Received: 22 May 2025 | Revised: 22 May 2025 | Accepted: 16 July 2025

DOI: 10.1002/suco.70260

SHORT PROJECT NOTE

fib CEB-FIP WILEY

High-density geopolymer concrete exposed to marine environment

Aziz Hasan Mahmood[1] | **Chowdhury Zubayer Bin Zahid**[2] | **Stephen J. Foster**[3]

[1]School of Civil and Environmental Engineering, University of Technology Sydney, Sydney, New South Wales, Australia

[2]Department of Civil Engineering, University of Malaya, Kuala Lumpur, Malaysia

[3]School of Civil and Environmental Engineering, The University of New South Wales, Sydney, New South Wales, Australia

Correspondence
Aziz Hasan Mahmood, School of Civil and Environmental Engineering, University of Technology Sydney, Sydney, NSW 2007, Australia.
Email: aziz.mahmood@uts.edu.au

Funding information
CRC for Low Carbon Living, Grant/Award Number: RP1020

1 | BACKGROUND

To withstand increasing wave energy resulting from a changing climate and protect the coastal ports and environments, a trial of dense breakwater armor units has been underway on a section of the northern breakwater of Port Kembla Harbour in New South Wales, Australia, since August 2018. These armor units utilize a unique high-density geopolymer concrete (GPC). The added density improves armor stability in increasing wave climates, as the mass of each unit is directly proportional to the cube of the wave height. In the GPC mix, steel furnace slag (SFS) replaces gravel and sand. Unlike ordinary Portland cement, the SFS can be effectively used in low-calcium GPC without delayed expansion. The calcium gradient between the free lime in SFS and the GPC matrix facilitates its absorption, thereby eliminating the agent of expansion. After exposure to the marine environment for 3 years, the units were inspected, and the material was subjected to testing. This project note presents outcomes of the assessment. This project expands Australia's efforts to use GPC in mainstream projects.

2 | FIELD TEST AND EXPERIMENT DETAILS

Extensive lab trials and testing developed the GPC mix for possible field supply.[1] Besides SFS aggregates, the GPC uses 35% ground granulated blast furnace slag (GGBFS) and 65% fly ash as the binder, activated by a solution of NaOH and sodium silicate, adjusted to maintain an ideal 5.5% Na_2O and a modulus ratio of 1.5. Wagners, a local concrete supplier, optimized the mix by incorporating a proprietary geopolymer-compatible admixture and activator, and enhanced the aggregate grading with river sand inclusion. The field trial batching commenced at Port Kembla, New South Wales, roughly 5 km from the breakwater site. The batching procedure added the activators and admixtures as the final step in the drum agitator of a concrete truck. Figure 1a illustrates the placement and compaction, and Figure 1b shows installed units. Thirteen armor units were fabricated in three pours in August 2018, cumulating to about 90 m^3 of high-density GPC; units were placed on the breakwater within the splash zone, and one unit was placed on shore.[2]

After 3 years of exposure, 100 mm diameter core specimens were obtained from accessible armor units, both onshore and splash zone (Figure 1c). Concrete specimens were also prepared during field batching (Figure 1e), and the specimens underwent air-curing or immersion in saline water (representing seawater) at the laboratory for 3 years. Both laboratory and field specimens were categorized as either saline water-cured (WC) or air-cured (AC) and were stored at 50% relative humidity and 23°C. Table 1 details the specimens investigated.

3 | OBSERVATIONS, RESULTS, AND DISCUSSIONS

Images of specimens exposed to the site and within the lab curing environment (saline water and ambient) are in Figure 1. The armor units in the splash zone had yellow/brown surface stains (Figure 1d), similar to the saline WC lab specimens as in Figure 1e. These stains are ferric oxide, as recognized by x-ray fluorescence analysis, caused by steel particles within the SFS aggregates; steel bits were

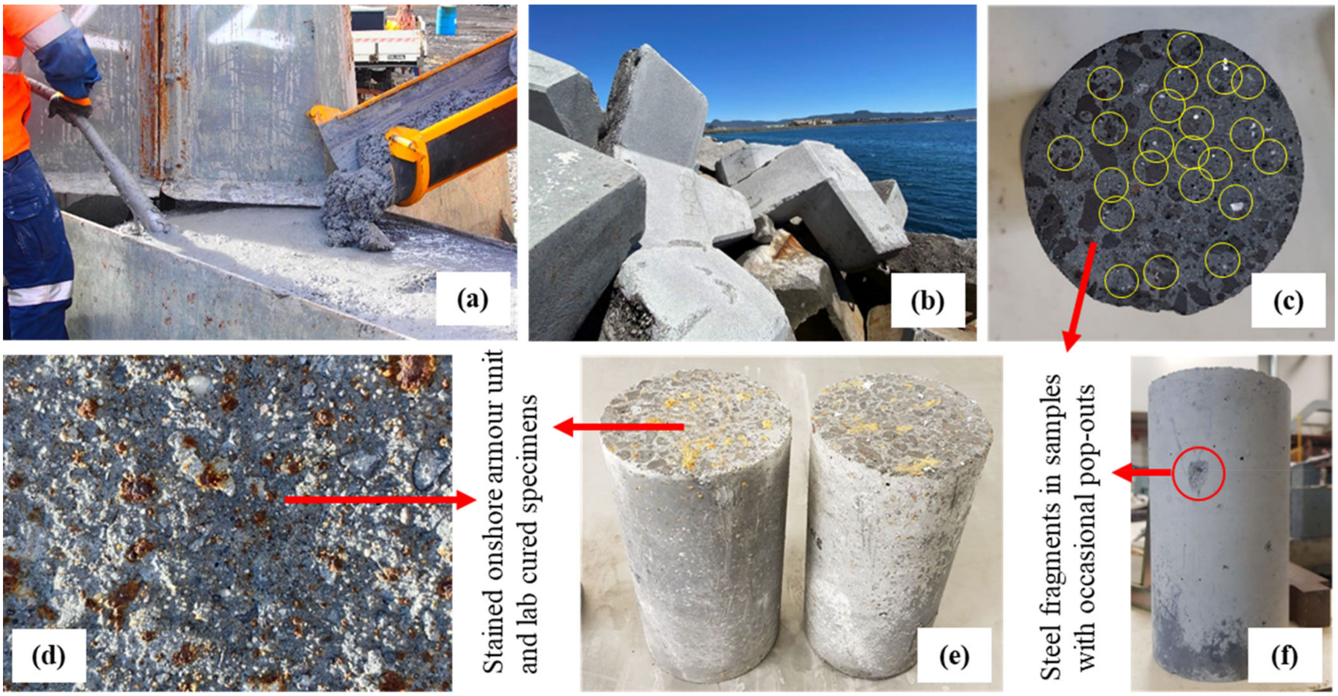

FIGURE 1 (a) Armor unit formwork filling and compaction; (b) GPC Hanbar units within the splash zone; (c) steel fragments visible on specimen surface; (d) stains on the base of a unit; (e) stains on specimens cured in saline water; (f) instance of aggregate popping. GPC, geopolymer concrete.

TABLE 1 Description of GPC specimens and their curing conditions.

Specimen/core ID	Batching	Source/placement	Conditioning	Evaluations
LB-AC	Laboratory trial	Cast in lab/lab	Air cured	CS, STS, CaP
LB-WC	Laboratory trial	Cast in lab/lab	Saline water cured	CS
PK-1-AC	Field trial pour 1	Cast in field/lab	Air cured	CS, STS
PK-1-WC	Field trial pour 1	Cast in field/lab	Saline water cured	CS, STS
PK-1-SZ	Field trial pour 1	Core/on-site	Splash zone	CS, STS, CaP
PK-1-OS	Field trial pour 1	Core/on-site	On-shore	CS, STS
PK-2-AC	Field trial pour 2	Cast in field/lab	Air cured	CS, STS
PK-2-WC	Field trial pour 2	Cast in field/lab	Saline water cured	CS, STS
PK-2-SZ	Field trial pour 2	Core/on-site	Splash zone	CS, STS

Abbreviations: CaP, calcium profile determined by energy-dispersive x-ray spectroscopy (EDS); CS, compressive strength; GPC, geopolymer concrete; STS, splitting tensile strength.

TABLE 2 Strength assessment after 3 years of exposure.

	Specimen ID	28 days	90 days	3 years
Compressive strength	LB-AC	36.5 ± 0.4	—	41.6 ± 1.1
	LB-WC	—	—	45.0 ± 0.9
	PK-1-AC	35.3 ± 1.5	44.9 ± 2.0	20.4 ± 0.8
	PK-1-WC	—	—	36.5 ± 4.4
	PK-1-SZ	—	—	40.7 ± 2.7
	PK-1-OS	—	—	40.0 ± 5.9
	PK-2-AC	46.8 ± 3.8	56.8 ± 3.4	37.6 ± 4.1
	PK-2-WC	—	—	65.5 ± 0.4
	PK-2-SZ	—	—	40.7 ± 2.7
Splitting tensile strength	LB-AC	2.5 ± 0.1	—	—
	LB-WC	—	—	3.0 ± 0.2
	PK-1-AC	3.0 ± 0.2	3.9 ± 0.2	3.1 ± 0.5
	PK-1-WC	—	—	3.6 ± 0.2
	PK-1-SZ	—	—	3.4 ± 0.3
	PK-1-OS	—	—	3.0 ± 0.3
	PK-2-AC	3.6 ± 0.4	4.3 ± 0.1	4.0 ± 0.1
	PK-2-WC	—	—	4.1 ± 0.3

discovered on the surface of all field batched specimens (Figure 1c).

While the Hanbar armor units did not experience SFS aggregate expansion, specimens batched on-site and air cured in the lab demonstrated occurrences of surface spalling caused by the expansion of aggregates. No similar pop-outs were observed in the saline WC specimens. However, saline water curing eliminated this expansion, and no unit in the splash zone experienced spalling. It is possible that the SFS aggregates utilized in the field could not completely absorb the free lime component within the geopolymer matrix, and the expansion was triggered when air dried. No surface spalling was noted in the laboratory trial concrete specimens (Table 1) because the SFS was treated to limit free lime within 4.4% before use. Data on the free lime of field batched SFS are unavailable.

The compressive and splitting tensile strengths of GPC batched on-site at Port Kembla, along with the strength of core specimens collected after 3 years of site exposure, are summarized in Table 2. The lab trial specimens' strength had a gradual 14% strength increase from 4 weeks to 3 years, suggesting ongoing geopolymerization, with no spalling indicating effective absorption of the free lime. The AC samples obtained from Pours 1 and 2 exhibit a substantial decrease in strength. Although strength development was observed in the first 90 days, Pours 1 and 2 specimens had a 42.2% and 19.7% drop in strength over 3 years under air curing conditions. These specimens exhibited occurrences of SFS aggregate expansion, causing spalling.

Cores from the site exhibited greater strength compared to AC specimens obtained from site pours and conditioned

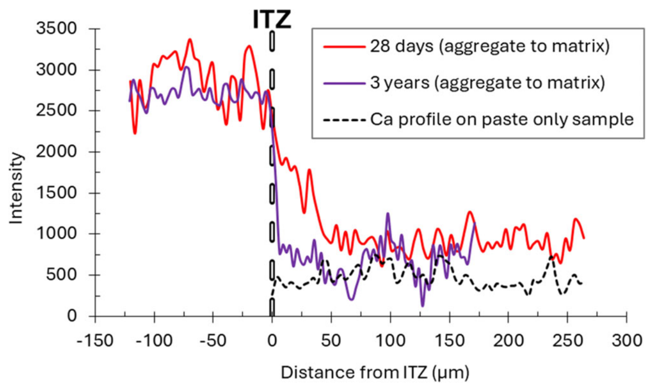

FIGURE 2 Calcium profile near the ITZ around SFS aggregate (EDS line scan). EDS, energy-dispersive x-ray spectroscopy; ITZ, interfacial transition zone; SFS, steel furnace slag.

in the laboratory.[3] The saline WC specimens provided the greatest strengths. The cause of GPC's increased strength in saline water, particularly when on-site in the splash zone, is still unclear, and further research is required to comprehend the underlying processes responsible for this occurrence.

Contrary to field specimens, the GPC batched in the lab (Table 2) showed no observable signs of deterioration in strength. This suggests no internal stress from free lime hydration. On-site batching lacks precise control of laboratory conditions, affecting the proportioning of GPC constituents.

The energy-dispersive x-ray spectroscopy (EDS) line scans in Figure 2 display Ca intensities observed on 28-day and 3-year-old specimens. The progressive difference in Ca intensities between the pure paste and the 28-day specimen indicates the free lime (Ca) migration into the matrix from the aggregate, away from the interfacial transition zone (ITZ). The Ca intensity drops sharply at the ITZ in the 3-year-old specimen, suggesting no diffusion of free lime. This means either free lime has been consumed over time or the geopolymer matrix's calcium gradient is insufficient.

4 | CONCLUDING REMARKS

The SFS aggregates must be free of residual steel fragments to prevent the armor units from oxidizing and scaling. The aggregate free lime content is to be below ∼4.4% to limit expansion. The fly ash/GGBFS ratio (35/65) is to be maintained for free lime absorption.

ACKNOWLEDGMENTS

The funding from the Australian Government's Cooperative Research Centres (CRC) program for Low Carbon Living Ltd (Grant Number RP1020) is gratefully acknowledged. Open access publishing facilitated by University of Technology Sydney, as part of the Wiley - University of Technology Sydney agreement via the Council of Australian University Librarians.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Aziz Hasan Mahmood https://orcid.org/0000-0002-4699-9919

Stephen J. Foster https://orcid.org/0000-0003-1162-0929

REFERENCES

1. Mahmood AH, Foster SJ, Castel A. Development of high-density geopolymer concrete with steel furnace slag aggregate for coastal protection structures. Construct Build Mater. 2020;248:118681.
2. Mahmood AH, Foster SJ, Castel A. High-density geopolymer concrete for Port Kembla breakwater upgrade. Construct Build Mater. 2020;262:120920.
3. Mahmood AH, Foster SJ. Performance of high-density geopolymer concrete at Port Kembla's Northern breakwater armour units: update June 2021. UNICIV Report No. R-469.

AUTHOR BIOGRAPHIES

Aziz Hasan Mahmood, School of Civil and Environmental Engineering, University of Technology Sydney, Sydney, NSW 2007, Australia. Email: aziz.mahmood@uts.edu.au

Chowdhury Zubayer Bin Zahid, Department of Civil Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia. Email: 22053918@siswa.um.edu.my

Stephen J. Foster, School of Civil and Environmental Engineering, The University of New South Wales, Sydney, NSW 2052, Australia. Email: s.foster@unsw.edu.au

How to cite this article: Mahmood AH, Zahid CZB, Foster SJ. High-density geopolymer concrete exposed to marine environment. Structural Concrete. 2025. https://doi.org/10.1002/suco.70260