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Comparative analysis of chloride and acid resistance in one-part geopolymer and low carbon dioxide concrete

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AQ: 1

A comparative analysis of the chloride and acid resistance of one-part geopolymer and low carbon dioxide concretes is presented, with a focus on their potential to replace traditional systems based on ordinary Portland cement (OPC) in construction. The performance of geopolymer concretes (GPCs) was compared with concretes made with OPC and OPC blended with supplementary cementitious materials (fly ash and slag) under aggressive environmental conditions. The findings revealed that, while GPCs exhibit superior resistance to acid attack, their chloride resistance is highly dependent on the specific precursor materials used. The study also highlights the limitations of using rapid chloride permeability tests at standard voltages for GPCs, suggesting that lower voltage tests at 30 V may offer a more accurate assessment. Overall, the results underscore the need for optimised precursor selection in GPCs to enhance durability and advocate for further research into testing methodologies tailored to these innovative materials.

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Keywords: acid resistance/chloride resistance/durability/geopolymer concrete/low carbon dioxide concrete

Once author's choice of keywords are added, will need to be checked that it is a minimum of zero/maximum of three of their own keywords and a minimum of two/ maximum of three keywords from the approved ICE Proceedings.

Notation

$C(x, t)$	chloride concentration measured at depth x and exposure time t (mass %)
C_i	initial chloride concentration of binder prior to submersion in exposure solution (mass %)
C_s	projected chloride concentration at interface between exposure liquid and test specimen, determined by regression analysis (mass %)
D_a	apparent diffusion coefficient (m^2/s)
N	exact normality of 0.05 N silver nitrate solution
t	exposure time (s)
V_1	volume of 0.05 N silver nitrate solution used for sample titration (ml)
V_2	volume of 0.05 N silver nitrate solution used for blank titration (ml)
W	weight of sample (g)
x	depth below exposed surface (m)

Introduction

Low carbon dioxide concrete is produced to have a smaller carbon footprint than traditional concrete, while aiming to match the performance and features of traditional concrete. There is no single definitive method for creating low carbon dioxide concrete because it is made up of various ingredients. Several strategies can be used to reduce the carbon dioxide emissions from each component and the production process. One common method includes using ordinary Portland cement (OPC) combined with supplementary cementitious materials (SCMs) in the concrete mix. Two SCMs frequently used for this purpose are ground granulated blast-furnace slag (GGBS) and class F fly ash (FA), and up to 55% class F FA and up to 80% GGBS are specified for construction applications (BSI, 2019). Most producers are already incorporating SCMs as partial substitutions for OPC into their cement or concrete mixes. By further optimising the utilisation of these materials, it is possible to significantly reduce the emissions associated with cement and concrete production.

Instead of partly replacing cement, another option is to use a type of binder that does not contain cement at all. These include alkali-activated materials or geopolymers. These materials do not have the carbon dioxide emissions ~~due~~ to the processing of limestone and they can be made using green energy. Geopolymer concretes (GPCs) are proving to be good alternatives to traditional cement concretes in some building projects, mainly because they are better for the environment (Hassan *et al.*, 2019; Teh *et al.*, 2017) ~~due~~ to their significantly lower carbon dioxide emissions and utilisation of industrial by-products.

In this research, the embodied carbon dioxide emissions of low carbon dioxide concretes, including concretes with various SCMs and two types of GPCs, were examined. The aim of this was to dispel misconceptions surrounding the environmental advantages of GPCs.

The durability of reinforced concrete (RC) against rust is an important issue. Standards and codes account for corrosion resistance in RC made with OPC by requiring certain concrete strengths and concrete cover around the reinforcing steel. However, less is known about how RC made with GPC holds up against steel corrosion. While many studies have shown that concrete made with alkali-activated materials is better at protecting steel from corrosion compared with OPC concrete (Almutairi *et al*., 2021; Nawaz *et al*., 2020; Wasim *et al*., 2021), conflicting findings have also been reported (Amran *et al*., 2021; Vu *et al*., 2022). Therefore, considerable effort is required to address practical challenges and build trust in GPC.

In coastal and marine environments, where concrete structures are frequently exposed to chloride ions, chloride attack becomes a major durability issue. When concrete is exposed to chloride ions, the ions accumulate on the concrete surface. If the chloride ion concentration reaches a certain level and there is also water and oxygen present, the protective layer on steel within the concrete can be damaged or even destroyed (Nguyen and Castel, 2023; Vu *et al*., 2022).

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To achieve their intended service life, structures need to have a certain level of resistance to chlorides, which varies based on their exposure classification. In ~~the~~ New South Wales, Australia, specific guidelines have been set to direct performance-based durability design, especially concerning chloride resistance (TfNSW, 2021). This specification includes classifications such as B2, C1 and C2, which help to ensure that concrete structures used in bridge construction comply with the necessary durability standards for environments rich in chlorides. For GPC, obstacles involve limited awareness among engineering professionals, its exclusion from industry standards and the absence of clear guidelines or requirements. Until recently, standard specifications for the use of geopolymers in concrete have not been available in Australia. However, SA TS 199:2023 (SA, 2023) has recently been issued to offer guidelines and specifications for the design and construction of building structures and elements made from GPC and alkali-activated binder concrete incorporating reinforcing steel or/and tendons. With the introduction of these specifications, it becomes possible to make a fair comparison between OPC-based concrete and GPC. This aim of this study was to compare the chloride resistance of 25% FA-blended OPC concrete with two types of one-part GPC to determine whether GPCs can effectively replace OPC-based concrete in construction applications. NT Build 443 (Nordtest, 1995) – which is considered a reference test method for determining chloride penetration in concrete with satisfactory precision (Tang and Sørensen, 2001) – was used for this purpose.

Another aspect of this work was to investigate the suitability of the rapid chloride permeability test (RCPT) as per ASTM C1202 (ASTM, 2022) in assessing the chloride resistance of GPCs. AQ: 3 The RCPT has been strongly criticised that it does not simulate well the transport of chloride ions in concrete structures in the field (Neville, 1995; Shi, 2003). However, the RCPT has several practical advantages, such as the simple procedure, short test duration and correlation with the compressive strength of concrete (VicRoads, 2007; Whiting and Mitchell, 1992). That said, these remarks apply specifically to OPC-based concretes, so another aim of this study was to determine whether these conclusions also hold for GPC. AQ: 4

Furthermore, the acid resistance of both blended OPC concrete and GPC was explored, particularly in the context of pipes and sewers where exposure to sulfates and other harsh chemicals frequently occurs. Laboratory tests for evaluating acid resistance typically expose concrete samples to acid solutions. However, such tests might not capture the full complexity of real-world conditions, especially those involving biomicrobes. This gap can result in differing outcomes regarding the observed performance of the materials (Khan *et al*., 2020; Monteny *et al*., 2000). Until there is a standardised laboratory test that more accurately reflects the presence of biomicrobes found in natural environments, this study relied on existing laboratory tests that assess factors such as mass loss and strength degradation to gauge the acid resistance of concrete. It is important to note that biogenic sulfuric acid, which is often more concentrated and localised, can cause more pronounced degradation than what is generally seen in standard laboratory acid tests.

Methodology

Materials and concrete mix proportions

Two one-part FA/slag geopolymer binders (called Geo 1 and Geo 2) were produced by mixing class F FA, GGBS and an alkaline activator in solid form. The chemical compositions of the FA and GGBS used are provided in Table 1. T1 The GGBS used in this work contained inherently reduced species such as iron, sulfate and AQ: 5

Table 1. Chemical compositions of aluminosilicate precursors

	FA	GGBS
Silicon dioxide (SiO_2): wt%	58.15	33.89
Aluminium oxide (Al_2O_3): wt%	22.29	14.14
Calcium oxide (CaO): wt%	5.39	40.46
Magnesium oxide (MgO): wt%	1.28	6.84
Ferric oxide (Fe_2O_3): wt%	6.95	0.45
Titanium dioxide (TiO_2): wt%	1.03	0.58
Sulfur trioxide (SO_3): wt%	0.15	1.59
Potassium oxide (K_2O): wt%	1.39	0.28
Sodium oxide (Na_2O): wt%	0.47	0.32
Other	1.81	1.56
LOI: wt%	1.09	−0.11

manganese, which gain mass on heating or oxidising. As a result, slag often gives nearly zero or a slightly negative loss on ignitions (LOI), as was recorded in this case. Anhydrous sodium metasilicate and a carbonate mineral that produces hydroxide anions (OH^-) on hydration were used as solid activators. The percentage of solid activators was 16% by weight of binder. The compositions of binders Geo 1 and Geo 2 are shown in Table 2. T2

An investigation into the chloride resistance of the one-part GPCs was carried out and compared with the chloride resistance of OPC concrete and concrete made with 75% OPC and 25% FA. The mix proportions of the concretes (given the same names as their binder type) are shown in Table 3. All the concrete mixes had the same amounts of binder, sand and aggregate, but different water/binder (w/b) ratios. The w/b in the geopolymer mixtures was the amount of water used for both the solid alkaline activator and precursor. T3

Chloride resistance test as per NT Build 443

After mixing the concretes, cylindrical specimens measuring 100 × 200 mm were cast and demoulded after 1 day. The GPC specimens were then wrapped in plastic film and heated in an oven at 60°C for 6 h. Subsequently, the plastic films were removed and the specimens were left to air-cure in the laboratory. For the OPC and OPC + 25% FA concretes, the specimens were submerged in a lime water tank and cured for 28 days. At age 28 days, all the specimens, both geopolymer- and OPC-based, were sectioned into 75 mm long segments. These 75 mm segments were sealed on all sides except for one circular face, using a silicone sealant known for its high resistance to water, chloride, fungus and weather conditions. The unsealed face was left exposed to allow chloride ions to penetrate the concrete during testing.

The specimens were then submerged in a water bath until their mass varied by no more than 0.1% over 48 h. After achieving stable mass, they were removed from the water bath. These fully saturated specimens were then placed into containers filled with a 16.5% sodium chloride (NaCl) solution. The containers were sealed and left in the laboratory for 3 months.

After being removed from the sodium chloride solution, the specimens were ground every 1 mm against a 25 mm depth of concrete specimens using a profile grinder. The sample powders were obtained in layers parallel to the exposed surface. The procedure for calculating the apparent chloride diffusion coefficient is described in detail by Noushini *et al*. (2019). The acid-soluble chloride (total chloride) was measured in accordance with ASTM C1152 (ASTM, 2012). A 20 ml aliquot of 20% nitric acid (HNO_3) was used to disperse 3.5 g of sample powder into a beaker. The beaker was covered by a watch glass and allowed to stand for 1–2 min. The solution in the covered beaker was rapidly heated to boiling point for several seconds and then removed from the hot plate. The solution was then filtered using filter papers with a pore size of 5–10 μm in a Buchner funnel and suctioned filtration flask. The beaker and the filter paper were rinsed twice with small portions of water. The solution obtained was about 50 ml. The chloride content of the solution (C) was determined using a Metrohm 855 Robatic Titrosampler with silver nitrate ($AgNO_3$) solution, as per ASTM C114 (ASTM, 2018), as:

$$C\,(\%) = \frac{3.545(V_1 - V_2)N}{W} \quad (1)$$

in which, V_1 is the volume (ml) of 0.05 N silver nitrate solution used for sample titration, V_2 is the volume (ml) of 0.05 N silver nitrate solution used for blank titration, N is the exact normality of the 0.05 N silver nitrate solution and W is the weight of the sample (g).

Determination of apparent chloride coefficient

The acid-soluble chloride contents were plotted against the depth below the surface exposed to the sodium chloride solution. The values of surface concentration and apparent chloride diffusion coefficient (D_a) were measured by fitting Equation 2 (Fick's second law) by means of non-linear regression analysis using the

Table 2. Mix proportions of binders Geo 1 and Geo 2

	Slag/(FA + slag)	Silica/alumina ratio	Sodium activator powder: %
Geo 1	0.4 (40% slag by weight of total precursor)	2.6	16
Geo 2	0.6 (60% slag by weight of total precursor)	2.4	16

Table 3. Mix proportion of concretes

Concrete/binder type	Binder: kg/m³	Natural coarse sand: kg/m³	10 mm aggregate: kg/m³	20 mm aggregate: kg/m³	w/b ratio	Compressive strength at 28 days: MPa
Geo 1	410	835	525	790	0.33	53.0
Geo 2	410	835	525	790	0.35	52.0
OPC	410	835	525	790	0.50	52.5
OPC + 25% FA	410	835	525	790	0.47	46.5

method of least squares. All other chloride content measurements were included in the regression analysis.

$$2. \quad C(x,t) = C_s - (C_s - C_i)\,.\,\mathrm{erf}\left(\frac{x}{\sqrt{4D_\mathrm{a}t}}\right)$$

In Equation 2, $C(x, t)$ is the chloride concentration measured at depth x and exposure time t (in mass %), C_s is the projected chloride concentration at the interface between the exposure liquid and the test specimen, determined by regression analysis (mass %), C_i is the initial chloride concentration of the binder prior to submersion in the exposure solution (mass %), x is the depth below the exposed surface (in m), t is the exposure time (in s), D_a is the apparent diffusion coefficient (m^2/s) and erf is the error function:

$$3. \quad \mathrm{erf}\,(z) = \frac{2}{\sqrt{\pi}}\int_0^z \exp\,(-u^2)\mathrm{d}u$$

Acid resistance test

The resistance to sulfuric acid (H_2SO_4) was evaluated based on the visual appearance of specimens, mass loss and the residual compressive strength of the concrete test specimens after acid exposure for up to 5 months.

The acid resistance specimens were prepared as follows. The mixed concrete was placed in cylindrical moulds (100 × 200 mm) and left to cure for 1 day, when the moulds were removed. The geopolymer specimens were wrapped in plastic film and placed in an oven at 60°C for 6 h. After removing the plastic films, these specimens were left to air-dry in the laboratory. The OPC-based concrete specimens were placed in a lime water tank where they were cured for 28 days. Following the curing period, all the specimens were oven-dried at 110°C for 7 days. This thorough drying aids in accelerating the penetration of acid solutions and allows for the measurement of dry mass before acid testing. Subsequently, the specimens were immersed in 5% sulfuric acid solution for up to 5 months. The specimens were taken out of the acid solutions after 1, 2 and 5 months. Their surfaces were cleaned to remove any deposits formed from the acid reaction with the specimens and they were then placed in an oven and dried at 110°C for 7 days. Once dried, the mass of each specimen and the residual compressive strength were measured.

Results and discussion

Chloride resistance of one-part FA/slag GPC compared with OPC-based concretes

The total chloride profiles of all the concretes (Geo 1, Geo 2, OPC and OPC + 25% FA) that had been immersed in 16.5% sodium chloride solution are presented in Figure 1. Based on these total chloride concentrations, the apparent chloride diffusion coefficient (D_a) was calculated (ASTM, 2016; (Nordtest, 1995) and the results are listed in Table 4. The apparent volume of permeable voids (AVPV) was determined as per ASTM C642 (ASTM, 2006) is also included in Table 4.

F1

T4

Geo 1 concrete was found to have the highest value of D_a (33.0×10^{-12} m^2/s), much higher than that of the OPC concrete (9.2×10^{-12} m^2/s). For Geo 2 and OPC + 25% FA, the D_a values were 8.2×10^{-12} m^2/s and 4.7×10^{-12} m^2/s, respectively. These results imply that OPC + 25% FA had the highest resistance to chloride penetration, followed by Geo 2. Hence with the right precursor materials (in this case FA/slag combination), it is possible to produce geopolymers that will be as effective as blended cement systems in terms of chloride ion diffusion. Also, it should be noted that with a poor selection of precursor materials, the geopolymer produced can become the least effective in chloride diffusion. Considering the chloride resistance levels exhibited by Geo 1 and Geo 2 concretes, they are not suitable for marine structures. However, they could be viable options for concrete structures with of grade S40, such as B1 S40 (used for bridges and roads). To enhance the chloride resistance of GPC, further research is required to explore the optimal selection of precursors and the alkaline activation method.

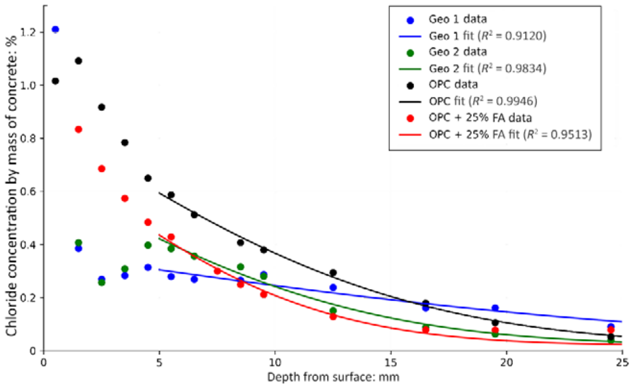

Figure 1. Chloride profiles in Geo 1, Geo 2, OPC and OPC + 25% FA concretes

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Table 4. Chloride penetration-related properties of concretes investigated

Concrete type	D_a: 10^{-12} m^2/s	AVPV: %	Compressive strength at 28 days: MPa
Geo 1	33.0	11.0	52.9
Geo 2	8.2	12.0	52.1
OPC	9.2	13.3	52.5
OPC + 25% FA	4.7	13.1	46.5

T5 The AVPV results (Table 5) show that all four types of concrete investigated had good quality in accordance with the VicRoads classification for concrete durability (VicRoads, 2007). The AVPV of Geo 1 and Geo 2 was 11.0% and 12.0%, respectively and their total porosities were almost the same (Vu *et al*., 2020). However, the chloride diffusion coefficient of Geo 1 concrete was four times higher than that of Geo 2 concrete. This is probably because Geo 2 concrete contained a higher percentage of slag (60% slag by weight of total precursor) than Geo 1 concrete (only 40% slag). Increasing the slag content (more than 50%) has been reported to result in an increase in pore tortuosity in alkali-activated systems (Balcikanli and Ozbay, 2016; Lee and Lee, 2016; Provis *et al*., 2012), thus slowing down the ingress of chloride ions into the alkali-activated material. The dominant reaction product in the system in this case was C-(N)-A-S-H gel, which could chemically and physically bind chloride ions (Ben Haha *et al*., 2011; Bernal *et al*., 2013; Yuan *et al*., 2009). On the other hand, in the alkali-activated system with a high percentage of FA, the main reaction product was N-A-S-H which is merely able to physically bind chloride ions (Ismail *et al*., 2013; Zhang *et al*., 2019). The difference in the chloride diffusion coefficients of Geo 1 and Geo 2 concretes, may thus be explained by the difference in the gels formed in Geo 1 and Geo 2 systems and demonstrates the importance of the FA to slag ratio in the precursors when tailoring FA/slag GPCs with high resistance to chloride attack. This aspect needs to be investigated in further research.

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Suitability of the RCPT for assessing the chloride resistance of GPC

For safety reasons, most RCPT instruments limit the current to 500 mA. When the current exceeds this threshold, overheating occurs and the test is terminated. When a voltage of 60 V was applied, 25.0% of the RCPT tests on Geo 1 concrete had to be stopped before the six-hour mark ~~due~~ to overheating. The issue was even more pronounced with Geo 2 concrete, where 42.8% of the specimens were terminated early. In contrast, the tests ran smoothly at 60 V for the OPC and OPC + 25% FA concretes, indicating that the RCPT performed at 60 V is not suitable for assessing the chloride resistance in one-part GPCs.

Table 5. Charge passed in RCPTs conducted at 30 V and 10 V

Concrete type	Charge passed: C	
	Mean (standard deviation)	Median [min, max]
RCPT at 30 V		
Geo 1	2027 (182)	2051 [1760, 2342]
Geo 2	1782 (218)	1670 [1643, 2033]
OPC	1246 (229)	1176.12 [1060, 1502]
RCPT at 10 V		
Geo 1	365 (70)	388.70 [266, 449]
Geo 2	497 (35)	496.47 [444, 553]
OPC	233 (54)	202.90 [200, 296]
OPC + 25% FA	157 (28)	156.70 [123, 192]

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However, the tests conducted at 30 V and 10 V were successfully completed for all types of concrete investigated. When the RCPT was performed at 30 V, Geo 1 concrete exhibited the highest average charge passed, at 2027 C (as shown in Figure 2 or Table 5). F2 Geo 2 concrete followed, with an average charge passed of 1782 C, while the OPC concrete had an average charge passed of 1246 C.

At 10 V (as shown in Figure 3 or Table 5), the OPC + 25% FA F3 concrete had the lowest average charge passed (157 C). Geo 2 concrete exhibited the highest value at 497 C, followed by Geo 1 concrete at 366 C and OPC concrete at 233 C.

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These observations suggest that the RCPT performed at 30 V is more aligned with NT Build 443 than RCPTs conducted at 60 V or

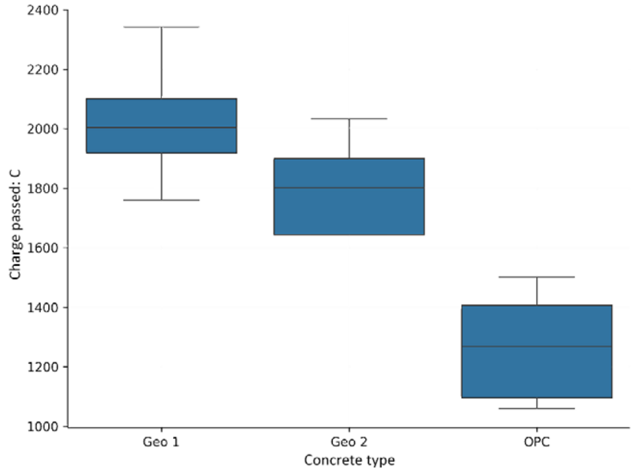

Figure 2. Charge passed in RCPT at 30 V

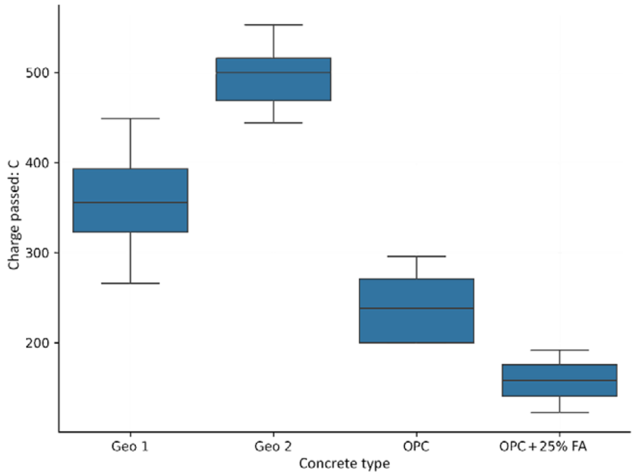

Figure 3. Charge passed in RCPT at 10 V

10 V. This finding highlights a potential research gap for future studies to explore the suitability of RCPT at 30 V for GPCs, given that the RCPT is a straightforward, short-duration test (only 6 h), making it ideal for quality control in field and laboratory settings.

Acid resistance

Appearance and change in mass of concrete cylinders after acid exposure

F4 Figure 4 shows the appearance of OPC-based concretes and GPCs
AQ: 6 after 1, 2 and 5 months of exposure to 5% sulfuric acid. The GPCs (Geo 1 and Geo 2) exhibited minimal surface changes, whereas
AQ: 7 the OPC, 15% FA and 25% slag concretes showed significant signs of corrosion, including substantial loss of cement paste and exposure of coarse aggregate. The mass losses ~~due~~ to corrosion are summarised in Table 6 and T6
illustrated in Figure 5. It is clear that the more cement paste loss, the F5
stronger the level of acid corrosion. The OPC-based systems experi- AQ: 8
enced significant mass loss, in the range 10–14%, while the geopolymer systems demonstrated superior resistance, with only 1–2% mass loss after 5 months of exposure to 5% sulfuric acid. This suggests a high level of corrosion in the OPC-based systems and the results of compressive strength changes, discussed in the next section, further support this conclusion.

Change in compressive strength after different acid exposure periods

After 1, 2 and 5 months of exposure to acid, the concrete cylinders were carefully cleaned and dried at 105°C for 2 days, then compression tests were carried out. Because the surface of the specimens was not flat ~~due~~ to the corrosion, rubber caps were placed

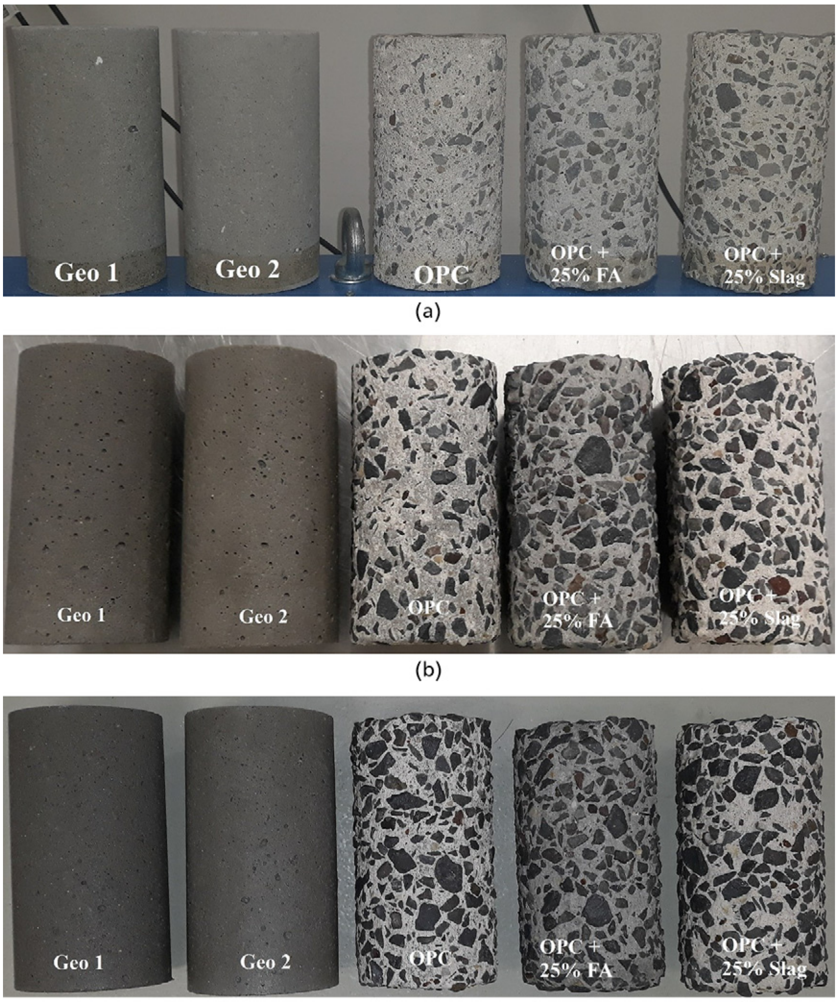

Figure 4. Appearance of concrete specimens after different durations of sulfuric acid exposure: (a) 1 month; (b) 2 months; (c) 5 months

Table 6. Mass loss ~~due~~ to acid corrosion

Concrete type	Exposure time to 5% sulfuric acid: months	Mass loss (standard deviation): %
Geo 1		
	1	1.6 (0.1)
	2	1.4 (0.1)
	5	2.0 (0.1)
Geo 2		
	1	1.4 (0.2)
	2	1.1 (0.1)
	5	1.1 (0.1)
OPC		
	1	6.3 (0.4)
	2	7.7 (0.4)
	5	10.3 (0.6)
OPC + 25% FA		
	1	7.7 (0.5)
	2	10.2 (1.3)
	5	14.2 (3.0)
OPC + 25% slag		
	1	8.1 (0.2)
	2	8.9 (0.6)
	5	11.8 (0.5)

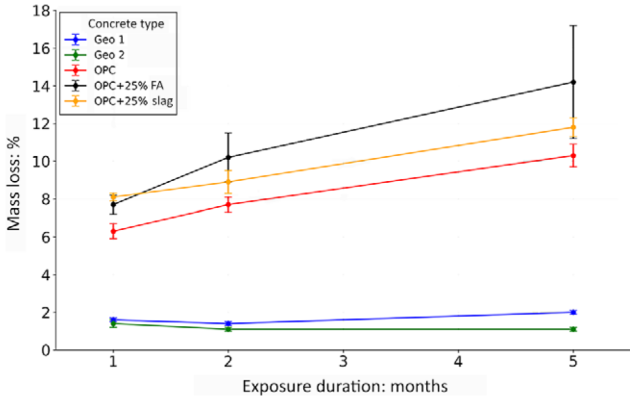

Figure 5. Mass loss ~~due~~ to sulfuric acid corrosion

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on the ends of the specimens to create a smooth surface for the
F6 compressive test, as shown in Figure 6. The changes in compres-
T7 sive strength of the concrete specimens are summarised in Table 7
F7 and plotted in Figure 7. After 5 months of exposure to 5% sulfuric
acid, the concretes containing 25% FA and 25% slag exhibited a 20–33% reduction in compressive strength, whereas the OPC concrete showed a 4.8% increase and the GPCs experienced an increase of 8.7% to 9.8%. The observed increases in compressive strength for the OPC-based concretes and GPCs does not indicate that acid enhances concrete strength; rather, it means that the impact of 5% sulfuric acid over 5 months was minimal, allowing the hydration process in OPC and the activation process in GPCs to continue within the interior of the specimens, leading to a continued increase in compressive strength.

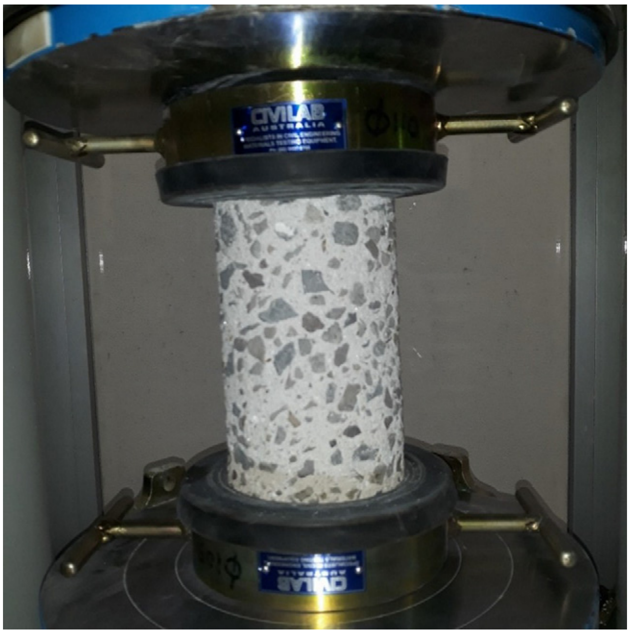

Figure 6. Rubber caps on the ends of a sample in compression test

Table 7. Change in compressive strength of concretes after 5 months of exposure to 5% sulfuric acid solution

Concrete type	Exposure to 5% sulfuric acid: months	Compressive strength (standard deviation): MPa	Change compared with no acid exposure: %
Geo 1			
	0	47.1 (0.7)	—
	1	51.0 (0.9)	+8.3
	2	49.0 (1.1)	+4.0
	5	51.7 (0.9)	+9.8
Geo 2			
	0	49.3 (2.7)	—
	1	48.8 (2.9)	−1.0
	2	52.8 (1.0)	+7.1
	5	53.6 (0.4)	+8.7
OPC			
	0	45.4 (2.3)	—
	1	53.0 (0.7)	+16.7
	2	48.9 (3.1)	+7.7
	5	47.6 (1.3)	+4.8
OPC + 25% FA			
	0	45.2 (2.1)	—
	1	43.2 (2.4)	−4.4
	2	40.7 (1.8)	−10.0
	5	30.3 (7.1)	−33.0
OPC + 25% slag			
	0	43.5 (0.8)	—
	1	42.2 (2.4)	−3.0
	2	38.6 (1.3)	−11.3
	5	34.5 (0.9)	−20.7

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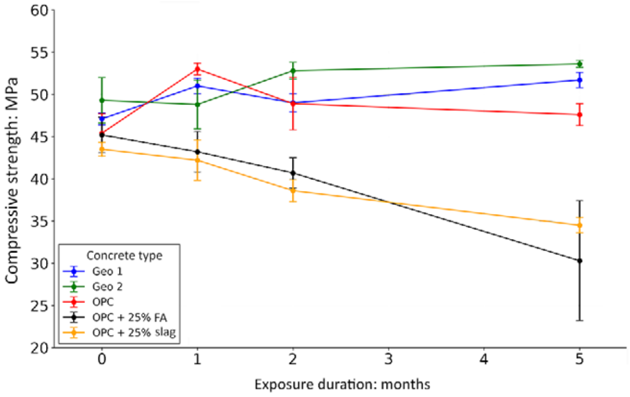

Figure 7. Change in compressive strength of concretes after 5 months of exposure to 5% sulfuric acid solution

Conclusions

This paper provides a comprehensive comparison of the durability characteristics of one-part GPCs and low carbon dioxide concretes against traditional OPC-based systems. The results demonstrate that GPCs, particularly when optimised with the appropriate precursor materials, can offer superior resistance to acid attack, making them suitable for use in harsh environments where chemical exposure is a concern. However, their resistance to chloride penetration was found to vary significantly, underscoring the importance of the careful selection of materials and mix designs tailored to specific durability requirements.

The research also highlights the limitations of the RCPT when applied to GPCs at standard voltages, suggesting that lower voltage testing at 30 V may provide more reliable results. Given the superior acid resistance and potential for lower environmental impact, GPCs represent a promising alternative to OPC-based systems. However, further research is needed to optimise their formulation and develop standardised testing methods that accurately reflect their performance in real-world applications. The results of this study provide valuable insights into the durability performance of GPCs, paving the way for broader adoption of sustainable concrete solutions in the construction industry.

Availability of data and materials

All data generated or analysed during this study are included in this published article.

Authors' contributions

Tran Huyen Vu prepared the manuscript. Yuxuan Yang and Liet Chi Dang revised the manuscript and visualised the data. Vute Sirivivatnanon revised the manuscript and supervised the work.

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AQ5—'reduced species': should this be 'reducing species'?

AQ6—Figure 4 shows OPC + slag concretes, but these have not been mentioned before: please advise.

AQ7—15% FA? Should this be 25% FA?

AQ8—Again we have OPC + 25% slag in Table 6 and Figure 5: why were these not included in the earlier test results?

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