Laidlaw Scholars Undergraduate Leadership and Research Programme
Research Report

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

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1.0 Abstract

This research investigates Fortera's ReAct® Cement, a vaterite-based cement (VBC), as a potential 100% Portland cement replacement for precast architectural applications. The study evaluated workability, compressive and flexural strength, capillary absorption, permeable voids, demoulding behaviour, surface quality, and preliminary binder-related carbon emissions at the mortar scale. VBC-M1 was designed to match the PLC control paste volume, while VBC-M2 was further adjusted based on the measured interparticle void volume of the ASTM C778 sand. The VBC mixes developed most of their measured strength within 48 hours and exceeded early-age PLC compressive strengths. However, at 28 days they remained weaker than the controls. Flexural strength remained lower than the PLC controls, with a flexural-to-compressive strength ratio of approximately 10.6% for VBC compared with 14.4% for PLC. The VBC mixes showed lower submersion absorption, similar 24-hour capillary absorption to PLC-M1, similar density, smoother surface finish, better edge retention, easier mould release, and a brighter white colour than the PLC controls. The binder-related carbon estimate showed that the VBC mixes reduced carbon intensity per volume by approximately 65% and performance-normalised carbon emissions by 54%. Overall, these results suggest that VBC has strong potential for precast architectural applications where early strength, smooth white surface finish, and easy demoulding are valued. However, further optimisation and concrete testing are still needed before precast implementation.

2.0 Introduction

Concrete is the most widely used manufactured construction material globally [1], but production of its primary binder, Portland cement, contributes significantly to global carbon dioxide emissions. Portland cement production accounts for approximately 7% of global CO2 emissions [2] and approximately a quarter of industrial emissions [3]. Because a substantial portion of cement emissions arises directly from the chemical process, cement is particularly challenging to decarbonize [1], [3]. As demand for sustainable urbanization grows, evaluating low-carbon alternatives for cement becomes increasingly important.

In Portland cement production, the main reactive component is clinker, which is made by heating limestone to high temperatures [4]. During this process, limestone, or calcium carbonate ($CaCO_3$), decomposes into lime, or calcium oxide (CaO), and carbon dioxide (CO_2), as shown in Equation 1. The calcium oxide then becomes the main intermediate ingredient for clinker formation. This makes the development of lower-carbon cement systems an important pathway for reducing emissions from the construction sector.

$$CaCO_3 + heat \rightarrow CaO + CO_2 \quad (1)$$

This research investigates Fortera's ReAct® Cement, a carbon-mineralized 100% replacement for Portland cement. The main ingredient is vaterite, an unstable and reactive polymorph of calcium carbonate. Captured CO_2 from the limestone calcination process reacts with calcium oxide (lime) to produce carbon-mineralized calcium carbonate [5]. Unlike conventional cement systems, vaterite-based cement (VBC) contributes to strength development through a recrystallization reaction, in which the unstable vaterite dissolves and reprecipitates into the stable calcium carbonate crystal matrix. This recrystallization-based setting mechanism enables rapid early strength development [5], [6], whereas Portland cement typically develops strength progressively over a 28-day period.

Precast architectural products require more than just strength. They also must demonstrate effective workability, demoulding behaviour, edge quality, surface finish, and porosity. Therefore, this project evaluated Fortera mortar using both mechanical and qualitative criteria. Workability was assessed using mortar flow testing and observations of each mix's ability to consolidate moulds. Mechanical performance was evaluated using compressive strength and three-point flexural bending tests.

Absorption behaviour and density were assessed using capillary absorption and Archimedes submersion testing, while architectural surface quality was evaluated through qualitative observation of demoulding behaviour, edge sharpness, surface smoothness, and visible defects.

Within the six-week research period, this study used a mortar-first approach to evaluate the fundamental behaviour of VBC. Mortar was selected as the initial testing scale because it is easier to prepare, requires less material, reduces variables, and allows the mix design to be refined more efficiently before progressing to larger concrete-scale testing. Overall, this project aims to determine if VBC can provide a practical balance of strong mechanical performance and high-quality surface finish for precast applications while reducing embodied carbon relative to Portland cement.

3.0 Materials and Methodology

3.1 Materials

The materials used in this study include Sika Portland-Limestone cement Type GUL (PLC), Fortera ReAct Cement (VBC), ASTM C778 standard graded sand, water, and admixture. PLC was used as the control binder for mixes PLC-M1 and PLC-M2. Type GUL is a general use limestone cement with a higher limestone content relative to ordinary Portland cement. It was selected as a lower-emissions conventional cement baseline for evaluating VBC's carbon reduction potential.

The VBC consisted of vaterite and calcite. The VBC mortars were labelled VBC-M1 and VBC-M2. Table 1 summarizes the mix designs, including water-to-binder (w/b) and sand-to-binder (s/b) ratios used in this study. The VBC mortars contain proprietary admixtures. The effective w/b ratios are corrected for the moisture content of the admixtures.

Table 1. Mortar mix designs used in this study, including shorthand labels, effective water-to-binder (w/b) ratio, sand-to-binder (s/b) ratio, measured flow, and purpose of each mix.

Full name	Label	w/b ratio	s/b ratio	Flow	Purpose
Portland-Limestone Cement - Mix 1	PLC-M1	0.559	2.75	108.8%	PLC control mix
Portland-Limestone Cement - Mix 2	PLC-M2	0.552	2.75	105.8%	PLC control mix
Vaterite-Based Cement - Mix 1	VBC-M1	0.287	2.32	104.3%	VBC mix with paste volume matched to PLC paste volume
Vaterite-Based Cement - Mix 2	VBC-M2	0.272	2.22	106.3%	VBC mix with paste volume adjusted based on measured sand interparticle void volume

3.2 Mixing and Casting

Mortar was mixed using a modified ASTM C305 procedure. A spade handle drill (DS4011, Makita Corporation, Anjo, Aichi, Japan) was powered through a variable transformer (3PN1210B, Staco Energy Products Company, Miamisburg, OH, USA). The transformer settings were calibrated to reproduce the ASTM C305 paddle speeds of 140 ± 5 rpm (slow) and 285 ± 10 rpm (fast). The required planetary motion was applied manually using a metronome set to approximately 62 rpm for both mixing speeds.

The PLC mixes contained 500 g of PLC. VBC-M1 was calculated to match the paste volume of the PLC control based on ASTM C109 material proportions. VBC-M2 was further adjusted based on the measured sand interparticle void volume. For the sand packing measurement, a known mass of sand was placed in a graduated cylinder, and its packed volume was recorded. Water was then added to fill the void spaces between the sand particles, and the volume of water required was used to estimate the interparticle void volume and required paste volume. Additional details on sand packing, sand gradation, and paste-volume adjustment are provided in Appendix A.

Fresh mortar workability was assessed using an ASTM C1437 flow table process. All mixes were adjusted with water until the measured flow reached approximately 110 ± 10% to maintain comparable fresh-state workability. Qualitative observations included cohesion, stickiness, segregation, and bleeding. Specimens were cast immediately after mixing. All specimens were cured for 24 ± 2 hours at 37 °C in a laboratory oven (ProJet Finisher, 3D Systems, Rock Hill, SC, USA) before demoulding. Mechanical strength specimens were then stored in saturated limewater until testing.

3.3 Compressive and Flexural Strength Testing

VBC strength specimens were tested at 1, 2, and 28 days. PLC-M1 was tested at 3, 7, and 28 days, while PLC-M2 was tested at 1, 2, and 28 days. Because PLC-M1 and PLC-M2 had nearly identical mix proportions and similar measured flow, their strength data were combined to represent the overall PLC strength-development trend.

Compressive strength was measured using 50 × 50 × 50 mm mortar cube specimens according to ASTM C109. The maximum load at failure was recorded, and compressive strength was calculated according to Equation 2.

$$F_c = \frac{P_{max}}{A} \tag{2}$$

Where F_c is the compressive strength in MPa, P_{max} is the maximum load at failure in N, and A is the loaded cross-sectional area in mm². Compressive strength testing quantified the load-bearing capacity of each mortar mix and allowed direct comparison between the VBC and PLC control mixes.

Flexural strength was measured using 40 × 40 × 160 mm mortar prism specimens according to ASTM C348 under three-point bending. The maximum load at failure was recorded, and flexural strength was calculated as:

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

Where F_f is the flexural strength in MPa, P_{max} is the maximum load at failure in N, L is the support span in mm, b is the specimen width in mm, and d is the specimen depth in mm.

Three-point flexural strength testing was particularly crucial because precast architectural specimens may experience bending stresses during demoulding, handling, and installation.

3.4 Capillary Absorption Testing

Capillary absorption was evaluated using an adapted ASTM C1403 method, modified by using approximately 40 × 40 × 40 mm cube specimens cut from one half of each flexural beam rather than standard moulded cubes. Specimens were cut using an abrasive diamond wet saw (R4021, Ridgid Tool Company, Elyria, OH, USA). The exposed test face dimensions were measured using calipers, and the average length and width were used to calculate the exposed contact area.

After curing, specimens were oven dried and weighed to obtain the dry mass (W_0). The curing ages at the start of absorption testing were 35 days for PLC-M1, 20 days for PLC-M2, 21 days for VBC-M1, and 19 days for VBC-M2. Specimens were then placed with one face in contact with shallow water. Mass readings were recorded after 15 minutes, 1 hour, 4 hours, and 24 hours. Capillary absorption was calculated as:

$$A_c, \frac{g}{100cm^2} = \frac{W_t - W_0}{L \times W} \times 10{,}000 \tag{4}$$

Where A_c is the capillary absorption in g/100 cm^2, W_t is the specimen mass at time t in g, W_0 is the oven-dry specimen mass in g, L is the length of exposed contact face in mm, and W is the width of exposed contact face in mm.

Capillary absorption testing was relevant because greater surface porosity in precast specimens can affect surface quality. Capillary absorption testing can be used to compare how quickly water entered the VBC and PLC mixes and give insights into pore connectivity.

3.5 Submersion Absorption and Permeable Voids Testing

Submersion absorption and permeable voids were evaluated using an adapted ASTM C642-style method. Specimens were prepared using the same cutting procedure described in section 3.4, with approximately 40 × 40 × 60 mm prism specimens cut from the flexural beams. The dimensions were measured using calipers and used to calculate specimen volume. Four masses were recorded during testing and were used in the equations summarized in Table 2.

Table 2. ASTM C642 equations used to calculate submersion absorption, boiling absorption, dry bulk density, apparent density, and permeable void content.

Calculated Property	Equation	
Submersion absorption (%)	$\frac{B - A}{A} \times 100$	(5)
Boiling absorption (%)	$\frac{C - A}{A} \times 100$	(6)
Permeable voids (%)	$\frac{C - A}{C - D} \times 100$	(7)
Dry Bulk Density (g/cm^3)	$\frac{A}{C - D}$	(8)
Apparent Density (g/cm^3)	$\frac{A}{A - D}$	(9)

Where A is the oven-dry mass in g, B is the mass after submersion in g, C is the mass after boiling in g, and D is the apparent mass suspended in water in g.

Submersion absorption and permeable void testing provided insights into water absorption, density, and accessible pore content within each mortar mix. These results were used to compare whether the VBC and PLC control mixes differed in these categories, and to connect the absorption and density trends with the strength and surface quality observations.

3.6 Surface Quality Analysis

Surface quality was assessed through visual observation and photographic documentation, with specific focus on dedicated architectural face panels measuring 180 × 180 × 15 mm. Observations included demoulding behaviour, surface smoothness, visible voids, edge chipping, cracking, surface tearing, and overall exposed finish quality.

The panel design included flat exposed surface fields, extruded and recessed features, 2-6 mm vertical and horizontal fillets, sharp corners, curved circular details, sanded regions, and fine 3D printed lines. These features were selected because they can be used to study improvements for common challenges in precast architectural elements, including fine feature reproduction, surface smoothness, and ease of demoulding. Figure 1 shows two labelled views of the architectural panel design created in SolidWorks.

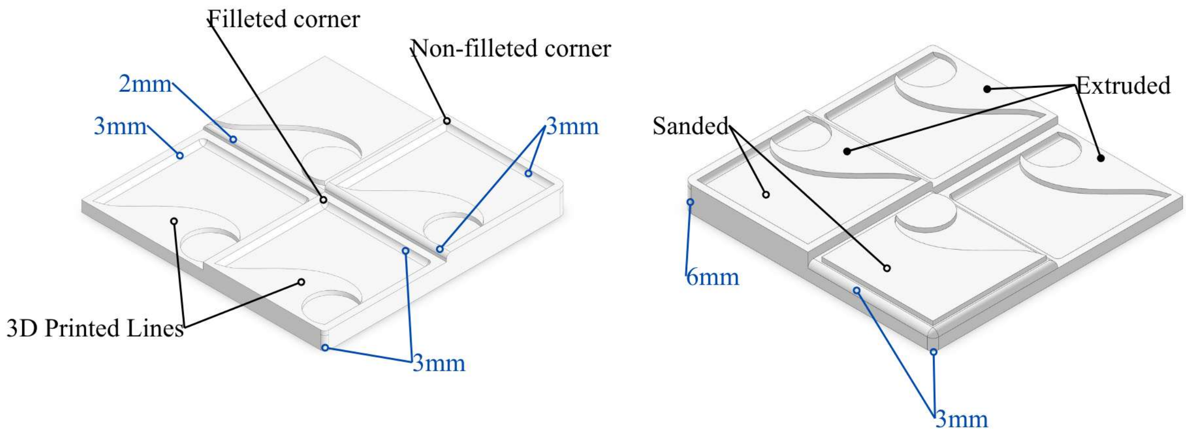


Figure 1. Labelled drawings of the architectural panel used for surface quality assessment, showing the main surface features and geometric details tested.

During casting, the panels were consolidated using manual tamping, vibration, or both, followed by tapping of the mould on a flat surface. These observations were therefore used to evaluate how well the VBC and PLC control mixes could reproduce fine surface details and produce high-quality surfaces. Additional mould photographs and consolidation-method observations are provided in Appendix B.

3.7 Embodied Carbon Analysis

A preliminary binder-related embodied carbon analysis was conducted to compare the PLC and VBC mixes. The calculation focused only on binder emissions and excluded sand, water, admixtures, transportation, curing, or equipment energy. PLC emissions were calculated using the emission factor for Type GUL cement in Canada, while Fortera-provided data were used to estimate emissions for the VBC. The mixes were compared using binder-related carbon intensity per unit volume and performance-normalised carbon emissions based on 28-day compressive strength.

4.0 Results

4.1 Workability and Casting Observations

A noticeable difference between PLC and VBC mixes was observed during handling. The VBC mixes were observed to slide more freely over parchment paper and aluminium scoop surfaces. When the tamper was applied at a faster loading rate, the VBC mix appeared to resist movement, whereas slower loading or vibration allowed the mix to loosen and flow more readily. VBC mixes were more difficult to introduce into mould openings smaller than approximately 10 mm. Under vibration, the paste phase became fluid and flowed into the mould more readily than the sand, sometimes leaving sand particles stuck near the mould opening.

4.2 Compressive Strength

The PLC controls reached an average 28-day compressive strength of 37.3 MPa. The VBC mixes reached 26.4 MPa at 1 day, 28.9 MPa at 2 days, and 28.2 MPa at 28 days. As shown in Figure 2, the VBC mixes developed most of their measured strength within the first 48 hours, while the PLC controls continued gaining strength through 28 days. Compared with the PLC-M2 early-age control, the VBC mixes were approximately 42% stronger at 1 day and 13% stronger at 2 days. By 28 days, however, the average VBC compressive strength was approximately 24% lower than that of the PLC controls.

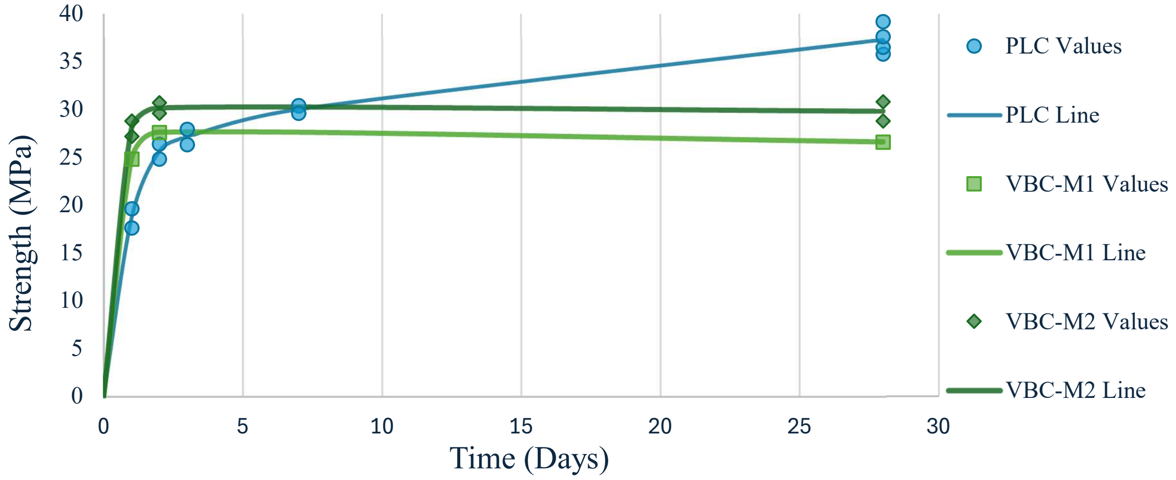


Figure 2. Compressive strength development of mixes over 28 days (n = 2 samples per mix).

4.3 Flexural Strength

The PLC controls had the highest overall flexural strength. The average PLC mortar strength reached 4.4 MPa at 28 days. As shown in Figure 3, the VBC mortars had a flexural strength of 3.2 MPa at 28 days, which is approximately 27% lower than the PLC control. Unlike the compressive strength results where the VBC mixes exceeded the PLC-M2 strengths at 1 and 2 days, the flexural strength of the VBC mixes remained lower than the PLC controls at all testing ages.

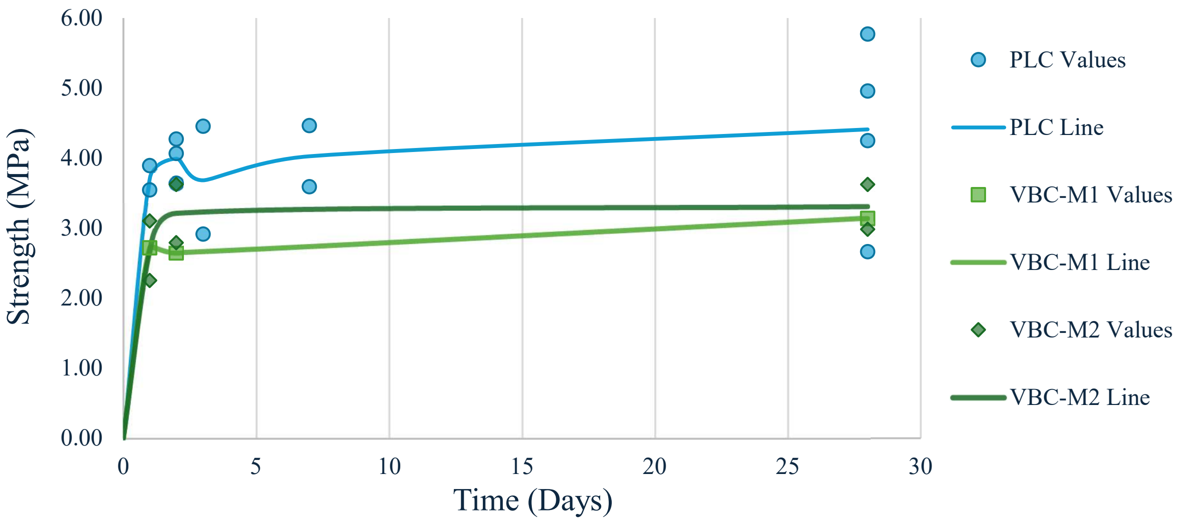


Figure 3. Flexural strength development of mixes over 28 days (n = 2 samples per mix).

See Appendix C for the complete table of the compressive and flexural strength results.

4.4 Capillary Absorption

Figure 4 shows VBC-M1 and VBC-M2 had higher early capillary absorption than PLC-M1. They reached capillary absorption values of 8.1 and 6.1 g/100 cm² at 15 minutes, increasing to 44.6 and 44.8 g/100 cm² at 24 hours, respectively. By 24 hours, both values were close to PLC-M1 at 40.6 g/100 cm².

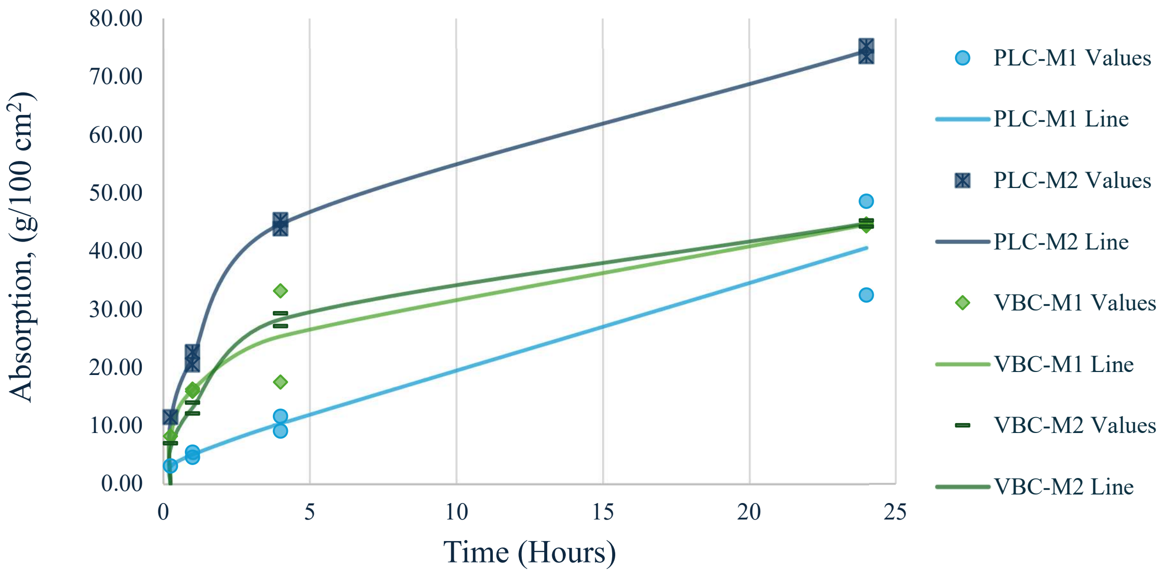


Figure 4. Capillary absorption over 24 hours for mortar mixes (n = 2 samples per mix).

The two PLC control mixes showed different absorption behaviour. PLC-M1 had the lowest absorption while following a linear trend, increasing from 3.0 g/100 cm² at 15 minutes to 40.6 g/100 cm² at 24 hours. In contrast, PLC-M2 showed a similar trend to the VBC mixes, with quicker early absorption followed by a slower rate of absorption. However, by 24 hours, PLC-M2 reached much higher absorption values than the rest of the mixes, reaching 74.4 g/100 cm², the highest value among all mixes.

4.5 Submersion Absorption and Permeable Voids

As shown in Figure 5, under normal submersion, the PLC control mixes had the highest absorption values. PLC-M1 and PLC-M2 reached 9.1% and 9.7%, respectively. The VBC mixes had the lowest normal submersion absorption values, with VBC-M1 at 5.0% and VBC-M2 at 4.7%. After boiling, the absorption values became much closer across all mixes, with all mixes falling within the range of 9.6 to 10.4%.

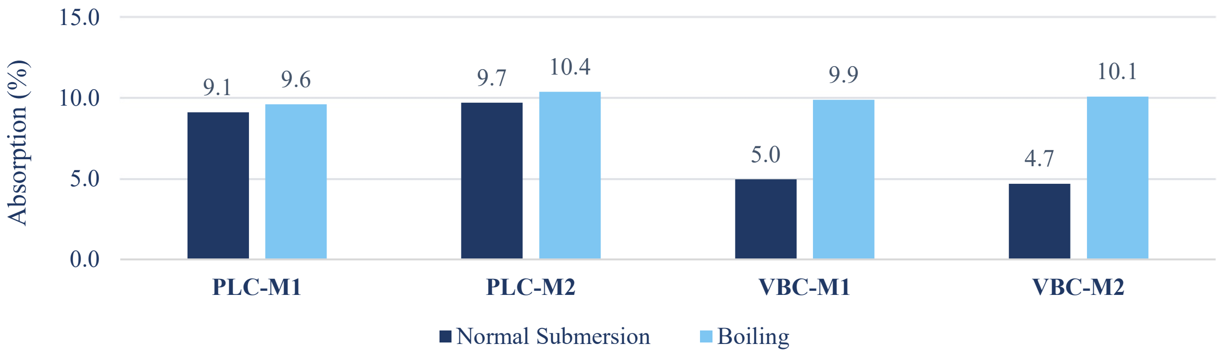


Figure 5. Submersion absorption compared to boiling absorption of mortar mixes (n = 2 samples per mix).

As shown in Figure 6, the dry bulk density values were relatively similar across the mixes. The PLC mortars had a dry bulk density of 1.98 g/cm^3, and the VBC mortars had a dry bulk density of 1.99-2.00 g/cm^3. The apparent density values were all greater than dry bulk density values and followed a similar trend. The PLC control mixes had an apparent density of 2.45-2.49 g/cm^3, and the VBC mortars had an apparent density of 2.49 g/cm^3.

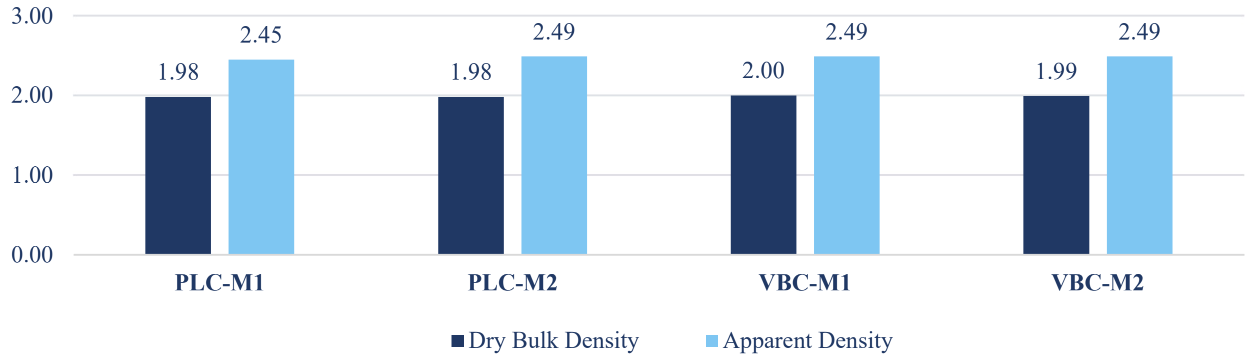


Figure 6. Dry bulk density compared to apparent density of mixes (n = 2 samples per mix).

The calculated permeable void content was similar across all mixes, as shown in Figure 7. PLC-M1 and PLC-M2 had values of 19.1% and 20.5%, respectively, while VBC-M1 and VBC-M2 had values of 19.7% and 20.1%. Overall, the permeable void values remained within a narrow range of approximately 19.1-20.5%.

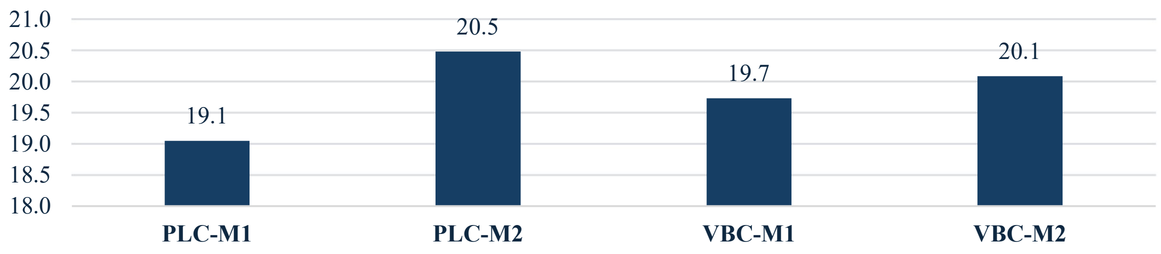


Figure 7. Bar chart comparing permeable void content of mortar mixes (n = 2 samples per mix).

See Appendix D for the complete table of the capillary absorption, submersion absorption, density, and permeable void results.

4.6 Surface Quality

Surface quality was evaluated using a visual scoring system based on demoulding ease, surface smoothness, visible pinholes or voids, edge sharpness, and chipping or corner damage, as summarized in Table 3. Each category was scored from 1 to 5, where 1 represented poor performance and 5 represented excellent performance. For pinholes, visible voids, and chipping, a higher score indicates fewer defects and better surface quality.

Table 3. Surface quality scoring of mortar specimens, including representative images.

Mix	Photo	Demould	Surface	Voids	Edge	Corner	Avg
PLC-M1		2	4	3	3	3	3.0
		Notes					
		Moderate sticking; moderate surface tearing	Moderate smoothness; rougher edges	Larger surface voids present	Sharp but not crisp edges	Good retention; rough corners	
PLC-M2		**Demould**	**Surface**	**Voids**	**Edge**	**Corner**	**Avg**
		2	4	4	4	3	3.4
		Notes					
		Moderate sticking; residue on mould hard to clean	Good smoothness	Less large surface voids present	Moderate sharpness	Good edge retention	
VBC-M1		**Demould**	**Surface**	**Voids**	**Edge**	**Corner**	**Avg**
		5	4	5	4	4	4.4
		Notes					
		Excellent release; minimal residue	Exposed sand; good smoothness	Few visible voids	Moderate retention; Moderate sharpness	Sharp corners; good retention.	
VBC-M2		**Demould**	**Surface**	**Voids**	**Edge**	**Corner**	**Avg**
		5	5	4	4	4	4.4
		Notes					
		Smoothest release; Least residue on mould	Smoothest surface; glossy finish; minimal visible sand	Few visible voids	Sharp edges; good retention	Sharp corners; good retention	

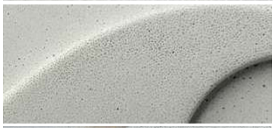
The VBC mixes had the highest overall surface quality scores, with VBC-M1 and VBC-M2 both averaging 4.4 and scoring consistently high for demoulding ease. The PLC control mixes had moderate surface quality scores of 3.0 for PLC-M1 and 3.4 for PLC-M2, with more noticeable sticking during demoulding. Additional demoulding observations are provided in Appendix E.

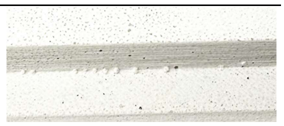
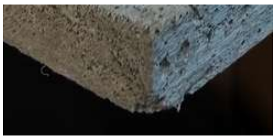
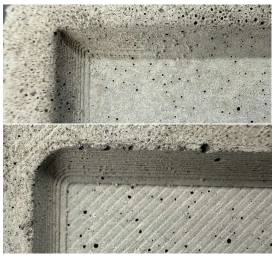
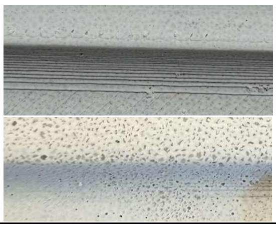
Figure 8 shows the visible colour difference between the PLC and VBC mortar cubes while wet. The VBC mixes appeared much whiter than the PLC mixes, and the bright white appearance was exaggerated when the specimens were wet.

Figure 8. Photograph of wet VBC and PLC mortar cubes (VBC-M1 and PLC-M2).

In addition to the numerical scoring results, individual architectural panel features were compared across different geometries. Table 4 summarizes the observed differences between PLC and VBC mixes for flat exposed surfaces, 3D printed textures, raised and recessed features, sharp edges, external and internal corners, wave tip, circular edges, and fillet details.

Table 4. Qualitative comparison of mortar performance across architectural panel features and geometries.

Panel feature	Specific Feature	PLC Notes	Images	VBC Notes	Images
Flat exposed surface fields	Smooth (sanded)	Good finish; Moderate sticking; damaged finish		Excellent flat surface finish; minimal visible voids	
	Rough (3D Printed Lines)	Easier mould release; good reproduction of 3D-printed line details		Fewer visible voids; excellent reproduction of 3D-printed lines	
Extruded and recessed features	Raised wave	Moderate edge tearing; minor crumbling; good retention	 	Surface tearing observed; well-defined edges; moderate edge retention	 
	Recessed wave	Minor surface tearing; excellent edge retention	 	Minimal surface tearing	 

Panel feature	Specific Feature	PLC Notes	Images	VBC Notes	Images
Edges	Sharp	Good edge definition; minor loss of crispness		Excellent edge definition; good edge retention	
External Corners	No fillet (sharp)	Good corner definition; minor crumbling		Excellent definition, good retention	
	3 mm	Good retention; poor definition of the upper edge; minor surface tearing		Excellent definition of filleted edge and top edge	
	4 mm (fully rounded corner)	Good retention; minimal crumbling; least surface tearing		Excellent corner retention; no major breakage or surface tearing observed	
	6 mm	Same as 3 mm		Same as 3 mm	
	Wave tip	Good reproduction; visible sand; minor crumbling		Excellent feature reproduction	
Internal corner	Filleted internal corner	Filleted curved corner released slightly easier		Improved retention for fully curved corners compared with sanded and non-filleted regions	
	Wave tip	Good tip definition; moderate edge tearing; minimal breakage		Sharp tip definition; minimal edge tearing; localized wall breakage observed	
Horizontal Convex Fillet Feature	2 mm	Crevice not too sharp; minimal surface tearing		Sharper crevice; less visible voids than PLC; smooth surface finish	
	4 mm	Performed similar to 2 mm		Sharp crevice; Excellent surface finish; performed similar to 2 mm	
Horizontal Concave Fillet Feature	3 mm	Moderate feature reproduction; minimal surface tearing		Excellent feature reproduction; well-defined 3D-printed lines; minimal surface tearing	

The panel observations showed clear differences between PLC and VBC mixes. For flat exposed surface fields, PLC produced a smooth finish, but some areas stuck to the mould and showed surface tearing after demoulding. The VBC mixes generally released more easily from the mould. The VBC mixes had a glossy finish. In the 3D printed regions, the VBC mixes showed clearer reproduction of the fine line texture than PLC.

For raised and recessed features, both PLC and VBC reproduced the main panel geometry, but differences were observed near edges and thin features. VBC generally showed better edge definition and retention, with less sticking and surface tearing than PLC. Rounded and filleted geometries generally showed better surface retention than sharp corners. The 4 mm rounded external corner showed the best observed corner performance, with excellent retention and minimal tearing or breakage. Internal curved features also released more cleanly than sharper internal corners. Overall, the VBC mixes showed the strongest combination of clean mould release, smooth exposed surfaces, bright white colour, and detailed feature reproduction.

4.7 Carbon Emissions Estimate

A preliminary binder-only carbon emissions estimate was performed to compare the PLC and VBC mixes. The Central Canada Type GUL emission factor of 0.798 kg CO_2e/kg was used for the PLC control binder [7]. Fortera reported that its ReAct Cement reduces emissions by 76% relative to an OPC reference value of 0.919 kg CO_2e/kg [8], giving an estimated emission factor of 0.221 kg CO_2e/kg for the VBC. CO_2 emissions per batch were calculated by multiplying the mass of binder used by the corresponding binder emission factor.

Batch volume was estimated by dividing each material mass by its density and summing the resulting component volumes. The total volume was then converted from litres to cubic metres. The density of PLC was measured using a helium pycnometer, and the density of VBC's components was provided by Fortera.

Binder-related carbon intensity was calculated by dividing the total binder-related CO_2 emissions per batch by the estimated batch volume in cubic metres (CO_2e/m^3). Performance-normalised carbon emissions were then calculated by dividing the binder-related carbon intensity by the corresponding 28-day strength, expressed in kg $CO_2e/(m^3\cdot MPa)$. Table 5 summarizes the binder-related carbon emissions, compressive strength, and performance-normalised carbon emissions for each mix.

Table 5. Binder-related carbon emissions and performance-normalised carbon emissions for mortar mixes.

Mix	Sand/binder	Carbon intensity (kg CO_2e/m^3)	28-day compressive strength (MPa)	Performance-normalised emissions (kg $CO_2e/(m^3\cdot MPa)$)
PLC-M1	2.75	415.4	36.2	11.5
PLC-M2	2.75	416.9	38.4	10.9
VBC-M1	2.32	141.7	26.6	5.3
VBC-M2	2.22	146.7	29.8	4.9

The table shows that the PLC control mixes had the highest binder-related carbon intensities per cubic metre at approximately 416 kg CO_2e/m^3. In comparison, VBC mixes had an average binder-related carbon intensity of approximately 144 kg CO_2e/m^3, corresponding to an average reduction of approximately 65% compared with the PLC controls.

When carbon emissions were normalised by 28-day compressive strength, the VBC mixes had an average performance-normalised carbon value of 5.13 kg CO_2e/m^3/MPa. Compared with PLC controls, the VBC mixes had approximately 54% lower performance-normalised carbon emissions.

5.0 Discussion

5.1 Workability and Casting Behaviour

The workability observations showed that similar flow values did not necessarily correspond to similar casting behaviour.

The VBC mixes responded differently to handling when compared with PLC. When handled on metal scoops, the VBC mixes tended to slip off the metal surface and leave behind a thin, watery paste residue. In contrast, PLC mixes tended to shear off the scoop more cohesively, leaving behind mortar that still contained both paste and aggregate. This showed that the VBC mixes had a different interaction with metal surfaces and a stronger tendency for the paste phase to separate from the sand during handling.

When applying force and vibration, a difference in behaviour was also observed in comparison with PLC. During tamping, the mortar appeared to resist stronger applied force, exhibiting a highly cohesive, elastic-like response, with resistance to deformation increasing as the tamping tool was pressed further into the material. Under weaker force or vibration, however, the mix became more fluid. This behaviour was useful for flat architectural moulds with surface details because vibration helped the material consolidate into fine features. However, in moulds with smaller openings, this behaviour created challenges. The paste phase would move into the mould first, leaving sand particles trapped in the opening, which made the mould more difficult to fill and could produce a less uniform mortar distribution.

Overall, VBC casting behaviour depended on more than flow value. Increasing paste volume to match PLC improved cohesion and reduced the water needed to reach the target flow in trial mixes.

5.2 Strength Development Mechanisms and Paste Adjustments

Using a low w/b is important with VBC because it does not develop strength through the same mechanism as PLC. PLC gains strength through hydration reactions, in which water reacts to form hydration products that bind water and the mortar together. In contrast, VBC is based on vaterite, a reactive calcium carbonate polymorph that hardens through dissolution and reprecipitation into a more stable calcium carbonate crystal matrix. Because VBC does not significantly and permanently bind water, virtually all mixing water results in porosity. As mixing water evaporates, it leaves behind voids, leading to lower strength.

This mechanism is consistent with the rapid strength development of the VBC mixes. The VBC mixes developed most of their strength within the first 48 hours before largely plateauing toward 28 days. Compared with PLC-M2, the VBC mixes were approximately 42% stronger at 1 day and 13% stronger at 2 days. By 28 days, however, the VBC mixes remained approximately 24% weaker than the PLC. This suggests that VBC mixes are highly promising for precast applications where early strength is valued; however, further mix optimisation is needed to scale to concrete production.

Flexural strength followed the same general trend as compressive strength. However, the average flexural-to-compressive strength ratio across matched test ages was approximately 14.4% for PLC and 10.6% for VBC. This can be important for architectural precast applications because thin panels or detailed elements must resist bending stresses during demoulding, handling, and transportation. Concrete tests would need to confirm that both PLC and VBC precast elements have sufficient flexural strength for handling, installation, and service. The reinforcement type and/or placement may need to be modified when converting a PLC element to a VBC element.

5.3 Absorption and Pore Connectivity

The absorption results help to explain how the mix designs affected water movement through the hardened mortar.

Capillary absorption results showed that VBC mixes had similar 24-hour absorption to PLC-M1, indicating broadly comparable water uptake. However, PLC-M2 showed greater absorption than both PLC-M1 and the VBC mixes. The difference between the two PLC controls may be related to their different curing ages at the time of testing. PLC-M1 had already exceeded the 28-day curing age, whereas PLC-M2 was tested at approximately 20 days. Since PLC continues to harden with time, the younger PLC-M2 specimens may have had a less developed pore structure, contributing to greater capillary water uptake. Additional capillary testing at consistent curing ages is therefore needed.

Under normal submersion, the VBC mixes showed lower absorption than PLC. The VBC mixes had the lowest values, averaging approximately 4.8%, which was about half of the PLC control average of approximately 9.4%. After boiling, however, absorption values became much closer across all mixes, falling within a narrow range of approximately 9.6-10.4%. Together, these results suggest that the total accessible pore volume of the VBC and PLC mortars may have been similar, but the accessibility and connectivity of those pores differed under normal exposure conditions. In the VBC mixes, some pore space may have been less readily connected to the exterior and therefore filled more slowly during normal submersion but became accessible under the more severe boiling condition. This interpretation is supported by the permeable void content, which remained within a narrow range of approximately 19.0–20.5% across all mixes. The density results supported the strength and absorption trends. The VBC mixes had dry bulk densities similar to or slightly higher than the PLC controls.

5.4 Surface Quality and Architectural Relevance

For the general surface quality analysis, the VBC mixes had the highest overall scores. VBC-M1 and VBC-M2 both had an average score of 4.4, compared with 3.0 for PLC-M1 and 3.4 for PLC-M2.
For all VBC mixes, the demoulding process was consistently easier than PLC.

As shown in Figure 9, less residue remained on the VBC moulds after demoulding, and the remaining residue was easier to remove compared with PLC (Appendix E). This is important because sticking to the mould can create surface tearing, which disturbs the exposed finish. The easier demoulding behaviour of the VBC mixes helped reduce surface tearing and protect the surface finish.

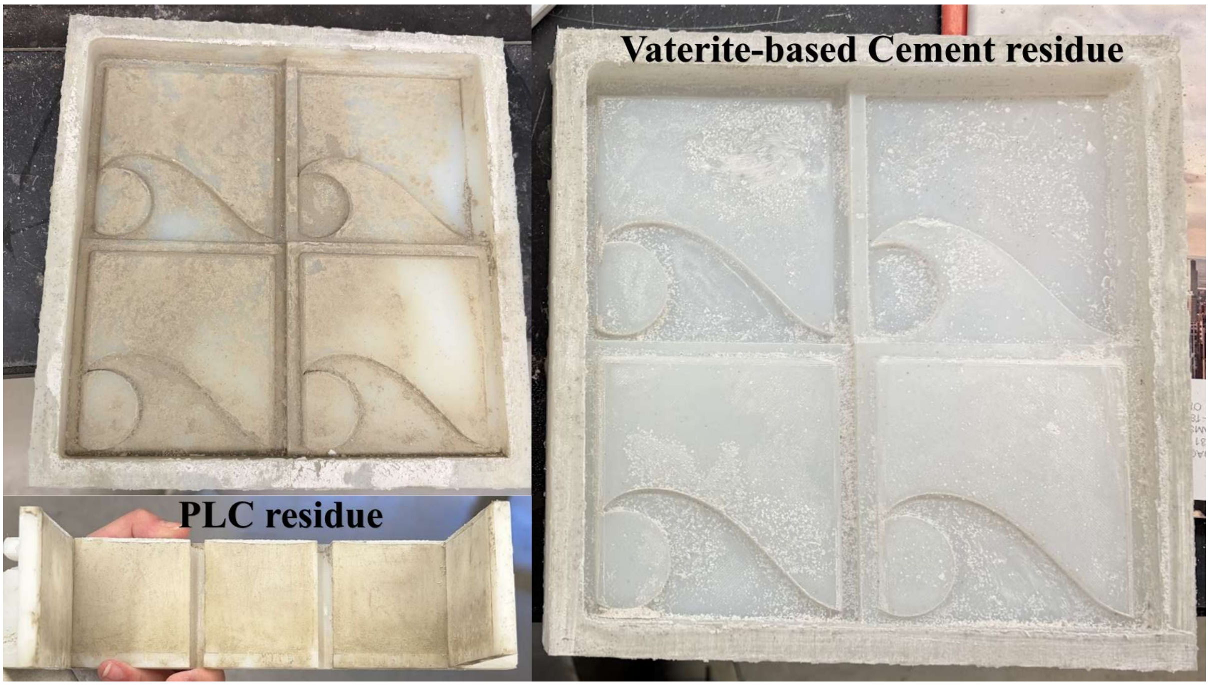


Figure 9. Photographs of PLC and vaterite-based cement residue on silicone and plastic moulds after demoulding.

The bright white colour of the VBC mixes is also important for architectural applications. The VBC mixes appeared much whiter than PLC, especially when wet. This colour may be desirable for exposed architectural products and may also make minor surface blemishes or tearing less visually noticeable.

Surface quality results from initial trial mixes also suggest that an increase in workable paste volume alongside the observed paste behaviour under vibration may have improved exposed surface finish. During vibration and consolidation, the paste phase appeared to form a paste-rich layer at the mould surface. This layer helped hide exposed aggregate particles, reduce visible surface porosity, and create a smoother, glossier finish. The paste-rich surface may also have contributed to easier demoulding, better fine-feature reproduction, and improved edge consolidation. In the specific feature surface photographs, the VBC features showed a smoother and glossier finish, along with a crisper edge profile. The VBC mixes also reproduced the fine 3D printed lines better than PLC. However, VBC's surface quality advantage depends on achieving sufficient strength and using the appropriate consolidation techniques.

5.5 Embodied Carbon

The embodied carbon calculations show that VBC systems have strong potential to reduce binder-related emissions. However, carbon reduction should be evaluated alongside mechanical performance. A low-carbon mix is only useful for architectural applications if it can also meet strength and surface quality requirements.

The VBC mixes achieved strength-normalised carbon values that were approximately 46% of the PLC values. This means that, for each unit of compressive strength, VBC mixes required less than half of the binder-related carbon emissions compared to the PLC controls.

Since only preliminary mix optimisation was completed, there is still potential to further improve strength and reduce the strength-normalised carbon value even more. Overall, the carbon emissions estimate showed that the VBC mixes provided the best balance between carbon reduction and mechanical performance.

5.6 Applications

The results suggest that VBC mixes may be most suitable for precast applications where early strength, easy demoulding, high-quality surface finish, and a bright white colour are important. These traits are valuable for products such as decorative panels, cladding, architectural tiles, pavers, and other visible precast components.

The casting observations also suggest that VBC may be promising for low-slump or zero-slump products, such as concrete masonry units, where low water content and vibration are used for compaction. This is relevant because VBC performed better when the effective water-to-binder ratio was reduced, consistent with the VBC system's sensitivity to excess water. Since concrete masonry units are released from the mould immediately after compaction, the slippery and non-sticky behaviour observed when VBC contacted metal tools and parchment paper may help with cleaner release and better shape retention. If high early strength can be maintained, VBC-based products may also reach handling and shipping strength significantly earlier than conventional PLC products.

6.0 Conclusion

This study evaluated VBC as a potential lower-carbon binder for precast architectural applications.

The VBC mixes' compressive strengths were higher than those of PLC at early ages, but weaker than the PLC controls at 28 days. The VBC mortars consistently developed most of their strength within the first 48 hours. This rapid early strength development is important for precast architectural applications because earlier demoulding can improve production efficiency.

The flexural strength of VBC mortars was lower than the flexural strength of PLC mortars at all ages. The flexural-to-compressive strength ratio was approximately 14.4% for the PLC mortars and 10.6% for the VBC mortars. When converting a precast element from PLC to VBC, the performance of the composite would need to be verified to meet the load demands and the type and placement of reinforcement may need to be modified.

The VBC and PLC mortars had similar densities, permeable voids, and water absorption values after boiling; however, the VBC mortars had lower normal submersion absorption values compared to PLC.

Surface quality was one of the strongest advantages of the VBC mixes. Overall, the VBC mixes showed easier demoulding, cleaner mould release, and a brighter white colour compared with PLC. Having sufficient paste volume helped create smoother exposed surfaces and a glossier finish, while the accompanying strength improved edge retention. These properties are especially relevant for architectural precast products, where surface finish, edge quality, colour, and demoulding ease are important.

The binder-related carbon emissions estimate showed that the VBC mixes reduced carbon intensity per volume by approximately 65% compared with the PLC controls. When normalised by 28-day compressive strength, the VBC mixes had approximately 54% lower carbon emissions than PLC.

Overall, these results suggest that VBC has strong potential for precast architectural applications where early strength, smooth white surface finish, easy demoulding, and lower carbon emissions are valued. However, further optimisation and concrete testing are still needed before precast implementation.

7.0 Limitations

This study had several limitations that should be considered when interpreting results.

First, the experiments were conducted at the mortar scale rather than the concrete scale. While mortar testing helped isolate binder behaviour without variability from coarse aggregate, the results may not fully represent concrete performance. Concrete-scale testing is therefore needed before drawing conclusions for precast architectural applications.

Second, the six-week research period limited both the number of mix-design iterations and the available curing time for some specimens. Only two paste-adjusted VBC mixes could be evaluated, and a broader range of sand gradations and binder-to-sand ratios could not be investigated. In addition, some specimens were cast later in the research period and were tested before reaching the 28-day reference age. For example, PLC-M2 was approximately 20 days old at the time of capillary absorption testing.

Third, the number of specimens tested was limited. Most ages and test conditions used only two specimens, which was sufficient to identify preliminary trends, but not for strong statistical conclusions. Additional replicate testing would improve confidence in the observed differences and trends.

Fourth, the carbon emissions estimate was preliminary and focused only on the binder. The calculations did not include the full life-cycle emissions from sand, water, admixtures, transportation, fuel, processing, or equipment energy.

Finally, the surface quality assessment was mostly qualitative. The visual scoring system was useful for comparing demoulding ease, smoothness, pinholes, edge sharpness, and chipping, but more quantitative methods would improve the analysis. Future work should include more quantitative image analysis methods.

8.0 Future Work

Future work should first focus on developing a larger repository of optimised mix designs for the VBC. A useful next step would be to create a mix design database for different target strength ranges, workability levels, and surface quality requirements. This would help identify material ratios and admixture dosages most suitable for specific applications.

An important area for future work is studying the early curing behaviour for the VBC mix, especially within the first 0-12 hours after casting. In precast manufacturing, production efficiency depends heavily on the waiting time required before demoulding. Therefore, future studies should investigate whether the VBC mixes experience a rapid increase in strength during this period. Testing strength development at shorter intervals, such as 2, 4, 6, 8, and 12 hours, could help identify the earliest safe demoulding time. This would be useful for determining whether VBC mixtures can support faster production cycles in precast manufacturing.

Future work should also investigate VBC mixes for low-slump or zero-slump precast products, such as concrete masonry units, which are cast using low water content and vibration-based compaction. Since VBC performed better after the effective water-to-binder ratio was reduced, low-water applications may allow the material to develop stronger early-age performance. The non-sticky behaviour observed when VBC contacted metal tools and mould surfaces may also be useful for products that require immediate release from the mould after compaction.

Finally, for architectural applications, future work should expand panel testing. Larger and more detailed panels should be cast to evaluate whether the material can consistently reproduce fine surface features. Further studies should compare consolidation methods, timing, and sequence to determine their effects on surface quality and demoulding.

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10.0 References

[1] J. Friedman, “Cement and Concrete Companies Leading the Net-Zero Transition,” *Center for American Progress,* Jul. 11, 2024. [Online]. Available: https://www.americanprogress.org/article/cement-and-concrete-companies-leading-the-net-zero-transition/

[2] “Cement technology roadmap plots path to cutting CO2 emissions 24% by 2050 - News,” International Energy Agency, Apr. 5, 2018. [Online]. Available: https://www.iea.org/news/cement-technology-roadmap-plots-path-to-cutting-co2-emissions-24-by-2050

[3] S. S. Volaity et al., “Towards decarbonization of cement industry: a critical review of electrification technologies for sustainable cement production,” *npj Materials Sustainability*, vol. 3, Art. no. 23, Jul. 2025, doi: 10.1038/s44296-025-00068-6.

[4] E. Worrell, L. Price, N. Martin, C. Hendriks, and L. Ozawa Meida, “Carbon Dioxide Emissions from the Global Cement Industry,” *Annual Review of Environment and Resources*, vol. 26, pp. 303–329, Nov. 2001, doi: 10.1146/annurev.energy.26.1.303.

[5] C. W. Hargis, I. A. Chen, M. Devenney, M. J. Fernandez, R. J. Gilliam, and R. P. Thatcher, “Calcium Carbonate Cement: A Carbon Capture, Utilization, and Storage (CCUS) Technique,” *Materials*, vol. 14, no. 11, Art. no. 2709, May 21, 2021, doi: 10.3390/ma14112709.

[6] Fortera, “Supplier certification: ReAct® Cement Type GU/HE/HS/MS/MH/LH,” Lot 141, San Jose, CA, USA, Dec. 11, 2025. [Online]. Available: https://forteraglobal.com/wp-content/uploads/2026/01/ReAct%C2%AE-Cement-Type-GU-HE-HS-LH-ASTM-C1157-Supplier-Certification-with-CTS-C1157-Strength-Report.pdf

[7] Cement Association of Canada, “Environmental Product Declaration for General Use (GU) & Portland-Limestone (GUL) Cements,” EPD No. 452, Apr. 21, 2023. [Online]. Available: https://pcr-epd.s3.us-east-2.amazonaws.com/919.CAC_General_Use_(GU)_and_Portland-Limestone_(GUL)_Cements.pdf.

[8] Portland Cement Association, “Environmental Product Declaration: Portland Cement,” EPD 195, ASTM International, Mar. 12, 2021. [Online]. Available: https://www.cement.org/wp-content/uploads/2026/07/PCA_EPD_Portland_Athena_Final_revised_Jul2026.pdf

11.0 Appendices

Appendix A. Sand Gradation, Sand Packing, and Paste-Volume Adjustment

ASTM C778 standard graded sand was used for all mortar mixes to maintain consistency between the PLC and VBC systems. Using the same sand allowed the binder systems to be compared under controlled aggregate conditions.

However, the ASTM C778 sand gradation was not optimised for VBC behaviour. ASTM C778 sand has a controlled, standardised particle-size distribution. The gradation left interparticle void spaces that had to be filled by paste. For VBC, this was important because insufficient paste volume can reduce sand coating and make the mix more sensitive to water content.

The sand-packing measurement was therefore used to estimate the interparticle void volume and adjust the VBC paste volume. This adjustment helped provide enough paste to coat the sand particles and fill the void spaces between them while maintaining the target flow range.

A broader aggregate gradation may improve future VBC mix designs by allowing smaller particles to fill the spaces between larger particles. This could reduce the paste volume needed to fill voids, improve packing density, and support better strength and surface quality. Future work should therefore evaluate VBC mixes with different sand gradations and aggregate packing designs.

Appendix B. Architectural Panel Mould and Consolidation Methods

During casting of the flat architectural panel, several consolidation methods were tested, including manual tamping, vibration, tapping the mould on a flat surface, and different combinations of these methods. Vibration helped the mortar flow into flat surface details, while tapping the mould helped release trapped air bubbles. However, smaller mould openings were more difficult to fill because the paste phase sometimes moved ahead of the sand. The best general approach was to place the material carefully into the mould, use vibration to help the mortar enter fine details, and tap the mould on the table to release bubbles without over-vibrating.

Figure B1. 3D-printed master architectural panel pattern and silicone mould used for casting.

Appendix C. Mechanical Strength Results

This appendix provides the complete compressive and flexural strength results for the PLC controls and VBC mixes at each testing age.

Table C1. Average compressive strength of PLC controls and VBC mixes at each testing age.

Mix	Age	Average Compressive Strength, MPa	Average Compressive Strength, PSI
PLC-M1	3 days	27.12	3933
PLC-M1	7 days	30.00	4351
PLC-M1	28 days	36.16	5245
PLC-M2	1 day	18.60	2698
PLC-M2	2 days	25.60	3713
PLC-M2	28 days	38.40	5569
VBC-M1	1 day	24.80	3597
VBC-M1	2 days	27.60	4003
VBC-M1	28 days	26.60	3858
VBC-M2	1 day	28.00	4061
VBC-M2	2 days	30.16	4374
VBC-M2	28 days	29.80	4322

Table C2. Average flexural strength of PLC controls and VBC mixes at each testing age.

Mix	Age	Average Flexural Strength (MPa)	Average Flexural Strength, (PSI)
PLC-M1	3 days	3.68	534
PLC-M1	7 days	4.03	585
PLC-M1	28 days	3.81	553
PLC-M2	1 day	3.72	540
PLC-M2	2 days	3.99	579
PLC-M2	28 days	5.01	727
VBC-M1	1 day	2.72	395
VBC-M1	2 days	2.64	383
VBC-M1	28 days	3.14	455
VBC-M2	1 day	2.68	389
VBC-M2	2 days	3.21	466
VBC-M2	28 days	3.30	479

Appendix D. Absorption, Density, and Permeable Void Results

Table D1. Capillary absorption results at 15 minutes, 1 hour, 4 hours, and 24 hours.

Mix	15 min (g/100 cm^2)	1 h (g/100 cm^2)	4 h (g/100 cm^2)	24 h (g/100 cm^2)
PLC-M1	2.96	5.04	10.36	40.56
PLC-M2	10.68	21.63	44.63	74.40
VBC-M1	8.14	16.11	25.36	44.57
VBC-M2	6.10	13.07	28.28	44.78

Table D2. Submersion absorption, boiling absorption, density, and permeable void results.

Mix	Submersion absorption (%)	Boiling absorption (%)	Dry bulk density (g/cm³)	Apparent density (g/cm³)	Permeable voids (%)
PLC-M1	9.10	9.60	1.98	2.45	19.1
PLC-M2	9.70	10.38	1.98	2.49	20.5
VBC-M1	4.95	9.88	2.00	2.49	19.7
VBC-M2	4.69	10.09	1.99	2.49	20.1

Appendix E. Additional Surface Quality and Demoulding Observations

The VBC mixes generally released more easily from the moulds than the PLC control mixes. This difference was especially noticeable during mould cleaning. After demoulding, the PLC residue on the plastic cube moulds was strongly attached and required scraping and thorough scrubbing with a rough-bristle brush. In contrast, the VBC mixes left little residue, and any remaining material appeared more paste-like and less bonded to the mould surface, allowing it to be wiped or washed off with minimal scrubbing.

A similar difference was observed with the silicone architectural moulds. VBC residue could generally be wiped off with a finger, while PLC residue was more strongly attached and required additional cleaning, including the use of WD-40 to help release bonded residue from the mould surface. These observations suggest that VBC may offer practical advantages for demoulding and mould cleaning in precast applications.