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Low-Carbon Concrete: Sustainable Performance at an Affordable Price

A White Paper for Engineers

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Low-Carbon Concrete: Sustainable Performance at an Affordable Price

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Abstract

The Canadian Government has set ambitious targets to reduce GHG emissions by 2025 and achieve net-zero emissions by 2050 to address the climate crisis. The construction industry must undergo a significant decarbonization process to help mitigate the climate crisis. This white paper provides information on general approaches that have been well-known or widely used in lowering the embodied carbon of concrete materials, as well as cost, without compromising performance or safety. It addressed some common perceived risks of using low-carbon concrete and discussed how current standards support low-carbon concrete materials in construction projects.

Understanding that great efforts are being undertaken globally in developing low-carbon concrete, which is a fast-evolving area and critical to reducing GHG emissions in the construction sector, it is not the intention of the paper to discuss the new, emerging and promising innovations. This white paper seeks to facilitate the procurement and implementation of concrete in construction projects across Canada that has lower embodied carbon, based on the evidence of the existing technologies and approaches that are widely accepted but may not have been seen as the low-carbon strategies among the concrete and structure engineers' communities. By increasing the use of low-carbon concrete, we can help reduce the construction industry's carbon footprint and move towards a more sustainable future.

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List of Abbreviations and Terms

Abbreviations

ASCMs: Alternative supplementary cementitious materials other than the conventional ones such as fly ash and slag

EPD: Environmental product declaration

GHG: Greenhouse gases

ISED: Innovation, Science and Economic Development Canada

NRC: National Research Council Canada

PC: Portland cement

PLC: Portland limestone cement

SCMs: Supplementary cementitious materials

Terms

Carbon footprint: an assessment of the amount of Greenhouse Gas Emissions (GHG) emitted by a particular person, group, product(item), or system.

Embodied Carbon: the amount of GHGs emitted during the extraction, refining, fabrication, and assembly of an item

Fly Ash: a waste product co-generated from the electric power generation from coal plants

Global Warming Potential: a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period, relative to the emissions of 1 ton of carbon dioxide (CO_2)

Low-carbon concrete: Concrete with lower embodied carbon, carbon contribution to the environment, compared to conventional concrete

Metakaolin: obtained from the calcination of clay mineral kaolinite

Portland limestone cement (PLC): Cement ground with raw limestone. This is used in the same way as conventional cement powder

Silica Fume: by-product from the production of silicon and alloys containing silicon

Slag: a by-product of the production of steel

Low-Carbon Concrete: Sustainable Performance at an Affordable Price

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In this white paper, the following questions were answered:
What is low-carbon concrete (Section 2)
What forms of low-carbon concrete are currently practiced by industry? (Section 3)
What are the perceived risks of using low-carbon concrete? (Section 4)
How do current CSA standards support the making of low-carbon concrete? (Section 5)

1. Introduction

Low-carbon concrete is conventional concrete with a quantified lower carbon footprint that can help mitigate climate change. It is not a new type of concrete with questionable characteristics, but the new nomenclature (i.e., low-carbon concrete) refines the long-standing practice of developing sustainable concrete materials by adding a new quantifiable attribute of embodied carbon in addition to the already tracked attributes of strength and durability.

Concrete is one of the most widely used construction materials globally and in Canada since it is an affordable, durable, and adaptive material that can provide safety, functionality and long service life to a large array of construction projects. This has resulted in the development and use of various forms of concrete for different construction applications. In Canada, concrete contributes about 75 billion dollars annually to our economy while providing over 150,000 jobs[1]. However, 60 million tonnes of concrete are used annually which accounts for about 1.5% of Canada's total annual Green House Gas (GHG)[2] emissions.

The main component of concrete responsible for its high carbon emission is Portland cement (PC), which is the primary binder for other components in concrete (e.g., aggregate/fillers). Globally, PC production is responsible for about 5% of the world's human-induced carbon dioxide emissions[3,4]. With increasing sustainability awareness and the imminent need to reduce carbon emissions for climate mitigation, significant efforts need to be put in place and implemented to achieve concrete with a lower carbon footprint, referred to here as 'low-carbon concrete'. There currently is no universally accepted, quantitative definition of the term 'low-carbon concrete' largely due to the rapidly evolving nature of material science and engineering technologies that continually seek to lower the carbon footprint of conventional concrete. These innovations range from reducing carbon emissions from the production of concrete components (i.e., PC, aggregate, etc.), and optimized mix designs, to the reuse of concrete at the end of their service life. Despite its evolving definition, low-carbon concrete can be engineered by using current best practices to provide similar or better performance compared to that of conventional concrete, including strength, durability and adaptiveness. This is because most best practices came from improving material efficiency, conserving natural resources, and reducing the amount of Portland cement to lower cost and improve performance[5,6]. Thus, these best practices are aligned with low-carbon strategies.

The Canadian Government has set ambitious targets to reduce GHG emissions of concrete by 30% (compared to 2019) by 2030 and achieve net-zero emissions by 2050[2]. To meet these targets, the construction industry must undergo a significant decarbonization process by reducing the components made with high carbon footprints. This white paper seeks to discuss some general approaches that are well-known or widely used in practice to lower the embodied carbon of concrete materials, address some common misconceptions about the use of concrete with lower embodied carbon, and demonstrate how current standards support the use of low-carbon materials in concrete construction without compromising performance or safety. We can help to reduce the carbon footprint of the construction industry and move towards a more sustainable future by increasing the use of concrete that has a lower GHG emissions profile.

2. How do we define the threshold of low embodied carbon for procurement?

Concrete procured for a construction project must meet specific performance criteria to be deemed acceptable. These criteria traditionally include workability, strength, durability, and physical/chemical properties. Embodied carbon must also be considered as a way to measure its environmental impact while meeting all the traditional performance requirements to be considered as ‘low-carbon’. A GHG emissions limit can be set to create a desired environmental performance minimum. In the case of Canadian federally funded projects, the initial reduction of GHGs is 10% less than the regional average for conventional concrete.

In the realm of procurement, the term ‘low-carbon concrete’ pertains to a type of concrete that possesses an embodied carbon level that falls below an emission threshold, which varies according to the region. Ready-mix concrete manufacturers across Canada have taken on the initiative to create environmental product declarations (EPDs) for their concrete mixtures[7–10], which are classified under specific performance categories, such as a Class C-1 being a 35MPa with entrained air mix. These EPDs are to serve as a means to calculate a regional average environmental performance for conventional materials.[11] The emissions limit used to define ‘low-carbon concrete’ will likely be ever-evolving as materials, strategies, and technologies continue to improve.

Concrete with lower embodied carbon leverages materials and methodologies to contribute to sustainable construction and does not denote a wholly new material with distinct mechanical characteristics or additional costs. Instead, it represents an enhancement of conventional concrete, using similar or improved constituents and mix designs, and declaring its embodied carbon. Despite its evolving definition, low-carbon concrete can be supplied by using current best practices to provide similar or better performance compared to that of conventional concrete, including strength, durability and adaptiveness. This is because best practices leveraged in creating concrete with lower embodied carbon come from improved material efficiency, natural resource conservation, and Portland cement content reduction to lower cost and improve performance[5,6]. Thus, traditional conventional concrete cost-saving measures are generally aligned with low-carbon strategies.

3. Methods of embodied carbon reduction for concrete

Reducing embodied carbon in concrete is achievable through efficient resource use. Many of the strategies to achieve carbon reduction involve deploying traditional cost-saving measures in an optimized way; these include but are not limited to those listed in this section.

3.1 Cementitious replacement

Most supplementary cementitious materials (SCMs), such as fly ash, slag, and silica fume, are sourced from wastes or by-products of other industries. For example, slag is a waste byproduct of steel and iron manufacturing and fly ash is a waste by-product of coal-generated power production. The concrete industry has already utilized these SCMs as replacements for cement in concrete with the reasons ranging from increasing strength, improving durability (e.g., alkali-silicate reaction (ASR), drying shrinkage resistance, reducing permeability or reducing the heat of hydration), to reducing costs.

While enhancing concrete performance and lowering cost, using SCMs is also an essential method of reducing its carbon footprint. Cement production requires about 3.5 GJ of energy[12,13] and generates about 0.6 tonnes of CO_2[14] per 1 tonne of cement produced. In contrast, SCMs have significantly lower embodied carbon as they are processed or derived from wastes or by-products. For example, producing one tonne of ground granulated blast furnace slag (slag) requires 1.3 GJ of energy and emissions of 0.07 tonnes of CO_2. There are also naturally occurring SCMs that require lower processing compared to the energy-intensive processing involved in the production of Portland cement. Hence, replacing cement with these low-carbon alternatives results in a corresponding reduction in the overall embodied carbon of concrete.

It is important to note that using SCMs in concrete already exists in various design and construction standards/guidelines[15,16]. These standards and guidelines recognize the inherent tradeoffs and provide limits to take advantage of the benefits while preventing negative side effects. An example of this type of tradeoff would be that high-level cement replacement with slag can reduce the workability of concrete, but the low workability can be eliminated using chemical admixtures such as superplasticizers.

3.2 Portland limestone cement

Portland limestone cement (PLC) has been adopted as a replacement for ordinary cement around the world. In Europe, there are two classes of PLC containing 6% to 20% (CEM II/A) and 21 to 35% ground limestone (CEM II/B-L)[17,18]. Limestone replacement in Canada under CSA A3001-18[15] allows up to 5% in Portland Cement and between 5% and 15% in PLC. Limestone powder is inert and doesn't hydrate like cement clinker, but it has been noted that the fine limestone particles are able to have a significant effect on the hydration of clinker. This contributive factor is termed the 'filler effect'[19] as the limestone filler provides nucleation sites from which the cement paste reactions can initiate. At replacement levels in the ranges provided for under CSA A3001-18, this effect can provide an increase in the material strength of concrete of up to 15-20%[20].

3.3 Optimization of concrete design

The partial replacement of Portland cement with lower carbon SCMs or limestones requires proper concrete mix design to achieve performance. Concrete design optimization encompasses other best practices that enhance performance and lower cost, such as aggregate packing optimization, use of water-reducing admixture, and improved mixing methods. In essence, these approaches improve material efficiency and thus lower the carbon footprint of concrete materials.

3.4 Increasing energy efficiency of clinker/cement production.

A significant portion of emissions is associated with the production and delivery of cement, of which approximately 50-60%, is from the calcination process of clinker[2,21] and about 30-40% from fuel combustion. Notable progress has been made in enhancing the efficiency of clinker production[22] but the ability is there to further increase efficiency. Alternative fuels, as well as implementing practices of carbon capture, utilization, and sequestration (CCUS), are likely to lead to the most significant emissions reductions related to cement production. These production process improvements could substantially decrease the embodied carbon in concrete without negatively affecting the performance of the resulting concrete.

4. Perceived risks of using low-carbon concrete

The NRC and Other Government Departments have heard feedback from key stakeholders about using low-carbon concrete. This feedback relayed concerns about using concrete with lower embodied carbon instead of conventional concrete on construction projects. This section is focused on allaying some of those concerns about using concrete with lower embodied carbon and pointing out with context where there is the potential for real concern.

4.1 "Experimental materials"

It would be easy to assume that meeting embodied carbon requirements would require new or untested constituent materials but, it isn't necessarily true for meeting the initial GHG procurement reduction requirement for concrete of 10%. To meet the initial targets, the strategies in line with those presented in section 3 can be employed to optimize the efficiency of the mix design, or efficient production of cement may be enough. It is likely that the next 2030 reduction target, 30%, will require more widespread use of carbon reduction strategies to hit the target. By optimizing the use of known constituents, concrete with lower embodied carbon supplied to a job will be required to meet performance criteria and can potentially be more cost-effective as well.

4.2 “Incremental cost increase”

The use of slag, fly ash, metakaolin, limestone, and other concrete additives has historically been explored to benefit performance and lower cost since the most energy-intense, and thus most expensive, component used in concrete is Portland cement. In the medium to long term, some byproducts of other industrial processes like slag and fly ash will be limited by their supply chains or could have decreased availability in the future[23]. There is a large amount of research going into new alternative SCMs (ASCMs) that can provide similar properties to replace or expand the supply of by-product materials for use in concrete. Industry, Government, and Researchers will work together to tackle this problem to ensure a continued supply of well-performing and economically desirable concrete constituents.

4.3 “Lower performance and reduced durability”

Some sources of SCMs which are being explored for use to lower the cost and GHG intensity of concrete have been used for up to 100 years. Fly ash was introduced in the 1930s[24] and slag was first used as a construction material in the 1800s[25]. The first significant use of limestone in cement was in the 1940s in Europe due to the limited supply of cement. A lot of the strategies being explored to meet the initial carbon reduction goals rely on the same strategies explored in the last century to find other benefits, whether they be to better economics or performance. The long history of use of these materials helps ensure that the strategies being considered for GHG reductions will maintain the existing high quality of concrete.

In the past three decades, concrete research has primarily concentrated on the development of ‘high-performance concrete’, which has resulted in progressive advancements in strength and durability. Many of these principles underlying high-performance concrete align directly with those of low-carbon concrete in section 3. Among these shared principles are the high replacement of cement with SCMs, the incorporation of limestone fillers, and the optimization of processing methodologies to maximize the durability performance of each constituent material. This alignment underscores how technological advancements in concrete production can not only improve the product's properties but also contribute to environmental sustainability.

In essence, low-carbon concrete can be viewed as a form of high-performance concrete, as it maintains or even improves upon strength and durability while reducing its carbon footprint. This perspective reframes low-carbon concrete as a natural progression within the field, continuing the longstanding trend towards enhancing the performance of concrete while concurrently responding to the current imperative of reducing carbon emissions.

4.4 “SCMs change the mix properties”

Different SCMs each bestow unique properties to the resulting mix. The popularity and widespread use of SCMs is due to the desirable qualities and cost efficiency of these materials. Each material has different replacement limits to achieve similar performance. As an example, each of the following cement replacements of 20% low-calcium fly ash, 35% slag, 4% silica fume, or 10% metakaolin might each provide similar 28-day compressive strengths[19]. Ground Granulated Blast Furnace Slag (GGBFS) and low-calcium fly ash enhance general-use cement’s sulphate resistance. Fly ash usually enhances workability and decreases concrete permeability, making it more resistant to chloride ingress[24]. The impact of using these SCMs on concrete is typically net positive (i.e., desirable) in terms of improved performance. Continuous efforts have been ongoing to ensure the proper use of SCMs to achieve improved performance, reduced cost and reduced carbon footprints.

4.5 “Availability of SCMs and low-carbon concrete”

Future challenges may arise concerning the availability of SCMs like slag and fly ash. A finite quantity of slag is produced with almost all sources currently being fully utilized[23], and Canada plans to terminate most of its coal power generation by 2030[26] which could significantly affect the supply of fly ash. To proactively address this potential issue, dynamic partnerships are being forged between industry stakeholders, governmental bodies, and research institutions. Their collaborative efforts focus on identifying new waste materials and wastes from Canada's mining industries to be used as SCMs. These new SCMs will undergo thorough scrutiny and will need to be accepted into standards before broad use in Canada to ensure they meet the required performance and emissions criteria.

5. Low-carbon concrete and CSA standards

General concrete design and construction is regulated in Canada by CSA A23. CSA A23's mandate is to set requirements for materials and structural design of concrete elements. The material requirements are broken down further into testing and quality control of the individual ingredients and the concrete mix properties. The property requirements of cement and SCMs are regulated under CSA A3001. Some relevant SCM and PLC provisions are highlighted below to provide a regulatory view on using these materials as described in section 3.

- CSA A3001-18[15] (clause 5 and Tables 7 and 8) provides the physical and chemical properties for each class of SCM. It would be helpful to also read annexes K and M for more context on SCM usage.
- CSA A3001-18[15] provides the requirements on limestone filler (Clauses 4.4.7 and 4.4.8) for two types of the limestone addition. At the same time, the performance of concrete is under consideration; for example, CSA A23.1 (Clause 4.1.1.6.2 and Table 3) restricts limestone filler usage in areas exposed to sulphate attack without blending with other cementitious materials to provide the necessary sulphate attack resistance.
- CSA A23.1[16] sets minimum and/or maximum values for concrete attributes. For example, max water-cement ratio, minimum strength, and air content range. CSA standards in their current state can accept strategies discussed within this paper to meet GHG reductions while ensuring that the required performance and safety are maintained.

It is to be noted that regional standards may provide different requirements or supersede these standard sections.

6. Conclusion

It's necessary to achieve widespread adoption of concrete with lower embodied carbon to reduce the carbon footprint of the construction industry, reduce waste, and improve concrete performance to mitigate the impact of climate change. This paper has addressed the common questions practiced engineers encounter regarding using low-carbon concrete.

What is low-carbon concrete (Section 2)? In the realm of procurement, the term "low-carbon concrete" pertains to a type of concrete that possesses an embodied carbon level that falls below a particular emission threshold, which can vary according to the region, while meeting specific performance criteria to be deemed acceptable for a construction project.

How to make low-carbon concrete (Section 3)? Producing concrete that is lower in carbon involves carefully optimizing the combination of constituent materials and proportions. The aim is to reduce embodied carbon without increasing material costs or sacrificing performance.

What are the perceived risks of using low-carbon concrete (Section 4)? Many common perceived risks of using low-carbon concrete are addressed. In essence, low-carbon concrete can be viewed as a form of high-performance concrete, as it maintains or even improves its strength and durability while reducing its carbon footprint. This perspective reframes low-carbon concrete as a natural progression within the field, continuing the longstanding trend towards enhancing the performance of concrete while concurrently responding to the current imperative of reducing carbon emissions.

How do current CSA standards support the making of low-carbon concrete (Section 5)? Canada's national standards are well positioned and regulate many of the early GHG reduction strategies suggested to be explored. Regional standards may provide different requirements or supersede these standard sections.

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