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Experimental Investigation of Mechanical Properties and Durability of the Self-Compacting Geopolymer Mortar using various Mineral Additions

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Abstract

A geopolymer is an unconventional inorganic binder prepared by an alkaline activator of alumina and silica-containing materials. This study has thoroughly evaluated the strength and durability performance of geopolymer mortars and represents a comprehensive attempt to highlight the advancement of environmentally conscious and innovative construction materials. The methodology used in this study includes X-ray diffraction (XRD), a scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), universal testing machines, and chemical methods (acid, sulfate, and chloride attack). The mechanical properties and durability of geopolymer mortars made at constant temperatures are evaluated and compared using different mineral additives. A comparative analysis of geopolymer mortar shows that M3 (fly ash) is an excellent choice for structural elements in construction projects where high strength and durability are paramount, as M3 (fly ash) has achieved the highest compressive (17.07 MPa) and flexural strengths (2.28 MPa) at all curing periods compared to M2 (RHA) and M1 (slag), which have intermediate (11.66 MPa, 2.17 MPa) and the lowest (10.10 MPa, 2.04 MPa) compressive and flexural strengths, respectively. In cases where acid resistance is a critical factor for construction, M1 appears to be the most suitable option, while M2 and M3 may require additional protective measures. M1, despite having slightly lower strength values than M2 and M3, demonstrates exceptional resistance to chloride attacks, making it a preferred option for projects in moderately chloride-rich environments. The compacted material increased strength and durability, while cracks, pores, and non-uniform particle arrangement reduced it. Overall, the abundance of minerals with elemental compositions such as Si, Al, O, and Na is responsible for the strong bonding for the cementation of geopolymer concrete. Therefore, keeping in mind the results of this study, different geopolymer mortars can be selected for construction purposes based on the demands of the projects.

Keywords:
geopolymer; fly ash; alkaline activator; strength and durability; mineral additions

1. Introduction

Concrete is a fundamental component of building construction (**LaLonde and Janes, 1961**). The basic core of the structure is concrete, which consists of portland cement, fine aggregates, and coarse aggregates. The type of aggregate used in concrete has a significant impact on its final mass and strength, as well as its structure. For the same grade of cement, the coarse aggregate of different rock types has different microroughness, mineral composition, structure, and final strength, resulting in different concrete compressive strengths (**Petrounias et al., 2018a, 2018b; Asif et al., 2022, 2024**). Portland cement has been used from the very beginning, acting as a binder between the various components of concrete. It is estimated that the global per capita concrete consumption is 1 m^3 (**Alehyen et al., 2017**).

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Cement demand is growing steadily and is likely to grow further in the coming decades. Some economists use specific production to estimate a country's economic strength (**Mikulčić et al., 2016; Shi et al., 2011**).

A geopolymer is an inorganic polymeric cementitious binder created by the interaction of aluminosilicate minerals (source materials) with alkali hydroxides and/or soluble silicates (**Chelluri and Hossiney, 2024**). Geopolymers are amorphous to semi-crystalline three--dimensional bulk materials that can be produced by reacting aluminosilicate powders in various alkaline solutions at ambient or slightly higher temperatures (**Debnath et al., 2022**). In the 1970s, Professor Joseph Davidovits and a team of researchers from France introduced the term "geopolymer" into scientific discourse. This term was explicitly coined to define a novel class of raw materials resulting from the chemical reaction between aluminosilicate powder and an alkaline solution (**Davidovits, 2020**). By utilizing industrial solid waste such as fly ash, steel slag, and rice husk ash, geopolymer concrete (GC) provides a sustainable substitute for conventional cement (**Bellum et al., 2024**). Geopolymer specimens were prepared by different techniques, one of the most common being mixing fly ash powder and various concentrations of NaOH solution (**Das and Rout, 2021**) and rice husk with sodium hydroxide (**Oti et al., 2024**). Fly ash can be obtained from thermal power plant waste (**Das and Rout, 2023**). The starting material was fly ash (industrial solid waste), and the alkaline activators were a solution of sodium hydroxide and sodium silicate solutions (**Das and Rout, 2023**). Geopolymer materials have great mechanical and durability features, thus researchers have been drawn to them for several decades (**Das et al., 2024**). Geopolymer binders are thought to be one of the most promising low-carbon building materials. Aside from minimal carbon emissions, the manufacturing of geopolymer materials also helps to mitigate a number of industrial solid waste management issues (**Nanda et al., 2024**). Geopolymer concrete (GPC) was created to mitigate the environmental damage caused by carbon dioxide emissions (CO_2) and the widespread use of fossil fuels in cement manufacturing. GPC concrete is more durable and has greater mechanical qualities than regular concrete; for all types of concrete composites, including GPC, compressive strength is the most important technical attribute (**Rihan and Abdalla, 2024**)

To reduce growing greenhouse gas emissions into the environment, the Earth World Summit recommended that the cement industry transition from portland cement to sustainable alternative adhesives with desirable structural and mechanical capabilities (**Khaiyum et al., 2023**). The global cement industry accounts for about 6% of all anthropogenic CO_2 emissions and therefore about 4% of anthropogenic global warming (**Khaiyum et al., 2023**). This is because the production of ordinary portland cement by burning the components in a kiln at 1400°C involves considerable energy consumption (**Álvarez-Ayuso et al., 2008**). The cement manufacturing process emits eight times more carbon dioxide than the conventional calcination process. Portland cement manufacturing releases about one ton of carbon dioxide into the atmosphere (**Mucsi et al., 2018**). Researchers have developed several alternatives to standard portland cement, such as geopolymer cement, as CO_2 emissions are expected to be extremely important to the industry in the future.

Geopolymer cement is an inorganic binder made from alumina and silica-containing materials through alkaline activation by a polycondensation process. Polycondensation is a process in which tetrahedral silica (SiO_2) and alumina (AlO_4) are linked together by shared oxygen atoms, also known as geopolymerization (**Davidovits, 1988, 1994a, 1994b, 2020**). The basic activator of geopolymers is usually a mixture of hydroxyl groups, such as sodium hydroxide (NaOH) or potassium hydroxide (KOH). The durability of geopolymer concrete is an important factor in its many commercial applications, including coating materials for marine structure protection, industrial sewers, and more. For the durability of geopolymer concrete, several additives are used to observe how they affect the strength and durability of the concrete, such as geopolymer cement, which is likely to be made from rice husk ash, slag, and fly ash (residual product from the burning of anthracite coal or bituminous coal) (**Chelluri and Hossiney, 2024; Oti et al., 2024; Barragán-Ramírez et al., 2024; Bellum et al., 2024**). Therefore, an alkaline solution comprising sodium hydroxide and sodium silicate is added, activating the cementitious properties of fly ash (**Jindal, 2019; Anju et al., 2024**). The series of stated CO_2 values for geopolymer concrete compared to ordinary portland cement is significant, with estimates ranging from 80% less than ordinary portland cement to 26–45% lower than ordinary portland cement concrete (**Patel et al., 2019**). Although the use of portland cement is inevitable for the foreseeable future, various initiatives are still underway to limit its use in concrete.

Geopolymer concrete is increasingly recognized as a viable alternative to traditional portland cement concrete, particularly in enhancing mechanical properties and durability. Unlike conventional concrete, geopolymer concrete is produced by activating aluminosilicate materials like fly ash or slag with an alkaline solution, forming a robust binder that does not rely on portland cement. The use of geopolymer concrete can significantly reduce carbon emissions, making it an environmentally friendly option. Moreover, geopolymer concrete exhibits superior resistance to chemical attacks, higher compressive strength, and better thermal stability compared to ordinary concrete, making it an excellent choice for various structural applications (**Hosseini et al., 2022, 2023; Das et al., 2024**).

Replacing pozzolan and micro-silica with geopolymer materials in concrete mixes can further enhance these benefits. Pozzolan and micro-silica are traditionally added to improve the mechanical properties of concrete, but geopolymer binders offer a more effective solution by providing a stronger and more durable matrix. The unique chemistry of geopolymer materials allows for the development of concrete with improved workability, setting time, and long-term durability, which are essential for infrastructure projects exposed to harsh environmental conditions (**Costa et al., 2022; Yaraghi et al., 2022**).

This research is dedicated to achieving a multifaceted set of objectives, with a strong emphasis on sustainability in construction. The central goals include exploring geopolymer cement as a viable substitute for ordinary portland cement, a critical step towards addressing the diminishing mineral resources associated with traditional cement production. Additionally, this study seeks to mitigate the adverse environmental impact of concrete by investigating geopolymer mortar formulations utilizing varying ratios of fly ash, blast furnace slag, and rice husk ash across distinct mix designs. This approach not only promises to improve internal curing mechanisms within the mortar, but it also has the potential to bolster material strength, advancing greener alternatives for construction materials. Integral to this research is the evaluation of the structural strength and long-term durability of the developed geopolymer mortars. Rigorous testing and analysis will provide insight into the mechanical properties and resilience of these materials under diverse conditions. Moreover, a microscopic analysis will provide a deeper understanding of the intricate structural attributes of the geopolymer mortar specimens. In essence, the research is poised to significantly contribute to sustainable construction practices through its exploration of geopolymer cement and its potential to reshape the landscape of construction materials using various types of mineral admixtures at ambient curing conditions.

2. Materials and methods

The experimental setup was created in the laboratory to evaluate the strength and durability of geopolymer mortars. Different specimens were cast and then cured. The specimens were then tested using universal testing equipment to determine their compressive and flexural strength. Cubes were cast to test their resistance to acid, sulfate, and chloride attack.

2.1. Materials

The properties of geopolymers vary depending on the raw materials used and the processing environment. To make the precursors, we used different (Si/Al) molar ratios and water concentrations, combined with potassium hydroxide or sodium hydroxide. Geopolymers were synthesized by combining precursors made from commercial sodium silicate solutions containing 9.07 wt.% Na_2O and 29.35 wt.% SiO_2 with geopolymer sources (blast furnace slag, rice husk ash, and F-grade fly ash). The geopolymer mortar in this study comprised a blend of essential raw materials, each playing a crucial role in the formulation. Class F fly ash (see **Table 1**), derived from the combustion of anthracite and bituminous coals and obtained from a coal-fired power plant, was subjected to laboratory analysis to determine its chemical composition, conforming to the American Society of Testing and Materials (ASTM) C618-22 (**Duxson et al., 2007; ASTM C618, 2022**) standard, which mandates a minimum $SiO_2 + Al_2O_3 + Fe_2O_3$ content of 70%. Fly ash is a waste by-product of the burning of pulverized coal in electric thermal power plants and is readily available worldwide. As mentioned in **Table 1**, rice husk ash (RHA) is an industrial waste produced when rice husks are burned. It is mainly used as a fuel for power generation and has a high silica content (95%). It also has strong pozzolanic properties, with about 18% of the rice husks turning into ash during combustion. The ground granulated blast furnace slag (a by-product of iron and steel manufacturing) was processed (GGBFS) (see **Table 1**), into a fine powder after it formed as a glassy, granular product through water or steam treatment.

GGBFS was employed as a partial cement replacement, significantly contributing to increased compressive strength, with its composition primarily consisting of Cao (30–50%), SiO_2 (28–38%), Al_2O_3 (8–24%), and MgO (1–18%). River sand, locally sourced and having a density of 1602 kg/m^3, was used as the fine aggregate after being assessed for its fineness (see **Table 2**). Sodium silicate (chemical formula of Na_2SiO_3) was acquired in liquid form from a local soup-making factory, adhering to specific density and solid content parameters. Sodium hydroxide (NaOH) was dissolved with a purity level of 99.9%, in the required amount of water to create a 12M solution (see **Table 2**). The water-reducing superplasticizer, known as polycarboxylate ether, was incorporated into the mortar mixture to enhance workability and reduce water requirements. These meticulously characterized and selected materials formed the foundation of an effective geopolymer mortar for the research project. Fly ash is rich in silica and alumina and is activated with an alkaline solution to form an aluminosilicate gel, which is used as a binder in geopolymer concrete.

The alkaline activator solution is prepared by mixing sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) before adding them to the dry components to ensure a more effective geopolymerization process. This premixing allows for the uniform distribution of the reactive species in the solution, which enhances the dissolution of aluminosilicate materials and promotes the formation of a stronger, more homogeneous geopolymer gel. Adding these solutions separately to the dry components could lead to inconsistent reactions and the uneven

Table 1: Showing the chemical composition of geopolymer sources

Geopolymer sources	Composition by wt. % of components								
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	LOI*
Slag	35.85	5.08	7.77	37.22	3.55	-	0.12	0.27	10.14
RHA	86.94	0.2	0.1	2.2	0.6	-	0.8	2.30	6.86
Fly ash	48.30	32.40	0.85	6.15	0.83	3.32	-	-	8.15

*LOI–Loss of ignition

Table 2: Final mix design of the geopolymer mortars

Sample ID	Molarity	Geopolymer source (g)	Sand (g)	Alkaline activator/ geopolymer source ratio	Water/ binder ratio	Na_2SiO_3/ NaOH ratio	Alkaline activator	
							NaOH solution (ml)	Na_2SiO_3 solution (ml)
M1 (slag)	12M	1055	900	0.37	0.3	3.3	32.56	107.44
M2 (RHA)	12M	703	900	0.37	0.3	3.3	32.56	107.44
M3 (fly ash)	12M	925	900	0.37	0.3	3.3	32.56	107.44

distribution of the activators, potentially resulting in lower material strength and durability. The pre-mixed activator ensures that the necessary chemical interactions occur uniformly, leading to optimal material properties (**Clements et al., 2024; Kwek et al., 2021**).

For the strength and durability tests, we used three different materials (GGBFS, RHA, and fly ash) to prepare a specimen and tested them on different time durations to specify their strength and durability according to ASTM C109/C109M-01 specifications (**ASTM C109/ C109M-01, 2021**). To increase their workability, we used a superplasticizer in 4 wt.% of the binder. Firstly, we prepared a sodium hydroxide (NaOH) solution and mixed it with sodium silicate (Na_2SiO_3) (see **Table 2**). The solution is stored in the laboratory for 24 h to complete the alkaline reaction. This solution is called an alkaline solution. Mix the GGBFS, RHA, fly ash, and sand well before adding the alkaline solution. A high-efficiency superplasticizer is added to improve processability and reduce the need for water. For the durability tests, cubes measuring 50mm x 50mm were fabricated as per ASTM C618-22 specifications (**ASTM C618, 2022**). The compressive strength of geopolymer mortar is measured using a 50mm x 50mm cube, while its flexural strength is measured with a sample 60mm wide, 60mm thick, and 160mm long. A total of 45 samples were cast for compressive strength testing, 45 samples for flexural strength, and 45 samples for durability testing. All samples were manufactured at room temperature and then placed in an oven at 800°C for 24 h. The rest of the curing process takes place at room temperature at 19°C. Various tests were carried out on all previously created samples, and the results were as follows.

2.2. Strength tests

Due to the importance of strength in the construction of concrete structures, strength was chosen as a benchmarking consideration, although other aspects were also evaluated. In order to measure the strength of the geopolymer mortar, we conducted two tests using universal testing equipment.

2.2.1. Compressive strength and flexural strength

The cube size is 50mm x 50mm and is used to evaluate the compressive strength of geopolymer mortars. To evaluate the flexural strength, a beam of 60mm x 60mm x 160mm was cast. Mortars of three different mixed designs (GGBFS, RHA, fly ash) and nine different specimens were evaluated over 7, 14, 28 and 90 days using universal test equipment. For each mixing ratio, three specimens are tested, and an average is calculated.

2.2.2. Durability tests

Several durability tests were carried out to determine the stability of the geopolymer mortar. Both organic and inorganic acids have the ability to damage concrete in a variety of ways. To test resistance to acid, sulfate, and chloride attack, 5% hydrochloric acid (HCl), 5% sodium sulfate (Na_2SO_4), and 5% calcium chloride ($CaCl_2$) solutions were used, respectively. A 50mm x 50mm x 50mm geopolymer mortar cube was dried in an electric oven at 105°C for 24 hours. The initial dry weight and compressive strength were recorded. Subsequently, samples from various geopolymer sources were immersed in a solution of 5% hydrochloric acid (HCl), 5% sodium sulfate (Na_2SO_4), and 5% calcium chloride ($CaCl_2$). A sealed beaker was used to avoid evaporation. The pH levels of the acidic, chloride, and sulfate media were monitored during the experiment. After checking the pH, the solution was changed every 30 days. After acid, chloride, and sulfate attack, specimens were rinsed with water after 30, 60, 90, and 180 days. The specimen was quickly dried with blotting paper to remove any de-

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Table 3: Compressive and flexural strength of geopolymer mortars (unit-MPa)

Geopolymer mortar	Compressive strength (MPa)					Flexural strength (MPa)		
	7th Day	14th Day	28th Day	56th Day	90th Day	7th Day	14th Day	28th Day
M1 (Slag)	6.80	8.08	10.10	12.11	14.19	1.45	1.75	2.04
M2 (RHA)	9.64	10.37	11.66	13.91	16	1.50	1.84	2.17
M3 (Fly Ash)	12.30	14.60	17.07	20.09	21.40	1.56	1.93	2.27

tached particles. The effects of acid, chloride, and sulfate attack were assessed by measuring the residual weight of the sample.

For water permeability, cubes of size 50mm x 50mm x 50mm with nine different mix proportions were used. Each composition's mortar specimens were evaluated for water absorption changes, following ASTM C-642-21 (**ASTM C642, 2021**). X-ray diffraction (XRD) was performed in the Centralized Resource Laboratory (CRL), University of Peshawar, Pakistan, to provide more detailed information about crystalline species, including phase identification and quantification. The test conditions of XRD are: count time (sec) is 1.0, tube voltage (kV) is 40,000, tube current (mA) is 30,000, step angle (deg.) is 0.050, and divergence slit is 1 degree. Scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS) analysis were performed at the National Centre of Excellence in Geology (NCEG), University of Peshawar, Pakistan. SEM analysis is used to study the microstructure of the specimens. To identify the impurities present in different specimens, EDS provides elemental identification and quantitative compositional information.

3. Results and discussion

After the geopolymer samples were manufactured, a number of tests were performed, i.e. including strength tests, durability tests, and microstructure characterization technique was used to briefly analyze the geopolymer mortar samples. Prepared specimens of geopolymer using GGBFS, RHA, and fly ash were tested for 7, 14, 28, 56, and 90 days to calculate their strength.

3.1. Compressive and flexural strength

Table 3 shows the compressive strength and flexural strength of geopolymer mortars at different curing times (7, 14, 28, 56, and 90 days) for three different mix formulations: M1 (slag-based), M2 (rice husk ash-based), and M3 (fly ash-based). For M1, the compressive strength increases from the 7th day to the 90th day, with values ranging from 6.80 MPa to 14.20 MPa. This indicates continued strength development over time. Due to its uneven particle morphology, the geopolymer composition of slag blending often results in less viable mixtures. More slag will speed up the initial and final solidification of the geopolymer mixture, improve compressive strength and durability, and can be pushed as a repair material. For M2 (rice husk ash-based geopolymer mortar), the compressive strength also increases with curing time, ranging from 9.64 MPa to 16 MPa. The compressive strength for M3 (fly ash-based geopolymer mortar) shows a similar trend, increasing from 12.30 MPa to 21.40 MPa.

The comparison of M1, M2, and M3 geopolymer mortar mixtures shows that M3 had the highest compressive strength at all curing times, thus having excellent resistance. M2 exhibited intermediate compressive strength values, which were also impressive. M1 had the lowest compressive strength, though it still demonstrated substantial strength (see **Figure 1a, b**). In terms of flexural strength, M3 demonstrated the highest flexural strength at all curing periods, implying excellent resistance to bending and tensile stresses. M2 showed intermediate flexural strength values, which were commendable. M1 (slag-based geopolymer mortar) exhibited the lowest flexural strength but still performed well (see **Figure 1c, d**).

The compressive and flexural strength results of the geopolymer mortars demonstrate the varying effects of the different precursor materials used (slag, rice husk ash, and fly ash). The observed increase in compressive strength for all mixes over time is consistent with the gradual geopolymerization process, which enhances the mechanical properties as the material cures.

For the slag-based geopolymer (M1), the lower compressive and flexural strengths can be attributed to the irregular particle morphology of the slag, which affects the packing density and, consequently, the mechanical properties. Previous studies have reported similar trends, where slag-based geopolymers, despite their durability and rapid setting time, exhibit lower mechanical performance compared to fly ash-based geopolymers (**Lam and Nguyen, 2023**).

Rice husk ash-based geopolymer (M2) showed intermediate strength values, which aligns with research indicating that rice husk ash, due to its high silica content, provides moderate mechanical strength when used in geopolymer formulations. The silica reacts well in the alkali activation process, contributing to the geopolymer network formation, though not to the extent of fly ash (**Sitarz et al., 2020**).

Fly ash-based geopolymer (M3) displayed the highest compressive and flexural strengths, which is supported

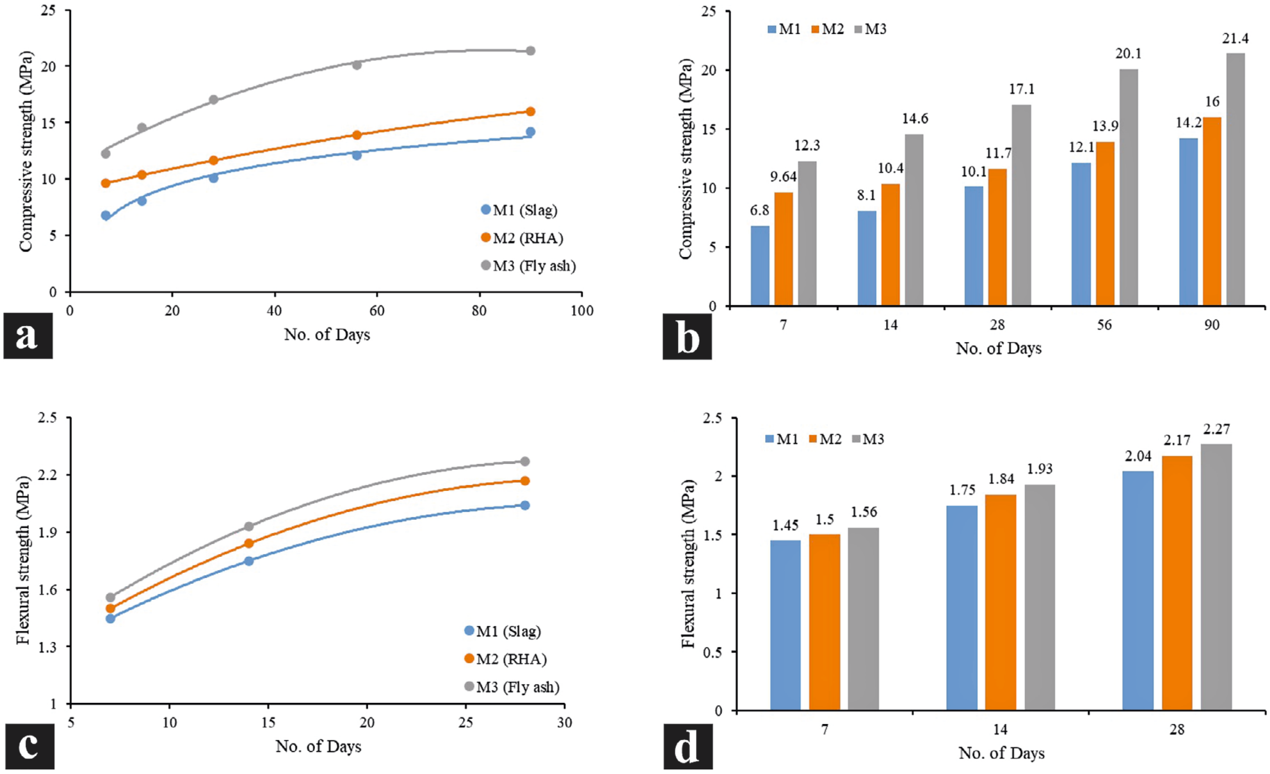

Figure 1: a-b) Showing compressive strength of geopolymer mortars, c-d) Showing flexural strength of geopolymer mortars

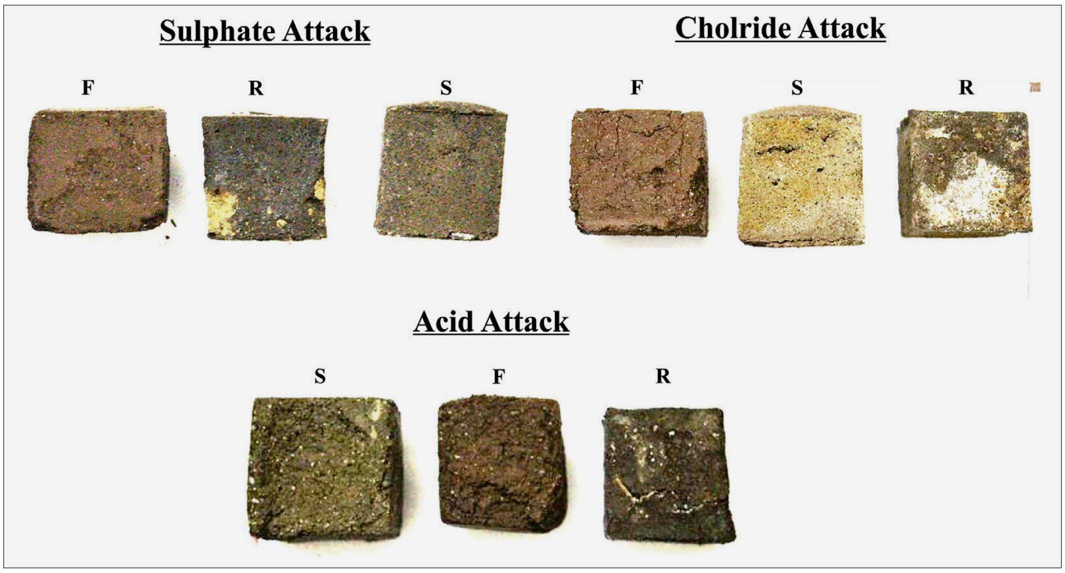

Figure 2: Samples mass loss against sulphate, chloride, and acid attack. "F" stands for fly ash, "R" stands for RHA, and "S" stand for slag

by existing literature that highlights the superior performance of fly ash-based geopolymers due to the pozzolanic activity and fine particle size of fly ash. This results in a dense microstructure, providing excellent mechanical properties over time (**Althoey et al., 2023**).

3.2. Durability

Durability is one of the most important factors used to evaluate the performance of various adhesive materials. The overall durability of geopolymer concrete is acceptable. Samples were immersed in solutions to test their tolerance to acids, chlorides, and sulfates, and removed at 30, 60, and 90 days, as shown in **Figure 2**. The samples were weighed before and after the test and the results are shown in **Table 4**.

The durability assessment of the geopolymer mortars under sulfate, chloride, and acid attacks provides valuable insight into their long-term performance. The weight loss percentages observed after 90 days indicate that all geopolymer mixes exhibit resistance to chemical degradation, with fly ash-based geopolymers (M3) showing the least weight loss across all tests. This superior performance can be attributed to the dense microstructure formed due to the pozzolanic activity of fly ash, which is known to enhance resistance to chemical attacks.

Additional studies corroborate these findings, showing that geopolymer concretes, particularly those based on fly ash, demonstrate excellent resistance to sulfate and acid attacks, outperforming traditional portland cement-based concretes. For instance, a 2015 study highlighted that geopolymer concrete has significantly better acid and sulfate resistance compared to conventional concrete, due to the stable aluminosilicate structure formed during geopolymerization (**Kumaravel et al., 2015**). Similarly, recent research in 2023 reinforced that geopolymer concrete exhibits superior durability, with lower water absorption and greater resistance to chemical erosion when exposed to aggressive environments (**Naghizadeh et al., 2023**).

The observed resistance to chloride attack is also noteworthy, especially given that chloride ingress is a major cause of steel reinforcement corrosion in conventional concretes. Geopolymer mortars' lower chloride penetration rates suggest they could provide enhanced durability in marine and de-icing salt environments (**Zhuang et al., 2017**).

3.2.1. Sulphate attack

Table 4 shows the weight of samples before and after sulphate attack. It shows that the M1 exhibited an initial weight of 268.652 grams, which decreased to 251.723 grams after 90 days of exposure to sulphate attack. This resulted in a weight loss of 7.282 grams, or a percentage loss of 2.71%. The data suggests that M1 experienced a moderate degree of weight loss due to sulphate attack. While the percentage loss is relatively low, it indicates some vulnerability to sulphate exposure. M2, the rice husk ash-based geopolymer mortar, had an initial weight of 214.316 grams, which decreased to 170.816 grams after the 90-day sulphate attack test. This led to a weight loss of 5.526 grams, with a percentage loss of 2.58%. Similar to M1, M2 exhibited moderate sulphate attack resistance, with a slightly lower percentage loss. The results suggest that M2 may need additional protective measures in sulphate-rich environments. M3, the fly ash-based geopolymer mortar, demonstrated the highest sulphate attack resistance among the three formulations. It started with an initial weight of 209.987 grams and experienced only a minimal weight loss, reducing to 207.61 grams after the 90-day test. This led to a weight loss of 2.747 grams and a low percentage loss of 1.31%. These findings indicate that M3 is relatively more resistant to sulphate attack compared to M1 and M2.

In comparison, the data suggests that M3 (fly ash-based) exhibits the highest sulphate attack resistance, with the least weight loss and percentage loss after the 90-day test. M1 (slag-based) and M2 (rice husk ash-based) demonstrated moderate resistance, with slightly higher weight and percentage losses, as shown in **Figure 3a**. Sulphate attack resistance is a critical property for construction materials, particularly in environments where sulphate exposure is a concern. While M3 appears to offer the best sulphate attack resistance, the choice among these geopolymer mortar formulations should consider other factors such as compressive strength, cost-effectiveness, and the specific environmental conditions of the intended application.

Literature supports the observed trends in sulfate resistance. Studies have shown that fly ash-based geopolymers generally outperform other materials in sulfate-rich environments due to their denser microstructure and lower calcium content, which reduces the formation of expansive products like ettringite (**Binici and Aksoğan, 2006**). The superior performance of M3 aligns with these findings, as the reduced porosity in fly ash-based geopolymers limits the ingress of sulfate ions, thereby enhancing durability (**Mane and Jadhav, 2012**).

Additionally, the moderate resistance observed in slag and RHA-based geopolymers (M1 and M2) can be attributed to their differing chemical compositions. While slag-based geopolymers benefit from the latent hydraulic properties of slag, their higher calcium content can make them more susceptible to sulfate attack compared to fly ash-based systems (**Bashar et al., 2014**). On the other hand, the performance of RHA-based geopolymers may vary depending on the quality of the RHA and the alkali activator used, as these factors significantly influence the material's microstructure and resistance to chemical attacks.

3.2.2. Chloride attack

The chloride attack resistance results for the three geopolymer mortar formulations are shown in **Table 4**. These are M1 (slag-based), M2 (rice husk ash-based), and M3 (fly ash-based). The data includes weight measurements before and after a 90-day chloride attack test, as well as weight loss and percentage loss.

In the chloride attack test, the symbol S2 exhibited an initial weight of 282.36 grams, which decreased to 278.1 grams after 90 days of exposure. This resulted in a weight loss of 4.26 grams, which is equivalent to a percentage loss of 1.51%. After 90 days, symbol Sb's initial weight of 278.37 grams dropped to 274.52 grams. The weight loss was 3.85 grams, resulting in a percentage loss of 1.38%. These results indicate that M1, the slag-based geopolymer mortar, showed a relatively low to moderate vulnerability to chloride attack. Both symbols S2 and Sb exhibited percentage weight losses within this range, suggesting that this formulation may require protective measures when exposed to chloride-rich environments for extended periods.

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Table 4: Weight of geopolymer mortars before and after attacks (unit-gram)

Tests	Nomenclature	Symbol	Wt. before test (g)	Wt. after test (g)	Loss in wt. after 90 days (g)	% age loss in (%) after 90 days
Sulphate Attack	M1 (Slag)	S1	268.652	261.37	7.282	2.71
		Sa	251.723	248.91	2.813	1.12
	M2 (RHA)	R1	214.316	208.79	5.526	2.58
		Ra	170.816	166.35	4.466	2.61
	M3 (Fly Ash)	F1	209.987	207.24	2.747	1.31
		Fa	207.61	205.49	2.12	1.02
Chloride Attack	M1 (Slag)	S2	282.36	278.1	4.26	1.51
		Sb	278.37	274.52	3.85	1.38
	M2 (RHA)	R2	195.553	189.21	6.343	3.24
		Rb	169.417	165.42	3.997	2.36
	M3 (Fly Ash)	F2	218.06	213.2	4.86	2.23
		Fb	201.933	194.12	7.813	3.87
Acid Attack	M1 (Slag)	S3	257.493	250.64	6.853	2.66
		Sc	255.903	250.36	5.543	2.17
	M2 (RHA)	R3	207.037	200.98	6.057	2.93
		Rc	169.441	163.16	6.281	3.71
	M3 (Fly Ash)	F3	216.319	208.42	7.899	3.65
		Fc	195.984	189.62	6.364	3.25

For M2, symbol R2 displayed an initial weight of 195.553 grams, which decreased to 189.21 grams after 90 days of exposure. This resulted in a weight loss of 6.343 grams, which is equivalent to a percentage loss of 3.24%. After 90 days, the initial weight of Symbol Rb dropped to 165.42 grams. The weight loss was 3.997 grams, resulting in a percentage loss of 2.36%. These results suggest that M2, the rice husk ash-based geopolymer mortar, exhibited moderate vulnerability to chloride attack. Both symbols R2 and Rb experienced percentage losses in weight that indicate some susceptibility to chloride ions, particularly symbol R2 with a higher percentage loss.

For M3, the symbol F2 displayed an initial weight of 218.06 grams, which decreased to 213.2 grams after 90 days of exposure. This resulted in a weight loss of 4.86 grams, which is equivalent to a percentage loss of 2.23%. After 90 days, symbol Fb's initial weight of 201.933 grams dropped to 194.12 grams. The weight loss was 7.813 grams, resulting in a percentage loss of 3.87%. These results reveal that M3, the fly ash-based geopolymer mortar, exhibited a moderate to relatively higher vulnerability to chloride attack compared to M1 and M2. Both symbols F2 and Fb experienced percentage losses in weight that indicate a notable susceptibility to chloride ions, with symbol Fb showing a higher percentage loss.

In comparison (see **Figure 3b**), M1 demonstrated relatively low susceptibility to chloride attack, with both symbols S2 and Sb showing percentage losses in weight within the range of 1.38% to 1.51%. These results suggest that M1 is suitable for applications in environments with moderate chloride exposure. While M2 exhibited moderate susceptibility to the chloride attack. Both symbols R2 and Rb experienced percentage losses in weight that indicate some vulnerability to chloride ions, with symbol R2 displaying a slightly higher percentage loss. This suggests that M2 may require protective measures in environments with significant chloride exposure. However, M3, the fly ash-based geopolymer mortar, exhibited moderate to relatively higher susceptibility to chloride attack compared to M1 and M2. Both symbols F2 and Fb experienced percentage losses in weight that indicate notable vulnerability to chloride ions, with symbol Fb showing a higher percentage loss. This suggests that M3 may require additional protective measures or may not be the best choice in environments with significant chloride exposure.

3.2.3. Acid attack

Table 4 shows the acid attack resistance results for the three geopolymer mortar formulations. For M1 (S3), it had an initial weight of 257.493 grams, which decreased to 250.64 grams after a 90-day acid attack test. The resulting weight loss was 6.853 grams, which is equivalent to a percentage loss of 2.66%. Similarly, after 90 days, the Sc sample's initial weight of 255.903 grams dropped to 250.36 grams. The weight loss was 5.543 grams, resulting in a percentage loss of 2.17%. This is consistent with research indicating that slag-based geopolymers tend to have better durability in acidic environments due to the formation of stable calcium-silicate-hydrate (C-S-H) phases that resist degradation by acids (**Bakharev, 2005**).

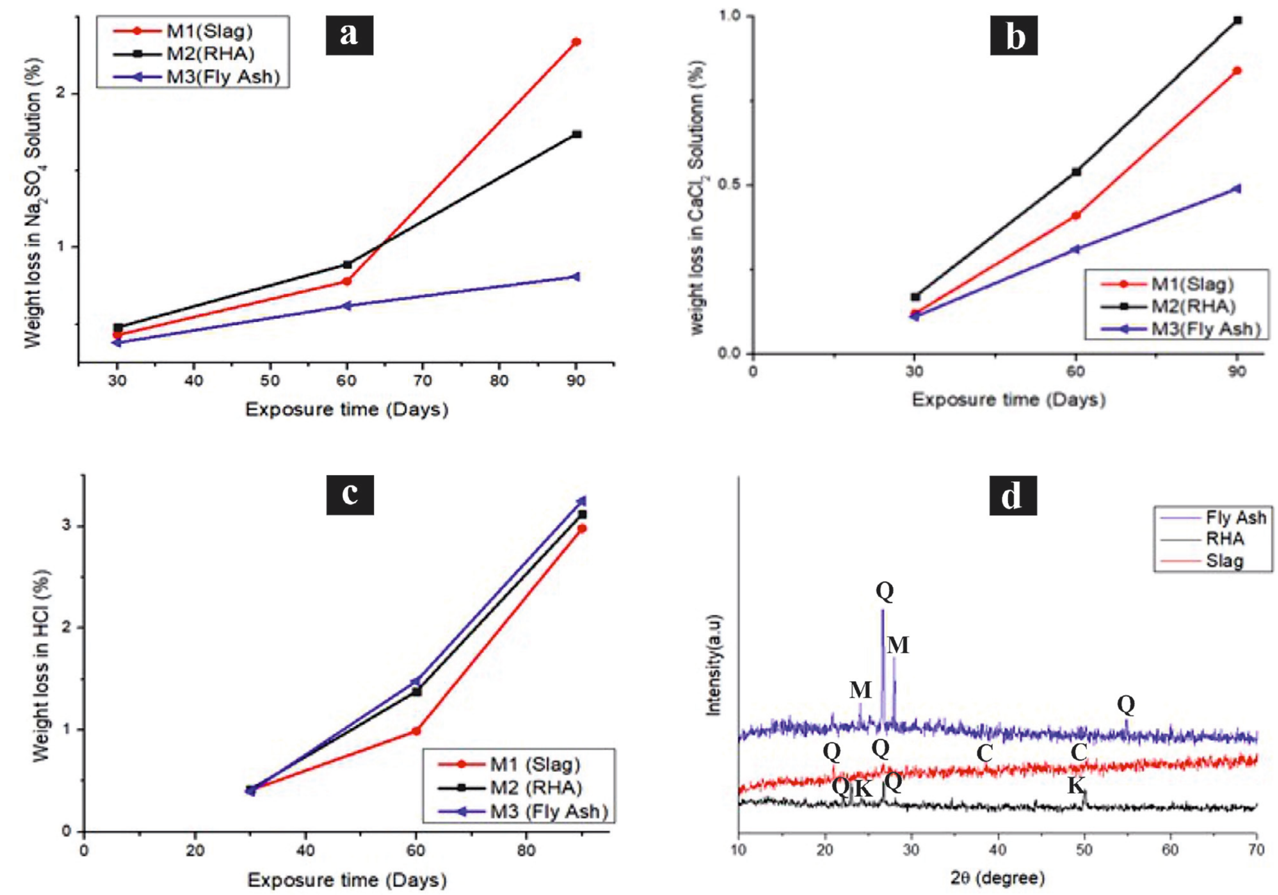

Figure 3 a) Weight losses (%) of geopolymer mortars in sulphate (Na_2SO_4); b) Weight losses (%) of geopolymer mortars in $CaCl_2$; c) Weight losses (%) of geopolymer mortars in HCl; d) XRD patterns of M1, M2, and M3 mortars cured for 28 days (in the 2h range of 5–80 Φ). Q: Quartz, M: Mullite, C: Calcite, K: Kaolinite.

For M2, the symbol R3 sample displayed an initial weight of 207.037 grams, which decreased to 200.98 grams after 90 days of acid attack exposure. The resulting weight loss was 6.057 grams, equivalent to a 2.93% percentage loss. Similarly, after 90 days, the initial weight of sample Rc dropped to 163.16 grams. The weight loss was 6.281 grams, resulting in a percentage loss of 3.71%. M2 (rice husk ash-based) geopolymer mortars showed slightly higher weight losses (2.93% to 3.71%) compared to M1, which may be attributed to the lower content of aluminosilicate materials that typically enhance acid resistance by forming stable aluminosilicate gels upon acid exposure. However, recent studies also highlight that the presence of reactive silica in rice husk ash can contribute to improved acid resistance through the formation of additional silicate structures, although this effect is less pronounced compared to slag-based systems (**Mostazid, 2023**).

M3 (F3) showed an initial weight of 216.319 grams, which decreased to 208.42 grams after 90 days of acid attack exposure. The resulting loss in weight was 7.899 grams, equivalent to a percentage loss of 3.65%. Similarly, Fc had an initial weight of 195.984 grams, which was reduced to 189.62 grams after 90 days. The weight loss was 6.364 grams, resulting in a percentage loss of 3.25%. M3 (fly ash-based) geopolymer mortars experienced the highest weight loss, with percentages ranging from 3.25% to 3.65%, indicating lower resistance to acid attack. This finding aligns with other studies that suggest fly ash-based geopolymers are more vulnerable to acid degradation due to the lower calcium content, which results in fewer C-S-H phases and more easily dissolvable aluminosilicate networks under acidic conditions (**Teshnizi et al., 2023**).

Comparative analysis of acid attack results, as shown in **Figure 3c**, showed that M1 demonstrated moderate resistance to acid attack. Both S3 and Sc experienced weight loss percentages ranging from 2.17% to 2.66%. This suggests that M1 can withstand exposure to acid to a certain extent, making it suitable for applications in environments with moderate acid exposure. Similarly, M2 exhibited moderate resistance to acid attack as well. Samples R3 and Rc both experienced weight percentage losses between 2.93% and 3.71%. This suggests that M2 can withstand acid exposure to a certain extent, although Rc showed a slightly higher percentage loss. M3 exhibited moderate resistance to acid attack, with both F3 and Fc experiencing weight percentage losses between 3.25% and 3.65%. This suggests that M3 can withstand exposure to acid to a certain extent but may be relatively more vulnerable compared to M1 and M2.

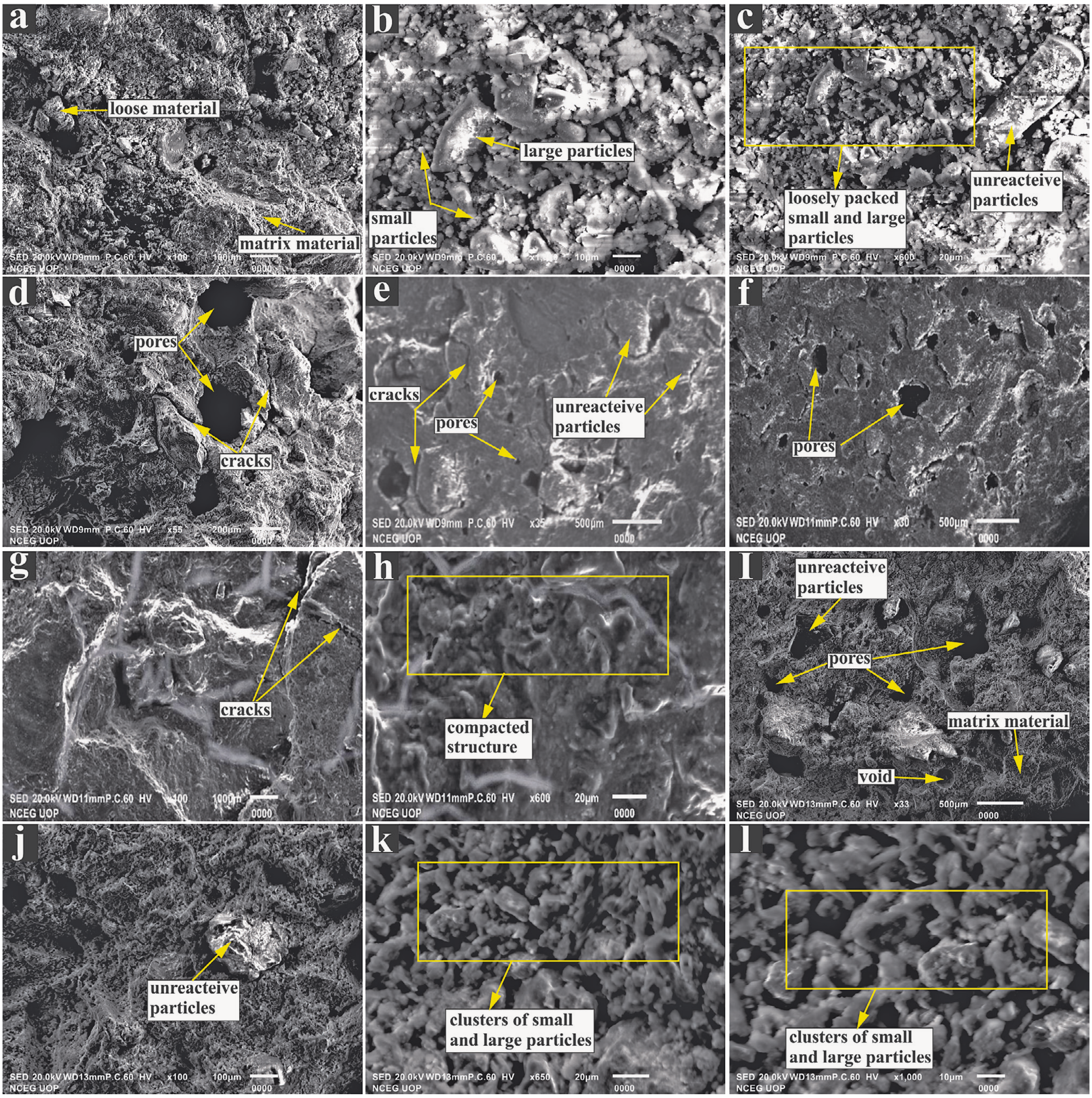

Figure 4: Representative SEM images of slag mortar (a-d), RHA mortar (e-h), and fly ash mortar (i-l)

This study has not specifically examined the porosity of the concretes after acidic attacks. However, it is important to note that porosity plays a significant role in assessing the durability of concrete. According to **Hosseini et al. (2023)**, lower porosity typically enhances resistance to chemical attacks, such as acid exposure, which is crucial for long-term performance in aggressive environments. Evaluating porosity could provide valuable insight into the durability advantages of the concrete in these conditions.

3.3. Mineralogy

XRD examination of mineralogy is a difficult process. However, the sample was evaluated by reviewing past studies and comparing the results. These peaks are caused by the formation of gels in the geopolymer mortar specimens, which ensures their great strength and durability (see **Figure 3d**) (**Álvarez-Ayuso et al., 2008; Davidovits, 1994a; Komljenović, 2015**). Different peaks were observed between 5-80 degrees, with the most dynamic of several samples occurring between 20-40 degrees, indicating the presence of amorphous components such as quartz (SiO_2) and mullite ($3Al_2O_3$ $2SiO_2$ or $2Al_2O_3$ SiO_2) was confirmed, which are common in geopolymer binders and contribute to their mechanical stability. The detection of sodalite [$Na_8(Al_6Si_6O_{24})Cl_2$] further suggests that the material has undergone adequate polymerization, as this mineral is

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often formed during the geopolymerization process, particularly in alkali-activated systems.

Studies emphasize that the presence of amorphous aluminosilicate phases, indicated by the broad peaks, is essential for the material's resistance to chemical attack and thermal stability. Additionally, the role of calcium silicate hydrate (C-S-H) phases, formed from slag or other calcium-rich precursors, is crucial in enhancing the geopolymer's overall durability (**Oh et al., 2011; Król et al., 2017**).

3.4. Microstructural characteristics

SEM and EDS analyses were conducted on geopolymer mortar specimens. The extent of the temperature-dependent geopolymerization reaction has a significant impact on the development of the microstructure and mechanical properties of the geopolymer matrix. The M1 (slag) mortar has mostly larger particles that are loosely packed and surrounded by small particles (see **Figure 4a–c**). There are visible pores and thermal cracks in the M1 (slag) mortar (see **Figure 4d**). The M2 (RHA) mortar has microcracks, and these cracks in turn make the matrix less compact. There are pores, and some unreactive particles remain embedded in the matrix (see **Figure 4e–g**). The overall structure of M2 (RHA) mortar is comparatively compacted (see **Figure 4h**). The M3 (fly ash) mortar has small and large particles in a more compacted structure and demonstrates a dense cluster formation (see **Figure 4i-l**). The presence of abundant Si, Al, and Na in all geopolymer mortars (see **Figure 5a-c**) corresponds to the XRD results that the materials have abundant quartz, mullite, and sodalite, thus revealing the proof of a geopolymer binder with strong aluminosilicate bonds, which are responsible for the cementation of geopolymer concrete. M2 (RHA) has a higher silica content compared to M1 (slag) and M3 (fly ash) (see **Figure 5a-c**).

The selection of a geopolymer mortar formulation for construction projects should be carefully aligned, considering various factors including strength, cost-effectiveness, environmental impacts, the presence of corrosive agents, and the specific demands of the project. Each of the three formulations of this study, M1 (slag-based), M2 (rice husk ash-based), and M3 (fly ash-based), offer distinct advantages and considerations. M3 stands out as the top performer in terms of compressive and flexural strength, making it an excellent choice for structural elements in construction projects where high strength and durability are paramount. However, it does exhibit a relatively higher susceptibility to chloride attack, which should be a concern in chloride-rich environments. M2 strikes a balance between strength and environmental benefits, making it a favourable choice when cost-effectiveness and eco-friendliness are key priorities. It does require caution in chloride-exposed environments, however, and may necessitate additional protective measures. In cases where acid resistance is a critical factor, M1 appears to be the most suitable option, while M2 and M3 may require additional protective measures. M1, despite having slightly lower strength values compared to M2 and M3, demonstrates exceptional resistance to chloride attack, making it a preferred option for projects in moderately chloride-rich environments. Additionally, it exhibits better acid attack resistance than the other formulations. In addition, replacing cement with blast furnace slag can address key social and environmental issues, such as industrial waste treatment in landfills and increased emissions from the cement industry.

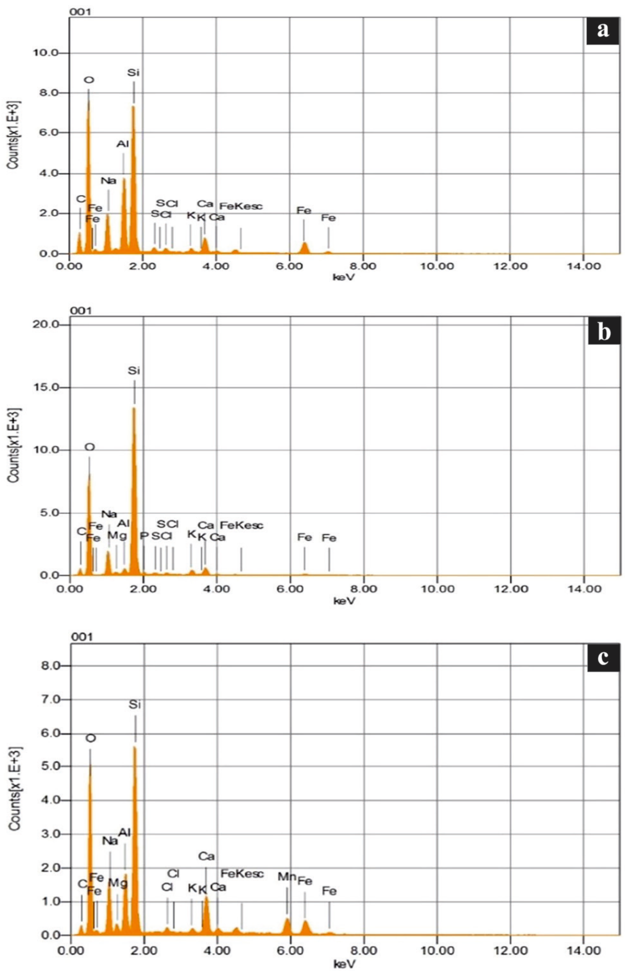

Figure 5: EDS analysis of a) M1(slag); b) M2 (RHA); c) M3 (fly ash) mortars

In addition to the SEM and EDS analyses, recent literature highlights the role of microstructural characteristics in influencing the mechanical performance of geopolymers. Studies have demonstrated that the formation of a dense and interconnected network of aluminosilicate chains, as seen in M3 (fly ash-based) mortar, is critical for enhancing compressive strength and durability in geopolymer matrices. The presence of minerals like mullite and sodalite, as identified through XRD and confirmed by SEM-EDS analysis, further supports the development of strong aluminosilicate bonds responsible for the improved mechanical properties observed in M3 (**Koçyiğit, 2024**).

Moreover, the literature underscores the importance of alkali activation conditions, particularly the Si/Al ratio, in determining the final microstructure and performance of geopolymers. Higher silica content, as found in M2 (RHA-based) mortar, contributes to the formation of a more compact matrix but may require careful control of alkali concentrations to optimize durability against environmental factors such as chloride attack (**He et al., 2020**).

Lastly, the incorporation of industrial by-products like blast furnace slag in M1 mortar not only enhances the material's resistance to chemical attacks but also aligns with sustainability goals by reducing industrial waste and minimizing carbon emissions associated with traditional cement production (**Koçyiğit, 2024**).

4. Conclusions

The following conclusions are drawn based on the experimental investigation of the mechanical properties and durability of the self-compacting geopolymer mortar using various mineral additions:

1. RHA is an effective alternative to ordinary portland cement, capable of reacting with an alkaline activator such as cement granular blast furnace slag sand to form a geopolymer mortar with notable reinforcing properties. The properties of the geopolymer mortar, including compressive strength and density, are significantly influenced by the concentration of the geopolymer binder and the liquid-activator/solid ratio of the mixture. Optimizing these parameters is crucial for achieving the desired material properties.
2. Oven heating significantly enhances the compressive strength and density of geopolymer mortars compared to water-curing and ambient temperature curing. This indicates that controlled thermal curing is beneficial for optimizing the mechanical properties of geopolymer mortar, making it a preferable method for achieving higher performance.
3. Geopolymer mortars demonstrate comparable qualities to portland cement mortars, particularly in terms of mechanical strength. Among the formulations studied, M3 (fly ash-based) exhibits superior compressive and flexural strength, making it highly suitable for structural applications where high performance is essential.
4. M1 (slag-based) geopolymer mortar is particularly effective for applications requiring high acid resistance. Conversely, M2 (RHA-based) and M3 (fly ash-based) mortars may need additional protective measures in environments exposed to chloride or acidic conditions. Careful evaluation of the specific project requirements, including environmental exposure and performance criteria, will guide the optimal selection of geopolymer mortar formulations, ensuring both durability and functionality in construction projects.

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SAŽETAK

Eksperimentalno ispitivanje mehaničkih svojstava i trajnosti samozbijajuće geopolimerne žbuke s različitim mineralnim dodatcima

Geopolimer je nekonvencionalno anorgansko vezivo pripremljeno kombinacijom alkalnoga aktivatora i materijala koji sadržavaju aluminij i silicij. Ova studija temeljito je procijenila performanse čvrstoće i trajnosti geopolimerne žbuke i predstavlja sveobuhvatan pokušaj da se istakne napredak ekološki osviještenih i inovativnih građevinskih materijala. Istraživanje je provedeno korištenjem rendgenske difrakcije, skenirajuće elektronske mikroskopije, energijsko-disperzijske spektroskopije X-zraka, univerzalnih strojeva za ispitivanje i kemijskih metoda (kiselinska, sulfatna i kloridna djelovanja). Procijenjena su i uspoređena mehanička svojstva i trajnost geopolimerne žbuke izrađene na konstantnim temperaturama s različitim mineralnim dodatcima. Usporedna analiza geopolimerne žbuke pokazuje da je M3 (lebdeći pepeo) izvrstan izbor za konstrukcijske elemente u građevinskim projektima gdje su visoka čvrstoća i trajnost najvažniji jer je M3 (lebdeći pepeo) postigao najveće tlačne (17,07 MPa) i savojne čvrstoće (2,28 MPa) u svim razdobljima stvrdnjavanja u usporedbi s M2 (RHA) i M1 (šljaka), koji imaju srednju (11,66 MPa, 2,17 MPa) odnosno najnižu (10,10 MPa, 2,04 MPa) tlačnu čvrstoću i čvrstoću na savijanje. U slučajevima kada je otpornost na kiselinu kritičan čimbenik za konstrukciju, M1 se čini kao najprikladnija opcija, dok M2 i M3 mogu zahtijevati dodatne zaštitne mjere. M1, unatoč nešto nižim vrijednostima čvrstoće od M2 i M3, pokazuje iznimnu otpornost na djelovanja klorida, što ga čini preferiranom opcijom za projekte u okruženjima umjereno bogatim kloridima. Zbijeni materijal povećao je čvrstoću i trajnost, dok su je pukotine, pore i nejednolik raspored čestica smanjili. Sve u svemu, obilje minerala s elementarnim sastavom kao što su Si, Al, O i Na odgovorno je za snažno vezivanje za cementaciju geopolimernoga betona. Stoga, imajući u vidu rezultate ove studije, različite geopolimerne žbuke mogu se odabrati za potrebe građenja na temelju zahtjeva projekta.

Ključne riječi:
geopolimer, lebdeći pepeo, alkalni aktivator, čvrstoća i trajnost, mineralni dodatci

Authors' Contribution

Ihtisham Islam (PhD, Lecturer) has done a formal analysis and investigation, writing, reviewing, and writing of the original draft. **Salman Ahmed Khattak** (MS, Lecturer/Researcher) has done a formal analysis and investigation, writing, reviewing, and writing of the original draft. **Petros Petrounias** (PhD, Professor) has done the interpretation, writing, and reviewing. **Abdul Rahim Asif** (PhD, Lecturer) has reviewed the manuscript. **Syed Samran Ali Shah** (PhD Scholar) and **Kanishka Sauis Turrakheil** (PhD Scholar) have reviewed the manuscript and drawn the figures. **Waqas Ahmed** (PhD, Associate Professor) has guided chemical analysis. **Mehboob Ur Rashid** (PhD, Student), **Qasim Ur Rehman** (PhD, Assistant Professor), and **Muhammad Naveed Khan** (PhD, Assistant Professor) have reviewed the manuscript. All co-authors made substantial contributions, read, and commented on several versions of the manuscript, and agreed with the contents of the manuscript.