carried out for the major types of alternative binders to identify which ones would produce best benefits. Case studies based on generic facilities and material sources would be useful to help illustrate the differences between standard binder and alternative binder production.

Any generic or site-specific analysis of environmental impacts should encompass the full range of possible impacts, not just greenhouse warming potential.

#### Medium Term

Site-specific LCAs should be carried out as part of the assessment process to determine viability of alternative binder production.

Product Category Rules (PCRs) for alternative binders will be needed to give guidance on the development of product-specific EPDs.

### **7.2.3 Alternative binder performance**

*“Canadians need to know more about what the construction industry uses in Europe in terms of alternative binders. What has been used, tested and accepted? Durability, strength and performance of these alternative binders would need to be assessed in the context of the Canadian climate through extensive R&D.”*

### **7.2.3.1 Activities Recommended by Workshop Participants**

#### Short term

- 
- *“Literature review of existing studies that have been completed in Europe and worldwide. There is some existing knowledge on the performance and durability of alternative binders that would act as a good starting point before performing more research to build on current knowledge.”*
  - *“Compare binders based on performance criteria due to the different categories of performance criteria.”*

#### Medium term

- *“Small scale pilot study to trial alternative binders on low-risk projects.”*

### **7.2.3.2 Research Pathways**

#### Short Term

A literature review on existing alternative binders should be carried out to summarize known information on the properties of alternative binders, including their performance in concrete in both the fresh and hardened states. This review should highlight any knowledge gaps that need to be filled, including potential performance issues in the Canadian environment. Alternative binders that are particularly worth pursuing in Canada should be identified. Differences in aggregate material, admixtures and other aspects of mix design between the published material and the Canadian context should be analyzed to ensure the applicability of the existing work to Canada.

#### Medium Term

If the TEA, environmental and materials review indicate that one or more alternative binders are worth pursuing, then a research program should be initiated to develop the knowledge needed to support standardization and commercial use. Confirmation of properties in the literature will be needed, but much of the effort will need to be focused on the use of the alternative binder(s) in a Canadian context. Examples of required work include durability studies and comparative studies on the ease of concrete production. Differences in how concrete made with the alternative binders will need to be produced in the plant and used on site will need to be understood and, if necessary, new design guidance for structures made with the alternative binders produced.

#### Long Term

Pilot studies and field trials will be needed to validate the results of the work above and demonstrate that the alternative binders can be successfully used. Installing samples in an outdoor environmental exposure site would be desirable both to build confidence in the concrete made with alternative binders and to gain a better understanding of the conditions under which it could be used.

---

## 8 Residential Concrete

### 8.1 Introduction

Concrete use in single and multi-family homes is estimated to represent about 25% of the Canadian cement market. Its application in these homes does not require the same strength development as other concrete applications and it is generally composed of low strength, high water to cement ratio concrete (CSA A23.1/2 concrete class R-1 to R-3). An exception is in high sulfate environments such as much of the Canadian prairies and coastal areas, where sulfate resistant concrete is required.

While the participants in the workshop included a wide variety of technical experts on concrete from both industry and academia, none of them identified as being experts on the use of concrete in home construction. This point is discussed further in section 1.2.1 below, which highlights the need for a greater understanding of how concrete is used in the residential construction market. The discussion in this section is therefore from an outsider's point of view and the identified knowledge gaps need validation with representatives of the home building industry.

### 8.2 Knowledge Gaps

#### 8.2.1 Gap between research expertise and home builders

*“Disconnect between research side of concrete industry for residential and actual installers or industry itself. This presents a problem with education between the groups.”*

Given the known emissions from Canadian cement production, the size of the residential construction market for concrete means that about 0.2% to 0.3% of Canada's GHG emissions can be attributed to residential construction alone. As a result, there is a clear need to provide this market with low carbon concrete solutions. It is not as clear, however, which solutions will be workable in this context. A better understanding of residential construction needs and concreting practices is therefore needed before significant research and development is undertaken to support the sector. At the same time, there needs to be better communication between researchers and the housing industry to support knowledge mobilization.

The use of low carbon concrete in residential construction needs to be considered in the context of major efforts to improve housing affordability and enhance climate resilience. Propositions for improvements range from making houses mostly or entirely from concrete through technologies such as precasting or 3D printing to moving to buildings without basements to improve flood resilience and lower the amount of concrete in

---

buildings. Better communications between the research community and builders would help to direct R&D efforts towards approaches that can be readily implemented by the industry.

### **8.2.1.1 Activities Recommended by Workshop Participants**

No specific activities were recommended on this topic.

### **8.2.1.2 Research Pathways**

#### Short Term

Convene a regular meeting/workshop between key research organizations, home builders, other industry representatives and policy makers/innovators to exchange information on issues related to decarbonization, cost of production, innovative housing construction approaches, resiliency, and other research issues. The use of low carbon concrete should be a key part of the discussions. Expected outcomes would include highlighting technical and other issues that prevent decarbonization, including needed regulatory changes. Research and other activities could then be targeted to produce optimal solutions that address all of the issues described above.

### **8.2.2 Research on low carbon concrete mixes for residential needs**

*“Research on performance of low-carbon concrete compared to conventional concrete i.e., Durability and longevity throughout the whole lifecycle whole assessing costing and feasibility.”*

While the concrete used in residential construction is relatively low strength, developing low carbon concrete mix designs for this application may be more complex than it seems. Any increases in cost of the mix may affect the affordability of the resulting homes, while small homebuilders may not have the capacity to manage complex casting requirements. Mixes that include high volumes of SCMs may take too long for strength development for use in residential construction, while some options that trade higher concrete strength for thinner basement walls may not meet building code requirements. A final consideration is the need for mix design approaches that use local materials where possible to reduce both costs and environmental impact.

### **8.2.2.1 Activities Recommended by Workshop Participants**

#### Short term

- *“Research to optimize low-end residential concrete to reduce carbon footprint.”*
- *“Performance durability testing with a series of low clinker concretes at different ranges of water/cement ratio to provide an alternative low carbon concrete material for use.”*

#### Medium term

- 
- *“Scaling up of adding SCMs starting with small scale buildings to generate buy-in and progress to a larger scale.”*

### **8.2.2.2 Research Pathways**

#### Short term

A number of workshop participants, including researchers and cement industry representatives, commented that they were unfamiliar with residential concrete. The first step to developing new mix designs for residential concrete therefore needs to be establishment of baseline information on existing mix designs, costs per cubic meter, construction practices and expected performance in different regions across the country. Ancillary information such as formwork practices, training needs, and relevant building codes should be collected at the same time.

#### Medium term

Once baseline information has been gathered, options for low carbon residential can be explored. Given the constraints on residential concrete described above, research may need to focus on new approaches such as the use of ASCMs, limestone calcined clay cements (LC3) or high volume Portland limestone cements, rather than refinements of approaches such as the use of traditional SCMs. Similar costs and performance to existing OPC and PLC will be critical to the successful deployment of the new mix designs. Demonstration of long-term performance will also be critical.

#### Long term

Regional variations of the basic mix design approach will need to be developed, along with wide spread demonstration projects. Government housing agencies, building regulators and home insurers should be engaged as part of the demonstration project process.

### **8.2.3 LCA of homes, including concrete**

*“Accurate measurement of lifecycle analysis. These measurements need to be more precise and agreed upon so that we’re all looking at the same thing when looking at the calculation of targets.”*

Life cycle assessment (LCA) is a powerful tool for analyzing the carbon and other environmental impacts. Considerable work has been done on the general LCA of construction processes, including the development of ISO standards. More specialized work in the Canadian context has been carried out to develop whole building LCA guidelines, as well as for bridges and other infrastructure. There has not, however, been the same level of focus on the application of LCA to Canadian homes. A range of activities would need to take place to develop guidance in this area for all housing construction materials, provide benchmarks and provide a standardized labelling

---

system. These deliverables would empower Canadians to control the GHG emissions from their homes in a way similar to the way the EnergyStar program supports choosing low energy appliances.

### **8.2.3.1 Activities Recommended by Workshop Participants**

#### Short term

- *“Build an LCA tool that is universally accepted by industry. Ideally adopted nationally with CSA recognition. This tool needs to be flexible to deal with the innovations and upcoming technologies that could impact the calculations as the market changes over time.”*

#### Medium term

- *“Develop a label to go onto houses letting new homeowners know what they are purchasing, what impact it has on the environment and assurance that the research on environmental impact has been done on their behalf.”*

#### Long term

- *“Standardize, codify or build a user-guide that would accompany the code unto the LCA tool in order to have an impact across the whole country.”*

### **8.2.3.2 Research Pathways**

#### Short term

Research should be undertaken to produce an EPD estimator for residential construction. Regional LCI datasets can be used to provide inputs, along with approximate transportation distances and operational energy costs. The approach should be robust enough to allow trade-offs between embodied carbon from materials and operational carbon.

The embodied and operational carbon of new homes should be benchmarked so that the expected distribution of life-cycle carbon on a per unit basis is known and can be used for comparisons.

#### Medium term

Using the initial research, an EPD estimator tool should be developed that can be used by home designers to optimize lifetime carbon in new and retrofit construction. Data collection for use in the tool should continue. The estimator should be validated against full LCAs of homes with the initial goal of obtaining 80-90% accuracy. At the same time, use the benchmarking data to underpin a labeling scheme similar to EnergyStar™, which can be used to show home purchasers how their home compares to others.

#### Long term

---

The EPD estimator should be refined over time to improve its accuracy. Additional modules could be added so that the carbon emissions impact of choices in finishes, cabinetry and facades can be compared at the same time as changes in cost. Benchmarking data should continue to be added to support the labelling scheme.

## **8.2.4 Use of recycled materials in residential concrete**

*“Research on the use of recycling construction materials into residential buildings and infrastructure both by using older concrete as well as new construction concrete that is leftover and can be used in other sites.”*

The low strength requirements and lack of reinforcement in most residential concrete applications means that the impact of using recycled materials may differ from use in regular reinforced concretes. Specific testing should therefore be explored for this application. The general issues related to recycled concrete aggregates are discussed in Chapter 6 of this report and would be expected to apply in the residential market as well.

It is possible that a wider range of recycled aggregates might be usable in residential construction. The use of other recycled materials as fill or low strength aggregate could also be explored. It should be recognized, however, that the potential for reuse of material in this application will be limited by issues of cost, ease of use, and long term performance. Home owners may also be unwilling to purchase homes with concrete made with atypical ingredients. Research in this area should focus on those materials that home builders and owners are most likely to accept.

It should also be noted that workshop participants focused on the use of recycled concrete aggregate in residential concrete. The use of other recycled materials was not considered. The activities recommended in the workshop sessions on recycled concrete essentially formed a subset of those recommended in Chapter 6.

### **8.2.4.1 Activities Recommended by Workshop Participants**

#### Short term

- *“Research on improving the performance on recycled concrete through use of additives or changing the production method.”*
- *“Better research on sorting and processing of construction waste so it is optimally used and recycled.”*

#### Long term

- *“Quantifying the amount of carbonation of recycled concrete aggregates.”*
- *“Quantification of carbon uptake (if any) should be included in the carbon calculation”.*

---

### 8.2.4.2 Research Pathways

The research pathways in Chapter 6 for recycled concrete aggregate would also apply to its use in residential construction. A medium term research topic would be to establish parameters for assessing the use of other recycled material as a fill or lightweight aggregate in residential concrete. This type of effort may more properly belong in a research program to improve the circularity of construction materials, rather than in one on concrete decarbonization.

### 8.2.5 3D printing in residential concrete

*“Research on the use of concrete in 3D printing for construction”*

3D printing is a form of additive manufacturing where layers of material are built up over time to produce a shape specified by a computer software file. It is typically used for prototyping purposes, the production of complex shapes or small production runs. Operating a 3D printer may be costly in terms of time and energy, although remarkable progress has been made in the last ten years in terms of improving and lowering the cost of printers. At the time of writing, most 3D printing is done using polymeric materials, with more specialized technology being used for other products such as ceramics and metals.

3D printing has also been successfully used with cementitious materials. Large scale printers sized for house production are available commercially and a variety of companies are producing houses by 3D printing in Canada and abroad. Industrial printers have also been produced to manufacture complex shapes in factories and in the field. A major advantage of 3D printing with cementitious materials is the ability to avoid the formwork needed for cast in place concrete, which is time consuming to erect, requires specialized skills and is recognized as a safety critical task.

Most of the current disadvantages of 3D printing technology are related to the way the printers operate. Although this technology is often referred to as 3D printing of concrete (3DPC), the actual materials in common use are either cement pastes or mortars, making 3D printing of cementitious materials (3DPCM) a more accurate description. Existing nozzles and printers are not well adapted to true concrete, with the aggregate causing problems in terms of damage to the equipment, poor materials distribution and clogging. As a result, 3DPCM currently requires significantly more cement on a per cubic meter basis than standard concrete, making it more embodied energy intensive. A related disadvantage is that technology does not currently exist to allow printing around reinforcing steel. Reinforcements need to be added after the fact if they are used at all, limiting the range of structural applications for the material. A final issue is that 3D printed materials are anisotropic, unlike isotropic cement pastes, mortars and concretes. The layered structure means that material properties will be different across the layers than along them, with the new test methods being needed to properly capture

---

these differences. The quality of the interface between the layers may also create vulnerabilities in terms of interlayer bonds due to carbonation and drying of the exposed surfaces, along with heightened vulnerabilities to certain concrete deterioration mechanisms such as freeze/thaw behaviour. While there is a rapidly growing body of literature on 3D printing of cementitious materials, research on durability issues has been very limited, creating a gap that needs to be filled if wide spread adoption of the technology is desired.

### **8.2.5.1 Activities Recommended by Workshop Participants**

No activities on this topic were recommended in the workshop sessions.

### **8.2.5.2 Research Pathways**

The research pathways in this report for 3DPCM focus on issues related to decarbonization. Other research activities are likely needed to fully develop and deploy this technology.

#### Short term

Research and development of 3DPCM is currently hampered by a lack of process-specific validated test methods. In many cases standard methods for concrete or mortar may apply, but the anisotropic nature of 3DPCM mean that those methods should be investigated to ensure they provide results representative of real performance. As an example, a flexural test carried out with loading perpendicular to the lamellae in the 3DPCM is likely to give a different result to one carried out across the lamellae, requiring tests in both directions to provide information needed for structural design. New approaches to testing should be developed where needed. In addition, LCA of commercial projects should be carried out to establish GHG emission baselines and allow comparison to other home building technologies.

#### Medium term

Development of appropriate test methods should simplify the process of developing new materials and structural testing to determine code compliance. Low carbon mix designs should be developed to reduce the GHG emissions related to this technology. In the case of 3DPCM, routes to GHG emissions reductions may include both the use of low carbon blended cements or similar binders, but also developing routes to use larger sizes and higher proportions of aggregate in the mix. Approaches to printing around reinforcing steel or automating the assembly of rebar cages should also be pursued.

A program of monitoring samples in outdoor environmental exposure sites should also be initiated. Finally, LCA of 3DPCM should be carried out as new mix designs and construction approaches are developed in order to ensure that using the technology does not increase GHG emissions compared to standard construction.

---

### Long term

Monitoring of samples in an outdoor environmental exposure site should be carried out to determine long term performance of different mix designs and construction approaches. Comparisons between different printing technologies should be carried out as part of the test program to allow technology optimization.

## **8.2.6 Use of precast in residential construction**

*“Research on precast low carbon concrete and if this can be used for residential concrete.”*

Residential construction has generally used cast in place concrete to produce foundations, basement slabs and walls. There is, however, the possibility of using precast concrete for some of the same applications, or even to precast the entire structure of a house off-site and then deliver it for installation. These approaches may have significant benefits in terms of controlling the quality of the structural element, reducing time on site, construction waste and need for skilled trades.

It is not clear, however, that the use of precast concrete for residential construction would reduce the total embodied carbon in a house. A more general discussion of the needed R&D support to enable precast concrete to move towards net-zero carbon emissions is contained in chapter 11 of this report. The discussion here relates only to decarbonization issues specific to the use of precast concrete in residential housing.

### **8.2.6.1 Activities Recommended by Workshop Participants**

No activities for this topic were identified in the workshop sessions.

### **8.2.6.2 Research Pathways**

#### Short term

A detailed analysis based on LCA principles and using comparable building designs is needed to determine the differences in carbon emissions between a precast concrete modular house and ones made by other construction methods. In order to provide a valid comparison, the analysis would need to extend to include emissions related to transportation to the job site (module A4, ISO ) and on-site construction (module A5).

The seals between modules in precast concrete modular construction is critical to produce adequate building performance. This would particularly be the case for below grade modules with respect to water ingress. New test methods the adoption of existing test methods from other applications may be needed to test seals between basement modules, including in-situ tests for quality control.

#### Medium term

---

Specific areas where the resilience of precast concrete construction could provide benefits for housing could be identified. As an example, if a precast concrete house is significantly more fire-resistant, preventing the GHG emissions from the burning of a conventional building in a wildfire may more than offset the emissions from the cement used in the precast concrete.

## 9 Precast concrete

### 9.1 Introduction

Most concrete is cast at the construction site, using formwork assembled in place. Precast concrete is instead cast at a manufacturing plant, with the completed product or product segment transported to the jobsite. Like other manufacturing processes, precast concrete is particularly successful at producing many copies of the same product, such as concrete pipe. It is also used to produce shapes that would be difficult, expensive, or impossible to cast in the field.

In order to maintain desired production levels, precast concrete mixes and casting procedures are typically designed to increase the speed of strength development in the concrete, allowing earlier demoulding from the form work. Typical methods include the use of high early strength cements and the use of heat and humidity during the initial curing period. The differences in production methods also mean differences in the profile of life cycle carbon emissions compared to cast in place concrete. More CO<sub>2</sub> emissions may be associated with the production of concrete products, but less with transportation to the job site and the construction process itself. The differences in production methods mean that targeted research will be needed to support the precast concrete industry's transition to net-zero carbon emissions.

The first of the knowledge gaps below addresses a general issue for the decarbonization of the precast concrete industry, while the remainder examine more specific issues where the extent of the gap is already known.

### 9.2 Knowledge Gaps

#### 9.2.1 Inclusion of A4 and A5 in LCA calculations

*“The impact of using precast concrete versus cast-in-place - carbon reduction related to accelerated construction. This could also include updates to concrete and precast PCRs to cover more modules than A1 to A3. A study on differences in waste generation would also be useful to compare precast to CIP.”*

---

The standard for life cycle analysis of buildings describes a series of modules that should be analyzed to determine the total life cycle impact of buildings on the environment. They are broadly divided into building construction (Module A), Operations (Module B), Demolition (Module C) and Re-construction/re-use (Module D) (ISO ). There are five sections within Module A, which include:

- A1: Raw material extraction;
- A2: Raw material transport to manufacturing plant
- A3: Finished product manufacturing;
- A4: Transport of finished product to construction site; and
- A5: Construction.

Infrastructure LCA is similar for the construction stage, although there are major differences in the operational phases between the two.

Most work on LCA of construction to date has focused on the first three stages (sometimes called “cradle to gate” analysis). However, this approach may disadvantage precast concrete, as more of the work of concrete construction takes place in the precast plant than is the case for ready mix concrete. As an example, precast concrete includes reinforcing steel when it leaves the plant, but the steel in cast in place concrete is only added during construction. Including modules A4 and A5 in LCA based materials selection process would therefore allow for a more accurate assessment of best options.

### **9.2.1.1 Activities Recommended by Workshop Participants**

#### Short term

- *“(LCA) demonstration project to compare a typical high-rise building (20 + stories); normal construction cycle versus accelerated precast. ...quantify and capture the effects of reduced construction emissions from more slender elements, lower transportation emissions from lighter elements and more elements on the same truck, lower erection footprint due to much smaller cranes, etc.”*

### **9.2.1.2 Research Pathways**

#### Short term

Comparisons between A4 emissions from transportation of cast-in-place concrete, precast concrete, wood, steel and other structural materials should be pursued by establishing per kilometer benchmarks based on typical travel times and conditions. Care should be taken to ensure that the full transportation emissions associated with transportation from the plant to the jobsite are captured. As an example, emissions

---

must be calculated from the manufacturing plant to the jobsite, not from a material distributor.

Jobsite construction processes should already be well mapped both in the research literature and in general contractor's knowledge bases. These processes need to be benchmarked in terms of emissions to produce A5 data, including consideration of the impact of different energy sources. Consideration also needs to be given to time of year and other external impacts on construction emissions. Cold weather cast-in-place concreting for example, may require on-site fossil fuel powered heaters, while heating a precast plant may use other, lower carbon energy sources.

#### Medium term

Guidelines for assessing modules A4 and A5 in construction should be developed and integrated with existing information to produce guidance for practitioners. This guidance could then be used to support a demonstration project of the type described in the workshop recommendations.

### **9.2.2 High early strength PLC**

*“Although PLC has been available for some time, there is still work to be done to facilitate its use in precast situations. There is a need for high-early strength PLC (possibly also including SCMs) for the precast industry.”*

The Portland limestone cement currently available from Canadian cement producers has been developed and tested to have the same performance as standard general use (Type GU) OPC. It is not, however, intended for use in high early strength cement applications. Instead, CSA A3000, which governs acceptable cements for use in construction, covers high early strength cement (type HEL) that contains similar levels of limestone as PLC. As of the time of writing, one Canadian cement company is selling this type of cement. It is likely that as OPC is largely eliminated from Canadian use that other cement companies will also produce this material.

#### **9.2.2.1 Activities Recommended by Workshop Participants**

##### Short term

- *“Need to evaluate the plastic and hardened characteristics unique to a precaster’s full product range and to their operations and curing practices. Some of the characteristics that should be considered, at a minimum (because they are directly or indirectly required by CSA A23.1/2 or CSA A23.4) include; setting time profiles, compressive strength profiles (0 – 24 hours, as well as 7 and 28-days tests), internal temperature profile/heat of hydration, air void spacing and rapid chloride permeability. Other properties that may be of interest to certain precasters may include colour uniformity, carbonation or efflorescence. Other*

---

*engineering properties should also be confirmed such as sulphate resistance, Alkali Silica reactivity (ASR), Delayed Ettringite Formation (DEF) potential, Young's modulus, tensile strength, linear shrinkage and creep, etc."*

### **9.2.2.2 Research Pathways**

#### Short term

A number of different pathways to producing a high early strength PLC are possible. Some possibilities include:

- Intergrinding current high early strength cements with limestone to produce a finer material with similar hydration and strength development characteristics;
- Modifying the oxide content of the high early strength cement before intergrinding to obtain the desired strength development with a coarser blend of materials than the first option; and
- Intergrinding with a SCM as well as limestone to produce a blended high early strength PLC with a coarser blend of materials than the first option.

Cement manufacturers will need to identify the best approach based on past experience with PLC and limestone specialty cements. This work has either been completed or is underway at Canadian cement companies at the time of the report.

#### Medium term

Once a manufacturing approach has been developed, sufficient material will need to be produced to carry out a full national test program, addressing those issues raised in the workshop and demonstrating the expected performance from HEL cements. Trial products will need to be produced at precast plants and any issues identified during production addressed.

#### Long term

Demonstration projects and long-term performance assessments may be needed to introduce precast products made with high early strength PLC to the market place.

### **9.2.3 Use of high volume SCM/ASCM mixes in precast concrete**

*"High volume SCM or ASCMs. Modifying the precast process including curing might allow use of high volumes of SCMs."*

The use of high volumes of SCMs or ASCMs (HVSCMs or HVASCMs respectively) can be challenging in precast concrete because they tend to slow strength development, in turn slowing product production. As discussed earlier in this report, the use of SCMs and ASCMs is, however, a key method for reducing the embodied carbon in concrete due to their ability to replace the use of clinker containing cements in concrete. Specific

---

research is therefore needed to develop approaches to support the use of higher levels of SCM/ASCM usage in precast concrete. This research also needs to explore whether accelerated curing regimes and/or the use of carbon dioxide as part of the curing process could allow for the use of higher levels of SCM/ASCMs in precast concrete than in other concrete materials.

### **9.2.3.1 Activities Recommended by Workshop Participants**

#### Short term

- *“Education program on HVSCM and high temperature curing. The program should focus on sharing that information so it can be used.”*

### **9.2.3.2 Research Pathways**

#### Short term

As noted earlier, traditional SCMs such as GGBFS and fly ash both typically delay the strength development of concrete and face potentially declining supply due to changes in steel production processes and closure of coal fired power plants. Further research on using accelerated curing, CO<sub>2</sub> activation or other activation methods may allow the successful use of high volumes of these SCMs. However, other classes of standardized SCMs such as reclaimed fly ash, calcined clays, metakaolin, natural pozzolans and ground glass should be investigated for use in precast concrete. Some of these materials may promote early strength development in addition to reducing GHG emissions. This investigation can be started through a literature review, but should include basic laboratory testing as well. While the focus should be on the use of HVSCM/HVASCMS replacement materials, identification of suitable accelerated curing regimes that will work with those materials should be part of this laboratory work.

#### Medium term

HVSCM/HVASCMS identified during the research outlined above should be used in trial production runs at precast plants to identify production issues and trial different curing regimes. At the same time, durability and longer term performance work should be initiated on the most promising mix designs. The suitability of the identified materials for use in precast HPC and UHPC should also be assessed.

#### Long term

Depending on the chosen SCMs and other factors, some redesign of concrete structures and formwork may be necessary to take advantage of the new SCMs. As with other new concrete products, demonstration projects and field trials may be needed to introduce HVSCM/HVASCMS precast concrete to the market.

---

## 9.2.4 Other approaches to low carbon precast concrete

*“Finding good ways to increase the one- and three-day strength (of precast concrete) without using high-carbon concrete”*

*“Research on the use of UHPC in precast”*

As noted in the introduction to this chapter, reducing the embodied carbon in precast concrete is limited by the need for the precast products to quickly develop sufficient strength to allow rapid formwork removal or demoulding in order to maintain production levels. Two areas of potential research have already been outlined. However, workshop participants also recognized that there is a broader need for research and development in this area in order to move the precast part of the concrete industry towards net-zero carbon emissions. A variety of potential activities are presented here.

### 9.2.4.1 Activities Recommended by Workshop Participants

#### Short term

- *A UHPC pilot bridge or high-rise building will help to demonstrate and promote the use of this excellent construction material.”*

#### Medium term

- *“Research better material systems that can use CO<sub>2</sub> activation which helps initial strength. We need to ensure it produces parts with acceptable performance.”*

#### Long term

- *“Develop other activation systems to compete with CO<sub>2</sub> to develop fast strength and good part performance.”*

### 9.2.4.2 Research Pathways

Some of the activities recommended by the workshop sessions appear to have indirect impacts on precast concrete decarbonization, rather than direct ones. As an example, new approaches to activating cementitious materials to make them more reactive might allow the use of slower strength development, low carbon approaches such as high volume SCMs. Most of the topics raised here should therefore be considered in the work on discussed in section 9.2.1. Other work recommended here or in Chapter 10 (HPC/UHPC concrete) would also support some participant recommendations. No separate research pathways are therefore presented.

---

## 9.2.5 Performance of novel low carbon materials in precast concrete

*“We need to find ways to convincingly prove longevity, repairability, and durability of precast concrete parts (made with new materials).”*

*“In order to reduce the volume of (precast) concrete used, ...we need to find good ways to optimize for strength, stiffness, durability, longevity and cost.”*

Sections 9.2.2 to 9.2.4 above highlight some of the potential approaches to reducing carbon emissions associated with precast concrete. They also highlight the point that in many cases new concrete products are in many cases developed with a focus on cast-in-place applications. Workshop participants specifically raised the need for testing in precast applications. The need for high early strength development and the potential that changing materials and production methods may require significant capital investments mean targeted R&D is needed to support the decarbonization of the precast concrete industry.

At the same time, precast concrete offers opportunities to optimize the design of concrete structural elements to minimize concrete and reinforcement volumes while still meeting performance requirements. As an example, girders can be designed and cast to support loads vary along the length of the beam, rather than having a constant cross-section. This approach is more challenging to achieve with cast-in-place concrete, but could result in substantial embodied carbon savings. Similarly, UHPC beams and columns may emit more GHGs per cubic meter of material, but have lower total emissions due to more slender cross-sections and design optimization.

It should be noted that the identified gaps quoted above were essentially repeated as recommended short term activities, emphasizing the need but without giving specific research directions.

### 9.2.5.1 Activities Recommended by Workshop Participants

#### Short term

- For newly developed high strength or low carbon materials and innovative precast parts, there is a need to find good ways to optimize for strength, stiffness, durability, longevity and cost.
- Find ways to convincingly prove longevity, repairability, and durability of precast concrete parts.

#### Medium term

- Determine the properties that the parts actually need to perform in order to enable part optimization.

- 
- Create longevity and durability models that are validated by real world testing.
  - Find a consistent way to evaluate repairability.

### **9.2.5.2 Research Pathways**

#### Short term

The differences between cast in place and precast concrete suggest that the latter industry needs to take a more holistic approach to decarbonization than the former. A specific study that investigates how to decarbonize the precast industry should be carried out. This study should investigate decarbonizing precasting operations as well as the use of low carbon materials and design optimization.

A separate study should investigate the existing models and tools for predicting the strength development and long term performance of precast concrete. In this case the goal would be to determine if the existing tools are adequate to support the use of novel precast materials and, if not, to look at what work needs to be done to develop such tools.

A gap analysis for the use of optimized design of precast structural elements should be carried out, including identifying needs for demonstration projects and other knowledge mobilization activities. Depending on the results of the gap analysis, standard low carbon designs for different applications could be developed in collaboration with major precast users such as Ministries of Transport.

#### Medium term to long term

New designs for optimized precast structural elements should be produced, tested in laboratories and then field trialed. This work should again be done in collaboration with major precast users to speed industry adoption of the designs if the trials are successful.

If the initial studies on general decarbonization of precast operations are promising, engineering studies and proof of concept work will be needed to support industry decisions on whether to invest in the recommended approaches.

Any gaps identified in the existing tools available to the precast industry for predicting product performance should be addressed through research by the organizations responsible for creating those tools.

### **9.2.6 Natural carbonation of precast concrete**

*“There is no Canadian-specific data on carbon uptake, or re-carbonation of concrete, either precast or ready mix, to quantify the long-term benefit that is not currently being recognized in EPDs or*

---

*LCI/LCA databases. Re-carbonation is now recognized in European countries, in certain calculators, for example the GCCA tool.”*

Concrete naturally sequesters CO<sub>2</sub> through chemical reactions between the gas and the reaction products found in hydrated cement. The implications of natural carbonation for carbon sequestration in concrete are discussed in Chapter 13 of this report. Specific research on natural carbonation of precast concrete may be needed as it is possible that differences in the materials and curing regimes between precast and cast-in-place concrete will have an impact on carbonation processes.

### **9.2.6.1 Activities Recommended by Workshop Participants**

No specific activities for this topic were identified in the workshop sessions.

### **9.2.6.2 Research Pathways**

The general approach to research and development activities in Chapter 13 should be followed for precast concrete. Direct comparisons between equivalent cast-in-place and precast products to determine if there are differences between the two materials should be considered. Although it was not mentioned in the workshops, it should be noted that research is needed on the application of carbon sequestration technologies inside pre-cast plants/

## **10 Low carbon high performance/ultra-high performance concrete (HPC/UHPC)**

### **10.1 Introduction**

High performance and ultra-high performance concretes (HPC/UHPC) use careful control of aggregates, cement contents and other materials to increase the mechanical performance of concrete used for specialized forms of construction. In the case of UHPC, the coarse aggregates are eliminated entirely and fiber reinforcements may be used to enhance crack resistance and ductility. Compressive strengths in UHPC may reach 200 MPa or more.

As a result of improved tensile and flexural strengths, structural designs are possible with HPC/UHPC that are impossible with traditional concrete mixes. The materials high strengths also allow for the use of structural elements with significantly lower cross-sections for the same overall load resistance, reducing the element's mass and aiding in transportation and construction. UHPC is essential for some specialty types of construction, such as very tall high-rise buildings, where the bulk of traditional concrete need to obtain the same levels of structural performance preclude its use. Its use may also be particularly beneficial in precast concrete, as the reduced mass of the finished

---

high strength product may reduce the unit cost of transportation and installation compared to one made with traditional materials.

In the context of reducing the embodied carbon in concrete, a major limitation of HPC and UHPC is that the materials require higher cement contents than traditional cast in place concretes. In particular cases the thinner cross-sections in HPC/UHPC may compensate for the increased cement content, but in many others, choosing HPC or UHPC for a project may also mean choosing a higher embodied carbon material. A related issue is that commercial UHPC may be based on proprietary formulations that require materials imported from other regions or even other countries, adding to its overall carbon burden. Research is therefore needed to allow these materials to be used to their full potential while still meeting GHG reduction targets.

## 10.2 Knowledge Gaps

### 10.2.1 Analysis of the potential for HPC/UHPC to reduce GHG emissions

*“Economics and GHG reduction of concrete volume reduction when using HPC/UHPC for applications that were traditionally made with ordinary concrete. Can optimizing the structural design reduce the carbon footprint?”*

*“Analysis to determine if HPC/UHPC use is beneficial in lowering CO<sub>2</sub>”*

UHPC is used in a relatively small range of projects, where its performance characteristics are essential for project success. As an example, it offers an alternative to structural steel for use in applications such as bridge girders, rather than competing with other forms of concrete. Lack of experience with the material, the need for specific rather than local materials and the high cement ratio of the concrete may all hinder the use of UHPC. At the same time, while substantial research may be needed to develop low-carbon versions of this material, the smaller cross-sections of structural elements made with UHPC may already provide significant GHG reductions. As a result, workshop participants explicitly raised the need to do a more detailed investigation of its potential and GHG warming potential, including a TEA and life-cycle assessment. Such a study would provide a better understanding of the potential for low-carbon UHPC and help to focus research in the areas that would provide the greatest benefit. Comparisons would need to be made not just to cast-in-place concrete, but also to steel products where HPC/UHPC would potentially replace that material.

#### 10.2.1.1 Activities Recommended by Workshop Participants

##### Short term

- 
- *“Develop efficiencies in wall designs, floor designs and pavement designs, there is a lot of potential to reduce GHG emissions. 25% of all concrete being used is on the housing side. If we can apply HPC to housing and reduce size of footing walls, etc., there are real potential gains.”*
  - *“Carbon content, performance durability and indexing with respect to HPC and UHPC.”*

### **10.2.1.2 Research Pathways**

#### Short term

Archetype structures and/or structural members made with HPC and UHPC should be designed and then compared in terms of GHG emissions to ones made with other construction materials that have the same functionality in order to determine which approaches produce minimal GHG emissions. The results from the comparison will help to demonstrate whether the use of HPC/UHPC should be prioritized as an approach to GHG emissions reductions. It will also provide benchmark data to track GHG emissions reductions produced by other research approaches. Emissions data should include the impact of the reduced concrete mass in HPC/UHPC products on transportation emissions, not simply the emissions associated with the materials themselves.

### **10.2.2 Low Carbon HPC/UHPC mix design**

*“Research into the notion that high performance concrete and ultra-high-performance concrete are two specialty concretes where cement can be replaced by high volume of SCMs and ASCMs by lowering the w/Cm enough and using chemical admixtures”*

*“Natural Pozzolans with other SCMs for use in concrete. With depleting levels of SCMs new sources of SCMs must be developed to help meet the goal of carbon neutrality by 2050. We could consider the use of pumice. Ternary mixes of fly ash and metakaolin produce a very well-performing concrete as well.”*

*“Necessity of the high particles packing density. A gap exists between presence of mathematical particle packing models and the lack of practical tools for complete de-agglomeration of the ultrafine powders and creating homogeneous cementitious matrix.”*

*“Use of mineral fillers such as silica flour or quartz powder, and ground limestone in UHPC”*

Developing mix designs for UHPC in particular is a much more complex process than the standardized mix designs used in typical concrete. High cement contents, particle grading and the use of fiber reinforcements are all key to obtaining desired properties,

---

but many other factors such as wet or dry mixing of mix components, duration of mixing, and temperature also come into play. In addition, most studies have focused on laboratory work, leaving questions of impact at industrial scales under investigated.

Almost all of the issues raised as gaps have been investigated in the research literature. Optimal packing models for UHPC are an area of on-going research, while additions of various SCMs and ASCMs with up to 50% replacement by mass of cement have been tested. The use of Portland Limestone cement in UHPC is also an area of active research. Comparisons have also been done of performance with different types of fibers, ranging from carbon sequestering natural fibers to high embodied carbon steel and polymers.

Although UHPC is essential for certain high-rise applications and may be advantageous in a number of different areas of concrete construction, the complexities of the mix design process may hamper its more general use as well as its decarbonization. Proprietary mix designs often require the use of standardized materials that need to be obtained from a particular source. If that source is a long distance away, the GHG emissions associated with transportation will contribute, possibly significantly, to the embodied carbon in the HPC/UHPC. Tools and information to support the development of UHPC mix designs using local and low carbon materials could substantially reduce its carbon and help to accelerate its acceptance. While cast-in-place and precast concrete suppliers would need to produce their own proprietary mix designs for sale, their development process would potentially be sped up. Information gathered during the development of such tools will also help concrete purchasers to understand the long term performance and durability of HPC/UHPC products.

### **10.2.2.1 Activities Recommended by Workshop Participants**

#### Short term

- *“How many years of performance data will be required for use of alternative natural pozzolans in codes and standards?”*
- *“Research will be required on the performance of harvested fly ash so architects and engineers will be willing to specify the product.”*

#### Medium term

- *“Developing equipment for mixing dry UHPC composition producing complete de-agglomeration of ultrafine powders and providing dry powder coating within the cementitious composition”.*

### **10.2.2.2 Research Pathways**

#### Short term

There are several recent literature reviews on different aspects of mix design for UHPC in particular. Building on that work, a targeted review of literature to establish

---

parameters for testing and materials classifications should be carried out for both cast in place and precast concrete applications. Once it is completed, available materials in major markets should be assessed for compatibility with UHPC mix design requirements. The range of test materials should then be adjusted to match commonly available material choices.

#### Medium term

Trial mix designs made with materials from different Canadian markets should be carried out in the laboratory to identify controlling parameters and the best options for mixing and curing procedures. The impact of casting temperature should also be explored. The laboratory test results should then be used to produce one or more archetype structures using industrial production techniques. The performance of these samples should be tested for comparison to the laboratory data.

#### Long term

Data from the previous test series should be used to optimize lower carbon HPC/UHPC mix designs. This work may be carried out in conjunction with archetype optimization so that minimum material is used to meet structural requirements. Based on this work, guidance documents or tools should be developed to allow UHPC suppliers and users to more easily develop and test UHPC mix designs.

### **10.2.3 Carbon sequestration in HPC/UHPC**

*“Carbon utilization and sequestration in HPC and UHPC”*

Carbon sequestration in concrete is discussed in detail in Chapters 6 to 10 of this report. It is worth noting, however, that the low porosity of HPC/UHPC limits the potential for those types of carbon sequestration that occur after the concrete set. Otherwise, the issues, activities and research pathway described in Chapter 16 also apply to HPC/UHPC.

#### **10.2.3.1 Activities Recommended by Workshop Participants**

##### Short term

- *“There is a need for a robust literature review to identify the utilization of carbon/CO<sub>2</sub> emissions [in UHPC] as well as research to understand the impact on concrete performance from different CO<sub>2</sub> sequestration, mineralization and utilization approaches (e.g., negative, neutral, positive).”*

#### **10.2.3.2 Research Pathways**

See the research pathways outlined in Chapter 16.

---

## 10.2.4 Guidance on use/selection of HPC/UHPC

*“There is a need to develop a training program for project planners and managers to incorporate low carbon HPC and UHPC into their specifications.”*

*“Additional research and clarity to users is required on choices, options and restrictions on lowering carbon concrete as it affects UHPC performance.”*

*“Outlining performance and durability relative to a benchmark to allow for selection”*

Workshop attendees expressed the belief that there is insufficient knowledge of the potential for HPC/UHPC on the part of designers and specifiers. As a result, the market for these materials and any potential GHG emissions reductions they can produce is underdeveloped. This lack of knowledge of HPC/UHPC would be compounded in the case of low-carbon versions of these materials. The development of guidance for potential users of HPC/UHPC was therefore identified as a knowledge mobilization need for the industry.

Expectations for the short and long term performance of standard concretes are based on industry standards and experience, making comparisons to low carbon versions of the same materials relatively straightforward. In the case of HPC/UHPC, benchmarks and standards need to be developed to allow the same type of comparison to take place. The work on archetypes and mix design described earlier in this chapter will provide some of the key information needed to support the use of HPC/UHPC. Additional information on design, long term performance and appropriate uses, including support for including HPC/UHPC in specifications is needed.

### 10.2.4.1 Activities Recommended by Workshop Participants

#### Short term

- *“Identify knowledge gaps from the municipal and provincial perspective with respect to specifying UHPC and HPC for structures.”*

#### Medium term

- *“Engage major cities and transportation departments (provincial and federal) in specifying more use of HPC and UHPC through the use of demonstrations or pilot projects such as pedestrian bridges in order to create a broader understanding of the uses of these products.”*
- *“Develop a training program for project planners and managers to incorporate low carbon HPC and UHPC into their specifications.”*

#### Long term

- 
- *“Continue to support code development and / or development of an implementation guide for use of UHPC / HPC.”*
  - *“Research recycling techniques, needs and end of life treatment for UHPC and HPC.”*

#### **10.2.4.2 Research Pathways**

##### Short term

As noted in the workshop recommendations, identifying knowledge gaps amongst specifiers and owners in major markets would provide key information for further work on this topic. Comparisons between knowledge of HPC/UHPC amongst potential users in the private sector versus public sector may also be helpful.

##### Medium term

While the research pathways described elsewhere in this chapter may fill some of the identified knowledge gaps, other research is likely to be necessary to encourage use of HPC/UHPC. As examples, long term durability and performance in different applications is likely to be an issue for government users, while contractors and construction engineers may need information on constructability. A research program to address these knowledge gaps should be initiated once they have been identified. Pilot / demonstration projects may be parts of the program. Training modules could be developed based on the results of the research program plus responses to the other research needs identified during the workshop. These modules should include material for architects, concrete and construction engineers, specifiers and owners as well as project planners and managers. Adding the use of HPC/UHPC to the core curriculum for civil engineers and concrete construction trades training would also be helpful.

##### Long term

Inclusion of HPC/UHPC in the CSA concrete standards would support both its inclusion in building codes. Recycling of UHPC in particular may prove to be challenging due to its higher strength, use of fibers and the presence of a wide variety of materials in the concrete mix. See Chapter 6 for more details on recycling concrete. The strength and toughness of UHPC may, however, make it more amenable to reuse than standard concretes. Design for reuse was not raised in the workshops, but is briefly discussed in Chapter **Error! Reference source not found.**

## **11 Nanomaterials**

### **11.1.1 Introduction**

Nanomaterials are generally considered to be materials with one or more dimensions smaller than 100 nanometers. They can consist of thin films (1 nanoscale dimension),

---

nanofibers/nanotubes (2 nanoscale dimensions) or nanoparticles (3 nanoscale dimensions). Nanoscale structure in larger materials also falls under this category.

Investigation of the use of nanomaterials in concrete has generally focused on nanoparticle and nanotube additions to the cement matrix, with a lesser amount of work being done on nanofibers. Nanomaterials are attractive for use in cement and concrete for several reasons:

- If the nanomaterial is reactive in the cement matrix (e.g., nanoscale silica), the high surface area per unit mass of the particles can speed hydration rates, reducing the time needed for setting and strength development;
- Non-reactive nanoparticles may act as nucleation sites for cement hydration reaction products, affecting initial concrete properties;
- As the cement itself has a pore structure that has nanoscale structure, non-reactive nanoparticles may also serve to reduce porosity in the resulting concrete, improving mechanical performance and durability;
- Nanoparticles may also create new product capabilities in the concrete, such as the case with trial methods to add titania nanoparticles to concrete products to break down pollutants; and
- The use of nanofibers or nanotubes may improve crack resistance, providing fine scale reinforcements that stop crack propagation in the matrix, again improving the mechanical performance of the concrete and also adding flexural strength and ductility.

Despite these potential benefits and an extensive research literature that explores them, there has been little commercialization to date of concrete-nanomaterial composites. Issues that need to be addressed include a lack of consistency in experimental results, lack of knowledge of the use and benefits of nanomaterials, discrepancies between the supply and cost of nanomaterials versus those expected for materials to be used in concrete, and a variety of health and safety issues. In context of low-carbon concrete, the potential GHG reduction benefits of using nanomaterials are also unclear. The knowledge gaps in this chapter of the report therefore address the use of concrete/nanomaterial composites in general as well as particular gaps around using them to produce low carbon concrete materials.

## 11.2 Knowledge Gaps

### 11.2.1 Understanding of nanomaterials

*“There is limited information on the types of nanomaterials are available or what the actual definition of what a nanomaterial is. Having a strong,*

---

*common definition of what is understood and available would be a good start. In addition, the implications and impacts of their use needs to be better understood”*

*“Understanding of the lifecycle of a nanomaterial is something that is not well-researched from manufacturing all the way to end of life and recycling.”*

While there are longstanding research activities in the application of nanotechnology to concrete, details about the impact it might have on commercial activities were not clear to most workshop participants. Work to provide appropriate information will be needed if other research activities provide clear evidence that one or more areas of nanotechnology should be pursued as a route to concrete decarbonization.

### **11.2.1.1 Activities Recommended by Workshop Participants**

#### Short term

- *“Conduct a literature review in order to help develop more education for people both in industry and government to understand how these materials can be used.”*

### **11.2.1.2 Research Pathways**

#### Medium term

Assuming that the results of the work described in the rest of this chapter are positive, guidance in the form of a primer or similar document should be written. Language and technical level should be aimed at the practitioner, rather than researcher. The guidance document will need to consider different aspects of the decision to use nanotechnology on a particular project, including technical benefits, costs, GHG emissions and other potential environmental impacts.

#### Long term

Field trials, demonstration projects, and case studies will be needed to support use of nanotechnology in the concrete where warranted.

### **11.2.2 Carbon reduction benefits of concrete containing nanomaterials**

*“Research needs to be done to ensure we’re not substituting something that has good enhancing properties but could also have a high impact on carbon levels before it gets to the actual concrete.”*

---

*“What are the GHG impacts of nanomaterials? What are the potential reductions associated with their use and can we identify the economic impacts?”*

As noted in the introduction to this section of the report, there are a wide variety of nanomaterials that have been used or could be used in concrete. Each of these nanomaterials have different production processes, which in turn means that their embodied carbon should be expected to vary. In some cases, production methods are being designed with the intent to sequester CO<sub>2</sub> in the nanomaterials themselves. In many other cases, the production methods are more energy intense than those needed for conventional materials made from the same elements or compounds, due to the need for further processing and purification to obtain consistent composition and size. As a result, there is a need to assess whether the potential performance benefits produced by nanomaterials will result in significant carbon reduction benefits.

Perhaps the simplest example to analyze would be the case where nanomaterials have been added to improve strength performance and therefore reduce the cross-section of a concrete structural element. In this case, the reduction embodied carbon from reducing the total mass of cement clinker in the concrete could be compared directly to the additional embodied carbon, if any, from the added nanomaterials. Other potential benefits from nanomaterials would need to be assessed for potential impact on embodied carbon in order to determine if they represent a net benefit. As a result, research is needed both on the carbon impact of nanomaterials, but also on how to balance potential performance improvements against those impacts.

### **11.2.2.1 Activities Recommended by Workshop Participants**

No activities for this topic were identified in the workshop sessions.

### **11.2.2.2 Research pathways**

#### Short term

Although each individual nanomaterial should eventually have its own EPD that can be used to assess its environmental impact and potential GHG reductions, this information is unlikely to be available early enough for general decision making about whether to pursue nanomaterials as a route to decarbonize concrete. Representative, more commonly studied nanomaterials should instead be assessed to provide emissions estimates. If possible, GHG emissions should be obtained based on information provided by manufacturers. If this information is not available, the assessment should be based on emissions estimated from the research literature on nanomaterial production and regional sources of energy.

#### Medium term

---

Using the information gathered from the work described immediately above and data on the performance benefits of nanomaterials in concrete, guidance should be produced on whether the benefits of the investigated nanomaterials will be sufficient to offset their emissions, resulting in lower overall GHG emissions. Information on cost of the nanomaterials could also be incorporated in the analysis. This study should be designed to produce criteria that could be used to analyze other nanomaterials as data becomes available, and to help nanomaterial manufacturers determine if applications in concrete should be pursued.

#### Long term

It is expected that the costs and performance benefits of nanomaterials will change over time and that more information on environmental emissions related to production should become available. As a result, the analysis described above should be repeated when warranted.

### **11.2.3 Performance benefits of nanomaterials in concrete**

*“Understanding the performance of concrete using nanomaterials. This includes a gap in the scaling up of testing data, as well as the overall durability of the concrete and its effect on the long-term durability of the final product.”*

Nanomaterials are attractive for use in concrete because work in the area has, in some cases, produced substantial improvements in concrete performance. There is, however, a high level of variability in experimental results to date. This issue is particularly apparent in the literature on the use of carbon nanotubes and other carbon nanomaterials in concrete, where the reported effects on compressive strength range from losses of 30% or more to increases in strength of over 200%. There are a number of possible reasons for these differences, with some of the possibilities including the type of carbon nanomaterial, purification methods, dispersion approaches, and rheological issues. Research is needed to understand the cause of the variability in results to date and to develop approaches to ensure performance is sufficiently consistent for commercial use of nanomaterial-concrete composites.

It should also be noted that in many cases the improved performance results reported for nanomaterial-concrete composites can also be produced in concrete by other, more traditional methods. Given the other challenges associated with using nanomaterials in concrete that are described in this chapter, it is clear that either:

- potential applications of nanomaterials need to be chosen carefully to obtain significant improvements in performance in cases where other approaches will not work; or

- 
- the nanomaterials to be used need to have low enough costs and environmental impacts to make their use viable.

An example of the former case might be the use of nanofibers, nanotubes or graphene to obtain strengths that significantly exceed those possible with UHPC in very tall high rise buildings. An example of latter case would be the use of naturally sourced nano-silica to speed C-S-H formation in the hydrating cement and being totally consumed in the reaction process. Careful analysis of the existing literature will be needed to identify what nanomaterials to target for future research and which applications should be pursued.

### **11.2.3.1 Activities Recommended by Workshop Participants**

#### Short Term

- *“Define the objectives of adding nanomaterials. Considerations include defining performance specification, developing accelerated methods for performance assessment and developing best practices to achieve good performance.”*
- *“Research is needed to adequately classify the different nanomaterials and the advantages and disadvantages of their use in cement production, and concrete properties.”*

#### Medium Term

- *“Research to better-understand the long-term durability aspects of nanomaterials and make sure we’re always keeping in mind strength, performance and durability of concrete.”*
- *“A pilot study to investigate the real field condition effects.”*

#### Long Term

- *“Integrate nanomaterials in real life designs which could eventually lead to standardization of certain concrete structures.”*

### **11.2.3.2 Research Pathways**

#### Short term

Most research on the use of nanomaterials in concrete has proceeded from perspective of materials development, where a nanomaterial is identified as potentially being usable in concrete and a program of research is then developed to determine how to disperse it and to measure the resulting performance. This is essentially a “technology push” approach, where a new technology is developed and then attempts to find a market. The recommendations from the workshop attendees suggest that a “technology pull” approach that focuses on the potential benefits of a nanomaterial or a class of nanomaterials as a starting point and then choosing the best options for further development.

---

While the five application categories outlined in the introduction to this chapter can provide a starting point for a classification system based on performance benefits, the initial step should be to review the existing literature on the use of nanomaterials in concrete and develop a framework for classifying the materials with correlations to expected benefits. This framework could then be used to identify the most promising approaches for subsequent work.

#### Medium term

The most promising nanomaterials should be targeted for testing in concrete to validate the results of the framework analysis. Initial work will need to be laboratory focused and should be carried out in a single location to allow direct comparison between results from different nanomaterials. If the results from one or more nanomaterials show promise for real world applications, one or more additional laboratories should validate those results and small scale field trials should be undertaken. Carrying out the field trials will require developing guidance on how to work with the nanomaterials, including safety procedures, mixing processes and clean-up. It is possible that the latter issues will be sufficiently complex or expensive to make the use of a particular nanomaterial impractical outside the laboratory. Problems of this nature should be identified before full scale demonstration projects or trials take place. Long term durability studies should also be initiated in this time period.

#### Long term

Results from laboratory testing and field trials should be used to support demonstration projects and develop design guidance. However, before demonstration projects are initiated, results from the emissions benefits study, work on safety of use (see below), and a cost/benefit analysis should be carried out to ensure that investment in the nanomaterials are justified. If the demonstration projects are successful, technical guidance for working with nanomaterials on the construction site and/or precast plants should be developed.

### **11.2.4 Safety of use**

*“Can we safely use nanomaterials in the production, delivery, construction and end of life phases? What are the health and safety considerations? How do we evaluate nanomaterials and keep in mind the performance characteristics of concrete as well as safety considerations?”*

Because of their small size, nanomaterials are likely to require special handling during construction. The use of Portland cement and other fine powders in the cement and concrete industry means trained workers are already well aware of the risks associated with handling those materials and the needed precautions. However, the specific approaches needed for dealing with nanomaterials may vary, depending on their size,

---

their aspect ratio, and their chemical reactivity. Special precautions may also be needed for managing concrete wash water and cleaning the interior of concrete trucks and mixers to avoid release of nanoparticles to the surrounding environment and/or inadvertently adding them to the next concrete batch made using the same equipment. Those precautions may need to vary depending on issues such as nanoparticle persistence in the environment and whether the nanoparticles in question may be present already in concrete. One possibility is that nanomaterials may only be suitable for use in a precast concrete plant, where environmental controls would be easier to maintain than in cast in place concrete. Research will be needed to assess the risks associated with using nanomaterials of different types in production, including possible methods of mitigating those risks.

Similar issues would also apply during the use and demolition of structures made with concrete/nanomaterial composites if the nanomaterials are not consumed in the hydration reactions. Demolition of these structures may release nanoparticles into the environment, while concrete made with nanomaterials may also be difficult or impossible to recycle. Concrete wearing surfaces, such as bridge decks or road surfaces, might also release nanoparticles during normal operations. These risks and potential mitigation measures should be investigated before attempts are made to use nanomaterials in concrete in the field.

#### **11.2.4.1 Activities Recommended by Workshop Participants**

No activities for this topic were identified during the workshop sessions.

#### **11.2.4.2 Research Pathways**

##### Short term

Experts on nanomaterial emissions, health impacts and environmental impacts should be enlisted to review the way in which nanomaterials would be used in a construction setting. This work would need to be done in collaboration with concrete professionals and should identify potential risk points and how those risks could be mitigated. Once that work is done, the costs associated with those mitigations should be assessed to help in understanding cost/benefit ratios for decision making on nanomaterial deployment. Guidance on appropriate precautions for testing procedures should also be developed at this time.

##### Medium term

Samples produced for laboratory studies on the performance benefits of nanomaterials in concrete should be destroyed to investigate how much nanomaterials would be emitted during demolition of a structure that contains them. The type of investigation required would likely depend on the type of nanomaterial being assessed. In some cases (e.g. nanosilica) the question may be to what extent the nanomaterial has reacted during hydration and whether any of it remains. In others such as carbon nanotubes,

---

the question may be to what extent the nanomaterials detach from the cementitious matrix and at what stage in the demolition process. These results should be reviewed in the context of the initial study.

#### Long term

Release of nanoparticles should be tracked during any demonstration projects to validate the medium term laboratory work. The results should again be reviewed in light of the initial study.

### **11.2.5 Supply**

*“Will there be a scaling or sourcing issue for the nanoparticles when moving to production?”*

Potential sources for nanomaterials vary widely. In general, however, they require specialized production facilities and are not available on the same scale as cement or concrete. They are also significantly more expensive, although this cost per kg of nanomaterial may be offset by a relatively low volume needed to produce beneficial effects. (It should be noted, however, that the lowest cost forms of a particular type of nanoparticle are likely both much more expensive per kilogram than cement and likely have less purity than more expensive versions, with the impurities potentially creating issues with their use in concrete). Understanding the economics, sourcing and ability to produce sufficient quantities of nanomaterials for regular use in concrete is therefore key to determining if this technology is scalable from the laboratory to commercial use.

#### **11.2.5.1 Activities Recommended by Workshop Participants**

No activities for this topic were identified during the workshop sessions.

#### **11.2.5.2 Research Pathways**

##### Short term

Cost and likely supply of nanomaterials should be part of the assessment framework described in the section on “Performance benefits of nanomaterials in concrete” earlier in this chapter. This information should be reviewed at each decision point in an overall “nanomaterials in concrete” development program to ensure that effort is focused on materials with a viable cost/benefit ratio.

---

# 12 Biomaterials

## 12.1 Introduction

The term biomaterials describe any material that has been produced from a biological source, such as animals, plants, or bacteria. In the case of the construction industry, lumber and related products such as oriented strand board (OSB) are by far the most familiar examples of biomaterials. There is, however, a considerable history of using biomaterials in cement and concrete. The most successful example is the use of cellulose fiber in cement / mortar products, which is used to produce siding materials, wall panels, and roofing, amongst other applications. This technology was introduced in 1980s in Australia and is now available worldwide.

Beyond fiber-cement boards, a wide variety of biomaterial usage has been proposed, ranging from the use of seashells as a raw material for cement production, through the use of bacteria to promote the self-healing of concrete cracks, to the addition of various types of biofibers (flax, hemp, etc.) to concrete as reinforcements that could replace steel or polymers. Rice husk ash has been used as a source for silica to replace silica fume, while in some cases cement has been used as a binder to hold together blocks primarily made of biofibers. Past research on concrete-biomaterial composites has, however, often involved adding a proposed local biomaterial to a concrete mix and observing the resulting change on fresh concrete properties and strength development. Longer term durability tests are not as common, nor are investigations to examine differences between biomaterials or the root causes of performance changes. Finally, the overall carbon reduction impact of using biomaterials in concrete needs further investigation to support decisions on where and when these materials should be used.

## 12.2 Knowledge Gaps

### 12.2.1 Improved understanding of biomaterials in concrete

*“A better understanding is required of what types of biomaterials are being tested in concrete. This is a very nascent area without a lot of industry or academic experience in Canada. We need to identify what role different biomaterials can play in concrete.”*

*A better understanding of biomineralization to develop self-healing concretes and bricks. This is complex resulting in high final costs while performance and durability are yet to be proven. (Raised during Alternative Binder session)*

While biomaterials are not commonly used, workshop participants appeared to have a better understanding of their potential and risks compared to those of nanomaterials.

---

Applications such as cement fiber board, lignosulfonate admixtures and hempcrete point to the potential of using biomaterials in concrete, costs appear to be lower than nanomaterials and, with the exception of the use of bacteria in concrete, health risks are better understood. Various trials of different biomaterials in concrete have also been carried out in Canada and elsewhere. As a result, the knowledge gaps identified in the workshop sessions focused less on improving fundamental knowledge and more on understanding the potential for commercial applications. An exception to the above is in the area of biomineralization of damaged concrete. This application is newer, requires knowledge of microbiology and the ability to manage biowaste. The work outlined for this knowledge gap addresses both areas of need.

### **12.2.1.1 Activities Recommended by Workshop Participants**

#### Short Term

- *“Basic ‘State of Play’ around what R&D, technology and pilots that use biomaterials to reduce the embodied carbon of concrete are already out there being discussed, proposed and tested.”*

#### Medium Term

- *“Given the ‘State of Play,’ an assessment of whether the technologies identified have any potential to scale or have any potential significant contribution to the decarbonization roadmap. ‘Is the juice worth the squeeze?’”*
- *“Research to determine if biomineralization is feasible for Canadian environment considering the freeze-thaw cycles.”*
- *“Appropriate facilities to treat potentially dangerous waste.”*

### **12.2.1.2 Research Pathways**

#### Short term

Building on the recommendations in the workshop session, a combined literature review and analysis of the current state of biomaterial use in concrete in Canada and globally should be undertaken. A guidance document for practitioners should be one of the outputs of the review, but it may also identify needs for further research activities. The review process should also examine work on biomineralization and consider whether it has the potential for large scale deployment in Canada.

#### Medium term

The information from the literature review and state of the art analysis should be combined with data on material supply, LCA results and cost information to provide a TEA that will give guidance on which biomaterial applications are worth pursuing. Depending on the applications chosen, additional R&D may be needed to fully develop them. This work may be fairly fundamental in nature (e.g., biomineralization) or may be

---

more focused on supporting deployment of biomaterials in specific applications (e.g. field trials using biofiber reinforced concrete).

### Long term

Larger scale demonstration projects should be undertaken and the results used to update guidance documents. In the case of biomineralization, field trials, including the use of damaged concrete specimens, would need to be undertaken before any demonstration projects. Using biomineralization in the field would also require developing a full set of guidance documents and potentially facilities for biowaste disposal.

## **12.2.2 Potential GHG benefits of using biomaterials**

*“Develop a common, multi-view way to assess true carbon embedded considering different times, geographies and geometry. This would be done to allow those who spec to be able to make wise decisions when comparing apples to oranges.*

*“A better understanding is required of the potential benefits of biomaterials in concrete. Is there a lifecycle carbon benefit?”*

Biomaterials offer an additional possibility for GHG reductions in concrete beyond most other additives in that they potentially offer an opportunity for carbon sequestration when used. The exact benefits will, however, depend on the emissions from producing the biomaterial, how those emissions are allocated (i.e. is the biomaterial a primary product, a co-product or a by-product), and how much emissions are produced in preparing the biomaterial for using in concrete. As an example, rice husk ash has been used as a pozzolan in concrete. The rice husks themselves are a by-product of food production. If, however, they have a significant economic value, they might instead be considered to be a co-product and have some of the emissions related to the rice production allocated to them. If the normal process for disposing of the rice husks is burning, then the ash may again be treated as a by-product. However, if the husks are specifically burnt to produce ash for use in concrete, the ash would be assigned the resulting emissions.

In addition, if the biomaterial degrades over time, determining GWP reductions in the concrete from using biomaterials become more complex as the release of CO<sub>2</sub> or other GHGs over time would need to be considered. The potential for degradation and the related emissions may vary not only between materials, but also with processing methods, biomaterial size, and volume of replacement of concrete. As a result, standardized protocols for determining GHG benefits of biomaterials in concrete will need to be researched and developed.

---

### 12.2.2.1 Activities Recommended by Workshop Participants

#### Medium term

- *“If promising biomaterial applications are identified, the usual R&D to support carbon accounting validation including testing regimes, codes and standards acceptance, market acceptance etc. would be required.”*

#### Long term

- *“Find a way to measure the real-world CO<sub>2</sub> sequestering and other carbon performance of biomaterials materials, and other building materials. Actually, do experiments to validate.”*

### 12.2.2.2 Research Pathways

#### Short term

LCA principles should be followed in determining the emissions benefits of incorporating biomaterials in concrete. Once potential biomaterials have been identified, the available Life Cycle Inventory (LCI) data for those materials should be collated so that gaps and quality issues with the data can be determined. Additional work would be required to fill those gaps, which may require data collection from biomaterial producers or, in some cases, identification of the type of data that needs to be collected and how to collect it.

#### Medium term

Collected LCI data should be incorporated in LCA tools so that comparisons can be made between different materials. If necessary, research should be carried out on the decomposition of biomaterials in concrete to account for long-term sequestration effects. Biomaterials used in concrete should be included in the development of methods to measure the CO<sub>2</sub> sequestered in concrete (Chapter 15).

#### Long term

If biomaterials exhibit significant degradation over time in concrete but are otherwise beneficial, research should be carried out on lifetime extension. This work would rely on the development of appropriate test methods, as discussed immediately below.

### 12.2.3 Testing protocols for concrete containing biomaterials

*“Create a standard way to assess performance of 'concrete' that includes biomaterials based on short term performance, long term durability and performance including real world validation.”*

As described in the introduction to this chapter, knowledge of the long term performance of biomaterials in concrete is essential for determining how broadly they can be used and extent of the GHG reductions they can produce. As with other potential concrete deterioration mechanisms, test methods will need to be developed to assess short and

---

long term durability of concrete containing biomaterials in order to support standardization and market acceptance.

Beyond standard concrete test methods, the susceptibility of these materials to damage from the alkaline environment of the concrete is often raised as a concern in regards to the use of some classes of biomaterials in concrete. While materials such as rice husk ash are unlikely to be affected, the effectiveness of fiber reinforcement and similar applications might decrease over time due to fiber degradation. The long term success of fiber-cement board argues against the concern being broadly applicable, but there is little work in the literature on the impact of cement alkalinity on different biomaterials or test methods to assess it. It is also possible that it is the degree of exposure to the environment outside concrete will affect whether this type of composite is durable or not. Swelling and shrinking of fibers with changing relative humidity levels in the environment, along with potential attack by biological degradation mechanisms such as moulds and bacteria may be dependent of the degree and type of cover provided by the cement or concrete matrix around the biomaterials. New test methods will therefore be needed to assess the durability of the biomaterials themselves.

### **12.2.3.1 Activities Recommended by Workshop Participants**

#### Short term

- *Set up standard committees and working group.*

#### Medium term

- *Create standards with committees set up to avoid silos in the industry. Do research and development work to model long term performance of novel concrete-based materials, and make sure the results are validated.*

### **12.2.3.2 Research Pathways**

#### Short term

The Canadian concrete standard (CSA A23.1/.2) references a variety of materials standards (cement, reinforcing materials, etc.) while retaining the testing requirements for the concrete itself. Standardizing the use of biomaterials in concrete would therefore require both the creation of specialized technical subcommittee within the CSA A23.1/.2 technical committee, but also the creation of one or more technical committees related to standardizing the biomaterials. While preliminary work could start in the short term, identification of which biomaterials should be pursued, as described earlier in this chapter, is essential for full committee development to get underway.

The other essential preliminary activity is to develop preliminary tests to evaluate the long-term durability and performance of biomaterials used in concrete and to develop preliminary data on whether new or modified concrete tests would be needed to assess the performance of the concrete itself. It is possible that the need for concrete tests

---

could be assessed through a literature review, but the biomaterial tests would require potentially extensive laboratory work. A full review of testing requirements, giving recommendations for test development and background work, should be carried out in the short term. Preliminary laboratory work on biomaterial durability and concrete compatibility could be initiated where potential materials have been identified.

#### Medium term

The CSA A23.1/2 technical committee should consider the information gathered in the short term activities described in this Chapter and decide whether to pursue standardization of the use of classes of biomaterials in concrete. If the standardization process moves forward, materials standardization will also need to be initiated, either within existing standards committees for the biomaterials or in one or more new committees.

A full scale development program would need to be initiated for developing standard test methods, building on the preliminary work described above. Further test development may be needed and any proposed tests would need to be trialled by interlaboratory studies. Some work is likely to involve accelerated aging methods, which would need to be identified and validated. The aging methods themselves may require a year or more for test completion, extending the duration of the test development.

#### Long term

Existing standards would need to be updated and new standards published to complete the process. Long term durability testing is likely to be needed to update the standard test methods in the future.

### **12.2.4 Supply**

*“A way to assess sourcing requirements for bio materials at full commercial volumes.”*

*“Is there a lifecycle carbon benefit? If so, is it applicable at scale?”*

As with other materials for use in concrete, the size and consistency of the long-term supply is an important factor in determining whether developing a biomaterial for use in concrete is worth pursuing. Materials that are widely available in a consistent form are more likely to warrant development than those that are more niche in nature. Processing and transportation costs are also significant factors that may affect the viability of a particular material. While some potential choices of biomaterial sources are more obvious than others (e.g., wood, wheat, and flax are widely produced in Canada), information is still needed on minimum source sizes and regional variability. This information will help to support decisions on which types of biomaterials should be prioritized for development.

---

### 12.2.4.1 Activities Recommended by Workshop Participants

#### Short term

- *“Develop a biomass assessment across Canada by population, biomass potential and location. Full assessment in much more depth than those available today including type, ash content, oily, etc.”*
- *“Identify the bio material source hub location for processing plant location, logistics and costs.”*

### 12.2.4.2 Research Pathways

#### Short term

A spatial mapping of potential biomaterials should be carried out. Amongst other topics, the analysis should consider the way in which the biomaterials would be used, potential levels of use in concrete, the likely market, supply size, trends in production and other related areas. Gaps in available data should be identified and filled during the research activity. Decisions related to further work on biomaterial development should ensure that supply volumes can either meet or easily grow to meet anticipated demand level.

#### Medium term

Processing requirements for biomaterials should be identified based on requirements developed in other activities in this Chapter. Location for plants should be identified based on economic and environmental factors to minimize overall costs and emissions. Processing technology should be scaled up simultaneously with other developments to allow field trials and demonstration projects to take place.

## 13 Natural Carbonation

### 13.1 Introduction

The process of carbonation describes the addition of carbon dioxide to a material. In the case of OPC, that addition is permanent and occurs due to chemical reactions between the CO<sub>2</sub> and the OPC constituents. In unhydrated Portland cement, tricalcium silicate (3CaO·SiO<sub>2</sub> or C<sub>3</sub>S) and tricalcium aluminate (3CaO·Al<sub>2</sub>O<sub>3</sub> or C<sub>3</sub>A) may both become carbonated in the presence of water vapour, producing different forms of calcium carbonate. Carbonation of unhydrated OPC and PLC is undesirable and prevented by minimizing exposure to atmospheric CO<sub>2</sub>.

Most Portland cement carbonation occurs, however, in hydrated cements in concrete. Long-term exposure to atmospheric CO<sub>2</sub> will cause the calcium hydroxide to react to form calcium carbonate, typically in the form of calcite. Minor phases such as ettringite will also react with atmospheric CO<sub>2</sub>. It is possible, but less common, for the calcium-silicate-hydrate (C-S-H) in the hydrated cement to also undergo some carbonation.

---

Natural carbonation in concrete has been described as having a “front” that gradually penetrates deeper into the concrete material. Historically, it has generally been considered as potential source of concrete deterioration, as the carbonation reaction may speed the corrosion of reinforcing steel once the carbonation front reaches that depth. Reinforced concrete elements are designed with sufficient concrete cover to prevent this problem.

More recently, the idea of concrete sequestering (permanently storing) CO<sub>2</sub> has become more prominent as a part of a tool set to reduce greenhouse gas (GHG) emissions in the concrete industry. Research suggests that between 16-24% of the total GHG emissions from producing concrete may be subsequently be removed from the atmosphere by in-service carbonation processes, although further validation of this result is necessary.

While various approaches have been proposed to accelerate the carbonation process in the concrete, natural carbonation remains important for understanding the true carbon footprint of the cement and concrete industry. It is, for example, included as a factor in LCA standards relating to the construction industry. The extent of natural carbonation in Canada is not, however, well understood, creating knowledge gaps that will be addressed in the rest of this chapter.

## 13.2 Knowledge Gaps

### 13.2.1 Quantification of carbonation of concrete structures

*“Quantify the rate and amount of the reaction in concrete parts in-situ given the environmental variables that might affect it.”*

*“Determine the effect of Supplementary Cementitious Materials on other knowledge gaps.”*

*“Need for consensus on measurement approaches to quantify natural carbonation.”*

Accurate measurements of natural carbonation in concrete are needed in order to include it in LCA calculations and to fully understand the cement and concrete industry’s carbon footprint. While information on carbonation rates in the laboratory and from individual field assessments is available, a broader range of Canadian data on rates of natural carbonation is required. If possible, this data should be made available on a regional basis in order to assess the impact of different environmental conditions and industrial activity on carbonation rates. Finally, the information on natural carbonation rates also needs to be correlated with expected lifetimes of concrete structures, allowing the total CO<sub>2</sub> that will be sequestered in those structures to be determined.

---

Part of this work will need to focus on the impact of SCMs and ASCMs on the carbonation process. Most SCMs and ASCMs react with the calcium hydroxide in hydrating or hydrated Portland cement to form C-S-H. In some cases, other reaction products are also formed. As CO<sub>2</sub> also reacts with calcium hydroxide to form calcium carbonate, the two processes compete for the same reactant. In the case of natural carbonation, the SCM/ASCM reactions with calcium carbonate will proceed more rapidly than the carbonation processes. The SCMs/ASCMs are already present in the concrete at the time of hydration and time frame for the bulk of their reactions is much quicker than the multi-year process of natural carbonation. At the same time, use of these materials often reduces the porosity of the concrete, which would be expected to slow the penetration of the CO<sub>2</sub> into the material. Understanding the effects of the use of SCMs/ASCMs on natural carbonation is therefore important to accurately quantifying the carbon footprint of this type of concrete.

### **13.2.1.1 Activities Recommended by Workshop Participants**

#### Short term

- *“Conduct literary research, begin modeling through lab experimentation and identify or form an oversight committee to begin getting a structure in place for eventual standards.”*
- *“Laboratory pre-work. Developing in-situ testing methods, developing a method for predicting the behaviour of the concrete in regards to carbonation.”*

#### Medium term

- *“Need to develop design models that balance durability goals with carbon sequestration potential as well as field tests.”*
- *“Perform field experiments, validate theoretical models and do analysis on existing structures”*

#### Long term

- *“Creation of standards for re-carbonation, concrete performance, mixes, etc.”*

### **13.2.1.2 Research Pathways**

#### Short term

While the workshop sessions called for the development of standards related to natural carbonation, it is not clear how they would be used in regular concrete practice. The extent of natural carbonation needs to be assessed from work on existing buildings and/or samples extracted from long-term exposure sites. Standard methods are needed to assess carbonation in general, a topic that is discussed in Chapter 15 in detail. Some or all of the same methods should be usable on naturally carbonated samples.

---

Instead, rates of natural carbonation need to be established for different Canadian cities, which would likely require an extensive testing program of concrete cores extracted from buildings with known construction dates. Enough different cores would need to be taken from each location to provide data to correlate with known changes in CO<sub>2</sub> levels over time and to project carbonation rates into the future. It would be expected that higher CO<sub>2</sub> levels in the atmosphere would lead to greater rates of concrete carbonation, but work would be needed to determine the relationship between the two and whether there are eventual limits to the correlation. Changes in humidity may also affect carbonation rates.

A literature review that focuses on natural carbonation rates, limits and test methods would be the first step for this work. A summary document for practitioners should be produced based on the short term work described here and in other sections of this chapter. It should be updated as more information becomes available.

#### Medium term

An appropriate sampling method for testing concrete samples for natural carbonation should be developed. Once validated, sufficient samples should be acquired from one location in Canada to allow the extent of natural carbonation to be correlated with the age of concrete. At the same time, laboratory studies should be carried out using accelerated aging methods to determine the effects of higher CO<sub>2</sub> levels and changes in environmental conditions on the rate of carbonation. Specific mixes designs, including varying amounts of SCMs, w/c ratios and air content values would need to be considered in the laboratory testing.

#### Long term

Samples should be collected from other major centres in Canada to determine if the rate of carbonation is the same in all locations. Any other conditions that would affect carbonation would also need to be determined. A predictive model could then be developed to estimate the amount of carbonation a concrete structure would be expected to experience over time, allowing for the accurate incorporation of natural carbonation into an LCA framework.

### **13.2.2 Effect of carbonation on long term performance**

*“Determine the effect of carbonation on concrete part performance – strength, durability, cracking, etc.”*

*“Knowledge on potential side effects of natural carbonation. If there are side effects, are they permanent or temporary? Short term or long term?”*

As noted in the introduction to this chapter of the report, carbonation of concrete materials can create durability issues due to corrosion of reinforcing steel. It is not as

---

clear as to whether carbonation can have other effects, either positive or negative, on other aspects of the long-term performance of concrete. Older examples of naturally carbonated concrete could potentially provide useful baselines for expected long-term performance of concrete materials that have been subjected to accelerated carbonation as the two processes may not produce the same results. More research is needed to explore whether using accelerated carbonation to age samples is a valid approach, as well as on the best methods to assess the naturally carbonated concrete to obtain the desired information.

### **13.2.2.1 Activities Recommended by Workshop Participants**

#### Long term

- *“Look at long term durability of carbonated concrete by comparing lab data to actual field results. Use low-risk environments for pilot projects with a purpose such as residential concrete.”*

### **13.2.2.2 Research Pathways**

#### Short term

A literature review on the impact of carbonation should be carried out, potentially in conjunction with the one outlined above on carbonation rates. Part of the goal for the literature review would be to summarize the available information on the effects of carbonation on the corrosion of rebar, but it should also focus on whether there is any evidence for other damage from natural carbonation. A summary document suitable for practitioners should be compiled from the results of the review.

#### Medium term

If possible, sufficient cores should be taken during the research program outlined in the section above to allow forensic investigation of the concrete. An appropriate series of tests would need to be developed to determine if there are significant performance results from carbonation. Key restrictions in developing the test protocols would include issues such as the presence of reinforcing steel in the concrete cores and the need to compare the carbonated outside of a sample to the uncarbonated inside, rather than to samples from other buildings. These results would help to provide direction to the work outlined in Chapter 14 and should be included in an updated version of the summary document for practitioners on natural carbonation.

### **13.2.3 Quantification of carbonation of crushed concrete**

*“Quantify the rate and amount of the reaction in concrete parts after crushed given the variables that might affect it.”*

Concrete from demolished structures is typically crushed and then used for fill or is land-filled. In some cases, it may also be reprocessed for use as recycled concrete

---

aggregate. In the latter instance, much of the hydrated cement paste will be removed from the crushed aggregate during processing. This fine material is typically not re-used, although new technology may offer a route to reprocess fine recycled aggregate as well.

Crushing concrete increases the exposed surface area of the material, which would be expected to significantly increase the rate of carbonation of the material. The fines from the crushed aggregate would be expected to have an even higher carbonation rate. At the same time, crushed material that is buried in landfills or in construction applications would be expected to have reduced exposure to atmospheric CO<sub>2</sub>, reducing its uptake in the material. Further research is needed to understand the extent of carbonation of crushed aggregate and, potentially, optimize its handling to maximize the amount of CO<sub>2</sub> it sequesters.

### **13.2.3.1 Activities Recommended by Workshop Participants**

#### Medium term

- *“Perform field experiments, validate theoretical models and do archaeologic analysis on existing structures. Conducting the archaeology based on existing materials would be more difficult, since waste concrete is gotten rid of right away for economic reasons. One potential source may be municipalities who might be convinced to keep demolished concrete around for the long periods necessary for this work.”*

### **13.2.3.2 Research Pathways**

The exact approach to investigating crushed concrete is likely to depend on the fineness of the material and its degree of exposure to CO<sub>2</sub> emissions and moisture. Unless they are reused in cement production or the manufacture of artificial aggregates, recycled concrete fines are likely to be landfilled after separation from the coarse aggregate. In this case carbonation will take place during the separation process and may take place after landfilling. Coarse aggregate that is not recycled will either be landfilled or used in the construction of roads. In either case it will be buried, but the degree of exposure to air after burial is likely to be different due to how easy it is for air to penetrate to the crushed concrete.

#### Short term

Samples of concrete should be prepared and their CO<sub>2</sub> content analyzed. They should then be crushed, with some sample material having the concrete fines separated from the coarse aggregate. Some of the crushed sample material should be buried, using simulated landfill conditions for the fines and part of the crushed concrete and simulated road base conditions for additional crushed concrete. The remainder of the crushed sample material should be exposed to atmospheric carbonation conditions to provide a baseline for carbonation. Building on the other work described in this chapter,

---

accelerated carbonation could also be used to determine how the crushed concrete will respond to changes in environmental conditions in the future.

### Medium to long term

Sample material should be periodically recovered to monitor carbonation levels. In principle, the same process could be carried out using crushed concrete that has been used in road construction, provided that samples of the original material are available at the time of construction to establish a baseline. However, extracting the crushed concrete samples in such a way as to obtain valid data and not damage the road would be challenging.

## **14 Long term performance of concrete containing sequestered carbon dioxide**

### **14.1 Introduction**

Knowledge of the process of natural carbonation of concrete has led to a number of different approaches to accelerate carbonation in the material, providing opportunities to sequester (permanently store) carbon dioxide. Some current approaches include:

- Exposing the hydrating cement in concrete to CO<sub>2</sub>;
- Exposing precast concrete to CO<sub>2</sub> from flue gases or other sources before installation;
- Carbonating the fine hydrated cement from recycled concrete; and
- Replacing the hydration process entirely by carbonation, again in precast concrete.

In addition, another approach to sequestering carbon in concrete is to use carbon dioxide from an atmospheric or other source to produce solid carbon nanoparticles, which then can be included in concrete as a form of permanent storage.

All of the approaches mentioned above have commercial proponents and are in different stages of commercial development. All of them also alter the composition of the concrete or create a different form of concrete entirely. As a result, independent information is lacking on the effects of these approaches on the long term performance of concrete. Given that concrete products are expected to have life times measured in decades, filling this information gap and providing tests to assess the performance of concrete that includes sequestered carbon is a key step for broad acceptance of the technologies.

---

## 14.2 Knowledge Gaps

### 14.2.1 New standardized tests for long term performance assessment

*“Additional need for CSA A23.2 tests. Are there any characteristics of the wet or hardened concrete made with sequestered carbon that should be tested beyond what is currently specified by CSA A23.2?”*

*“Knowledge on the use of shorter term testing to evaluate long term performance to prevent waiting decades on test results.”*

The performance of concrete is typically assessed using a variety of standardized test methods that have been adopted through an appropriate standards body. It is not clear, however, whether all of the existing tests can be applied to products containing sequestered carbon. In general, physical tests (compressive strength, flexural strength, etc.) would be expected to be applicable to any concrete material. It is, however, possible that the test procedures such as rate of loading would need to be adjusted. Degradation mechanisms are, however, more material dependent. As mentioned in Chapter 13, work is needed to determine whether existing long term performance tests can be successfully applied to concrete made with sequestered carbon and whether new tests need to be developed. This requirement is separate from that covered in Chapter 15, which focuses on tests to assess the extent of carbonization in concrete.

#### 14.2.1.1 Activities Recommended by Workshop Participants

##### Short Term

- *“Standardized test methods to characterize plastic and hardened concrete performance with sequestered CO<sub>2</sub>. There is a need to evaluate the existing test methods in order to validate the applicability of these tests to concrete with sequestered CO<sub>2</sub>.”*

#### 14.2.1.2 Research Pathways

##### Short Term

A technical subcommittee of CSA A23.1/2 should be convened to examine existing test methods and to determine if they could be affected by sequestering carbon in concrete. In addition to CSA A23.1/2 members, the subcommittee should include representatives of suppliers of carbonation technology and other experts not ordinarily on the CSA technical committee. One factor in making this evaluation would be whether the test measures an inherent concrete property or is related to how the concrete interacts in the construction process. As an example of the first case, it might be found that a different rate of loading in compression or flexural testing is needed for carbonated

---

concrete, which would be an acceptable change if properly documented. However, slump rates are tied to the workability of the concrete. In that case, the mix design would need to be changed to produce an acceptable slump, rather than the test being changed. In the case of technologies where the binding mechanism of the concrete is mostly or solely CO<sub>2</sub>, the subcommittee should indicate what existing tests can still be applied to the concrete and where new tests or modifications are needed.

Although the review is needed, it is likely that little modification to tests for mechanical properties or constructability will result. The situation with long term durability and performance testing is less clear. Carbonation may make concrete more or less vulnerable to common deterioration mechanisms. Laboratory and field work to explore this possibility is discussed in the next section of this chapter. It is also possible that carbonation will create new durability issues that will need to be identified and have tests developed. This issue is also discussed below.

#### Medium Term

Each test method in question will need to be examined by one or more laboratories to determine if it is still valid. In order to carry out this work, the technical subcommittee will need to develop criteria that indicate the test is no longer appropriate or needs modification. If a key property of the carbonated concrete is not being measured, a program to develop a test method and validate it will be needed.

#### Long Term

Some concrete test methods may require longer term evaluation to establish their suitability for use.

### **14.2.2 Long term performance, including field trials**

*“Long term performance research field trials and exposure sites.”*

*“Comparative long-term performance with different carbonation methods such as natural carbonation, captured in aggregate, captured in SCM and injection in wet concrete mix.”*

Although carbonation is a natural process, commercial methods of sequestering CO<sub>2</sub> in concrete greatly accelerate its pace. As a result, the extent to which the existing body of knowledge on long-term performance of concrete can be applied to carbonated concrete is not clear and may vary from product to product. Laboratory and field work is needed to understand the degradation mechanisms in these new materials and determine to what degree, if any, they differ from those of traditional concrete materials.

Since natural carbonation is known to accelerate the corrosion of reinforcing steel, a key issue to be resolved is whether sequestering CO<sub>2</sub> in concrete will affect any reinforcements that may be present. Some sequestration methods carbonate the

---

concrete before casting, making it unlikely that there will be a corrosion impact afterwards. Other methods carbonate cast concrete and corrosion may be more of a concern. In addition, natural carbonation may still occur in artificially carbonated concrete. If the initial artificial carbonation blocks pores in the concrete, it may tend to slow the progression of the carbonation front, extending the time until it reaches the reinforcement. If, however, the artificial carbonation moves the carbonation front into the concrete without blocking pores, it will likely reduce the time until the reinforcement starts to corrode. More investigation is also needed to understand how the combination of natural and artificial carbonation will affect long term performance.

### **14.2.2.1 Activities Recommended by Workshop Participants**

#### Medium Term

- *“Characterization of performance in order to distinguish between the laboratory-developed concrete with sequestered CO<sub>2</sub> and field-produced concrete. The results of the comparative studies would affect the design methods, applications, QC procedures, and standard considerations. Strategic planning might be affected by the findings of this study once the various aspects of different carbonation technics are evaluated.”*

#### Long Term

- *“Field trials and exposure sites. Long term effects of carbonation on pH of concrete and potential for corrosion of reinforcement. How can we reduce or avoid carbonation’s detrimental effects to steel reinforcement or prestressed strands within concrete?”*

### **14.2.2.2 Research Pathways**

#### Short Term

Existing work on the artificial carbonation of concrete should be reviewed and gaps in long term performance data identified. Different carbonation mechanisms and timing should be considered as part of the review, as well as potential impacts of under- or over-carbonating the system. As an example, too much exposure to CO<sub>2</sub> in the early stages of hydration can cause carbonates to form on the hydrating cement grains, slowing or preventing strength development. Conversely, too little exposure to CO<sub>2</sub> when the gas is the binding agent will also have a negative effect on strength of the final concrete product. The review should also consider whether the available data has been peer-reviewed and whether it is based solely on laboratory testing or includes the results of field trials. Major concrete deterioration mechanisms (sulphate attack, alkali-aggregate reactivity, thaumasite formation, carbonation, etc.) should be considered and the potential pathways for changes in behaviour in those mechanisms mapped out.

#### Medium term

---

Comparative studies between uncarbonated control samples and carbonated experimental samples should take place to explore the effect of carbonation on long term performance, with a focus on behaviour under adverse environmental conditions. While most of the work may involve laboratory testing, exposing concrete to adverse conditions in the field will be needed to demonstrate the comparability of the two approaches. Multiple exposure sites may be needed to cover off particular environmental conditions. Existing projects where carbonation has been used should be assessed for any evidence of environmental damage, while new projects could be instrumented to gather in-situ data.

#### Long term

Data gathering from field trials and environmental exposure site(s) should continue in the long term, with the results being distributed through research publications and technical documentation for practitioners. As additional sequestration methods are developed, the research program should be extended to incorporate them.

### **14.2.3 Effect of different CO<sub>2</sub> sources on sequestration and concrete performance**

*“Considerations should include the amount of CO<sub>2</sub> sequestration that can be used, **the purity of CO<sub>2</sub> ...**”*

*“CO<sub>2</sub> is currently being sourced from food-grade CO<sub>2</sub>, is this required? Could we use a lesser quality?”*

Note: This topic was raised in the workshop sessions on Guidance on Sequestration Use and Sequestration in high volume SCMs, but appears here as it requires experimental work before any guidance can be issued.

The exhausts of industrial sources of CO<sub>2</sub> would generally be expected to also include other chemicals, often in the form of sulfur and nitrogen oxides (SO<sub>x</sub> and NO<sub>x</sub> respectively). These contaminants are typically monitored to ensure they do not exceed acceptable levels in the environment. The exhaust from a source may also be processed (“scrubbed”) to remove some or all of them.

While it is possible to use high purity (“food grade”) CO<sub>2</sub> in sequestration processes, it would be beneficial economically to be able to use industrial sources, such as cement kiln emissions, directly. It may also be an added environmental benefit due to reduced release of contaminants to the atmosphere and reduced levels of energy compared to those used to produce higher purity CO<sub>2</sub>. Research is, however, needed to determine if and at what level the contaminants would damage the performance of the concrete. Both sulfates and nitrates are known to cause damage to concrete through chemical reactions with aqueous ions. It is possible that similar damage would be caused by the same classes of compounds in airborne form. The effects of other contaminants are

---

less studied, but work is still needed to determine if they may be harmful to the concrete.

### **14.2.3.1 Activities Recommended by Workshop Participants**

No activities on this topic were identified during the workshop session.

### **14.2.3.2 Research Pathways**

#### Short term

Emissions data for large industrial emitters is reported to Environment and Climate Change Canada on an annual basis. An initial starting point to fill this knowledge gap would be to determine profiles for typical industrial emissions and develop an approach to simulate them in the laboratory. This approach is likely to require specialized laboratory facilities to ensure safe and environmentally sound handling of the pollutants. The contaminants found in most industrial emissions are the same as those typically found in air pollution. The literature on damage to concrete from air pollution should be therefore be reviewed and, if possible, concrete samples exposed to high levels of air pollution should be collected for analysis. It should be noted, however, that long-term atmospheric exposure to low levels of contaminants may not produce the same results as short term exposure to higher levels of contaminants in a carbonation facility, making the medium and long term research outlined below necessary.

#### Medium term

Accelerated aging experiments should be carried out under different environmental conditions to determine whether the contaminants could cause short or long term damage to the concrete. As a baseline, exposures should simulate expected conditions during carbonation processes, which may vary depending on the method used. Variations in temperature, humidity and/or contaminant content may then be employed as part of the accelerated aging process. While exposure to CO<sub>2</sub> plus a single contaminant should be used to establish the impact of those contaminants, the work should also include studying multiple contaminants at the same time to fully simulate the CO<sub>2</sub> sources. The results of this work should indicate the degree to which CO<sub>2</sub> needs to be cleaned to be used as a carbonation source.

#### Long term

If CO<sub>2</sub> is used to produce ASCMs or fillers for use in concrete, a similar program of research could be carried out to determine the impact of contaminants in that application. If the tests indicate that CO<sub>2</sub> from industrial sources may be detrimental to concrete performance due to a particular contaminant, work could also be carried out to develop concrete based methods to mitigate the damage mechanism. As an example, if SO<sub>x</sub> compounds cause sulfate attack in the concrete, using sulfate resistant cements may prevent the problem, allowing industrial sources to be used without cleaning. The

---

long term study of carbonated samples in outdoor exposure sites should be used to confirm the accelerated aging test results.

## **15 Assessing/quantifying sequestration**

### **15.1 Introduction**

Successfully procuring low carbon concrete requires the ability to verify that the delivered concrete meets the procurement requirements. Similarly, EPDs for concrete need to be verified before they can be accepted for use in LCA studies. In most cases this verification can be done through the use of LCI datasets for the cementitious and other materials used in the concrete.

In the case of carbon sequestration in concrete, however, the issue becomes more complicated. The time of exposure, flow rate, concentration and pressure of CO<sub>2</sub> used to accelerate concrete carbonation does not necessarily directly correlate to the amount of CO<sub>2</sub> that is eventually sequestered in the concrete. Other factors, such as pore structure, humidity, temperature and loss of CO<sub>2</sub> to the atmosphere may all result in lower levels of carbonation than is expected.

Assessing and quantifying the success of sequestration methods is essential to their acceptance in the market place. Just as other requirements such as compressive strength, chloride permeability and slump are specified and testable in the laboratory or in the field, methods are needed to assess the quality of sequestration of CO<sub>2</sub> in concrete. This chapter addresses the development of those methods, as well as how the information gained from them might best be used.

### **15.2 Knowledge Gaps**

#### **15.2.1 New standardized tests, including field tests**

*“Development and evaluation of quick quantitative testing methods.”*

*“Need appropriate test methods for assessing sequestration that are standardized, accepted methods with metrics to measure and confirm amount of CO<sub>2</sub> sequestered. These methods should take into account different types of concrete.”*

The measurement of carbon sequestration in concrete provides some unique challenges compared to other testing issues. The simplest approach is to look at differences in mass loss as samples are heated to above 1000 °C. The presence of limestone in most cements and some aggregates means that a simple measurement of mass loss is insufficient and that a comparison approach is essential. Depending on

---

the carbonation method, the comparison can be between material collected before and after carbonation in a plant or to material taken from different sections of a core, where the outside of the core is exposed to CO<sub>2</sub> and the inside is assumed to be the uncarbonated material. It is possible that carbonation of cylinders would provide a reasonable surrogate for taking core samples, but more research would be needed to confirm this point, as most of concrete structures have flat surfaces.

Using mass loss as a test method is quantitative, but is also destructive and may not offer results in a timely manner. A field measurement should be quick, quantitative, and able to evaluate carbonation of bulk concrete, not just surface carbonation. Developing such a method, which could potentially also be used to measure natural carbonation will be significantly more challenging than standardizing the use of mass loss measurements.

### **15.2.1.1 Activities Recommended by Workshop Participants**

#### Short term

- *“Quantification of CO<sub>2</sub> in sequestered in concrete”*
- *“Literature review to determine if other countries, jurisdictions or research groups that already have a means to assess and quantify CO<sub>2</sub> sequestration.”*
- *“Recruit participation of industry to help define standardized metrics.”*

### **15.2.1.2 Research Pathways**

#### Short term

A literature review of current practices and potential measurement methods should be carried out. The review should include examining whether novel inspection techniques or the placement of low-cost sensors in the concrete would supply the needed information.

Methodologies for using mass loss as a measurement method using an appropriate technique should be defined and initial data on the reliability of the method should be developed to serve as a basis for discussion.

#### Medium term

The mass loss methodology should be presented to the appropriate technical subcommittee (TSC) within the CSA A23.1/.2 technical committee for consideration. If the approach is supported by the TSC, a round-robin test program should be developed to identify any issues with the test approach and produce data on intra- and inter-laboratory variability. Participation of representatives from companies offering carbonation services should be encouraged.

---

If the literature review results suggest one or more non-destructive evaluation or sensor approaches can measure bulk carbonization, then a research program should be initiated to test the technology.

### Long term

The validated mass loss methodology should be standardized in CSA A23.1/.2. If the results of tests on a field measurement approach indicate that it can be successful, the same standardization process of presentation to CSA A23.1/.2 should be followed.

## **15.2.2 Including long term concrete behaviour in Life Cycle Assessments**

*“Consideration of concrete performance and application in the LCA of concrete exposed to carbonation”*

*“Does sequestration affect the natural carbonation of concrete (natural, slow absorption of carbon over time)?”*

*“Consideration of permanent versus temporary carbon sequestration. Injecting CO<sub>2</sub> as a gas into underground cavities has been criticized as temporary, whereas chemically changing the carbon into a solid matrix such as cement or concrete is more likely to be considered as a permanent sequestration.”*

Concrete is generally a durable material. Products made from it can have long service lives compared to other materials, which in turn may affect how their LCA should be carried out. Some issues to be resolved include:

- How should LCAs account for concrete designed to have a longer service life than typical? How should concrete with an 80 year service life that has the same cradle to gate emissions as concrete with a 40 year service life be treated?
- Should there be a difference in LCA approaches related to the type of sequestration? Is there data to support different approaches?
- Does accelerated carbonation of concrete with a hydrated cement binder provide long-term CO<sub>2</sub> benefits or does it simply speed up the natural process, with no long-term benefits? How should these differences be included in LCA? Is including both forms of carbonation in an LCA a form of double counting?

While these questions will ultimately be dealt with in LCA practice using documentation such as PCRs and EPDs, they are currently beyond the scope of LCA practice. The current cement PCR does not cover sequestration, although the next edition, expected to be issued in 2025, should include it. There is, however, insufficient information to allow differentiating based on sequestration stability over time or the differences

---

between natural and artificial carbonation. Moreover, as discussed in Chapter 2, LCA considerations should be one part of a design process that optimizes a number of different factors to develop the best design for any given structure.

Of the three issues mentioned here, resolving the second is beyond the scope of this report. A number of geological sequestration sites would need to be monitored for carbon dioxide releases in order to determine how likely they would be to occur over a given time frame. The potential for geologically sequestered CO<sub>2</sub> to form carbonates underground and be permanently sequestered would also need to be assessed. Once that information is in hand, CO<sub>2</sub> emissions over time could be included in LCA in a manner similar to that currently used for losses such as those in transmission from an emitting site to the sequestration location.

The other two issues are more directly tied to cement and concrete properties, but are challenging to address. LCA practice looks at the life cycle emissions, but does not necessarily look at emissions per year of service life, which would be needed to properly assess the emissions benefits of longer concrete lifetimes. Determining whether artificial carbonation will sequester the same amount of CO<sub>2</sub> as natural carbonation over a period of 30 or more years will require long term testing. Approaches to both issues are discussed below.

### **15.2.2.1 Activities Recommended by Workshop Participants**

#### Short term

- Recruit a LCA specialist to find a way to include performance in the LCA methodology.

### **15.2.2.2 Research Pathways**

#### Short term

Existing LCA standards should be reviewed to determine to what extent emissions can be reported on a yearly basis throughout the service life, as opposed to a total emissions basis. As part of this examination, consideration should be given to when annualized data is appropriate. Attempting to annualize emissions data for cement and concrete may not work as well, for example, as annualizing the data for a project with longer or shorter design service lives.

Examining the combined effects of natural and artificial carbonation should start by determining an appropriate set of concrete mix designs to test, sample size and shape and carbonation procedures. The samples should then be produced, some of them artificially carbonated and placed outdoors or in a simulated system to experience natural carbonation. Sufficient samples will need to be produced to allow for destructive testing to check for carbonation extent.

---

### Medium to long term

Depending on the current state of the LCA standards, efforts may need to be directed to standards updates, to ensuring that relevant PCRs and guidelines allow for the reporting of annualized data, and/or to efforts to having it included in LCA practice.

The concrete carbonation samples should be assessed periodically to track how quickly carbonation is proceeding. Samples will need to be analyzed until a clear enough trend line has developed that longer term behaviour can be predicted. They will also have to be tested to make sure that samples in the assembly are all experiencing the same rate of carbonation.

### **15.2.3 Determination of factors affecting sequestration performance**

*“Determine factors affecting the amount of sequestration in concrete. Does humidity at time of CO<sub>2</sub> injection or concrete placing have an effect? Does moisture content have an effect? What are the best areas for use of sequestration?”*

As is the case for other industrial processes, sequestration methods will need to be optimized for different operating and environmental conditions. When the sequestration takes place in a manufacturing plant as part of the production of concrete products, the optimization will presumably take place during the process development in the plant. In the case of field carbonation, however, it may be necessary to take into consideration issues such as temperature or humidity during sequestration.

Initial, publicly available research should be undertaken to develop a basic understanding of environmental condition impacts on carbonation. It should be noted, however, that the impact of environmental conditions may vary between carbonation methods. Concrete end users and project engineers are, however, unlikely to need specific information on the precise impact of those conditions. Instead, the operators of the carbonation equipment will need to know how to adjust their equipment to obtain the desired result. Gaining this knowledge should be part of the equipment development process. Project specifications should, however, include provisions requiring that these environmental impacts be accounted for in the application of the carbonation process.

#### **15.2.3.1 Activities Recommended by Workshop Participants**

##### Short term

- *“Consolidate all information that is currently available, review it and benchmark it for Canadian use.”*

---

### 15.2.3.2 Research Pathways

#### Short term

A literature review on the topic of environmental impacts on cement and concrete carbonation should be carried out. Unless clear evidence of the effects under Canadian environmental conditions can be determined from the literature review, a laboratory study should be carried out to determine how much changes in the concrete carbonation would be caused by environmental changes. In addition to the environmental work, correlations between the physical properties of concrete (strength, porosity, etc.) and the ability to sequester CO<sub>2</sub> should be explored and quantified.

#### Medium term

Vendors of carbonation services and equipment should carry out their own studies of the impact of environmental changes on their own processes. These impacts should be documented and provided to equipment operators where appropriate. Language should be developed to be included in specifications for carbonated concrete to ensure that environmental effects have been accounted for in the operation of the equipment.

#### Long term

If standards are developed for concrete carbonation, language around accounting for environmental effects should be included in the standards.

## **16 Sequestration in high volume SCM and other specialized concrete mixes**

### **16.1 Introduction**

Most work to date on carbon sequestration in concrete has been carried out on traditional concrete mixes that are typical of those used on most construction sites. Carbonation processes in concrete rely primarily on the reaction of the calcium hydroxide formed during hydration with carbon dioxide to form calcium carbonate, although the carbonation of other phases in hydrated cement also occurs. Many SCMs and ASCMs also react with calcium hydroxide, potentially creating a competition between the two chemical processes.

The predominant process is likely to depend on the timing of the carbon sequestration and how rapidly the carbon dioxide penetrates to the interior of the concrete. It is likely that natural carbonation will not affect concrete made with high volumes of SCMs/ASCMs less than it would other types of concrete. Penetration of the CO<sub>2</sub> into the concrete would be slowed due to lower porosity in this type of concrete compared to traditional mixes. In addition, the calcium hydroxide would already be consumed by

---

reactions with the SCMs/ASCMS. On the other hand, intensive carbonation at an early stage of hydration might reduce the long term strength development of the concrete as some calcium hydroxide would not be available for reactions with the SCMs/ASCMS. It also possible that other carbonation reactions would occur with other metallic oxides or hydroxides in the SCMs/ASCMS. Additional research is therefore needed to determine when carbon sequestration could be used with these specialized mixes and how to determine the amount of carbon dioxide they contain.

The other area of research discussed during this workshop session is the potential to sequester CO<sub>2</sub> in SCMs and ASCMS, rather than in the cement. This approach is particularly of interest where the sequestration takes place before blending and hydration, rather than afterwards. Commercial technology is currently available for the production of an equivalent to precast concrete using electric arc furnace dust with CO<sub>2</sub> as a binder (Carbocrete, 2025). Similar products may be possible with other industrial by-products as well. There is also interest in using less carbonated SCMs/ASCMS in blended cements, including some discussion in regards to whether the carbonation process beneficiates certain ASCM materials. From the point of view of a cement producer, being able to use CO<sub>2</sub> emitted in cement production to make a new ASCM that can then be blended into cement for sale would be a desirable outcome.

## 16.2 Knowledge Gaps

### 16.2.1 Ability of SCMs and ASCMS to sequester CO<sub>2</sub>

*“Investigate and quantify the potential for direct CO<sub>2</sub> sequestration in a variety of conventional and alternative SCMS. What are the economic considerations of one technology over another and how do regulations factor in? How does the upcycled SCM affect the chemistry of the concrete pore solution? What is the impact of CO<sub>2</sub> sequestration in SCMS on their ultimate performance in concrete?”*

As noted above, work in this field with EAF dust bound together by carbonation has already advanced to commercialization. There are, however, a number of existing or potential SCM type materials that could potentially be used either as the basis for a similar product or in a more typical hydrating system. Some of these materials are being explored in the research literature, but a more systematic approach, focussing on Canadian SCM/ASCM supply, is needed to determine if it is worth investing in this area of technology.

#### 16.2.1.1 Activities Recommended by Workshop Participants

##### Short term

- 
- *“Determine the impact of CO<sub>2</sub> sequestration on fresh, hardened and durability performance of concrete. Determine the economics of different technologies to assess whether or not it’s worth investing in and whether it is scalable.”*

### **16.2.1.2 Research Pathways**

#### Short term

An initial literature review should be carried out in this area. Using the results of the literature review, a classification system should be developed to assist in assessing different SCMs, ASCMs and other industrial by-products in regards to their potential for carbonation and for use in cementitious systems when they have been carbonated. Once the classification system has been completed, available materials identified through the work outlined in Chapters 3 and 4 should then be classified according to their potential for carbonation and the effect carbonation is expected to play in their performance in concrete.

#### Medium term

The materials with the best potential identified in the short term study should be tested to confirm their suitability for carbonation and to identify the optimal exposure to CO<sub>2</sub> and the CO<sub>2</sub> uptake capacity. After carbonation, performance in concrete should be assessed, including during mixing, pouring and over the long term. Degree of carbonation should be adjusted based on the results of the concrete studies. This stage should also explore issues discussed in previous chapters of the report such as the impact of impurities in the CO<sub>2</sub> on the carbonated products and concrete.

#### Long term

A technoeconomic study will be needed based on the results of the medium term work to determine whether the technology is worth implementing on an industrial scale. If it is, the industrial processes would need to be designed, developed and tested. Issues such as the necessity for grinding the carbonated product, particle size control, gas flow rates, etc. would need to be considered and appropriate solutions developed. The resulting carbonated SCM/ASCM would then need to be tested and refined to produce a commercial material. A small scale, flexible pilot facility may be of use to work out the details before investment is made at production facilities.

### **16.2.2 Effect on longterm performance**

*“How to measure long term performance of high SCM concrete. Understanding how the materials will perform throughout 100 year expected design life.”*

Investigation of long term performance of carbonated concrete in general is discussed in detail in Chapter 14. The same basic principles and issues apply to the carbonation

---

of mix designs with high volumes of SCMs and other specialty mix designs. Issues such as the potential for competing reactions, the impact of lowered porosity and optimal timing of carbonation that were described in the introduction to the current chapter should all be addressed in the studies outlined previously.

Long term performance of carbonated SCMs/ASCMS in concrete is likely, however to need to be treated as a separate study area. Over carbonation may affect long term strength development of concrete made using these materials and it is possible that the carbonation process will affect concrete deterioration mechanisms and/or their control. As an example, alkali-silica reactions in concrete are often controlled through the use of SCMs. Testing would be needed to ensure that the carbonation of those SCMs will not affect that ability in addition to ensuring that the effect of the SCMs in the hydration process and strength is unchanged.

It should be noted that the short term action identified in the workshop session addresses the need for a general facility for testing concrete innovations. This type of facility would have much broader applications than the carbonation of SCMs alone and similar needs were raised in other sessions. As a result, the topic is addressed in the report conclusions, rather than here.

### **16.2.2.1 Activities Recommended by Workshop Participants**

#### Short term

- *“Incubation program for pilot projects. Government-funded ‘test track’ for deploying new technologies in controlled settings to alleviate concerns about being the first to use a new product/material/technology.”*

### **16.2.2.2 Research pathways**

#### Short Term

The classification system for the carbonation of SCMs, ASCMS and industrial by-products described earlier in this chapter should include an analysis of potential impacts on known concrete deterioration mechanisms and their mitigation. These impacts may be negative or positive and should be considered in selecting materials for development.

#### Medium Term

Long term strength development and dimensional stability testing should be part carried out on the selected materials experiencing different degrees of CO<sub>2</sub> exposure. In addition, a program of comparisons between standard concrete durability tests and field exposures should be undertaken to ensure that the tests are still applicable to concrete made with the carbonated materials. Successful durability tests should be used to further screen the carbonated materials.

---

## Long term

Samples should be installed in long term exposure sites to continue the comparison between existing test methods and real performance. Although more challenging to implement, exposing samples under load would be helpful for duplicating behaviour in the field. If necessary, new durability tests should be developed to address novel deterioration mechanisms that are identified in the course of testing. As noted for other novel concrete products, typical repair and rehabilitation approaches should be tested to ensure they are still applicable. If necessary, new repair approaches should be developed.

### **16.2.3 Guidance documents and standards**

*“Having technology to measure achievement of standards and regulations and having standards that can be reached given the available technology.”*

The need for standards and measurement approaches was a common theme in the sessions on carbon sequestration. It has been discussed in Chapters 14 and 15 and will also be discussed in Chapter 17. Other than noting that the standards need to be written to cover carbonated SCMs/ASCs, no other coverage will be given here.

#### **16.2.3.1 Activities Recommended by Workshop Participants**

No specific activities on this topic were identified during the workshop session.

#### **16.2.3.2 Research Pathways**

Research pathways for this subject have been discussed in other chapters of this report.

### **16.2.4 Quantification of CO<sub>2</sub> uptake**

*“How do we measure what we’ve done to the concrete?”*

Issues around assessing CO<sub>2</sub> uptake are described in chapter 15 of this report. It is worth noting, however, that the subject was also highlighted in this workshop session. Quantifying the carbon dioxide sequestered in concrete is essential for accurate EPDs and qualifying carbonated concrete as low or net-zero carbon materials. As with other topics discussed in this chapter, work will be needed to ensure that the quantification procedures developed for typical concrete mixes can be generalized to work with other, more specialized concrete materials.

#### **16.2.4.1 Activities Recommended by Workshop Participants**

## Short term

- 
- *“Development of best practice document to evaluate new direct CO<sub>2</sub> sequestration technologies using SCMs. Include provisions for test sections and areas to allow for standardized testing of different CO<sub>2</sub> sequestration technologies in the field to verify CO<sub>2</sub> and performance results.”*

#### **16.2.4.2 Research Pathways**

Research pathways in this area have been described in Chapter 15.

## **17 Guidance on sequestration use**

### **17.1 Introduction**

Many of the carbon sequestration technologies discussed in this report are relatively new to the cement, concrete and construction industries. Most information on them is available either through academic papers or the documentation provided by corporate proponents. As a result, there is a general need for guidance documents that would support decision makers, although the best form for that guidance is not entirely clear. The workshop sessions documented in Chapter 13 to 16 all called for standards to be developed or updated, but in cases such as natural carbonation or where a technology has a single commercial proponent, this approach might not be the most applicable. Guidance can also take the form of primers, decision support tools, case studies and other documents. In some cases, experience of using that guidance can then lead to standardization, while in others the initial guidance may suffice. This chapter discusses the need for guidance on sequestration technologies and the possible approaches.

### **17.2 Knowledge Gaps**

#### **17.2.1 CSA standards for sequestration**

*“CSA standards need to be developed across the user chain. Considerations should include the amount of CO<sub>2</sub> sequestration that can be used, the purity of CO<sub>2</sub>, types of injection nozzles, tolerance limits, and guidelines on storage and monitoring of tank levels.”*

Standards are an essential tool for ensuring that a product performs as expected. They aid market entry for new products, simplify the process of specifying materials and products and help to ensure end-user safety. Developing standards for carbon sequestration in concrete is, however, complicated by the need to address different types of sequestration processes. Moreover, most of the existing methods of sequestration have a single industrial proponent. Detailed standardization of a particular process may require the release of company intellectual property. It may also

---

inhibit future innovation if, for example, a standard requires the use of a particular equipment design and a subsequent design is found to work better.

### **17.2.1.1 Activities Recommended by Workshop Participants**

The research topics outlined by the participants in response to this topic were largely related to information that would be needed before standardization could take place. They are included here for completeness, but have been addressed where appropriate in other chapters of this report. Development of specific industrial technologies for concrete carbonation is, as noted in the introduction, outside the scope of this report.

#### Short term

- *“Develop guidelines on best practices for production, research on testing and certification of production process and product, research on best methods for transportation, placement and compaction. Research is needed regarding available sources of CO<sub>2</sub> to be sequestered (post-industrial or other) by province. Research is required to quantify what is the most effective method of sequestering CO<sub>2</sub> in fresh concrete production; direct injection into mixer, injection in process water, or other method? Research entire supply chain of the CO<sub>2</sub> sequestration to confirm that the sequestration is in fact carbon negative, when all inputs (transportation, CO<sub>2</sub> source, energy, etc.) are considered.”*
- *“Engineering research on strength and durability of carbon sequestered concrete. Investigate if a field test to measure the amount of CO<sub>2</sub> sequestered in a concrete mix can be developed. Tests are required to determine rapid chloride permeability, alkali silica reactivity, carbonation of concrete, fire behaviour and design life of structures.”*

### **17.2.1.2 Knowledge Mobilization Pathways**

#### Short term

A committee of experts on concrete carbonation should consider what aspects of the field, if any, are amenable to standardization beyond the calculation of carbon emissions. These discussions should also give direction in regards to whether a separate standard is needed, if the Carbonstar standard should be extended beyond covering GHG emissions calculations or if the existing cement and concrete standards should be updated to cover carbon sequestration.

#### Medium to long term

Work should be undertaken to develop any required new standards or changes to existing standards.

---

## **17.2.2 Guidance on the inclusion of sequestration in analysis of global warming potential**

*“How is carbon sequestration accounted for in regards to the global warming potential of a concrete mix?”*

The need for inclusion of carbon sequestration in life cycle assessments and related documents has been discussed in Chapter 15. It is included here for completeness.

### **17.2.2.1 Activities Recommended by Workshop Participants**

#### Short term

- Research for determining how carbon sequestration is accounted for in regards to the GWP of a concrete mix. Research can also be done on the actual amount of CO<sub>2</sub> sequestered in a concrete mix to help develop method for verifying results. Methods can be established for incorporating carbon sequestration into the EPD process.

### **17.2.2.2 Research Pathways**

As noted earlier, a CSA Standard for calculating the carbon emissions associated with concrete already exists, while the next update of the North American cement PCR document is expected to include guidance on including carbon sequestration in cement EPDs. Once the new PCR has been issued, secondary documents such as the Low Carbon Concrete Primer may need to be updated to reference the new provisions. No additional work is anticipated in this area.

## **17.2.3 Guidance for Decision Makers**

*“Architects or other professionals do not have the knowledge or awareness to start integrating this product.”*

Adoption of innovative products in construction can be complex due to the number of different professions who can play a role in making a decision to use them. Architects and engineers are key players in decision making around innovations, but owners can also play a significant role. They may require the use of a novel product or have project requirements that will be easier to meet when that product is used. Ensuring that these decision makers have adequate information to understand, recommend or specify low-carbon construction materials is important for any of the topics outlined in this report. It is particularly important for novel technologies such as carbon sequestration, where there is a lower level of existing knowledge than would be the case for approaches which build on existing concrete technologies.

### **17.2.3.1 Activities Recommended by Workshop Participants**

#### Short term

- 
- *“Guidelines and initiatives for awareness and uptake for integration of carbon sequestered concrete into mainstream concrete projects. Develop targeted documents for users including architects, engineers and specification writers. Develop demonstration projects and research for enabling project certification in terms of carbon content so a user knows what they are getting. Considerations include the effect of carbon sequestration on air entrainment in concrete, “carbon points” for carbon sequestered concrete and a knowledge base of applications.”*

### **17.2.3.2 Knowledge Mobilization Pathways**

#### Short term

Independent evaluations of projects that used carbon sequestration in concrete should be carried out to provide the information needed for guidance documents. Particular attention should be paid to points of perceived risk as well as potential benefits and ease of application.

#### Medium term

Guidance documents based on the project evaluations plus other short term work described in Chapters 13 to 16 should be developed for different participants in the construction process, including architects, owners, specification writers and engineers. Sample specification language should be developed and documentation such as the Low Carbon Concrete Primer updated.

#### Long term

Additional updates to guidance documents should occur as new technologies are developed and further research and testing is carried out. Material on low carbon intensity concrete, including the use of sequestration, should be added to university and college course curricula.

## **18 Alternative Fuel Choices**

### **18.1 Introduction**

There are many types of alternative fuels available across Canada. These alternative fuels can be liquids, solids or gases and produced from various feedstocks, including agriculture products and residuals, forestry products and residuals, wastes, captured CO<sub>2</sub> and clean process from fossil fuels (e.g., H<sub>2</sub> from natural gas with steam methane reforming and carbon capture and storage). This commercial production of alternative fuels has been primarily driven by current and pending regulations for liquid fuels for transportation applications, as well as solid fuels for export for power production. There are, however, many abundant feedstocks in Canada that are not yet being used to produce alternative fuels because of a lack of cost-effective production methods and applications. The same is the case for fuel-switching in cement kilns; the cost,

availability, carbon footprint and environmental impact can make many of these fuels an unfeasible option.

Despite these potential limits, a wide variety of alternative fuels (AFs) can potentially be used or are currently in use for cement production. Different types of wastes from industries, construction and communities can be processed suitably (Chatterjee & Sui, 2019). Examples of such waste derived fuels include crop residues and shells, saw dust, wood waste, food waste, municipal solid waste (MSW), sewage sludge, and waste oils. Waste streams may also be processed to create energy dense AFs such as renewable natural gas, green hydrogen, biogas, pyrolysis gas, and pyrolysis oil. Table 3 lists some examples of fuels derived from waste streams that can be used in cement production. About 40% of the CO<sub>2</sub> emissions from the industry originate from the combustion of fuels used in the cement kiln and other plant operations (GCCA, 2021). One forecast predicts AF usage to increase from 6% in 2020 to 22% by 2030 and 43% by 2050 in order to reduce the net GHG emissions of the industry (GCCA, 2021). This can potentially redirect waste from landfills while reducing fossil fuel usage. Certain waste-derived AFs can also provide minerals which can benefit the clinker production. Additionally, use of AFs can potentially reduce the cost of cement production (Zygodlo, Purgal, 2020).

*Table 3 - Examples of fuels derived from waste streams (Murray & Price, 2008)*

Agricultural Biomass	Non-agricultural Biomass	Industrial	Chemical and hazardous waste
<ul style="list-style-type: none"> <li>• Rice hull</li> <li>• Bagasse</li> <li>• Coconut residue</li> <li>• Wood chips</li> <li>• Animal waste and bone meal</li> </ul>	<ul style="list-style-type: none"> <li>• Sewage sludge</li> <li>• Saw dust</li> <li>• Paper</li> <li>• Waste Wood</li> </ul>	<ul style="list-style-type: none"> <li>• Railway ties</li> <li>• Waste oils</li> <li>• Crude glycerol</li> <li>• Rubber tires</li> <li>• Packaging material (paper and plastic)</li> <li>• Construction and demolition waste</li> </ul>	<ul style="list-style-type: none"> <li>• Spent solvents</li> <li>• Electronic scraps</li> <li>• Pesticides</li> <li>• Paint residue</li> </ul>

## 18.2 Knowledge Gaps

### 18.2.1 Supply Chain Security

*“Consistency, availability and abundance of the supply.”*

---

While many AFs continue to be used in cement manufacturing in Canada and abroad, the key is to facilitate and sustain the supply chain of the AF suitable for the particular location of the cement manufacturing plant. Cement production is a continuous process which needs to be sustained by a steady supply of raw materials and fuels. Supply constraints can not only inhibit the operation of the plant but also make it difficult to justify the capital investment (e.g. specialized material handling equipment) required for utilizing such AFs in the plant. Several important considerations were highlighted in the workshop which can be divided into technical and non-technical categories. The non-technical considerations are mostly related to policy and regulation which will be discussed in subsequent sections.

### **18.2.1.1 Research into the impact of inconsistent fuel supplies on production**

One of the most significant technical issues is managing the intermittency of the AF supply which may require that the AF be co-fired at a suitable rate with the conventional fuel. In order to justify the cost of implementing the AF, it may be necessary to determine the minimum fraction of conventional fuel replacement. A study by (Wojtacha-Rychter K, Kucharski P, Smolinski A, 2021 Mar 11) provides an analysis of the environmental and financial benefits of substituting coal with AFs. According to their analysis, a 10% saving of coal by mass requires that 0.56 TJ/h must be provided by the AF. Another important parameter is the CO<sub>2</sub> emission factor of the AF with respect to coal. For example, co-firing with 70% AF whose emission factor is higher than that of coal produces a lower reduction in the net emission of CO<sub>2</sub>.

Research is also needed in developing technology to collect, sort, pre-treat, recover, recycle and co-process waste so as to ensure a reliable and consistent AF supply (GCCA, 2021)). The net CO<sub>2</sub> benefit of using the AF must consider the overall GHG footprint of all these steps rather than just the displacement of fossil fuels. For instance, use of urban sewage sludge as fuel in the cement kiln would cause additional GHG emissions when transported from the urban centre to a possibly remotely located cement plant. Discarded tires have been used as fuel by the cement industry in certain provinces of Canada (Quebec, British Columbia, and Nova Scotia) and many locations outside of Canada (Solutions, Advanced Waste, 2020). Emission stack data from the Lafarge cement plant in Nova Scotia suggests that using a mix of low carbon fuels including discarded tires and shingles causes no statistically significant increase in the vast majority of emissions (Chandler J., 2021). An LCA study by (Sai Kishan G, Himath Kumar Y, Sakthivel M, Vijayakumar R, Lingeshwaran N, 2021) concluded that in comparison to coal, use of discarded tires had a lower impact on climate change, human health, eco system quality and resources compared to traditional fuels like coal.

Since its launch in 2015, co-processing has played a pivotal role in Argos Colombia's sustainability strategy (GCCA, 2024). Initially starting at the Rioclaro plant with just 1,000 tons of alternative fuel from a single supplier, the system has since expanded

---

significantly. It now encompasses eight active suppliers collectively providing nearly 30,000 tons of alternative fuels.

### **18.2.1.2 Design of kiln systems to handle multiple alternative fuels**

The properties of the AF are another important technical consideration (Chatterjee A, Sui T, Ryden, 2019 Sept). The energy value is fundamental to offsetting the thermal energy of coal as mentioned previously. AFs with lower energy densities may be limited for use in preheaters/precalciners while higher energy density AFs could be used in the kiln. Certain AFs may require additional air and fuel feed to maintain the kiln temperature due to higher moisture content, and consequently generate higher volumes of waste gases (Nhuchhen DR, Sit SP, Layzell DB, 2022 July). For instance, using high quantities of low calorific value MSW can be challenging due to issues with maintaining kiln temperature, increased kiln volume requirement, and high quantity of ash produced (Ryden A, Doukas E, Pantazis G, Adamopoulou T, Gklinos P, Doukas C, et al, 27-28 Feb 2020). Certain AFs can cause the kiln temperature profile to shift towards the kiln inlet which can lead to higher radiative heat loss.

Certain AF applications may also need more precise fuel dosing compared to conventional fuels in order to achieve stable kiln operation. Volatile content in the AF can cause build-ups and obstructions in the cyclones, kiln and riser duct. Clinker process and quality can also be affected by the compounds of sulphur, zinc, phosphorus, magnesium, chlorine, and fluorine in the AF (Ryden A, Doukas E, Pantazis G, Adamopoulou T, Gklinos P, Doukas C, et al, 27-28 Feb 2020). Additionally, the ash from the AF combustion, similar to ash from coal combustion, will directly impact the chemistry of the clinker. Certain AFs may cause higher emissions of NO<sub>x</sub>, CO, and SO<sub>2</sub>, in addition to other volatile compounds. Alkali metal oxides such as potassium oxide and sodium oxide can react with other alkali-reactive aggregates in the presence of moisture to produce expanding gels which can lead to cracking of concretes and mortars (Asamany, 2017).

Taking all these factors into account, though undesirable, in certain situations modification of core plant components such as the kiln burner may be necessary. For example, in one study by (Asamany, 2017), the highest coal substitution of coal by mass was achieved by using a separate burner pipe to feed the AF (shredded waste shingles) onto the top of the main burner pipe. Burner diameters have also had to be increased to accommodate the injection of certain AFs (Xavier d'Hubert, 2022). Another possibility is a satellite burner located above the main burner which can feed the AF into the kiln allowing the unburnt AF to be utilized in the main burner flame. The satellite burner can also be adjusted to match different AFs thereby letting the kiln operate with some variability in terms of AF fuel type and supply (Xavier d'Hubert, 2022).

Asia Cement (GCCA, 2024) for instance, has installed air ducts which direct high-oxygen tertiary hot air into the combustion furnace to improve the combustion efficiency.

---

After rounds of optimization, they were able to increase the residence time of the AFs and boost their input quantity. This system also provided more flexibility in the size of the AFs used, thereby increasing the total amount of AFs used in the facility.

Huaxin Diwei Company's 2500t/d clinker production line has successfully implemented the large-scale, continuous, and stable use of alternative fuels such as waste tires, rubber, and textiles (GCCA, 2024). This achievement is the result of the company's independently developed systems for alternative fuel pretreatment, feeding, and intelligent control. The production line has maintained a fuel substitution rate exceeding 60%, with the comprehensive energy consumption of cement clinker reduced to less than 50kg of standard coal per ton. Direct CO<sub>2</sub> emissions per ton of cement have decreased to 417kg, representing a reduction of 123kg compared to the previous 540kg, resulting in an annual CO<sub>2</sub> emissions reduction of 110,000 tons.

At Secil of Portugal, the industrial test demonstrated that through the modifications to the main kiln burner and utilization of new sensing technologies, the use of alternative fuels could be increased between 13% and 34%, with a consequent reduction of 7% to 11% in the net CO<sub>2</sub> emissions from combustion (GCCA, 2024). In February 2024, Votorantim Cimentos of Brazil implemented a project of alternative fuels in one of its plants in Brazil, using different sources of fuels (biomass and tyres) and has currently replaced almost 70% of its fossil fuel use.

### **18.2.1.3 Electrification of Cement Production**

The main purpose of fossil fuels used in cement production is to generate heat through combustion. In addition to heat, combustion also leads to emissions of pollutant gases such as NO<sub>x</sub>, SO<sub>x</sub> and CO in addition to CO<sub>2</sub>. Use of electricity to generate the heat is one possible option which can avoid pollutant formation, and there is some potential to use electric furnaces for the calcination of limestone into calcium oxide and CO<sub>2</sub> (Antunes, et al., 2021), (Madeddu S, Ueckerdt F, Pehl M, Peterseim J, Lord M, Kumar KA, et al., 2020 Dec 1). If the electricity is derived from renewable sources, then the net GHG emissions can be reduced further. (Antunes, et al., 2021) also list other electrification possibilities in cement manufacture. First is the use of plasma technology, especially with the use of the CO<sub>2</sub> gas generated from calcination as plasma through over-heating, the electrode life and maintaining heat transfer in the kiln would prove to be challenging. Second is the use of resistive heating furnaces in which heat may be transferred to the input material through conduction, radiation and/or convection. Third is the use of electromagnetic heating such as induction and microwave furnaces. However, many challenges remain in the form of overheating, suitability for ceramic processing, and scale-up of the technology.

### **18.2.1.4 Electrochemical generation of calcium silicates**

Participants in the workshop also pointed out the emerging technology of electrochemical generation of calcium silicates. There is very limited literature on this.

---

The most commonly referred to study is by (Ellis LD, 2020 June 9) which describes a neutral water electrolysis method to convert limestone to calcium hydroxide, which precipitates a high purity oxygen-CO<sub>2</sub> mixture, and hydrogen is released at the cathode and the anode respectively. Calcium hydroxide can decompose and react with silicon dioxide to form alite – one of the main components of OPC. The high concentration of CO<sub>2</sub> in the two-gas mixture of oxygen-CO<sub>2</sub> makes it easier to capture and sequester CO<sub>2</sub>. Oxygen can be used to enrich any fuel combustion in the process, and hydrogen can be used as an energy source.

### **18.2.1.5 Activities Recommended by Workshop Participants**

#### Medium Term

- Research on adapting kilns and process to account for inconsistent materials and supply. Research on use of hydrogen coupled with oxygen.

### **18.2.1.6 Research Pathways**

#### Short Term

Potential sources of AFs should be assessed for each cement plant in Canada for size, proximity to the plant, need for kiln changes, processing requirements and potential issues with permitting. The cost of using the fuel should be determined, along the replacement percentage possible. Combining this information with that produced by the research outlined in the next section should allow potential candidates for alternative fuels to be selected.

Start-up companies are already working on deploying cements made by electrochemistry. Research pathways for that topic are therefore not covered in this report.

#### Medium Term

As outlined above, cement plants will need to be re-engineered to accept different alternative fuel sources. A research program on this topic is outside the scope of the specific knowledge gap identified in the workshops, but the need is included here because the necessary work will be highly dependent on the proposed fuel source. If the goal is to use two or more types of AFs in a single plant, additional research will almost certainly be needed to obtain optimal fuel mix designs.

Replacement of fuels by electricity for heating would need initial engineering feasibility studies in the medium term. Capital costs are likely to be significant and electricity supply and costs would need to be assessed. These studies should take into account the benefits of not only reducing CO<sub>2</sub> emissions from the plants, but also of the remaining emissions having reduced levels of pollutants, potentially simplifying carbon capture and sequestration. As per the Global Cement and Concrete Association

---

(GCCA, 2024), use of hydrogen and kiln electrification are forecast to play a small role from 2040, providing 10% of energy needs by 2050.

### Long Term

If the feasibility of electrical heating is demonstrated, significant research and development may be needed to build the knowledge base necessary to modify plants for the new heat source. Details of the necessary work are outside the scope of this report.

## **18.2.2 Decision support for fuel selection**

*“Lack of decision-making tools on best alternative fuel options. How do we decide what fuels provide the best energy source while not polluting more?”*

As stated above, there are many available options for alternative fuels in Canada. However, the cost, availability, carbon footprint and environmental impact can make many of these fuels an unfeasible option for fuel-switching in cement kilns. For example, the locations of cement kilns in Canada are dispersed, and types and supply of alternative fuels inventory and analysis has to be completed on a case by case basis. As the goal of fuel-switching to alternative fuels is to lower overall greenhouse gas emissions associated with cement production, it is necessary to understand the emissions created over the entire lifecycle of the fuel to know if it's a good option for fuel-switching in a given location. There are standardized methodologies to calculate the lifecycle emissions of alternative fuels, such as ISO 14040-series to define well-to-wake boundaries that should be the minimum for such calculations. The methodology for lifecycle inventory and lifecycle analysis should be transparent, consistent and quantified. There are several reports that can provide considerations on the impacts of alternative fuels for use in cement manufacturing generally, including both the social and environmental impacts of various solid feedstocks (e.g., plastics, sewage, MSW, hazardous waste, biomass, used tires (Network for Business Sustainability)). In addition, more specific LCAs have been generated for specific cases for (Gorski J, Israel B, 2018 Nov). However, a transparent, translational tool that quantifies specific impact categories is still a gap for many sites in Canada that considers a wide range of potential alternative fuels.

Votorantim Cimentos has introduced AIMO (Artificial Intelligent Mix Optimiser), a cutting-edge system that combines machine learning with process expertise to create a virtual twin of the kiln—an AI with process-awareness. Currently implemented in five facilities across Brazil, AIMO supports operational teams by providing guidance for weekly planning and adjustments to delivery schedules for different AFR streams. This tool enables Votorantim Cimentos to prioritize sustainable and cost-effective co-

---

processing solutions, offering both short- and medium-term perspectives, rather than simply aiming for a thermal substitution target.

### **18.2.2.1 Activities Recommended by Workshop Participants**

Short Term

- Development of clear LCA rules for evaluation of AF. Rules should include scope, boundary, and cut-off rules, but also evaluation of alternative "uses" of the material which is particularly important for materials that have calorific value that are wasted through landfilling. LCA should also consider incineration and waste to energy options and how they compare to combustion in a cement kiln

### **18.2.2.2 Research Pathways**

Short Term

In the near term, the development of clear LCI and LCA guidelines for the evaluation of alternative fuels options is needed. These guidelines should follow standard methodology for LCI and LCA, and the research outputs should include scope, boundaries, and cut-off rules, as well as evaluation of alternative "uses" of the material, which is particularly important for materials that have calorific value that are wasted through landfilling. LCA should also consider incineration and waste to energy options and how they compare to combustion in a cement kiln. This research should be completed with the input and consultation of a wide-range of stakeholders and experts, as there are many alternative fuels to be considered and each fuel has its own considerations, properties and potential end-uses. The output tool should be translational to various sites due to the dispersed nature of both cement plants and various applicable feedstocks.

### **18.2.3 Hydrogen fuel in cement kilns**

*“Research on use of oxygen enrichment and use of hydrogen as a fuel”*

Hydrogen is being explored as a fuel for many industrial applications including the cement industry (UY, Qazi, 2022 Jun 28). There are challenges associated with using hydrogen as the exclusive fuel in a cement kiln such as its high reactivity, corrosiveness, tendency for explosive combustion, and low flame emissivity (compared to high carbon fuels). However, hydrogen can be used in combination with other AFs or low carbon fuels (such as compressed natural gas) as a GHG reduction strategy (Xavier d'Hubert, 2022). One strategy is use of an electrolyser which can convert renewable electricity to hydrogen and oxygen. The hydrogen can be used as fuel while the oxygen can be used for enrichment (Xavier d'Hubert, 2022). Oxygen enrichment can balance the high air requirement of AFs so that the high flue gas flow rate associated with certain AF uses can be managed (Xavier d'Hubert, 2022). Combustion of the fuel in almost pure oxygen (known as oxy-combustion) enhances the combustion process in

---

addition to other benefits of lower NO<sub>x</sub> pollution and high concentration of CO<sub>2</sub> in the flue gas which is favorable for CCUS systems (El-Emam & Gabriel, 2021).

Kilns fired exclusively with hydrogen as fuel would require significant re-design and investment (Fennell PS, David SJ, Mohammad A, 2021 Jun). Hydrogen enrichment of conventional fuels such as natural gas may be more viable, but again, more research is required to increase the efficiency of this enrichment process since hydrogen compression is very energy intensive (El-Emam & Gabriel, 2021). During the workshop, the scaling of hydrogen (and oxygen) supply was highlighted as an issue since a typical kiln would require high capacity electrolyzers (in the order of several megawatts) to make an impact. Nevertheless, a study by (Nhuchhen DR, Sit SP, Layzell DB, 2022 July) shows that extracting oxygen from electrolytic hydrogen production is more cost effective than using an air separation unit (ASU) to extract oxygen even if the electrolytic oxygen has to be transported by pipeline over some distance. However, the availability of a renewable energy-powered oxygen supply is an issue. Manufacturers may choose to have a more reliable on-site ASU in addition to oxygen produced through electrolysis (Nhuchhen DR, Sit SP, Layzell DB, 2022 July). Thermal hydrogen plants (copper-chlorine thermochemical water splitting) have been proposed as an alternative to electrolysis owing to the copious amounts of waste heat available in the cement manufacturing process (El-Emam & Gabriel, 2021).

As per the Global Cement and Concrete Association (GCCA, 2024), use of hydrogen and kiln electrification are forecast to play a small role from 2040, providing 10% of energy needs by 2050.

### **18.2.3.1 Activities Recommended by Workshop Participants**

No activities on this topic were identified during the workshop.

### **18.2.3.2 Research Pathways**

#### Short term

Implementing technologies such as using alternative fuels from waste streams, CCUS or hydrogen are all likely to be capital intensive. Of the three, the use of hydrogen fuel on an industrial scale is the least developed and is therefore likely to require the most effort and have the longest time line for success. A detailed techno-economic analysis should therefore be undertaken to determine whether hydrogen fuels are worth pursuing for the cement industry. The TEA should take into account that CCUS or changes to production methods would be needed in any event to capture process emissions, potentially reducing the attractiveness of switching to hydrogen.

A similar analysis should be undertaken in regards to oxygen enrichment, with an emphasis on potential GHG benefits and costs.

#### Medium to long term

---

Assuming the TEA shows that hydrogen fuel is worth pursuing, a full scale research program on its use in kiln applications should be undertaken, leading from theoretical designs to demonstration projects. Due to the multi-national nature of the cement industry, it is likely that this effort would be collaborative in nature in its initial stages, with later work being more site specific in nature.

#### **18.2.4 Research into the use of aluminum as a fuel source**

*“Research into aluminum as a fuel source”*

Aluminum was proposed as potential fuel for cement kilns during the workshop session. Aluminum has been used as a rocket fuel by NASA in the form of a powder which is combusted with ammonium perchlorate as the oxidizer (Perry, 2016). Treated scrap aluminum can react with water to produce hydrogen which can subsequently be used to generate electricity in a fuel cell (Nancy W. Stauffer, 2021). According to the authors’ search, there is very limited evidence on the viability of aluminum as an industrial fuel. No research activities in this area are recommended.

## **19 Standardization of fuels to produce stable fuel performance**

### **19.1 Introduction**

Standardization of alternative fuels (AFs) is critical to their use in cement kilns to avoid operational problems and maintain low emissions. Cement kilns are designed to operate on solid fuel with specific properties including particle size, bulk density, grindability, heating value, and ash and moisture content. As well, inorganic contaminants in waste solid fuels including chlorine, fluorine and sulphur can be converted to harmful gases that must be cleaned prior to exhausting of the flue gas.

Standardization and subsequent use of certified fuels gives confidence to plant operators and environmental regulators that the fuel will behave in a certain way within the plant, not cause operational issues, and have a known emission profile. Without standardization and third party certification, a plant operating on alternative fuels would have to test each batch of fuel for compliance with the plant’s handling requirements and emission’s profile. For example, solid alternative fuels such as sawmill residue and municipal solid waste can have a wide variety of bulk properties (bulk density, particle size, etc.) and can be a challenge for fuel handling systems. The use of standardized solid fuels such as Solid Recovered Fuel (SRF) and wood pellets/briquettes would alleviate these problems.

---

The use of alternative, solid waste fuel could potentially require adopting a new, or altering an existing, regulation to allow for the use of the fuel. The use of standardized fuels with well-defined properties and known emissions profiles makes this simpler and can facilitate the process of modifying or obtaining an environmental permit to operate.

A common alternative fuel utilized in Europe for cement kilns is SRF and European standards are already developed; however, Canada must follow suit and develop/adopt standards that are relevant to the Canadian context, including characteristics and location. In addition, standardization and characterization ensure that AFs perform reliably and safely during distribution and storage, as well as in the kiln.

In Canada, Lafarge, a member of the Holcim Group, has commissioned its state-of-the-art Low-Carbon Fuel facility at the Exshaw Cement Plant (GCCA, 2024). Developed over the past five years through extensive environmental studies, economic and logistical reviews, and community consultation, this facility will reduce the plant's reliance on traditional fuels by replacing up to 50% of natural gas used for one of its kilns. This shift is expected to divert as much as 120,000 tonnes of construction demolition materials (CDM), a majority of which is wood based from landfills annually, resulting in lowering CO<sub>2</sub> emissions by as much as 30,000 tonnes annually. Standardization and characterization would be necessary to meet the natural gas replacement targets.

The need for standardization of gaseous fuels such as hydrogen and RNG is less critical for the operation of the cement kiln as the variation in these fuels from different suppliers is significantly less than solid fuels. For gaseous fuels, standardization is needed at the production site to ensure the fuel can be transported in a pipeline without issue. The research gaps discussed below deal primarily with solid alternative fuels.

## 19.2 Knowledge gaps

### 19.2.1 Applicability of Existing Standards

*“ISO standards from TC238 for solid biofuels and TC300 for solid recovered fuels (SRF) can be considered but must be researched on the proportion to ensure cement and concrete meets performance expectations by the end user.”*

For alternative solid fuels there are existing standards to govern certain properties including ISO standards under TC238 for solid biofuels and TC300 for solid recovered fuels (SRF). These standards were primarily designed for applicability to transportation and combustion in solid fuel power plants. Their usefulness for cement kiln operators must be investigated to determine whether or not it is worth the cement manufacturer using fuels certified to these standards. For instance, ISO 21640:2021 “Solid Recovered

---

Fuels - Specifications and Classes” does not have a specification for the inorganic components of the fuel, something that would be of importance to the quality of the clinker produced. As well, there is no requirement to specify biogenic content of the solid fuel as would be necessary for carbon accounting of the cement production process. There is no standard for hazardous wastes used as a fuel.

### **19.2.1.1 Activities Recommended by Workshop Participants**

#### Short Term

- Assess opportunities to leverage TC238 standards on 'major traded forms' regarding fuel particle size, density, dimensions, etc. for material conveyance. Assess opportunities to co-process alternative fuels to appropriate feed points in the kiln systems. As an example: fines at the main burner, coarse at the calciner, lumps at mid kiln or kiln inlet.

### **19.2.1.2 Research Pathways**

#### Short Term

A thorough review of the existing standards in ISO TC238 and TC300 is required to assess their applicability to cement kilns in terms of fuel chemical and physical properties, specifically: heating value, ash composition, particle dimensions, grindability and bulk density. The chemical properties of the solid fuel will affect the suitability of the fuel for combustion in the pre-calciner and kiln. The physical properties of the fuel will determine the suitability of existing fuel storage, handling and grinding equipment, as well as determining if one standardized fuel is more suited to one part of the cement production system than another, for example: fines at the main burner, coarse at the calciner, and lumps at mid kiln or kiln inlet. Based on the review of existing standards and the analysis of available fuels, modifications to the existing standards under TC238 and TC300 could be recommended.

The assessment of the available waste streams in the proximity of cement plants and the applicability to the available standards described in Chapter 18 would also need to take place.

#### Medium Term

Support from regulators is a necessary component for the adoption of standardized fuels. In the short and medium term, consultations with regulators and modification of existing regulations can be conducted to ensure alternative solid fuels can be used.

#### Long Term

Existing standards may be deemed inadequate for cement plants and require updating or the creation of new standards specifically for application to cement plants. This would require significant testing of different fuels and their performance in demonstration or full scale systems. As well, the process of creation/modification of standards is lengthy,

---

requiring significant input and consultations with experts from industry, regulators and the academic community.

## **19.2.2 Performance of Standardized Fuels**

*“Standard tests for consistent performance in terms of temperature, radiative heat fraction, heating value of fuel, and consistent operation with low maintenance”*

Alternative fuels vary significantly in their chemical properties and combustion dynamics from typical coal. The heating value of the fuel determines the feeding rate required, and alternative fuels typically have a lower heating value than coal, with the exception of high ash lignite, affecting the carbon accounting for the system. The relative fractions of volatiles and fixed carbon can affect the type of heat produced, convective or radiant. The heterogeneity of alternative fuels can affect their combustion dynamics as well; however, the use of standardized, densified fuels reduces this effect. The combustion performance of alternative fuels in terms of maintaining consistent temperature, effectiveness in heat transfer to the clinker and operability is required research for the adoption of these fuels. Standard tests for consistent performance in terms of temperature, radiative heat fraction, heating value of fuel, and consistent operation with low maintenance are needed.

### **19.2.2.1 Activities Recommended by Workshop Participants**

No research activities on this topic were identified during the workshop session.

### **19.2.2.2 Research Pathways**

#### Short Term

Determining the performance of standardized fuels requires combustion testing or modelling of fuel combustion in different stages of the cement production process. In the short term modelling could be conducted based on existing models of fuel combustion in cement kilns. As well, design of test methods and apparatus for combustion testing of alternative fuels could begin.

#### Medium Term

Laboratory studies on the performance of standardized solid fuels in a bench scale combustion would require the establishment of a testing facility with a laboratory scale kiln and pre-calciner. The emphasis would be on emissions from combustion of standardized fuels and performance in terms of temperature, radiative heat fraction, heating value of fuel, and consistent operation with low maintenance.

#### Long Term

---

Demonstration scale studies on the performance of standardized fuels in operational cement kilns are required as a proof of concept. This would require significant effort from an established/emerging alternative fuel producer as cement kilns use large quantities of fuel.

### **19.2.3 Effects of Fuel Impurities on Cement**

*“Waste fuels can have a very different ash composition to fossil fuels (increased alkali metals). How will these effect quality of cement?”*

Impurities including: alkali metals (Na, K), alkali earth metals (Ca, Mg), halogens (Cl), heavy metals (Fe, Al, etc.) and other non-metals (e.g., S) in the fuel can impact the quality of the clinker/cement. At high temperature, impurities in the ash such as alkali metals will combine with each other and with the clinker to form a wide variety of different compounds.

Waste fuels can have a very different ash composition to fossil fuels (increased alkali metals). Type and quantity of impurities in alternative fuels vary greatly depending on the source of the fuel, e.g., agricultural waste biomass would contain significant amounts of silica and potassium, whereas SRF from sewage sludge would contain significant amounts of sulphur. Research on the effects of impurities on cement quality is needed prior to wide scale adoption to maintain the cement and resulting concrete quality and ensure its safety as a building material.

#### **19.2.3.1 Activities Recommended by Workshop Participants**

No activities for this gap were identified during the workshop sessions.

#### **19.2.3.2 Research Pathways**

##### Short Term

Chemical analysis of specific targeted fuels should be conducted to determine their potential impact on cement quality based on previous studies in literature. As well, the chemical compositional analysis of the ash from alternative solid fuels produced in a similar environment to that in the cement kiln should be carried out. Simulating kiln conditions is essential for this work, as the extreme temperatures and high carbon dioxide atmosphere can affect the types of compounds produced in the ash.

##### Medium Term

Combustion testing of different fuels with a wide range and types of impurities still within the acceptable range in the standards, in bench/laboratory scale combustion systems simulating the conditions experienced in a cement kiln or calciner should be carried out in order to determine the effect of the impurities on the resulting cement and flue gas

---

stream. This work should produce small amounts of clinker that can be used to make OPC or PLC, allowing the performance of the cement to be tested.

### Long Term

As with the previous gaps around the use of standardized fuels, a demonstration of cement production in a full scale cement plant utilizing fuels that fit the existing standards should be conducted. Such demonstrations are already underway in many parts of the world (GCCA, 2024). A key part of the demonstration project would be the assessment of the quality of the resulting concrete to determine if it meets short and long term performance requirements.

## **19.2.4 Storage and Handling of Low Carbon Fuels**

*“Since low carbon fuels such as solid biofuels and SRF have biomass components, they cannot be left outside for long periods...”*

Storage and handling of solid fuels is a challenge for all solid fueled systems. The challenges increase when the solid fuel contains organic components as they cannot be left outside uncovered like coal. Prior to combustion, solid fuels must be transported to the plant site, stored (potentially for weeks or months), transported into the plant via conveyor or screw, ground/chopped into fine particles, and fed into the furnace/kiln. At each step in this handling, fines are created and pose an explosion hazard. As well, biogenic based alternative solid fuels can self-heat and spontaneously combust due to a combination of biological and chemical decomposition. This has resulted in significant loss of property and even life due to storage of wood pellets. These decomposition reactions also release potentially toxic gases and consume oxygen, generating a lethal environment within a storage vessel. Several deaths have occurred from workers entering spaces where wood chips and pellets are stored.

Much work has been conducted on the storage and self-heating of wood-based fuels, in particular wood pellets, which are a globally traded commodity in the millions of tonnes per year. The storage of used or post-consumer waste fuel is little understood and is likely to be significantly different than for wood-based fuels given the differences in chemical makeup.

In addition to safety hazards, care in storage and handling is necessary to avoid loss of fuel or significant alteration in particle size due to attrition or weathering of densified fuels, which would make handling more challenging.

Standards exist outlining safe handling and storage for alternative solid fuels including: ISO 20024:2020 “Solid biofuels - Safe handling and storage of solid biofuel pellets in commercial and industrial applications” and ISO 21912:2021 “Solid recovered fuels — Safe handling and storage of solid recovered fuels.” The applicability of these standards to cement plants needs to be examined. In addition, the cement and concrete plants

---

may need to be modified to accept these low carbon fuels. The compatibility of existing material handling systems with alternative solid fuels remains to be determined.

#### **19.2.4.1 Activities Recommended by Workshop Participants**

##### Short term

- Fuel storage testing (off-gassing, weatherability) of different standardized fuels. Assess the opportunity to "drop in" low carbon fuels into existing plant infrastructure instead of having to replace material conveyance systems to accept low carbon fuels. Guidelines for pre- and co-processing highlighting best practices in safety, operations and management.

#### **19.2.4.2 Research Pathways**

##### Short Term

Physical characterization of potential waste fuels should be carried out to assess bulk properties: bulk density, durability (for densified fuels), grindability, and bulk flow properties such as angle of repose. Fuel storage testing (off-gassing, weatherability) of different standardized fuels should be tested in bench scale systems. In addition, the opportunity to "drop" low carbon fuels into existing plant infrastructures instead of having to replace material conveyance systems to accept low carbon fuels should be assessed. Guidelines for pre- and co-processing should be produced, highlighting the best practices in safety, operations and management.

##### Medium Term

Lab / demonstration scale experimental studies of storage of an array of alternative solid fuels should be carried out to determine their self-heating and off-gassing characteristics, with the focus on post-consumer and densified solid fuels as these are less understood.

##### Long Term

The laboratory scale testing could take a significant amount of time and could therefore continue into the long term if a significant number of fuels are tested. The next step would be full scale testing of alternative solid fuels for self-heating and off-gassing in storage vessels on the scale of full scale systems.

## **20 Accessing waste streams**

### **20.1 Introduction**

Cement manufacturing facilities use significant quantities of fuel for the cement making process, on average about 4.7 GJ of heat energy for every tonne of cement produced, and Canada's 15 cement plants produce upwards of 14.3 million tonnes of cement per year, or 67 million GJ of heat energy (Natural Resources Canada, 2009). Some plants

---

consume in excess of 200,000 tonnes of coal per year. To replace this heat input with potentially lower heating value alternative fuels is an enormous logistical task. For example, Canada exports approximately 1,369,000 tonnes of wood pellets per year which equates to approximately 25 million GJ, so the total wood pellet production would need to be more than doubled to replace the heat input from non-renewable sources. This will require fuel from a wide variety of sources, emphasizing again the need for standardization of fuel and highlighting the need for significant supply chain logistics. As well, transportation costs and GHG emissions are significant for biomass or solid waste fuels due to their relatively low energy density, so sourcing fuel close to the plant is essential for minimizing cost and GHG emissions. This gap discussion will focus on solid waste streams.

TEA / LCA tools are the basis for understanding the feasibility, cost and GHG emission reduction potential of using alternative fuels for cement production and determining the best, locally available fuel sources for decarbonization. As such, primary research is needed for all the gaps before the development of a robust TEA/LCA model for fueling of a cement plant, incorporating all aspects of using alternative fuels, including but not limited to: cost of plant modifications, GHG emissions from transportation and processing of waste fuels, impact of any required pre-processing of waste fuels, and the impact of waste disposal policies on the supply and cost of alternative fuels.

As per the Global Cement and Concrete Association (GCCA, 2024), by promoting the adoption of alternative fuels necessitates policies that provide access to appropriate waste and secondary material streams, such as biowaste, by minimizing the landfilling of waste that could be co-processed in cement kilns. These policies should also support the segregation of waste streams to enhance resource efficiency and simplify the environmental permitting process for cement plants. Furthermore, it is essential to establish fair access to biomass across all sectors of the economy.

## 20.2 Key Knowledge Gaps

### 20.2.1 Benefits of co-processing versus traditional disposal

*“Specific benefits of coprocessing waste-based fuel in cement kilns compared to incineration or alternative energy recovery processes.”*

The majority of waste in Canada is sent to landfills; however, some waste is used for energy generation. The bulk of the waste to energy in Canada is from anaerobic digestion and incineration of sewage sludge. There are a few solid waste-to-energy facilities including the Durham-York energy Center, Covanta waste-to-energy facility in BC and Enerkem’s waste to fuels facility in Alberta. The usage of waste as an energy source is likely to increase in the future and decisions will need to be made regarding the best use of waste streams. Specific benefits of co-processing waste-based fuel in

---

cement kilns compared to incineration or alternative energy recovery processes needs to be examined.

As with waste-to-energy facilities, there is public opposition to combustion of waste. Lack of regionally-specific research is a barrier to social acceptance of using these materials in our kilns.

In Canada, Votorantim Cimentos has unveiled a new cement kiln infrastructure at its St. Marys, Ontario plant, signifying a major step towards its goal of achieving net zero emissions by 2050 (GCCA, 2024). This advanced system is designed to utilize waste materials, including non-recyclable plastics, as a lower-carbon fuel source, replacing up to 30% of the fuel traditionally used in cement production. The initiative is expected to cut carbon emissions by over 39,900 tonnes by 2030—comparable to removing more than 9,400 cars from the road for a year. Backed by Environment and Climate Change Canada’s Decarbonisation Incentive Program, the project not only reduces emissions to address climate change but also helps divert waste from landfills, supporting broader sustainability objectives.

### **20.2.1.1 Activities Recommended by Workshop Participants**

#### Short term

- Literature Review to understand the benefits and impacts of using waste as fuels compared to alternatives including societal impacts. The review should indicate data and knowledge needs.

#### Medium term

- Laboratory/facility studies to quantify and confirm the results of the literature review and fill identified needs.

### **20.2.1.2 Research Pathways**

#### Short Term

The benefits and impacts of using waste as fuel in cement plants compared to traditional disposal methods should be quantified, including societal impacts. This would start with a thorough review of the literature to examine existing studies on the impacts of different disposal techniques. The review should be designed to provide understanding of what information is needed to complete the desired TEA and LCA investigations. Specific attention should be paid to the impact of non-biogenic wastes as their GHG reduction capacity over traditional fossil fuels could be limited in cement production. A further recommendation is the use of artificial intelligence (AI) to create Canada specific models for optimizing waste feedstock for each region to provide a reliable supply and maximize GHG reductions.

#### Medium/Long Term

---

The primary means to elucidate the impact of waste use in cement kilns versus traditional disposal is through TEA and LCA. As such in the medium and long term, a robust TEA/LCA tool could be built and continuously improved through data collection and increasing levels of complexity/granularity to the modelling.

Laboratory studies on the combustion of waste fuels are more critical to other research gaps, but the results of them could be used to determine inputs to the TEA / LCA modelling such as combustion efficiency and required emissions clean-up.

## **20.2.2 Regional fuel availability**

*“Lack of regionally-specific research is a barrier to social acceptance of using these materials in our kilns.”*

As mentioned in the introduction, the significant fuel heat input required for cement production in Canada will require robust local supply chains for both biomass and waste fuels. Other than wood pellets, these supply chains do not exist. Sourcing locally available fuels that meet the requirements of the cement plant will be a significant challenge. Research is required to identify all the potential alternative fuel streams regionally available as it will undoubtedly take a large number of sources to supply a single cement plant.

### **20.2.2.1 Activities Recommended by Workshop Participants**

No activities for this topic were identified during the workshop sessions.

### **20.2.2.2 Research Pathways**

#### Short Term

Supply chain issues related to materials have previously been discussed in Chapter 18. In addition, a literature review on the impacts of waste management policy on the supply of waste fuels should be carried out to guide policy makers on the correct drivers to support waste to energy. This work should include a survey of existing policies/market conditions in Canada (by province/region) and comparison to other jurisdictions with high fuel substitution rates. Questions might include “How do landfill costs, EPR policies, waste hierarchies, zero waste mandates etc. impact the availability and commercial viability of different alternative fuel streams?” “What's working and what are the barriers?”

#### Medium/Long Term

Once the local biomass / waste fuel supply is determined, model supply chains could be derived for each of Canada's cement production facilities. An important aspect of these supply chains would be the pre-treatment required for each waste stream to make it suitable for use in a cement plant. As mentioned previously, the reduced heating value

---

of biomass / waste fuels is a significant hurdle to their application, and densification, drying, torrefaction or pyrolysis is likely required to make a suitably energy dense fuel. This analysis could identify the best suited pre-treatment to each biomass / waste fuel stream regionally available.

### **20.2.3 Impacts of current waste disposal policies on fuel availability**

*“Understanding (potentially unintended) impacts of current waste policies on access and supply of potential fuels”.*

Regional waste disposal policies can have a significant impact on the available waste stream. For example, Vancouver’s policy of zero organics in the municipal waste stream increases the tipping fees for this waste and provided an opportunity for waste-to-energy producers with a more favourable business case. Future restrictive policies on waste disposal are likely to be favourable to the waste-to-energy facilities in increasing tipping fees; however, increasing carbon pricing, increased recycling requirement policies, or policies to reduce waste generation could increase the demand for waste as a fuel or reduce the supply, negatively affecting the economics of using waste as a fuel. For example, Sweden imports waste from nearby countries to supplement their waste-to-energy facilities as increased recycling has reduced the amount of waste locally available. This decreases the funds generated from tipping fees and increases the GHG emissions of the process through long distance transportation of waste.

#### **20.2.3.1 Activities Recommended by Workshop Participants**

##### Short Term

- White Paper on impacts of waste management policy supply of materials. Survey of existing policies/market conditions in Canada (by province/region) and comparison to other jurisdictions with high fuel substitution rates. How do landfill costs, EPR policies, waste hierarchies, zero waste mandate etc. impact the availability and commercial viability of different alternative fuel streams? What's working and what are the barriers?

#### **20.2.3.2 Research Pathways**

##### Short Term

A review of the impacts of different policies on general waste-to-energy and bioenergy practices in different jurisdictions would be the first required research effort. The TEA/LCA model described earlier in this chapter should incorporate the effect of policies on the model outputs.

##### Medium/Long Term

---

TEA / LCA models can have significant variations in level of complexity. Once the model is developed it can be continuously improved upon through increasing granularity and expansion of the dataset.

## **20.2.4 Engineering kilns for high levels of waste use**

*“Accessing higher grade biofuels to get beyond 40-50% substitution.  
What capital investments at the kiln would be needed?”*

As discussed in the introduction, low heating values are the limiting factor to increasing the substitution ratio of alternative fuels in cement kilns beyond 40-50%. Additionally, the combustion characteristics, physical properties and potentially increased emissions from impurities in the fuel are engineering challenges to increase the substitution ratio. Pre-treatment of the fuel through densification, drying, torrefaction and pyrolysis are potential fuel side solutions to some of these challenges. These challenges could also be overcome potentially more economically by altering or engineering kilns to accept lower quality fuels. Research is needed to determine what capital investments at the kiln would be needed, and how these fuels can be cost competitive without the need for significant pre-treatment.

### **20.2.4.1 Activities Recommended by Workshop Participants**

#### Medium Term

- Quantification of capital investments that would be needed for advanced zero carbon fuels.

## **20.2.5 Research Pathways**

#### Short Term

A literature review of the modifications that would be required to the kiln and fuel handling systems to allow for the use of low quality fuels should be carried out. Research to quantify the capital investments that would be needed for advanced zero carbon fuels should be conducted to provide data to into the fuel switching TEA / LCA model described earlier determine if it is more economical and favourable for GHG emission reductions to modify the kiln and associated fuel handling for the use of low quality fuels or to pre-treat the fuels for direct use in an unmodified kiln.

#### Medium Term

As in previous gaps, a TEA / LCA tool built in the short term would benefit from continued improvement, reducing the uncertainty of the model and allowing for application to individual facilities.

#### Long Term

---

In the long term there may be opportunities for greenfield kilns designed to operate on alternative fuels. A robust TEA / LCA tool could guide the design of a new cement plant in choosing the best available fueling option for cost and GHG emission reductions.

## **21 Evidence in support of alternative fuel use regulation**

### **21.1 Introduction**

In order to have regulations for cement kilns that protect human health, as well as the environment, evidence and data are required to develop methods and requirements for regulations. There are several areas where this is important for cement kilns, as fuel-switching can have impacts on emissions in unanticipated ways and perhaps produce pollutants that wouldn't normally be monitored or regulated prior to fuel-switching. Therefore, comprehensive data and an understanding of the behaviour of an alternative fuel throughout the process are needed. In addition, standardization and regulation of the fuel itself are needed, as described in Chapter 19, and data is required understand variability and classifications of fuels, particularly for wastes. For fuels such as hydrogen, evidence on compatibility with infrastructure is critical to ensure its use does not cause problems such as embrittlement.

### **21.2 Key knowledge gaps**

#### **21.2.1 Alternative fuel standards**

*“Standards for low-emission fuels with high energy density”*

As discussed in Chapter 19, there are a number of standards that cover the quality of biomass and Solid Recovered Fuels (SRFs) under ISO TC238 and TC300. These standards do not directly cover fuels for use in kilns, but were tailored more to combustion in energy generating facilities. The unique conditions inside the kiln, particularly the high concentration of CO<sub>2</sub> and extreme temperatures in excess of 2000°C in the flame and 1400°C in the burning zone, could lead to the generation of different pollutants compared to combustion for energy production which it typically reaches 1200°C.

##### **21.2.1.1 Activities Recommended by Workshop Participants**

No activities for this topic were identified in the workshop session.

---

### 21.2.1.2 Research Pathways

The research pathways for this gap are the same as those proposed in Chapter 19 on the Applicability of Existing Standards. It involves: identification of gaps in the standards through review; experimentation at the bench, lab and eventually demonstration scale to determine the emission profile of different alternative fuels that fit the existing standards; and suggesting modifications of the existing standards to account for the unique aspects of fuel combustion in the kiln.

### 21.2.2 The effect of low carbon alternative fuels on air pollutants

*“Lack of understanding of the effects of low carbon alternative fuels on air pollutants (NO<sub>x</sub>, SO<sub>2</sub>, PMs, metals, D/F, etc...)”*

The emissions of a cement kiln can be divided into four categories – gases (such as NO<sub>x</sub>, CO, and acid gases), particulate matter (PM), semi-volatile and volatile organic compounds, and heavy metals. NO<sub>x</sub> comprises of nitric oxide (NO) and nitrogen dioxide (NO<sub>2</sub>). Carbon monoxide is generally a consequence of incomplete combustion. Acid gases emitted by kilns are typically made up of compounds of chlorine, sulphur or fluorine. Particulate emissions can be comprised of dust originating from the raw material (limestone and clay) and the fuel combustion. Organic compounds in the kiln’s emissions may include dioxins and furans in addition to volatile organic compounds (VOCs). Metal emissions may originate from the raw materials and can consist of non-volatile metals like vanadium, semi-volatile metals like cadmium and lead, and volatile metals like thallium and mercury. Increasing use of AFs in cement kilns requires comprehensive research on their impact on the kiln emissions.

The type of AF and the amount of co-processing can affect the kiln emissions. While there is a lot of location-specific emission information, a general understanding of how different AFs impact the kiln emissions is limited. This can be addressed by laboratory and field scale research. A brief overview on the four categories of emissions from the AF perspective is provided below.

#### Gases

One of the most common NO<sub>x</sub> formation pathways in a kiln is the thermal NO<sub>x</sub> which is dependent on the peak flame temperature of the burner. NO can also be formed from the fuel bound nitrogen and the char nitrogen (Nance, Abbas, Lowes, & Bretz, 2011). One way to reduce the NO<sub>x</sub> formed in the kiln is through a process called reburning in the calciner (downstream of the kiln) under fuel-rich conditions. Subsequently, selective catalytic/non-catalytic reduction (SCR/SNCR) is used to remove the remaining NO<sub>x</sub>. Use of plastic waste and shingle/tire waste as fuel reduces the NO<sub>x</sub> emissions according to studies by (Prakash A, Palkar RR, 2021 Nov 26) and (Chandler J., 2021) respectively. (Hannoun G, 2019) and (Ningsih RY, Goembira F, Komala PS, Putra NP,

---

2019 Sep 30) have also reported a decrease in SO<sub>2</sub> and NO<sub>x</sub> with use of biomass-based and sewage-sludge-based AF when compared to exclusive coal use. In most AFs, the sulphur content is usually less than coal, and additionally, the formed SO<sub>2</sub> may be trapped within the clinker (Hannoun G, 2019).

Chlorine-based salts can affect the clinker quality, and the chlorine content in the AF should be evaluated accordingly (Hannoun G, 2019). Chlorine present in polythene waste is typically converted to sodium/potassium chloride instead of being released as hydrochloric acid fumes (Prakash A, Palkar RR, 2021 Nov 26). Hydrogen fluoride (HF) may also be produced in small amounts when co-processing polythene waste.

### *Particulate Matter*

Bag filters and cyclones with electrostatic precipitators are generally used to capture PM emissions at efficiencies of over 98% (Gupta RK, Majumdar D, Trivedi JV, Bhanarkar AD., 2012 Dec). However, owing to the wide variety of AFs, information on PM emissions for individual AFs is limited. According to one study, there is no change in PM emissions with plastic waste used as AF (Prakash A, Palkar RR, 2021 Nov 26).

### *Semi-volatile and volatile organic compounds*

Dioxins (polychlorinated dibenzo-p-dioxins or PCDDs) and furans (polychlorinated dibenzofurans or PCDFs) are a group of 210 organic chemical species that are toxic micro-pollutants (Cunliffe AM, Williams PT, 2009 Feb). Waste incineration is a major source of dioxin and furan pollution therefore waste utilization in cement kilns is a concern. The most important formation mechanism is the heterogeneous reaction mechanism (de-novo synthesis) occurring in the temperature range of 200-400 °C (Cunliffe AM, Williams PT, 2009 Feb). Pre-co-processing and co-processing of plastic waste can cause minor formation of dioxins and furans but emissions are below the regulated limits (Prakash A, Palkar RR, 2021 Nov 26). According to a study by (Muliane U, Lestari P, 2018), benzene and toluene are the highest concentration VOCs from a cement plant using AFs such as biomass, MSW or a mix of both. Again, the fraction of individual VOCs is dependent on the AF.

### *Heavy Metals*

Non-recycled plastic waste AF generally does not increase heavy-metal pollution of cement kilns (Prakash A, Palkar RR, 2021 Nov 26). Sewage sludge may contain various heavy metals such as chromium, vanadium and mercury. While the non-volatile heavy metals may be captured in the clinker, volatile metals like mercury may be an issue and require remedial actions at the kiln and stack level (Lafarge, 2024) (Hannoun G, 2019). Therefore, heavy-metal emissions need to be examined in detail with respect to AF use in the cement production.

---

### **21.2.2.1 Activities Recommended by Workshop Participants**

#### Short Term

- Study the environmental impacts of alternative fuels.

### **21.2.2.2 Research Pathway**

#### Short Term

Once potential AF feedstocks have been identified, they should undergo combustion in simulated kiln conditions so that potential emissions can be assessed.

#### Medium Term

Depending on the results of the short term tests, further work may be needed to develop methods to remove excess emissions from kilns. Methods of testing and frequency of testing feedstocks to ensure consistent emissions levels should be developed and demonstrated. Engagement with regulatory agencies in the development of the testing protocols is recommended.

#### Long Term

Demonstration projects will be needed to confirm the emissions predicted by laboratory studies and the effectiveness of emissions testing protocols and scrubbing methods.

### **21.2.3 Support for consistent fuel supply**

*“Verifying constant and consistent feedstock availability. Agreement between provinces and waste management companies to streamline the non-recyclable plastic to cement kilns.”*

Constant and consistent feedstock availability is critical to ensure that switching to alternative fuels does not affect product quality or process downtime. This has been described in Chapters 18 to 20 and is an important gap for all areas. Evidence on the availability will be needed to de-risk investments in this area and support required regulation to allow for fuel-switching.

### **21.2.3.1 Activities Recommended by Workshop Participants**

#### Short Term

- Market research in support of availability for waste fuel around the cement kilns and transportation options.
- Separate research project examining the impact of transportation from collection facility to the cement plant.

### **21.2.3.2 Research Pathways**

Research pathways for this knowledge gap have been described in previous chapters.

---

## 22 Discussion

### 22.1 Knowledge Gap Categories

The workshops identified 75 separate knowledge gaps, sixty related to cement and concrete and 15 to alternative fuels. Twenty one of the gaps reflect topic specific issues, such as the need for research on the use of hydrogen as a cement kiln fuel or investigation of safety issues related to the use of nanomaterials in cement. The remainder can, however, be grouped into seven categories, as shown in Table 4.

*Table 4 Common Knowledge Gaps by type*

Knowledge Gap Category	Number
Development or improvement of test methods	8
Concrete performance and durability	11
Assessing GHG emissions reductions benefits	12
Improvements to understanding of fundamentals	6
Supply chain issues	10
Changes to Standards	7

The Knowledge Gap categories in Table 4 include Alternative Fuels issues as well as those for cement and concrete. Test methods, applicability of standards, supply chain issues, etc. were all raised as issues for both types of work, although the specifics of the issues differed.

In the case of cement and concrete, these categories correspond to basic questions that are likely to be asked for any new low carbon construction material or process:

- Is it clear what the material does and how it differs from existing choices?
- How will it perform compared to what is currently used?
- Can the performance be tested?
- Does the material really provide greenhouse gas reduction benefits?
- Is it available in enough quantity to meet the demand?
- Is it covered by a standard, reducing the risk of using it? If not, does it need to be standardized?

Being able to supply answers to the above is likely key to successful deployment of the technology. Other factors such as cost and customer acceptance are, of course, likely to come into play in decisions to adopt new materials, but they are outside the scope of the Workshops and this report. NRC is, however, pursuing research on the reasons and roadblocks for technology adoption in the first place.

Very similar questions need to be addressed for alternative fuels, barring perhaps the first one. In that case an additional technical/policy question is likely to take priority:

- Will governments allow the use of alternative fuels in cement kilns?

Changes in kiln fuels are capital intensive, meaning that this last question will need to be answered positively before significant investments are made.

Since many of the knowledge gaps can be grouped together, it is worth considering whether the actual research activities can be grouped together as well in order to reduce costs or time to deployment. In order to aid in this analysis, Table 5 shows the Workshop sessions that fall into each category. Cement and concrete issues are divided from those related to alternative fuels by a bar where both occur. Examining the specifics of the knowledge gaps recorded in each session suggests that there are some areas of overlap that can be exploited. No one category can, however, be addressed by a single research activity. Possibilities for combined research are discussed below following the order of the categories in Table 4Table 5.

*Table 5 Knowledge Gaps Corresponding to Workshop Sessions/Report Chapters*

Knowledge Gap Category	Workshop Sessions/Report Chapters
Development or improvement of test methods	<ul style="list-style-type: none"> <li>• Alternative approaches to design and construction</li> <li>• Alternative Sources of Standard SCMs</li> <li>• Alternative supplementary cementitious materials (ASCMs)</li> <li>• Biomaterials</li> <li>• Natural Carbonation</li> <li>• Long term performance of concrete containing sequestered carbon dioxide</li> <li>• Assessing/quantifying sequestration</li> <li>• Sequestration in high volume SCM and other specialized concrete mixes</li> </ul>
	<ul style="list-style-type: none"> <li>• Standardization of fuels to produce stable fuel performance</li> </ul>

Table 5, continued

Knowledge Gap Category	Workshop Sessions/Report Chapters
Concrete performance and durability	<ul style="list-style-type: none"> <li>• Alternative approaches to design and construction</li> <li>• Alternative Sources of Standard SCMs</li> <li>• Alternative supplementary cementitious materials (ASCMs)</li> <li>• Increasing limestone content in Portland limestone cement (PLC)</li> <li>• Coarse and fine recycled concrete aggregate</li> <li>• Alternative binders</li> <li>• Residential concrete</li> <li>• Precast concrete</li> <li>• Nanomaterials</li> <li>• Long term performance of concrete containing sequestered carbon dioxide</li> <li>• Sequestration in high volume SCM and other specialized concrete mixes</li> </ul> <hr/> <ul style="list-style-type: none"> <li>• Standardization of fuels to produce stable fuel performance</li> </ul>
Assessing GHG emissions reductions benefits	<ul style="list-style-type: none"> <li>• Alternative approaches to design and construction</li> <li>• Increasing limestone content in Portland limestone cement (PLC)</li> <li>• Alternative binders</li> <li>• Residential concrete</li> <li>• Precast concrete</li> <li>• Low carbon high performance/ultra-high performance concrete</li> <li>• Nanomaterials</li> <li>• Biomaterials</li> <li>• Natural Carbonation (2x)</li> <li>• Assessing/quantifying sequestration</li> </ul> <p>Guidance on sequestration use</p>

Table 5, continued

Knowledge Gap Category	Workshop Sessions/Report Chapters
Improvements to understanding of fundamentals	<ul style="list-style-type: none"> <li>• Residential concrete</li> <li>• Low carbon high performance/ultra-high performance concrete</li> <li>• Nanomaterials</li> <li>• Biomaterials</li> <li>• Guidance on sequestration use</li> </ul>
Supply chain issues	<ul style="list-style-type: none"> <li>• Alternative fuel choices</li> </ul>
Changes to Standards	<ul style="list-style-type: none"> <li>• Alternative Sources of Standard SCMs</li> <li>• Alternative supplementary cementitious materials (ASCMs)</li> <li>• Coarse and fine recycled concrete aggregate</li> <li>• Alternative binders</li> <li>• Nanomaterials</li> <li>• Biomaterials</li> </ul>
	<ul style="list-style-type: none"> <li>• Alternative Fuel Choices</li> <li>• Accessing waste streams (2x)</li> <li>• Evidence in support of fuel use regulation</li> </ul>
	<ul style="list-style-type: none"> <li>• Alternative approaches to design and construction</li> <li>• Alternative Sources of Standard SCMs</li> <li>• Increasing limestone content in Portland limestone cement (PLC)</li> <li>• Sequestration in high volume SCM and other specialized concrete mixes</li> <li>• Guidance on sequestration use</li> </ul>
	<ul style="list-style-type: none"> <li>• Standardization of fuels to produce stable fuel performance</li> <li>• Evidence in support of fuel use regulation</li> </ul>

---

## 22.2 Cement and Concrete

### 22.2.1 Development or improvement of test methods

In the case of test methods, most of the issues described are subject matter dependant. New modelling and full scale testing approaches are needed to validate alternative designs and material specific tests are needed for SCMs and ASCMs. Alternative approaches to qualifying ASCMs and comparing them to existing SCMs are also identified. However, there are clear overlaps in the various carbon sequestration knowledge gaps. Quantifiable field measurement techniques would be useful for assessing both natural and artificial carbonation of concrete, while laboratory methods to provide performance assessments would apply to both approaches and are essential for broad acceptance of the technology. Research projects in these areas should be therefore designed to apply any developed test methods as widely as possible.

### 22.2.2 Concrete performance and durability

In the case of concrete performance and durability, the same types of tests will need to be carried out on many of the different materials in question. Concrete durability, creep and resilience tests would be expected to apply in general. In some cases, specific classes of materials may not need to have some tests applied (i.e. an alternative binder may not have the chemistry that would produce alkali-aggregate attack), but it is likely that testing would be required initially to demonstrate that the test is truly unnecessary.

It is also possible that some novel materials might experience different deterioration mechanisms, which would need to be identified and tested to understand their long term performance. That being said, there are significant benefits to be gained by testing materials under the same conditions, particularly when decisions need to be made on which ones to support or use from a selection of options. Direct comparisons between results taken on the same equipment and in the same environment would allow the best performing materials to be identified prior to expanded, multi-laboratory testing. In addition, calls for better accelerated testing methods and the use of outdoor, long-term environmental exposure sites are common to a number of the chapters. The former should be developed so that they are applicable to most or all concrete materials, while one or two long term exposure sites should be used for all samples, with new materials added over time. Not only would the use of one or two national sites improve comparison between materials, they would also minimize the cost of site set up and simplify on-going maintenance. Field trials of materials to allow correlation between laboratory and real world performance will also be necessary. This may include analysis of aging concrete elements recovered from demolition sites to validate test methods and models.

---

It should be noted that any one laboratory will have limited capacity in terms of the number of samples that can be tested at one time and that the cost of testing would be likely to limit the number of different materials that can be tested. An initial screening process would be needed to select the materials to be tested at any given time. Additional materials might be tested at later times to add to the options for low carbon materials. A potential screening process will be discussed later in this chapter.

### **22.2.3 Assessing GHG emissions reductions benefits**

Unlike the work on concrete performance and durability where the same basic activity is needed for many different materials, work under this heading includes multiple different types of activities. In the case of the sessions on Alternative Approaches to Design and Construction (Chapter 2) and Residential Housing (Chapter 8), the gap is identified as the lack of tools to support what amounts to a simplified LCA process. For the sessions on Increasing limestone content in Portland limestone cement (Chapter 5), Alternative binders (Chapter 7), High Performance/Ultrahigh Performance Concrete (Chapter 10), Nanomaterials (Chapter 11) and Biomaterials (Chapter 12), the need is assist in determining whether particular technologies are worth pursuing. Similar needs are expressed in the sessions on carbonation (Chapters 13, 15 and 17), with the additional issue of determining whether artificial approaches to carbonation provide any additional benefits in the long term to decarbonization over natural ones. Finally, for precast concrete (Chapter 9), the gap is in how to evaluate emissions on the job site, in order to truly compare the carbon impact of precast concrete to cast in place. Multiple lines of research would therefore be needed to address all of these gaps. The technology assessment analyses that do not involve carbon sequestration might be done as a single project, with the assessments for carbon sequestration being a separate one. Individual research projects may be needed for the other topics.

### **22.2.4 Improvements to understanding of fundamentals**

Workshop sessions identified a number of areas where basic knowledge of the technology was lacking or guidance documents were needed. Residential concrete is perhaps a surprising inclusion on this list, but very few of the workshop participants were familiar with the particular needs of that part of the construction sector. That point suggested the need for improved communications and caused residential concrete to be included in this group of needs. None of these areas overlap, however, and separate activities would be needed to address each of them.

### **22.2.5 Supply Chain Issues**

Availability and reliability of supply is a common theme across many workshop sessions. It could be addressed using the same general approach in each case, although the actual work might need to be broken into separate projects to allow completion in a reasonable amount of time. Sufficient supply of materials at a

---

reasonable cost and the actual carbon reduction benefits of moving to those materials are likely to be key factors in determining whether an alternative approach to concrete is worth adopting.

### **22.2.6 Changes to Standards**

At least three different CSA cement and concrete standards (CSA A3000-23, A23.1/2-24 and A23.3-24) would need to be updated based on the results of the workshops. Multiple new materials and test methods may need to be added, resulting in a substantial workload for the standard technical committees and a need to prioritize which approaches are most beneficial.

## **22.3 Alternative Fuels**

While individual workshop sessions raised knowledge gaps that correspond to many of the cross-cutting themes described above, Supply Chain issues stood out as the single most important gap, being raised in 3 of the four sessions on Alternative Fuels. Initial work to determine available AF supply and whether it can be successfully used in cement kilns is clearly key to determining whether fuel switching is possible. A secondary question that was raised indirectly in many of the sessions is whether switching to alternative fuels is desirable. This question is highlighted by the need for research on whether the use of alternative fuels will impact cement performance or pollutant emissions, but also by fundamental questions of capital cost versus benefits in terms of GHG emissions and operating costs. The work on suitable TEA/LCA models outlined in Chapter 20 is a clear next step if suitable AF supply is available

## **22.4 Approaches to Technology Adoption by Cement and Concrete Users**

As noted earlier, there were 60 different knowledge gaps related to cement and concrete that were identified in the workshops. In some cases, each of those gaps represents multiple areas of research (i.e., alternative binders covers a wide variety of cements, any one of which would need substantial work to deploy in Canada). In addition to cost, material supply and effectiveness at reducing GHG emissions, a fourth screening requirement that should be considered in prioritizing work is the difficulty of technology adoption. Some of the technologies discussed in this report would require substantial changes in practice or high levels of additional knowledge amongst industry practitioners to put in place, while others are relatively easier to adopt because the procedures used to make concrete would not substantially change.

As examples, the use of alternative fuels, carbon sequestration at the cement plant and the use of recycled cement fines in clinker production would all produce carbon emissions reductions with little or no impact on the user of the cement. The use of

---

nanomaterials in concrete may, in contrast, require new health and safety measures, different mix designs, additional expertise at the concrete plant and the job site and provision for eventual appropriate demolition or recycling of the concrete. These would require significantly more effort on the part of the concrete producer and user to adopt. Other innovations discussed in this report fall somewhere between these two extremes. The more complex the route to technology adoption, the higher the benefits in terms of GHG emissions would need to be in order to justify the required effort.

Adoption of novel construction materials has not been well studied to date, although NRC has initiated research in this area. As a result, it would be difficult to quantify the impact of the degree of adoption difficulty in the same way one can quantify GHG emissions or cost. A qualitative approach suitable to support decision making is likely to be one outcome of the current research project.

## **22.5 Advantages and Disadvantages of Various Research Areas**

Given the wide number of knowledge gaps identified in the workshops, it is worth considering the advantages and disadvantages of each in order to prioritize where work should take place. It should be noted that the discussion below is not intended to assess the absolute value of particular research topics, but rather how they much they may reduce GHG emissions from cement and concrete and how easy the resulting changes may be to implement.

### **Alternative approaches to design and construction (Chapter 2)**

This session identified knowledge gaps performance based approaches to design, design to minimize concrete volumes, optimizing concrete reliability and modelling of long term concrete performance in novel low carbon materials. Work on including performance based design is underway in the National Building Codes and planned for relevant CSA cement and concrete standards. While fully developing performance based approaches are likely to take more than one code cycle, moving to performance based design for concrete fits well with existing codes and standards activities. Minimizing concrete volumes in design may require guidance for design practitioners and changes to specifications, but should not require changes in construction practices or concrete production, making a change in that area relatively easy to implement. Increasing materials reliability factors for concrete in buildings could potentially result in 10% or higher reductions in concrete volumes and therefore GHG emissions, but the extent of work necessary to make this change still needs to be determined. Finally, modelling of long term performance of low carbon concretes is likely necessary for performance based design to be completely implemented, but requires identification of the materials of interest and the development of data to support the models.

---

With the exception of the work on materials reliability factors, improving design practices by filling the knowledge gaps outlined in Chapter 2 is likely to have beneficial impacts on GHG emissions without requiring changes across the entire concrete construction value chain. Investigations into concrete materials reliability factors may also provide significant GHG reductions, but may also indicate requirements for broad changes in existing practices to improve quality control.

### **Alternative sources of Standard SCMs (Chapter 3)**

The workshop sessions on standard SCMs noted knowledge gaps around the availability of current SCMs, aspects of testing of harvested fly ash and availability and performance of ground glass. Calcined clays were not raised in the workshops, but also fall into this category. These SCMs are currently covered in the relevant CSA standards and all activities outlined in Chapter 3 on the results of these sessions should be relatively easy to implement. Understanding the available supply of standard SCMs is particularly important because they are essential for control of concrete deterioration in situations such as chloride penetration and alkali reactive aggregates as well as reducing the GHG emissions of concrete.

### **Alternative supplementary cementitious materials (ASCMs) (Chapter 4)**

ASCMs can replace existing SCMs, but may also have different beneficial properties in concrete mixes. They may also have different regional availability than traditional SCMs, resulting in lower transportation costs and emissions. They require more extensive testing than SCMs, however, and there may be little or no experience in their use amongst participants in a particular construction project. Knowledge gaps were identified related to supply chain security, the qualification of ASCMs and their performance in concrete. If SCMs will be in decreasing supply in the future, ASCMs will be essential as replacements. Transportation costs may make them regionally important even if they are not needed to replace SCMs. Considerable work has already been done to develop blended cements made with ASCMs such as limestone calcined clay cements (LCCC). This work could be used to accelerate the development of similar materials in Canada.

### **Increasing limestone content in Portland limestone cement (PLC) (Chapter 5)**

PLC with up to 15% limestone use has already been successfully deployed in Canada and is being used to provide reductions in emitted carbon in concrete. Further work to increase the limestone content in the cement is likely to be successful, given experience in Europe. Identified knowledge gaps included long term performance issues, quantification of GHG reduction benefits and the need for performance based standards to support adoption. European usage of higher limestone content PLC is restricted in terms of applications. Similar restrictions may be needed in Canada, which may complicate technology adoption.

---

## **Coarse and fine recycled concrete aggregate (Chapter 6)**

Coarse aggregate may take up a half or more of the mass per m<sup>3</sup> of concrete, but is responsible for a relatively small percentage of the concrete's carbon emissions. The processes such as crushing and cleaning needed to produce recycled coarse aggregate are also similar to those needed to produce virgin aggregate. While there has been a significant history of research on recycled concrete aggregate, the recycled concrete aggregate sessions produced the single highest number of knowledge gaps and related actions from any of the workshop sessions, suggesting that the industry does not find the available information sufficient to warrant the material's use. Recycling of fine aggregate to recover sand and the hydrated cement for potential re-use may make, however, make coarse concrete recycling more attractive in terms of GHG reduction benefits.

## **Alternative binders (Chapter 7)**

A wide variety of alternative binders have been proposed and, in many cases, implemented in other countries. Some of these binders, such as belite cements, are based on similar chemistries to OPC, while others use the hydration of different compounds or do not use hydration at all. Supply, environmental impacts, and performance were identified as key knowledge gaps in this area. Depending on the binder, production might require significant changes to cement plants or may require entirely different approaches to production. Changes to other parts of the current value chain during the concrete life cycle may also be needed, potentially making adoption of these technologies more challenging than others.

## **Residential concrete (Chapter 8)**

Residential concrete is estimated by the Canadian concrete industry to represent as much as 25% of annual concrete sales. Discussion in the workshop suggests that there are communication gaps between the broader concrete industry, including academics, and the residential concrete end users. Other knowledge gaps include the development of suitable low carbon concrete mixes for residential use, development of LCA tools for homes, use of recycled materials in residential concrete, 3D printing of residential concrete, and the use of precast concrete in residential construction. Aside from the communications gap, the development of suitable low carbon concrete mixes is likely to have the greatest immediate impact on reducing GHG emissions in residential concrete.

## **Precast concrete (Chapter 9)**

Precast concrete represents about 10% of the total market for concrete. It's market share may increase over time due to labour shortages in the broader construction industry and precast concrete's higher degree of automation compared to cast in place concrete. The production process also creates different needs for decarbonization,

---

particularly around various low carbon materials options, which should be addressed. The issue of inclusion of modules A4 and A5 in construction LCA raised in this section is significant for all construction and should also be addressed.

### **Low carbon high performance/ultra-high performance concrete (HPC/UHPC) (Chapter 10)**

HPC and in particular, UHPC are currently materials whose use is limited by the complexity of mix designs, cost and need for specialty expertise. They have a significantly higher carbon footprint per m<sup>3</sup> of concrete due to their high percentage of cement in the mix design. It is not clear at this point whether the increased strength in the material and resulting lower volumes of concrete for the same load resistance is sufficient to provide GHG reduction benefits. The initial gap identified in the workshop session on this topic is “Analysis of the potential for HPC/UHPC to reduce GHG emissions”, which should be pursued before additional decarbonization research is undertaken.

### **Nanomaterials (Chapter 11)**

Nanomaterials can potentially increase the strength of concrete, improve its durability or speed its rate of hydration. However, they are expensive, have potential safety issues that would need to be addressed and most of the properties reported to date can be obtained using other approaches. They are often energy intensive to make. As result, it is not clear that their use would provide significant GHG benefits. Other technologies are likely to bring faster and larger reductions in emissions. A possible exception is that the addition of nanomaterials to UHPC might help to increase the strength and resilience of the material to point where it would provide useful GHG benefits.

### **Biomaterials (Chapter 12)**

Some biomaterials are already in use in cementitious products such fiber-cement board or lignosulfonate superplasticizers. The percentage of replacement of concrete by these materials is limited, but there is potential for biofibers to replace the polymer and steel fibers used to provide certain types of reinforcement in concrete. Unpublished work at NRC suggests that some biofibers can provide better fire resistance than other materials. Durability concerns would, however, need to be addressed. Self healing concrete is potentially useful for concrete life extension, but would not bring immediate GHG reduction benefits.

### **Natural Carbonation (Chapter 13)**

Understanding natural carbonation is key to understanding whether technologies that artificially carbonate concrete are providing true GHG reductions or only accelerating the natural process. Values for the amount of natural carbonation to be expected in different parts of the country also needed for LCA since the process is included in the

---

relevant ISO standards. Knowledge of the process of concrete deterioration caused by natural carbonation is also relevant to assessing any risks from artificial carbonation.

### **Long term performance of concrete containing sequestered carbon dioxide (Chapter 14)**

#### **Assessing/quantifying sequestration (Chapter 15)**

Work in both of these areas is essential for wide spread adoption on concrete carbonation technologies. Confirmation is needed that carbon sequestration will not impact the service life of concrete structures, while measurement techniques are needed quantify the amount of sequestered carbon for purposes of LCA and obtaining carbon credits. While it might appear desirable for the question of long term performance to be resolved first, it is likely that the measurement techniques needed to quantify the extent of carbonation in concrete will also be needed to quantify the amount of carbonation being produced during sequestration. These research areas therefore need to be pursued in parallel.

#### **Sequestration in high volume SCM and other specialized concrete mixes (Chapter 16)**

Since it is highly likely that the use of SCMs and ASCMs will increase in the future as part of efforts to decarbonize concrete, the first knowledge gap identified in this session on the impact of those materials on carbon sequestration is significant. The assessment techniques described in Chapter 15 will, however need to be developed before the full impact of SCMs on sequestration is understood.

#### **Guidance on sequestration use (Chapter 17)**

While fully developed guidance in this area, including standards, will need the results of the work outlined in Chapters 13 to 16, an initial guidance document to provide support for decision makers would be useful in the interim.

#### **Alternative Fuel Choices (Chapter 18)**

AF supply is the key question that must be addressed before other work on alternative fuels is pursued. Research to understand the available supply and whether particular AFs are worth developing should be undertaken before other work in this area. The use of hydrogen as a fuel is a longer term solution where developmental research could be useful, but the technology is unlikely to be in place in time to meet the 2030 GHG emission reduction targets.

#### **Standardization of fuels to produce stable fuel performance (Chapter 19)**

---

Addressing the knowledge gaps raised in this workshop session is significant for the potential use of AFs. The supply chain issues raised in Chapter 18 will, however, need to be addressed before significant work on standardized AFs takes place. Once potential AFs have been identified, research on fuel performance and potential impacts on cement quality should be undertaken. Actual standardization and work on storing and handling should only be pursued once an AF is known to be successful.

## **Accessing Waste Streams (Chapter 20)**

### **Evidence in support of alternative fuel use regulation (Chapter 21)**

The work outlined in these chapters is critical to the success of AFs, but requires the AFs that will be pursued to be identified before it can begin. Kiln design will need AF performance properties to proceed, while initial studies of pollutants from the chosen AFs should be undertaken as part of the laboratory work on fuel performance. It should be noted that kiln designs and regulatory requirements to use multiple AFs in one kiln may add significant complexity to the adoption process. The TEA/LCA model described in Chapter 20 would be useful in assessing whether the use of multiple AFs is worth pursuing.

## **23 Conclusions**

### **23.1 Summary of Knowledge Gaps and Research Needs**

The NRC-CAC Workshops on Low Carbon Concrete Research included sessions on twenty different topics that ranged from the fuels and materials needed to produce cement to carbon sequestration in concrete. Seventy five knowledge gaps were identified during the work, sixty related to cement and concrete and 15 related to alternative fuels. Using actions proposed during the workshop sessions as a basis, research pathways were outlined for each of the knowledge gaps.

In many cases similar gaps were identified in different workshop sessions. The individual chapters highlight where identical needs were found in different sessions, but broader overlaps where research activities could potentially be combined were also identified and summarized. These overlaps included work in the areas of:

- Development or improvement of test methods;
- Concrete performance and durability;
- Assessing GHG reduction benefits;
- Improvements to the understanding of fundamentals;

- 
- Supply chain issues; and
  - Changes to standards

With one exception, knowledge gaps identified in the workshops for both cement and concrete and for the use of Alternative Fuels fall into each of these categories. The need to assess GHG reduction benefits was not explicitly identified as a knowledge gap for AF fuels, but it was clearly identified in the action items as a key issue in determining the potential benefits of fuel switching. Fifty four of the knowledge gaps fall into these six areas.

The remaining twenty one knowledge gaps cover a variety of topics that are significant for the subject area of an individual workshop session. These topics are diverse, ranging from the pollutants produced by alternative fuels, through alternative cementitious binders to the development of LCA guidance for the assessment of GHG emissions on the jobsite. Some of the individual knowledge gaps, such as Design to Minimize Concrete Material Volumes (covered in Chapter 2) may have significant overall impacts on industry GHG emissions.

The large number of knowledge gaps means that it may not be possible to carry out the research, development and knowledge mobilization needed to address all of them. Cost, expected GHG benefits, and the availability of materials are all factors that should be considered in prioritizing work on knowledge gaps. In addition, ease of technology adoption should also be considered. The cross-cutting areas of work identified in the report correspond to fundamental questions about the suitability of a material or approach to decarbonization that need to be answered to support adoption of new low carbon concrete technologies. Work is underway at NRC to better understand concrete materials technology adoption in the construction industry, but it is clear that choosing to support technologies that are easier to adopt by the broader industry will speed its decarbonization.

## **23.2 Recommendations**

The range of knowledge gaps identified in the workshops ranges from industry wide ones that could have a significant impact on GHG emissions to niche areas such as 3D concrete printing where the GHG reduction benefits are unknown. In addition, while the gaps cover all of the “five C”s, the areas covered in chapters 2 to 17 primarily address cement, concrete and carbon sequestration. Chapters 18 to 21 address combustion, while only the work in Chapter 6 on the potential re-use of concrete fines in cement production and in Chapter 7 on alternative binders supports decarbonizing clinker. The technologies discussed in this report are therefore likely to support meeting 2030 GHG reduction targets, but will not be sufficient to produce net-zero concrete or cement. Even the use of hydrogen fuel or electric heating in the kilns will not suffice, since they will not reduce the process emissions from heating limestone.

---

Carbon capture, utilization and storage (CCUS) technologies do have the potential to capture all emissions from cement plants. CCUS technologies have also reached the demonstration stage, with net-zero cement being produced in Norway. A fully commercial plant using CCUS is currently in development in Alberta and net-zero cement should be produced there within a few years of the time of writing. The major limitation to the approach of decarbonizing cement manufacture using CCUS is that most plants in Canada will not be able to easily use geological sequestration. The sedimentary basin in Alberta and Saskatchewan is much better suited to this approach than the geology in the rest of country, raising the question of what to do with the captured carbon. Creating or reversing pipelines to ship it to Alberta would be challenging, with the only other option being rail transport. For a plant producing 200,000 tons of CO<sub>2</sub> a year, this would amount to the equivalent of 1000 100 ton capacity rail cars or perhaps 10-20 trains a year. Transporting all of the CO<sub>2</sub> from cement plants outside Alberta to the province could require 50 times that amount of capacity. Until such time as the means exist to utilize the CO<sub>2</sub> at the cement plant, reducing emissions through the approaches covered in this report will be essential.

At the same time, it is important to differentiate between approaches that can be implemented before 2030 and those that will take longer times to deploy. The recommendations that follow are split into those that will support 2030 emissions reductions targets and those that will support 2050 targets. The differentiation is made based not only on technology development times, but also on estimated difficulty for the concrete industry to adopt the technologies.

Ana Milena noted: For all the research it is very important to define clearly parameters to be evaluated for different applications. The list should be published and discussed with main stakeholders before trials start. Procedure for evaluation and mockups preparation/industrial trial parameters to be clearly defined and discussed for different relevant applications. This applies almost for all the research pathways

### **23.2.1 Recommendations to support 2030 GHG emissions targets**

1. Alternative fuels provide a clear route to reduce combustion emissions, particularly in cases where coal is the primary kiln fuel. Changing fuel sources also does not create technology adoption issues for cement users. While it is difficult to estimate how long conversion to the use of AFs would take, starting as soon as possible is desirable. It is therefore recommended that research be carried out to:
  - Identify potential alternative fuels (AFs) on a regional basis across the country (Chapter 18).
  - Once potential fuel sources have been identified, initiate laboratory testing for fuel performance, cement quality and pollutants (Chapter 19)

- 
- Develop a suitable TEA/LCA model to assess which AFs are worth pursuing (Chapter 20);
  - If the TEA/LCA model shows benefits in the use of AFs, obtain regulatory permission for trial burns in order to support the use of AFs (Chapter 21).

Early engagement with regulators and a focus on overall pollution reductions compared to coal are also recommended.

2. SCMs and ASCMs are relatively simple ways to reduce GHG emissions from concrete. Most concrete users will already be familiar with SCMs. It is therefore recommended that:
  - The survey work, testing and updates to specifications described in Chapter 3 be carried out to support the use of existing standardized SCMs and determine their long term availability;
  - The work outlined in Chapter 4 be carried out, including a focus on limestone calcined clay cements and blended cements made with other aluminum silicates; and
  - The National Master Specification be updated to cover the usage of high-volume SCMs, newer SCMs and ASCMs.
3. One or more environmental exposure sites should be established in Canada to support long-term durability studies of low carbon concrete materials.
4. Work on design to minimize concrete material volumes and investigation of materials reliability factors (Chapter 2) should be initiated so that appropriate guidance can be issued before 2030.
5. Increasing limestone content in Portland Limestone Cement (Chapter 5) be pursued as it can provide a relatively simple means of reducing carbon emissions and is an extension of existing technology. Care would need to be taken with amount of additional limestone used and which applications would be appropriate for it.
6. Residential concrete represents a significant percentage of Canadian concrete consumption, but little is currently being done to support its decarbonization. It is recommended that work on improving industry communications, developing low carbon concrete mixes for residential use and the development of simplified LCA tools for home builders and owners (Chapter 8) be pursued.
7. Precast concrete (Chapter 9) needs specific tools and support to decarbonize. It is recommended that:
  - Low carbon mix designs be developed for precast concrete, including support for field trials and demonstration projects; and
  - Work be pursued to incorporate modules A4 and A5 of the LCA process into whole building or whole infrastructure LCA.

- 
8. The potential benefits of HPC and UHPC for concrete decarbonization are unclear. It is therefore recommended that analysis of their benefits as outlined in the initial knowledge gap of Chapter 10 be pursued. Further work in this area would be dependent on the outcome of the analysis.
  9. Research on natural carbonation (Chapter 13) should be pursued to support work on artificial carbonation and LCA. In addition:
    - Development of test methods for assessing and quantifying carbonation should be pursued to support the work on natural carbonation and work on the long term performance of concrete containing sequestered carbon (Chapter 15); and
    - Long term performance studies on concrete containing sequestered carbon should be initiated (Chapter 14).
  10. The development of performance based design, building codes and specifications (Chapter 2) should be pursued. Inclusion in the National Building Code should be targeted for 2035, with work on performance based specifications, including in the National Master Specification, contributing to meeting the 2030 targets.
  11. Preliminary assessments of alternative binders (Chapter 7) should be carried out to determine their viability at the industrial scale in the Canadian context.
  12. Efforts to produce cement using electrochemical methods (Chapter 18) are already underway. If successful, performance and comparison studies as per Chapter 7 are recommended.

Where possible, activities should be combined as covered in the Discussion to minimize time and costs and improve results.

### **23.2.2 Recommendations to support 2050 GHG emissions targets**

13. Research on the use of recycled concrete fines as feedstock for cement making should be pursued as it provides a potential route to decarbonizing clinker production.
14. Models incorporating long term behaviour of low carbon concretes (Chapter 2) should be developed for use in concrete design once sufficient experimental data is available.
15. If the results of recommendation 11 are successful, further industrial scale development of alternative binders (Chapter 7) should be pursued.
16. If the results of recommendation 8 are successful, further work on decarbonizing HPC/UHPC (Chapter 10) should be pursued.

- 
17. The status of nanomaterials (Chapter 11) and biomaterials (Chapter 12) should be reassessed in the 2029-2030 time period to see if research on using these materials to decarbonize concrete is warranted.
  18. If the results of recommendation 9 are successful, then the additional work outlined in Chapters 14 to 17 should be carried out.
  19. The need and potential for hydrogen fuel and electric heating for kilns (Chapter 18) should be reassessed in the 2029-2030 time period to see if further work in these areas is warranted.

## 24 References

- Antunes, M., Santos, R. L., Pereira, J., Rocha, P., Horta, R. B., & Colaço, R. (2021). Alternative Clinker Technologies for Reducing Carbon Emissions in Cement Industry: A Critical Review. *Materials* 15, no. 1, 209.
- Asamany, E. A. (2017). Waste-Derived Fuels for Co-Processing in Rotary Cement Kilns. PhD Thesis, Dalhousie University. *PhD Thesis*. Dalhousie University, Halifax, Nova Scotia.
- ASTM International. (2023). *C1157/C1157M-23 Standard Performance Specification for Hydraulic Cement*. West Conshohocken, PA, USA: ASTM International.
- ASTM International. (2024). *C150/C150M-24 Standard Specification for Portland Cement*. West Conshohocken, PA USA: ASTM International.
- Canadian Commission on Building and Fire Codes. (2020). *National Building Code of Canada: 2020*. Ottawa, ON, Canada: National Research Council Canada. doi:<https://doi.org/10.4224/w324-hv93>
- Carbon Upcycling. (2024). *Ash Grove Mississauga Cement Plant*. Retrieved June 10, 2025, from <https://development.carbonupcycling.com/index.php/ash-grove-projects/>
- Caro, D. e. (2024). Environmental and socio-economic effects of construction and demolition waste recycling in the European Union. *Science of the Total Environment*, 168295.
- Cement Association of Canada. (2023). *Concrete Zero: Canada's cement and concrete industry action plan to net-zero*. Ottawa, ON Canada: Cement Association of Canada. Retrieved from <https://cement.ca/sustainability/concrete-zero/>
- Chandler J. (2021). *A Comparison of Emissions from the Lafarge Brookfield Facility in Nova Scotia - A Review of Stack Testing Data 2017-2020. Report Prepared for LafargeHolcim*.
- Chatterjee A, Sui T, Ryden. (2019 Sept). *Alternative Fuels - Effects of Clinker Process and Properties. Cement and Concrete Research*. 123:105777.

- 
- Chatterjee, A., & Sui, T. (2019). Alternative fuels – Effects on clinker process and properties. . *Cement and Concrete Research* 123, 105777.
- Chung, E. (2025, October 11). *How Canadian steelmakers are 'greening' their steel amid tariffs, global challenges*. Retrieved from CBC: <https://www.cbc.ca/news/climate/green-steel-explainer-9.6933400>
- CSA Group. (2023). *CSA A3000:23 Cementitious materials compendium*. Toronto ON Canada: CSA Group.
- CSA Group. (2023a). *CSA A3001:23 Cementitious Materials for Use in Concrete*. Toronto, ON Canada: CSA Group.
- CSA Group. (2024a). *CSA S6:19 (R2024) Canadian Highway Bridge Design Code*. Toronto ON Canada: CSA Group.
- CSA Group. (2024b). *A23.3:24 Design of Concrete Structures*. Toronto, ON Canada: CSA Group.
- CSA Group. (2024c). *CSA A23.1:24 Concrete Materials and Methods of Construction*. Toronto, ON Canada: CSA Group.
- Cunliffe AM, Williams PT. (2009 Feb). De-novo Formation of Dioxins and Furans and the Memory Effect in Waste Incineration Flue Gases. 29(2):739-48. *Waste Management*.
- ECCC. (2025). *National inventory report : greenhouse gas sources and sinks in Canada*. Greenhouse Gas Division. Ottawa, ON Canada: Environment and Climate Change Canada. Retrieved from <https://publications.gc.ca/site/eng/9.506002/publication.html>
- El-Emam, R. S., & Gabriel, K. S. (2021). Synergizing hydrogen and cement industries for Canada's climate plan – case study. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 43(23) , 3151–3165.
- Ellis LD, B. A. (2020 June 9). Toward Electrochemical Synthesis of Cement - An Electrolyzer-based Process for Decarbonating CaCO<sub>3</sub> while Producing Useful Gas Streams. 117(23):12584-91. *Proceedings of the National Academy of Science*.
- Fennell PS, David SJ, Mohammad A. (2021 Jun). Decarbonizing Cement Production. 5(6):1305-11. *Joule*.
- GCCA. (2021). *Concrete Future - The GCCA 2050 Cement and Concrete Industry Roadmap for Net Zero Concrete. Version 0.1*.
- GCCA. (2024). *Cement Industry Net Zero Progress Report 2024/25*.
- Gorski J, Israel B. (2018 Nov). Life Cycle Assessment of Low-carbon Fuels - Lafarge Exshaw. *Pembina Institute*.
- Gupta RK, Majumdar D, Trivedi JV, Bhanarkar AD. (2012 Dec). Particulate Matter and Elemental Emissions from a Cement Kiln. 104:343-51. *Fuel Processing Technology*.
- Hannoun G. (2019). *Energetic Potential and Environmental Assessment of Solid Wastes as Alternative Fuel for Cement Plants*. . Retrieved from Applied Ecology and Environmental Research.: [http://aloki.hu/pdf/1706\\_1515115168.pdf](http://aloki.hu/pdf/1706_1515115168.pdf)

- 
- Heidelberg Cement. (n.d.). *Carbon Capture and Storage (CCS) - The Brevik CCS Project*. Retrieved from Heidelberg Cement: <https://www.heidelbergcement.com/en/carbon-capture-and-storage-ccs>
- Hewlett, P., & Liska, M. (. (2019). *Lea's Chemistry of Cement and Concrete, 5th Edition*. Oxford,, United Kingdom: Butterworth-Heinemann.
- International Energy Agency. (n.d.). *Technology Roadmap: Low-Carbon Transition in the Cement Industry, accessed June 2022*. Retrieved from IEA: <https://www.iea.org/reports/technology-roadmap-low-carbon-transition-in-the-cement-industry>
- ISED. (2022). Innovation, Science and Economic Development Canada. Ottawa, ON Canada: Government of Canada. Retrieved June 10, 2025, from <https://ised-isde.canada.ca/site/clean-growth-hub/en/cement-and-concrete-canada/roadmap-net-zero-carbon-concrete-2050>
- Lafarge. (2024). *Leading the Industrial Transition to Net Zero: Lafarge Canada and Hyperion Launch World's First Tandem Carbon Recycling System*®. Retrieved June 6, 2025, from <https://www.lafarge.ca/en/lafarge-canada-and-hyperion-carbon-recycling>
- Leilac. (2020). *The Core Technology - Direct Separation*. Retrieved from Leilac - Low Emissions Intensity Lime & Cement: <https://www.project-leilac.eu/the-core-technology>
- Leilac. (2021). *Leilac Technology Roadmap to 2050*. Retrieved from <https://www.project-leilac.eu/leilac-roadmap-to-2050>
- Madeddu S, Ueckerdt F, Pehl M, Peterseim J, Lord M, Kumar KA, et al. (2020 Dec 1). The CO2 Reduction Potential for the European Industry Via Direct Electrification of Heat Supply (Power-to-Heat). 15(12):124004. *Environmental Research Letters*.
- Makar, J. M., Beaudoin, J. J., Trischuk, K., Chan, G. W., & Torres, F. (2012). Effect of n-CaCO<sub>3</sub> and metakaolin on hydrated Portland cement. *Advances in Cement Research*, 211-219.
- Medji et al., M. (2022, January). Hydration and microstructure of glass powder cement pastes – A multi-technique investigation. *Cement and Concrete Research*, 106610.
- Muliane U, Lestari P. (2018). Utilization of Alternative Fuels and Materials in Cement Kiln Towards Emissions of Benzene, Toluene, Ethyl-benzene and Xylenes (BTEX). 147:08002. *MATEC Web Conference*. Roosmini D, Pribadi K, Sugeng B, Hadihardaja IK, editors.
- Murray, A., & Price, L. (2008). Use of alternative fuels in cement manufacture: analysis of fuel characteristics and feasibility for use in the Chinese cement sector.
- Nance, G., Abbas, T., Lowes, T., & Bretz, J. (2011). Calcliner design for lower CO and NO<sub>x</sub> using MI-CFD analysis to optimize "Hot-Reburn" Conditions. h. *IEEE-IAS/PCA 53rd Cement Industry Technical Conference*, (pp. 1–18).
- Nancy W. Stauffer. (2021). *Using Aluminum and Water to Make Clean Hydrogen Fuel - When and Where it's Needed*. Retrieved from MIT News: <https://news.mit.edu/2021/using-aluminum-and-water-to-make-clean-hydrogen-fuel-0812>
- Natural Resources Canada. (2009). *Canadian Cement Industry Energy Benchmarking Summary Report*. Accessed July 2022. Retrieved from

---

<https://www.nrcan.gc.ca/energy/publications/efficiency/industrial/6003#c1-1>, ISBN 978-1-100-14036-0

Network for Business Sustainability, D. o. (n.d.). *Alternative Energy Sources in Cement Manufacturing: A Systematic Review of the Body of Knowledge*. Bari, Italy.

Nhuchhen DR, Sit SP, Layzell DB. (2022 July). *Decarbonization of Cement Production in a Hydrogen Economy*. 317:119180. Applied Energy.

Ningsih RY, Goembira F, Komala PS, Putra NP. (2019 Sep 30). Emission and Heavy Metal Content Characteristic of Densified Refused Derived Fuels of Oil Sludge and Biomass Combination as an Alternative Fuel for Cement Plant. 3(3):100-5. *Indonesian Journal of Environmental Management and Sustainability*.

Omran et al., A. (2018). Performance of ground-glass pozzolan as a cementitious material-a review. *Advances in Civil Engineering Materials*, 7(1), 237-270.

Perry, B. (2016). Rocketology. *NASA's Space Launch System; Tag: Aluminum*.

Plaza MG, Martinez S, Rubiera F. (2020). CO2 Capture, Use and Storage in the Cement Industry: State of the Art and Expectations. *MDPI*, 28.

Prakash A, Palkar RR. (2021 Nov 26). *Co-processing of Plastic Waste in Cement Kiln: A Better Option*. Cited 2022 Apr 20. Retrieved from Environmental Science and Pollution Research: <https://link.springer.com/10.1007.s11356-021-17725-7>

Ryden A, Doukas E, Pantazis G, Adamopoulou T, Gklinos P, Doukas C, et al. (27-28 Feb 2020). Selection and Use of Alternative Fuels in the Cement Manufacturing Process for Greece, Sweden and Germany. *6th HSWMA Conference, Athens, Greece*.

Sai Kishan G, Himath Kumar Y, Sakthivel M, Vijayakumar R, Lingeshwaran N. (2021). *Life Cycle Assessment on Tire Derived Fuel as Alternative Fuel in Cement Industry*. *Materials Today: Proceedings*. 47:5483-8.

Solutions, Advanced Waste. (2020). *Tire Derived Fuels Making Inroads in Canada*. Retrieved from <https://advancedwastesolutions.ca/2020/01/12/tire-derived-fuels-making-inroads-in-canada/>

Statistics Canada. (2019, July 8). *Annual Survey of Cement, production and exports*. Retrieved from Statistics Canada: <https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=1610000901>

The Concrete Centre. (2016). *Whole Life Carbon and Buildings*. London: The Concrete Centre.

Tinnis, P. D., Thomas, M. D., Weiss, W. J., Farny, J. A., & Giannini, E. R. (2024). *State-of-the-Art Report on Use of Limestone in Cements at Levels of up to 15%*. Washington, D.C.: Portland Cement Association.

UNEP. (2022). *Sand and sustainability: 10 strategic recommendations to avert a crisis*. Geneva, Switzerland: GRID-Geneva, United Nations Environment Programme.

UY, Qazi. (2022 Jun 28). Future of Hydrogen as an Alternative Fuel for Next-Generation Industrial Applications; Challenges and Expected Opportunities. 15(13):4741. *MDPI - Energies*.

- 
- Wojtacha-Rychter K, Kucharski P, Smolinski A. (2021 Mar 11). *Conventional and Alternative Sources of Thermal Energy in the Production of Cement - An Impact on CO2 Emission*; 14(6):1539. *Energies*.
- World Economic Forum. (2024). *Cement is a big problem for the environment. Here's how to make it more sustainable*. Retrieved June 10, 2025, from <https://www.weforum.org/stories/2024/09/cement-production-sustainable-concrete-co2-emissions/>
- Xavier d'Hubert, X. E. (2022, Jan 25). *Future Burners*. Retrieved from Global Cement: <https://www.globalcement.com/magazine/articles/1247-future-burners>
- Zidol, A., Tognovi, M. T., & Tagnit-Hamou, A. (2021). Concrete incorporating glass powder in aggressive environments. *ACI Materials Journal*, 118(2), 43-52.
- Zygadlo, Purgal. (2020). *The benefits of partial substitution of fossil fuel with alternative fuel in cement plant. Case study. Cited 2022 Apr 20; 46(1)*. Retrieved from Environment Protection Engineering: [http://epe.pwr.wroc.pl/2020/Zygadlo\\_1-2020.pdf](http://epe.pwr.wroc.pl/2020/Zygadlo_1-2020.pdf)