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Durability of sisal fiber-reinforced mortar with glass powder as cement substitute in aggressive environment

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Abstract

Mortar plays a crucial role in construction, serving as a binder in masonry, plastering, and repairs. However, durability remains a key challenge, especially under harsh environmental conditions. This study investigates the durability and mechanical performance of sisal fiber reinforced-mortar (FR-M) incorporating waste glass powder (GP) as a partial cement replacement. Mortar mixes with 0–20% GP and 1% sisal fiber were prepared, and their properties were evaluated under exposure to magnesium sulfate (MgSO_4). Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD) analyses revealed that GP enhanced the formation of C–S–H gel, reduced porosity, and promoted a denser matrix, which correlated with improved strength and sulfate resistance. The results demonstrated that the balanced mix, which is 7.5% GP with 1% fiber, showed the highest compressive strength (18 MPa) and flexural strength (6.7 MPa) after 90 days of curing. Furthermore, this mix exhibited superior sulfate resistance, with only 13.8% and 14.8% loss in compressive and flexural strengths, respectively, and minimal expansion (0.096 mm). In contrast, higher GP levels (15% and 22.5%) led to reduced strength and durability. This study highlights the combined effect of GP and sisal fiber in improving both the mechanical properties and sulfate resistance of mortar, offering a sustainable solution for durable construction materials.

1 Introduction

Mortar is a fundamental construction material used as a binding agent in masonry, plastering, and repair applications. It is composed of cementitious materials (such as cement or lime), fine aggregates (typically sand), and water, mixed to form a cohesive paste [10]. Unlike concrete, mortar lacks coarse aggregates, resulting in a smoother, more workable consistency that allows it to fill gaps between bricks, stones, or blocks, ensuring structural integrity and load distribution. Mortar serves multiple functions, including bonding masonry units, sealing joints against weather penetration, and providing a finished surface for plastering. Its properties—such as workability, strength, and durability—are



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influenced by the mix proportions, type of binder, and curing conditions. Traditional mortar types include cement mortar (high strength, rigid), lime mortar (flexible, breathable), and gypsum mortar (fast-setting, interior use) [9]. However, despite its long history, the production of mortar, particularly cement-based varieties, imposes a significant environmental burden, making sustainable alternatives a pressing research need. This study addresses this gap by exploring the combined role of waste glass powder (GP) and fiber reinforcement in improving both the mechanical performance and durability of mortar systems. The overarching goal is to develop eco-friendly, high-performance formulations suited for demanding construction applications.

Waste glass (WG) offers a dual advantage: diverting a major waste stream from landfills while reducing reliance on cement. Instead of undergoing energy-intensive remelting, glass can be finely ground into glass powder (GP), which functions as a supplementary cementitious material (SCM). Prior studies have demonstrated that finely ground WG exhibits pozzolanic reactivity, enhances matrix densification, and contributes to sustainability efforts by reducing CO₂ emissions by up to 12% and cutting energy use in cement production by around 15% [2, 11, 17]. To achieve sustainability goals, the principles of reducing, reusing, and recycling are crucial. Managing demand and minimizing waste production through improved material quality is the first step. Reusing glass is prioritized over recycling by the EU, as it is more sustainable by avoiding the additional remelting step [8]. Recent studies indicate that waste-derived glass can act effectively as a supplementary cementitious material and microfiller, densifying the matrix and providing pozzolanic activity [1] and, when combined with mineral SCMs (like metakaolin, GGBFS, Pulverized clay waste) [5, 7, 18] and fibre reinforcement, can restore or enhance mechanical strength, crack control, and durability [1, 24], while scientometric reviews of nanomaterials emphasize that particle processing, dispersion, and dosage critically govern these performance gains [19]; additionally, regional studies underline the practical need for durable, resilient mortars in real-world construction settings [25].

Alongside SCMs, fibers, especially natural ones, play a critical role in mortar sustainability and performance. Historically, straw and horsehair were added to plaster and bricks for strength; modern research extends this approach to fibers such as coir, sisal, jute, flax, bagasse, bamboo, banana, and kenaf [14, 23]. Natural fibers are renewable, biodegradable, and capable of improving tensile strength, flexural behavior, and crack resistance of cement composites. For instance, coconut fibers often outperform synthetic fibers in durability under load [29]. Sisal fibers, when added to concrete, tend to reduce its strength compared to samples without fibers. The length of fibers, such as sisal and banana, influences the load transfer mechanism in the concrete matrix (Dhand et al., 2015). The performance of cement composites is enhanced by long sisal fibers arranged in layers within a steel mold. Vegetable fibers, like those from eucalyptus, improve mechanical performance compared to pine-based fibers after 200 aging cycles [30]. Natural fibers in concrete combinations exhibit varied tensile strengths under different conditions, such as exposure to water, sodium, and other immersions. The impact of saturated lime significantly reduces the tensile strength of fibers like sisal, jute, and hibiscus [26]). After prolonged wet and dry cycles, fibers like coir retain a portion of their initial strength. Adding sugarcane bagasse marginally increases flexural strength by 3% [20]. Raw jute, when applied to concrete with 1% cement weight, enhances flexural strength [21]. Coconut fiber reinforcement also improves the flexural properties of

epoxy polymers and concrete, with reinforced concrete glass and carbon fiber showing the best results [15]. Natural fibers like polypropylene and kenaf reduce water absorption due to their hydrophobic nature. Coir in concrete shows increased water absorption as its content increases [6]). Although numerous studies have investigated glass powder (GP) as a cement replacement and natural fibers as reinforcement in mortar, the combined use of these two materials has not been widely presented as a clear methodological innovation. The incorporation of recycled waste glass and fiber reinforcement has emerged as a promising approach for producing sustainable, high-performance cement-based composites. Researchers like [22] investigated the effect of recycled waste glass (WG) on the flowability, strength, durability properties, and temperature resistance of concrete. The mixtures were prepared by replacing natural sand with varying ratios of WG. The samples were submerged in 2% H_2SO_4 and 5% MgSO_4 solutions and subjected to high temperatures for 1.5 h. The results showed that the flowability increased with WG content, while the compressive strength decreased for the substituted 2% natural sand. [12] and [27] observed that incorporating up to 45% GP, with or without superplasticizer (SP), reduced chloride ion penetration. As concrete ages, its pore structure improves, reducing chloride penetration, although higher penetration might be observed in the early stages of its life. [27] also studied the effects of combining glass powder (GP) with furnace slag (SG), limestone powder (LP), and fly ash (FA) on sulfate attack resistance. They discovered that increasing the amount of GP enhanced resistance to 5% H_2SO_4 after 12 weeks, with the best results observed in mixes containing 20% GP, 20% LP, and 45% GP alone. All three additives positively influenced sulfate resistance, with higher GP percentages having a more significant effect. However, this improvement came with a considerable reduction in compressive strength, ranging from 30% to 54%, which is quite substantial. These findings highlight that while glass-based supplementary cementitious materials (SCMs) and fibers are individually well-studied, their synergistic use in mortar systems under aggressive chemical environments remains underexplored. So, the construction sector continues to grapple with durability challenges in concrete structures exposed to harsh environmental conditions; despite the known advantages of fiber reinforcement, the potential benefits of incorporating recycled materials like glass waste powder (GP) in mortar systems remain underexplored. The objectives of this project are to evaluate the chemical composition and microstructural properties of waste glass powder (GP), determine the strength properties of the fiber-reinforced mortar (FRM) blended with GP when exposed to magnesium sulfate at varying curing periods, and assess the impact of magnesium sulfate exposure on the chemical composition and microstructural properties of the mortar samples.

2 Materials and methodology

2.1 Materials

This section explains the materials used, the mixing techniques, and the testing methods employed in this research project. The materials utilized include Ordinary Portland Cement (OPC), fine aggregate, water, waste glass powder, sisal fibers, and magnesium sulfate. The cement used was BUA 42.5R grade OPC, sourced from Mohadis Construction Limited in Ilorin, Kwara State, and it complied with ASTM C150 (2021) specifications for structural applications. The fine aggregate, obtained from the same supplier in Ilorin, met the requirements of ASTM C33 (2016). Potable water conforming to ASTM

**Fig. 1** Materials**Table 1** Mix proportion

S/N	Mix ID	Sisal Fiber Content (%)	Cement (kg)	GP (kg)	Sand (kg)	Water (kg)
1	M1	0	5.2	0	14.3	4.948
2	M2	0.5	5.2	0	14.3	4.948
3	M3	1	5.200	0	14.3	4.948
4	M4	0	4.810	0.39	14.3	4.948
5	M5	0.5	4.810	0.39	14.3	4.948
6	M6	1	4.810	0.39	14.3	4.948
7	M7	0	4.42	0.78	14.3	4.948
8	M8	0.5	4.420	0.78	14.3	4.948
9	M9	1	4.420	0.78	14.3	4.948
10	M10	0	4.03	1.17	14.3	4.948
11	M11	0.5	4.03	1.17	14.3	4.948
12	M12	1	4.03	1.17	14.3	4.948

D1193-20 was used in all mix preparations. Waste glass was collected from restaurants, bars, and shebeens in Ilorin; after thorough cleaning and manual sorting to remove non-glass materials, it was mechanically crushed, ground to fine particles using a mechanical grinder, and sieved to pass through a 90-micron sieve. This ensured a uniform particle size suitable for use as a supplementary cementitious material in mortar production, with the grinding carried out at the Civil Engineering Department Laboratory, LAUTECH, Ogbomosho. Sisal fibers were sourced in Ilorin, where they were cleaned, sun-dried, manually separated for uniformity, and trimmed into 30 mm lengths before use in the concrete mix. Finally, magnesium sulfate heptahydrate ($\text{MgSO}_4 \cdot 7 \text{H}_2\text{O}$), AR grade with a purity of $\geq 99\%$, was locally sourced from Irebamidele Chemical Store in Ilorin and supplied in 500 g bottles Fig. 1.

The mix proportions in Table 1 were designed to evaluate the effects of varying waste glass powder (GP) contents as partial cement replacements and different sisal fiber volumes. The control mix used a cement: sand: water ratio of 1:2.75:0.95 without GP or fiber. GP was introduced at 7.5%, 15%, and 22.5% replacement levels, and sisal fiber was added at 0%, 0.5%, and 1.0% by volume. Glass powder (GP) was incorporated at 7.5%,

15%, and 22.5% cement replacement to capture the range where pozzolanic activity enhances durability without significant early strength loss, as reported in studies recommending 5–25% GP use [12, 27]. Sisal fiber was added at 0%, 0.5%, and 1.0% by volume, aligning with findings that volumes above 1% often reduce workability and increase void content (Mastali et al., 2018). These dosages allow a balanced evaluation of GP's SCM potential and fiber reinforcement synergy under sulfate exposure. A total of twelve mixes were prepared, starting with the control mix (M1) containing 5.2 kg of cement, 14.3 kg of sand, and 4948 ml of water. In M2 and M3, the same base mix was used, but sisal fiber was added at 0.5% and 1.0% to assess its individual effect. For M4 to M6, 7.5% of cement was replaced with 0.39 kg GP, reducing cement to 4.81 kg, and fiber was varied across 0%, 0.5%, and 1.0%. M7 to M9 incorporated 15% GP (0.78 kg) with cement reduced to 4.42 kg, and the same fiber variations, while M10 to M12 used 22.5% GP (1.17 kg) with 4.03 kg of cement and the same range of fiber content. In all mixes, sand and water remained constant to ensure comparability. Three 50 mm cubes were cast for compressive strength, three 40 × 40 × 160 mm prisms for flexural strength, and three 50 mm cubes for durability. All specimens were cast using a mechanical vibration table, left at room temperature for 24 h, demolded, and cured in water at 27 °C until testing. Curing durations were 7, 28, 56, and 90 days.

2.2 Experimental programme

2.2.1 Tests on microstructural properties

X-ray fluorescence (XRF), X-ray diffraction (XRD), and scanning electron microscopy (SEM) were conducted to evaluate the chemical composition, crystalline phases, and microstructural morphology of the mortar and glass powder samples. Figure 2 presents the powdered mortar samples used in these tests.

2.2.2 X-ray fluorescence (XRF)

Glass powder samples were oven-dried at 105 °C for 24 h and ground to below 75 µm. The powder was either pressed into pellets or fused into glass beads, then analyzed using an XRF spectrometer. The instrument detected emitted fluorescent X-rays to determine the elemental oxide composition, including SiO₂, Al₂O₃, CaO, and Fe₂O₃, using calibrated standards and analysis software.

2.2.3 Scanning electron microscopy (SEM)

Mortar and glass powder specimens were first rinsed with distilled water to remove surface contaminants, then oven-dried to halt ongoing hydration and eliminate residual moisture. Each sample was mounted on a conductive stub and coated with a thin gold layer to prevent charging. SEM imaging was conducted under high vacuum with optimized voltage and working distance. Surface morphology and fiber–matrix interaction were observed at various magnifications, and EDS was used to determine elemental composition. The analysis followed ASTM E1508 (2012) at the Integrated Research Laboratories, Ibadan.

2.2.4 X-ray diffraction (XRD)

Crushed and ground mortar samples (≤ 75 µm) were spread onto holders and analyzed using Cu-Kα radiation ($\lambda = 1.5406 \text{ \AA}$) at 40 kV and 30 mA, over a 2θ range of 5°–70°, with



Fig. 2 Powdered samples

a 0.02° step size. Diffraction patterns were interpreted using HighScore or Match!® software and the ICDD database to identify phases like C–S–H, portlandite, and ettringite, as well as amorphous glass phases. All procedures adhered to ASTM C1365-18.

2.3 Mechanical properties test

To evaluate the mechanical performance of mortar incorporating sisal fiber and waste glass powder, compressive strength, flexural strength, and magnesium sulfate resistance tests were conducted following relevant ASTM standards.

2.3.1 Compressive strength test

The compressive strength test was performed to determine the load-bearing capacity of the modified mortar. Standard $50 \times 50 \times 50$ mm cubes were prepared by thoroughly mixing the constituents, casting them into molds, and compacting the mix. The specimens were cured in water for 7, 28, 56, 90, and 120 days. After each curing period, the samples were removed, surface-dried, and tested using a Universal Testing Machine (UTM) at the University of Ilorin. The load was applied gradually until failure, and the peak load was recorded in accordance with ASTM C109 (2021), as shown in Figs. 2, 3.



Fig. 3 compressive strength test

2.3.2 Flexural strength test

The flexural strength test assessed the mortar's bending resistance using prismatic specimens of size $40 \times 40 \times 160$ mm, cured for the same durations. The test was conducted under a three-point loading configuration using a UTM, following ASTM C348 (2002). Each beam was placed on two support rollers, and a central load was applied until fracture occurred. The maximum breaking load was recorded and used to calculate flexural strength. This test provided insights into the contribution of sisal fibers and glass powder to tensile performance and crack resistance of the mortar under flexural stress (Fig. 4).

2.3.3 Sulfate attack

To assess resistance to sulfate attack, mortar bars were tested according to ASTM C1012/C1012M–24. After 28 days of moist curing, the bars were immersed in a freshly



Fig. 4 flexural strength test

prepared 5% magnesium sulfate ($\text{MgSO}_4 \cdot 7 \text{H}_2\text{O}$) solution, made by dissolving 50 g of MgSO_4 in 1 L of distilled water. The solution was maintained at $23 \pm 2^\circ\text{C}$, with pH controlled between 6.0 and 8.0. Each specimen was exposed at a solution-to-mortar volume ratio of 4.0 ± 0.5 , typically requiring 625–800 mL per bar. Deterioration was monitored at 30, 60, and 90 days by visual inspection for cracks and scaling, followed by compressive strength testing. A control group was submerged in tap water for comparison. This test simulated long-term exposure to aggressive environments and evaluated the durability of the modified mortar (Fig. 5).



Fig. 5 Measuring length change after MgSO_4 exposure

3 Results and discussion

This section presents and interprets the findings from all experimental tests conducted on mortar mixes incorporating sisal fiber and waste glass powder (GP), highlighting key observations, trends, and implications.

3.1 XRF analysis

The XRF results (Table 2) confirm the pozzolanic potential of the glass powder used. SiO_2 content was 52.54%, while the combined oxides ($\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$) amounted to 85.04%, surpassing the ASTM C618 minimum requirement of 70% for Class N pozzolans. These values indicate the material's suitability as a supplementary cementitious material. Although the glass powder shows high siliceous and aluminous oxide content, the measured LOI of 10.2% indicates a substantial non-reactive/volatile fraction that reduces the effective pozzolanic mass and likely contributed to the increased water demand, higher porosity, and diminished strength observed at elevated replacement levels.

3.2 XRD analysis

The XRD pattern in Fig. 6 reveals sharp peaks indicating a predominantly crystalline structure with phases such as kaolinite, quartz, albite, and muscovite. The absence of a broad hump suggests minimal amorphous content, pointing to an aluminosilicate ceramic. This correlates with the findings of Floxy et al. (2022).

XRD patterns before and after magnesium sulfate exposure (Figs. 7, 8, 9 and 10) reveal both crystalline and amorphous phases. Quartz consistently dominates all mixes, while portlandite, calcite, and C–S–H phases indicate cement hydration. Post-exposure patterns show reduced portlandite intensity and formation of secondary phases such as ettringite and calcite. Amorphous humps were minimal, indicating limited gel-phase

Table 2 Chemical composition of glass powder

Component	Content (%)
SiO ₂	52.54
Al ₂ O ₃	28.85
Fe ₂ O ₃	3.65
MnO	0.01
CaO	1.94
P ₂ O ₅	—
K ₂ O	0.95
TiO ₂	1.17
MgO	0.08
Na ₂ O	0.05
LOI	10.2
Trace Elements (ppm)	
Ba	460
Ce	58
Rb	95
Zr	70
Cr	105
Cu	35
Ni	40
Pb	10
Σ (SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃)	85.04

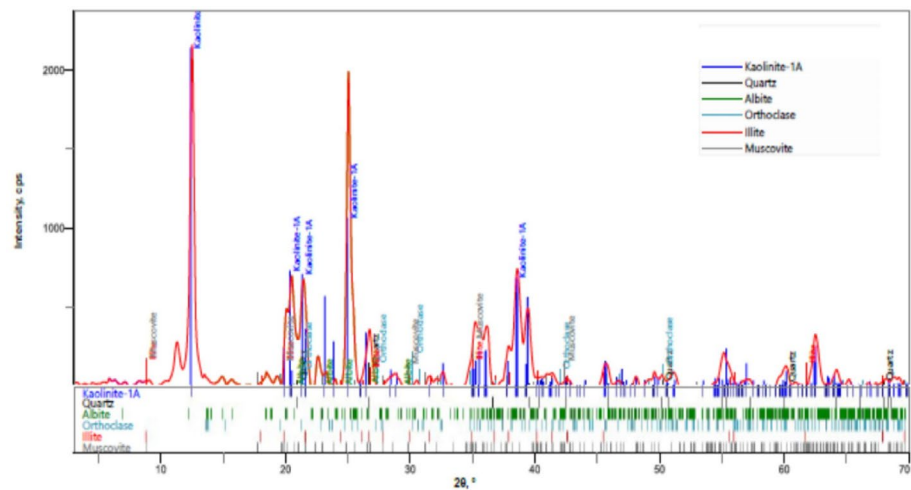
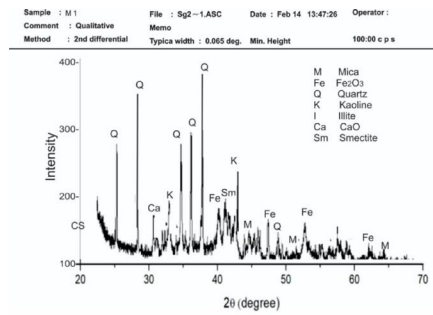


Fig. 6 XRD pattern of glass powder

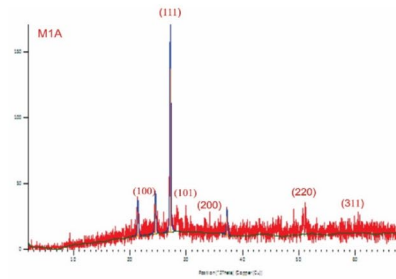
formation. M3 and M7 show signs of carbonation and secondary product formation, suggesting sulfate interaction and leaching effects.

3.2.1 XRD of M1 (control)

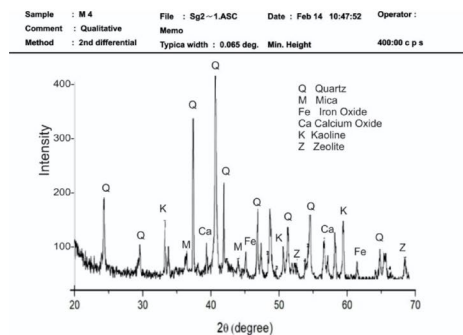
The XRD pattern of Sample M1 (Fig. 7) shows a combination of crystalline and amorphous phases. Prominent sharp peaks were identified at 21°, 26.5°, 31°, 36°, and 50°, corresponding to quartz, which is chemically stable and persists through hydration. Additional reflections are associated with kaolinite, CaO, Fe₂O₃, and traces of mica, smectite, and illite, suggesting the presence of secondary clay and oxide phases within the matrix. A key feature of the M1 spectrum is the broad hump between 20°–25°, which



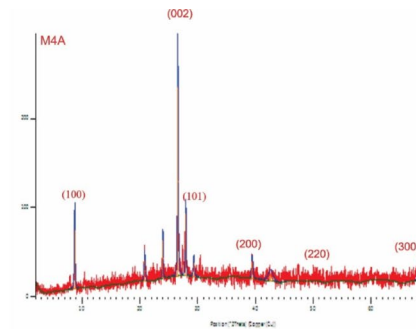
(a) Before Exposure



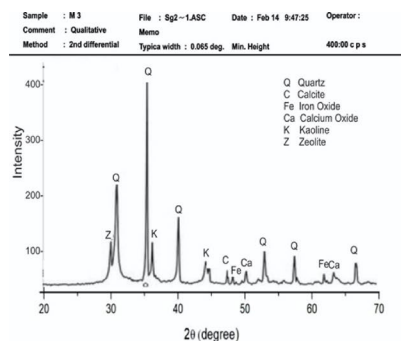
(b) After Exposure

Fig. 7 XRD pattern of M1

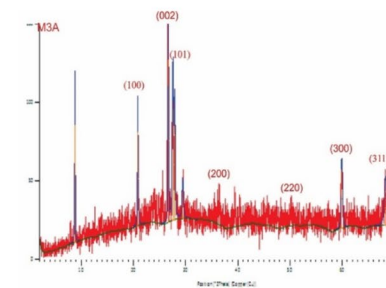
(a) Before Exposure



(b) After Exposure

Fig. 8 XRD pattern of M2

(a) Before Exposure



(b) After Exposure

Fig. 9 XRD pattern of sample M3

is characteristic of the poorly crystalline calcium silicate hydrate (C–S–H) gel. This confirms the coexistence of crystalline minerals and amorphous hydration products, consistent with active pozzolanic reactions. After sulfate exposure, the XRD profile of Sample M1A (Fig. 7b) reveals distinct changes in the phase assemblage. Well-defined reflections corresponding to (100), (101), (200), (220), and (311) planes were observed, mainly linked to quartz, calcite, and portlandite. Compared to the unexposed sample, the intensity of portlandite peaks is reduced, indicating its consumption through leaching or secondary reactions. The appearance of stronger calcite peaks suggests carbonation of CaO

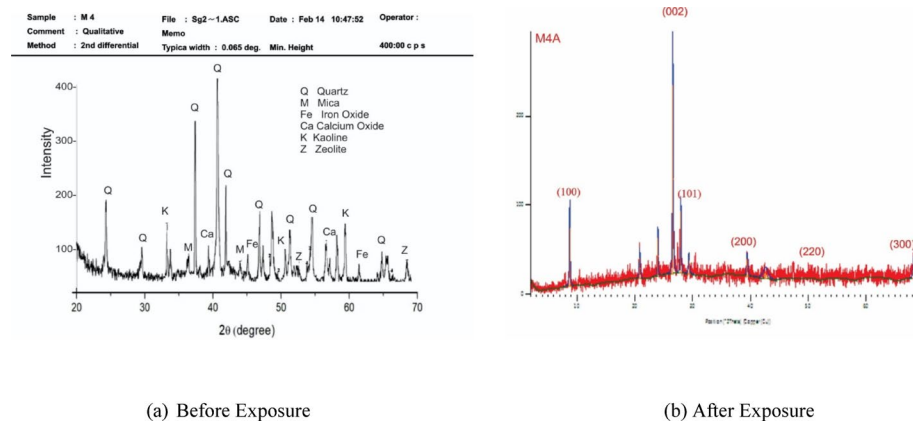


Fig. 10 XRD pattern of M4

or residual portlandite during exposure. Notably, the absence of gypsum peaks implies that sulfate-induced degradation was dominated by leaching rather than expansive ettringite or gypsum formation. Furthermore, the increased diffuse background between 20° – 30° points to higher amorphous content, likely arising from partial breakdown of C–S–H or precipitation of silica phases under sulfate attack.

3.2.2 XRD of M2 (0.5% Sisal Fiber)

The XRD pattern of Sample M2 (Fig. 8) exhibits a wide range of crystalline reflections between 5° and 75° 2θ , confirming the multiphase nature of the material. The most dominant peaks were recorded at 21° , 27° , 31° , 39° , and 50° , all of which are characteristic of quartz, an inert and stable crystalline phase. In addition to quartz, weaker reflections corresponding to kaolinite, mica, and iron oxides were detected, indicating the presence of aluminosilicate minerals and residual impurities derived from the raw materials. The detection of CaO at 25° and 38° suggests unreacted lime or partially hydrated lime phases, while distinct signals at 45° and 70° were assigned to zeolitic phases, a product often associated with secondary hydration or pozzolanic interactions between reactive silica and calcium hydroxide. Importantly, a broad amorphous hump below 15° was observed, which can be attributed to the formation of C–S–H gel, confirming the presence of poorly crystalline hydration products that underpin the strength development in cementitious systems. After sulfate exposure, the XRD profile of Sample M2A demonstrates notable alterations in crystalline phases. Sharp peaks indexed to the (002), (100), and (101) planes were identified, representing contributions from quartz, residual portlandite, and carbonate phases. The persistence of quartz highlights its chemical inertness, while the presence of residual portlandite suggests incomplete consumption of $\text{Ca}(\text{OH})_2$ during hydration and pozzolanic reactions. A particularly important observation is the peak associated with the (002) plane, which may correspond to ettringite formation or layered double hydroxide (LDH) phases, both of which typically develop during sulfate interaction with the matrix. The occurrence of these reflections indicates the possibility of secondary crystalline products forming in the presence of external sulfate ions. In contrast to Sample M1A, the XRD pattern of M2A does not display a significant amorphous hump in the 15° – 25° region. This implies that the C–S–H gel did not undergo major degradation, and amorphous silica phases remain relatively intact.

Before Exposure (b) After Exposure.

3.2.3 XRD of M3 (1% Sisal fiber)

The XRD pattern of Sample M3 before sulfate exposure (Fig. 9) revealed a crystalline profile within the 20° – 70° 2θ range, strongly dominated by quartz reflections, confirming the stability of silica-based minerals in the matrix. Additional diffraction peaks corresponded to kaolinite, zeolite, calcite, CaO, and Fe_2O_3 , which indicate the coexistence of aluminosilicate minerals, hydration by-products, and minor carbonated phases. The detection of zeolite and kaolinite is consistent with the presence of reactive aluminosilicates, which contribute to pozzolanic activity, while calcite may have formed through partial carbonation of portlandite. Importantly, the incorporation of sisal fiber did not disrupt the crystalline arrangement of the binder system. Instead, the profile suggested improved phase uniformity, implying that fiber addition contributed to a more homogeneous distribution of crystalline phases without introducing new mineral phases.

Following sulfate exposure, distinct changes in the crystalline structure were observed. The diffractogram of Sample M3A exhibited sharp and well-defined reflections at (002), (100), (200), and related planes, confirming the persistence of quartz alongside the presence of residual portlandite and calcite. The intensity of the (002) reflection is of particular interest, as it may indicate the formation of secondary sulfate-induced crystalline products, such as ettringite or layered double hydroxides (LDHs), both commonly associated with external sulfate attack. These phases typically form through the reaction of sulfate ions with calcium-bearing compounds in the matrix. Notably, the absence of a broad amorphous hump in the 20° – 30° region implies that the C–S–H gel network experienced minimal disruption during exposure. The XRD results for Fig. 9 demonstrate that Sample M3 exhibited strong resistance to sulfate-induced deterioration. Quartz remained stable, while portlandite and calcite underwent moderate chemical transformation, producing secondary crystalline phases without destabilizing the C–S–H gel.

3.2.4 XRD of M4 (7.5% GP)

Before sulfate exposure, the XRD pattern of Sample M4 was dominated by quartz peaks at 26.6° , 36.5° , and 50° , alongside kaolinite, mica, CaO, Fe_2O_3 , and zeolite, reflecting strong pozzolanic potential. The presence of zeolite and kaolinite suggested active secondary hydration, while quartz provided mineral stability. After exposure, intensified peaks at (100), (200), and (300) indicated the formation of sulfate-related crystalline products such as gypsum or ettringite. A slight baseline elevation near 10° pointed to minor amorphous phases from ground pozzolan (GP), though crystalline products dominated. Importantly, a reduction in portlandite peaks showed greater pozzolanic consumption of $\text{Ca}(\text{OH})_2$, limiting its availability for expansive sulfate reactions. The sample M4 displayed enhanced sulfate resistance, with stable quartz, reactive aluminosilicates, and GP-derived pozzolanic activity contributing to matrix durability and minimal C–S–H degradation.

3.2.5 XRD of M7 (15% GP)

Before exposure, Sample M7 showed a quartz-dominant profile, accompanied by kaolinite, mica, CaO, Fe_2O_3 , and zeolite, with a broad amorphous hump indicating ongoing pozzolanic activity. After exposure, the emergence of a new (311) peak signaled sulfate-induced secondary phases, while stable quartz and calcite peaks confirmed structural retention. The reduced intensities of (220) and (300) peaks suggested moderated

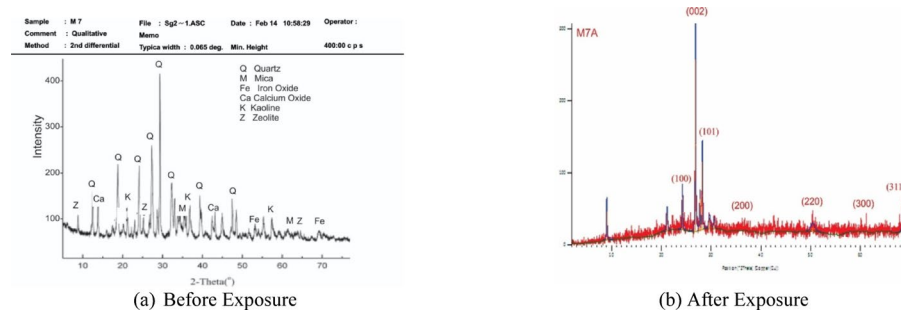


Fig. 11 XRD pattern of M7

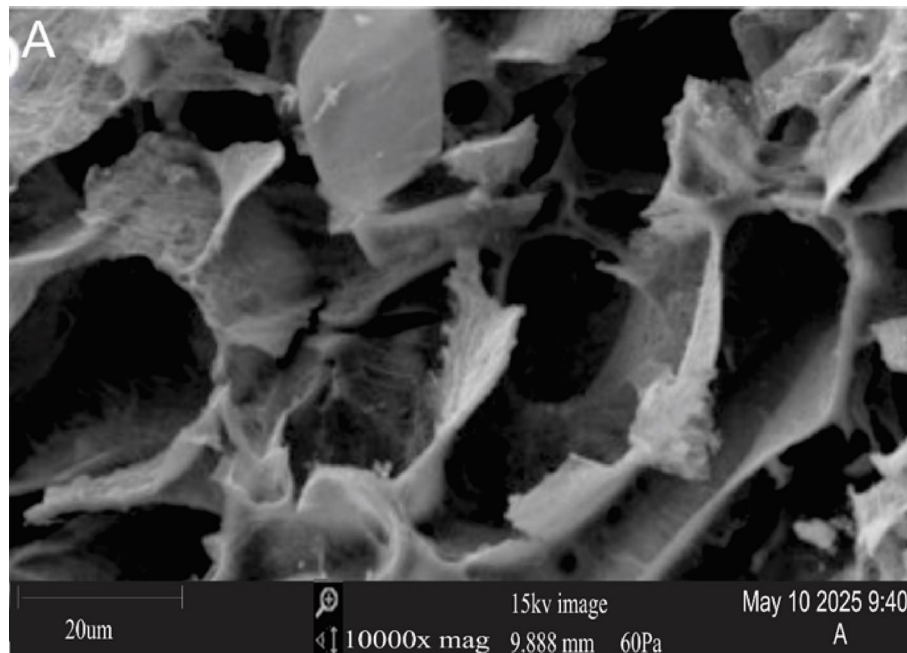


Fig. 12 SEM image of Waste glass powder

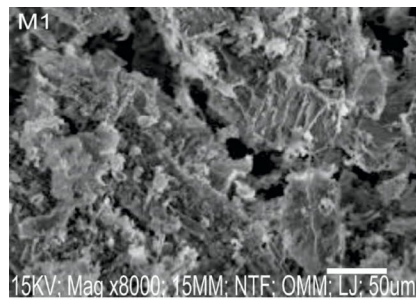
reactivity, and a slight background rise between 20°–30° pointed to amorphous silica formation or minor fiber degradation. Overall, M7 maintained structural stability under sulfate attack, with limited C–S–H disruption Fig. 11.

3.3 SEM analysis

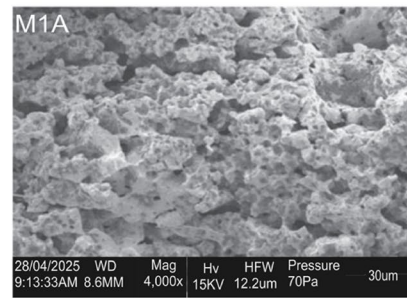
Waste Glass Powder (Fig. 12):

The powder exhibits layered, porous structures with high surface area, ideal for pozzolanic reactivity.

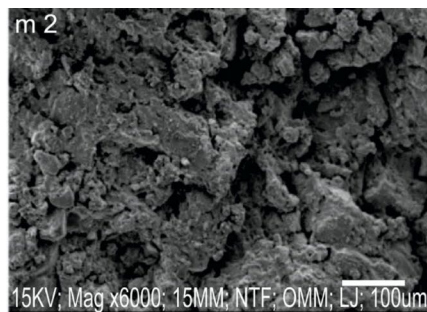
SEM images before exposure show relatively dense matrices, with fiber–matrix interaction improving in M2 and M3. After sulfate exposure, samples exhibited micro-cracking, pitting, and loss of matrix cohesion. M2 and M6 (containing fibers) showed moderate resistance due to crack-bridging, while M4 and M10 revealed deeper structural deterioration due to high GP content. M7 (high GP + fiber) showed the most severe porosity and internal stress.



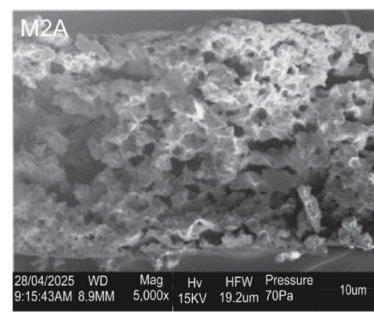
(a) Before Exposure



(b) After Exposure

Fig. 13 SEM image of M1

(a) Before Exposure



(b) After Exposure

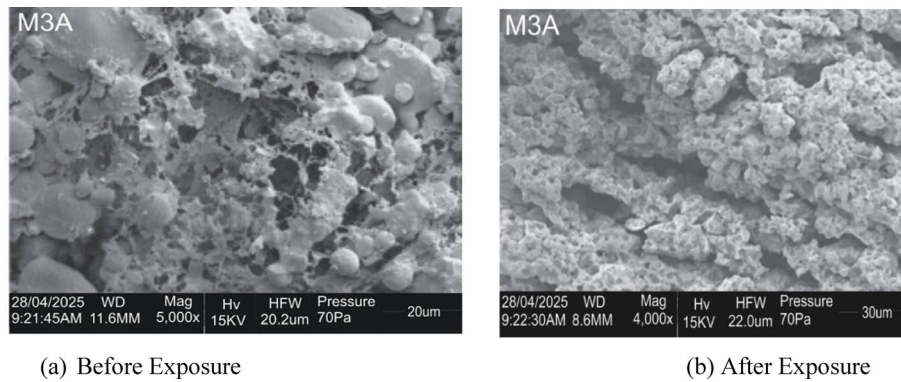
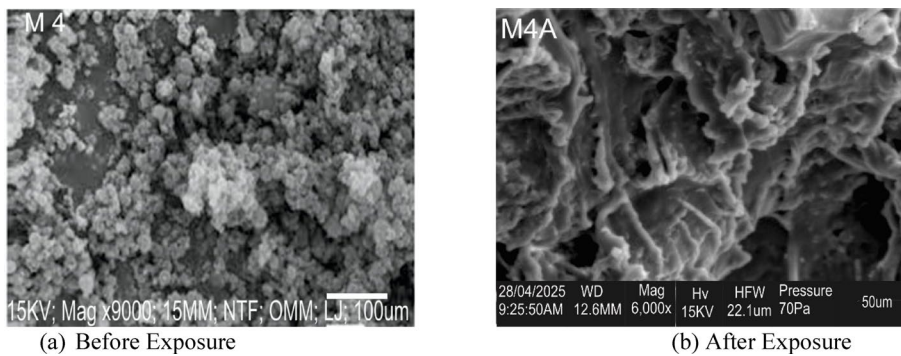
Fig. 14 SEM image of M2

3.3.1 SEM image of M1 (Control)

Before exposure, SEM imaging at 9,000 $\times$ magnification revealed that M1 contained non-uniform particles ranging from sharp-edged to smooth, with surface irregularities and microvoids characteristic of brittle cement-based composites. After exposure, the 4,000 $\times$ image showed extensive degradation marked by increased porosity, surface etching, and microcracks resulting from sulfate attack. In the absence of ground pozzolan (GP) or fibers, the matrix exhibited uniform damage, poor cohesion, and no apparent resistance to sulfate ingress, consistent with literature findings that control mortars are more susceptible to sulfate-induced deterioration Fig. 13.

3.3.2 SEM image of M2 (0.5% Sisal Fiber)

Before exposure, SEM imaging at 6,000 $\times$ magnification showed M2 as a hydrated cement matrix embedded with sisal fibers—some well-bonded, others partially detached—suggesting early-stage matrix–fiber interaction. After exposure, the 5,000 $\times$ image revealed fine microcracks, pitting, and interfacial degradation, including fiber swelling and debonding due to sulfate hydrolysis. While the limited fiber dosage provided minor crack-bridging effects, the absence of ground pozzolan (GP) compromised sulfate resistance, leading to degradation of the interfacial transition zone (ITZ) and reduced overall durability Fig. 14.

**Fig. 15** SEM image of M3**Fig. 16** SEM image of M4

3.3.3 SEM image of M3 (1% Sisal Fiber)

Before exposure, SEM imaging at 5,000 $\times$ magnification revealed that M3 had a porous, loosely packed matrix with voids and micro-fissures, where fiber presence appeared to limit matrix densification. After exposure, sulfate attack led to microcracks, surface erosion, and visible fiber degradation. While the fibers provided slight delay in crack propagation, the absence of pozzolanic additives left the matrix highly vulnerable to sulfate-induced damage Fig. 15.

3.3.4 SEM image of M4 (7.5% GP)

Before exposure, M4 exhibited smooth, spherical glass particles embedded within a rough, compact matrix, featuring distinct interfaces that suggested potential for long-term pozzolanic reactivity. After exposure, SEM imaging at 6,000 $\times$ revealed deeper surface cavities, merged microcracks, and signs of delamination, indicating more severe damage than observed in M3A. While the presence of ground pozzolan (GP) enhanced chemical resistance by reducing $\text{Ca}(\text{OH})_2$ content, the absence of fibers limited mechanical integrity, making the matrix more susceptible to sulfate-induced deterioration Fig. 16.

3.3.5 SEM image of M7 (15% GP)

Before exposure, M7 exhibited well-dispersed additives with clearly defined interfacial zones and a compact matrix morphology influenced by the high ground pozzolan (GP) content, indicating strong load transfer and active pozzolanic reactions. After sulfate

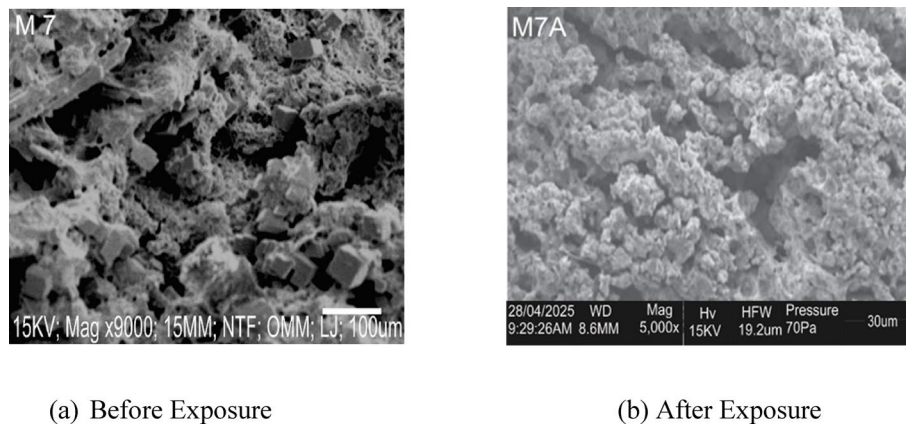


Fig. 17 SEM image of M7

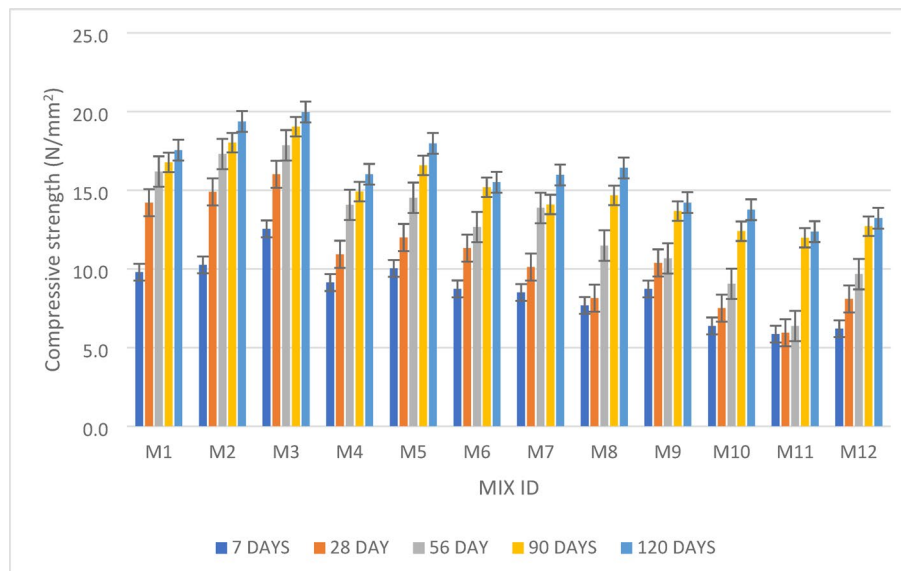


Fig. 18 Compressive strength results

exposure, the microstructure showed increased porosity, microcracking, and particle breakdown, reflecting sulfate-induced stress and matrix degradation, although the pozzolanic contributions appeared to mitigate the rate of deterioration Fig. 17.

3.4 Compressive strength

Compressive strength (Fig. 18) improved with fiber addition in M2 and M3, reaching 19.4 MPa and 20.0 MPa respectively at 120 days, outperforming the control (17.5 MPa). The Sisal fiber improving the strength of cementitious materials aligned with the findings of [3, 4]. Moderate GP levels (7.5–15%) with fibers yielded good strength retention. However, excessive GP (22.5%) reduced performance (like M11: 12.4 MPa), indicating that high replacement levels dilute cementitious content and hinder hydration, similar to the findings of [32].

3.5 Flexural strength

Flexural strength results (Fig. 19) exhibited similar trends to compressive strength. The highest value was recorded in M3 (1% sisal fiber) at 8.0 MPa, while the lowest was observed in M12 at 5.7 MPa, representing a 14.93% reduction compared to the control. Fiber incorporation at 0–1% significantly enhanced strength in mixes without glass powder, consistent with the findings of [6] who reported that fiber addition improves flexural performance. Moderate glass powder (7.5–15%) replacement maintained flexural strength, whereas 22.5% GP consistently led to reductions. This outcome aligns with [31]’s findings, which showed that flexural strength is maintained or slightly improved at GP dosages of 5–15%.

3.6 Magnesium sulfate attack

3.6.1 Compressive strength after exposure

Compressive strength decreased across all mixes after sulfate exposure (Fig. 20). The least deterioration was observed in M6 (7.5% GP + 1% sisal fiber, 14.16% loss) and M8 (15% GP + 0.5% sisal fiber, 14.81% loss), suggesting an optimal synergy between glass powder and sisal fiber at these dosages. The inclusion of fiber helped mitigate strength loss, consistent with the findings of [3]. In contrast, the highest deterioration occurred in M11 (22.5% GP + 0.5% sisal fiber, 34.29% loss), indicating poor sulfate resistance at higher GP content. Increasing the dosage of glass powder reduced resistance to sulfate attack, in agreement with [16] who reported that incorporating 15% GP weakens cementitious materials against sulfate-induced deterioration. The synergy between glass powder (GP) and sisal fiber delayed ettringite and gypsum formation during sulfate attack. XRD patterns showed reduced ettringite peaks and weaker gypsum reflection, while SEM micrographs revealed fewer needle-like crystals and less microcracking than in high-GP mixes. The pozzolanic reaction of GP consumed portlandite, generating additional C–S–H that densified the matrix and limited sulfate ingress. Sisal fibers further restricted crack propagation and increased diffusion path tortuosity, preserving matrix integrity under expansion stress. Consequently, the combined chemical refinement (from GP) and physical reinforcement (from fibers) mitigated internal

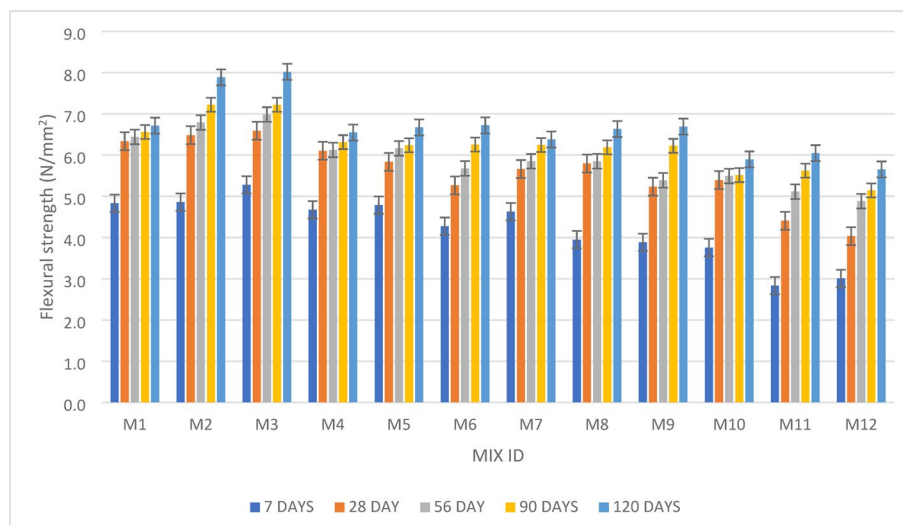


Fig. 19 Flexural strength results

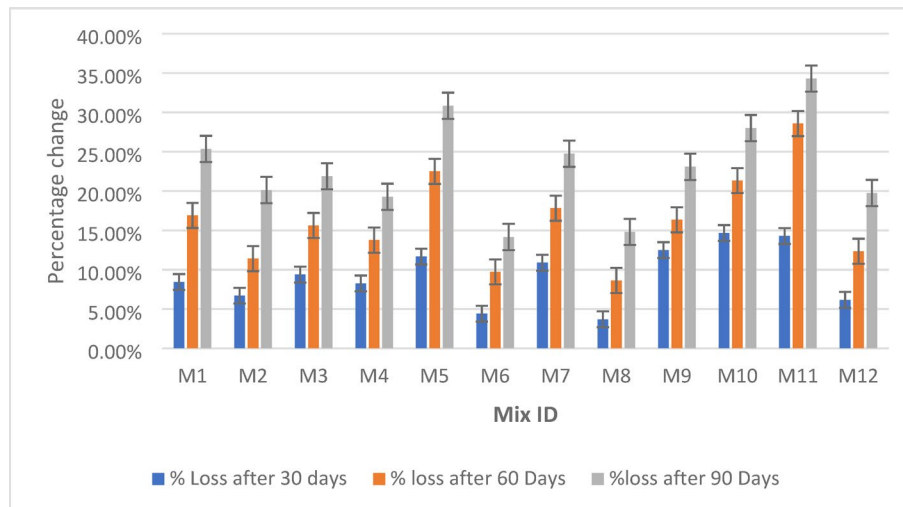


Fig. 20 Compressive Strength Analysis After MgSO_4 Exposure

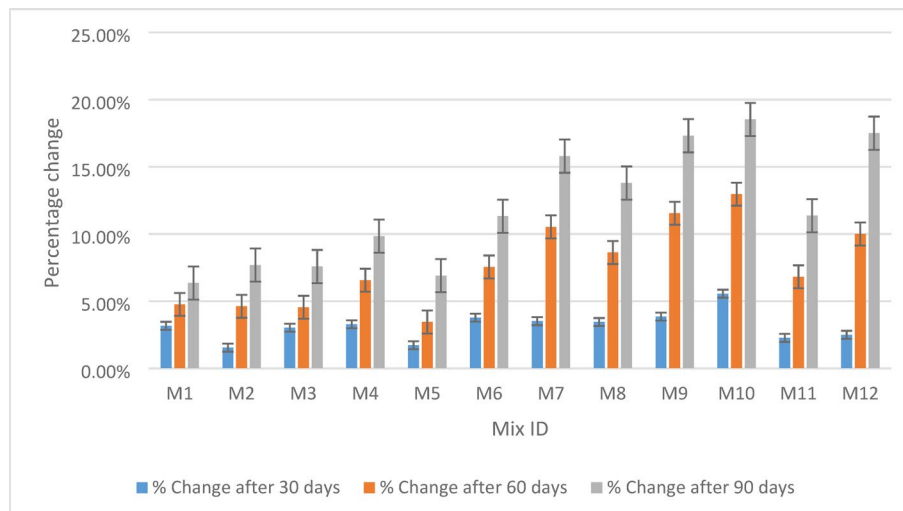


Fig. 21 Flexural Strength Analysis After MgSO_4 Exposure

deterioration, explaining the minimal strength losses observed in M6 (14.16%) and M8 (14.81%) compared with higher GP mixes.

3.6.2 Flexural strength after exposure

Figure 21 illustrates that all mixes experienced flexural strength loss after sulfate exposure, reflecting matrix deterioration and chemical stress. Among the mixes, M5 (7.5% GP + 0.5% sisal fiber) achieved the lowest reduction (6.90%), suggesting that moderate glass powder (GP) replacement enhances pozzolanic activity, densifying the matrix and mitigating sulfate ingress. In contrast, M10 (22.5% GP, no fiber) exhibited the highest reduction (18.52%), indicating that excessive GP content can reduce early-age strength and microstructural integrity, leaving the composite more vulnerable to chemical attack. Fiber addition alone did not significantly enhance resistance at high GP contents, likely due to poor fiber–matrix adhesion caused by insufficient cementitious gel formation. Overall, sulfate resistance depends on achieving a balanced synergy between GP and

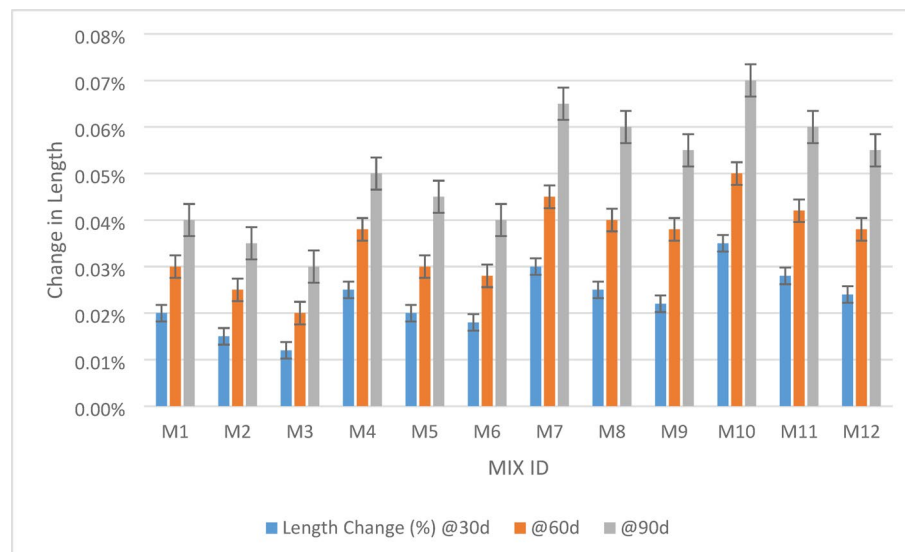


Fig. 22 Change in length percentage result

fiber: adequate GP refines the pore structure, while optimal fiber content improves crack control, both necessary to maintain flexural performance under aggressive environments.

3.7 Length change

Length change measurements (Fig. 22) demonstrated progressive expansion across all mixes, a well-documented response to sulfate attack caused by delayed ettringite formation and gypsum crystallization within the cementitious matrix. Control mixes (M1–M3) exhibited minimal deformation, reflecting their relatively dense microstructure and limited sulfate penetration. In contrast, glass powder (GP)-rich mixtures—particularly M10 (22.5% GP, 0.112 mm)—showed the highest dimensional instability, likely due to slower pozzolanic reaction kinetics at high GP replacement levels, which may reduce early-age matrix cohesion and increase permeability. Notably, the incorporation of sisal fibers mitigated this deformation: M12 (15% GP + 0.75% fiber) exhibited reduced expansion (0.088 mm), highlighting the fibers' ability to bridge microcracks, restrain crack propagation, and enhance dimensional stability under chemical stress. These observations are consistent with prior work demonstrating a synergistic benefit when combining glass powder and natural fibers. For example, a study by [28] incorporating 15 vol% glass powder and 1.5% sisal fibers reported reduced mass and strength loss under sulfuric/hydrochloric acid attack, attributed to improved pore filling and fiber-based barriers against chemical ingress.

4 Conclusions

The following are conclusions of study:

1. GP showed high pozzolanic potential with a combined oxide content ($\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$) of 85.04%, exceeding ASTM C618 minimum. SEM revealed rough, porous particles with high surface area, suitable for C–S–H formation. However, XRD indicated the presence of crystalline phases like quartz and kaolinite, suggesting partial amorphousness or mixed-source origin.

2. Magnesium sulfate exposure reduced strength across all mixes; however, compressive and flexural strengths were best retained in M6 (7.5% GP + 1% Sisal fiber) with only 14.16% compressive strength loss, and M5 (7.5% GP + 0.5% Sisal fiber) with just 6.90% flexural strength loss. While fiber enhanced crack resistance and toughness, excessive GP replacement at 22.5% led to significant strength loss and expansion regardless of fiber inclusion.
3. XRD patterns after exposure revealed leaching of portlandite, formation of calcite, and reduced amorphous C-S-H gel. SEM confirmed microcracking, porosity, and sulfate-induced degradation, especially at higher GP levels. Expansion tests showed greater deformation with increased GP, while fiber inclusion mitigated damage. A 7.5% GP replacement with 0.5–1% Sisal fiber is considered optimal, improved durability and strength retention after sulfate exposure, acceptable microstructural stability as confirmed by SEM and XRD, and controlled expansion with minimal internal damage.

4.1 Recommendations

Based on the findings, it is recommended that glass powder (GP) be used at a moderate replacement level of 7.5%, as it offers an effective balance between strength, durability, and workability. This dosage enhances the pozzolanic activity without significantly diluting cement hydration, as shown by the stable performance in both mechanical strength and sulfate resistance. To further improve the structural integrity and mitigate sulfate-induced deterioration, the incorporation of 0.5% to 1% natural fiber, particularly sisal fiber, is advisable, as it enhances crack-bridging and reduces expansion. However, excessive fiber content or GP levels above 15% are not recommended, as they tend to reduce workability, compromise microstructural uniformity, and accelerate degradation under aggressive chemical environments. Proper mix design adjustments, such as the use of water-reducing admixtures, may be necessary to counterbalance the increased water demand associated with GP's porous and irregular structure. Overall, optimizing both the pozzolanic and reinforcing components is crucial to producing a durable, sustainable, and chemically resistant mortar composite.

4.2 Limitations of study

The scope of chemical exposure was limited to magnesium sulfate, which restricts the applicability of the findings to other aggressive environments such as chloride-rich or combined sulfate–chloride conditions. The dosage range was also narrow, with GP replacement levels capped at 22.5% and fiber content at 1%, leaving the performance of higher dosages unassessed. Furthermore, mechanical testing was confined to compressive and flexural strength, without evaluation of other critical parameters such as tensile strength, modulus of elasticity, or long-term creep and shrinkage. The experiments were performed under controlled laboratory conditions; field-scale validation is still required.

Author contributions

Author Contributions: All authors (Mutiu Adelodun Akinpelu, Abdulbaaqi Abiodun Olayiwola, Ash-Shu'ara Marafa Salman, Munirat Romoke Ibrahim, Zainab Tolu Giwa) contributed to the conception, design, material sourcing, experimental procedures, data analysis, and preparation of the manuscript. All authors read and approved the final version.

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Data availability

The datasets generated and/or analyzed during the current study are available from the corresponding author, Dr. Abdulbaaqi Abiodun Olayiwola, upon reasonable request. All relevant data supporting the findings are included within the manuscript.

Declarations**Ethics approval and consent to participate**

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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