Cost, Performance, and Emissions Analysis of Sustainable Concrete Alternatives for Sidewalk Construction

-- Green Concrete

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Disclaimer

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Table of Content

Executive Summary

The City of Vancouver has set ambitious targets to reduce carbon emissions by 2030 and achieve carbon neutrality by 2050. However, with current progress falling short, there is an urgent need to update the climate emergency plan. Concrete plays a critical role in achieving these goals, particularly in the construction and maintenance of sidewalks, which constitute a significant portion of the City’s infrastructure. Moreover, sustainable sidewalk construction is essential for reducing transportation emissions and advancing the City’s 'How We Move' action plan.

The report provides a comprehensive analysis of sustainable concrete alternatives for sidewalk construction, with a focus on reducing carbon emissions. Key findings include the evaluation of existing Green Concrete technologies and the identification of potential breakthroughs. The report emphasizes that while some innovative materials are still in the research phase, several widely accepted approaches, such as the use of supplementary cementitious materials (SCMs) and Portland Limestone Cement (PLC), offer immediate opportunities for emission reductions without compromising performance or safety.

The report highlights several misconceptions about Green Concrete, including the belief that it is always more expensive or less durable. On the contrary, SCMs like fly ash and slag not only reduce emissions but also enhance the quality and durability of concrete. The use of these materials is critical for achieving the City’s sustainability goals.

The analysis also evaluates the lifecycle carbon emissions of existing sidewalks in Vancouver, identifying opportunities to reduce emissions through alternative materials for concrete pavement and granular base. The report presents both short-term and long-term recommendations, including increasing the use of supplementary cementitious materials (SCMs), optimizing concrete mix designs, and incorporating recycled materials. It also recommends updating procurement policies to include Environmental Product Declarations (EPDs) and fostering partnerships for piloting new technologies

In conclusion, advancing the adoption of Green Concrete requires collaboration among researchers, manufacturers, and policymakers. Government policies will play a crucial role in driving this transition. Immediate action is needed to implement these sustainable practices, ensuring that Vancouver remains a leader in climate action and meets its long-term emission reduction targets.

Introduction

The Importance of IPCC's 1.5°C Goal

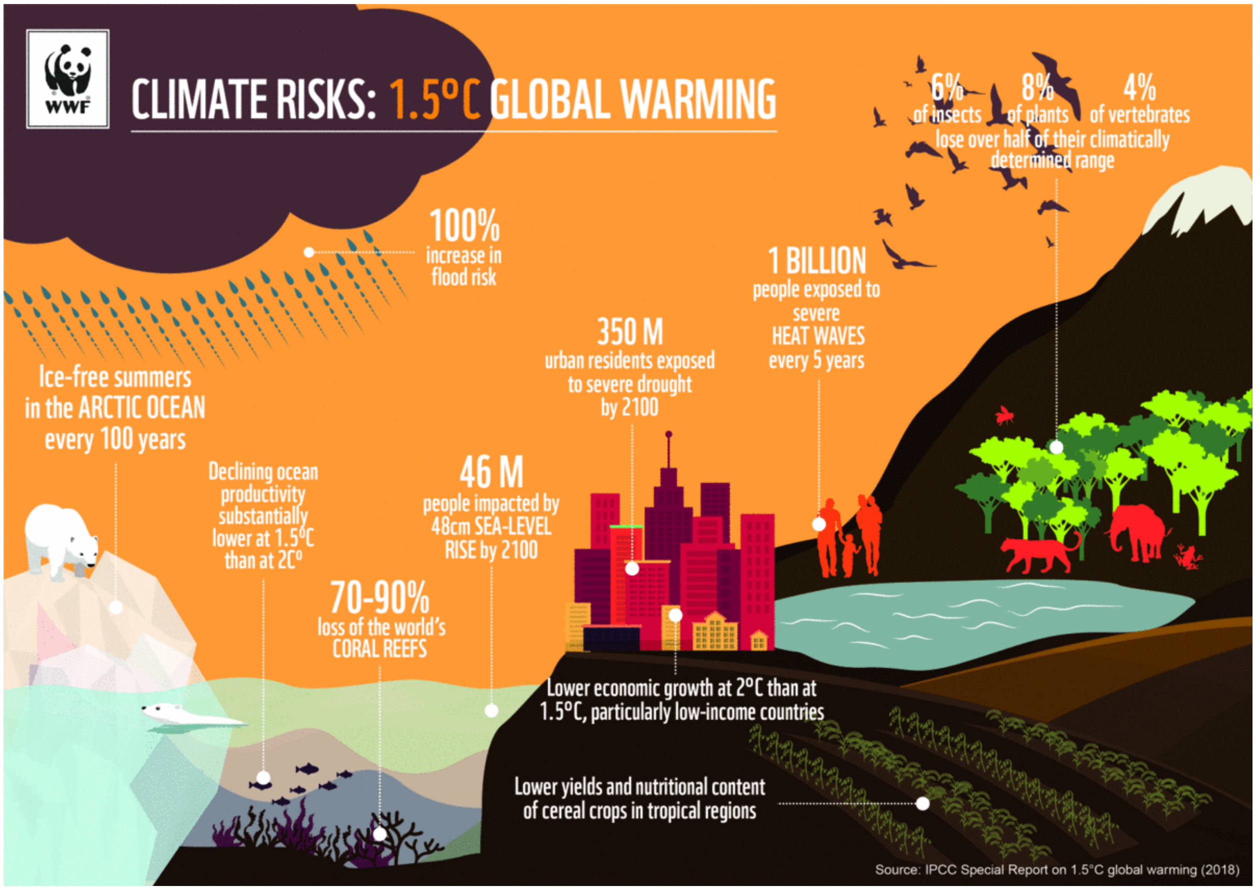


Figure 1.IPCC 1.5 Global Warming Impact (image source: https://wwf.panda.org/wwf_news/?8151466/ipcc-climate-report-key-findings-climate-crisis)

Temperature Increase Within 1.5°C to Avoid Devastating Impacts

The IPCC 1.5 Report underscores the urgent need to limit global temperature increases to within 1.5°C to avoid catastrophic impacts on the environment and human society. In North America, this is particularly evident as the region faces heightened risks from extreme weather events, such as heatwaves, storms, and fires. In Canada, these extreme events are becoming increasingly frequent and severe, exemplified by the several months of wildfires in 2023 that led to widespread smog and poor air quality. The ongoing fire in Alberta's Jasper National Park, which remains out of control as of early August 2024, further highlights how climate change hazards are posing significant risks to both economic stability and social well-being.

Figure 2.Wildfire caused by high temperature in Canada (Photo by Matt Howard)

British Columbia's Escalating Climate Challenges

1. Rising temperatures are leading to longer, hotter summers with more frequent and intense heatwaves.
2. The province is experiencing an unprecedented forest fire season, driven by higher temperatures, extended hot periods, and drier conditions, which make wildfires more likely to ignite and spread rapidly.
3. Weather patterns are becoming more unpredictable, with an increase in storms and heavy rainfall. This leads to rivers being overwhelmed, resulting in flooding and landslides.
4. The region is also facing warmer, drier conditions and water scarcity.

Figure 3. Floods due to unpredictable weather(image source: https://cleanbc.gov.bc.ca/about-climate-change/impacts-of-climate-change/)

City of Vancouver's Climate Strategy

2024 program priorities

Accelerating Vancouver's climate targets to cut carbon pollution in half by 2030, and to be carbon neutral before 2050 through policies including: Climate Emergency Action Plan, A Climate Justice Charter for Vancouver, Green Operations Plan, Vancouver Plan, Zero Emissions Economic Transition Action Plan, etc.

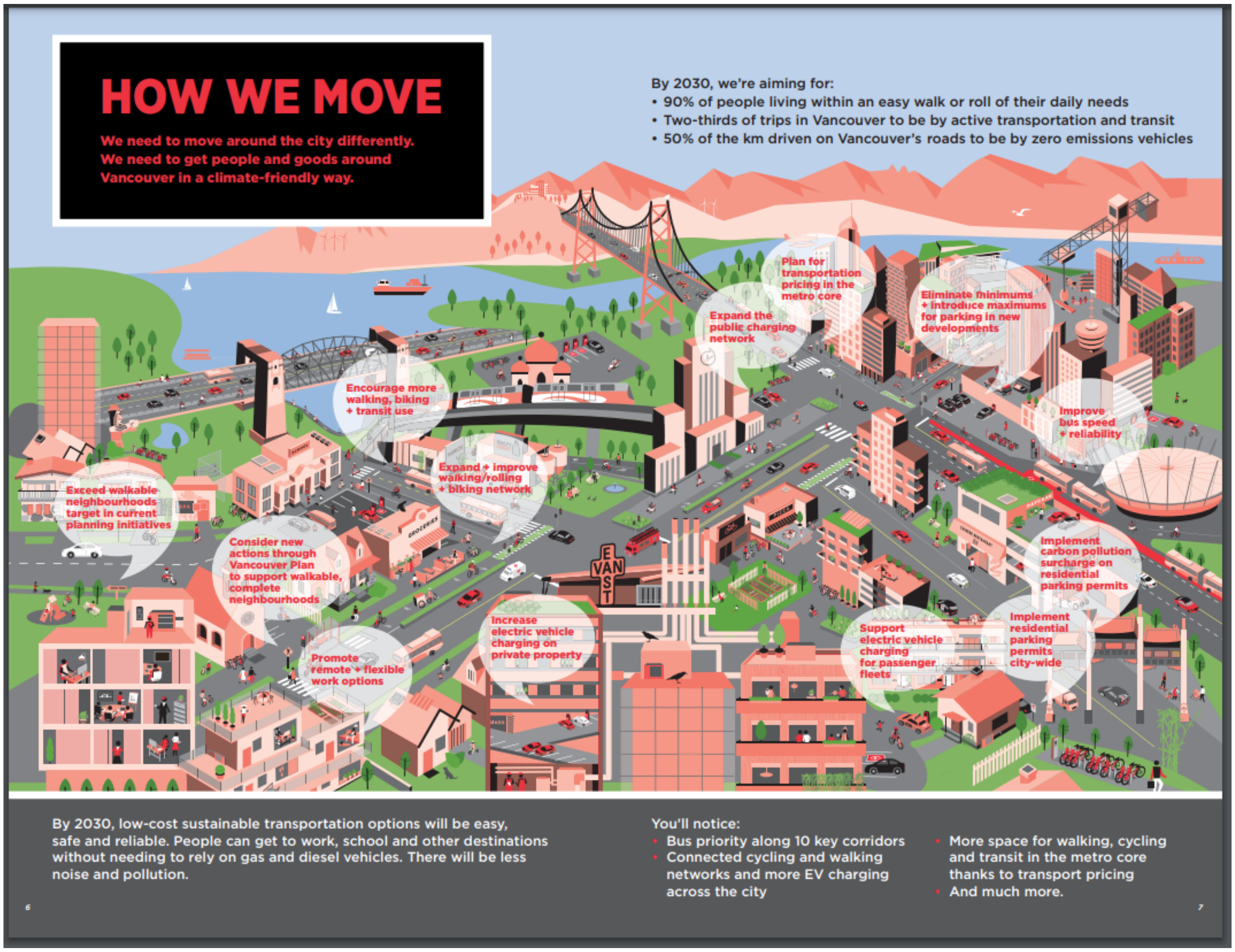
Ensuring Vancouver is prepared for the impacts of a changing global climate while enhancing the City's resilience to climate-related shocks and stresses through policies including: Biodiversity Strategy, Climate Change Adaptation Strategy, Climate Emergency Action Plan, A Climate Justice Charter for Vancouver, Rain City Strategy, Resilient Vancouver Strategy, Urban Forestry Strategy, Vancouver Plan, VanPlay Framework, etc.

Achieving the City's long-term vision for healthier people, healthier places, and a healthier planet while working towards a fairer, safer, and more inclusive city through policies including: Equity Framework, Healthy City Strategy, Reconciliation Framework, etc.

Figure 4.2024 City of Vancouver Priorities Program (Information Source: City of Vancouver)

The City of Vancouver’s 2024 climate strategy introduces three key strategies to tackle climate change challenges, with a strong emphasis on reducing carbon emissions. The plan aims to cut carbon pollution in half by 2030 and achieve carbon neutrality by 2050. This will be achieved through various initiatives, including the Climate Emergency Action Plan, which promotes sustainable practices across the City, such as the 'How We Move' initiative. In addition to reducing emissions, the plan prioritizes building resilience against climate-related shocks to ensure a secure and sustainable future for the community. However, the primary focus remains on taking decisive action to transition to a low-carbon future.

The Critical Role of Sidewalks in Climate Action



HOW WE MOVE

We need to move around the city differently.
We need to get people and goods around Vancouver in a climate-friendly way.

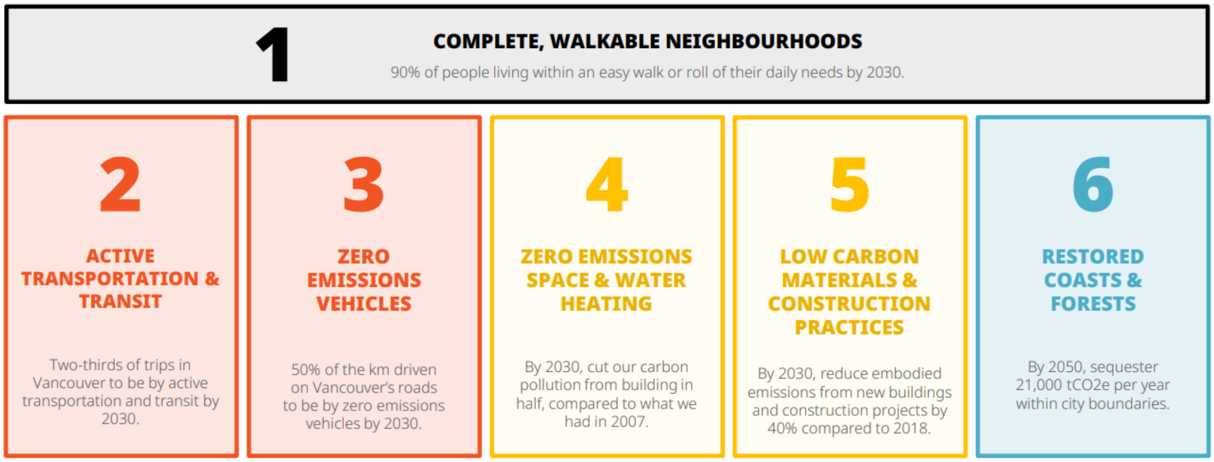
By 2030, we’re aiming for:
- 90% of people living within an easy walk or roll of their daily needs
- Two-thirds of trips in Vancouver to be by active transportation and transit
- 50% of the km driven on Vancouver’s roads to be by zero emissions vehicles

By 2030, low-cost sustainable transportation options will be easy, safe and reliable. People can get to work, school and other destinations without needing to rely on gas and diesel vehicles. There will be less noise and pollution.

You'll notice:
- Bus priority along 10 key corridors
- Connected cycling and walking networks and more EV charging across the city
- More space for walking, cycling and transit in the metro core thanks to transport pricing
- And much more.

Figure 5.Shifting "How We Move" to reduce emission (image source: https://vancouver.ca/green-vancouver/transportation.aspx)

In the climate action of City of Vancouver, we know 40% of emission from burning fossil fuels. With the City's population expected to grow from 675,000 today to around 920,000 by 2050, higher emissions are inevitable unless proactive measures are taken. By encouraging walking, cycling, and the use of public transit as primary modes of transportation, the City can significantly decrease its carbon footprint. As we target by 2030, 90% of residences will live within an easy walk and roll of their daily needs and the demand for sidewalk replacement will increase. Considering greener sidewalks will reduce the City's emissions and play a key role in meeting our target.



1

COMPLETE, WALKABLE NEIGHBOURHOODS

90% of people living within an easy walk or roll of their daily needs by 2030.

2

ACTIVE TRANSPORTATION & TRANSIT

Two-thirds of trips in Vancouver to be by active transportation and transit by 2030.

3

ZERO EMISSIONS VEHICLES

50% of the km driven on Vancouver's roads to be by zero emissions vehicles by 2030.

4

ZERO EMISSIONS SPACE & WATER HEATING

By 2030, cut our carbon pollution from building in half, compared to what we had in 2007.

5

LOW CARBON MATERIALS & CONSTRUCTION PRACTICES

By 2030, reduce embodied emissions from new buildings and construction projects by 40% compared to 2018.

6

RESTORED COASTS & FORESTS

By 2050, sequester 21,000 tCO2e per year within city boundaries.

Figure 6. Six Moves of Climate Emergency Action Plan (Information Source: City of Vancouver)

The existing Sidewalk network condition map for 2021 highlights that a portion of the infrastructure is in poor and very poor condition. This indicates that there will be an increased demand for sidewalk construction in the coming future.

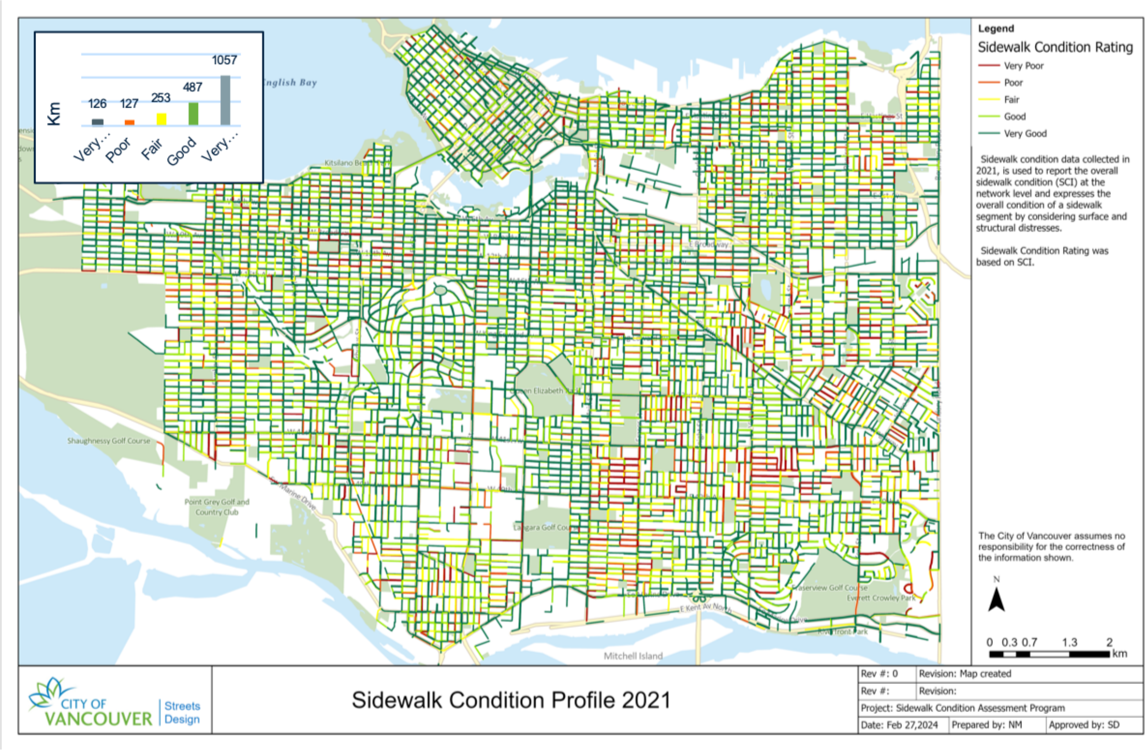


Figure 7.Sidewalk Condition Profile 2021 (Information Source: City of Vancouver)

Such large-scale replacements will inevitably result in substantial construction-related emissions. Addressing the carbon footprint of sidewalk construction is essential to mitigating the overall environmental impact of these necessary upgrades. **As we approach 2050 and strive to meet our carbon neutrality goals, it's essential to explore new construction methods. Replacing infrastructure with sustainable alternative materials is crucial to achieving these future targets.**

Why Choose Concrete for Sidewalks

Sidewalk Design Standards and Material Selection

Sidewalk Design Principles and Standards

The City of Vancouver's Engineering Services design sidewalks according to seven universal design principles that focus on making spaces accessible and easy to use for everyone. First, the design is meant to be useful for people with different abilities (Equitable Use). It’s flexible, allowing a wide range of preferences and abilities to be accommodated (Flexibility in Use). The design is simple and intuitive, so it’s easy to understand, no matter what a person’s experience or skills (Simple and Intuitive Use). It communicates information clearly, even in different conditions or for people with sensory challenges (Perceptible Information). The design also reduces risks by minimizing potential hazards (Tolerance for Error). It’s easy to use without requiring much physical effort (Low Physical Effort), and it provides enough space for people to move and interact comfortably, no matter their size or mobility (Size and Space for Approach and Use).

Following the above design principle, the specific design standard for City of Vancouver can be summarized as following:

- **Width**: Sidewalks must be wide enough to accommodate all users, with minimum width standards set at 1500mm for low-density residential areas and 1800mm for higher-density residential areas. In commercial areas, sidewalks should be between 3000mm and 3650mm wide, with a minimum 1800mm clearance around obstructions.
- **Surface Quality**: Sidewalk surfaces should be broom-finished concrete with saw-cut control joints to reduce vibrations, especially for wheelchair users. When concrete pavers are used, they must be laid smoothly, uniformly, and in a 90-degree herringbone pattern with a small chamfer edge (2-6mm).
- **Cross Slope**: The sidewalk should have a cross slope of 2% to allow proper drainage while minimizing the impact on pedestrians, particularly those using manual wheelchairs.
- **Curb Ramps**: Curb ramps should be installed at all corners, preferably with a double design, and must have a maximum grade of 8% (5-7% is ideal) to provide easy access for wheelchair users and clear tactile cues for visually impaired pedestrians.
- **Surface Covers and Grates**: Covers and grates should be flush with the surrounding surface, slip-resistant, and have openings no larger than 13mm. If elongated, openings should be aligned perpendicular to the direction of travel to avoid tripping hazards.

- **Clearance Heights**: Overhead clearance should be a minimum of 2440mm above pedestrian paths, with signs requiring a minimum clearance of 2743mm if suspended over footways.

These design requirements ensure that sidewalks are accessible, safe, and user-friendly for everyone, including those with disabilities. The standards also emphasize the importance of reducing vibrations, providing clear pathways, and ensuring that sidewalks are durable and properly drained.

Sidewalk Performance Requirements

- **Durability**: Sidewalks must be able to withstand various environmental conditions, including freeze-thaw cycles, heavy foot traffic, and exposure to de-icing chemicals, without significant deterioration.
- **Slip Resistance**: The surface of the sidewalk should provide adequate traction in all weather conditions, reducing the risk of slips and falls for pedestrians.
- **Strength**: Sidewalks should be designed to support not only pedestrian traffic but also occasional loads from maintenance vehicles, bicycles, or small delivery carts without cracking or failing.
- **Easy access**: A uniform surface is essential for accessibility, ensuring that the sidewalk is safe and comfortable for all users, including those with mobility impairments, wheelchair users, and people pushing strollers.
- **Thermal Performance**: Sidewalk materials should be able to manage temperature extremes, reducing heat absorption in the summer (urban heat island effect) and resisting damage from frost heave in the winter.
- **Drainage Efficiency**: Proper slope and drainage design are crucial to prevent water pooling on the surface, which can lead to slips or long-term water damage to the sidewalk.
- **Ease of Maintenance and Repair**: The sidewalk should be easy to maintain and repair with minimal disruption to pedestrians and the surrounding environment. This includes considerations for quick setting times and minimal downtime during repairs.
- **Accessibility Compliance**: Sidewalks must comply with accessibility standards and regulations, including the Americans with Disabilities Act (ADA) in the United States or equivalent standards in other regions, ensuring that all users, regardless of ability, can use the sidewalk safely and comfortably.
- **Cost-Effectiveness**: While ensuring high performance, the materials and construction methods should also be cost-effective, balancing upfront costs with long-term durability and maintenance considerations.

Types of Materials

Concrete: Concrete is the most prevalent material for sidewalks in North America due to its durability and minimal maintenance needs over time. Although the initial installation costs are higher than asphalt, concrete sidewalks reflect more light, which can lower the costs of sidewalk lighting.

Figure 8.Sidewalk Concrete Construction (Image source: https://todayshomeowner.com/driveway/guides/concrete-thickness-for-driveway/)

Asphalt: Asphalt sidewalks have lower upfront construction costs, but a shorter lifespan compared to concrete. They are more prone to damage, especially during snow removal, and generally require more frequent maintenance. Asphalt is typically chosen for areas where a shorter service life is acceptable.

Figure 9.Asphalt Sidewalk Construction (Image credit from: https://www.builderspace.com/why-are-roads-made-of-asphalt-and-not-concrete)

Interlocking Pavers: Interlocking pavers do not require curing time once installed, which means they are less vulnerable to vandalism during the curing process. They can accommodate slight settling in the subgrade without cracking. However, over time, the joints in interlocking pavements tend to accumulate sediment and debris, which can increase runoff. Additionally, improper compaction of the subgrade and base can lead to localized settlement, exacerbating ponding issues.

Figure 10.Interlock sidewalk (Image source: https://www.angi.com/articles/what-are-interlocking-pavers.htm)

Interlocking pavers offer a more aesthetically appealing option than concrete or asphalt. However, they generally come with higher construction costs. For municipal projects, it is advisable that concrete pavers meet or exceed the specifications outlined in the Canadian Standards Association CSA-A231.2 (Latest Edition) for Precast Concrete Pavers.

Alternative Materials: Some municipalities in the United States have started using recycled rubber as an alternative to concrete for sidewalks. As the first installation of a recycled rubber sidewalk took place only in 1999, the assessment of its long-term advantages and disadvantages is still ongoing.

Sidewalks are vital elements of the urban landscape and represent a significant financial commitment. Poor construction can lead to deformations that negatively impact safety, walking comfort, aesthetics, and the intended lifespan of the sidewalk.

Considering the performance requirements above and cost-effectiveness, **Concrete is so far the best option followed by Asphalt**. In this report, we only focus on the concrete sidewalk.

The Evolution of Green Concrete

Understanding Concrete

Concrete, the second most used substance in the world after water, is the foundation of modern civilization, forming the backbone of infrastructure such as bridges, buildings, and roads. Made from a mixture of cement, water, and aggregates, concrete is prized for its strength, durability, and widespread availability, making it an affordable choice for construction. However, its extensive global use has significant environmental implications, **contributing approximately 8% of total global CO2 emissions**. The environmental impact is largely driven by the cement component, which, while essential for binding materials and ensuring the performance of sidewalks, is responsible for around 80% of the CO2 emissions in the concrete lifecycle. Despite its critical role, the environmental footprint of concrete underscores the urgent need for more sustainable production and usage practices.

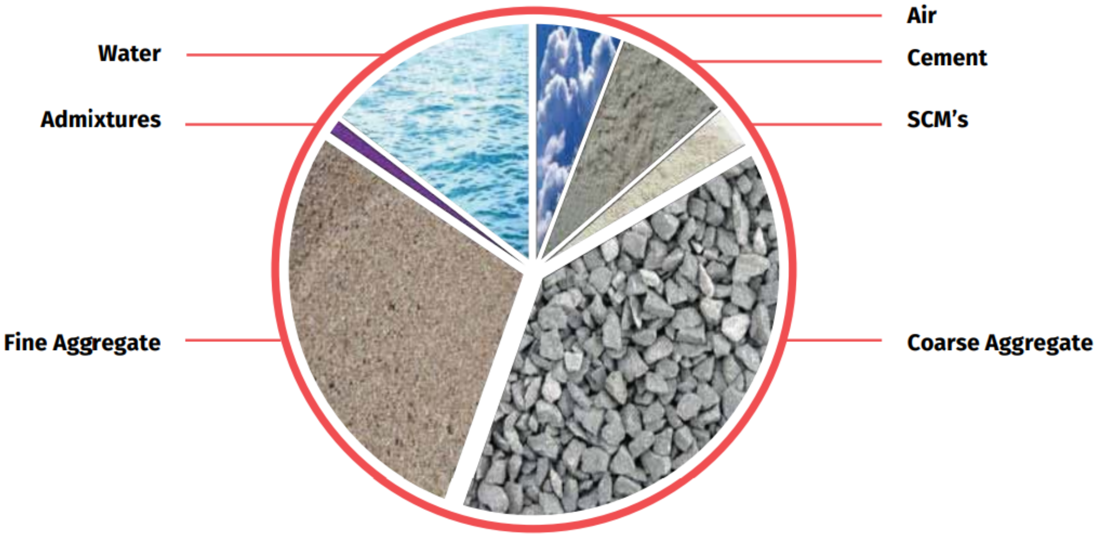


Figure 11. Concrete ingredients (Image source: https://www.constructionspecifier.com/cement-and-concrete-still-outperforming-in-the-sustainability-era/3/)

Why there is no substitution of concrete in the foreseeable future due to following factors:

- **High durability and strength:**

    - Ideal for sidewalks, meeting the required compressive strength of 32 MPa in 28days.
    - Ensures sidewalks remain in good condition under traffic and resist chemical damage.
- **Low cost and easy accessibility:**
    - Limestone, the primary raw material for cement, is abundant and widely distributed across the globe. Finding another material with such widespread availability is challenging.
    - Widespread availability keeps costs low and ensures easy global access.
- **Longevity:**
    - Lifespan of up to 50 years minimizes maintenance and replacement costs.
    - Economically sound choice due to its long-term durability.
- **Versatility and adaptability:**
    - Can be poured into almost any shape, supporting a wide range of designs.
    - Suitable for use in various weather conditions with quick setting times.

Traditional Portland Cement Concrete (OPC/General Use)

General Use concrete, commonly known as Portland cement concrete, is a conventional hydraulic concrete where Ordinary Portland Cement (OPC) is the primary binding ingredient. OPC is known for its predictable performance and well-established standards, making it the preferred choice for a wide range of construction projects worldwide. This type of concrete is versatile and reliable, often used in building structures, pavements, bridges, and more. While OPC provides the strength and durability required for such applications, it is associated with a significant carbon footprint due to the energy-intensive manufacturing process. The limestone content in Portland cement is typically less than 5%, which relatively high percentage of clinker contributes to its high carbon emissions compared to other types of cement like Portland-Limestone Cement (GUL) or more sustainable options such as Green Concrete. Despite these environmental considerations, General Use concrete remains a staple in construction due to its extensive use and proven reliability.

PLC–Portland Limestone Cement Concrete (General Use Limestone/GUL)

Portland Limestone Cement Concrete (General Use Limestone) is a type of concrete that uses Portland-limestone cement (PLC) as its binder instead of the traditional Ordinary Portland Cement (OPC). PLC is an environmentally friendly alternative to OPC, introduced in the last decade, offering up to a 10% reduction in CO2 emissions while maintaining similar strength and durability. This reduction in emissions occurs because, unlike OPC, which contains up to 5% ground limestone, PLC is made by intergrinding up to 15% limestone. This process reduces the amount of clinker required, leading to lower energy consumption and fewer emissions. As a result, PLC generates less CO2 without compromising performance. Widespread adoption of PLC in Canada could potentially reduce CO2 emissions by approximately one megaton annually.

Table 1Average Material Content for 1 metric ton (1,000 kg) of Types GU and GUL, in absolute and percentage basis

Material	Type GU (kg)	GU Input %	Type GUL (kg)	GUL Input%
Clinker	920.4	92%	834.5	83%
Limestone	31.4	3%	120.5	12%
Gypsum	48.2	5%	45	5%
Total	1,000	100%	1,000	100%

Today, extensive research is focused on developing and optimizing Green Concrete to further reduce carbon emissions and meet the demands of sustainable construction.

Green Concrete

Green Concrete, often referred to as "low-carbon concrete," is designed to have a lower level of embodied carbon, falling below a specific threshold that can vary by region, while still meeting all necessary performance criteria.

Green Concrete describes conventional concrete modified to reduce its carbon footprint by decreasing the amount of Portland cement, the main source of emissions in concrete. Although there isn’t a universally accepted definition of “Green Concrete” due to the constantly evolving nature of material science and engineering, the key focus is on reducing carbon emissions. Instead of creating a new material, Green Concrete involves improving existing concrete mixes to lower their carbon content while maintaining important properties like durability, strength, and workability. This is often achieved by adding supplementary cementitious materials (SCMs) such as fly ash, slag, and silica fume, which are industrial by-products with lower carbon emissions. Additionally, Green Concrete can involve reducing emissions from the production of its components, like cement and aggregates, or by optimizing the mix design to use less cement or enable the reuse of concrete at the end of its life. Essentially, the greener the concrete, the lower its carbon emissions, making it an essential element in sustainable construction.

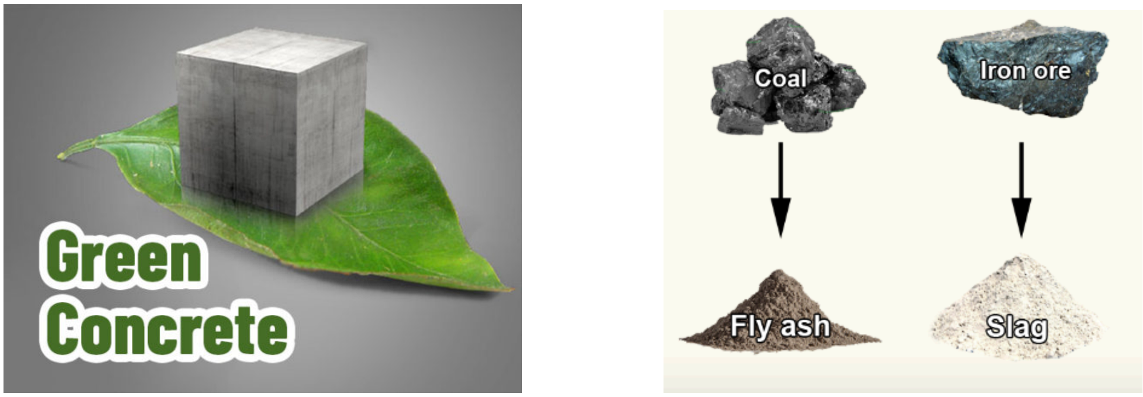


Figure 12.Green Concrete with SCMs substitution (Image source: https://turritopsis.org/en/author/rachid/; https://www.facebook.com/EMSPetrography/posts/add-ons-to-your-cement-supplementary-cementitious-materials-or-scms-are-fine-gra/166490525077950/)

Misconceptions About Concrete Alternatives

There are several misconceptions about Green Concrete that need to be clarified.

First, many people believe that only new materials can reduce carbon emissions. However, this isn't true. We can achieve up to a 30% reduction in carbon emissions by using existing concrete ingredients.

Another common belief is that Green Concrete always costs more. In reality, materials like slag, fly ash, metakaolin, and limestone not only enhance performance but also lower costs by replacing some of the expensive and energy-intensive Portland cement.

Some worry that using these more affordable materials might compromise the quality or durability of concrete, but this is not the case. For example, fly ash has been successfully used since the 1930s, demonstrating that supplementary cementitious materials (SCMs) can maintain high-quality concrete while reducing both carbon emissions and costs. Decades of research on "high-performance concrete" show that SCMs often improve performance. With the right approach, Green Concrete can be stronger, more cost-effective, and better for the environment.

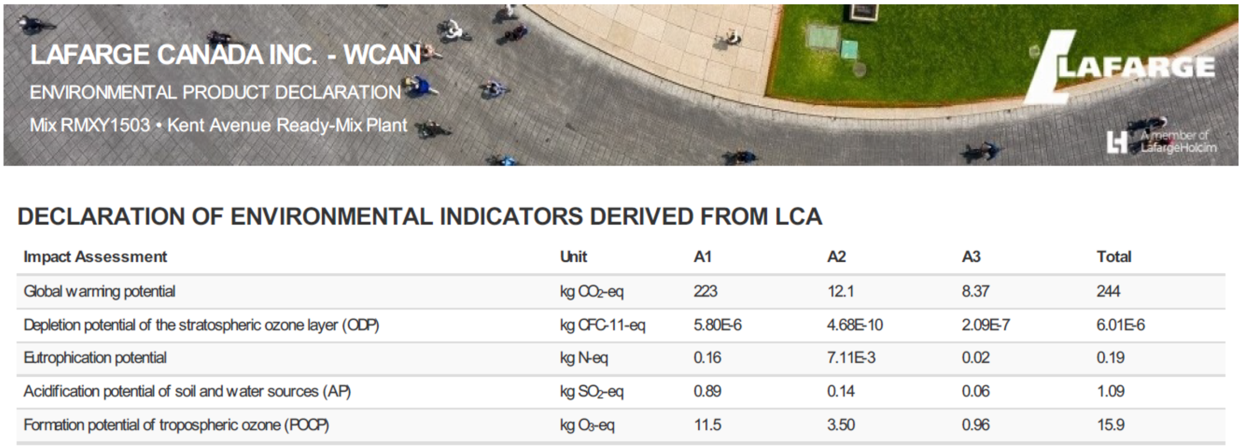
Finally, some people think there is a single "magic" green material that could replace existing concrete or cement while meeting both cost and performance requirements. Although this might be possible in the future, various factors like weather and land moisture affect road construction performance, making it unlikely that one solution will meet all needs. Instead, achieving truly Green Concrete will require a combination of actions tailored to the supply availability in each region.

How to Measure the Green Level: Environmental Product Declaration (EPD)

An Environmental Product Declaration (EPD) is a third party verified document that reports the environmental impacts of a product throughout its life cycle. In the case of the EPD for Lafarge Canada Inc.'s ready-mix concrete from the Kent Avenue Ready-Mix Plant, the EPD covers the environmental impacts associated with 1 cubic meter of concrete mix (RMXY1500A). The EPD is based on a cradle-to-gate life cycle assessment (LCA), which includes the extraction of raw materials, transportation, and the manufacturing process but excludes the impacts related to the construction, use, and end-of-life stages.

The EPD measures various environmental indicators, with a primary focus on Global Warming Potential (GWP), which represents the carbon dioxide equivalent (CO2-eq) emissions. For the specified concrete mix, the EPD reports a GWP of 244 kg CO2-eq per cubic meter. This value is calculated by considering emissions from three key stages:

- **A1**: Raw material extraction and processing.
- **A2**: Transportation of raw materials to the manufacturing site.
- **A3**: The manufacturing process itself.



LAFARGE CANADA INC. - WCAN
ENVIRONMENTAL PRODUCT DECLARATION
Mix RMXY1503 • Kent Avenue Ready-Mix Plant

LAFARGE
A member of LafargeHolcim

DECLARATION OF ENVIRONMENTAL INDICATORS DERIVED FROM LCA

Impact Assessment	Unit	A1	A2	A3	Total
Global warming potential	kg CO_2-eq	223	12.1	8.37	244
Depletion potential of the stratospheric ozone layer (ODP)	kg CFC-11-eq	5.80E-6	4.68E-10	2.09E-7	6.01E-6
Eutrophication potential	kg N-eq	0.16	7.11E-3	0.02	0.19
Acidification potential of soil and water sources (AP)	kg SO_2-eq	0.89	0.14	0.06	1.09
Formation potential of tropospheric ozone (POCP)	kg O_3-eq	11.5	3.50	0.96	15.9

Figure 13.The Global Warming Impact from A1 to A3 (Information source: Lafarge Canada Inc. (2024). Environmental product declaration: Mix RMXY1500A – Kent Avenue Ready-Mix Plant (Version 1). ASTM International.)

In addition to GWP, the EPD also quantifies other environmental impacts, such as ozone depletion potential, acidification potential, eutrophication potential, and more. The EPD provides detailed information on how each stage contributes to the overall environmental impact, allowing for a clear understanding of the carbon footprint and other related impacts of the concrete product. By using EPDs, stakeholders can make informed decisions about the environmental performance of building materials.

Why Action Now

Climate hazards

As one of the world's greenest cities, Vancouver must take urgent and effective action to reduce emissions or face escalating climate hazards. Without intervention, the City will endure more frequent and intense heatwaves, severe flooding from extreme rainfall, worsening droughts, rising sea levels threatening coastal areas, and deteriorating air quality driven by pollution and wildfires. These threats jeopardize public health, strain resources, and could cause irreversible damage to Vancouver's environment and economy. Immediate action is crucial to safeguard the City's future.

Figure 14.Five hazards due to climate change (Information source: City of Vancouver)

Behind Strategy Target

The City of Vancouver has been actively working towards establishing itself as a leader in environmental sustainability, with the ambitious goal of becoming the world’s greenest city. This strategy is central to Vancouver's branding and identity on the global stage, influencing not only its environmental policies but also its economic development, tourism, and international reputation. Right now, we are behind track to reach our target based on the latest forecast, so the only thing we need to do now is make more forward-thinking efforts to maintain our green leader image and reputation.

Despite progress to date, we're not on track to reach our targets.

2024 Annual Report & 2026-2030 Scope | 2024 07 23 | 5

Projected reductions, assuming successful implementation of the remainder of CEAP and the province's CleanBC Roadmap

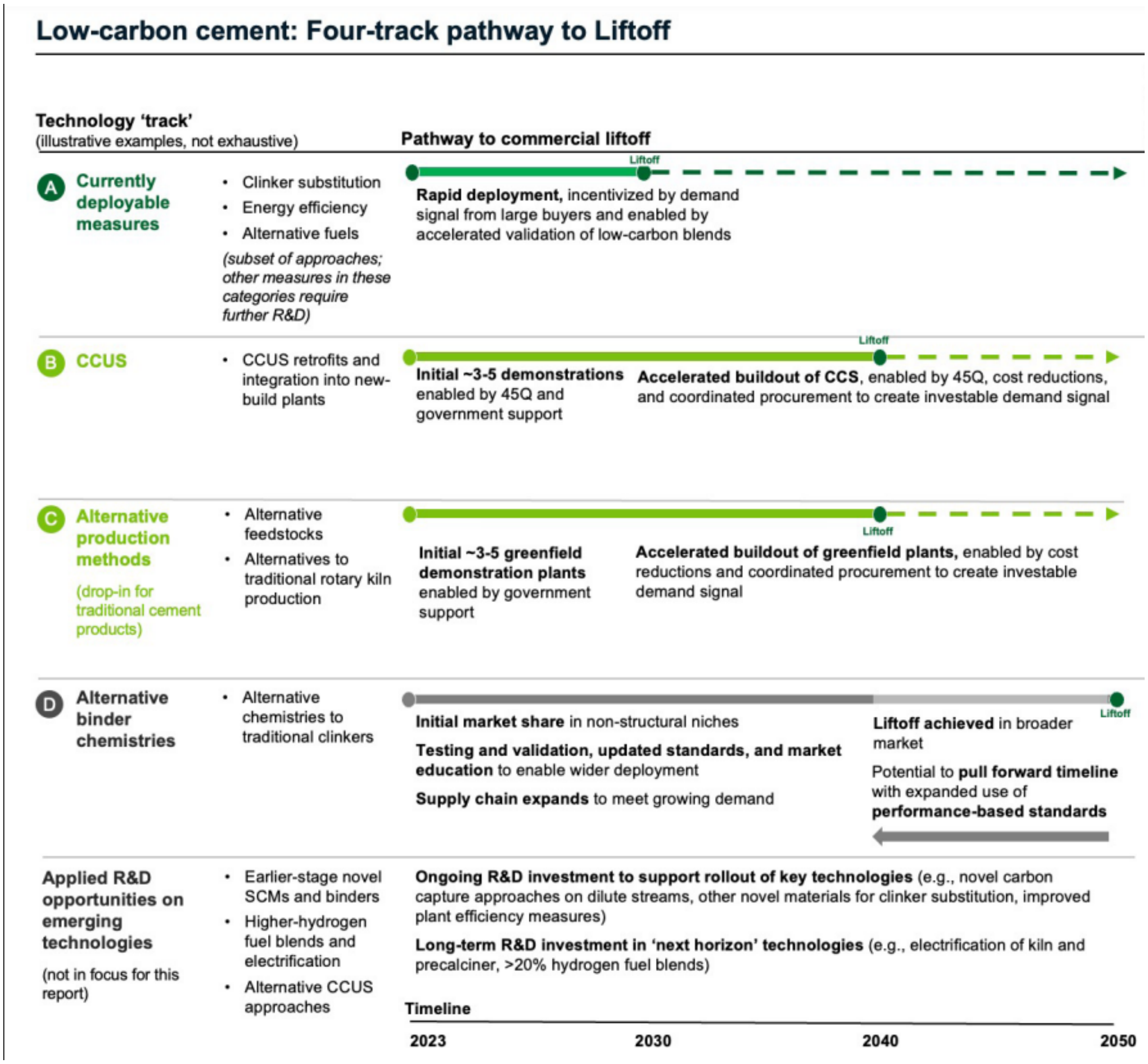
Figure 15.The gap of our climate target (Information source: City of Vancouver)

Technology Progressing

Significant research is focused on developing alternative materials for conventional concrete to reduce emissions. Emerging materials like graphene-based concrete and self-healing concrete show promising performance, fueling hopes for future technological breakthroughs.

A recent white paper from the National Research Council of Canada, titled "Low-Carbon Concrete: Sustainable Performance at an Affordable Price," highlights several widely accepted technologies based on their proven performance. These include cementitious replacements, Portland limestone cement, concrete design optimization, and increasing energy efficiency in clinker/cement production.

A U.S. report provides an overview of key approaches (as below figure shows) to reducing cement emissions. It summarizes the readiness levels of these technologies, from currently deployable measures, CCUS, to future emerging technologies, which help me have an overview of technologies development.



Low-carbon cement: Four-track pathway to Liftoff

Technology 'track'
(illustrative examples, not exhaustive)

Pathway to commercial liftoff

A Currently deployable measures

- Clinker substitution
- Energy efficiency
- Alternative fuels

(subset of approaches; other measures in these categories require further R&D)

Rapid deployment, incentivized by demand signal from large buyers and enabled by accelerated validation of low-carbon blends

B CCUS

- CCUS retrofits and integration into new-build plants

Initial ~3-5 demonstrations enabled by 45Q and government support

Accelerated buildout of CCS, enabled by 45Q, cost reductions, and coordinated procurement to create investable demand signal

C Alternative production methods

(drop-in for traditional cement products)

- Alternative feedstocks
- Alternatives to traditional rotary kiln production

Initial ~3-5 greenfield demonstration plants enabled by government support

Accelerated buildout of greenfield plants, enabled by cost reductions and coordinated procurement to create investable demand signal

D Alternative binder chemistries

- Alternative chemistries to traditional clinkers

Initial market share in non-structural niches

Testing and validation, updated standards, and market education to enable wider deployment

Supply chain expands to meet growing demand

Liftoff achieved in broader market

Potential to **pull forward timeline** with expanded use of **performance-based standards**

Applied R&D opportunities on emerging technologies

(not in focus for this report)

- Earlier-stage novel SCMs and binders
- Higher-hydrogen fuel blends and electrification
- Alternative CCUS approaches

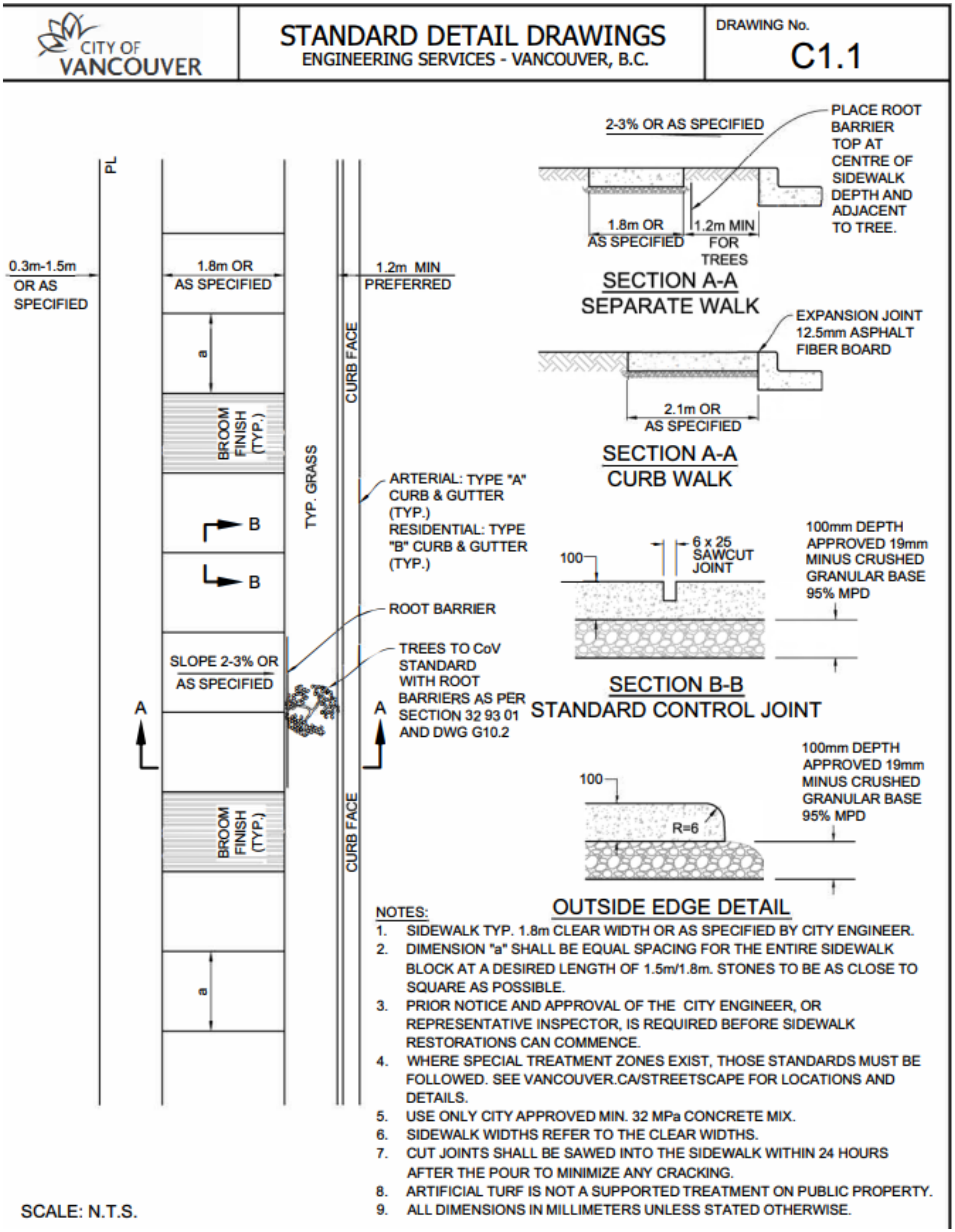
Ongoing R&D investment to support rollout of key technologies (e.g., novel carbon capture approaches on dilute streams, other novel materials for clinker substitution, improved plant efficiency measures)

Long-term R&D investment in 'next horizon' technologies (e.g., electrification of kiln and precalciner, >20% hydrogen fuel blends)

Figure 16.Emission reduction technology path and deployable analysis (Information source: https://liftoff.energy.gov/industrial-decarbonization/low-carbon-cement/)

Potential Opportunities in Sidewalk Design Updates to Reduce Emissions

The current sidewalk design and drawings utilized by the City of Vancouver's Engineering Services have remained unchanged for over five years. These specifications mandate the use of GUL cement and designate granular or crushed stone as the base material. However, with the rapid advancements in technology and innovation, it is crucial to review and update these processes. By doing so, we can explore opportunities to improve the design and reduce emissions.



CITY OF VANCOUVER

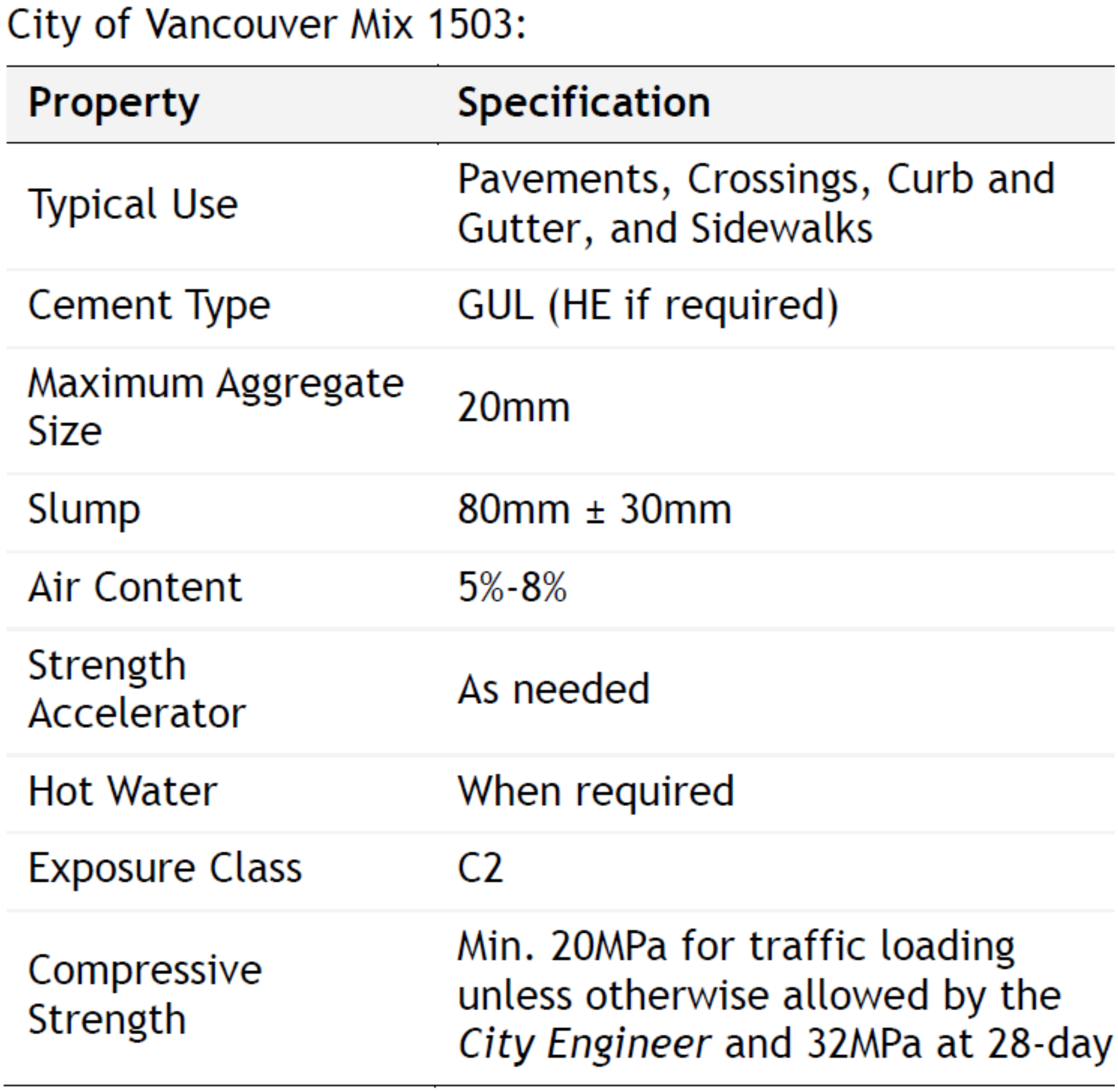
STANDARD DETAIL DRAWINGS
ENGINEERING SERVICES - VANCOUVER, B.C.

DRAWING No.
C1.1

NOTES:
1. SIDEWALK TYP. 1.8m CLEAR WIDTH OR AS SPECIFIED BY CITY ENGINEER.
2. DIMENSION "a" SHALL BE EQUAL SPACING FOR THE ENTIRE SIDEWALK BLOCK AT A DESIRED LENGTH OF 1.5m/1.8m. STONES TO BE AS CLOSE TO SQUARE AS POSSIBLE.
3. PRIOR NOTICE AND APPROVAL OF THE CITY ENGINEER, OR REPRESENTATIVE INSPECTOR, IS REQUIRED BEFORE SIDEWALK RESTORATIONS CAN COMMENCE.
4. WHERE SPECIAL TREATMENT ZONES EXIST, THOSE STANDARDS MUST BE FOLLOWED. SEE VANCOUVER.CA/STREETSCAPE FOR LOCATIONS AND DETAILS.
5. USE ONLY CITY APPROVED MIN. 32 MPa CONCRETE MIX.
6. SIDEWALK WIDTHS REFER TO THE CLEAR WIDTHS.
7. CUT JOINTS SHALL BE SAWED INTO THE SIDEWALK WITHIN 24 HOURS AFTER THE POUR TO MINIMIZE ANY CRACKING.
8. ARTIFICIAL TURF IS NOT A SUPPORTED TREATMENT ON PUBLIC PROPERTY.
9. ALL DIMENSIONS IN MILLIMETERS UNLESS STATED OTHERWISE.

SCALE: N.T.S.

Figure 17.Sidewalk drawing details (Information source: City of Vancouver)



City of Vancouver Mix 1503:

Property	Specification
Typical Use	Pavements, Crossings, Curb and Gutter, and Sidewalks
Cement Type	GUL (HE if required)
Maximum Aggregate Size	20mm
Slump	80mm ± 30mm
Air Content	5%-8%
Strength Accelerator	As needed
Hot Water	When required
Exposure Class	C2
Compressive Strength	Min. 20MPa for traffic loading unless otherwise allowed by the *City Engineer* and 32MPa at 28-day

Figure 18.Sidewalk cement type and performance specification (Information source: City of Vancouver)

Peer Municipalities Engaged in Pilot Projects

Peer municipalities, including Richmond and North Vancouver, are actively piloting Green Concrete projects in collaboration with companies like Heidelberg and Lafarge. Now is an ideal time for us to join forces with these cities, sharing knowledge and learning from each other, while taking a leadership role in addressing climate challenges. To maintain our leadership in green initiatives and protect our reputation, it's crucial that we stay proactive in green city building and not fall behind other municipalities.

Where Are We

Lifecycle Analysis of Existing Sidewalks

Sidewalks in the City of Vancouver are essential to promoting walking as a key mode of transportation. As shown in the chart below, the percentage of people choosing to walk is expected to increase significantly in the coming years.

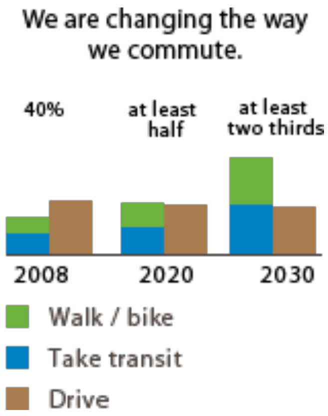


Figure 19.The percentage of Walk by 2030 (Information source: City of Vancouver)

Based on existing data, the City of Vancouver has approximately 2,200 kilometers of sidewalks. For simplicity in calculations, we assume an average sidewalk width of 1.8 meters, as per the design specifications. The typical sidewalk structure consists of three layers: the surface layer, made of 0.1 meters of cement concrete; a middle layer of 0.1 meters of granular base, composed of crushed stone and gravel; and the lowest layer, which is the subgrade or existing soil. Please refer to the simplified graph below for a visual representation.

•Width : 1.8 m
•Length: 1 km
•concrete thickness : 0.1 m

•Granular Thickness: 0.1m
•Granular Material: Crushed stone and Gravel

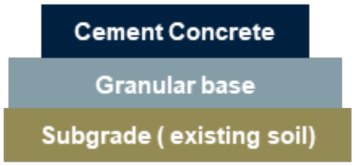


Figure 20.Sidewalk Three-layer structure

System Boundaries and LCA methods

The lifecycle of a sidewalk's carbon emissions can be divided into three phases: cradle to gate (material production and transportation), gate to gate (construction and use), and gate to grave (maintenance and end of life) as shown in the graph. Industry data shows that about 90% of these emissions occur during the cradle to gate phase, mainly due to material production and transportation. Therefore, this report will focus on emissions before construction, as the remaining phases contribute less than 10% and won't significantly affect our goal of identifying ways to reduce concrete emissions. In the case of the City of Vancouver, where concrete and granular materials are produced locally, transportation emissions are negligible. Thus, our emphasis will be on emissions from material to concrete production.

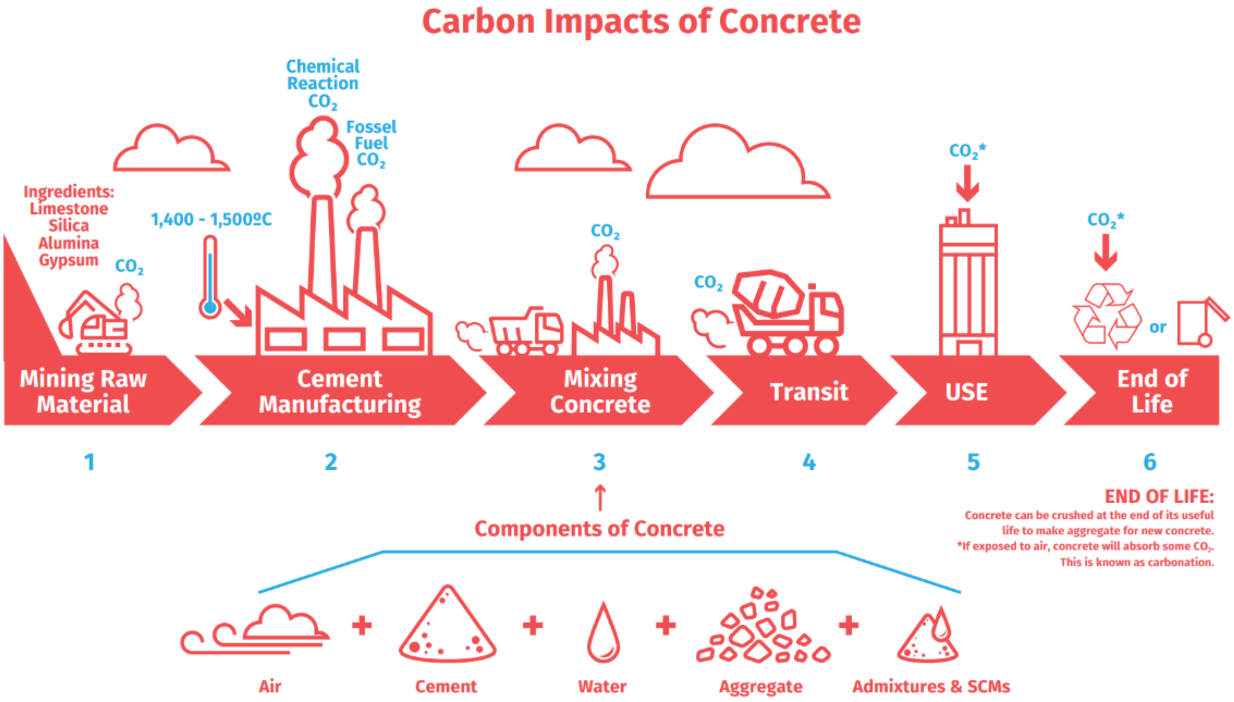
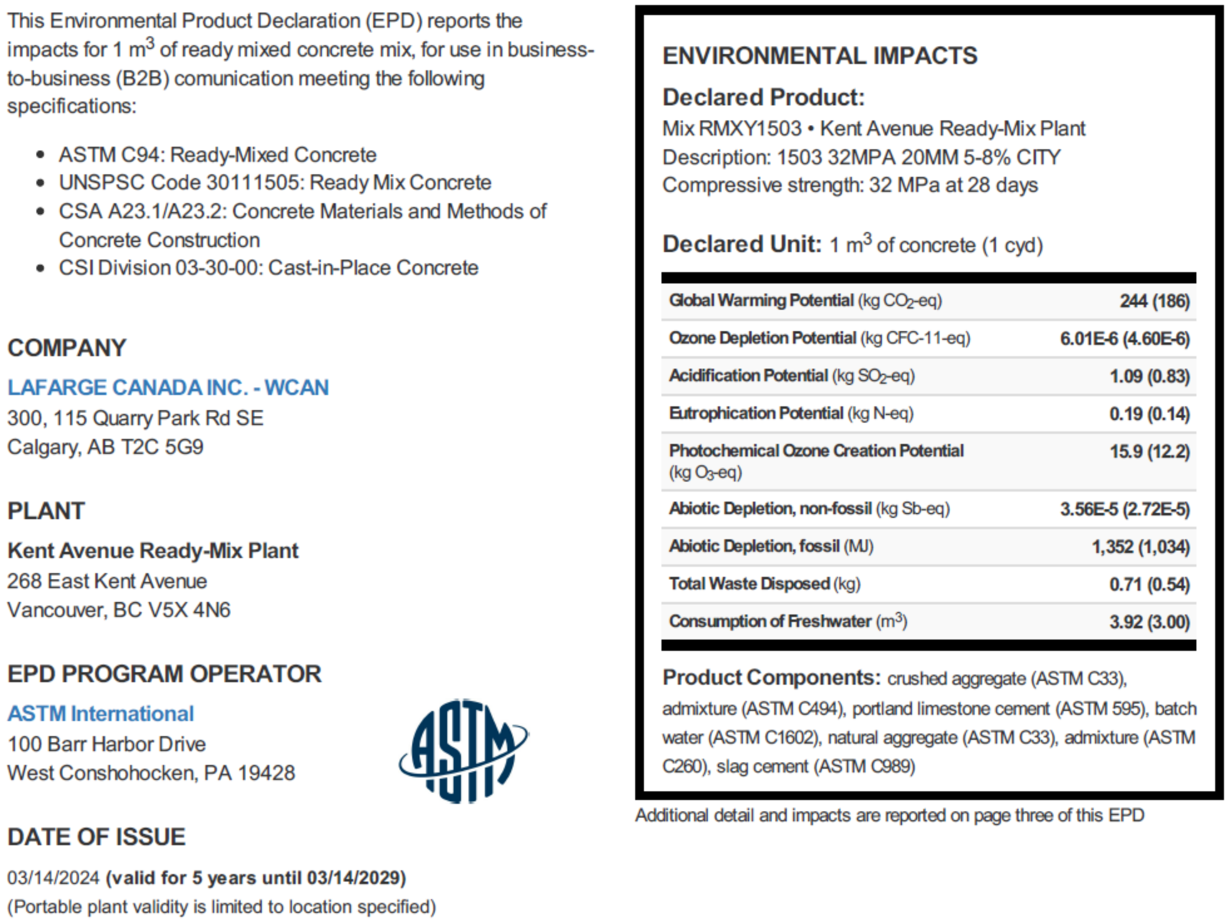


Figure 21.Sidewalk concrete lifecycle (Image source: https://doi.org/10.4224/40002759)

1) Granular material emission, as we know the carbon emission of crushed stone is 6.18kg per ton, and the density of Crushed stone is about 1.6 ton per cubic meter. we figure out that:
   Emission in kg/m³=6.18kg/ton×1.6t/m³=9.89kg/m³
2) For concrete emissions, we can refer to the Environmental Product Declaration (EPD) of a concrete product from Lafarge, which is one of the typical concretes used for sidewalks. The EPD provides data on CO2 emissions from the entire lifecycle, including upstream material extraction, transportation to the factory, and concrete manufacturing. According to the EPD, the CO2 emissions from cradle to gate amount to 224 kg kg/m³.

Table 2. Global warming potential for sidewalk concrete (from A1 to A3)

Global Assessment	Unit	A1	A2	A3	Total
Global warming potential	Kg CO2-eq	208	10.1	5.42	**224**



This Environmental Product Declaration (EPD) reports the impacts for 1 m^3 of ready mixed concrete mix, for use in business-to-business (B2B) comunication meeting the following specifications:

- ASTM C94: Ready-Mixed Concrete
- UNSPSC Code 30111505: Ready Mix Concrete
- CSA A23.1/A23.2: Concrete Materials and Methods of Concrete Construction
- CSI Division 03-30-00: Cast-in-Place Concrete

COMPANY

LAFARGE CANADA INC. - WCAN
300, 115 Quarry Park Rd SE
Calgary, AB T2C 5G9

PLANT

Kent Avenue Ready-Mix Plant
268 East Kent Avenue
Vancouver, BC V5X 4N6

EPD PROGRAM OPERATOR

ASTM International
100 Barr Harbor Drive
West Conshohocken, PA 19428

DATE OF ISSUE

03/14/2024 **(valid for 5 years until 03/14/2029)**
(Portable plant validity is limited to location specified)

ENVIRONMENTAL IMPACTS

Declared Product:
Mix RMXY1503 • Kent Avenue Ready-Mix Plant
Description: 1503 32MPA 20MM 5-8% CITY
Compressive strength: 32 MPa at 28 days

Declared Unit: 1 m^3 of concrete (1 cyd)

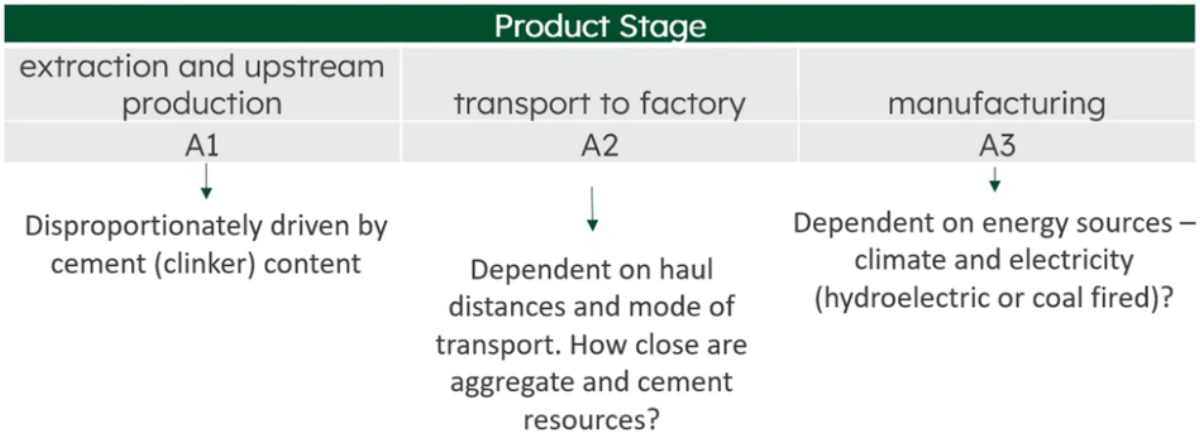
Global Warming Potential (kg CO_2-eq)	**244 (186)**
Ozone Depletion Potential (kg CFC-11-eq)	**6.01E-6 (4.60E-6)**
Acidification Potential (kg SO_2-eq)	**1.09 (0.83)**
Eutrophication Potential (kg N-eq)	**0.19 (0.14)**
Photochemical Ozone Creation Potential (kg O_3-eq)	**15.9 (12.2)**
Abiotic Depletion, non-fossil (kg Sb-eq)	**3.56E-5 (2.72E-5)**
Abiotic Depletion, fossil (MJ)	**1,352 (1,034)**
Total Waste Disposed (kg)	**0.71 (0.54)**
Consumption of Freshwater (m^3)	**3.92 (3.00)**

Product Components: crushed aggregate (ASTM C33), admixture (ASTM C494), portland limestone cement (ASTM 595), batch water (ASTM C1602), natural aggregate (ASTM C33), admixture (ASTM C260), slag cement (ASTM C989)

Additional detail and impacts are reported on page three of this EPD

Figure 22.Environmental Impacts from Environmental Product Declaration Report (Information source: Lafarge Canada Inc. (2024). Environmental product declaration: Mix RMXY1500A – Kent Avenue Ready-Mix Plant (Version 1). ASTM International)

For a 1 km sidewalk, the volume of concrete required is 180 cubic meters, and the same volume is needed for the granular material. The carbon emissions associated with these materials are significant. The granular material emits approximately 1.78 tons of CO_2, while the concrete contributes 40.32 tons of CO_2. This results in a total emission of 42.10 tons of CO_2 for every kilometer of sidewalk constructed. When scaling up to a total sidewalk length of 2,200 km, the overall Global Warming Potential (GWP) during the lifecycle of the sidewalk amounts to 92,620 tons of CO_2.



Product Stage		
extraction and upstream production	transport to factory	manufacturing
A1	A2	A3
Disproportionately driven by cement (clinker) content	Dependent on haul distances and mode of transport. How close are aggregate and cement resources?	Dependent on energy sources – climate and electricity (hydroelectric or coal fired)?

Figure 23.Definition of A1, A2, A3 (Information source: Lafarge Canada Inc. (2024). Environmental product declaration: Mix RMXY1500A – Kent Avenue Ready-Mix Plant (Version 1). ASTM International)

Challenges to Implementing Change

- **Asset Management Budget Constraints**: Existing budget limitations and concerns about increased maintenance costs hinder the adoption of new materials. For example, C$ 1.2 million budget can fund around 6km sidewalk construction. Comparing this to the 2,200 km of sidewalks across the city, it becomes clear that the available budget is insufficient to cover widespread upgrades, making it challenging to allocate funds for innovative materials or technologies without compromising other essential services.
- **Team Expectations:** Team hopes for a "silver bullet" solution from the industry, leading to delays in action as we wait for an easier fix.
- **Pilot Material Challenges**: Piloting new materials involves a complex testing and adaptation process, which is lengthy and requires dedicated personnel—an issue given limited resources.
- **Design Team Risk Aversion**: The design team's low tolerance for risk, with a focus on safety and zero-risk attitudes, hampers the willingness to pilot new materials, especially under strict control requirements.
- **Construction Team Reluctance**: Construction teams are often hesitant to adopt unproven or more complex curing methods, which may increase their workload and carry additional risks.

Furthermore, user concerns have made Green Concrete procurement a lower priority. The cement industry is capital-intensive, with significant investments already made and limited demand growth. This lack of market assurance provides little incentive for companies to upgrade production systems or invest in new material development.

Research institutions have focused extensively on developing new materials, but finding an alternative with the global availability of limestone is challenging. Most research remains confined to lab tests, lacking industry-scale production and user testing needed for commercialization. Without practical application and market support, even extensive research is unlikely to lead to successful products, as developing new materials often involves numerous failures before achieving success.

How Can We Make Sidewalk Concrete Greener

Where Should We Focus

When examining the life cycle of concrete, it's evident that 90% of emissions occur before the construction phase. Typically, only a small portion of carbon emissions comes from the extraction of aggregates, mixing of materials at the concrete plant, and transportation to the construction site. The largest contributor to emissions in the concrete production process is the manufacturing of cement. Consequently, the amount of embodied carbon in concrete largely depends on the quantity of cement used in the mix. **Reducing cement content is an effective strategy for lowering concrete's carbon footprint, so in this report we will focus on cement emission reduction.**

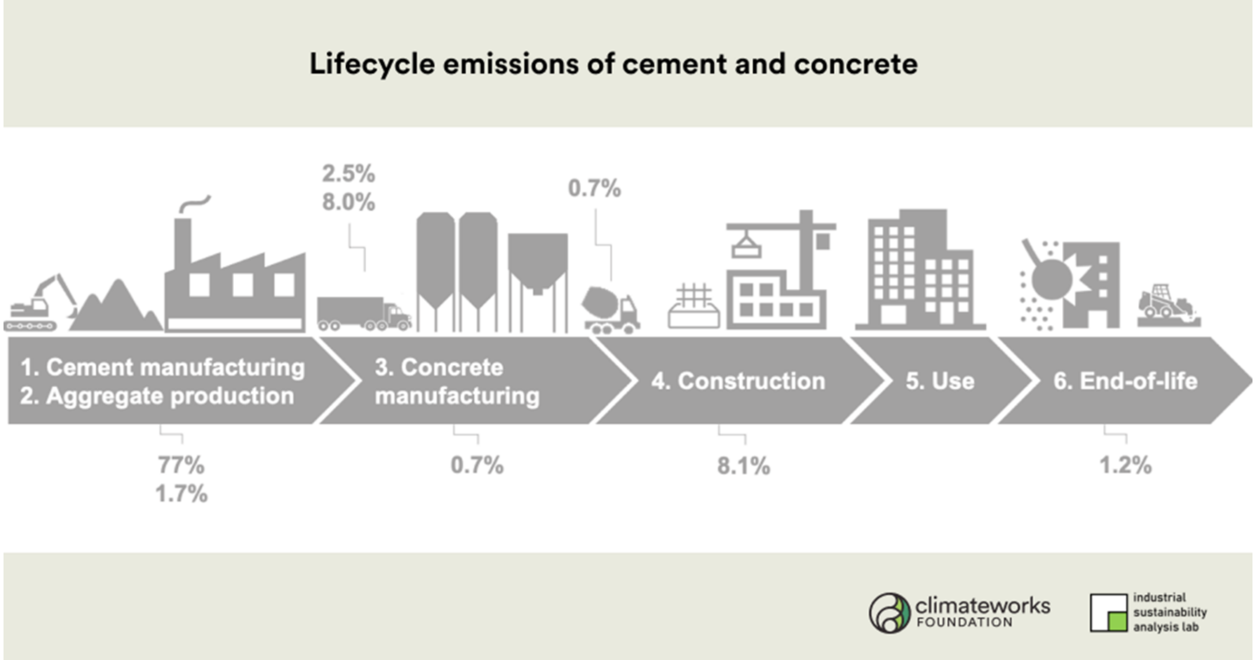


Figure 24.Lifecycle emissions of cement and concrete (Infographic Credit: Climate Works Foundation)

Where Do Emissions Come From

The cement production process begins with the extraction and grinding of raw materials, with limestone as the main ingredient. The material is then heated in a preheater to around 1500-2000°C before being fed into a rotating kiln. In the kiln, a chemical reaction known as calcination occurs, breaking down calcium carbonate ($CaCO_3$) into calcium oxide (CaO) and releasing carbon dioxide (CO_2). This reaction produces clinker, which is then cooled. The cooled clinker is mixed with gypsum and ground into a fine powder to produce Ordinary Portland Cement (OPC).

In the cement life cycle analysis, about one-third (34%) of the emissions from cement production stem from the combustion of fossil fuels needed to heat the cement kiln, while 51% result from chemical reactions, particularly the calcination of carbonates like limestone, which produces CO_2.

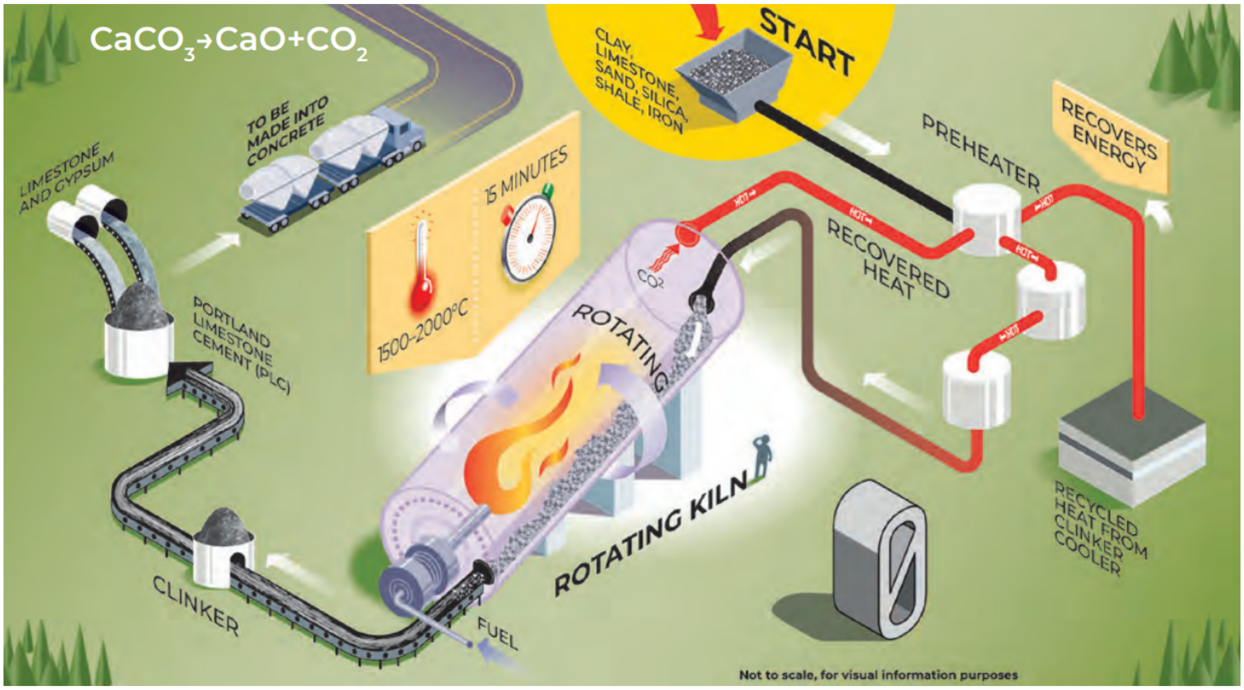


Figure 25.Production Process from raw material to cement (Information source: https://liftoff.energy.gov/industrial-decarbonization/low-carbon-cement/)

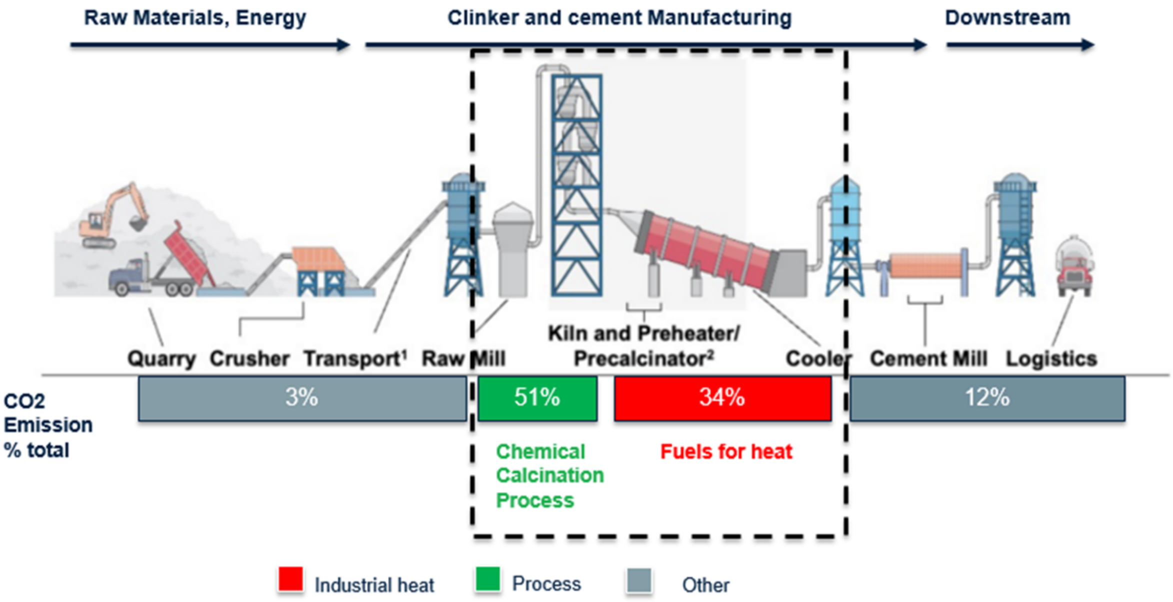


Figure 26.Emission distribution of cement production (Information source: https://liftoff.energy.gov/industrial-decarbonization/low-carbon-cement/)

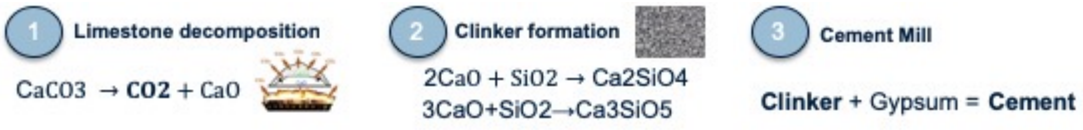
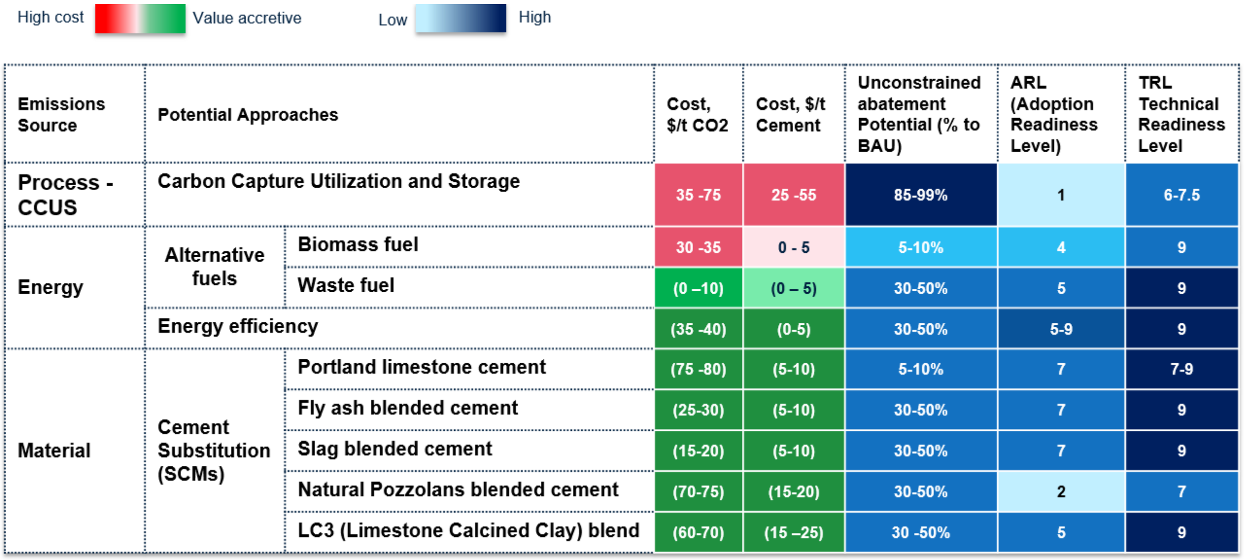


Figure 27.Chemical reaction during cement production (Image credit from: https://www.quora.com/Is-there-a-better-alternative-to-concrete-that-s-stronger-more-common-and-eco-friendlier)

Reducing Cement Emissions: Current Technologies and Approaches

Existing technologies for emission reduction span various levels of readiness and encompass a range of approaches. In the energy sector, improvements are being made through enhanced energy efficiency and the adoption of alternative energy sources. On the materials front, efforts include substituting traditional materials with more sustainable options, such as maximizing the use of supplementary cementitious materials (SCMs) and increasing material efficiency through recycling technologies and optimized design structures. Additionally, carbon capture, utilization, and storage (CCUS) technologies are being retrofitted into existing plants and integrated into newly constructed facilities to further reduce emissions.

Table 3.Cost of CO2 Reduction compared to Standard Cement (OPC) (Information source: https://liftoff.energy.gov/industrial-decarbonization/low-carbon-cement/)



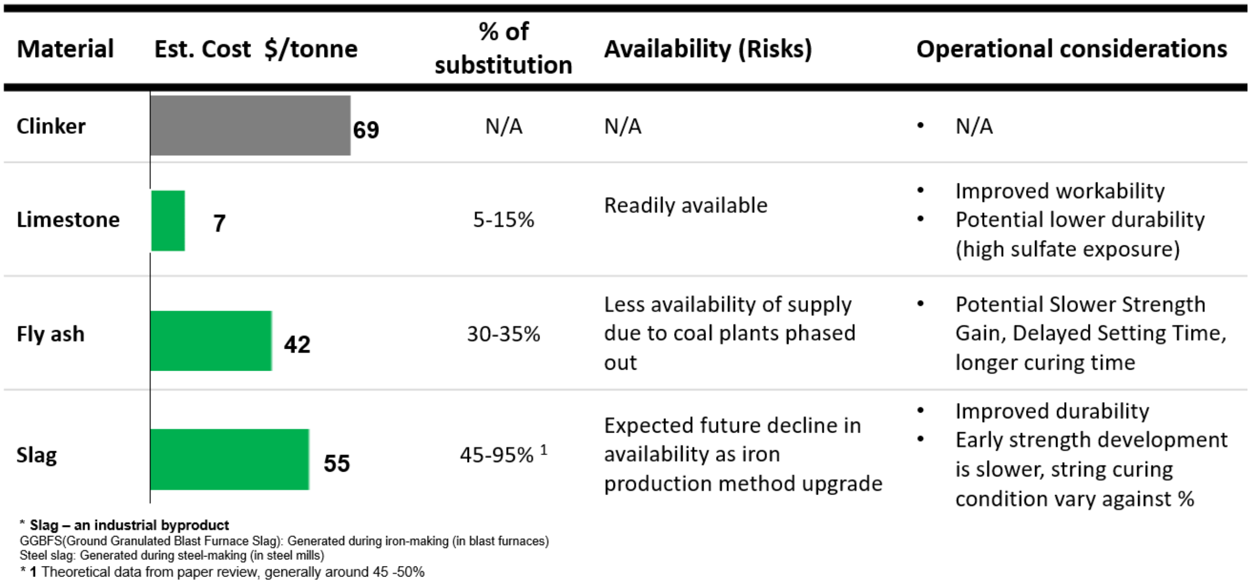
Emissions Source	Potential Approaches		Cost, $/t CO2	Cost, $/t Cement	Unconstrained abatement Potential (% to BAU)	ARL (Adoption Readiness Level)	TRL Technical Readiness Level
Process - CCUS	Carbon Capture Utilization and Storage		35 -75	25 -55	85-99%	1	6-7.5
Energy	Alternative fuels	Biomass fuel	30 -35	0 - 5	5-10%	4	9
		Waste fuel	(0 –10)	(0 – 5)	30-50%	5	9
	Energy efficiency		(35 -40)	(0-5)	30-50%	5-9	9
Material	Cement Substitution (SCMs)	Portland limestone cement	(75 -80)	(5-10)	5-10%	7	7-9
		Fly ash blended cement	(25-30)	(5-10)	30-50%	7	9
		Slag blended cement	(15-20)	(5-10)	30-50%	7	9
		Natural Pozzolans blended cement	(70-75)	(15-20)	30-50%	2	7
		LC3 (Limestone Calcined Clay) blend	(60-70)	(15 –25)	30 -50%	5	9

In Table 3, we compare three emission reduction strategies—CCUS, energy efficiency, and materials substitution—we find that the high cost of CCUS poses a significant barrier to adoption. Energy costs are still constrained by the availability and competitiveness of green energy. **In contrast, material substitution shows promising cost savings, supported by high Technology Readiness Levels (TRL) and Adoption Readiness Level (ARL).** Thus, in this report we will detail about how material strategy reduces emission.

Reducing Cement Emissions Through Material Substitution

Cement is made from clinker, derived from limestone decomposition at high temperatures. Reducing the clinker ratio in cement production can be achieved by replacing clinker with materials that lack carbonates, such as clays, natural pozzolans, and industrial by-products like fly ash and slag. Relating technologies in Canada have made significant progress, with some cement producers committing to a 30% clinker substitution, resulting in a clinker ratio of 0.7. Based on the marketing Adoption readiness level and technology readiness level**, in this report, we only compare three most widely accepted and technology mature technologies, including Portland limestone, fly ash cement and slag cement.** Compare the carbon emission, cost and performance against traditional cement OPC.

Table 4. Cost, substitution %, Availability and operational considerations of SCMs substitution cement



Material	Est. Cost $/tonne	% of substitution	Availability (Risks)	Operational considerations
Clinker	69	N/A	N/A	- N/A
Limestone	7	5-15%	Readily available	• Improved workability • Potential lower durability (high sulfate exposure)
Fly ash	42	30-35%	Less availability of supply due to coal plants phased out	• Potential Slower Strength Gain, Delayed Setting Time, longer curing time
Slag	55	45-95% [1]	Expected future decline in availability as iron production method upgrade	• Improved durability • Early strength development is slower, string curing condition vary against %

* **Slag – an industrial byproduct**
GGBFS(Ground Granulated Blast Furnace Slag): Generated during iron-making (in blast furnaces)
Steel slag: Generated during steel-making (in steel mills)
* **1** Theoretical data from paper review, generally around 45 -50%

Portland Limestone Cement (PLC): Achieving ~10% Emission Reduction vs OPC

Cost: The clinker was replaced with limestone, compared with cost of clinker 69$/tonne, the limestone cost 7$/tonne. And it's readily available. The substitution range can be between 5-15%.

Emissions: Lower CO2 emissions compared to traditional Portland cement. The addition of limestone (typically 5-15%) reduces the clinker content, leading to a reduction in carbon emissions by approximately 10-12% compared to traditional Portland cement (OPC).

Performance: Offers comparable strength and durability to traditional Portland cement. However, there may be some variations in performance depending on the specific application and environmental conditions (less durability under high sulfate environment). It is generally well-suited for most standard construction projects. It has been widely promoted by cement association of Canada, and it has been adopted as our existing sidewalk concrete cement. In USA, it has been approved under widely used ASTM C595 standard in 2012 and today accounts for roughly one third of cement shipped in US.

Fly Ash Blended Cement: Achieving ~32% Reduction in Emissions vs OPC

Cost: Fly ash is a by-product of coal combustion, 42$/tonne estimated cost, 27$ less expensive than clinker. It can be used to replace clinkers up to 30%-35%. As the coal plant closes, the availability will decline, as a result, the cost might slightly go up due to demand greater than supply.

Emissions: Significantly lower CO2 emissions compared to Portland cement. The substitution of clinker with fly ash can reduce emissions by up to 30-40%, depending on the proportion used.

Performance: Fly ash blended cement is known for improved workability, reduced permeability, and enhanced durability, particularly in aggressive environments. It tends to gain strength more slowly than traditional cement, which may be a consideration for time-sensitive projects. It's particularly beneficial in reducing the heat of hydration, making it suitable for large pours.

Slag Blended Cement: Achieving ~42% Emission Reduction vs OPC

Cost: Slag, a by-product of industry production (Ground Granulate Blast Furnace Slag), has costs that can vary depending on local sourcing and processing requirements. The estimated cost in North America is around $55 per tonne. It offers a high substitution rate, ranging from 45% to 95%. However, the 95% substitution rate is theoretical, based on literature; in practical applications, the substitution level typically hovers around 50%

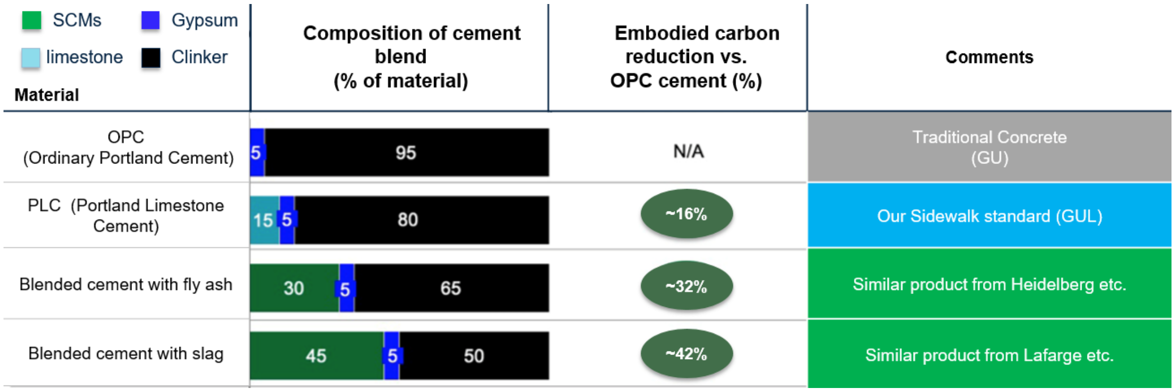
Emissions: Substantial reduction in CO2 emissions, like fly ash blended cement. The use of slag as a clinker substitute can reduce emissions by 30-50%, depending on the percentage of slag used.

Performance: Slag blended cement offers excellent durability, particularly in harsh environments (e.g., sulfate or chloride exposure). It enhances resistance to chemical attacks, making it ideal for marine or industrial applications. Like fly ash, slag cement gains strength more slowly but results in higher ultimate strength. It also contributes to reduced heat of hydration, which is beneficial for mass concrete applications.

Summary and Future Directions

The City of Vancouver currently relies on OPC and PLC as its primary cement products. However, we have a significant opportunity to lead in carbon emission reduction by increasing the use of supplementary cementitious materials (SCMs). The following factors have been identified to guide further decisions.

Table 5. Identifying opportunities by comparing the composition/emission reduction of existing products and SCM cement



🟩 SCMs 🟦 Gypsum
▨ limestone ⬛ Clinker

Material	Composition of cement blend (% of material)	Embodied carbon reduction vs. OPC cement (%)	Comments
OPC (Ordinary Portland Cement)	🟦 5 ⬛ 95	N/A	Traditional Concrete (GU)
PLC (Portland Limestone Cement)	▨ 15 🟦 5 ⬛ 80	~16%	Our Sidewalk standard (GUL)
Blended cement with fly ash	🟩 30 🟦 5 ⬛ 65	~32%	Similar product from Heidelberg etc.
Blended cement with slag	🟩 45 🟦 5 ⬛ 50	~42%	Similar product from Lafarge etc.

- **Availability:** Ensuring local availability is a key factor when considering alternative materials. As shown in the table, similar products to fly ash and slag are available from local suppliers.
- **Cost**: Limestone, Fly ash and slag blended cements generally offer cost savings compared to traditional Portland cement.
- **Emissions**: Fly ash and slag blended cements significantly reduce CO2 emissions compared to Portland limestone cement, which still offers a reduction over traditional cement.
- **Performance:** All three types of cement offer performance benefits, with fly ash and slag-blended cements providing enhanced durability and resistance in challenging environments. However, there are operational considerations to address. These can be mitigated by optimizing the concrete mix design, such as incorporating admixtures and adjusting the percentage of substitution based on specific project requirements.

Concrete Mix Design Innovations

Concrete is composed of cement, aggregates, supplementary cementitious materials (SCMs), water, and air. While higher SCM substitution can potentially reduce performance or present operational challenges, these issues can be mitigated by incorporating admixtures into the concrete mix design

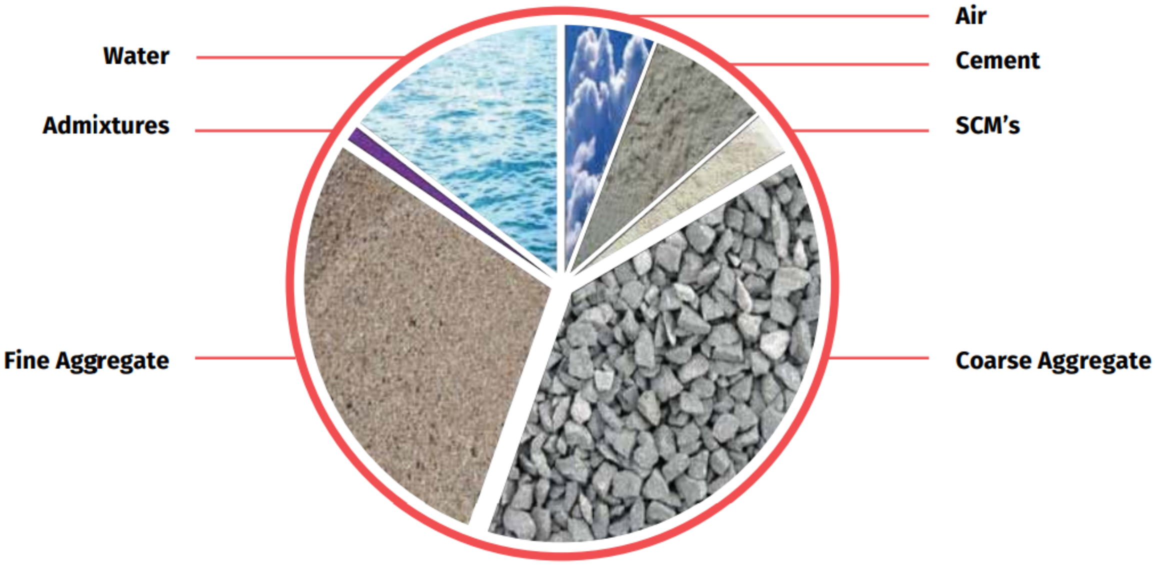


Figure 28.Composition of Concrete(Image credit from: https://www.constructionspecifier.com/cement-and-concrete-still-outperforming-in-the-sustainability-era/3/)

As we talked before, using supplementary cementitious materials (SCMs) to replace a portion of cement is a common practice for reducing greenhouse gas (GHG) emissions in concrete production. However, the proportion of SCMs can vary significantly depending on the application. For instance, higher percentages of slag or fly ash can slow down strength development, longer the curing time, particularly in cold weather conditions.

Admixtures are natural or manufactured chemicals added during concrete mixing to enhance specific properties such as workability, durability, and strength. Despite accounting for less than 1% of concrete's carbon emissions, admixtures play a crucial role in improving concrete performance. They enhance workability and finishing operations, while also reducing the environmental footprint by minimizing the amount of cement needed to achieve desired performance levels. There are some emerging researches about graphene concrete has brought a deep interest, because using graphene as admixtures can greatly enhance the concrete performance.

Recycling Technologies in Concrete

Emerging research shows that recycled concrete can be effectively used as aggregates in new concrete mixtures.

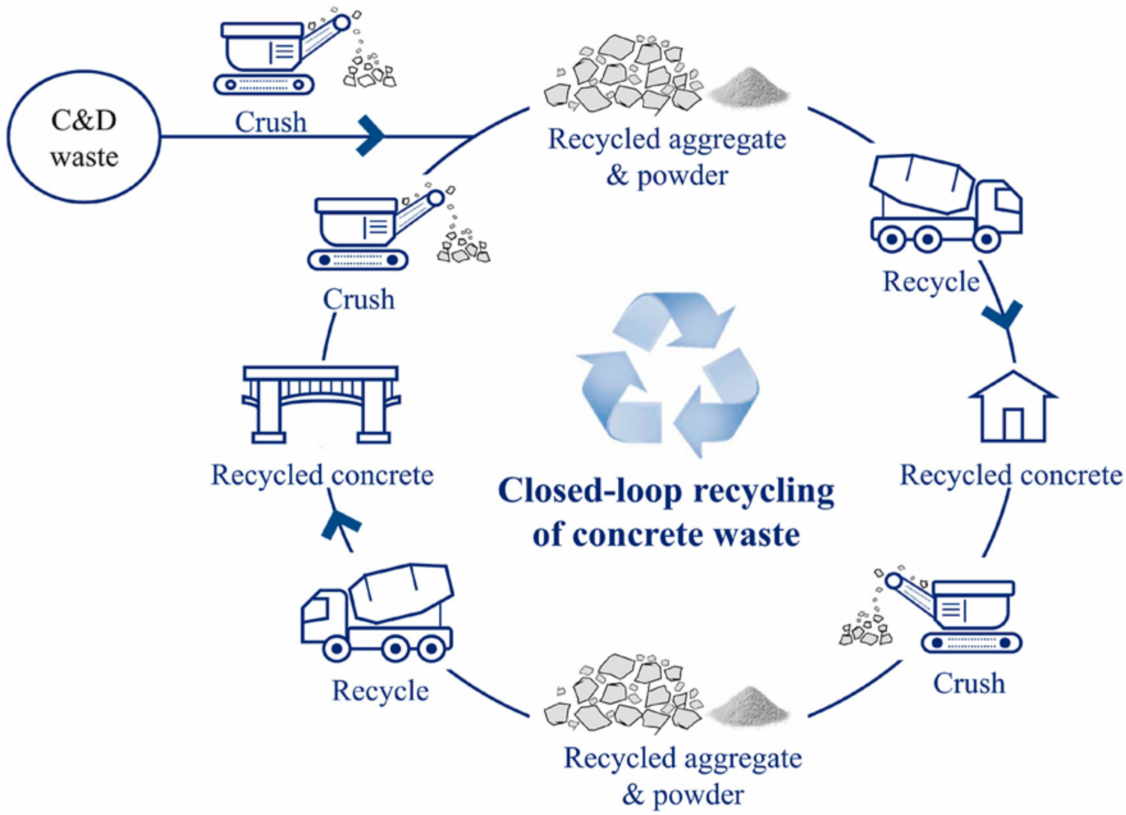


Figure 29.Concrete Recycle Loop (Imagecreditfrom:https://www.sciencedirect.com/science/article/pii/S0959652622006126)

In addition, sidewalks are not made entirely of concrete; they also include a granular base, typically composed of crushed stone. A proven and successful practice is to use recycled concrete as this granular base material. This approach not only reduces the carbon footprint by minimizing the need for new natural resources and decreasing landfill waste but also lowers emissions through reduced transportation, especially when locally sourced recycled concrete is used.

Emerging Technologies for Low-Carbon Concrete

Several new materials and technologies are currently under active research in the concrete industry. While they show significant promise for reducing carbon emissions and enhancing performance, they face challenges related to cost, scalability, or durability. As a result, further breakthroughs are necessary before they can be widely adopted in mainstream construction. Below are some of these emerging technologies:

Self-healing concrete

- Self-healing concrete contains bacteria or microcapsules that produce healing agents to automatically repair cracks. When a crack occurs, water enters the crack and reacts with the bacteria, triggering the formation of a material that fills the crack. This process enhances the lifespan of the structure and significantly reduces maintenance costs.
- In 2019, researchers at The University of British Columbia successfully installed an eco-friendly, self-healing road in the Chawathil First Nation community using a novel fiber-reinforced concrete made from recycled materials, including scrap tire fibers and cellulose fibers. This innovative concrete not only self-heals when cracks form, reducing maintenance needs and extending the pavement's lifespan, but also minimizes environmental impact by repurposing waste materials. The installation includes 30 solar-powered sensors that provide continuous data to monitor the pavement's performance, enabling future improvements. This project exemplifies advanced, sustainable infrastructure and has garnered attention at major conferences, including the American Concrete Institute Annual Convention.

Graphene-Enhanced Concrete

- Includes graphene, a form of carbon, which significantly improves strength, durability, and thermal properties. Allows for thinner, lighter structures with increased longevity.
- Nova Scotia-based AlterBiota is transforming the concrete industry with its innovative Bio Graphene Oxide (hBGO) additive, made from forestry waste. This admixture strengthens concrete while significantly reducing the need for carbon-intensive Portland cement, thus lowering the overall carbon footprint. Produced through a waste-free, circular process, hBGO also offers carbon credits for cement avoidance. This summer, AlterBiota secured a CAD$4 million investment to fund industrial trials and build a commercial-scale plant, advancing the commercialization of this sustainable technology

3D Printable Concrete

- Designed for use in additive manufacturing (3D printing) of complex architectural forms. Focuses on optimizing mix designs for printability, speed, and strength
- One example of 3D-printed concrete for road construction is the project developed by the Eindhoven University of Technology in the Netherlands. In collaboration with several partners, the university created a series of 3D-printed concrete bridges and road elements. The technology uses a robotic arm to layer concrete precisely, creating complex structures with minimal material waste.

Fiber-Reinforced Concrete (FRC)

- Incorporates various types of fibers (steel, glass, synthetic, natural) to improve crack resistance, durability, and impact resistance. Used widely in pavements, bridges, and earthquake-resistant structures.

Conclusion

To summarize the technologies discussed, the following bubble chart provides an overview of each one. The size of the bubble represents the cost of the technology, with larger bubbles indicating higher costs for CO2 capture. CCUS has the largest bubble due to its significant investment and operational costs. The bubble colors represent different emission reduction strategies: green for energy pathways and purple for material strategies. OPC is used as a benchmark, showing the highest Technology Readiness Level (TRL) and Application Readiness Level (ARL), but also the highest emissions. For the City of Vancouver, our priority should be the yellow area, which includes PLC, SCMs, and Recycled Concrete Materials as Granular (RCM-G). We can then focus on emerging technologies like graphene concrete and self-healing concrete

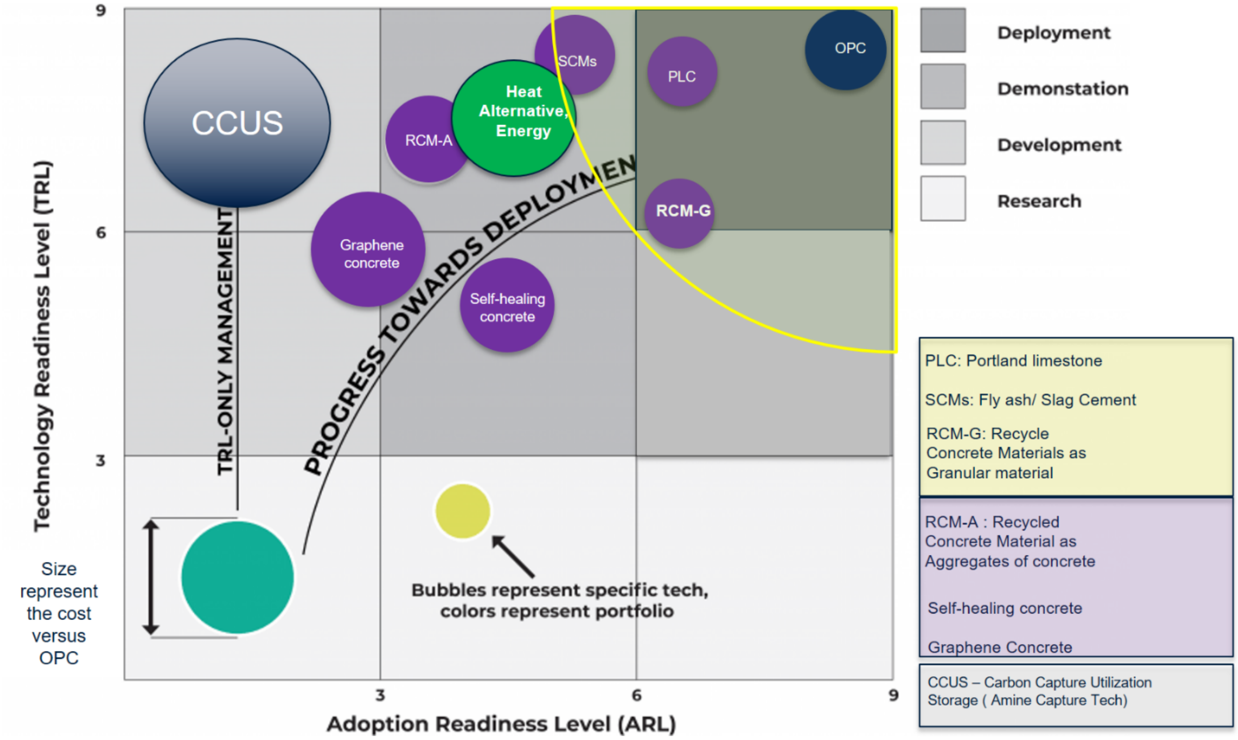


Figure 30. Overview of different technology base on TRL, ARL and Cost (https://www.energy.gov/technologytransitions/adoption-readiness-levels-arl-complement-trl)

Recommendations for Future Work

To advance the implementation of greener sidewalk construction in Vancouver, a strategic approach is essential. The following areas outline the key opportunities across people, projects, partnerships, purchasing, and pilot initiatives.

Short-Term Opportunities

- **People Awareness:** Train and equip the Engineering Team with the latest knowledge on Green Concrete to ensure informed decision-making. Focus on the benefits and application of Supplementary Cementitious Materials (SCMs) such as fly ash and slag, and the use of recycled aggregates.
- **Project for Quick Win:** Lead the implementation of greener concrete solutions in upcoming projects by utilizing high supplementary cementitious material (SCM) content mixes, specifically those incorporating slag and fly ash cement products readily available in the local market.
- **Purchasing Documents:** Review existing drawings and specifications to transition towards performance-based standards, allowing for greener materials like recycled concrete in the granular base. Incorporate Environmental Product Declarations (EPDs) as a mandatory criterion in procurement documents.

Mid-Long-Term Opportunities

- **Partnership for Next Technology:** Form partnerships with industry to initiate pilot projects focused on the use of recycled materials and emerging supplementary cementitious material (SCM) technologies, such as Limestone Calcined Clay.
- **Purchasing Policy:** Adopt low-carbon concrete procurement policies by emulating models like Portland, Oregon’s, which prioritize low-emission products. This will further reinforce Vancouver’s commitment to sustainability.
- **Pilot in Technology:** Spearhead pilot projects on cutting-edge materials and technologies in collaboration with research institutes and manufacturers. Partner with stakeholders, including Nova Scotia, First Nations, and UBC, to focus on innovative solutions like graphene-reinforced and self-healing concrete, paving the way for broader adoption in future sidewalk construction.

Glossary

Admixture: A chemical additive used in concrete to modify its properties, either in its fresh or hardened state, to improve workability, durability, or other characteristics.

Adoption Readiness Level (ARL): A measure used to assess how ready a technology is for widespread adoption in the market, considering factors like industry acceptance, regulatory approvals, and supply chain readiness.

Aggregate: Granular materials like sand, gravel, or crushed stone that are mixed with cement and water to make concrete.

Bubble Chart: A type of chart that displays three dimensions of data. In the context of this report, the size of the bubble represents the cost, the color represents the technology sector, and the position represents the Technology Readiness Level (TRL) and Adoption Readiness Level (ARL).

Carbon Capture, Utilization, and Storage (CCUS): A technology that captures carbon dioxide emissions from industrial sources and either reuses it or stores it underground to prevent it from entering the atmosphere.

Clinker: A solid material produced during the cement manufacturing process, formed by heating limestone and other materials in a kiln. It is ground to produce cement.

Concrete: A composite material made of cement, aggregates, water, and sometimes admixtures, used widely in construction for its strength and durability.

Environmental Product Declaration (EPD): A third-party verified document that reports the environmental impacts of a product throughout its life cycle, including its carbon footprint.

Fiber-Reinforced Concrete (FRC): Concrete that includes fibrous materials like steel, glass, or synthetic fibers to improve its tensile strength and durability, reducing the risk of cracking.

Fly Ash: A byproduct of coal combustion in power plants, used as a Supplementary Cementitious Material (SCM) to replace a portion of cement in concrete, improving durability and reducing carbon emissions.

Global Warming Potential (GWP): A measure of how much heat a greenhouse gas traps in the atmosphere, used to assess the impact of carbon dioxide (CO2) emissions from materials like concrete.

Granular Base: A foundation layer for roads or sidewalks, typically made of compacted crushed stone or gravel, providing stability and drainage.

Green Concrete: Concrete designed to have a lower carbon footprint, typically by reducing the amount of Portland cement and incorporating

Supplementary Cementitious Materials (SCMs) or other sustainable practices.

Ground Granulated Blast Furnace Slag (GGBFS): A byproduct of steel manufacturing used as an SCM to replace a portion of Portland cement in concrete, reducing emissions and enhancing durability.

Lifecycle Assessment (LCA): A method used to evaluate the environmental impacts associated with all stages of a product's life, from raw material extraction through production, use, and disposal.

Ordinary Portland Cement (OPC): The most common type of cement used in concrete, known for its reliability but associated with high carbon emissions due to its energy-intensive production process.

Portland Limestone Cement (PLC): A type of cement that includes a higher percentage of limestone, reducing the clinker content and lowering carbon emissions compared to traditional Portland cement.

Recycled Concrete Aggregate (RCA): Crushed concrete waste that is repurposed as an aggregate in new concrete mixtures, reducing the need for new raw materials and lowering the environmental impact.

Self-Healing Concrete: Concrete that contains bacteria or microcapsules that automatically repair cracks when water enters, extending the lifespan of the structure and reducing maintenance costs.

Supplementary Cementitious Materials (SCMs): Industrial byproducts like fly ash, slag, and silica fume used to replace a portion of cement in concrete, reducing carbon emissions and often improving durability.

Technology Readiness Level (TRL): A scale used to assess the maturity of a technology, ranging from basic research (low TRL) to fully operational and commercially available products (high TRL).

Urban Heat Island Effect: A phenomenon where urban areas experience higher temperatures than their rural surroundings due to human activities and the concentration of heat-absorbing materials like concrete and asphalt.

Versatility: The ability of a material, like concrete, to be used in various applications and environments, adaptable to different shapes, designs, and conditions.

Appendices.

Appendix A. Emission Calculation of 2200km sidewalk.

As 1 km sidewalk requires the volume of concrete and volume of granular as below:

- **Concrete Volume (V_concrete)**:

Vconcrete =Width×Length×Concrete Thickness
Vconcrete =1.8m×1000m×0.1m=180m3

- **Granular Material Volume (V_granular)**:

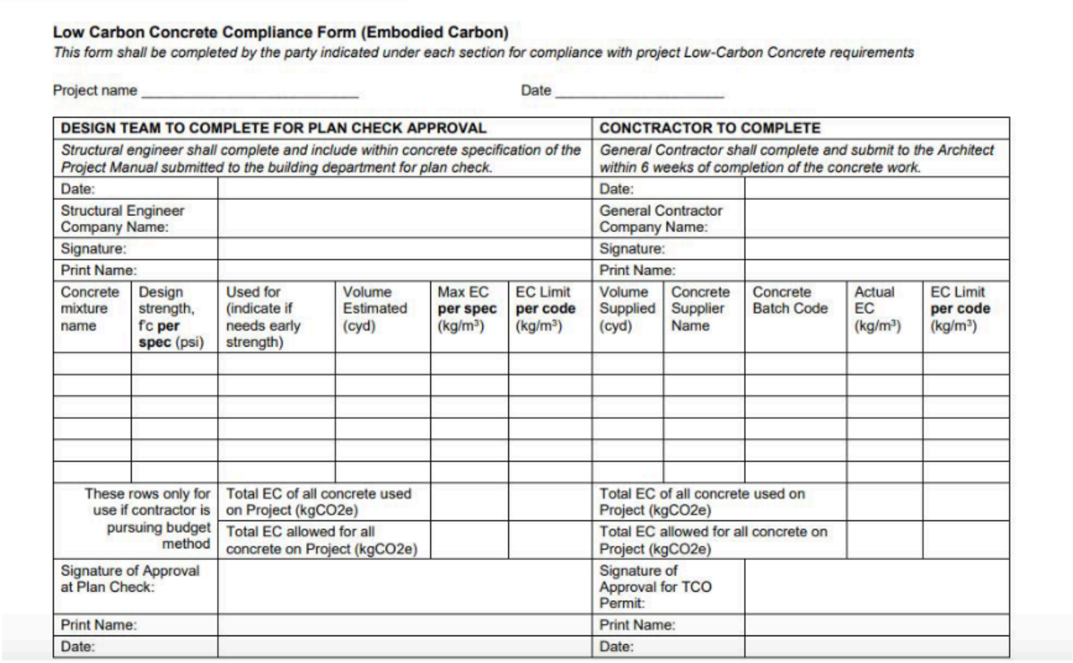
Vgranular =Width×Length×Granular Thickness
Vgranular =1.8m×1000m×0.1m=180m3

Thus, Base om Emission data, the emissions are:
E_granular =9.89kg CO2 /m3×180m3=1779.84kg CO2
E_concrete =224kg CO2 /m3×180m3=40,320kg CO2

So E_total =1779.84kg CO2 +40,320kg CO2 =42,099.84kg CO2 for 1km sidewalk.

For a total sidewalk length of 2,200 km, the Global Warming Potential (GWP) over its lifecycle is:
Total GWP=42,099.84kg CO2 /km×2200km=92,619,648kg CO2

Appendix B. Low Carbon Concrete Compliance form from Oregon city USA.



Low Carbon Concrete Compliance Form (Embodied Carbon)

This form shall be completed by the party indicated under each section for compliance with project Low-Carbon Concrete requirements

Project name ____________________________ Date ______________________

DESIGN TEAM TO COMPLETE FOR PLAN CHECK APPROVAL						**CONCTRACTOR TO COMPLETE**				
Structural engineer shall complete and include within concrete specification of the Project Manual submitted to the building department for plan check.						*General Contractor shall complete and submit to the Architect within 6 weeks of completion of the concrete work.*				
Date:						Date:				
Structural Engineer Company Name:						General Contractor Company Name:				
Signature:						Signature:				
Print Name:						Print Name:				
Concrete mixture name	Design strength, f'c **per spec** (psi)	Used for (indicate if needs early strength)	Volume Estimated (cyd)	Max EC **per spec** (kg/m^3)	EC Limit **per code** (kg/m^3)	Volume Supplied (cyd)	Concrete Supplier Name	Concrete Batch Code	Actual EC (kg/m^3)	EC Limit **per code** (kg/m^3)
These rows only for use if contractor is pursuing budget method		Total EC of all concrete used on Project (kgCO2e)				Total EC of all concrete used on Project (kgCO2e)				
		Total EC allowed for all concrete on Project (kgCO2e)				Total EC allowed for all concrete on Project (kgCO2e)				
Signature of Approval at Plan Check:						Signature of Approval for TCO Permit:				
Print Name:						Print Name:				
Date:						Date:				

List of Figures

List of Tables

References

- Intergovernmental Panel on Climate Change. (2018). *Global warming of 1.5°C: An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. https://www.ipcc.ch/sr15/
- Government of British Columbia. (n.d.). *Impacts of climate change*. CleanBC. https://cleanbc.gov.bc.ca/about-climate-change/impacts-of-climate-change/#:~:text=Climate%20change%20can%20impact%20us,of%20emergency%20for%20two%20months.
- City of Vancouver. (n.d.). *How we move: Targets and actions*. Vancouver.ca. https://vancouver.ca/files/cov/how-we-move-targets-and-actions.pdf
- City of Vancouver. (n.d.). *Accessible street design*. City of Vancouver Engineering Services. https://vancouver.ca/files/cov/AccessibleStreetDesign.pdf
- Greenis, M., Adesina, A., & Zhang, J. (2023). *Low-carbon concrete: Sustainable performance at an affordable price*. National Research Council Canada.
- Cement Association of Canada. (2023). *Technical introduction to Portland-limestone cement for municipal and provincial construction specifications* (Revision 2.0, August 2023). https://www.cement.ca
- U.S. Department of Energy. (2023). *Pathways to commercial liftoff: Low-carbon cement*. https://www.energy.gov
- City of Vancouver. (2018). *Standard detail drawings: Concrete and miscellaneous details* (Issue Date: September 2018, Approved by: J. Lee). Engineering Services - Vancouver, B.C. https://vancouver.ca/files/cov/standard-detail-drawings-concrete-and-misc-details.pdf
- ClimateWorks Foundation. (2021, August 5). *Achieving a sustainable U.S. infrastructure bill: New pathways to fully decarbonizing cement and concrete*. ClimateWorks Foundation. https://climateworks.org/blog/achieving-a-sustainable-u-s-infrastructure-bill-new-pathways-to-fully-decarbonizing-cement-and-concrete/
- City of Vancouver Engineering Services. (2023). *Asset management plan: Streets and sidewalks* (Draft). Streets Design Team.
- National Stone Sand & Gravel Association. (2021). *The aggregates industry: Greenhouse gases—Low emissions, high resiliency*. Alexandria, VA: Author. https://www.nssga.org/sites/default/files/202105/NSSGAGreenhouseGasEmissionsReport04-26-21.pdf
- National Ready Mixed Concrete Association. (2012, June). *Concrete CO2 fact sheet*. https://docshare.tips/concrete-co2-fact-sheet-feb-2012_587bafeeb6d87fa1738b521a.html

- Canadian Green Building Council. (2019, December 11). *Taking concrete steps to a carbon neutral future*.
- Federation of Canadian Municipalities & National Research Council. (2004). *Sidewalk design, construction, and maintenance: A best practice by the National Guide to Sustainable Municipal Infrastructure* (Issue No. 1.0). Federation of Canadian Municipalities and National Research Council. ISBN 1-897094-64-7
- Federation of Canadian Municipalities & National Research Council. (2005). *Reuse and recycling of road construction and maintenance materials* (Version 1.0). Federation of Canadian Municipalities and National Research Council. ISBN 1-897094-86-8
- Cement Association of Canada. (2016). *Environmental product declaration (EPD): General use (GU) and Portland-limestone (GUL) cements*. Cement Association of Canada. https://www.cement.ca
- Lafarge Canada Inc. (2024). *Environmental product declaration: Mix RMXY1500A – Kent Avenue Ready-Mix Plant* (Version 1). ASTM International.
- De Koster, S. A. L., Mors, R. M., Nugteren, H. W., Jonkers, H. M., Meesters, G. M. H., & van Ommen, J. R. (2015). *Geopolymer coating of bacteria-containing granules for use in self-healing concrete*. Procedia Engineering, 102, 475–484. https://doi.org/10.1016/j.proeng.2015.01.193
- City of Vancouver. (2019). *Construction specifications* (First Edition). City of Vancouver. https://vancouver.ca/files/cov/engineering-construction-specifications.PDF
- City of Vancouver. (n.d.). *Engineering design manual*. City of Vancouver. https://vancouver.ca/files/cov/engineering-design-manual.PDF
- Springwise. (n.d.). *Strengthening concrete with bio-graphene*. Springwise. Retrieved August 26, 2024, from https://springwise.com/innovation/property-construction/strengthening-concrete-with-bio-graphene/
- IC-IMPACTS. (n.d.). *Eco-friendly self-healing road* [Web page]. Retrieved August 26, 2024, from https://icimpacts.com/communities/chawathil/#:~:text=Eco%2DFriendly%20Self%2DHealing%20Road,when%20cracks%20begin%20to%20form
- City of Vancouver. (n.d.). Climate emergency action plan: Summary. Vancouver.ca. https://vancouver.ca/files/cov/climate-emergency-action-plan-summary.pdf\
- City of Vancouver. (n.d.). Vancouver climate change adaptation strategy 2024-2025. Vancouver.ca. https://vancouver.ca/files/cov/vancouver-climate-change-adaptation-strategy-2024-25.pdf
- City of Vancouver. (2024). Climate financial strategy: Staff presentation. Vancouver.ca. https://council.vancouver.ca/20240313/documents/cfsc2staffpresentation.pdf

- City of Vancouver. (2012). Vancouver climate change adaptation strategy. Vancouver.ca. https://vancouver.ca/files/cov/Vancouver-Climate-Change-Adaptation-Strategy-2012-11-07.pdf
- Interlocking Concrete Pavement Institute. (2017). *Construction of interlocking concrete pavements* (Tech Spec No. 2). https://www.icpi.org
- Federal Highway Administration. (n.d.). *The effects of higher strength and associated concrete properties on pavement performance* (FHWA Publication). https://www.fhwa.dot.gov
- Czarnecki, B., & Poon, B. (2017). *Concrete sidewalk design analysis and optimization for improved life cycle and sustainability*. Tetra Tech Canada Inc. and The City of Calgary. Paper presented at the Transportation Association of Canada, St. John's, NL (czarneckib-concrete_sid…).
- Engineering & Construction Services Division. (2018). *Construction specification for concrete unit pavers* (TS 3.80). City of Toronto (9801-ecs-specs-roadspec…).
- Janowska-Renkas, E., Kuczyńska-Wydra, M., & Orłowska, A. (2019). *A mathematical model of behavior of normal and high-performance concretes in corrosive medium*. Journal of Mechanical and Behavioral Materials, 28(1), 50-62. https://doi.org/10.1515/jmbm-2019-0014
- Zizzo, R., Masoudi, R., & Cooney, R. (n.d.). Strategies for low carbon concrete: Primer for federal government procurement. National Research Council Canada. https://doi.org/10.4224/40002759
- Oliver-Solà, J., Josa, A., Rieradevall, J., & Gabarrell, X. (2009). Environmental optimization of concrete sidewalks in urban areas. International Journal of Life Cycle Assessment, 14(4), 302-312. https://doi.org/10.1007/s11367-009-0083-7
- Cement Association of Canada. (2023). Canada's cement and concrete industry action plan to net-zero https://cement.ca/sustainability/concrete-zero/
- Favier, A., De Wolf, C., Scrivener, K., & Habert, G. (n.d.). A sustainable future for the European cement and concrete industry: Technology assessment for full decarbonisation of the industry by 2050. Swiss Federal Institute of Technology.
- Interlocking Concrete Pavement Institute. (n.d.). Comparison of pavement maintenance costs. Issuu. https://issuu.com/icpi-icpi/docs/comparison_of_pavement_maintenance_costs
- Global Cement and Concrete Association. (2023). Cement industry net zero progress report 2023. https://gccassociation.org/cement-industry-net-zero-progress/
- Spacing Vancouver. (2022, April 18). *What you should know about Vancouver's new city plan*. https://spacing.ca/vancouver/2022/04/18/what-you-should-know-about-vancouvers-new-city-plan/