DEVELOPMENT OF HIGH-DENSITY GEOPOLYMER CONCRETE FOR BREAKWATER ARMOUR UNITS FOR PORT KEMBLA HARBOUR

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Coastal infrastructure is under constant attack from the marine environment. Under current conditions, breakwaters and seawall armoured by rock or concrete units require regular monitoring and maintenance. But with anticipated changes to the coastal wave climate due to climate change scenarios, costal structures would be exposed to even greater wave energy, and higher rates of damage. In this project, researchers and industry partners worked together in the development and trial of a unique, sustainable high-density Geopolymer concrete mix for coastal structures. The system developed in the laboratories of UNSW was upscaled and is being tested at the northern breakwater of NSW Ports' Port Kembla Harbour. The concrete uses steel furnace slag (SFS) aggregate in a blended fly ash-blast furnace slag binder to eliminate delayed hydration and expansion of the aggregate. The concrete properties were measured and microstructural analysis undertaken. The results show that SFS aggregate offers higher bulk density to the concrete and can reduce armour mass requirements. This important result provides a novel approach to both repair of existing structures, and construction of new structures with reductions to both cost and carbon footprint.

1.0 INTRODUCTION

Infrastructure along the Australian coastline is under continuing environmental attack. Apart from the hostile marine environment that gradually but continually degrades materials, episodic storms have the potential to severely damage breakwaters, seawalls and other structures. Under current conditions, breakwaters and seawall armoured by rock or concrete units require regular monitoring and maintenance, but with anticipated changes to the coastal wave climate due to predicted climate change scenarios, costal structures would be exposed to even greater wave energy, and higher rates of damage (Howe and Cox[1]). As armour unit design equations predict a significant enhancement of stability with relatively small increases in material density, there is an opportunity to improve repair strategies by using high density concrete, or to reduce the armour mass and overall cost of new structures. At the same time, it is recognised that construction is a significant contributor to greenhouse gas emissions, and that significant energy is required to generate the cement for traditional concretes.

Breakwaters and other coastal structures are designed to ensure the protection of ports, harbours and coastal beaches by breaking waves and in dissipating wave energy. Though quarried rocks are the most common armour units, difficulties associated with finding, quarrying and transporting rocks of required mass has led to the use of fabricated concrete armour units in breakwaters. The required mass of an armour unit is a complex relationship between their interconnectivity, the shore and wave profile and the amount of sustainable damage that is acceptable.

It is notable that wave energy is a square function of wave height (USACE[2]) and, thus, a small increase in the depth of water leads to a significant increase in wave energy encountered by structures in depth limited wave breaking conditions. Also of interest is, for a given armour unit design, the mass needed for stability can be determined by Hudson's equation (Hudson[3]). This relationship relates the armour unit weight (W) to its submerged relative density (Δ) as:

$$W \propto 1/\Delta^x \tag{1}$$

where x is a constant coefficient, determined as x = 3 by both Hudson and van der Meer based on extensive physical modelling investigations (Hudson3, van der Meer4). So, while wave energy is a square function of wave height, armour unit stability is a cubic function of submerged relative density; thus, a small increase in the material density may result in a significant enhancement of armour stability and, therefore, a significant reduction in total armour unit weight and volume.

The submerged relative density Δ of the armour unit is:

$$\Delta = \rho_a/\rho_w - 1 \tag{2}$$

where ρ_α is the armour concrete density and ρ_w is the density of sea water. From Eqs. (1) and (2) it may be determined that by increasing the material density from 2300 kg/m^3 to 2600 kg/m^3, a 47 per cent reduction of unit weight might be possible (taking the density of sea water as 1020 kg/m^3). A recent study by Howe and Cox[1] showed that the relationship also holds for Hanbar units. Hanbar units are coastal protection unit designed and used extensively in NSW, Australia.

Since almost ¾ of the concrete by volume is aggregate (coarse and fine), the use of high-density aggregate is a convenient way to produce high-density concrete. Steel furnace slag (SFS), a by-product of steel manufacturing process, has 25-30% higher density than conventional basalt aggregate (Wang and Yan[5]; Khan et al.[6]; Brand and Roesler[7]) and substitution of conventional aggregate with SFS can provide a high density end product. Aside from offering higher density, SFS offers the potential for improved mechanical strength to concrete (Brand and Roesler[7]). However, SFS aggregates are associated with free lime, which hydrates in ordinary Portland cement (OPC) concrete resulting in a delayed volumetric expansion of the binder matrix. This expansion leads to concrete cracking and durability and longevity is significantly threatened. For this reason SFS aggregate is not used in OPC concrete, despite being researched for over a decade (Brand and Roesler[7]; Maslehuddin et al.[8]; Xue et al[9]).

This paper describes the development of a high-density SFS aggregate Geopolymer concrete (high-density GPC) for use in armour units designed for coastal protection and the construction and placement of the units at the northern wall of the Port Kembla breakwater (Figure 1); the armour units used are known as Hanbars. The project forms part of on-going research for the CRC for Low Carbon Living into the development of alternative binder concrete.

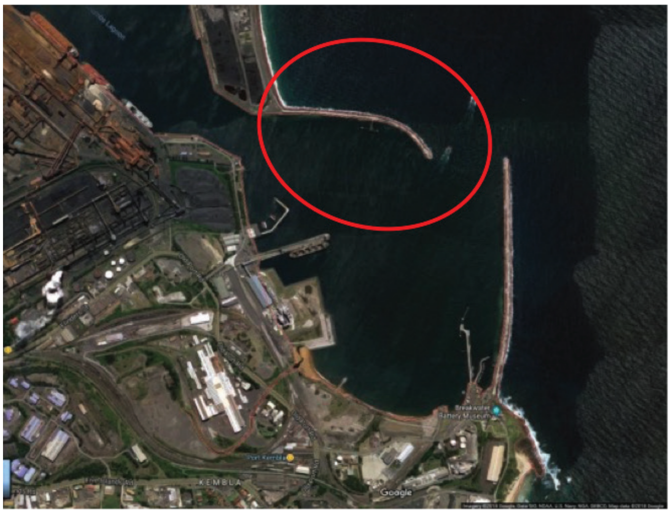


FIGURE 1. Site location - Port Kembla northern breakwater (Google maps)

2.0 RESEARCH SIGNIFICANCE

This unique high-density geopolymer concrete addresses two major issues of our time – climate change and the sustainable use of resources. The Geopolymer concrete used consisted of a blended fly ash and slag as the binder, and steel furnace slag as aggregates; all of which are by-products of various industries. Replacement of cement combined with lower volumes of total materials (due to the lower mass requirement) is an effort to reduce the carbon footprint associated with manufactured breakwater armour units. Australia generates 14 million tonnes of fly ash (from coal fired power generation) and three million tonnes of various metallurgical slags (from steel manufacture) as industrial by-products, which have considerable potential for full utilisation within a circular economy. Moreover, this research opens a new potential pathway for sustainably using SFS aggregates.

3.0 DEVELOPMENT OF THE MIX DESIGN

Extensive research at Centre for Infrastructure Engineering and Safety (CIES) at UNSW has confirmed that when used in low calcium Geopolymer concrete, the free lime of SFS aggregate diffuses into the Geopolymer matrix due to the high differential in Calcium (Ca) intensities between the aggregate and the binder, eliminating the risk of delayed expansion (Khan et al.[6]). Khan et al. used a blend of 90% low calcium fly ash (FA) and 10% ground granulated blast furnace slag (GGBFS) as a Geopolymer binder to minimise the overall calcium content.

The binders were activated with an alkaline solution of 12 molar (12M) Sodium Hydroxide (NaOH) and grade D Sodium Silicate (Na_2SiO^3) solution. However, such proportions of the FA-GGBFS blend may not be applicable to construction projects where members are cured in an ambient environment, as the strength gain in concrete is too slow due to the low calcium content of the binder (Yang and Song[10], Rangan[11], Noushini and Castel[12]). Moreover, a highly alkaline activator solution is a drawback to on-site applications as it results in vigorous reactions between the precursor (binders) and activator ions, producing rapid reaction products and thus resulting in a significantly short setting time.

To overcome the inherent weakness of a high FA blend, several trials were made with varying GGBFS contents and activator concentrations to develop a high-density GPC mix design that satisfied the requirements of workability, setting time, density and strength gain under ambient curing when produced in the field. Most importantly, the GGBFS content was determined to be sufficient to meet strength gain needs yet proportioned to allow for sufficient free lime diffusion from the aggregate into the Geopolymer matrix. The final laboratory mix design is given in Table 1; the 28 day cylinder strength was 37 MPa, the saturated surface dry (SSD) bulk density was 2500 kg/m^3.and the workable time was 90 minutes.

Wagners (from Toowoomba, Queensland) was engaged to refine the laboratory mix to field delivery at scale; some minor adjustments were made to adapt the mix design to their commercial methods, including use of Wagners' activator. A small quantity of Sydney sand was also added to the mix to improve the grading, density and workability; the field mix for pours 2 and 3 is given in Table 1. The field-design mix was batched using Cleary Brothers commercial plant, located at Port Kembla approximately 5 km from the site, using conventional concrete batching facilities.

With the field mix, 13 high-density low carbon Geopolymer concrete 17.4-tonne Hanbar units were cast and placed on the North breakwater at NSW Ports' Port Kembla Harbour. Concrete samples were cast on site and brought back to laboratory to monitor the strength gain, durability characteristics, and study the microstructure to ensure the elimination of the risk of delayed expansion of the SFS aggregates.

The binders used in this study consist of low calcium fly ash (FA) obtained from Vale Point Power Station in NSW, Australia, and GGBFS and SFS both sourced from Australian Steel Mill Services, Port Kembla, NSW, Australia. The low calcium FA used belongs to Class F fly ash by composition according to ASTM C618[13]. The blended Geopolymer binder consisted of 65% low calcium FA combined with 35% GGBFS.

Material	Lab: unit content (kg/m^3)	Field: unit content (kg/m^3)
Coarse aggregate (SFS510)	1314	1098
Fine aggregate (SFS500)	656	510
Fine aggregate (Sand)	–	273
Fly ash	276	276
GGBFS	149	149
NaOH solid	8.23	–
Na_2SiO_3 solution	115.5	–
Other alkali metal solution	–	57.64
Admixture	–	6.375 litres

TABLE 1. Mix design.

The SFS aggregates used in this study are basic oxygen furnace slag obtained from BlueScope Steel located at Port Kembla in NSW, Australia. The aggregates were crushed and processed by the manufacturer through four wet and dry cycles over a month in order to reduce the free lime associated with the aggregates. Physical properties of all aggregates used are shown in Table 2. The table shows that SFS coarse aggregate density is about 17.5% higher than that of conventional basalt aggregates having a density of ~2.80 t/m^3 and SFS fine aggregate density is 15.5% higher than that of Sydney sand having a density of ~2.65 t/m^3. Moreover, SFS coarse aggregate abrasion resistance indicates a higher toughness and abrasion resistance. However, the water absorption of SFS fine aggregates is very high due to its porous texture; the volume of the fine SFS aggregate was adjusted in the field mix with partial replacement by Sydney sand to control better the water content and improve overall grading.

Aggregate type	SSD density (t/m^3)	Oven dry density (t/m^3)	Water absorption (%)	Loss in Los Angeles abrasion test (%)
SFS coarse	3.19	3.02	3.84	15.8
SFS fine	3.31	2.98	11.23	-

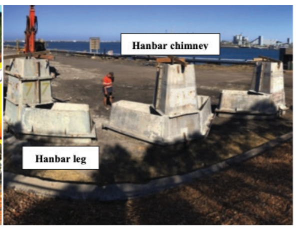
***TABLE 2.* Properties of aggregates**

4.0 FIELD TRIALS

4.1 GENERAL

This section describes the upscaling of the laboratory mix design to the field and the construction of the Hanbar armour units. The concrete batching, delivery to site, casting and placement are shown in Figure 2(a)-(f). The thirteen units were cast in three pours; in pour 1 two units were cast (approximately 14 m^3 of high-density GPC), in pour 2 five units were cast (35 m^3) and in pour 3 a further six units were cast (42 m^3). The field mix design was adjusted slightly for pours 2 and 3 based on the experience gained from the prior pours (with small adjustments to Sydney Sand/SFS fine aggregate ratio and water).

(a) Batching at Cleary Brothers plant, Port Kembla



(b) Hanbar unit formwork

(c) Concrete pouring and compaction

(d) After removal of formwork

(e) Placement of Hanbar units on breakwater

(f) Aerial view after placement

***FIGURE 2:* High-density GPC batching and Hanbar armour unit construction.**

4.2 BATCHING, CASTING AND STRIPPING

The concrete components were dry batched (Figure 2(a)) at the Cleary Brother plant in Port Kembla and mixed for 5~10 minutes in the truck agitator drum. Next the activator and water were added and the wet mix agitated in the truck at the plant for a further 10 minutes (approximately) before being dispatched to the site.

The steel formwork for the Hanbars was prepared (cleaned and greased) on the site in the days prior to casting. Reinforcement were provided into the formwork specifically for lifting, transporting and placing the Hanbars onto the breakwater once it had gained sufficient strength (Figure 3).

Once mixed for about 15~20 minutes, the trucks discharged the concrete into the formwork and the fresh concrete was vibrated for consolidation. For each Hanbar unit, the casting was done in two steps. The legs of the formwork (Figure 2b) were filled first, left for about an hour for partial setting and then freshly mixed high-density GPC was poured into the Hanbar chimney (the top leg of the three-legged armour unit) and vibrated. The concrete pouring was done in two steps to prevent fresh concrete overflow through the open surfaces of the formwork legs. Several trucks were used for continuous supply of the Geopolymer concrete.

The formwork was removed between 12 and 48 hours after casting of the Hanbar units. The units were then kept at the casting yard until the concrete had gained sufficient strength before transporting and placement on the breakwater. In pour two the forms were released after just 12 hours of setting after a cold night – the concrete was found to have not set sufficiently and some minor damage was observed due to the stripping process. Further research is needed to improve the strength gain at lower air temperatures.

(a) vertical bars with hooks at bottom and an exposed lifting eye at top (not shown in image).

(b) Timber hangers & tie wire used to position reinforcement.

***FIGURE 3:* Reinforcements for lifting Hanbar units.**

4.3 CONTROL SPECIMEN PREPARATION, CURING AND TESTING

For each pour 100 mm by 200 mm concrete cylinder specimens were cast on site according to AS 1012.8.1[14] and transported to the testing laboratory. The specimens were sealed and stored in a temperature and humidity controlled environmental room at a temperature of 23±2 ^{0}C and relative humidity of 50% until the day of testing. The specimens were tested for compressive strength, splitting tensile strength and elastic modulus in accordance with AS 1012.9[15], ASTM C496[16] and AS 1012.17[17], respectively. The compressive strength and elastic modulus presented in this paper are an average of three tests. The specimens were further tested for bulk density in accordance with ASTM C642[18].

4.4 MICROSTRUCTURAL ANALYSIS CRACKING

Scanning electron microscopy (SEM) and energy dispersive X-ray spectrometer (EDS) techniques were used to analyse the elemental intensities (Ca and Si) around the aggregate-matrix interface. Prior to scanning, samples were mounted in epoxy, polished, and coated with carbon. A scanning electron microscope, Hitachi S3400, with an electron energy dispersive spectrometer was used for elemental analysis. The analysis was carried out at 20 kV beam strength with a 10 mm working distance.

5.0 RESULTS AND DISCUSSIONS

5.1 DENSITY

The SSD bulk densities of the field manufactured Geopolymer concrete achieved for each pour were 2570 kg/m^3, 2590 kg/m^3, and 2630 kg/m^3 for pours 1, 2 and 3, respectively. The water content was reduced slightly for pour 3 providing the higher density but the workability of the concrete was reduced (see comments in Section 5.4).

5.2 STRENGTH

The compressive strength gains of the high-density GPC are shown in Figure 4. After 28 days of ambient curing (23 ^{0}C temperature and 50% relative humidity), the concrete strength was 35.3 MPa, 46.8 MPa and 47.8 MPa for pours 1 2 and 3, respectively, and at 90 days the strengths were 44.9 MPa, 56.8 MPa and 58.3 MPa, respectively, giving a 21 – 27 per cent gain in strength compared to the 28 day results. This gain in strength is attributed to the complex hydrolysis of the siliceous and aluminium species of the fly ash and further geopolymerisation with the activator ions and formation of products over time (Oh et al.[19]). Moreover, the contribution of GGBFS in supplying Ca ions has resulted in the early age strength development of the concrete (Ismail et al.[20]).

Figure 5 illustrates the splitting tensile strength and the elastic modulus of the high-density GPC. There is a noticeable gain in both tensile strength and the elastic modulus over time; the increase in tensile strength and elastic modulus are consistent with the increase in compressive strength.

5.3 MICROSTRUCTURAL ANALYSIS

Several Energy Dispersive x-ray Spectroscopy (EDS) point scans were carried out to identify, and measure, the proportions of various elements of interest (Ca and Si) in concrete specimens around the interfacial transition zone (ITZ) in the vicinity of the SFS aggregates and into the Geopolymer matrix. Figure 6 illustrates 40 EDS points scanned around the ITZ of SFS aggregate and in the Geopolymer matrix in order to calculate the Ca/Si mass ratios. Analysis of the results reveals that the Ca/Si ratio around the SFS aggregate is 0.88 compared to 0.39 in the matrix. The higher Ca/Si around the ITZ indicates possible diffusion of the free lime from the SFS aggregate and subsequent accumulation around the ITZ, which is analogous to the findings of (Khan et al.[6]). This indicates that the free lime is absorbed in the matrix and, thus, the delayed aggregate expansion due to free lime hydration will likely be avoided. The armour units were placed in August 2018 and will be monitored over the next years for any evidence of expansion, for property changes due to environmental conditions and for damage due to storm events.

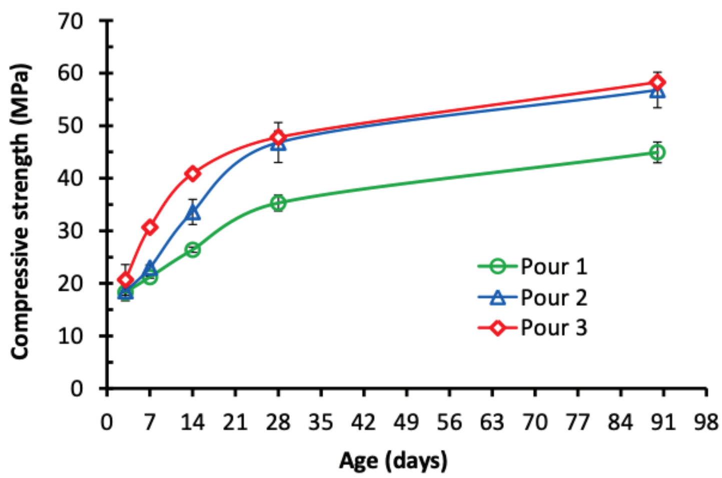
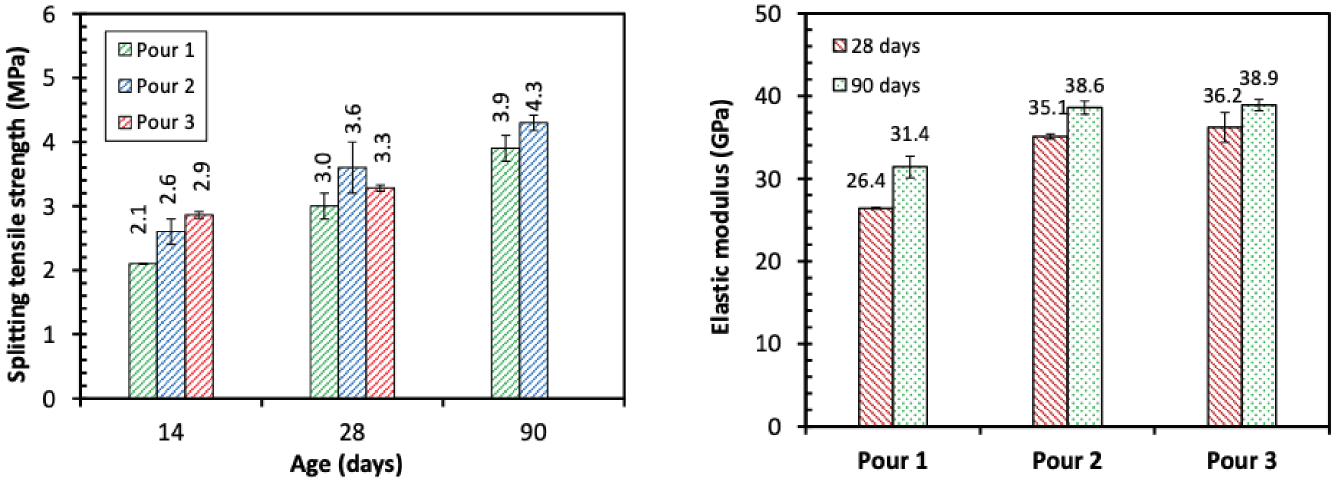
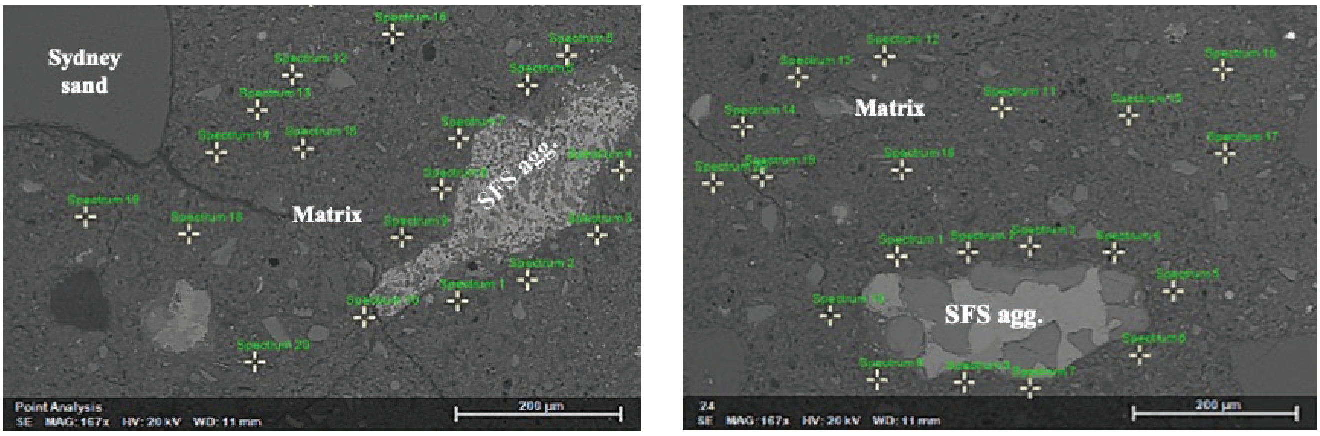


FIGURE 4: Compressive strength gain of high-density GPC



(a) (b)

FIGURE 5. (a) Splitting tensile strength and (b) modulus of elasticity of high-density GPC.



Ca/Si ratio around ITZ = 0.88 ± 0.33

Ca/Si ratio in matrix = 0.38 ± 0.13

Ca/Si ratio around ITZ = 0.81 ± 0.26

Ca/Si ratio in matrix = 0.40 ± 0.20

FIGURE 6. EDS Point scans around ITZ of SFS aggregate and in the Geopolymer matrix..

5.4 OTHER OBSERVATIONS

Geopolymer concrete workability is somewhat different to that of OPC concrete; where there is a delay between deliveries on a given pour, the mix appears to harden; as soon as vibration is applied, the Geopolymer liquefies and becomes highly fluid, and workable, once more – liquefaction is not observed in OPC concrete hardening. Training of the workforce on the nuances of Geopolymer concrete, and differences with conventional concrete in placement and compaction is needed. Pour 3, which had slightly less water in the mix, challenged the on-site crew and evidence of poor compaction was seen in some units. Further work on the development of superplasticisers is needed for ease of placement, compaction and workability for Geopolymer concrete and the industry would benefit greatly from such research.

6.0 CONCLUSIONS

In this project, researchers and industry partners worked together in the development and trial of a unique, sustainable high-density geopolymer concrete mix for coastal structures. The system developed in the laboratories of UNSW was upscaled and is being tested at the northern breakwater of NSW Ports' Port Kembla Harbour. The concrete uses steel furnace slag (SFS) aggregate in a blended fly ash-blast furnace slag binder to eliminate delayed hydration and expansion of the aggregate.

The results of the laboratory tests conducted on high-density concrete and subsequent microstructural analyses confirm that SFS aggregate Geopolymer concrete can be a promising material in manufacturing high-density armour units for breakwaters. This project uses industrial by-products for the upgrading breakwaters for climate change adaptation due to increased load demand due to an increase in the predicted storm surge and, hence, wave heights and energy. The density of the concrete is found to be acceptably higher than conventional concrete, and has the potential to significantly reduce armour unit size without compromising the structural stability of breakwaters, with a size reduction as much as 40 to 50% possible.

Thirteen high density low-carbon Geopolymer concrete 17.4-tonne Hanbar units were cast and placed on the Northern breakwater at NSW Ports' Port Kembla Harbour; these units will be monitored for stability and integrity and will provide a valuable benchmark for future use of Geopolymer concrete. This could allow for the upgrade of existing breakwaters with reduced cement requirements, placement cost, and overall footprint, to provide increased stability while retaining good interlocking with existing armours.

Most importantly, a great compatibility between SFS aggregate and the Geopolymer binder was observed due to their chemical interactions. Diffusion of free lime associated with SFS aggregate into the binder minimises the risk of delayed expansion. The increased hardened concrete strength can be attributed to the stronger ITZ due to diffusion of the Ca contributing to an improvement of the interface. Besides breakwater armour units, this unique concrete can also be used in gravity structures that would benefit from high-density.

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