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Utilization of recycled concrete powder in the production of geopolymer mortars based on fly ash

Keywords: fly ash, FA, cement, OPC, recycled concrete powder, RCP, geopolymer mortars

Introduction

Concrete is the second most utilized material on earth, just after water, and it comprises about 20% portland cement (PC). Aa amount of 1 ton of PC produces approximately 1 ton of carbon dioxide (CO₂) emissions into the atmosphere (Davidovits, 1991). Consequently, researchers continue to study more viable and eco-friendly building materials that can lead to a diminished energy consumption and also minimize environmental effects. Geopolymers are a new binder that has the potential to substitute portland cement in concrete works (Ababneh et al., 2020). Geopolymers are synthetic alkali aluminosilicate materials formed through the reaction of aluminosilicate substances with aqueous alkaline solutions, such as sodium hydroxide or silicate solutions (Davidovits, 2020). Geopolymer concrete (GPC) is an innovative, sustainable, and eco-friendly binding agent derived from geological raw materials or by-products containing aluminosilicates, such as calcined kaolin clay (CKC), fly ash (FA), red mud,

and ground granulated blast furnace slag (GGBFS), which entirely substitute cement in concrete (Kumar, 2015).

Wan et al. (2023) examined the mechanical and microstructural characteristics of cement-based products using recycled powder (RP) with high replacement rates (70–100%). It was found that compressive strength decreased significantly with the increase in the RP content, but alkali activation showed significant enhancement. Compressive strength also increased by more than 100% at 70% replacement of RP under optimum sodium silicate modulus conditions. At full replacement, the alkali-activated mixes exhibited a high proportion of strength recovery relative to the unactivated ones; therefore, these results showed that alkali-activated RP would be a viable, sustainable binder in cementitious systems.

Midhin et al. (2023) study included a systematic review of ultra-high-performance geopolymer concrete (UHP-GC), addressing its mechanical, microstructural, and physical aspects. It was found that when slag was partially replaced with 2,535% silica fume, the optimal ratio of Na_2SiO_3 to NaOH was 35, and the molarity of NaOH was 16M, resulting in better compressive and tensile strength. The paper has highlighted that an optimized mix design improves the formation of geopolymeric gel and porosity, which makes UHP-GC a high-strength and sustainable substitute in current concrete technology.

The current improvements in geopolymer sturdiness were discovered by Alahmari et al. (2023). They are water absorption, temperature resistance, sulfuric, sulfate, chloride ion penetration, and freeze-thaw resistance. The analysis screen has implications for a great life of geopolymer concrete compared with conventional cement-majority-based concrete. Moreover, this analysis presents suggestions and highlights the capacities of research on the geopolymer concrete that is closely related.

Razak et al. (2020) evaluated the compressive strength of geopolymer paste with FA and ordinary portland cement (OPC) paste under the effects of porosity and water absorption. Using the Brunauer–Emmett–Teller technique, the researchers found that geopolymer paste exhibited lower surface area, pore volume, and pore length compared with OPC. The geopolymer was based on micropores as its main microstructure, while OPC used mesopores. The decreased pore length and water absorption, therefore, enhanced the compressive strength of geopolymer to 76.7 MPa after 28 days. The authors concluded that geopolymers based primarily on FA show great resistance to wear and the environment and superior to the conventional OPC paste.

Sharma et al. (2022) explored the potential of the recycled fine powder (RFP) being used as an activator and partial alternative for FA within the production

of geopolymer mortar. The test involved unique alternative ranges (10–50%) and kept the combination parameters consistent, including an alkali-to-binder ratio of 0.45, a 12M sodium hydroxide molarity, a sodium silicate-to-sodium hydroxide ratio of 2, and a water-stable ratio of 0.35. The study compared workability (slump flow, setting time), mechanical strength, and durability based on the tests of compressive strength, water absorption, porosity, and drying shrinkage under ambient and heat-curing conditions. It was found that a 30% replacement of FA with RFP gave optimal strength and durability-enhancing results. Microstructural analysis revealed the presence of calcium-rich compounds and an additional $\text{Na}_2\text{O}-\text{Al}_2\text{O}_3-\text{SiO}_2-\text{H}_2\text{O}$ gel phase, which provided a denser structure and improved the overall performance of the geopolymer mortar.

Zhang et al. (2023) studied the mechanical, durability, and microstructural properties of geopolymer recycled aggregate concrete (GPRAC). The researchers have found that the performance metrics, including compressive and flexural strength, elastic modulus, and freeze-thaw resistance, could be significantly enhanced through the optimization of curing temperature, precursor combinations, and mix proportions. Recycled aggregates increased the use of better recycled aggregates, which minimized porosity and water absorption by about 19% and 25%, respectively, with no reduction in density. In general, the research proved that GPRAC can be used to address the needs of the engineering profession, minimize carbon emissions, and establish low-carbon and sustainable construction methods.

Purpose and goals of research

This paper will examine the possibility of using concrete waste powder as a partial replacement material in FA-based geopolymer mortars, and more specifically, its ability to improve sustainability while maintaining acceptable mechanical and durability properties.

The targeted objectives of the research are to:

- Assess how the addition of concrete waste powder would alter the compressive and flexural strength of the FA-based geopolymer mortars.
- Measure the performance of the developed geopolymer mortars in terms of acid resistance by mass loss and strength retention.
- Examine the microstructure of the geopolymer mortars with scanning electron microscopy (SEM) and correlate it with mechanical and durability behavior.
- Determine the appropriate amount of replaced concrete powder that would compromise between mechanical performance, durability, and microstructural integrity.

- Enhance the creation of low-carbon and sustainable construction materials by fostering the valorization of concrete waste in geopolymer systems.

Scientific novelty and contribution

The novelty of this research lies in the systematic use of the recycled concrete powder (RCP) in FA-based geopolymer mortar systems, whereby RCP was experimentally explored both as a partial substitution of the binder and the fine aggregate, with the latter studies within the same research. Contrary to the majority of the earlier conducted studies that considered one specific replacement position or low rates, this study assessed high replacement ratios (up to 75%) and emphasized the unique effects of RCP, given the functional role in the mix design.

Furthermore, this paper offers a comparative evaluation of the OPC-based mortars and alkali-activated FA mortars with RCP, providing a complete insight into strength progression, durability, and microstructural transformation of these mortars under the same curing conditions. Another innovation made is the finding that compressive strength retention is a more credible indicator of acid resistance than mass loss, as evidenced by the SEM results that distinguish internal microstructural degradation processes (gel dissolution and micro-cracking) and surface erosion.

The results not only provide definite levels of performance for sustainable use of RCP in geopolymer mortars but also suggest the most optimal mix strategies to balance mechanical performance, durability, and environmental performance, which adds new knowledge on designing eco-effective cementitious materials to work in aggressive exposure conditions.

Experimental work

Material

The materials that were used in this study were OPC with the brand Almas, following the Iraqi standard IQS 5/2019 (Central Organization for Standardization and Quality Control [COSQC], 2019), and FA type F obtained from Eurobuild Constructions Chemicals and examined according to the ASTM C618-22 standard (ASTM International, 2022). The alkali activator was liquid sodium silicate with alkali modulus ($M_s = \text{SiO}_2/\text{Na}_2\text{O}$) equal to 3.3, with silicon dioxide (SiO_2) content of 43.25% and sodium oxide (Na_2O) content of 13.1%. The alkalinity was adjusted

to 1.5 by adding sodium hydroxide (NaOH) flakes with 99% purity to the sodium silicate solution to adjust the total alkalinity within the desired range for alkaline polymerization. The activator was used in 15% (as solid content) of the binder. The chemical and physical properties of the binders are shown in Table 1.

TABLE 1. The physical and chemical properties of cement and fly ash used in this study

Specification	Cement	Fly ash
Silica (SiO ₂) content [%]	20.90	48.15
Alumina (Al ₂ O ₃) content [%]	6.20	18.87
Iron oxide (Fe ₂ O ₃) content [%]	3.10	4.59
SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃ content [%]	–	–
Sulfate (SO ₃) content [%]	1.75	1.53
Lime (CaO) content [%]	62.30	14.52
Magnesia (MgO) content [%]	2.70	2.48
Loss on ignition (LOI) [%]	3.3	6.0
Specific gravity [-]	3.15	2.32

Source: own work.

Moreover, aluminum foil was used to increase the solubility and reactivity of FA. Aluminum foil was incorporated into very small amounts as an auxiliary aluminum source to enhance the geopolymerization process. Under highly alkaline conditions, metallic aluminum reacts with hydroxide ions and contributes to the formation of soluble aluminate species (Al(OH)₄⁻), which increase the availability of reactive aluminum necessary for aluminosilicate gel formation (Duxson et al., 2007; Davidovits, 2020). Previous studies have demonstrated that the introduction of additional aluminum sources, such as metallic aluminum powder or soluble aluminate compounds, can accelerate geopolymerization kinetics and promote matrix densification, particularly in FA-based geopolymer systems cured under ambient conditions (Provis & van Deventer, 2014; Ariffin et al., 2021). The dosage of aluminum foil was carefully controlled to avoid excessive gas formation associated with aluminum–alkali reactions and was kept constant across all mixtures to ensure consistency and comparability of results. RCP obtained from different types of demolished cubes was ground into fine materials that were thoroughly mixed and passed through a 600-micron sieve and used as a partial replacement for binder, as shown in the mix details presented in Table 2 and Figure 1. The water-to-binder ratio was 0.45 for all mortars, whereas the binder-to-sand ratio was 1 : 2.75.

TABLE 2. Mix proportions

Mix ID ^a	Fly ash [kg]	Portland cement [kg]	Fine aggregates [kg]	Water [kg]	Sodium silicate ^b [kg]	Aluminum [g]	Recycled concrete powder [kg]	Super-plasticizer [%]
P100 (S100) ref1	–	4.6	9.2	2	–	–	–	1
P100 (S75W25)ref2	–	4.6	6.9	2	–	–	2.3	1
P100 (S50W50)ref3	–	4.6	4.6	2	–	–	4.6	1
F100 (S100)	4.6	–	9.2	2	1.5	2.5	–	–
F100 (S75W25)	4.6	–	6.9	2	1.5	2.5	2.3	–
F100 (S50W50)	4.6	–	4.6	2	1.5	2.5	4.6	–
F75 W25(S100)	3.45	–	9.2	2	1.5	2.5	1.15	–
F75 W25(S75W25)	3.45	–	6.9	2	1.5	2.5	3.45	–
F75W25(S50W50)	3.45	–	4.6	2	1.5	2.5	5.75	–

^aMix ID code: P – portland cement, S – sand, W – concrete waste powder, F – fly ash, ref1–3 mix – reference samples, P100(S50W50) means 100% of OPC + (50% of sand + 50% of recycled concrete powder).

^bM_s = 1.5.

Source: own work.



FIGURE 1. Materials used in this study: a – ordinary portland cement, b – fly ash, c – recycled concrete powder; d – sodium silicate (activator solution)

Source: own work.

Curing conditions

After casting, all specimens were placed in an oven and cured inside the molds at a temperature of 80°C for 24 h to promote geopolymerization. Following heat curing, the specimens were removed from the oven and demolded after 24 h. The samples were then stored under ambient laboratory conditions at a temperature of 25 ±2°C until the designated testing ages. This combined curing regime (initial heat curing followed by ambient curing) was adopted to ensure adequate geopolymer gel formation at early ages while allowing subsequent strength development under realistic service conditions.

Mix proportions

The alkaline solution used in this study was prepared by mixing sodium silicate liquid with NaOH to adjust the alkali modulus ($M_s = \text{SiO}_2/\text{Na}_2\text{O}$) from 3.3 to 1.5, followed by the addition of mixing water and aluminum foil. The components were thoroughly stirred for 10–15 min using a continuous mixer under constant heating conditions, then left to rest for 24 h before casting mortar to obtain a homogeneous alkaline activator.

The silicate modulus of the alkaline activator ($M_s = \text{SiO}_2/\text{Na}_2\text{O}$) was adjusted to 1.5 to provide a balanced ratio between soluble silica and alkalinity. This value is widely reported as favorable for FA-based geopolymer systems, as it enhances dissolution of aluminosilicate species while facilitating the formation of a compact and stable geopolymeric gel under ambient curing conditions. A high M_s could cause a high viscosity ratio and restrict reaction kinetics, and a low M_s could cause inadequate silica supply and gel connectivity.

In the current paper, the concentration of the NaOH was chosen at range of 12–16M, as this has been commonly reported in the literature to be effective when it comes to using FA-based geopolymer binders, especially when allowed to cure under ambient conditions. An increase in molarity increases the dissolution of aluminosilicate species and the geopolymerization rate, whereas decreasing it can lead to aluminosilicate species not being fully activated and becoming weak. In this study, NaOH molarity was kept constant to limit the number of variables and to focus on the influence of concrete waste powder content and replacement strategy.

The dry ingredients (cement, sand, and RCP) were first mixed for 3 min using an eight-liter batch mixer. Separately, FA was blended with the prepared alkaline solution and mixed for 3 min for consistency. Then this mixture was combined

with the dry ingredients and mixed for at least 5 min. Fresh properties were then tested accordingly.

For the hardened properties, molds were washed and oiled, and the mortar was cast and compacted on a vibrating table, and the ASTM C109/C109 M-16a standard on compressive strength (ASTM International, 2016) and ASTM C348-98 standard on flexural strength (ASTM International, 1998) were followed. The specimens were then wrapped with nylon to avoid evaporation (Al-Bayati et al., 2022). The samples were kept at room temperature in covered plastic bags until the predetermined ages of 7 days and 28 days.

The mix proportions were selected to ensure consistency and allow direct comparison between different replacement strategies. The water-to-binder ratio (0.45) and binder-to-sand ratio (1 : 2.75) were maintained constant for all mixtures to minimize the influence of workability variations. The alkaline activator content was fixed at 15% of binder with an alkali modulus of 1.5, based on reported optimal ranges for FA-based geopolymer mortars under ambient curing.

Concrete waste powder replacement levels of 25%, 50%, and 75% were chosen to represent incremental substitution scenarios, enabling the evaluation of both physical (packing and filler effects) and chemical (reactivity and geopolymerization) contributions. This approach allows the identification of performance limits and durability implications associated with increasing RCP content.

Tests

Hardened properties

The mortars' mechanical properties, such as compressive and flexural strengths, were determined. Cube specimens with dimensions of 50 × 50 × 50 mm were used to determine compressive strength according to the ASTM C109/C109M-16a standard (ASTM International, 2016). The tests were conducted at 7 days and 28 days, with the average value of three specimens reported for each age. The loading rate was maintained constant at 900 N·s⁻¹. Additionally, prism specimens measuring 40 × 40 × 160 mm were cast to evaluate the flexural strength of the cement mortars at 28 days, following the ASTM C348-98 standard (ASTM International, 1998) by using the one-point bending load. Beyond mechanical properties, durability-related characteristics such as porosity and water absorption were also assessed following the ASTM C642-13 standard (ASTM International, 2013).

Fresh tests

Fresh properties like workability, flow ability, and setting time are essential to cement mortars that include FA and RCP, as they directly determine the quality of the casts, compaction, and finally the longevity of hardened mortar. It has been found that FA is more effective in enhancing the flow and spreading behavior, whereas RCP tends to decline workability because of the smaller particle size and greater water retention capacity (Cunha et al., 2025). In the same vein, alkali-activated mortar with concrete sludge was studied, and it was shown that the level of fineness of binders, chemical composition, and activator dosage have a significant influence on viscosity and flow performance, with the consequent implication being that the formulation of mixtures must be considered in ensuring the best fresh properties are attained (Kesikidou et al., 2021). Additionally, rheological studies of mortars prove that zeta potential and packing density, which determine plastic viscosity and yield stress, change with the addition of FA, affecting the compaction efficiency and the number of voids in the mortar (Ma et al., 2022; Delihowski et al., 2024). Consequently, the fresh behavior of FA- and RCP-based mortars should be evaluated in order to provide sufficient workability, allow proper placement, and increase the durability behavior in the conditions of service.

Scanning electron microscopy test

Microstructural analysis of the hardened mortar was performed using a SEM in accordance with ASTM C1723-10 standard (ASTM International, 2010). Small fragments were carefully extracted from the broken specimens after the completion of the compressive strength test at 28 days, ensuring that the observed microstructure accurately represents the post-failure condition of the mortar. The SEM analysis was conducted at the College of Materials Engineering, University of Babylon, using a TESCAN MIRA3 field-emission scanning electron microscope (FE-SEM), model number MIRA3-XMU, operating at an accelerating voltage of 15 kV. High-magnification images were obtained to evaluate the morphological changes, pore distribution, and the bonding characteristics between the reaction products and the aggregates.

Results and discussion

Compressive strength test results

The compressive strength data presented in Figure 2 clearly indicate that the combination of binder chemistry, reactivity of the precursors, and the time taken to cure the resin are controlling factors in the development of strength. The reference OPC-based mixes (P100 series) demonstrated a gradual augmentation of compressive strength between 7 days and 28 days, and this is typical of the gradual hydration process and the constant development of calcium silicate hydrate (C–S–H) gel. Out of these blends, P100 (S50W50) had the best compressive strength (49 MPa at 28 days), which means that even partial substitution of cement with waste powder enhances packing of particles and increases microstructural densification without majorly affecting cement hydration.

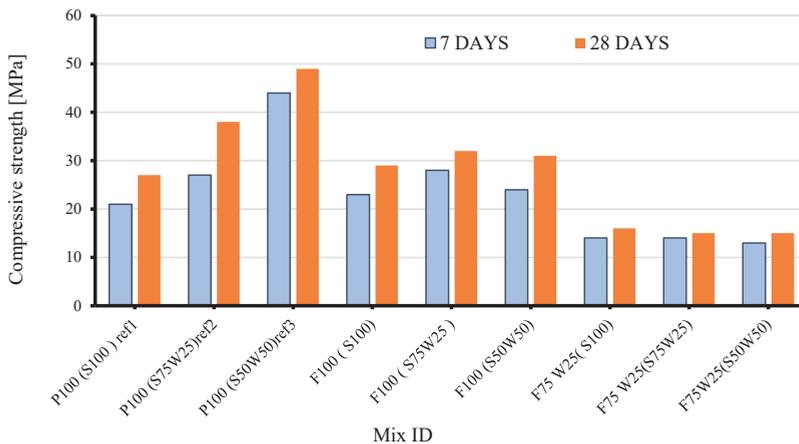


FIGURE 2. Compressive strength test results of mortar mixes at 7 days and 28 days

Source: own work.

The higher performance of P100 (S75W25) and P100 (S50W50) than P100 (S100) indicates that the addition of the optimal quantity of waste powder enhances the availability of fine reactive particles, which causes refinement of pores and enhances the transfer of loads in the hardened matrix. This observation indicates the importance of optimized solid packing and more sites of nucleation in speeding up hydration and strength gain.

Contrary to this, the FA-based systems showed slower strength development, which could be explained by the fact that a different reaction mechanism determines geopolymerization. The homogeneous compressive strength attained by F100 (S75W25) and F100 (S50W50) after 28 days (28–31 MPa) corresponds to the gradual dissolution of an aluminosilicate over time and formation of sodium aluminosilicate hydrate (N 50W50 50W50) gel. These findings permit to conclude that the partial inclusion of waste powder results in higher efficiency of geopolymerization because it provides reactive silica and alumina and thus, consolidation of the matrix.

Nevertheless, higher replacement levels, as was the case with the F75W25 (S75W25) and F75W25 (S50W50) mixes led to much lower compressive strength values (13–16 MPa at 28 days). The loss is mechanistically attributed to a lack of sufficient content of reactive binder, incomplete polymerization, and porosity, which together contribute to the weakening of the geopolymeric network. To this extent to which this behavior proves that the disproportion of the precursors constrains the network of gel connectivity and impairs the structural integrity.

In general, the findings show that compressive strength is very sensitive to the composition of the precursors and the balance of reactivity. Whereas OPC-based systems have the advantage of optimized particle packing, FA-based binders need a minimum ratio of reactive content in the form of aluminosilicate and enough curing time to result in good geopolymerization. The results are in accordance with earlier research on the significance of precursor optimization and curing conditions in the creation of dense and mechanically robust binder systems (Sajedi & Razak, 2011; Matos Riscado et al., 2025; Shamsah et al., 2025).

Flexural strength test results

The findings of the flexural strength results, as illustrated in Figure 3, point to the high reliance of the tensile performance on the binder composition, the continuity of the microstructure, and interfacial bonding. The flexural strength of the reference OPC-based mixes was shown to improve conspicuously with the waste powder content peaking at 10 MPa, with P100 (S50W50) having the best flexural strength value at S50W50. Mechanically, this can be explained by the fact that the particle packing is better and that a denser and more uniform gel network of calcium silicate hydrate (C1050) forms, which effectively seals the microcracks and makes the substance resistant to tensile stresses. The same has been extensively observed in cementitious systems with a well-established C–S–H phase, which is the major contributor to flexural capacity (Mehta & Monteiro, 2006).

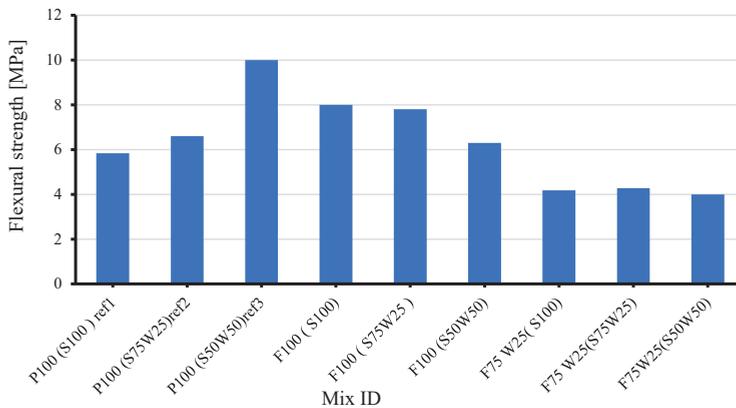


FIGURE 3. Flexural strength test results of mortar mixes at 28 day

Source: own work.

The gradual growth of flexural strength between P100 (S100) and P100 (S75W25) is another indication of partial replacement of waste powder, contributing to the refinement of microstructures and eliminating stress concentrations at weak interfaces. The relationship between flexural and compressive strength trends is confirmed to be close; that is, both the increase of hydration and the increase of matrix densification lead to an increase in both, load-bearing and crack-resisting capacity.

The F100 (S100) and F100 (S75W25) mixes had competitive flexural strengths of 8.0 MPa and 7.8 MPa, respectively, among the other alternative binders. This indicates that geopolymerization of such mixes resulted in a fine enough interconnected aluminosilicate gel (N–A–S–H), an ability to transfer stress throughout the matrix, and enhanced interfacial bonding. F100 performance of moderate (S50W50) (6.3 MPa) shows that, although waste powder contributes to the formation of gels, the over-replacement could interfere with gel continuity and tensile resistance.

Incomplete geopolymerization and weak interfacial transition zones can be attributed to significantly lower flexural strengths in the F75W25 series (4.0–4.28 MPa). Weak reactive levels of aluminosilicate and weak gel development contribute to a more uniform and porous structure, which is very disadvantageous during flexural loading; the crack starts and spreads as controlled by microstructural flaws.

These results are in agreement with recent research that has pointed out that the flexural performance of geopolymer mortars is very sensitive to the precursor chemistry, concentration of activators, and curing regime. Optimized proportions

of activators have been presented to bring a significant increase in the flexural response of FA-based geopolymers (Altawil & Olgun, 2025), whereas the use of micro-reinforcing or fine reactive additives enhances tensile bridging and matrix adhesion (Naenudon et al., 2022; Paramban & Gavindarajulu, 2024). Moreover, the fact that the improvement is reported by Ebrahim et al. (2024), supports the idea that a proper curing environment is a significant factor in the ability of geopolymer to obtain a compact and mechanically efficient matrix.

In general, all the findings show that P100 (S50W50) offers the best ratio of microstructural integrity and tensile resistance, whereas F100 (S100) and F100 (S75W25) are promising in terms of the flexural behavior of geopolymer systems, with the flexural behavior comparable to that of OPC-based systems. The subpar performance of the F75W25 series underscores the need to optimize precursor ratios, activator molarity, and curing conditions in a bid to realize higher flexural capacity in blended binder systems.

Acid resistance test

The influence of acid exposure on the mechanical properties of the examined mixes is shown by the correlation between mass loss and compressive strength loss, as depicted in Figure 4. The acid resistance findings show that the relationship between the loss of mass and compressive strength degradation is not linear or direct, which also confirms that the processes of the acid attack on cementitious and geopolymer systems are complex and multi-scale.

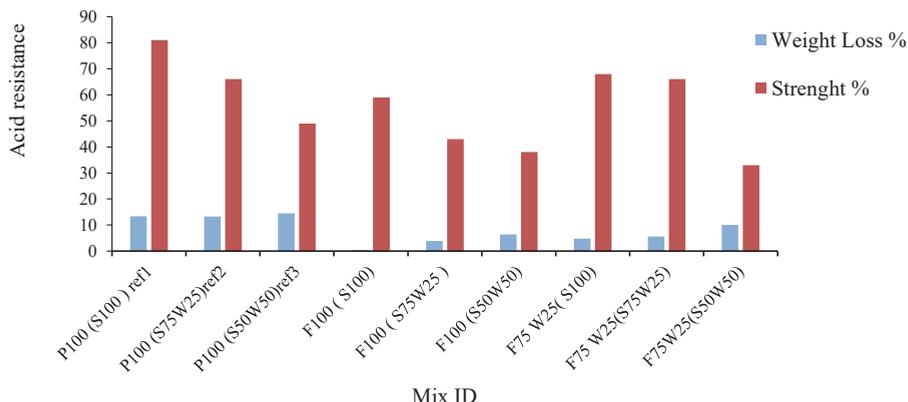


FIGURE 4. Acid resistance test results of mortar mixes at 28 day
Source: own work.

As an example, the P100 (S100) mix had a small decrease in compressive strength (13.35), although it had a drastic mass loss (about 81) (Fig. 4). Such behavior implies that not only surface dissolution but also internal microstructural integrity is important in retaining the load-bearing capacity. On the contrary, the P100 (S50W50) mix experienced a considerable reduction in compressive strength (49%) but experienced a comparatively low mass loss (14.5%). It implies that weakening of the binding phases and the interfacial transition zones under the influence of acids can be disastrous to the mechanical strength, even when the loss of material is hardly visible.

The mechanistic explanation of this behavior is the preferential dissolution of calcium-rich hydration products when exposed to acidic conditions. During the decalcification process of the C–S–H gel in OPC-based systems, microcracking and a decrease in cohesion and internal damage occur, directly causing the reduction in compressive strength irrespective of the extent of surface erosion (de Siqueira & Cordeiro, 2022). This effect determines the loss of compressive strength that can be independent of the loss of mass.

On the other hand, it was observed that the FA-based geopolymer mixes (F100 series) exhibited significantly reduced mass losses (0.46–6.39%) and a gradual loss of compressive strength with increasing waste replacement, reduced by approximately 59% in F100 (S100) to 38% in F100 (S50W50), as shown in Figure 4. This has been possible because of the perfection of the pore structure and greater production of chemically stable aluminosilicate gels (N3A3S3H), which are much less prone to acidic dissolution compared with calcium-based hydration products.

The same situation could be noted with the F75W25 series, where the compressive strength loss was reduced to about 33.0% with increasing waste replacement, albeit with moderate values of mass loss between 4.76% and 10.0% (Fig. 4). This observation suggests that waste addition enhances chemical stability and decreases permeability, thereby restricting internal degradation and acid intrusion. The overall impact of the decreased calcium content, microstructural densification, and the existence of acid-resistant binding phases leads to enhanced resistance to the effects of acid on the mechanical deterioration.

On the whole, the findings indicate that compressive strength retention is a more effective predictor of acid durability compared with mass loss only; the trends in Figure 4 also support this point of view. The addition of complementary materials or waste powders to cementitious components and partial replacement is a good approach toward improvements in long-term mechanical performance in hostile acidic conditions. This finding is consistent with other researchers who have identified the key functions of gel chemistry and microstructural densification to enhance durability (Bayapureddy et al., 2023; Abdalla et al., 2024).

Scanning electron microscopy

The SEM analysis also helped to provide a crucial insight into the microstructural characteristics that controlled the mechanical and durability performance of the mortars that were under study. It was found in the micrographs that there are pores and voids of different shapes and sizes that exist in the entire matrix, and that the reaction products and packing density are heterogeneous as presented in Figure 5. Such gaps may be explained by a lack of full geopolymerization, a lack of dissolution of the aluminosilicate precursors, and localized excess water or trapped air during mixing and casting.

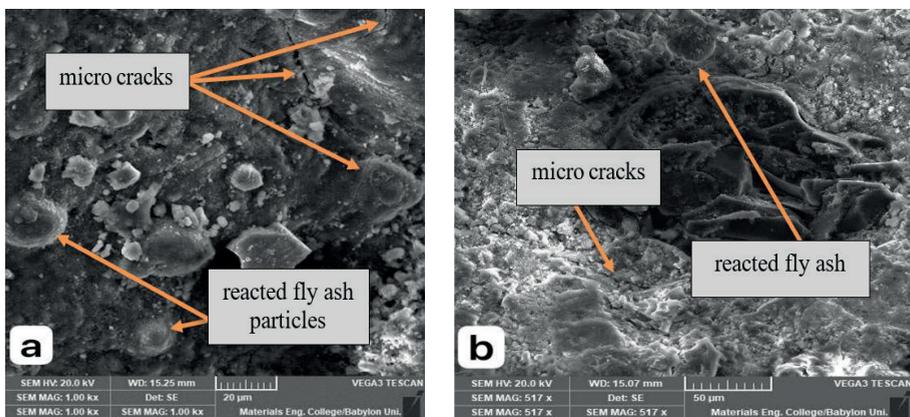


FIGURE 5. The SEM images of geopolymer mortar-based on F75W25(S50W50) (a), and geopolymer mortar-based on F100 (S100) (b)

Source: own work.

In the FA-geopolymer mortars, the unreacted FA particles that were partially spherical and partially sub-rounded were evidently encased in the hardened matrix with no major dissolution occurring on the surface. The fact that such unreacted particles persist indicates a low extent of alkali activation efficiency, which can be related to inappropriate proportions of the reactants toward the activators, ambient curing conditions, or inadequate curing times. Consequently, these particles become inert inclusions but do not bear geopolymeric gels.

The presence of unreacted FA particles together with interconnected voids compromises the continuity of the binding phase and interferes with stress transfer through the matrix. This microstructural discontinuity explains the lower compressive and flexural strengths of the mixes that have a greater composition of concrete waste powder and lower geopolymer reactivity. Further, these defects

provide favorable access to fluid ingress and thus enhance vulnerability to chemical attack, adding to the loss of strength seen during the acid exposure experiments.

Conversely, mixes with increased mechanical performance were characterized by relatively denser matrices with lower amounts of unreacted particle content and lesser porosity, suggesting superior geopolymer gel formation and enhanced particle packing. The result of this densification is an increase in interfacial bonding between the products of exchanges and aggregates, which results in better distribution of loads and high resistance to environmental degradation.

In general, the results of mechanical and durability tests are effectively supported by the SEM observations, which prove that the level of precursor activation, polymer continuity, and refinement of pore structure control the behavior of geopolymer mortars. The results show that the composition of the activators, the curing regime, and the incorporation level of waste to be used are important in order to produce a compact microstructure and a durable geopolymer matrix.

Conclusions

This paper proved that FA and RCP can be used as alternatives to OPC or even as partial replacements of sand when making mortar. Mortars were made with various replacements (25%, 50%, and 75%) were made. Their mechanical and durability performances were tested using compressive strength, flexural strength, and acid resistance tests. The findings showed that alkaline activation had a considerable effect on enhancing strength and microstructural compactness.

The compressive strength findings showed that the reference OPC mortars showed the best overall performance, and the mixes with FA showed average strength depending on the concentration of the activators. Comparatively, the mixes containing a higher RCP content exhibited significantly less strength, which was mainly explained by a lack of material reactivity and an increase in porosity. On the whole, the results indicate the potential sustainability of FA-based mixes as an alternative, but there is a risk of overusing RCP at the cost of mechanical performance.

Similar tendencies were observed in flexural strength results, with FA-based mortars at approximately 8 MPa, which is close to the reference value of 10 MPa, and RCP-rich mixes at a significantly lower level of approximately 4 MPa, which is explained by a lack of complete geopolymerization and weak interfacial bonding.

The acid resistance tests showed that the mass loss/strength degradation relationship was not linear. Gel dissolution and micro-cracking, which were internal damages, had a greater effect on the loss of strength compared with erosion on the surface. Blends with an optimum ratio of FA and partial replacement of sand with fine waste powder showed optimum durability, whereas over-replacement of the binder with RCP performed poorly.

All in all, it can be inferred that using FA mortars with the right amount of activation and proper curing, it is possible to achieve similar strength and better durability than with OPC. It was found that the best combination was achieved when the sand was partly substituted with ground waste materials, but the substitution of the binder with RCP led to a significant decrease in strength. These findings indicate that a balanced mix design, controlled dosage of activators, and proper curing conditions are key to the creation of eco-efficient and long-lasting cementitious systems.

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Summary

Utilization of recycled concrete powder in the production of geopolymer mortars based on fly ash. This research examined the performance and durability of geopolymer mortars with fly ash (FA) and fly ash with recycled concrete powder (RCP) as a partial replacement for fly ash and/or the fine aggregate in the production of sustainable alternative mortars when compared with references based on ordinary portland cement (OPC). Mortar mixes were made by substituting binder and sand with RCP at varying ratios (25%, 50%, and 75%), and the mechanical and durability properties of the mortar mixtures were evaluated. The findings demonstrated that OPC-based mortars exhibited the highest performance, whereas the FA-based system activated with sodium silicate also presented significant strength with improved compactness and long-term stability. In contrast, high RCP content reduced reactivity, which highlights the importance of maintaining balanced binder proportions. There was also the use of geopolymer binders with the replacement of manufactured sand with FA fine aggregate (GFFA), 10–20% of manufactured sand, which resulted in enhanced mechanical performance and sustainability, as well as improved recycling of industrial by-products. Acid resistance tests confirmed the presence of stronger microstructural deterioration, such as gel dissolution and micro-cracking, compared with surface erosion, in influencing the reduction in strength. Furthermore, FA and RCP improved acid resistance capacity by refining microstructure and stabilizing binders. Overall, compressive strength retention proved to be a more reliable indicator of acid durability than mass loss. Therefore, properly designed FA-based mortars provide an effective, durable, and eco-friendly alternative to OPC, suitable for construction applications exposed to aggressive or challenging environments.