Performance Evaluation of Recycled Aggregate Geopolymer Concrete for Low-Carbon Breakwater Systems

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Abstract

Achieving circularity in the construction through the use of geopolymer concrete requires sustainable alternatives to natural virgin aggregates specially in the case of mass concrete application. However, the application of recycled aggregate (RA) in manufacturing concrete breakwaters for aggressive marine environments remains largely unexplored. A significant gap exists in comprehensive data regarding their long-term durability, leaching behavior, and mechanical performance under real-world coastal conditions. This study investigates the leaching behaviour and durability performance of a fly ash–GGBS-based geopolymer incorporating 100% RA and compared against conventional cement and natural virgin aggregate based concrete, targeting sustainable applications in coastal breakwater structures. Key parameters evaluated include compressive strength, porosity, chloride ion migration, electrical resistivity, and the leachability of metal ions under both freshwater and seawater exposure.

Results demonstrate that the cement-free RA-based geopolymer mix not only achieves comparable or superior durability, with up to 82% improved chloride migration resistance, but also maintains low metal ion leaching well below regulatory limits in saline conditions compared to conventional OPC-based concrete. Despite a reduction in strength relative to the natural aggregate (NA)-based geopolymer, the RA-based mix achieved a 28-day compressive strength of 38.9 MPa, exceeding the 35.6 MPa of conventional OPC concrete, and exhibited significantly greater strength gain over time.

The leaching behaviour of geopolymer concrete under simulated marine conditions was also revealed. Reduced porosity and enhanced microstructure further contributed to its durability highlighted the material's viability as a durable, low-carbon alternative for marine infrastructure, supporting circular economy practices and advancing the decarbonization of coastal construction.

Keywords: Geopolymer concrete; recycled aggregates; leaching; durability; breakwaters; construction and demolition waste; circular economy; low-carbon concrete

Highlights

- Recycled aggregates reduce strength but maintain performance in geopolymers
- Chloride resistance in geopolymers depends on chemistry, not porosity
- Geo-RA shows greater result variability due to inconsistencies in recycled aggregate
- Leaching of Ca and Mg is lower in geopolymer than in control concrete
- Geopolymers can stabilize recycled materials for sustainable non-structural applications

1. Introduction

Concrete has been leading, and is expected to lead in the years to come, the construction and infrastructure materials demand. The global population is projected to exceed 9 billion by 2050, with around 70% of the global population expected to live in urban areas. (WRAP, 2015, Hoornweg and Bhada-Tata, 2012). However, rapid urbanization based on the utilization of traditional concrete, based on Portland cement and naturally mined aggregates, will have negative environmental consequences such as i) the depletion of natural resources such as aggregates and water, ii) a high share of global emissions, iii) significant waste generation and iii) far-reaching economic and social impacts (Beiser, 2018). As a consequence, the construction industry (the major consumer of both metallic and non-metallic materials and responsible for 40% of global carbon emissions), seeks more sustainable practices (MPA The Concrete Centre, 2017).

7.3 million tonnes of CO2 were emitted in 2018 by the UK cement industry (MPA UK Concrete, 2020). The high levels of CO_2 rely on Ordinary Portland Cement (OPC), accounting for up to 90% of the greenhouse gas emissions (GHG) associated with the production of concrete. In response to the environmental impact of the high exploitation of natural resources and the emissions resulting from OPC production, researchers are exploring alternatives such as i) the utilization of alkali-activated materials, such as geopolymers, to replace OPC in concrete production, and ii) the use of alternative aggregates such as recycled aggregates.

Geopolymer is a cement-free binder developed in pursuit of sustainable and eco-friendly construction materials. It is an inorganic aluminosilicate polymer with a unique network of amorphous structures (Garcia-Lodeiro et al., 2015). By utilizing alternate binders such as bio-ashes, natural pozzolans, silica fume, ground-granulated blast furnace sludge (GGBS), and fly ash (FA) in geopolymer production, the environmental impact is significantly reduced due to the elimination or minimization of clinker-based cement (Pacheco-Torgal et al., 2015), offering both environmental and economic benefits. A recent study by (Patil et al., 2023) have quantified this benefit: geopolymer binders composed of FA, GGBS, sodium hydroxide, and sodium silicate generate a lower emission value of 256.2 kg CO_2-e/m^3, whereas OPC-based concrete emits 311.6 kg CO_2-e/m^3 although its dependency on curing temperature is reported (Sadique, 2025). Life cycle assessments (LCA) confirm that using recycled aggregates in geopolymer mixtures further amplifies sustainability, reducing embodied energy and construction waste simultaneously (Ali et al., 2024). Geopolymers have been found to be able to immobilize waste and toxic materials such as copper, cadmium or chromium and encapsulate radioactive waste (Gasca-Tirado et al., 2017, Zhang et al., 2008, Fernández Pereira et al., 2009).

In addition to their environmental advantages, geopolymers demonstrate superior mechanical and durability properties. They offer rapid compressive strength, fire resistance, acid resistance, and dimensional stability (Pacheco-Torgal, 2015). However, they have some barriers in terms of material handling (Kadhim et al., 2021). As industrial by-products rich in aluminosilicates and calcium, FA and GGBS not only reduce reliance on OPC but also improve the mechanical performance and durability of geopolymer concrete (Provis, 2014). Compared to other alternatives such as metakaolin or agricultural ashes, FA and GGBS offer greater consistency in composition, lower energy input, better workability, widespread availability, low cost, and high reactivity in geopolymerisation (Duxson et al., 2007, Sadique, 2025).

As a direct consequence of urban population growth and improved living standards, the consumption of non-metallic minerals for construction is predicted to double by 2060, reaching 86 Gt, (OECD, 2019) of which 70% are used as construction aggregates, such as sand, gravel, and crushed stone. Considering that the typical mass proportion of aggregates (gravel and sand) accounts for 70-85% of total mass of concrete (Engineers, 2022), the forecast demand of this material will put more pressure on the environment. The extraction of sand and gravel causes severe habitat degradation in rivers and the seabed, leading to a range of negative consequences for both the environment and human life, including infrastructure failures, disruptions in cultivable land and drinking water, diseases, and human rights abuses in illegal markets (Beiser, 2018, WWF, 2018, UNEP, 2016).

Amid growing environmental concerns and the projected rise in concrete demand, the incorporation of more sustainable materials, particularly recycled aggregates (RA), is increasingly vital, especially for mass concrete applications such as breakwaters. In 2021, in the UK 200 million aggregates were used of which 63 million were sourced from recycled materials of which 56.5 were recycled construction, demolition and excavation waste (CD&EW) (MPA The Concrete Centre, 2023). Recycling construction and demolition waste materials into aggregates diverts waste from landfills, reduces the environmental burden of waste disposal, promotes the conservation of natural resources, and reduces energy and water consumption (Coelho and Brito, 2013, Debieb et al., 2010, Silva et al., 2017, Bond and Harris, 2005). Additionally, using locally sourced RA can reduce transportation costs and associated emissions, as they are often sourced closer to construction sites.

The possibility of using RA in concrete represents one important trend toward the circular economy and decarbonizing construction industries (WRAP, 2013). One major issue is the inherent variability in RAs due to differences in source materials, previous exposure conditions, and contamination levels (with impurities like wood, plastics, mortar, or other inert and non-inert materials). This heterogeneity can affect the consistency, workability, and long-term performance of the resulting geopolymer concrete especially those requiring high strength and durability (Mathur et al., 2023). However, the quality of a RA is generally lower if referred to that of a natural aggregate (NA), and considering this, the application of RCA in the non-structural application in mass will be a prompt technology to adopt. According to the EUROSTAT dataset (European Commission, 2018), UK C&D waste production for 2018 was in the region of $70x10^6$ tonnes. The end quality of the RCA is, nevertheless, dependent on the properties of the original materials, their state of decay, and the process adopted to clean them. In addition, RA may contain contaminants that might be leached if the concrete containing RA is exposed to water. In this context, geopolymers entail a potential sustainable option to counteract the leaching of contaminants from the RA.

The utilization of RA has primarily been confined to non-structural purposes such as sidewalks and road bases (McGinnis et al., 2017, Silva et al., 2017). The utilization of RA has primarily been confined to non-structural purposes such as sidewalks and road bases (McGinnis et al., 2017, Silva et al., 2017) in addition to specified level of utilisation in structural concrete is allowable in the British Standards and Design Manual for Roads and Bridges (Sadique, 2025). The principal impediments to their wider adoption include the variability in their properties, which leads to a lack of confidence, limited experience, insufficient case studies on the service and ultimate load performance of concrete structures, and the scarcity of engineering guidelines and standards for designing and constructing reinforced concrete using RA.

The Low Carbon Concrete Group proposes low-risk applications when implementing emerging technologies to be used as case studies to learn from and inform the use in further applications (Low Carbon Concrete Group, 2022). Although breakwaters are not temporary works, the use of this type of infrastructure as a testing bed seems appropriate since i) its failure does not pose a risk to life, and ii) it represents different relevant and aggressive exposures. Therefore, breakwaters entail an opportunity to de-risk the adoption of geopolymer concrete containing RA while serving the purpose of a testing bed.

The construction of breakwaters, especially in the context of the United Kingdom (UK), remains a necessary and vital component of coastal and marine infrastructure for resilient development. While there is an increasing necessity for breakwater construction for coastal protection, it is important to emphasize that the design and implementation of these structures should consider environmental impact, habitat protection, and sustainable practices. Therefore, the use of novel low-carbon formulations containing waste or unexplored materials should investigate the impact that the leaching of these materials on the very near ecosystems and biodiversity may have.

Portland cement has encapsulated and immobilized heavy metals like zinc (Zn), lead (Pb), cadmium (Cd), and chromium (Cr) into less soluble durable matrix by solidification (Hunce et al., 2012, Liu et al., 2022). The use of geopolymerization to solidify high-concentration waste, including landfill leachate has drawn a lot of attention in recent years. When compared to Portland cement, research shows that geopolymers provide superior performance in terms of reduced permeability, a greater pH buffering capacity, and reduced leachability (Sithole et al., 2025). (Zhang et al., 2022) have reported that using GGBS-based geopolymer for solidifying landfill leachate achieved ~99% of heavy metal stabilization with higher solidification efficiency. The European Commission has commissioned the European Committee for Standardization (CEN) to develop standardized assessment methods for hazardous substances released from building products. In addition to meeting mechanical property requirements, assessing the leaching safety of solidification/stabilization materials under various environmental conditions is crucial. This is particularly important for evaluating the leaching behavior of GGBS/FA-based materials or the immobilization of non-ferrous metal tailings containing high concentrations of Pb and Zn.

Breakwaters are fundamental engineered components for the protection of shorelines and rivers from erosion or flooding. They are often made using conventional concrete containing energy-intensive cement and natural aggregate. This research aims to demonstrate the suitability in terms of durability and resistance to leaching of a sustainable breakwater through full replacement of NA and conventional cement using recycled concrete aggregate (RCA) and cement-free geopolymer additionally activated with alkaline calcium carbide residue (CCR) an industrial waste going to landfill sites in the UK and around the world.

Despite their importance, limited research exists on the combined use of geopolymer and 100% RA in marine infrastructure. Furthermore, there is a lack of comprehensive data on their long-term durability, leaching behaviour, and mechanical performance under real-world coastal conditions. Existing guidelines for RA use in structural applications are sparse, and the variability in RA properties undermines confidence among practitioners (Silva et al., 2016). While CCR enhances early strength development, its high alkalinity and potential sulphate content may pose durability and environmental risks (Bawab et al., 2025). The leaching behaviour and long-term lifecycle safety of CCR-activated geopolymer mixes warrant further investigation. This study addresses this gap by evaluating a novel low-carbon concrete formulated with 100% RA and a geopolymer binder enhanced with CCR, an industrial by-product with potential as a sustainable alkali activator. The goal is to demonstrate the technical feasibility, environmental safety, and long-term durability of this mix for use in breakwater construction - an application that provides both functional value and a platform for innovation in sustainable concrete.

The integration of long-term exposure testing with durability relating potential leachability of metal ions from 100% RA based geopolymer concrete under both normal and marine water exposure has not yet been systematically addressed, leaving a critical gap in validating the performance of geopolymer concrete made with recycled aggregates for breakwater construction. The feasibility of employing 100% recycled aggregates in conventional geopolymer as a sustainable alternative to cement and virgin aggregates for mass concrete applications such as breakwaters remains largely unexplored, despite their potential to advance circularity in coastal protection.

The primary objective of this study is to develop a technologically viable and environmentally sustainable alternative to conventional concrete by incorporating 100% recycled aggregate into a geopolymer matrix, further enhanced with CCR, a low-value industrial by-product generated in significant volumes by the bulk chemical and metallurgical sectors. This approach seeks to advance circular economy principles and promote industrial symbiosis by repurposing RA and CCR waste for the production of low-carbon breakwater units, while simultaneously assessing metal ion leachate and evaluating durability under saline conditions. The proposed solution not only addresses waste valorization but also contributes to the decarbonization of global coastal protection systems.

2. Materials and Methods

The subsequent section details the laboratory-based experimental procedures designed to simulate marine conditions, which were employed to (i) characterize the proposed binder system, (ii) details of the proposed aggregates and activators, (iii) proposed geopolymer concrete mix design, and (iii) assess durability through parameters such as density, surface porosity, electrical resistivity, resistance to chloride migration, and, leachability of metal ions. To ensure data quality, error bars have been incorporated into the results where appropriate. Additionally, all ICP-OES measurements were validated through calibration curves with R^2 values ≥0.996 for most analytes and limits of detection (LoD), ensuring high analytical accuracy and confidence in the reported leachate concentrations

Binder: An equal proportion of FA and GGBS was used as silica and alumina-containing solid precursor sources was activated with 15% CCR in this study. For the control mix, CEM II 32.5N as per BS EN 197-1:2011 (British Standard Institution, 2011) was used. The elemental composition of binders and the additional activator is shown in Table 1, and the particle size distributions (PSD) are presented in Figure 1.

Table 1: Elemental composition (%) of binders

	Al	**Si**	**P**	**S**	**Cl**	**K**	**Ca**	**Ti**	**V**	**Cr**	**Mn**	**Fe**	**Ni**	**Cu**	**Zn**	**As**	**Pb**
PFA	15.54	38.86	0.64	1.52	0.04	5.56	9.03	2.16	0.12	0.05	0.17	24.59	0.08	0.07	0.20	0.04	0.07
GGBS	6.26	15.67	-	1.80	0.00	0.91	71.70	1.39	0.05	-	0.54	0.87	-	-	-	-	-
CCR		1.59			0.28		96.4	765ppm		28ppm	81ppm						
CEM II	2.2	26.7	0.9	-	-	0.6	64.1	1.3	-	-	0.2	2.4	-	-	-	-	-

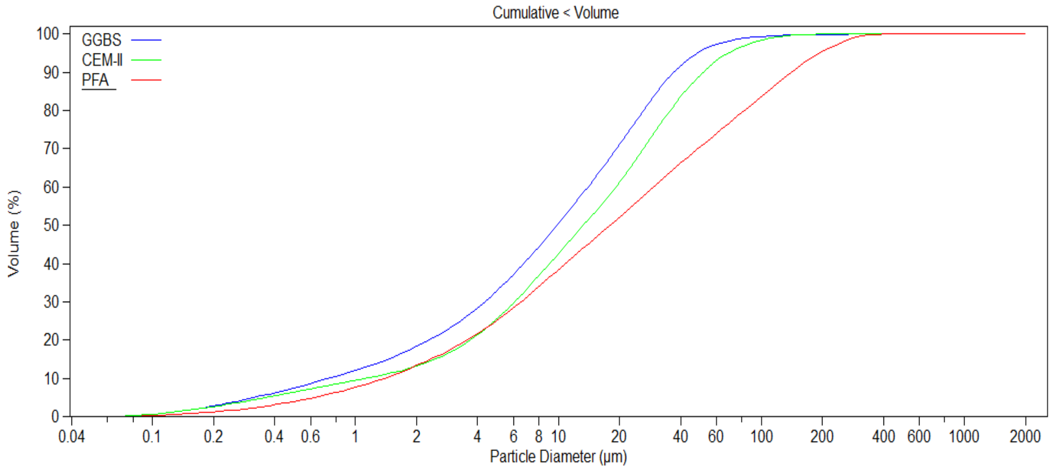

Figure 1 Particle Size Distribution (cumulative volume) of binders.

Natural aggregate, NA: 10mm and 20mm aggregates that accord with the British Standard BS EN 12620:2002+A1:2008 (British Standard Institution, 2008) have been used. The quantity of 10 mm and 20 mm was adjusted to get a similar particle size distribution to that of recycled aggregates. Fine natural dried sand with a size under 600mµ was used and natural fine aggregate (FA).

Recycled aggregates, RA: Recycled coarse aggregate and fine aggregate were supplied by a local waste management organization that processes construction and demolition waste (C&DW) which was a combination of different materials (ceramic, plastic, metal, clay, glass, concrete or stones), densities, shape, roughness and porosities (as shown in Figure 2). The PSD was determined by dry sieving according to the BS EN 933-1 (British Standards Institutions, 2012). Three individual determinations were conducted on separate test oven-dried portions (105±2°C until mass stabilization) of RA. The range of sieves employed covered up to 34 mm. The results show that 90% of the total mass has a size lower than 20 mm. The amount of 10 mm aggregates was such to adjust the PSD to that of RA 13(c).

Figure 2: Presence of different types of materials in recycled coarse aggregates (scale in mm)

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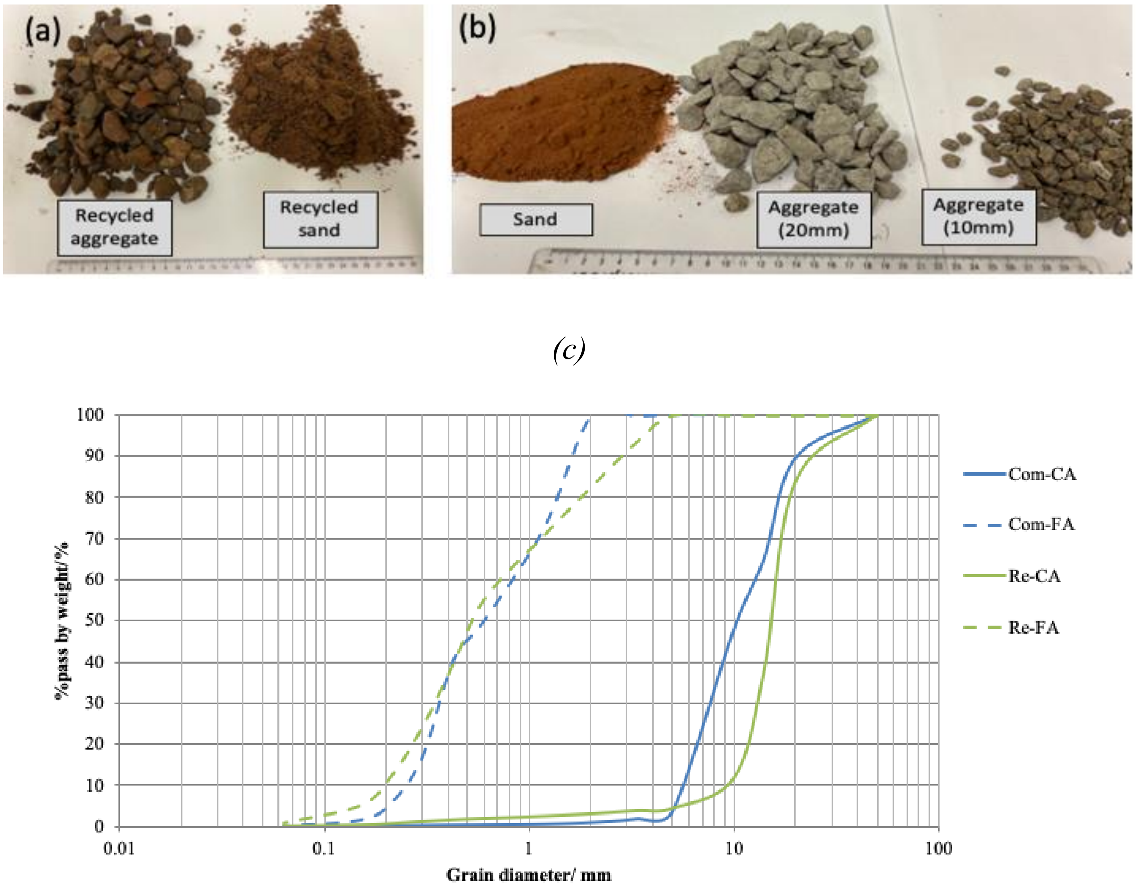


Figure 3: Images of (a) RA (b) NA. Scale in mm, (c) Particle size distribution of RA and NA

The activators used represent the alkaline source that increases the pH of the chemical reaction and eases the dissolution (Provis, 2014). For this research, the liquid activators 4M Sodium hydroxide, NaOH, (NH) and Sodium silicate, Na_2SiO_3 (NS), were used in a proportion 1:2.5.

To assess the performance of geopolymers containing RA, geopolymer concrete using NA and RA was cast in addition to a control mix (CON-NA) where 100% cement with only NA was used. The details of the mix proportions are shown in Table 1. The binder-to-aggregate ratio was 1:3.

Table 2 Concrete constituents and mix proportions

	CEM	GGBS	PFA	CCR	Aggregate 20 mm+ 10mm	Sand	Water	NH	NS
				kg/m^3					
CON-NA	450	-	-	-	1350[1]	585[1]	158	-	-
Geo-NA	-	191	191	67.5	1350[1]	585[1]	158	68	170
Geo-RA	-	191	191	67.5	1350[2]	585[2]	158	68	170

[1] Natural aggregates

[2] Recycled aggregates

After casting, the concrete samples were kept under laboratory conditions for 24 h before being demolded. CON-NA samples were wet cured in water tanks until the testing date and geopolymer samples were wrapped in polyethylene film for 7 days and then unwrapped and left under laboratory conditions. This was to reduce the amount of superficial cracking on the surface of the material.

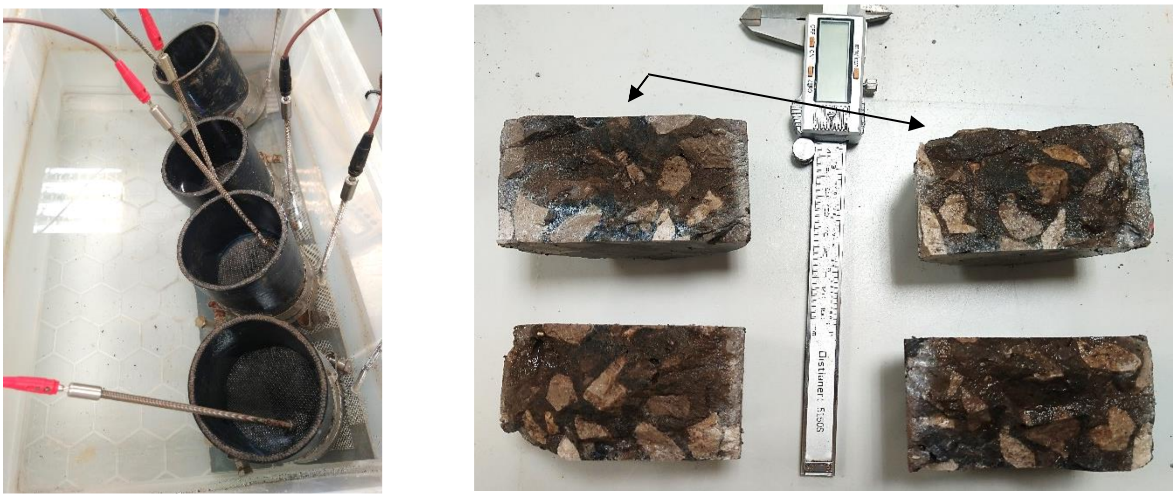
Experimental campaign for assessing concrete durability: The durability of concrete is influenced by both the environmental exposure conditions and the intrinsic properties of the material. Among these intrinsic factors, the microstructure plays a critical role, particularly the size, distribution, shape, and interconnectivity of pores. Reduced pore interconnectivity generally leads to lower permeability, thereby limiting the ingress of aggressive external ions and enhancing durability. These microstructural characteristics can be assessed using various techniques. In this study, open porosity, surface electrical resistivity, and chloride migration tests were employed to evaluate the durability performance. However, in geopolymer systems, these properties may not exhibit the same well-established correlations observed in conventional Portland cement-based concrete, due to differences in binder chemistry and pore structure. To investigate this, geopolymer compositions incorporating 0%, 10%, 20%, and 30% ash content were prepared. Each mix was cast into nine cubes (150 × 150 × 150 mm) and nine cylinders (100 mm diameter × 200 mm height). Prior to conducting leaching tests, the hardened properties of the specimens were evaluated, as detailed in Table 3.

Table 3: Concrete durability tests summary table

Characteristic		Tests	Age (days)
Concrete performance	Density of hardened concrete	BS EN 12390-7 (British Standard Institution, 2019)	7, 14, 28
	Compressive strength	BS EN 12390-3:2019 (Bristish Standards Institution, 2019b)	7, 14, 28
	Total open porosity	BS EN 1936: 2006 (British Standard Institution, 2006)	7, 14, 28
	Chloride migration of concrete	NT Build 492 (NORDEST, 1999)	7, 14, 28
	Surface electrical resistivity	Wenner four-probe system	7, 14, 28
Leaching	Leachability of metal ions to water/ sea water	BS 6920	1, 2, 3

Compressive strength was tested as per BS EN 12390-3:2019 (British Standard Institution, 2000) by using a Control Automax 5 compression tester with a load rate set of 0.4 MPa/s. Although BS EN 12390-3:2019 was originally developed for testing conventional Portland cement-based concrete, it is employed in this study to facilitate direct comparison between geopolymer and OPC concrete systems.

A set of samples were oven-dried at 40°C until mass stabilization before being subjected to rapid chloride migration and porosity tests. The chloride migration coefficient of concrete was evaluated following the guidelines of NT Build 492 (NORDEST, 1999), employing a non-steady state migration test conducted at 7, 14, and 28 days. A cylindrical specimen of 50 mm in height was subjected to an external potential, prompting chloride ions in the catholyte solution to migrate into the specimen. The vacuumed specimens impregnated in $Ca(OH)_2$ were enclosed in a rubber sleeve filled with an anolyte solution (0.3 M NaOH) containing the anode (refer to Figure 4 (a)). This setup was immersed in a reservoir holding a catholyte solution (10% NaCl), with the entire system connected to a power supply (see Figure 4(a)). After 24 hours, the specimens were dissected, and the depth of chloride penetration was determined using silver nitrate (refer to Figure 4(b)).


(a)

(b)

Figure 4: Rapid chloride migration test: (a) application of potential, (b) Chloride penetration depth assessed with silver nitrate (Geo-NA samples).

The data were worked out as per eq. (1) where D_{nssm} is the non-steady-state migration coefficient ($\times 10^{-12}$ m^2/s); U is the absolute value of the applied voltage, (V); T is the average value of the initial and final temperatures in the anolyte solution, (°C); L, thickness of the specimen, (mm); x_d, average value of the penetration depths, (mm) and t, test duration, (hour).

$$D_{\mathrm{nssm}} = \frac{0.0239(273+T)L}{(U-2)t}\left(x_{\mathrm{d}} - 0.0238\sqrt{\frac{(273+T)L\,x_{\mathrm{d}}}{U-2}}\right) \quad \text{eq. (1)}$$

A Wenner four-probe system, type RESIPOD PROCEQ model with 50 mm spacing, was employed to gauge the surface electrical resistivity. This measurement served to evaluate concrete's resistance to the passage of charged ions, such as chlorides, through the material when subjected to an external current (Azarsa and Gupta, 2017). The readings were used to qualitatively assess the evolution of the concrete since increments or reductions on the electrical resistivity can indicate changes on the permeability due to a refinement of the pore microstructure due to further hydration, or a reduction of the hydroxyl ions when reactive supplementary cementitious materials are used (Bahurudeen et al., 2015, Azarsa and Gupta, 2017).

Experimental campaign for assessing concrete leachate: This analysis was mainly focused on testing the leaching of toxic elements based on the XRD analysis of binders and the recycled aggregates where traces of As, Pb, Zn, Ni, Mn, Fe, Mg, Cr, Cu and Ca were found. To compare 3 types of concrete have been tested through a series of tank tests according to BS 6920-2.6 (British Standards Institutions, 2014), for 3 consecutive days.

The tests are labelled GEO-RA, GEO-NA, and CON-NA (as shown in figure 4) and were repeated using chlorine-free fresh tap water (in accordance with standard test method) and 3% NaCl synthetic seawater (to mimic the real-world application in marine environment). The leachate ions were measured using a Inductively Coupled Plasma Optical Emission Spectroscope iCAP-PRO SERIES ASX560 (ICP-OES). ICP-OES calibration solutions have been prepared at 5 different concentrations (0.1 to 5 ppm) to improve measurement accuracy, for each element, except Ca and Mg ranging from 1 ppm to 10 ppm with 4 different concentrations, as these two ions showed higher concentrations compared to the trace elements. ICP-OES calibration curve for each ion has been repeated until coefficient of correlation of each curve was $R^2 > 0.99$. Each concrete sample of a specific surface of 14000 mm^2 has been inserted in a clear container with up to 1l of chlorine-free water and salt water, each sample has been tested in 3 different repetitions (S1, S2 and S3) for a total of 54 tests. A sample of water was collected at the end of each day, using 3 different repetitions for ion detection accuracy.

3. Results and discussion

Compressive strength

The corresponding strength class as per BS EN 12390-3:2019 (British Standard Institution, 2000) of CON-NA, Geo-NA, and Geo RA were C30/37, C40/50, and C30/37, respectively. The results show (Figure 6) that the use of RA decreases the compressive strength (CS) of concrete in comparison to Geo-NA by an average of 30% (33.1%, 29.88%, and 27.63% at 7d, 14d, and 28 days, respectively. The compressive strength trends observed in this study are consistent with established research on recycled aggregate performance. The ~30% reduction in strength recorded for the Geo-RA mix relative to Geo-NA aligns with the performance ranges reported by Silva et al. (2014), who showed that strength loss is strongly governed by the quality of the recycled aggregate. Their study found that concretes made with 100% high-quality RCA (Class A) experienced only 8–10% strength reduction, whereas those incorporating lower-quality RCA (Class B) exhibited substantially higher losses of 31–34%. The magnitude of reduction observed in the present work therefore reflects behaviour typical of mixes produced with lower-quality RA containing adhered mortar and contaminants, reinforcing that aggregate quality is a more critical determinant of strength than replacement level alone.

Geopolymer mixes experienced a greater strength gain than the CON-NA. Between 7 and 28d, the compressive strength gain of Geo-NA and Geo-RA is 50.3% and 62.6%, respectively, while for CON-NA concrete is 14.5%. This is due to the delayed polymerization of geopolymers in comparison to the hydration of OPC which, at 7 days, usually achieved 75-85% of the compressive strength at 28 days (in this specific case 85%). The trend observed here is consistent with previous work. Neupane et al. (2015) showed that ambient-cured geopolymer concretes continued to develop strength well beyond 28 days, achieving an additional 15–20% strength gain between 28 and 90 days, compared with only 3–8% for Portland cement concretes. Despite incorporating 100% recycled aggregate, the Geo-RA mix achieved compressive strengths of 24.1 MPa, 33.3 MPa, and 38.9 MPa at 7, 14, and 28 days, respectively surpassing the corresponding values of the conventional CON-NA mix (31.1 MPa → 35.6 MPa) by 7.8% at 28 days. This demonstrates that although early-age strength is reduced due to RA quality, the long-term strength development of geopolymer systems can compensate effectively, reflecting the progressive densification of the aluminosilicate gel network.

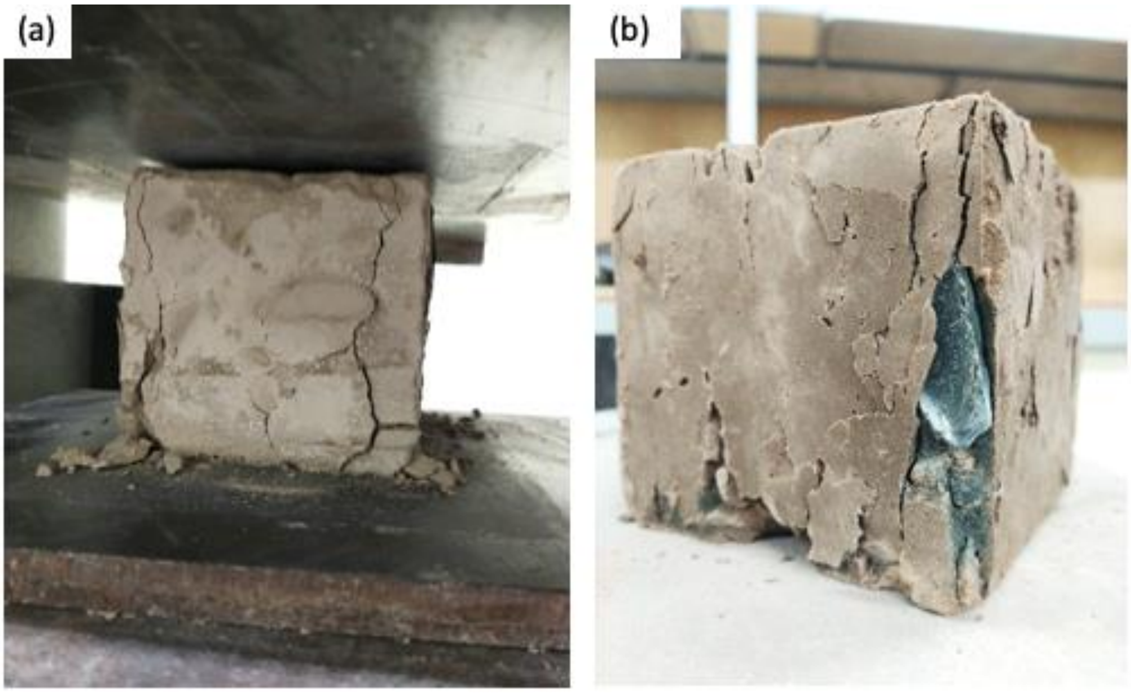


Figure 5(a) Geo-NA cube during a compressive test, (b) Geo-RA cube after a compressive test. The cube failed in the area where a piece of glass was found.

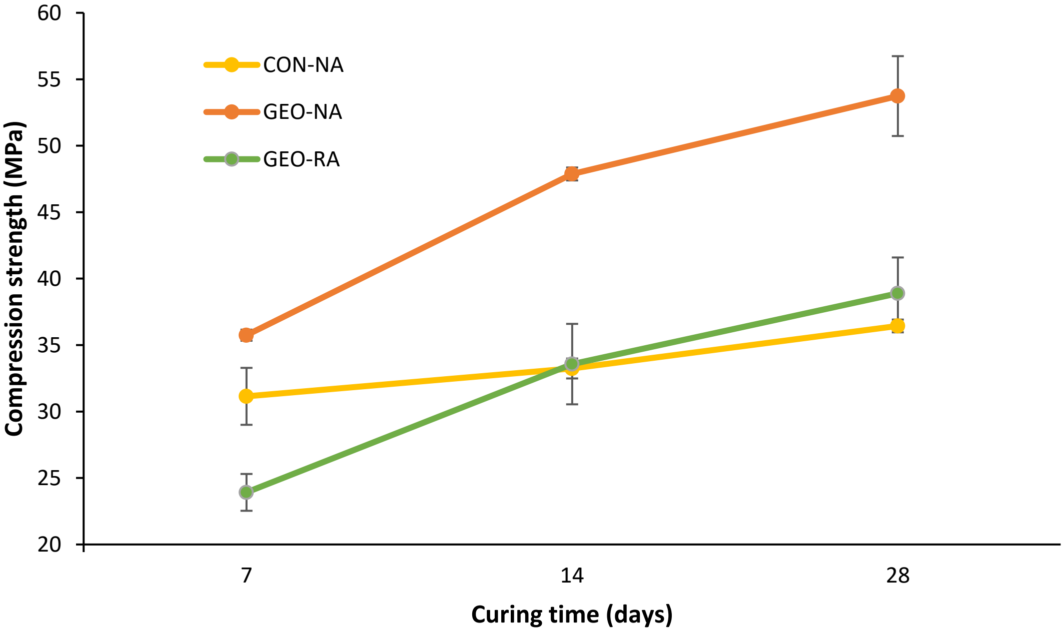


Figure 6: Compressive strength of CON-NA, Geo-NA and Geo-RA mixes

The use of RA lowers the average density of geopolymer concrete with normal aggregates (2487 kg/m^3) by 5.9% (2340 kg/m^3), **Error! Reference source not found.**7. This concords with the data provided by Sata and Chindaprasirt (Sata and Chindaprasirt, 2020) who stated that geopolymer concrete with RA is 6%-10% lighter than that with natural aggregates due to the high porosity and the low density of RA. Additionally, a slight reduction in bulk density is also observed in the Geo-NA mix compared to the CON-NA OPC mix. This reduction can be attributed to the intrinsic characteristics of geopolymer binders, which tend to produce lower-density matrices due to the absence of dense calcium silicate hydrate (C–S–H) gel typically found in OPC systems. It can be observed that, in the case of geopolymers, and more specifically for those containing recycled aggregates, the bulk density is not indicative of the compressive strength of the material.

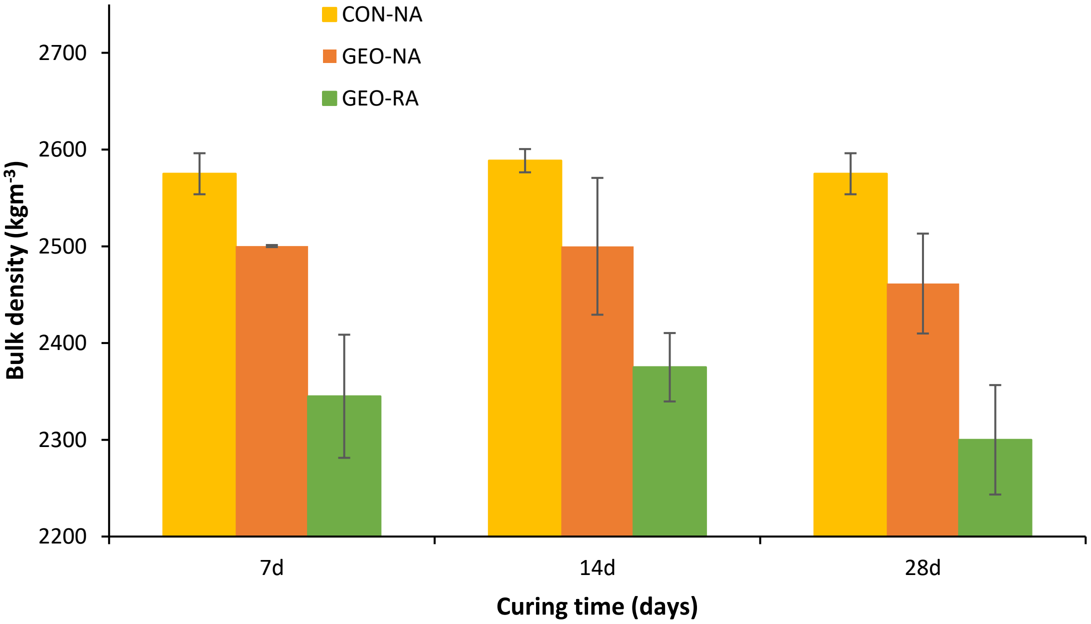


Figure 7: Hardened bulk density of CON-NA, Geo-NA and Geo-RA mixes

The splitting strength was obtained from the splitting of concrete cylinders during the RCMT. The splitting strength of geopolymer concretes are expressed as gains or losses in percentage with regard to the CON-NA samples, **Error! Reference source not found.**8. The values obtained are aligned with those from the CS. After 14 days, the Geo-RA overpassed the strength capacity of the CON-NA samples. This improvement reflects the progressive densification of the geopolymer matrix and the strengthening of the interfacial transition zone (ITZ), which continues to evolve beyond the early curing stages due to ongoing geopolymerisation reactions. These observations are consistent with previous findings, such as Chowdhury et al. (2021), who reported that geopolymer concretes exhibit 8–12% higher splitting tensile strength than OPC concretes, highlighting the inherently superior tensile performance of alkali-activated systems.

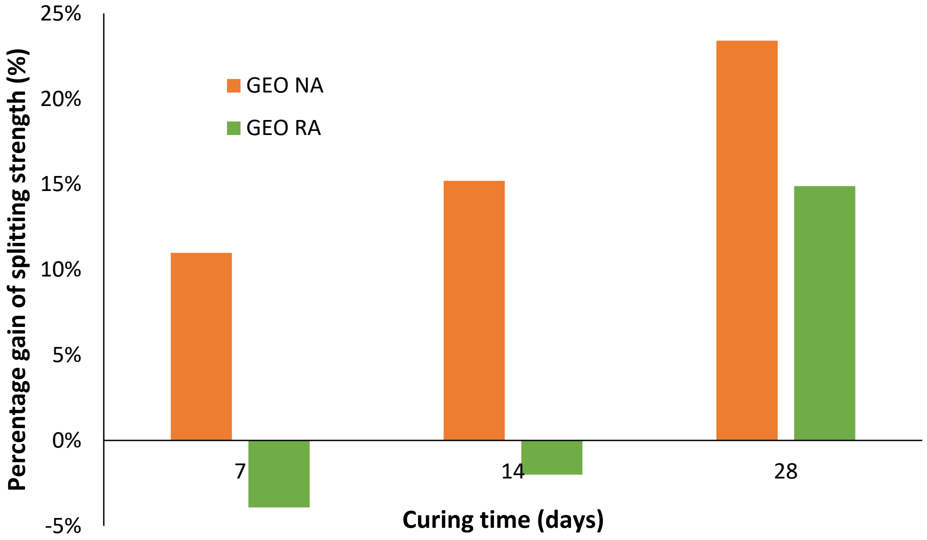


Figure 8: Gains and losses on splitting strength

Open porosity

The results obtained in this research (as shown in Figure 9-10) showed a significative variability of the results over time for the geopolymer mixes. The initial decrease in porosity was attributed to the ongoing polymerisation aligned with the observed strength gains. Later increase in the open porosity values was attributed the appearance of cracks mapping the surface of the concrete. These cracks are caused by delayed shrinkage and may appear in geopolymers that have been cured under ambient conditions (Khan et al., 2019). This phenomenon is not affecting the compressive strength of concretes. In addition to this, it was observed that the standard variation was higher for geopolymers containing RA, responding to the variable characteristics of these aggregates.

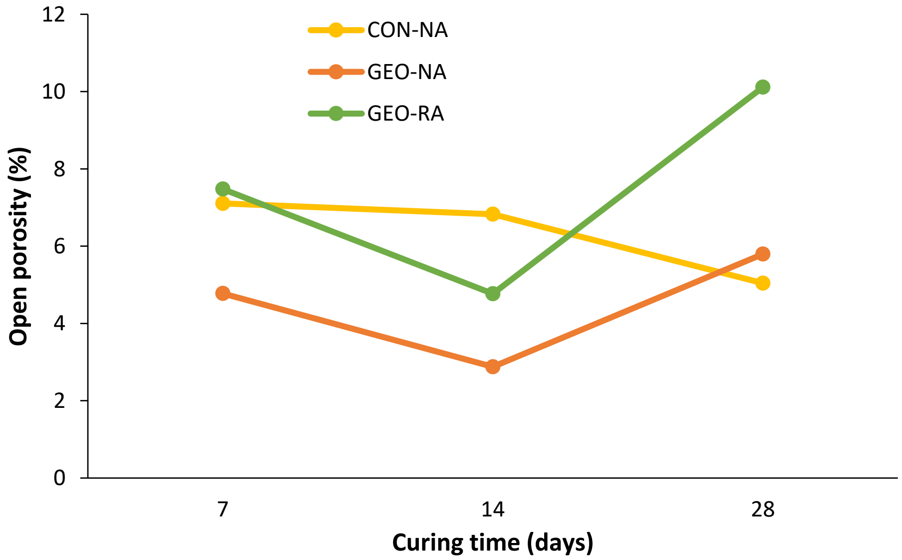
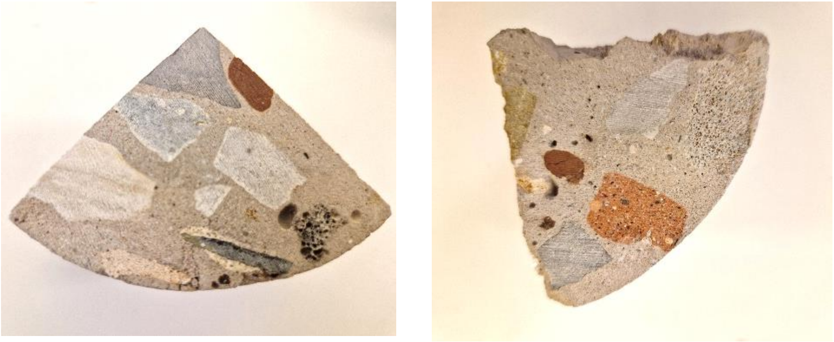


Figure 9: Open porosity of CON-NA, Geo-NA and Geo-RA concrete



(a) *(b)*

Figure 10: Samples of (a) Geo-NA and (b) Geo-RA used for open porosity test

Chloride migration and surface electrical resistivity

Figure 11 shows the RCMT and superficial electrical resistivity results for three concrete types (Con-NA, Geo-NA, and Geo-RA) at 7, 14, and 28 days of curing. The results demonstrate that geopolymer concretes significantly reduce chloride ingress compared to conventional concrete. At all curing ages, the Geo-NA mix achieved the lowest D_{nssm} values: 4.35, 3.30, and 3.28 ($\times 10^{-12}$ m^2/s) at 7, 14, and 28 days, respectively. This suggests a consistently superior resistance to chloride penetration. Conversely, Con-NA exhibited the highest D_{nssm} values, particularly at 7 days (31.60 $\times 10^{-12}$ m^2/s), although it decreased over time (18.61 and 17.90 at 14 and 28 days). This highlights the higher chloride migration of traditional concrete, especially at early ages.

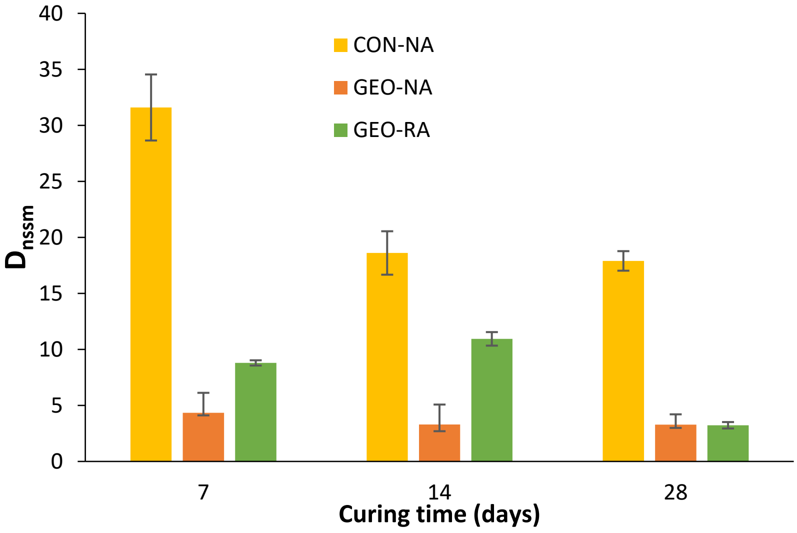
The performance of Geo-RA was more variable. At 7 days, it had a relatively high D_{nssm} of 8.80, which improved significantly at 14 days (10.94), and nearly matched Geo-NA at 28 days (3.23). This variation is likely due to the inconsistent properties of the recycled aggregates used in Geo-RA mixes.

Interestingly, the results reinforce that there is no direct correlation between open porosity and chloride migration in geopolymer concretes. Previous studies (Shi, 1996; Chindaprasirt & Chalee, 2014) have shown that chemical composition plays a more significant role than pore structure. Specifically, the high aluminate content and the large surface area of the N-A-S-H gel in geopolymers are thought to contribute to enhanced chloride binding capacity. However, higher concentrations of NaOH can reduce this binding effectiveness (Chindaprasirt & Chalee, 2014).

Furthermore, the surface electrical resistivity trends do not correlate directly with the D_{nssm} values of geopolymer concretes, particularly at early curing stages. Although resistivity measurements can provide indicative insights into chloride resistance, their variability during the first 14 days may stem from moisture redistribution after demoulding and exposure to the ambient environment.

While the RCMT results confirm the superior chloride resistance of geopolymer concretes, particularly Geo-NA, further research is needed to understand the microstructural factors such as pore fineness, tortuosity, and connectivity that influence chloride transport. The polymerisation process in geopolymers may play a role in physically impeding chloride ingress, but the RCMT cannot capture chloride binding mechanisms directly. Therefore, a combination of physical and chemical analyses is necessary to fully characterise the long-term durability of these systems.

(a)



(b)

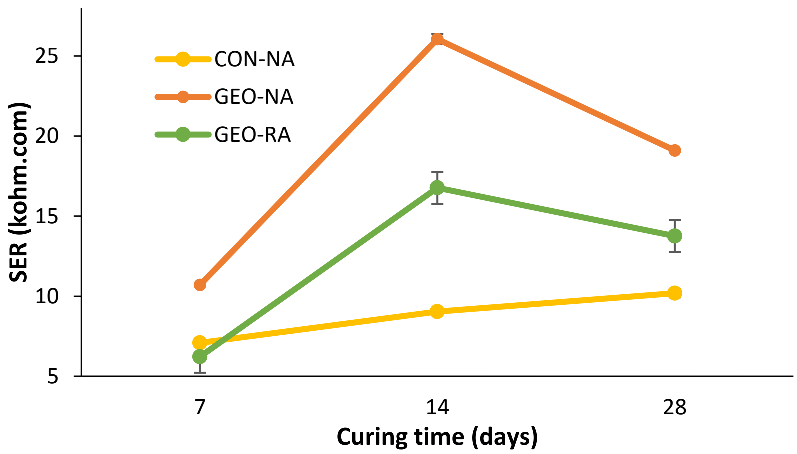


Figure 11: (a) RCMT results; (b) surface electrical resistivity

Open porosity and chloride migration results critically show how higher porosity typically leads to increased permeability, allowing aggressive ions such as chlorides and sulphates to penetrate more readily into the concrete matrix and undermining long-term durability (Chen et al., 2022). In this study, while geopolymer samples containing RA exhibited higher porosity, the chloride migration coefficients remained comparable to or lower than those of the CON-NA mix. This suggests that porosity alone does not fully determine durability where geopolymer concretes often show lower permeability than OPC mixes, due to denser gel structure attributed to their, microstructure and chemical composition of the binder matrix.

Efflorescence

Samples used for the leaching tests were allowed to dry under laboratory conditions. Efflorescence was observed on geopolymer samples containing RA as shown in Figure 12. This corresponds to previous research where a high content of chlorides or sulphates was observed (Kenai, 2018). The contaminants may have their origin in plaster from demolition sites; de-icing salts applied to pavements or roads or others. These salts are commonly unbound and soluble in water (Debieb et al., 2010).

The efflorescence was primarily visible as white crystalline deposits on the surface of the RA-based geopolymer specimens after 7–14 days of exposure to ambient air. The control and Geo-NA samples showed no visible signs of efflorescence, indicating that the recycled aggregate was the main source of the soluble salts.

This observation is significant as it suggests that RA introduces not only physical porosity but also chemical instability to the geopolymer matrix. The migration of sodium ions from the alkaline activator towards the surface, where they react with atmospheric CO_2 and moisture, can lead to the formation of sodium carbonate, manifesting as efflorescence.

Figure 12: Appearance of efflorescence on geopolymer samples containing RA

The presence of efflorescence is not merely an aesthetic concern but may indicate deeper chemical instability within the matrix. Over time, repeated exposure to moisture can lead to further salt migration and recrystallization at the surface, potentially causing microcracking and reducing long-term durability. In geopolymer concretes, especially those incorporating RAs, the interaction between unreacted alkalis and external moisture can exacerbate this effect. Long-term implications include degradation of surface integrity, increased permeability, and accelerated ingress of harmful ions such as chlorides and sulphates, factors that compromise structural performance and service life. Therefore, mitigation strategies such as RA pre-treatment or reducing the alkali concentration in the activator solution may be necessary to enhance durability.

Leaching tests

Results obtained from the ICP-OES tests for both chlorine free tap water and 3% NaCl water over day 1(D1), day 2 (D2) and day 3(D3) are shown in Figure 13 and figure 14. The latter is used to simulate an environment close to seawater to understand the leachate potential in conditions closer to reality. The ICP-OES produces two sets of results, i.e., axial and radial detection of the backscattered signal from the plasma. These sets differ in terms of calibration quality, sensitivity and accuracy, with the axial generally showing lower limit of detection (LoD see

). They have both been reported here for completeness without averaging between the two values. Concentrations below the detection limits have been replaced with the LoD provided by the calibration procedure and marked with an < mark at the end of axis label. This means that in certain conditions the comparison have been produced using LoD values. Additionally, it should be noted that for very low concentration, due to the resolution of the sensor, a single unit change of backscattered intensity could results in twice the amount of analyte concentrations.

Table 4: R^2 values of calibration curves and LoD values for various ions in tap water and 3% NaCL

	Test water		Test water + NaCL 3%	
Analyte (Measure Mode)	**R^2**	**LoD**	**R^2**	**LoD**
As 189.042 (Aqueous-Axial-iFR) [ppm]	0.9991	0.0029	0.9996	0.0037
As 189.042 (Aqueous-Radial-iFR) [ppm]	0.999	0.0099	0.9999	0.009
Zn 213.856 (Aqueous-Axial-iFR) [ppm]	0.9997	0.0005	0.9986	0.0198
Zn 213.856 (Aqueous-Radial-iFR) [ppm]	0.9994	0.001	0.9996	0.1874
Pb 220.353 (Aqueous-Axial-iFR) [ppm]	0.9995	0.0008	0.9998	0.0046
Pb 220.353 (Aqueous-Radial-iFR) [ppm]	0.9993	0.0071	0.9998	0.0094
Ni 231.604 (Aqueous-Axial-iFR) [ppm]	0.9994	0.0004	0.9999	0.0012
Ni 231.604 (Aqueous-Radial-iFR) [ppm]	0.9991	0.0011	0.9999	0.0039
Mn 257.610 (Aqueous-Axial-iFR) [ppm]	0.9992	0	0.9999	0.0001
Mn 257.610 (Aqueous-Radial-iFR) [ppm]	NA	NA	0.9999	0
Fe 259.940 (Aqueous-Axial-iFR) [ppm]	0.9996	0.0001	1	0.0053
Fe 259.940 (Aqueous-Radial-iFR) [ppm]	0.9994	0.0008	0.9999	0.0004
Cr 283.563 (Aqueous-Axial-iFR) [ppm]	0.9993	0.0002	0.9997	0.0003
Cr 283.563 (Aqueous-Radial-iFR) [ppm]	0.9994	0.0005	0.9999	0.0001
Mg 279.553 (Aqueous- Axial-iFR) [ppm]	0.9919	0.0001	0.9999	0.0017
Mg 279.553 (Aqueous- Radial-iFR) [ppm]	0.9997	0.0002	0.9999	0.0009
Cu 324.754 (Aqueous-Axial-iFR) [ppm]	0.9995	0	1	0.0002
Cu 324.754 (Aqueous-Radial-iFR) [ppm]	0.9993	0.0006	1	0.0014
Ca 393.366 (Aqueous-Axial-iFR) [ppm]	0.9961	0.0014	0.9982	0.0018

Ca 393.366 (Aqueous-Radial-iFR) [ppm]	0.9997	0.0019	0.9999	0.0048

Leaching to chlorine-free tap water

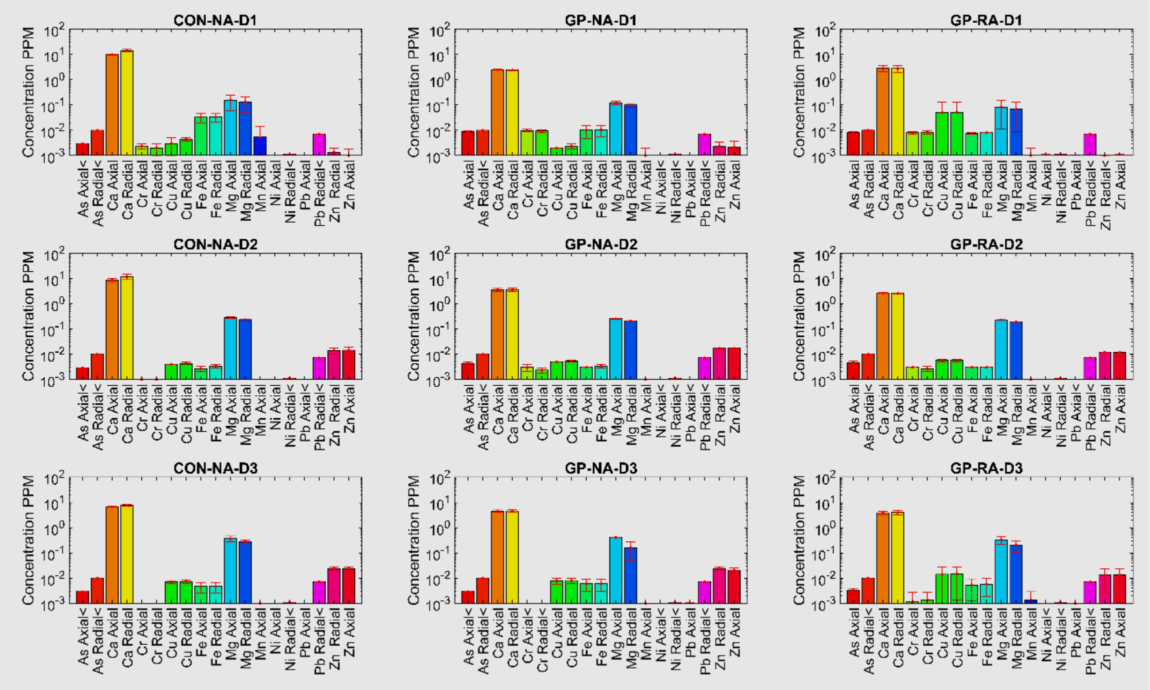


Figure 13: Chlorine free tap water test average and standard deviation concentrations from 3 samples for CON-NA, Geo-NA and Geo-RA, for three different days

The highest analyte concentration observed across all samples and exposure durations (D1, D2, and D3) was for calcium (Ca^{2+}), ranging between 100 ppm to 1000 ppm, while magnesium (Mg^{2+}) and iron (Fe^{2+}/Fe^{3+}) appeared in significantly lower concentrations (10^{-1} to 10 ppm). The leaching profiles in both cement-based and geopolymer concrete show consistent trends aligned with the elemental composition of the constituent materials where Ca content found in GGBS (72%) and CEM II (64%) as confirmed by EDX analysis (Table 1). The dominant presence of Ca^{2+} and its corresponding counterions, particularly hydroxide (OH^{-}) influences the pH values of the leachate solutions.

As previously reported by Conner (1990), the high pH environment typical of cementitious pore solutions (often exceeding pH 13) can enhance the mobility of certain heavy metals.

In this study, elevated zinc (Zn^{2+}) concentrations, of the order of 10^1 ppm, were observed exclusively in the GP-RA mix, while Zn levels in both the CON-NA and GEO-NA remained below the limit of detection (LoD). Given that none of the binder components contained more than 0.2% Zn, this suggests that the recycled aggregate (RA) is the primary source of Zn leaching.

Other trace elements, including chromium Cr, Mn, Pb and Ni were detected at very low concentrations. Cr remained below 0.1 ppm in all samples, while Mn, Pb, and Ni typically were below 0.01 ppm. The remaining analytes were undetectable, remaining below the LoD of the ICP-OES analysis. Notably, the concentrations of these analytes remained relatively stable across all three exposure durations (D1, D2, and D3). Differences in the concentration of analytes of control and geopolymers are presented in Figure 14.

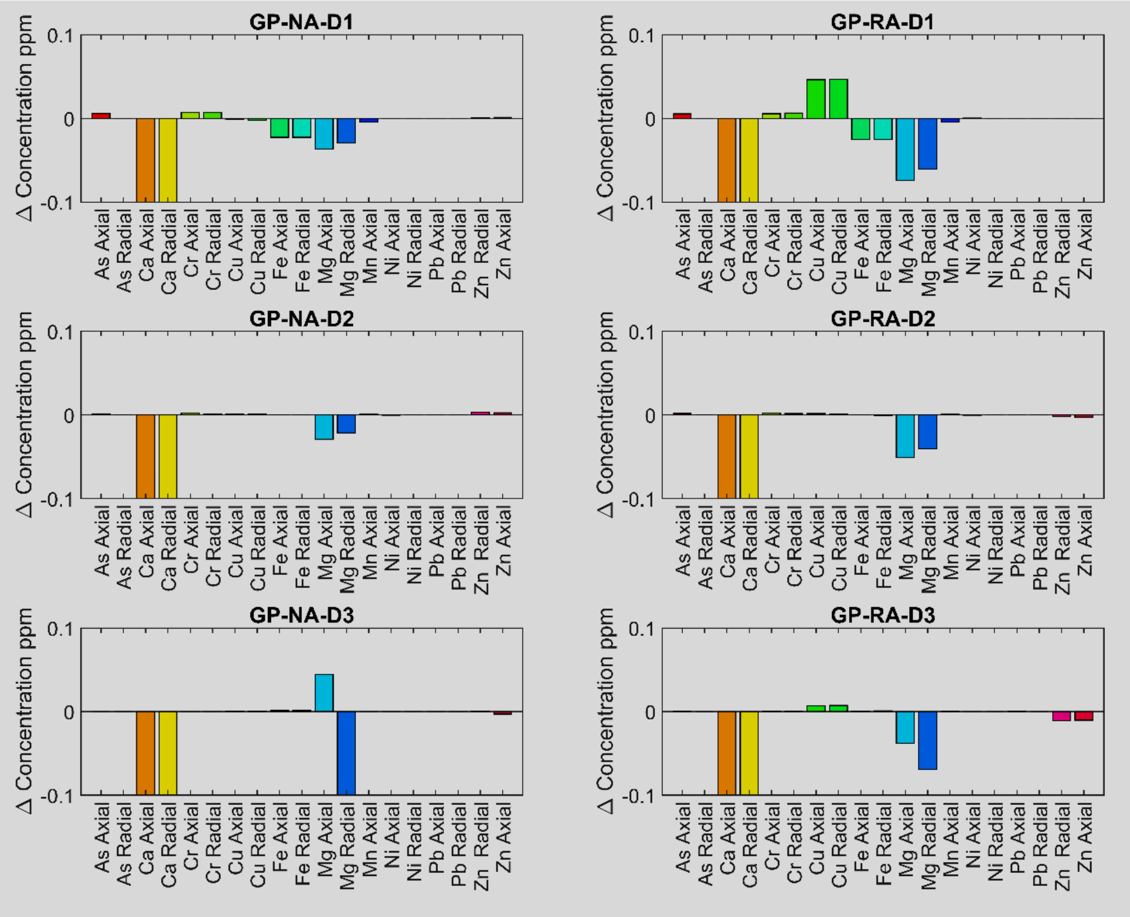


Figure 14: Chlorine-free tap water test average concentrations differences for Geo-NA with the CON-NA mix Geo-RA with the CON-NA mix, for three different days

Notable differences in leaching behaviour were observed between the control and geopolymer mixes, particularly for Ca^{2+} and Mg^{2+}, with both geopolymer samples exhibiting reduced concentrations of these ions in the leachates compared to the conventional CBC. For other elements except Ca and Mg, major differences are visible on D1 between geopolymer and control where Cr levels are slightly higher and Fe levels are lower in D1 leachate of GBCs than that of CBC, but both are very limited and generally less than 0.1 ppm. A notable difference was observed in Cu concentrations, with levels higher in Geo-RA and lower in Geo-NA compared to the CBC mix. This disparity may be attributed to the nature of the aggregates, as RA are likely to contain higher Cu content than NA. Supporting this, (Cabrera et al., 2019) reported that recycled aggregates derived from C&DW could contain more soluble components or cause a migration. .

In D2 and D3 leachates, trace elements did not exhibit notable presence, with the exception of Ca and Mg. This observation may be indicative of the reduced leaching potential of geopolymer systems, particularly those incorporating RA, once the materials have undergone initial weathering. These results align with previous research, which reported that the cumulative leaching concentrations of heavy metals in geopolymer materials were significantly lower than those observed in Portland cement-based bricks, suggesting a reduced environmental risk (Liang et al., 2024; Ren et al., 2024).

Leaching to saltwater

The saltwater leaching test was conducted using a 3% NaCl solution, calibrated to closely match the ionic strength of the test environment. This calibration approach ensured consistent and reliable detection across test samples and reference standards, achieving detection limits comparable to those used in the chloride-free freshwater tests.

Figure 15 presents the average elemental concentrations and standard deviations for each mix over three days. The amount of Ca was significantly higher when compared to the freshwater samples, possibly due to chlorine migration into the sample. In general, saltwater triggered higher elemental concentrations in both control and geopolymer specimens, though the values remained within the same order of magnitude for trace elements. Similar to freshwater leaching, a significant reduction in most ion concentrations was observed after 3 days of exposure.

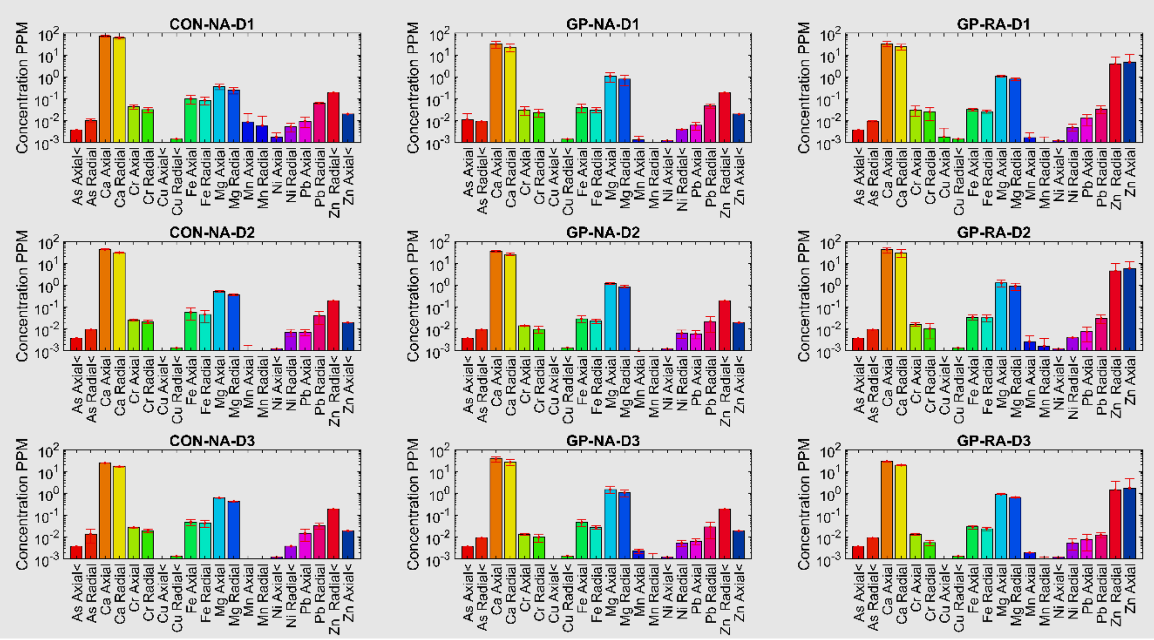


Figure 15: 3% NaCl water test average and standard deviation concentrations from 3 samples for CON-NA, Geo-NA and Geo-RA, for three different days

Compared to the freshwater leaching profile, the saltwater exposure exhibited distinct trend: During the initial two days a pronounced reduction in Ca and Fe concentrations was observed across all mixes while Mg in the virgin aggregate mix and Zn in both geopolymer mixes displayed elevated concentrations relative to the CON-NA. Other trace elements exhibited minimal variation or showed slight decreases over time.

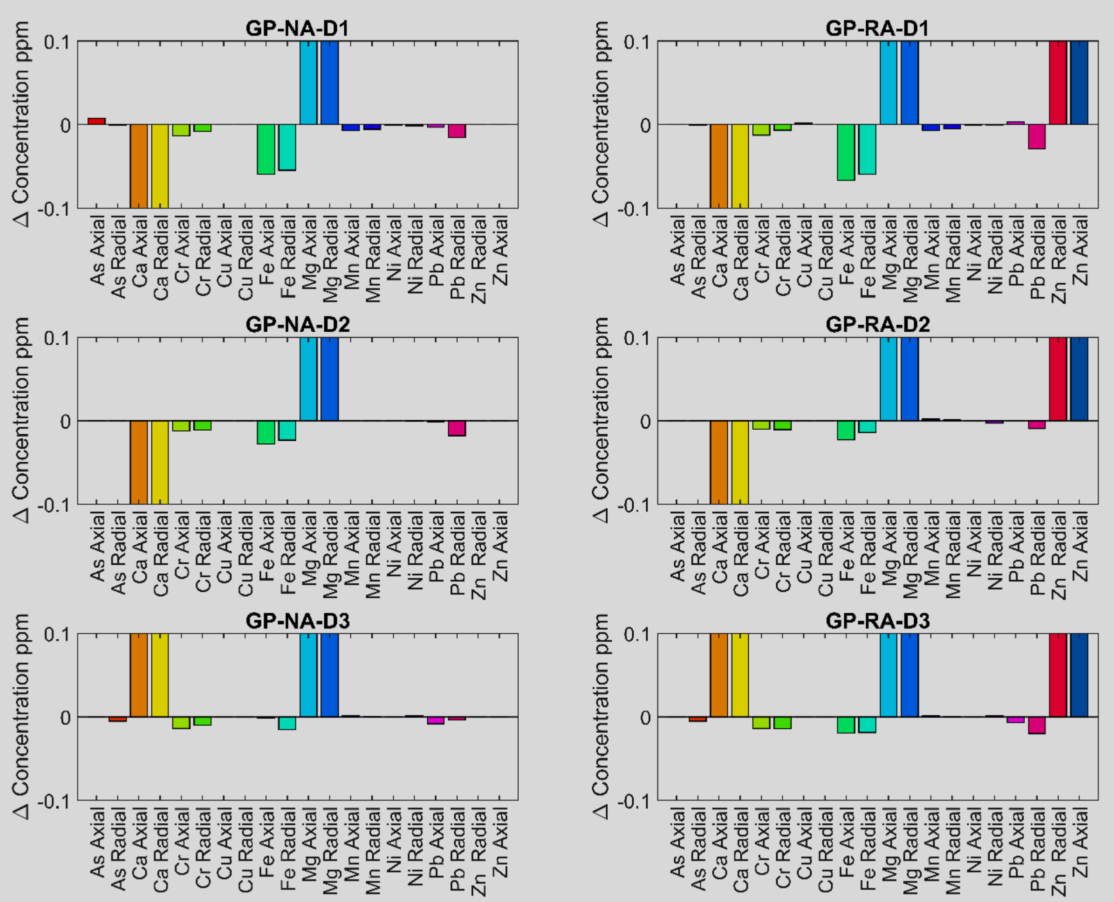


Figure 16: 3% NaCl water test average concentrations differences for GP-NA with the CON-NA mix and GP-RA with the CON-NA mix, for three different days

The behaviour of Zn leaching was notably different between freshwater and saltwater tests (Figure 16). In freshwater, high Zn amount has leached in D2 and D3 compared to D1, while in saltwater, Zn remained relatively stable over the three days for all mixes. This may be attributed to the influence of pH and ionic buffering in saltwater, which limits the desorption of Zn^{2+} and controls the kinetics of Zn erosion from the material. Zhang et al., 2021 has observed that the Zn based materials releases Zn faster in acidic medium. High alkalinity in the leachate in D1 might have hindered the release of Zn^{2+} ions to tap water while high salinity in sea water has buffered the solution to avoid above effect. Lead (Pb) followed a similar trend, with lower desorption in freshwater compared to saltwater, aligning with the explanation above. Galvin et al. (2014) also found that the release of metal cations such as Cu, Ni, Pb, Cd, and Zn increases at lower pH levels (between 4 and 7), further supporting the buffering hypothesis.

Sanusi et al. (2016) examined the toxicity characteristics of coal fly ash-based geopolymer concrete with virgin aggregates in accordance with the Netherlands

Normalisation Institute standard (NEN 7371, 2004) identifying a peak cluster of arsenic (As), chromium (Cr), and selenium (Se), with As exhibiting the highest leachate concentration of 13 ppm, which decreased to 10 ppm and 9 ppm when recycled concrete aggregate (RCA) was substituted at 10% and 50%, respectively. In contrast, the present study observed no significant leaching of As or Cr across any of the mixes, which may be attributed to differences in the mineralogical composition of the recycled versus natural aggregates employed. Field studies by Engelsen et al. (2017) reported Pb concentrations below detection limits in RCA leachate, consistent with the current results.

The observed differences in performance between Geo-RA and the conventional OPC-based control mix highlight several important implications. While the Geo-RA mix exhibited a reduction in compressive strength compared to the CON-NA, it demonstrated superior durability characteristics such as reduced chloride migration and enhanced resistance to efflorescence. These results suggest that although strength performance may be slightly compromised due to the variable quality and porosity of RAs, the long-term durability and sustainability of geopolymer systems could make them more suitable for specific infrastructure applications where exposure to aggressive environments is a concern. Furthermore, the ability of Geo-RA to incorporate industrial by-products and eliminate OPC contributes to significant environmental benefits, supporting the move toward circular and low-carbon construction practices. However, to fully realise these benefits in practice, further optimisation of mix design and better standardisation of RA quality are essential.

High concentrations of Calcium and Magnesium was observed in both fresh water and salt water in tank leachate test. In particular, the geopolymer showed lower concentrations for both elements, while freshwater tests showed low changes between geopolymer and control samples in terms of trace elements. The saltwater test showed generally higher concentration in all the sample tested and a general tendency to increase the amount of magnesium and Zinc leached from the geopolymer, while most of the trace elements showed minimal variations.

The variability observed in geopolymer mixes incorporating RA is primarily attributed to the heterogeneous nature of RA in terms of particle size distribution, residual mortar content, and contaminants. To address this, standardization efforts should include thorough pre-treatment and classification protocols for RA, such as mechanical screening, density separation, or selective crushing. Additionally, developing mix design guidelines that account for RA characteristics such as absorption capacity and adhered mortar content can enhance consistency across batches. Recent studies also recommend the use of machine learning models to optimize mix proportions based on input variability (Ali et al., 2024). Implementation of material certification schemes and performance-based specifications, rather than prescriptive ones, can further support the large-scale adoption of RA in geopolymer concrete.

Despite the promising mechanical and environmental performance of geopolymer concrete, its large-scale application faces notable scalability challenges. These include the variability and availability of industrial by-products (e.g., FA, GGBS, CCR), inconsistent supply chains, the need for controlled curing, and health and handling concerns associated with alkaline activators like NaOH and Na_2SiO_3. In addition, current construction codes and industry familiarity are geared toward OPC-based systems, limiting immediate adoption. Recent studies highlight that while geopolymer systems can be upscaled, ensuring consistency in mix design and performance requires standardisation of raw material characterization and binder formulations (Tempest et al., 2015; Wijesekara et al., 2025). These findings underscore the potential of geopolymer formulations for large-scale coastal applications, provided that scale-dependent variations are incorporated into design evaluations. This highlights a critical need for future research involving real-world field trials to generate data on mechanical weathering and associated leaching from RA under operational conditions, which is currently unavailable. While the use of geopolymer concrete incorporating RA supports circular economy objectives by reducing waste and lowering embodied carbon, its large-scale implementation requires further assessment of economic feasibility, including the cost of activators, processing recycled aggregates, and potential infrastructure adaptation.

4. Conclusions

- The incorporation of recycled aggregates reduced the density and compressive strength of geopolymer concretes by 5.9% and approximately 30%, respectively, compared to geopolymer mixes using natural aggregates.
- While the use of recycled aggregates decreased chloride penetration resistance relative to natural aggregate-based geopolymers, the RA-based geopolymer still demonstrated up to 82% improved resistance compared to conventional OPC concrete, indicating promising performance for durability in marine environments.
- Variability in test results for RA-based mixes was higher due to heterogeneity in the recycled aggregates. This highlights the need for improved material characterization and quality control in mix design to enable broader adoption.
- A low-carbon concrete completely free of Portland cement and natural aggregates was successfully developed, offering a viable and environmentally preferable alternative for manufacturing sustainable breakwater units and similar coastal structures.
- Leaching tests showed consistently high releases of Ca^{2+} and Mg^{2+} in both freshwater and 3% NaCl environments, with Ca concentrations reaching 100-1000 ppm across all mixes. Geopolymer samples exhibited lower Ca^{2+} and Mg^{2+} release than OPC concrete, indicating better chemical stability. Under saltwater exposure, all mixes showed increased ion release compared to freshwater, with Mg^{2+} and Zn^{2+} showing slight elevations in the geopolymer mixes particularly Zn in Geo-RA although values remained within the same order of magnitude and trace metals stayed below 0.1 ppm. These results confirm that although salinity marginally increases leaching, overall trace-metal release from the geopolymer mixes remains low and environmentally stable.
- This low carbon geopolymer-matrix can facilitate the use of recycled aggregates in mass non-structural concrete in saline condition by fixing the leachable elements, or generally not changing performance dramatically compared to conventional concrete.

Future work

This study is mainly focused on the durability performances of geopolymers containing recycled aggregates from C&DW. Future works could focus on the optimisation the both the geopolymer mix design and the curing regime by varying activator ratios, molarity, curing temperature and duration to improve early strength development and reduce porosity, especially when using low-reactivity recycled materials., the investigation of the influence of the polymerisation on the porous microstructure and the ITZ. Additionally, for future studies could investigate the use of more sustainable solid activators from waste sources considering that it accounts for the highest single contribution to the embodied carbon of the material (Kadhim et al., 2020, Jones, 2019). Future work coupling chemical leachate analysis with biological assays or ecological risk modelling (e.g. predicted environmental concentration vs predicted no effect concentration) is recommended to assess real-world impacts. Additionally, repeated screening under dynamic seawater exposure and inclusion of multiple contaminant interactions can provide a more accurate representation of long-term ecological risk. The scalability of production techniques for industrial applications must also be explored, along with techno-economic feasibility analyses, to enable large-scale deployment in coastal and offshore structures. The adopted technology with validated product will not only reduce the demand for mineral-based construction materials and chemicals but also improves the circularity and economic value of wastes, thus promoting UN Sustainable Development Goals 7 11, 12 and 13 with the potential to be expanded for protecting low-income communities around the world.

Acknowledgments

The authors of this paper wish to acknowledge the support of the Institution of Civil Engineers (ICE) research and development enabling (RDE) fund for the funding of the research project at Liverpool John Moores University.

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