



Laidlaw Scholars Undergraduate Leadership and Research Programme
Research Proposal

**Vaterite-Based Cement for Precast Architectural Applications: Evaluating
Performance, Finish, and Embodied Carbon**

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Abstract

Concrete is the most widely used man-made material [1]. Cement, the essential binder in the concrete matrix is fundamental to modern infrastructure, yet Ordinary Portland Cement (OPC) production accounts for 8% of global CO_2 emissions [2]. As populations grow, the demand for sustainable urbanization makes identifying viable alternatives to conventional cement increasingly urgent. This research investigates whether Fortera carbon-mineralized cement, a lower-carbon cement system based on captured carbon dioxide stored as stable carbonates [3], can serve as a viable alternative to OPC in precast architectural concrete. The central question is whether Fortera-based cement systems can maintain acceptable mechanical performance and exposed surface quality while reducing embodied carbon.

Within the six-week Laidlaw research period, the study will use a mortar-first approach to evaluate the fundamental behaviour of Fortera-based cement before scaling up to concrete. Mortar isolates the cementitious binder and fine aggregate without the additional variability introduced by coarse aggregate. Because mortar forms the binder-rich phase within concrete, its performance will directly relate to future concrete mix designs for precast architectural applications. The research will evaluate workability through mortar flow testing, mechanical performance through compressive and flexural strength testing, absorption through mortar-appropriate water absorption measurements, and architectural surface quality through panel-based assessment of demolding behaviour, edge sharpness, surface smoothness, and visible defects.

This research is important because lower-carbon cement technologies must be evaluated not only for sustainability, but also for their suitability in real construction applications. By focusing on mortar as the first testing stage, this project will assess the fundamental engineering performance and exposed finish quality of Fortera-based cement systems before future concrete scale-up. The results will help determine whether Fortera-based cement can become a realistic material option for high-quality precast architectural concrete products.

Introduction

I chose this topic because I am interested in advancing scalable decarbonization solutions within Chemical Engineering, especially those that can be applied to real-world industrial materials, processes, and infrastructure. My earlier work on hydrogen fuel cell integration strengthened my interest in practical pathways for reducing emissions, and this project extends that interest into materials science and engineering. Concrete is used globally at an enormous scale, so even small improvements in the carbon footprint of cement systems could have meaningful environmental impact.

This research is interdisciplinary, combining sustainability, materials science, chemical engineering, and civil engineering. It evaluates Fortera carbon-mineralized cement (CMC) as a lower-carbon alternative to Ordinary Portland Cement (OPC) for precast architectural applications. Through this research, I hope to determine whether Fortera-based mortar can meet key performance and quality requirements, including workability, mechanical strength, absorption behaviour, and exposed surface finish, while also reducing embodied carbon. The results will help guide future concrete mix design and may support later studies involving additional industrial by-products such as slag, soot, or other steelmaking waste materials from another carbon-intensive industry that generates significant waste and greenhouse gas emissions.

Research Objectives & Questions

The primary objective of this study is to determine whether Fortera-based mortar systems can provide acceptable mechanical performance and architectural surface quality for precast applications while reducing embodied carbon relative to OPC.

Secondary objectives are to:

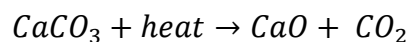
- Compare a Fortera-based mortar mix against an OPC mortar control.
- Evaluate the fresh-state flowability and handling behaviour of Fortera-based mortar.
- Measure compressive and flexural strength development at selected testing ages.
- Quantify whether changes in workability are associated with changes in surface defects, demolding behaviour, and absorption.
- Estimate embodied carbon reductions for mixes that achieve comparable performance.
- Discuss possible future studies involving industrial by-products such as slag, soot, or other steelmaking waste materials.

Key Research Questions

1. How do the selected Fortera-based mixes compare with OPC in compressive and flexural strength?
2. How does fresh state flowability influence demolding behaviour and architectural surface quality/finish?
3. How do visible surface defects and water absorption differ across the selected mixes?
4. What reduction in embodied CO_2 can be achieved by using CMC-based mixes?
5. Which Fortera-based mix or mixes provide the best balance of performance, finish, quality, and estimated embodied carbon reduction for precast architectural applications?

Background

Concrete is used at an enormous scale in modern-day infrastructure, and there is currently no complete replacement for it in most structural applications. This makes cement one of the most important targets for decarbonization. The cement industry is responsible for about 8% of global CO_2 emissions [2], which highlights why even partial improvements in cement systems could have meaningful environmental impact. A large share of these emissions comes not only from the energy used in production, but from the cement chemistry itself: about 60% of CO_2 emissions are process emissions released during calcination, when limestone is heated and calcium carbonate decomposes into lime and CO_2 [4].



This makes cement especially difficult to decarbonize, because much of the carbon is released as part of the chemical reaction rather than only from fuel use.

One research direction that has emerged in response is the development of lower-carbon cement systems that reduce process emissions or incorporate captured CO_2 into new cementitious materials. Fortera is particularly relevant in this context because it is developing a carbon-mineralized cement system designed to lower the carbon footprint of concrete. Fortera's approach is based on vaterite, a highly reactive metastable polymorph of calcium

carbonate ($CaCO_3$) [5]. Vaterite's higher solubility and reactivity allow it to influence hydration, microstructure development, and early strength development [6].

However, a lower-carbon cement system is only useful if it can also meet the requirements of real applications. For precast architectural applications, this means the material must not only reduce embodied carbon, but also provide acceptable workability, strength, demolding behaviour, and exposed surface quality. That is why this research focuses not just on whether Fortera-based mortar is lower carbon, but whether selected Fortera-based blends can perform well enough for precast architectural applications.

Methodology

Organizations and supervisors involved in this research include the University of Toronto Materials Laboratory, Professor Scott Ramsay as research advisor, and Fortera as an external industry collaborator supplying CMC materials in kind and providing technical guidance on procedures.

Materials

The project will investigate three main mixes:

1. Mix 1 – OPC control
 - a. OPC matrix, standard sand, water.
2. Mix 2 – Fortera baseline
 - a. Fortera carbon-mineralized cement, standard sand, admixtures, and water.
3. Mix 3 – Optimized Fortera mortar
 - a. A refined Fortera-based mortar selected based on early flowability, casting behaviour, and strength observations.

If time allows, the project may also expand to preliminary concrete testing by introducing coarse aggregate and, potentially, a selected dosage of soot.

The project will use the following specimen plan for each mix:

- 6 compressive cubes
- 6 flexural prisms
- 1 architectural panel
- 2 absorption specimens

Total: 15 specimens per mix = 45 specimens

Mixing and Casting

All specimens will be mixed according to ASTM C305 using identical procedures across specimen types, cast into molds, and wrapped in plastic to minimize moisture loss. Fresh state flowability will be measured for each mix using flow testing (ASTM C1437) [7] to compare workability and consistency during casting. Because this project focuses on precast architectural applications, a dedicated set of flat face panels will be cast for demolding and surface-quality assessment in addition to standard strength specimens. Specimens will be demolded after sufficient early hardening, with observations recorded on ease of release, surface tearing, and edge damage.

Mechanical and Durability Testing

CMC reaches near-final strength around 48 hours due to a recrystallization-based setting mechanism [8], whereas OPC typically cures over 28 days. Accordingly, Fortera-based mortar samples will be tested at 1, 2, and 28 days to capture early strength development and

later-age performance. The OPC control will be tested at 3, 7, and 28 days, reflecting conventional cement strength-development timelines.

Compressive strength (ASTM C109)

Compressive strength will be measured according to ASTM C109/C109M [9] using mortar cube specimens, typically 50 mm × 50 mm × 50 mm. The maximum load at failure will be recorded and used to calculate compressive strength:

$$F_c = \frac{P_{max}}{d^2}$$

This test quantifies load-bearing capacity and enables a direct comparison of CMC and OPC.

Flexural strength (ASTM C348)

Maximum flexural strength will be calculated according to ASTM C348 [10]. Prismatic mortar prisms (40 mm × 40 mm × 160 mm) will be tested under three-point bending.

$$F_f = \frac{3P_{max}L}{2bd^2}$$

This test is included because precast architectural concrete elements are more sensitive to bending and handling.

Surface finish and defect quantification

Surface finish quality will be assessed using dedicated architectural face panels (150 mm × 150 mm × 30 mm). At demolding, the panels will be evaluated for ease of release, demolding damage, edge chipping, and initial edge sharpness. After curing, standardized images of the same panels will be analyzed using optical microscopy to quantify visible void area percentage and void size distribution.

$$Voids (\%) = \frac{A_{void,est}}{A_{total}} \times 100$$

These comparisons will support evaluation of whether Fortera-based mixes are suitable for high-quality exposed precast surfaces.

Water Absorption and Porosity Assessment

To evaluate absorption and porosity-related behaviour, two complementary tests will be used: capillary absorption followed by full submersion absorption.

First, capillary water absorption will be measured using a mortar-appropriate method (ASTM C1403) [11]. Mortar specimens will be dried, placed with one exposed face in contact with water, and weighed at selected time intervals to measure water uptake by capillary action. This test will show how quickly water enters the mortar matrix and will produce a graph that helps to compare the internal connected porosity.

$$Absorption(\%) = \frac{m_{sat} - m_{dry}}{m_{dry}} \times 100$$

Second, full submersion absorption (ASTM C642) [12] will be adapted to mortars and used a supplementary method to estimate total water uptake and permeable void content. Specimens will be weighed in dry, saturated, and submerged conditions.

$$Void (\%) = \frac{m_{sat} - m_{dry}}{m_{sat} - m_{sub}} \times 100$$

This test will help determine whether mixes with better visible surface quality also demonstrate lower absorption and connected porosity.

Embodied Carbon Analysis

Published life-cycle data for OPC, CMC, standard sand, admixtures, and optional aggregate materials if concrete scale-up is completed will be used to estimate embodied CO_2 for each mix based on contributions from the cementitious matrix and aggregates.

Only mortar blends that achieve mechanical strength equivalent to OPC will be directly compared to the control to find the percentage reduction in embodied carbon:

$$CO_{2,reduction}(\%) = \frac{CO_{2,OPC} - CO_{2,blend}}{CO_{2,OPC}} \times 100$$

Data Analysis and Comparison

The results will be analyzed to compare workability, strength development, surface quality, absorption, and embodied carbon between OPC and the selected Fortera-based blends. These results will be used to identify which mix or mixes provide the best balance between mechanical performance, architectural face quality, and lower embodied carbon for high-quality precast architectural applications.

Training/ Certifications Needed

The research will require completion of lab safety and equipment-related training before the start of the summer research period. This includes:

- Summer student engineering lab safety training
- Materials laboratory orientation
- Safe use of compression and flexural testing equipment
- Training for optical microscopy equipment.

Research Location

This research will be conducted in Canada at the University of Toronto Materials Laboratory, Wallberg.

Research Ethics Board

This research does not require Research Ethics Board approval because it does not involve human participants, animals, or personal data.

Timeline

Pre-Research Preparation Stage

- Finalize mortar mix design and specimen plan.
- Order OPC, Fortera CMC, standard sand, admixtures, mold materials, and lab consumables.
- Molds for cubes, prisms, absorption specimens, and small panels.
- Confirm access to mixing, curing, testing, absorption, and imaging equipment.
- Plan and execute trial batches.

Week 1: Main Casting, Demoulding, and Early CMC Testing

- Cast the three core mortar mixes and their specimens
- Perform mortar flow testing for each mix.
- Record flow value, cohesion, segregation, stickiness, bleeding, and general workability notes.
- Cover specimens and begin curing.
- Demould specimens after sufficient early hardening (~24 hours)
- Record ease of release, sticking, visible damage, chipped corners, surface tearing, and cracking.
- Complete early Fortera-based testing at 1 and 2 days

Week 2: OPC Early Testing and Data Organization

- Complete OPC control testing at 3 and 7 days.
- Record maximum load, calculated strength, and failure observations.
- Organize mortar flow data, demoulding notes, early strength results, and panel photos

Week 3: Panel Appearance Analysis

- Analyse and photograph architectural panels.
- Standardize images using the same orientation, scale, lighting, and face region.
- Measure or record visible voids, pinhole density, edge sharpness, surface smoothness, and demoulding damage.
- Compare surface quality and relate appearance results to flowability, demoulding behaviour, and early strength trends.

Week 4: Absorption Testing and Data Organization

- Dry absorption specimens to a consistent condition before testing.
- Place one exposed face of each specimen in contact with water.
- Record mass gain at selected time intervals to measure capillary uptake.
- Complete submersion absorption test
- Begin embodied carbon calculation worksheet.
- Start preparing comparison tables and graphs for flowability, early strength, demoulding behaviour, and panel appearance.

Week 5: 28-Day Testing and Optional Exploratory Work

- Complete 28-day compressive and flexural strength testing.
- Complete final absorption measurements.
- If time allows, conduct optional exploratory testing with slag, soot, or preliminary concrete mixes with coarse aggregate.

Week 6: Final Comparison and Interpretation

- Compare mixes across flowability, compressive strength, flexural strength, absorption behaviour, demoulding behaviour, architectural surface quality, and estimated embodied carbon.
- Identify which mix provides the best balance of strength, workability, surface quality, and lower embodied carbon.

- Explain how the mortar results can guide future concrete mix design for precast architectural applications.
- Finalize figures, tables, conclusions, and the final report.

Resources & Support Needed

This research will require access to the University of Toronto Materials Laboratory, compression and flexural testing equipment, absorption testing equipment, photography area and optical microscopy access, molds and casting materials, laboratory consumables, guidance from Professor Scott Ramsay, and technical support from Fortera.

Potential Impact

Fortera cement has already shown promise in field pours and as a lower-carbon cement system. However, to be a realistic option for broader construction use, it must also be evaluated in terms of handling, finish quality, and suitability for precast applications. This is especially important for precast architectural applications, where the material must not only achieve acceptable strength, but also demold well, maintain good edge quality, and produce a consistent exposed surface finish.

Because vaterite-based cement systems can crystallize and gain structure more quickly than conventional cement, Fortera may be a strong candidate for commercially produced precast architectural elements, where early handling, repeated molding, and efficient production cycles are important. This research will help determine whether selected Fortera-based blends can meet those practical requirements while also reducing embodied carbon.

The significance of this research lies in evaluating both the carbon impact of the material and its ability to perform well in a specific and demanding application. If the material shows high workability, mechanical performance, demolding behaviour, and surface quality, it could support further work in low-carbon precast concrete and help identify promising directions for future mix design and application testing. More broadly, this research could contribute to the adoption of lower-carbon cement systems in construction by showing that performance and quality can be achieved alongside sustainability.

Budget

A revised budget reflecting the final six-week project scope will be submitted separately in Excel format, as required by the programme.

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