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Research Article

Acid Resistance of Geopolymer Concrete - Literature Review, Knowledge Gaps, and Future Development

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Keywords

Geopolymer concrete,
Reaction mechanism,
Acid resistance,
Strength.

Abstract

Geopolymer concrete, a sustainable and durable alternative to conventional Portland cement-based concrete, has gained significant attention in recent years. Its reduced carbon footprint and superior mechanical properties make it a viable option for various construction applications. However, acid resistance remains a critical area of concern, particularly in environments where exposure to acidic substances is prevalent. This review paper delves into the acid resistance of geopolymer concrete, providing a comprehensive overview of the latest research findings, methodologies, and advancements in the field. The paper commences by exploring the fundamental principles of geopolymer chemistry. Subsequently, the paper meticulously reviews the experimental results of studies investigating the acid resistance of geopolymer concrete. It focuses on the effects of various acids commonly encountered in industrial and environmental settings, such as sulfuric acid, hydrochloric acid, and organic acids. The paper summarizes the key findings from the reviewed literature, highlighting the strengths and limitations of geopolymer concrete in terms of acid resistance. It identifies the factors that contribute to enhanced acid resistance and suggests potential strategies for further improvement. Furthermore, the paper outlines future research directions, emphasizing the need for long-term studies, the development of standardized testing methods, and the exploration of novel geopolymer formulations with superior acid resistance.

1. Introduction

Ordinary Portland Cement (OPC) is a popular binding material in the production of concrete, but it is also responsible for around 8% of global anthropogenic CO2 emissions [2]. As a result, researchers are focusing more on developing environmentally friendly construction materials to curb CO2 emissions from the construction industry [[3] – [9]]. Recently, geopolymer binders (also known as inorganic polymers) have drawn enormous attention and are expected to eventually replace the traditional OPC. In this binder, aluminosilicate materials are activated using an alkali hydroxide/alkali silicate solution to form molecular chains and networks by special polycondensation reactions [10]. As industrial solid waste, these aluminosilicate materials are readily available and relatively abundant. Their use not only reduces the potential for global warming [11], but the physical encapsulation and chemical stabilization of these solid wastes in geopolymer materials (GM), including geopolymer paste (GP), mortar (GPM), and concrete (GPC), also impart a stable network structure that significantly improves their engineering properties [12].

The aluminosilicate materials are classified as "no calcium" (or "little calcium") [[12] – [14]], "low calcium," and "high calcium" [16] precursors according to their calcium content. The common examples are metakaolin, fly ash (FA), and slag, respectively. However, FA and slag are the most common and well-studied source materials to produce GM [17]. The "no" and "low" calcium systems are dominated by sodium aluminosilicate hydrate (N-A-S-H) gels with a pseudo-zeolitic structure. The high calcium system predominantly produces a calcium aluminosilicate hydrate (C-A-S-H) gel with a tobermorite-like structure. However, N-A-S-H and C-A-S-H can coexist in a blended or binary system.

GPC has been reported to have better or equivalent physio-mechanical characteristics to those made of OPC [18]–[21]. The seismic safety of concrete structures is paramount in resisting seismic damage [[22]–[24]]. Recent research has shown that GPC has the potential to replace cement concrete, especially in highly seismic-prone areas [25]. Concrete corrosion is a major cause of premature failure in concrete structures. The corrosion resistance of GPC was also found to be higher than that of cement concrete, as observed from half-cell potential measurements [26] a rapid and non-destructive corrosion evaluation tool for concrete structures [[27], [28]]. However, the response of GMs to harsh environments is influenced by the gel structures present in the system. The hydration product in cement chemistry contains approximately 25% Ca(OH)2, which decalcifies in acidic media and is one of the primary reasons for cement's low resistance to all aggressive environmental factors [29], [30]. While aluminosilicate-rich materials improve the structure of GM gels, they produce less Ca(OH)2 and have higher chemical resistance [31], [32]. Concrete structures could be exposed to various acidic environments during their lifetime. The acid environments can be found in many forms [33], including- sewage and industrial wastewater, soil may contain huminous acids, organic and inorganic acids in sea-water owing to bacteriological activity, air pollution by the oxides of carbon, sulfur, and nitrogen (CO2, SO2, NOx), and acid rain [34]. The deterioration of cement concrete (CC) begins when acid dissolves the binder and calcareous aggregates [35]. In most cases, the reaction produces calcium salts, which are water-soluble by nature. While depolymerization of aluminosilicates and the liberation of silicic acid are the reasons for the acid-associated damage in GPC [36]. The damage is exacerbated with time as the pH of concrete drops in an acidic environment. The severity of the damage is also affected by the acid concentrations. Owing to the nature of the hydration products, GPC shows better acid resistance than CC, including those produced with High-Ca precursors [37]. Visual appearance, mass loss,

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compressive strength loss, [38] change in density [39], and depth of corrosion [40] are some common indicators used to assess the extent of acid damage.

Globally, there is a growing demand for maintenance-free and long-lasting structures, which makes the durability of GM exposed to harsh environments a vital issue for its field applications. The durability research of GM has thus emerged as a pressing need in the construction sector. Numerous studies have been conducted over the last few decades to determine the durability of geopolymeric systems using different precursors. Despite having a diverse scientific background, the question of whether the available scientific background is sufficient for the filed application for GM remains unanswered.

This study provides a critical and comprehensive review of the published literature on the acid resistance durability of GM. This paper focused on presenting a separate discussion on the durability responses of geopolymer paste (GPP), mortar (GPM), and concrete (GPC) produced solely from fly ash and/or slag. It is intended to: (1) advance our understanding of the current state of knowledge of GM's durability in terms of acid resistance; (2) provide a synopsis of gap analysis to identify and prioritize knowledge gaps in published data; and (3) develop new research lines for other researchers to pursue. The study will aid in understanding the potential for GM to be used in civil engineering applications.

2. Summary of published information

2.1. Geopolymer concrete (GPC)

Researchers have conducted extensive studies to evaluate the acid resistance of FA/slag-based GPC. Lavanya and Jegan (2015) observed that the strength loss of CC after 45 days of exposure to H2SO4 solution is higher (28% compared to 20%) than that of high calcium FA-GPC [41]. Also, the fall in density is greater for cement concrete (CC) than for GPC. FA-GPC loses only a fraction of its mass (0.4-0.5%) after 90 days of H2SO4 exposure compared to CC (18-25%) of identical strength grades as noted by Sathia et al. (2008) [42]. Additionally, numerous studies support that FA-GPC has substantially higher acid resistance than CC [43], [44], [45], [46], [47]. The low calcium content of FA is the reason for this high resistance [48]. The loss of calcium ions from the C-S-H gel causes the CC surface to soften and degrade. While the formation of CaSO4 is less in FA-GPC, which makes it more resistant to H2SO4. According to Nguyen et al. (2013), curing condition affects the acid resistance of FA-GPC [49]. Heat-cured GPC was found to perform better in an HCl acid environment than CC. According to Song et al. (2005), FA-GPC has strong acid resistance (H2SO4) regardless of curing conditions, whether ambient or heat cured [50]. The degradation trend is almost similar. Process modification also improves acid resistance as reported by Adak and Mandal (2019) [51]. In H2SO4 solution, the mass loss of GPC prepared by heat activation of FA and alkaline liquid at 60 °C with continuous stirring for 45 minutes had a lower mass loss than GPC heat-cured at 60 °C for 48 h. While Alireza et al. (2021) demonstrated better acid resistance of FA-GPC when NaOH was added to the fresh mix containing KOH and Na2SiO3, after 3 minutes of mixing [52]. Kumaravel and Girija (2013) investigated the effect of NaOH concentrations (8, 10, 12, and 14 M) on H2SO4 acid resistance of FA-GPC [53]. Optimized acid resistance was observed at 12 M concentration. Singh et al. (2019) also demonstrated that FA-GPC performs better in an H2SO4 environment when prepared with a high concentration of NaOH [54]. Nonetheless, they concluded that the performance of GPC is equivalent to that of CC. Use of granulated lead smelter slag also influences the acid resistant characteristics of FA-GPC. According to Albitar et al. (2017), H2SO4 has a greater negative impact on CC, reducing compressive strength by 26.6% compared to 10.9% and 7.3% reductions in fly ash-GPC and FA-GPC incorporated granulated lead smelter slag, respectively [55]. Incorporation of recycled asphaltic concrete aggregates in FA-GPC enhances H2SO4 acid resistance owing to have partial coating with asphalt as found by Wongkvanklom et al (2021) [56]. Also, the acid resistance of GPC increases with a lower solution-to-binder (s/b) ratio. Another way of improving H2SO4 acid resistance of FA-GPC is the inclusion of OPC as mentioned by Mehta and Siddique (2017) [57]. The ideal dose of OPC, however, is 10%; above that, resistance decreases due to the formation of additional CaSO4. Steel fibre improves acid resistance by increasing the density of GPC as described by Ganesan et al. [48] whereas rubber particles increase porosity and thereby reduces acid resistance as demonstrated by Luhar et al. [58]. Kannapiran et al. (2013) found through their investigation that reinforced FA GPC exhibits enhanced performance in acidic environments, which aligns with the observations made for plain FA GPC [59]. Few studies have investigated the effect of slag incorporation on acid resistance [39], [60], [61]. Bellum et al. (2020) evaluated the acid durability loss factor (ADLF) to investigate the acid resistance of FA-GPC; greater ADLF values result in poor performance [60]. The ADLF of FA-GPC was found to decrease as the slag content and s/b ratio increased. Nagajothi et al. (2022) mentioned that the performance of binary blended GPC (FA:Slag = 80:20) in terms of strength loss in an H2SO4 environment was similar to that of CC [61]. The findings of Kumar et al. (2022) support this conclusion, who produced binary-blended GPC with 25% of slag [39]. However, the mass loss behaviors of binary GPC in Nagajothi et al. (2022) and Kumar et al. (2022) are different. In the former study, GPC lost more weight when exposed to acid than CC, while in the latter, the scenario was just the opposite. In the case of slag-GPC, the most influential parameter on H2SO4 resistance characteristics was discovered to be the NaOH concentrations followed by s/b ratio [62]. Specimens prepared with a high concentration of NaOH were found to be more resistant to acid attack (H2SO4, HNO3, and HCl) than specimens prepared with a lower NaOH concentration. This might be due to the higher alkalinity and the stronger pore structure of the concrete. When compared to CC, slag-GPC outperforms CC in the H2SO4 environment [[63], [47]]. It also performs better in an acetic acid environment [38]. According to Elyamany et al. (2020), the slag GPC demonstrated superior resistance to sulphuric acid attack when compared to the samples that contained fly ash [64]. Table 1 summarizes the published literature on acid resistance of geopolymer materials.

2.2. Geopolymer mortar (GPM)

Fernandez-Jimenez et al. (2007) observed a substantial decrease in strength of NaOH-activated FA GPM in 0.1 N solution of HCl, while waterglass (NaOH + Na2SiO3) activated mortars showed strength fluctuations [65]. This strength loss is attributed to the dealumination of FA GPM in acidic media. However, geopolymer mortars exhibited a better performance than OPC mortars. According to Vafaei et al. (2019), FA GPM exhibits superior durability in an HCl environment when compared to Portland cement and high alumina cement mortars [66]. However, in H2SO4, all three mortars demonstrated a greater degree of deterioration compared to HCl, as evidenced by the decrease in weight and strength. Chindaprasirt et al. (2013) found that H2SO4 resistance of FA GPM can be enhanced through microwave treatment [67]. Another way to improve the H2SO4 resistance is to increase the alkali content of the activator used, as noted by Thokchom et al. (2009) [68]. Increasing the alkali content can also enhance the HNO_3 resistance of FA GPM in terms of strength loss; however, it is noteworthy that the rate of dealkalization appears to be faster in HNO_3 [69]. This study also revealed that the behavior of FA GPM in terms of weight loss differs in H2SO4 and HNO_3 with varying alkali content. Degirmenci (2017) investigated the impact of the Na2SiO3 to NaOH ratio on the acid resistance of FA, slag, and FA-slag GPM [70]. The results showed that weight loss was gradually reduced with an increase in the Na2SiO3/NaOH ratio for all specimens when immersed in HCl and H2SO4 acids. The study also revealed that the Na2SiO3/NaOH ratio was effective in determining the residual compressive strength of the geopolymer mortars under both acid exposures. A higher ratio of Na2SiO3/NaOH led to higher residual compressive strength. In H2SO4 media, FA-GPM experienced a greater degree of neutralization and loss in alkalinity as compared to sulphate-resistance Portland Cement mortars as observed by Khan et al. (2020) [71]. However, it was observed that to sulphate resistance Portland Cement mortars exhibited a greater degree of mass loss and reduction in strength than FA-GPM. Mohamed et al. (2022) found that immersion of slag GPM and binary blended GPM in H2SO4 did not cause mass loss but rather resulted in mass gain due to the formation of hydration and geopolymerization products in a closed curing environment [72]. Prusty and Pradhan (2022) demonstrated that exposure of binary GPM specimens to acidic environments resulted in a higher deterioration factor than the strength measured during 28 and 180 days of ambient curing. GPM prepared from a fly ash/GGBS blend of (55:45) displayed poor resistance to H2SO4 and HCl solutions. In contrast, GPM made from fly ash/GGBS blend (85:15) showed better resistance to acid solutions, likely due to the lower deterioration of aluminosilicate gels. GPM specimens prepared with an s/b ratio of 2.5 exhibited higher permeable voids and maximum mass loss but comparatively lower strength loss when subjected to acid solutions. The study of Zhang et al. (2018) found that as the fly ash/slag ratio varied from 100/0 to 0/100, all samples experienced a decrease in compressive strength during acid attack. Pure fly ash binder was the most resistant mixture, retaining 83.5% strength after 28 days of exposure. Acid attack decreases Al/Si atomic ratios in the corroded layer, with smaller reduction ratios observed as the slag content increases. This indicates that a dense matrix is advantageous in preventing the loss of aluminum from gel structures. Bernal et al. (2012) found that the compressive strength of slag GPM remained relatively unaffected during exposure to mineral acids (HCl, H2SO4, and HNO_3). Still a reduction in strength and an increase in pore volume were observed when exposed to CH3COOH [73].

2.3. Geopolymer paste (GPP)

According to Lakhssassi et al. (2019), when subjected to H2SO4, FA GPP gained mass, while the OPC paste experienced a loss of mass. The authors attributed the lower acid resistance of OPC to the formation of ettringite and gypsum [74]. As per Bakharev's (2004) findings, the FA GPP prepared using NaOH as the activator demonstrated superior performance compared to the paste prepared with Na2SiO3 or a combination of NaOH and KOH. This was attributed to the formation of a more stable cross-linked aluminosilicate polymer structure in the former material [36]. Temuujin et al. (2011) reported that the acid resistance properties of the FA GPP could be enhanced by controlling the quantity of quartz impurity and the level of iron oxides present in the fly ash [75]. This regulation was found to assist the geopolymer calcination process. Furthermore, it has been found that the acid and alkali resistance of FA-GPP can be significantly increased by calcination at 600°C. The inclusion of Ca(OH)2, on the other hand, was found to increase the mass loss of FA GPP in acid media (HCl and H2SO4) as observed by Buchwald et al. (2005) [76]. Several studies have studied the effect of slag incorporation in FA binders. According to Aiken et al. (2018), the addition of slag to FA GPP decreases porosity while increasing the susceptibility of the resulting reaction products to H2SO4 attack [77]. Moreover, the study revealed that raising the alkaline activator dosage in FA GPPs has an insignificant effect on their resistance to H2SO4. However, geopolymer binders exhibited greater resistance to H2SO4 compared to their Portland cement counterparts.

Table 1. Summary of the research on the acid resistance of GPC

Ref.	Precursor		Activator	Curing	SP	Focused area of study	Test method/ environment
	Primary	Secondary					
[48]	FA	–	SH, SS	60 °C – 1 d	N,W	Plain and fibre reinforced GPC	ASTM C 452-02 (3% H_2SO_4)
[56]	FA	–	SH, SS	25 °C	–	Recycled asphaltic con-crete aggregate; s/b ratio	ASTM C267-20 (1% H_2SO_4)
[64]	Slag	FA	SH, SS	70 °C – 2 d	N	H_2SO_4 acid resistance	pH= 1.5 H_2SO_4
[41]	FA	–	SH, SS	28 – 31 °C	–	Durability of high calcium FA-GPC	2% H_2SO_4
[42]	FA	-	SH, SS	85 °C– 1 d	W	Durability of low calcium FA-GPC	3% H_2SO_4
[55]	FA	Slag	SH, SS	Ambient- 90 d	SP, W	Durability of geopolymer and ordinary concretes	3% H_2SO_4
[61]	FA	Slag	SH, SS	Ambient	N	Durability of blended GPC	ASTM C 642 5% H_2SO_4
[52]	FA	-	SH, KH, SS	90 °C– 1 d	C	Different activators	pH 1 H_2SO_4
[60]	FA	Slag	SH, SS	32 °C	-	Slag and AAS/b ratio	ASTM C 267-01 5% H_2SO_4
[58]	FA	–	SS, SH	90 °C, 2d	N, W	Durability of rubberized GPC	3, 5, 10% H_2SO_4
[62]	Slag	-	SH, SS	27 ± 3 °C	N	Mix design parameters	5% HCL, H_2SO_4, and HNO_3
[43]	FA	-	SH, SS	60 °C- 1d	SP, W	Durability of GPC and CC	10% H_2SO_4
[63]	Slag	-	SH, SS	27 °C	N	Copper slag as fine aggregate	pH 1 H_2SO_4
[47]	FA Slag	-	SH, SS	-	SP, W	Acid and sulphate resistance of FA/Slag GPC	5% H_2SO_4
[39]	FA	Slag	SH, SS	60 °C- 1d	N,W	Different durability characteristics	5% H_2SO_4
[38]	Slag	-	SH, SS	Water	N	Acid attack	pH 4 CH_3COOH
[57]	FA	-	SH, SS	80 °C– 24 h	N	Acid resistance	2% H_2SO_4
[49]	FA	-	SH, SS	80 °C- 10 h	W	Acid Resistance	1, 2, 4 M HCl
[50]	FA	-	SH, SS	23 & 70 °C- 1d		Curing	10% H_2SO_4
[44]	FA	-	SS, SH	60 °C- 1 d	-	Sulfuric acid resistance	2% H_2SO_4
[45]	FA	-	SS, SH	85 °C- 1 d	-	Sulfuric acid resistance	3% H_2SO_4
[54]	FA	-	SS, SH	600°C- 1 d in hot air oven	-	NaOH concentration	5% H_2SO_4
[46]	FA	-	SS, SH	40- 90 °C, 12 h	-	Acid resistance	100% CH_3COOH; 20% HNO_3, HCl, H_2SO_4
[51]	FA	-	SS, SH	27; 60 °C- 2 d		Process modification	3% H_2SO_4
[53]	FA	-	SH	60 °C- 1 d		NaOH molarity	0.5, 1, 2% H_2SO_4
[59]	FA	-	SS, SH		-	Reinforced concrete durability	10% H_2SO_4; 5% (HCl + H_2SO_4)

d= day; nS= nano-silica; MK= metakaolin; RH= relative humidity; SH= sodium hydroxide; KH= potassium hydroxide; SS= sodium silicate; LS= lime slurry; SC= sodium carbonate; mSS = sodium metasilicate; AN-mSS = anhydrous sodium metasilicate; SP= superplasticizer; N = naphthalene-based SP; C = poly carboxylic ether-based SP; W= water; GGF= ground glass fibre; Ms = SiO_2/Na_2O by mass; FT-IR= Fourier transformation infrared spectroscopy

Lloyd et al. (2012) stated that the presence of calcium, which can be provided by either Class C FA or slag, as well as high alkali concentrations, has a positive effect on acid resistance (H_2SO_4, HNO_3) [78]. The improved acid resistance of these binders is attributed to the finer and more complex pore networks, which result in reduced mass transport rates. Also, under the experimental conditions, the resistance to acid of the binders was not significantly affected by the type of alkali (Na, K, or an equimolar mixture of Na and K) or the presence of aggregate, according to the findings of the study. Lee and Lee (2016) indicated that the addition of slag to the binder increases its susceptibility to sulfuric acid attack [79]. The authors identified two reasons for the deterioration of the binary blended system. Firstly, SO42- can penetrate through the surface of the blended binder, which is related to permeable voids and water absorption rate. Secondly, the reaction products present in the binary system are prone to corrosion due to the difference in sulfuric attack resistance between the C-A-S-H gel and the N-A-S-H gel. At high sulfuric acid concentrations (pH=1), the degradation of blended binder starts with an ion exchange reaction between sodium and calcium cations in the framework and H+ or H3O+ ions from the solution as explained by Allahverdi and Škvára (2005) [80]. This reaction, along with an electrophilic attack on polymeric Si-O-Al bonds by acid protons, constitutes the first step. In the second step, calcium ions that have diffused towards the acid solution react with sulphate anions, forming and depositing gypsum crystals within the corroding layer. When exposed to nitric acid, binary system is attacked through an electrophilic process in which acid protons attack polymeric Si-O-Al bonds, leading to the expulsion of tetrahedral aluminum from the aluminosilicate framework [81]. These vacancies in the framework are then mainly filled with silicon atoms, resulting in the formation of a relatively hard but brittle, imperfect, highly siliceous framework. Generally, slag binder shows better sulphuric acid durability than that of blended binder. According to Shi and Stegemann (2000), Ca was found to be more sensitive to a pH decrease than Si, but less sensitive than Al [40] as studied on slag GPP. The experimental results suggest that alkali-activated slag pastes undergo corrosion at a slower rate than OPC pastes in CH_3COOH [[82], [40]]. Bingol et al. (2020) observed an increase in the compressive strength of water-cured slag GPM specimens when subjected to H2SO4 media. The authors utilized a sodium metasilicate activator in their investigation [83].

3. Critical discussion

The general discourse indicates that FA, slag, and FA-slag GPC exhibit superior resistance to H2SO4 acid when compared to CC. In contrast to slag or binary GPC, FA-GPC exhibits significantly higher resistance to acid attack, primarily due to the relatively low calcium content of its constituent materials. Limited research has shown that the performance of FA-GPC is comparable to that of CC. Under HCl exposure, specimens cured under heat perform superior to those cured under ambient conditions. Nonetheless, FA GPC demonstrates better acid resistance to H2SO4 regardless of the curing conditions. Observations indicate that the resistance to acid attack of FA GPC can be enhanced through process modifications, such as utilizing high NaOH molarity, delayed addition of NaOH to the fresh mix, lowering the s/b ratio, and improving the density of the mixture via steel fibers. Moreover, the use of NaOH as an activator has been observed to yield better performance of the FA binder compared to Na2SiO3 or a combination of hydroxide activators, such as NaOH and KOH. Reducing the s/b ratio and utilizing high NaOH molarity promotes an improvement in acid resistance in binary GPC. The effect of slag incorporation in the FA system remains somewhat contentious. On the one hand, augmenting the slag content in GPC has been found to enhance its acid resistance. On the other hand, in a different study of GPM, it was observed that acid resistance decreases with increasing slag content. It can also be seen that incorporating up to 15% slag in FA GPM yields optimal results for acid resistance. Additionally, the mass loss behavior of blended systems exhibits some inconsistencies with the performance of CC, as both mass loss and mass gain have been observed for slag and binary GPC under H2SO4 exposure. For slag GPM, strength increases have also been observed in acid exposure. The responses of various binders to acid exposure vary significantly. For instance, FA GPM degrades to a greater extent under H2SO4 than HCl, and its acid resistance performance, as indicated by weight loss, varies with the alkali content when exposed to H2SO4 and HNO3. Conversely, slag GPM demonstrated relatively minimal impact when exposed to mineral acids (HCl, H2SO4, and HNO3), although exposure to CH3COOH led to a decrease in strength and an increase in pore volume. The Na2SiO3/NaOH ratio is an important factor influencing the acid resistance of geopolymer binders. Acid resistance in terms of weight loss was observed to increase gradually with an increase in the Na2SiO3/NaOH ratio for all specimens, including FA, slag, and FA-slag, when immersed in HCl and H2SO4 acids.

4. Contribution of GPC to environment

GPC is an innovative and environmentally friendly alternative to traditional Portland cement-based concrete. It is making substantial contributions to environmental sustainability by emitting significantly fewer greenhouse gases during production than conventional concrete [1]. Conventional concrete relies on the energy-intensive production of clinker and releases substantial carbon dioxide emissions. In contrast, GPC is produced using industrial waste products, such as fly ash and slag, which reduces the need to mine and process virgin raw materials. It has been reported that the use of coal-combustion waste materials such as fly ash in GPC manufacturing can reduce CO2 emissions by 25%-45% [1]. Additionally, GPC curing requires less energy than cement curing.

5. Knowledge gaps

The effect of slag incorporation in the FA system remains a topic of debate, both for GPC and GPM. This raises the question of whether the behavior observed in GPM is representative of that in GPC. Additional investigation is necessary to establish a correlation between the presence of calcium, engineering characteristics, and durability properties in geopolymers. Such a study would expand readers' comprehension of the role of calcium in these materials. Several measuring parameters for acid resistance can be found in the literature, including visual appearance, mass change, strength change, density change, and corrosion depth. Different researchers have adopted different measuring tools to check the acid durability characteristics of geopolymer materials. Whether all measuring parameters present similar resistance or are correlated remains to be investigated. Studies on GPC have shown that acid resistance characteristics can vary for weight change and strength change. The literature reports several parameters for measuring acid resistance in geopolymer materials, including visual appearance, mass change, strength change, density change, and corrosion depth. Researchers have used various measuring tools to evaluate the acid durability properties of geopolymer materials. It is worth exploring whether these measuring parameters exhibit similar resistance or are correlated. For instance, studies on GPC have shown that the acid resistance characteristics can differ depending on whether weight change or strength change is measured. An in-depth understanding of the acid attack/resistance mechanism is necessary. In addition to mass gain, an increase in strength was also observed for slag GPM specimens exposed to acid media.

6. Conclusion

The goal of this paper was to undertake a thorough review of the acid resistance performance of geopolymer materials (GMs), ranging from paste to concrete. The paper reviewed the published literature on acid resistance to determine whether the available scientific knowledge is sufficient for GPC's field applications. The review found that while numerous studies have demonstrated GPC's superior performance over ordinary Portland cement (OPC), there is still a lack of credible data on GPC's acid resistance performance. This indicates that GPC has a more complex durability mechanism than OPC concrete due to the variability of precursor compositions and the absence of a unified mix design approach. This complexity leads to significant scientific challenges that require a better understanding of the setting reactions involved, the relationship between mix design characteristics, and the short- and long-term mechanical properties, as well as overall durability. This study highlighted current gaps in research, indicating that the existing knowledge on GPC's acid resistance durability is inconsistent. In conclusion, this paper suggests that further research is necessary to determine GPC's long-term performance with respect to acid resistance and to establish its suitability for field applications.

Declaration of Conflict of Interests

The author declares that there is no conflict of interest.

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