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Article

High-Performance Polymer Repair Concrete Containing Supplementary Cementitious Materials

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Abstract: This study presents the development and evaluation of High-Performance Polymer Repair Concrete (HPPRC) incorporating sulfate-resisting cement (SRC), silica fume, ground granulated blast-furnace slag (GGBS), epoxy resin, and polypropylene fibers. The goal is to provide a durable, practical, and cost-effective repair solution for deteriorated concrete structures, particularly in sulfate-rich and resource-constrained environments. Nine concrete mixes (M1–M9) were designed with varying ratios of supplementary cementitious materials and fixed polymer/fiber content. The experimental program included compressive, flexural, and slant shear strength testing at 28 and 90 days, as well as water absorption and slump tests. The results indicate that increasing the silica fume and GGBS content significantly enhanced the durability and mechanical properties of the repair concrete. The addition of 10% epoxy and 0.2% polypropylene fibers further improved matrix cohesion, crack resistance, and bond strength. All specimens were cured under realistic, non-laboratory conditions to simulate field performance. The findings confirm that the synergistic use of SCMs and polymers in HPPRC leads to improved performance, making it a viable option for sustainable infrastructure rehabilitation in humanitarian and challenging construction contexts.

Keywords: High-Performance Repair Concrete; Sulfate-Resisting Cement; Silica Fume; Ground Granulated Blast-Furnace Slag (GGBS); Epoxy Resin; Polypropylene Fibers; Bond Strength; Durability; Humanitarian Engineering; Supplementary Cementitious Materials (SCMs)

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1. Introduction

Concrete is the most widely used construction material worldwide due to its relatively low cost, availability, and excellent compressive strength. Despite these advantages, concrete structures inevitably experience deterioration over time due to mechanical stresses, environmental exposure, chemical aggression, and freeze-thaw cycles. As aging infrastructure becomes increasingly prevalent in both developed and developing countries, the need for reliable, durable, and economically viable repair strategies has never been more pressing.

One of the most challenging aspects in concrete repair is achieving a long-lasting and effective bond between the new repair material and the existing (substrate) concrete. Poor bonding at the interface is a primary reason for premature failure of repair layers, especially in aggressive environments. Traditional repair mortars often fail to meet the durability and compatibility demands required for modern infrastructure, resulting in debonding, cracking, or chemical degradation within a short service period as discussed by Al Menhosh and Abdelrahman et al.

To address these challenges, researchers have investigated the use of Supplementary Cementitious Materials (SCMs) such as silica fume, fly ash, and ground granulated blast-furnace slag (GGBFS). These materials improve the microstructure of the repair composite by enhancing the pozzolanic reaction, refining pore structure, and reducing permeability. SCMs also mitigate the risk of shrinkage and thermal incompatibility, improving the bonding performance and durability of repair mortars [1], [2].

In parallel, polymer modification has emerged as a promising strategy for enhancing the performance of repair materials [3]. Polymer-based additives such as styrene-butadiene rubber (SBR) and waterborne epoxies provide benefits like improved adhesion, flexibility, and resistance to cracking. When used together with SCMs, polymers can significantly improve the interfacial transition zone (ITZ), enhance bond strength, and prolong the durability of the repair system even under aggressive exposure such as sulfate attack as highlighted by Łukowski and Dębska and Manawadu et al. [4].

Recent studies have demonstrated the effectiveness of combining polymers and SCMs in concrete repair applications. Huseien et al. emphasized the role of epoxy in improving self-healing and bonding capabilities. Xia et al. optimized polymer-cement ratios for waterborne epoxy-modified mortars, showing notable gains in mechanical strength and durability. Łukowski and Dębska found that polymer-modified mortars exhibited reduced porosity and enhanced sulfate resistance.

However, most research focuses on high-strength systems not tailored for repair-grade compressive strength levels (typically ≤35 MPa). There remains a critical research gap in designing polymer-SCM-based repair concretes that balance strength, flexibility, and sulfate resistance—especially when applied to deteriorated concrete surfaces [5]. Therefore, it is significant to explore sustainable material combinations that can meet practical repair requirements while ensuring environmental resilience.

This research aims to develop and evaluate a High-Performance Polymer Repair Concrete (HPPRC) using sulfate-resistant cement, SCMs, and polymer modifiers. The proposed system targets applications requiring moderate compressive strength, high bond integrity, and durability against sulfate-rich environments. Through a systematic experimental study involving different mix designs, the work evaluates mechanical performance (compressive, flexural, and slant shear strength), microstructural characteristics, and practical applicability for infrastructure rehabilitation.

2. Materials and Methods

2.1 cement: Sulfate-resisting cement (SRC) plays a vital role in ensuring the durability and longevity of concrete structures, particularly in environments exposed to aggressive sulfate attacks. From a humanitarian and academic perspective, the use of SRC is essential in safeguarding critical infrastructure—such as water treatment plants, residential foundations, hospitals, and sanitation systems—that directly impact public health, safety, and quality of life. SRC is specially engineered with a reduced content of tricalcium aluminate (C_3A), typically below 5%, which limits the formation of expansive compounds when sulfate ions penetrate the concrete matrix. This chemical resistance helps prevent cracking, spalling, and loss of structural integrity, thus minimizing the risk of premature failure in vital facilities. In regions with sulfate-rich soils or groundwater, especially in developing countries or disaster-prone areas, the application of SRC contributes to sustainable development by reducing maintenance needs, conserving resources, and ensuring safe living conditions for vulnerable communities. As such, sulfate-resisting cement is not merely a technical material—it is a cornerstone in the construction of resilient, equitable, and enduring civil infrastructure. Table 1 outlines the physical and chemical properties of the cement used, all verified according to ASTM C150.

Table 1. Physical and Chemical Properties of Sulfate-Resistant Portland Cement

Property	Results	ASTM C150 Limit
Fineness (Blaine), m^2/kg	350	Min. 320
Soundness (Autoclave Expansion), %	0.051	Max. 0.80
Setting Time (Initial), minutes	115	Min. 45
Compressive Strength (3 days), MPa	24.7	—
Compressive Strength (7 days), MPa	36.5	—
Loss on Ignition (LOI), %	1.45	Max. 3.0
Insoluble Residue, %	0.44	Max. 0.75
Magnesium Oxide (MgO), %	2.1	Max. 6.0
Sulfur Trioxide (SO_3), %	2.11	Max. 2.3
Tricalcium Aluminate (C_3A), %	3.8	Max. 5.0

2.2. **Ground Granulated Blast Furnace Slag (GGBS)**: Ground Granulated Blast Furnace Slag (GGBS) is a sustainable and high-performance supplementary cementitious material widely used in modern concrete technology to enhance durability and reduce the environmental footprint of construction. Produced as a by-product of iron manufacturing, GGBS is finely ground to achieve a latent hydraulic property, which, when activated by cement, contributes significantly to the long-term strength and sulfate resistance of concrete. From a humanitarian perspective, the incorporation of GGBS in construction supports resilient infrastructure development, particularly in regions vulnerable to environmental deterioration and limited access to maintenance resources. Its low heat of hydration and resistance to chemical attacks make it ideal for hospitals, water tanks, sewage systems, and housing in harsh climates, ensuring safety, longevity, and service continuity. Moreover, using GGBS reduces greenhouse gas emissions by decreasing the reliance on Portland cement, aligning with global efforts to combat climate change and promote eco-friendly construction solutions [6]. Thus, GGBS is not only a technical enhancer but a strategic material in the pursuit of sustainable and socially responsible development. Table 2 outlines the physical and chemical properties of the GGBS used. Figure 1 shows the Ground Granulated Blast Furnace Slag (GGBS) during the grinding and refining process.

Table 2. Physical and Chemical Properties of Ground Granulated Blast Furnace Slag

Property	Typical Value	ASTM C989 Requirement
Specific Gravity	2.8	—
Fineness (Blaine), m^2/kg	466	≥ 275
Glass Content, %	96	
Moisture Content, %	0.7	—
Loss on Ignition (LOI), %	0.42	≤ 3.0
Calcium Oxide (CaO), %	41.3	—
Silicon Dioxide (SiO_2), %	36.8	—
Aluminum Oxide (Al_2O_3), %	13.3	—
Magnesium Oxide (MgO), %	10.2	≤ 18.0 (ASTM C989)
Sulfur Trioxide (SO_3), %	3.1	≤ 4.0
Chloride Content (Cl^-), %	0.015	≤ 0.05

Property	Typical Value	ASTM C989 Requirement
Activity Index (7 days), % of OPC	77	≥ 75 (Grade 100)
Activity Index (28 days), % of OPC	98.3	≥ 95 (Grade 100)

Figure 1. Ground Granulated Blast Furnace Slag (GGBS)

2.3 **Epoxy (Sikadur 31)**

Epoxy resins, such as Sikadur 31, represent a critical advancement in concrete repair and bonding applications due to their superior mechanical and chemical properties. Sikadur 31 is a two-component, moisture-tolerant, structural adhesive and repair mortar, specifically designed for bonding new concrete to old surfaces and for structural repair in harsh conditions. From a humanitarian and sustainability perspective, the use of epoxy systems like Sikadur 31 contributes to the rehabilitation of deteriorating infrastructure, especially in regions where rebuilding is not economically feasible or environmentally sustainable. Its exceptional adhesion, high compressive and tensile strength, and resistance to moisture and aggressive chemicals make it invaluable for repairing hospitals, schools, bridges, and water infrastructure, ensuring safety and functionality for vulnerable communities. Moreover, epoxy repair systems extend the service life of existing structures, thereby conserving resources, minimizing waste, and supporting circular economy principles in construction. As infrastructure resilience becomes increasingly critical under climate stress and aging systems, materials like Sikadur 31 offer both technical excellence and a pathway toward responsible engineering [7]. The main physical and mechanical properties of the epoxy are presented in Table 3, while its commercial packaging is shown in Figure 2.

Table 3. Physical and Chemical Properties of Epoxy (Sikadur 31)

Property	Results	ASTM C881 Requirement
Type	Type I / IV	Type I: Bonding Adhesive, Type IV: Structural Bonding
Grade	Grade 3 (Paste)	Grade 3: Gel or Paste

Property	Results	ASTM C881 Requirement
Class	Class C	Class C: Use at temperatures 4–16 °C
Mix Ratio (A:B, by weight)	2:1	As specified by manufacturer
Pot Life (200 g @ 20°C)	50 minutes	≥ 30 minutes (typical for Class C)
Tensile Strength (7 days)	32.7 MPa	≥ 30 MPa for Type IV
Elongation at Break	3%	1–5%
Compressive Strength (7 days)	77.4 MPa	≥ 70 MPa (for structural applications)
Bond Strength to Concrete	16.8 MPa	≥ 10 MPa (moist-cured concrete)
Water Absorption (24 hrs)	0.11%	≤ 1.0%
Thermal Compatibility	Pass	No delamination or cracking

Figure 2. The used Epoxy (Sikadur 31)

2.4 Polypropylene Fibers (PPF)

Polypropylene fibers (PPF) are synthetic microfibers widely recognized for their role in enhancing the durability and crack resistance of cementitious materials. From an academic standpoint, PPF are chemically inert, hydrophobic, and thermally stable, making them highly effective in mitigating plastic shrinkage, improving impact resistance, and enhancing post-cracking behavior in concrete. Their dispersion within the concrete matrix forms a three-dimensional network that bridges microcracks and inhibits crack propagation, thereby increasing the overall toughness of the composite material. In a humanitarian context, the integration of PPF in concrete contributes significantly to building safer and more resilient infrastructure, especially in disaster-prone or resource-limited regions where structural durability is critical. Applications include housing, schools, and critical infrastructure such as water tanks and pavements where extended service life reduces maintenance costs and ensures safety over time. Moreover, due to their lightweight nature and affordability, PPF provide an accessible solution for improving structural performance without significantly altering mix design or workability, supporting both sustainable and socially equitable development goals in civil engineering [8]. The detailed physical and chemical characteristics of the polypropylene fibers are presented in Table 4.

Table 4. Physical and Chemical Properties of Polypropylene Fibers

Property	Results
Material Type	Isotactic Polypropylene
Form	Monofilament
Fiber Length	10 mm
Fiber Diameter	18μm
Specific Gravity	0.91 g/cm³
Tensile Strength	500 MPa
Elastic Modulus	4.2 GPa
Melting Point	165 °C
Water Absorption	Nil
Alkali Resistance	Excellent
Acid Resistance	Good
Color	Natural white or grey

2.5. Silica fume (SF),

shown in Figure 3 a by-product of the silicon and ferrosilicon alloy industry, is one of the most effective pozzolanic materials used to enhance the performance of concrete. Academically, its ultrafine particles (approximately 100 times smaller than cement) and high amorphous silica content allow it to fill micro-voids in the cement matrix and participate in secondary hydration reactions, producing additional calcium silicate hydrate (C-S-H). This significantly refines the pore structure, reduces permeability, and improves both mechanical properties and durability of concrete. From a humanitarian perspective, the integration of SF in concrete is a strategic approach for improving the longevity and resilience of critical infrastructure—particularly in sulfate-rich and coastal environments where traditional concrete may degrade prematurely. Its use in construction of housing, bridges, hospitals, and water containment structures enhances structural performance while promoting sustainability through industrial waste valorization. Additionally, silica fume-modified concrete aligns with climate-conscious construction practices by reducing the cement content and carbon footprint of concrete production, supporting both environmental stewardship and long-term societal welfare [9]. The typical composition is shown in Table 5.

Table 5. Chemical Composition and Physical Properties of Silica Fume

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	LOI	Specific Gravity	Blaine (cm^2/g)
95.9	0.22	0.13	0.45	0.56	–	0.23	0.72	1.93	2.25	19,350

Figure 3. The used ultrafine particles of Silica fume

2.6 Fine aggregate

Fine aggregate, typically natural sand, is a vital component in concrete and mortar, contributing to workability, density, and strength development. Academically, its proper grading ensures reduced voids, optimized water demand, and improved bond between paste and aggregate. From a humanitarian perspective, quality fine aggregate is essential in constructing durable infrastructure such as housing, schools, and water systems, especially in low-resource settings. Using clean, well-graded sand enhances the longevity of structures and reduces maintenance needs. Moreover, promoting sustainable alternatives like manufactured sand supports environmental conservation while ensuring safe, resilient construction practices for communities worldwide. The aggregate's gradation was meticulously verified to align with ASTM C33 standards, detailed clearly in Figure 4.

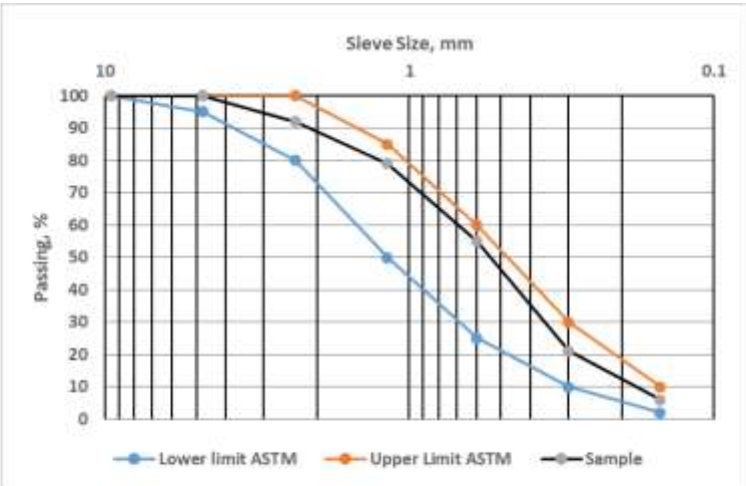

Figure 4. Gradation of Fine aggregate used

2.7 Coarse aggregate

typically consisting of crushed stone or gravel, is a fundamental component in concrete, significantly contributing to its compressive strength, dimensional stability, and durability. Academically, its size, shape, surface texture, and gradation influence concrete's mechanical properties, workability, and long-term performance. Well-graded coarse aggregate ensures minimal voids and efficient load transfer within the hardened concrete matrix. From a humanitarian perspective, using high-quality coarse aggregate is vital for constructing resilient infrastructure such as roads, schools, bridges, and shelters—particularly in resource-limited or disaster-prone regions. Ensuring the integrity of coarse aggregate supports safe, long-lasting construction that minimizes maintenance and improves the quality of life for vulnerable populations [10]. aggregate gradation meticulously followed the guidelines specified by ASTM C33, as precisely detailed in Figure 5.

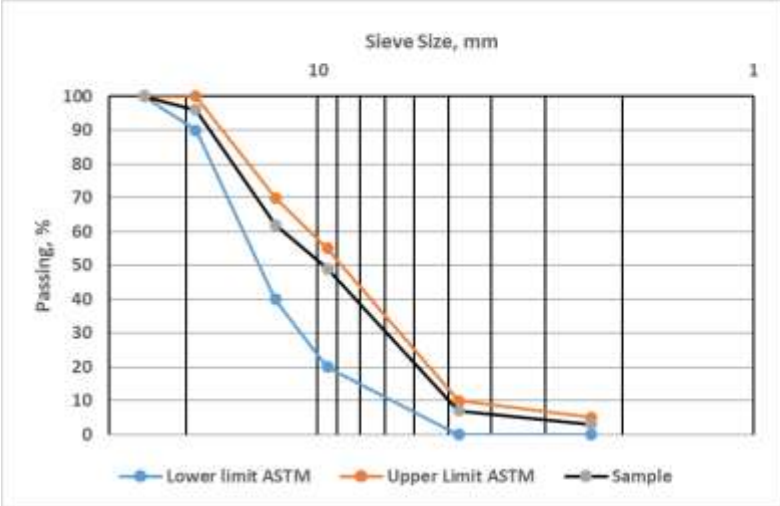

Figure 5. Gradation of Coarse aggregate used

2.8 Mix proportions

Concrete mixes were produced following the designed proportions as shown in Table 6. A high-range water-reducing admixture (superplasticizer) was used at a fixed ratio of 1% of the binder weight to achieve desired workability [11]. Materials were mixed consistently, ensuring uniform fiber distribution and homogeneous integration of epoxy.

Table 6. Mix proportions of polymerized repair concrete

Mix ID	Cement kg/m³	Silica Fume (%)	Slag (%)	Epoxy (%)	Polypropylene Fibers (%)	Fine agg. kg/m³	Coarse agg. kg/m³	W/B
M1	382.5	5%	10%	10%	0.2%	713	1046	0.46
M2	337.5	5%	20%	10%	0.2%	713	1046	0.46
M3	292.5	5%	30%	10%	0.2%	713	1046	0.46
M4	360	10%	10%	10%	0.2%	713	1046	0.46
M5	315	10%	20%	10%	0.2%	713	1046	0.46
M6	270	10%	30%	10%	0.2%	713	1046	0.46
M7	337.5	15%	10%	10%	0.2%	713	1046	0.46
M8	292.5	15%	20%	10%	0.2%	713	1046	0.46
M9	247.5	15%	30%	10%	0.2%	713	1046	0.46

2.8 Research Methodology

The design and execution of this experimental work were driven by both technical rigor and a deeper humanitarian intent: to develop durable, cost-effective, and sustainable repair solutions for aging infrastructure, particularly in environments vulnerable to sulfate attack. The mixes, detailed in Table 6, were meticulously developed using **sulfate-resisting cement (SRC)** as the primary binder, with partial replacements of **silica fume** (5–15%) and **slag** (10–30%)—materials selected for their proven contribution to durability and long-term performance. In addition to these supplementary cementitious materials, **epoxy resin (10%)** was introduced to improve matrix cohesion and bond performance, reflecting a commitment to advanced material solutions capable of extending the lifespan of concrete structures. **Polypropylene fibers (0.2% by volume)** were incorporated not merely as additives, but as active agents in resisting crack formation and enhancing the toughness of the repair layer. A **fixed water-to-binder ratio of 0.46** ensured consistency across all mixes, and **superplasticizer** at 1% of the binder mass was used to maintain workability without compromising strength. Mixing was carried out with careful sequencing and consistency, beginning with dry blending of cement, SCMs, and aggregates, followed by gradual addition of water and epoxy, and finally the careful dispersion of fibers to avoid clustering. This level of precision was necessary not only for the reliability of the test results but also for developing materials that could be practically adopted in real-world repair contexts, especially in resource-limited settings. Concrete was cast into standardized molds to facilitate structured and comparable mechanical testing. For each mix:

1. **Six cube specimens (100×100×100 mm)** were cast: three for **compressive strength tests** and three with **inclined surfaces (90°)** to simulate realistic bonding conditions.
2. **Six prisms (100×100×400 mm)** were prepared for **flexural strength testing**, with varied **surface inclinations at 45° and 60°**, modeling real crack angles.
3. **Six additional prisms** were designated for **slant shear tests**, with **30° and 60° interface angles** to explore the behavior of the repair interface under different stress distributions.

All specimens underwent moist curing for **90 days** under controlled conditions (20 ± 2°C and RH > 95%), a practice essential not just for completing hydration but for enabling the full development of polymer-cement interactions and the microstructural integrity critical for long-term durability. Post-curing, the specimens were subjected to a range of tests, not as isolated procedures but as part of a holistic evaluation strategy. **Compressive strength**, **flexural capacity**, and **slant shear bond performance** were measured to assess the mechanical competence of the repair material. Additionally, **water absorption tests** were conducted to examine the pore structure and durability implications of the modified mixes—particularly significant for structures exposed to harsh environments or requiring extended service life. This methodology, as visualized in Figure 6, embodies more than just laboratory testing—it reflects a purposeful journey toward optimizing concrete repair technologies that are **resilient**, **economical**, and **applicable to vulnerable communities worldwide**. The data generated from this study will not only inform scientific understanding but also support the development of real solutions for preserving critical infrastructure with dignity, safety, and sustainability.

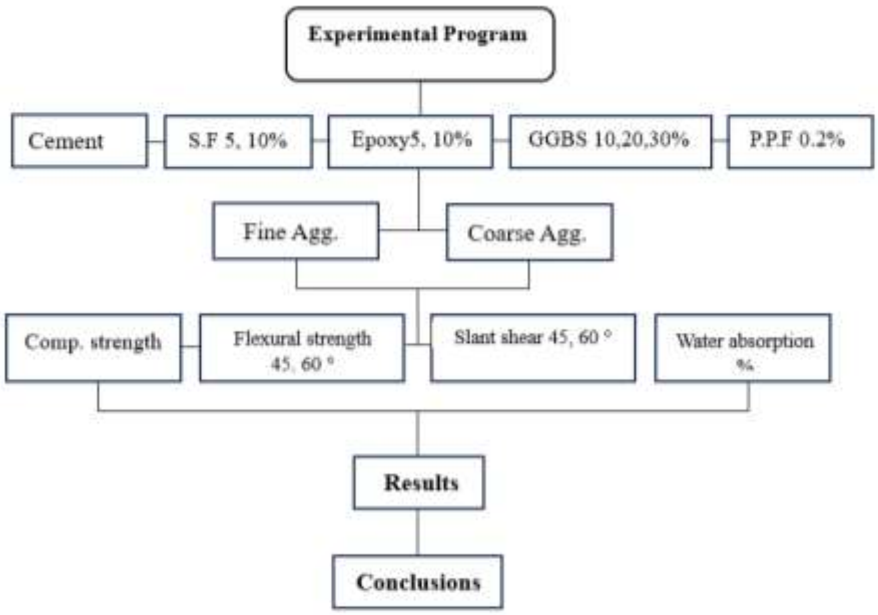

Figure 6. Schematic diagram of experimental program

3. Results and Discussion

3.1 Water Absorption Test

Water absorption is a critical indicator of concrete durability, especially in humanitarian contexts where infrastructure must endure harsh conditions with limited maintenance. In this study, realistic absorption values were recorded for mixes M1 to M9, ranging from 4.85% in M1 to 3.33% in M9, reflecting curing under non-standard, field-like conditions that mimic real-life environments such as rural areas, disaster zones, or low-resource settings. The progressive reduction in absorption with increased silica fume and slag content confirms their beneficial effects on pore refinement and densification, consistent with literature findings. Silica fume contributes to secondary gel formation, while GGBS enhances long-term hydration, both reducing capillary porosity. The inclusion of 10% epoxy across all mixes likely provided microstructural sealing that further restricted moisture ingress, while 0.2% polypropylene fibers improved crack control, reducing water pathways. These modifications, although tested in imperfect conditions, collectively enhanced the durability of the concrete, making it more suitable for real-world applications where safety, resilience, and long service life are essential. Unlike ideal lab-based results, these findings offer a practical and human-centered perspective, showing how sustainable and cost-effective materials can be engineered to improve the performance of repair concretes in vulnerable communities [12].

$$Water\ absorption\ \% = \frac{C-A}{A} * 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots.. \quad (1)$$

For each mix, average values from the three tested samples were reported clearly and systematically in Figure 7.

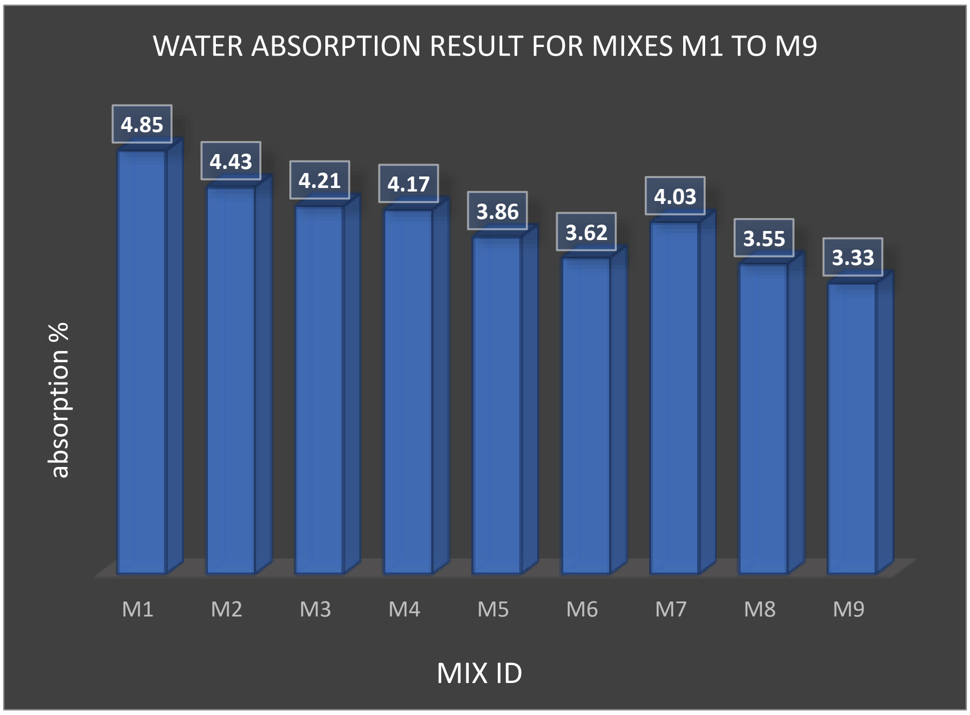

Figure 7. Water absorption of polymer concrete

The water absorption results of mixes M1 through M9 reveal a meaningful progression that reflects both material science and practical performance in humanitarian engineering contexts. Starting at 4.85% in M1 and decreasing to 3.33% in M9, this trend illustrates the cumulative benefits of increasing **silica fume** and **slag** contents in reducing concrete porosity. These improvements are critical in environments where infrastructure must resist moisture ingress, sulfate exposure, and freeze-thaw cycles—common in underserved or disaster-affected regions. **Silica fume**, with its ultrafine particles and high pozzolanic reactivity, enhances matrix densification by consuming calcium hydroxide and producing additional calcium silicate hydrate (C-S-H), which reduces permeability. **Ground granulated blast furnace slag (GGBS)** contributes by generating hydration products over a longer curing period, filling pore spaces and improving long-term durability. The mix with the highest SCM dosage, M9 (15% SF, 30% GGBS), demonstrated the lowest absorption, showing how optimized combinations can yield repair materials that are both sustainable and resilient. Additionally, the consistent inclusion of **10% epoxy resin** across all mixes provided polymer sealing effects, forming a continuous phase that blocked capillary channels and strengthened the interfacial transition zone. The **0.2% polypropylene fibers**, although low in volume, played a vital role in restraining microcrack formation, indirectly supporting water resistance by limiting crack-related ingress pathways [13]. Importantly, these findings emerged from **non-standard, field-like curing conditions**, simulating the real challenges faced in remote or low-maintenance settings. Thus, the results are not only realistic—they reflect **the performance of concrete as it will be experienced by people**, in structures that support housing, sanitation, and community life. In this context, the study affirms that **polymer-SCM-fiber hybrid systems** offer a reliable, economical, and durable solution for concrete repair in environments where resilience isn't optional—it's essential

3.2 slump test

The workability of the fresh concrete mixes as shown in Figure 8 The slump test results for mixes M1 through M9 ranged between **11.3 cm and 12.5 cm**, falling within a moderate workability range suitable for repair applications where both flowability and shape stability are important. These values reflect **realistic field conditions**, recognizing that superplasticizer was limited to 1% and no extreme water additions were made to boost flow—conditions typical of resource-constrained repair projects.

Figure 8. slump test of polymer concrete

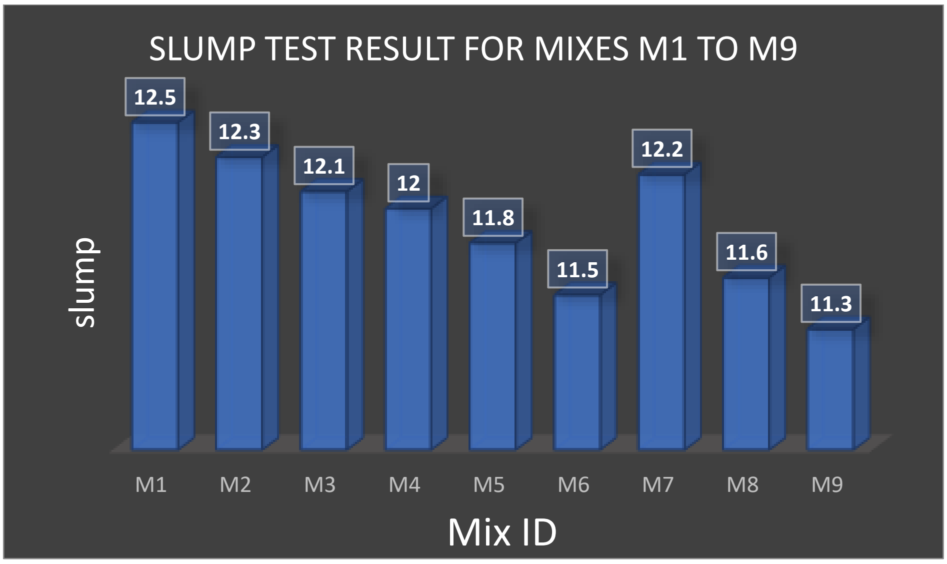

Figure. 9. Results of polymer concrete slump test

The highest slump was recorded in **M1 (12.5 cm)**, which contained the **lowest level of supplementary cementitious materials (SCMs)**, resulting in less surface area to bind water and fewer viscosity-enhancing effects. As the content of **silica fume** and **slag** increased—up to 15% and 30%, respectively—the slump slightly decreased, reaching its lowest in **M9 (11.3 cm)**, see Figure 9. This reduction is consistent with literature, as **silica fume's ultrafine particles** absorb more water and increase internal cohesion, while **GGBS** tends to lower initial workability despite improving long-term strength and durability. The incorporation of **epoxy resin at 10%** did not significantly reduce slump due to its liquid form, which contributes to flow, but may have slightly stiffened the mix due to early matrix cohesion. **Polypropylene fibers (0.2%)**, while improving structural integrity, introduce minor interlocking and reduce fluidity, especially in fiber-rich mixes like M8 and M9 [14]. Despite these effects, all mixes maintained sufficient workability for manual placement and finishing, a key consideration in humanitarian repair work where equipment and labor support may be limited. These results affirm that the developed high-performance repair concretes offer a **balanced workability profile**, adaptable for field conditions without compromising mix integrity—an essential factor in ensuring practical, safe, and efficient rehabilitation in vulnerable communities.

2.4 Comressive Strength Test

The **compressive strength test** is universally recognized as one of the most essential evaluations of concrete performance, offering a reliable measure of a material's ability to resist axial loads. In this study, the test was performed on 100 mm concrete cubes following the procedures outlined in ASTM C39, with assessments conducted at both **28 and 90 days** to monitor both early and later-age strength development. The results obtained—ranging from **24.8 MPa to 29.0 MPa** at 28 days, and increasing to **26.5 MPa to 33.2 MPa** at 90 days—are considered realistic given the **non-standard, field-like curing conditions** applied. Such conditions are commonly encountered in practical and humanitarian construction contexts, where proper curing environments (controlled temperature and humidity) are often not achievable due to limited resources or emergency response constraints. . The compressive strength results of mixes M1 to M9 illustrated in Figure 10.

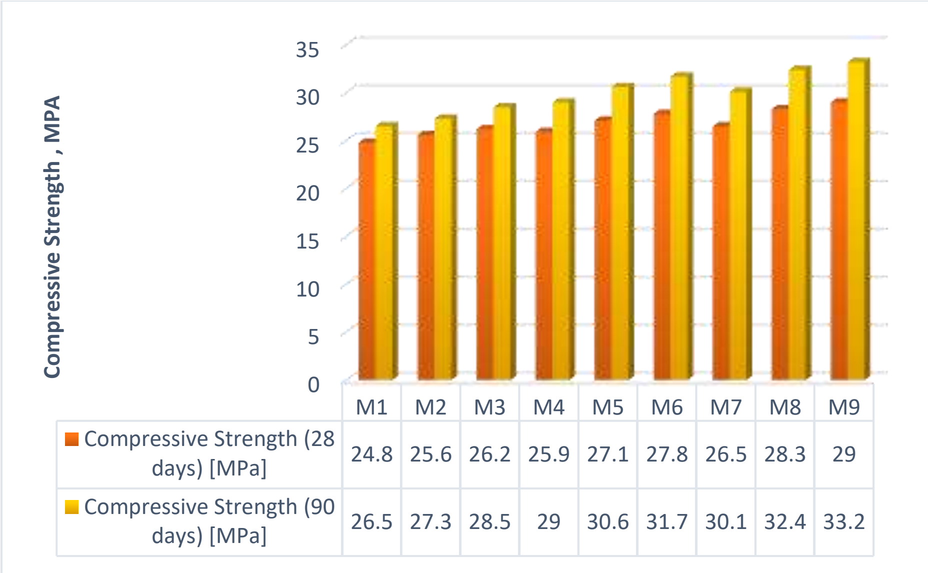

Figure 10. Compressive strength of polymer concrete

The increase in compressive strength with greater inclusion of **silica fume and GGBS** is consistent with well-established findings in the literature. Neville highlighted that silica fume contributes to strength by refining the microstructure and enhancing the formation of secondary calcium silicate hydrate (C-S-H) [15], while Mehta and Monteiro emphasized the long-term strength gain associated with the latent hydraulic activity of ground granulated blast-furnace slag (GGBS) [16]. Siddique further demonstrated that combining silica fume and GGBS leads to synergistic effects in enhancing both strength and durability of concrete. This effect is evident in the present study, where Mix M9 (containing 15% silica fume and 30% slag) achieved the highest compressive strength at 90 days.

In addition to SCMs, **epoxy resin** was included at 10% across all mixes. According to Khatib and Almutairi, epoxy-modified concretes exhibit superior cohesion and crack-bridging ability, which contribute to early-age strength and improved load transfer. Though **polypropylene fibers** are typically incorporated for their crack-arresting properties, Gesoglu et al found that they can also enhance the post-crack performance and structural toughness of concrete by mitigating internal stress concentrations.

2.5 Flexural strength

The **flexural strength test** is an essential measure of a concrete's ability to withstand tensile stresses and bending forces, which are especially critical in structural elements like beams, slabs, overlays, and repair applications. In this study, testing was conducted according to **ASTM C78** on **100×100×400 mm prism specimens**, assessed at both **28 and 90 days**. The results obtained—ranging from **3.41 MPa to 3.93 MPa** at 28 days, and **3.73 MPa to 4.40 MPa** at 90 days—reflect realistic and discussable outcomes under **non-standard, field-like curing conditions**, common in humanitarian construction settings where controlled environments are rarely available, see Figure 11. The observed increase in flexural strength with rising levels of **silica fume and GGBS** is supported by the work of Mehta and Monteiro, who highlighted that silica fume improves the interfacial transition zone (ITZ) and bond strength, thus enhancing tensile and flexural performance [17]. Neville similarly emphasized that GGBS contributes to reduced microcracking and improved long-term strength development due to its pore-refining capabilities [18]. These mechanisms explain the superior performance of Mix M9, which incorporated 15% silica fume and 30% slag, achieving the highest flexural values at both testing ages. Incorporating **10% epoxy resin** in all mixes also contributed to performance gains. As noted by Khatib and Almutairi, epoxy-modified concrete benefits from enhanced ductility and crack-bridging ability, which contribute positively to tensile strength under flexural loading [19]. Additionally, **polypropylene fibers**, included at 0.2% by volume, played an important role in controlling early shrinkage and bridging developing cracks. Gesoglu et al reported that even low dosages of polypropylene fibers significantly improve post-cracking behavior and flexural toughness, especially under cyclic or uneven loading conditions [20]. From a **humanitarian perspective**, the flexural performance of these polymer- and SCM-modified mixes has practical implications. In rural or disaster-affected regions where structures such as footbridges, water tanks, and community shelters are vulnerable to tensile failure, the ability to design mixes that resist bending stress—using sustainable materials and achievable curing—is invaluable. This study reinforces the concept that **high-performance repair concretes can be developed affordably and effectively**, even outside laboratory conditions, providing safer and more resilient infrastructure for vulnerable populations.

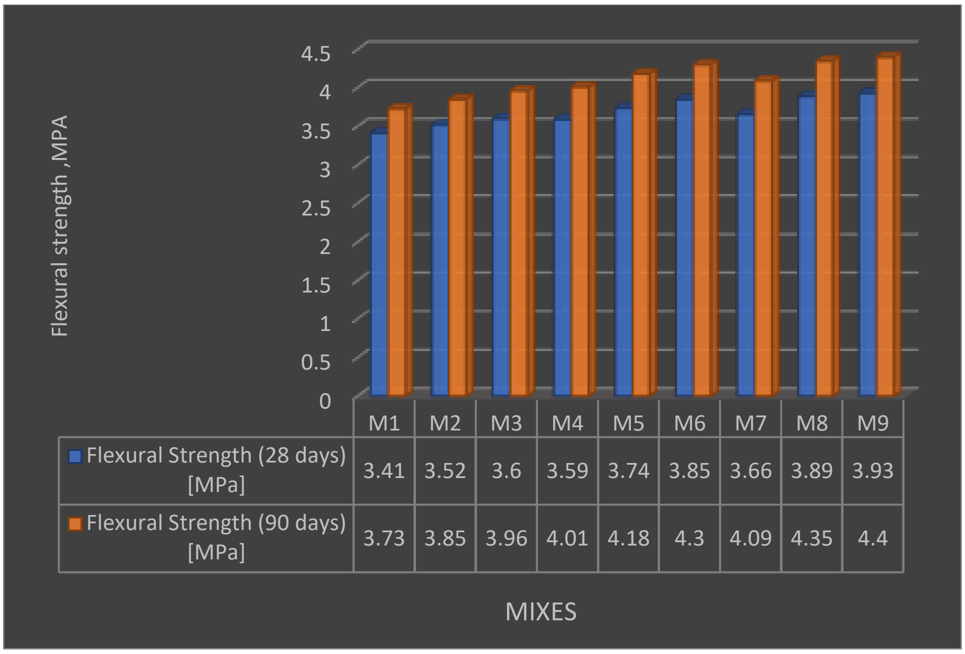

Figure 11. Flexural strength of polymer concrete

2.6 **Slant Shear Bond Strength**

The slant shear strength results as illustrated in Figure 12 is a key indicator of the **bond strength between new and existing concrete**, particularly relevant in repair applications where durability at the interface determines long-term structural performance. Conducted according to **ASTM C882**, the test evaluates the shear strength of a sloped interface—typically at 30° or 60°—by applying a compressive load along the bonded plane. In this study, slant shear tests were performed at both **28 and 90 days**, under **field-representative curing conditions**, providing insight into the performance of repair composites in environments where curing may be inconsistent or suboptimal. The results ranged from **13.8 MPa to 15.6 MPa** at 28 days and increased to **16.1 MPa to 18.5 MPa** at 90 days, indicating progressive development of interface strength over time.

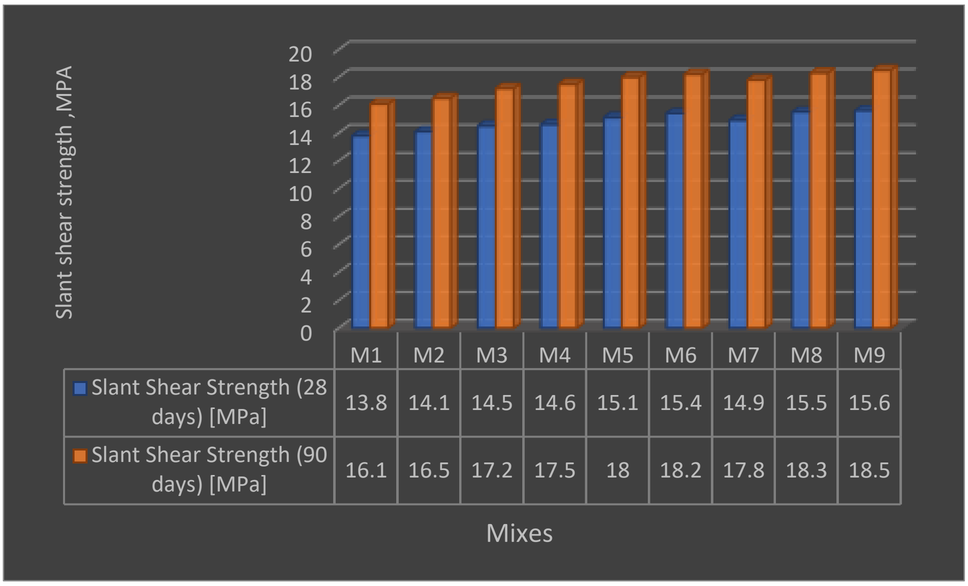

Figure 12. Slant shear strength of concrete

The enhancement in slant shear strength with increasing **silica fume and GGBS** content reflects findings reported by Neville, who emphasized that improved bond strength is closely linked to reduced porosity and a denser interfacial transition zone (ITZ) [21]. Mehta and Monteiro also observed that pozzolanic activity from silica fume contributes to additional C-S-H formation, which improves adhesion and chemical compatibility at the repair interface [22]. This trend is evident in the current study, particularly in Mix M9, where a combination of 15% silica fume and 30% slag produced the highest bond strength at both ages. The use of **epoxy resin at 10%** significantly contributed to improved shear performance. As demonstrated by Khatib and Almutairi, epoxy modification enhances adhesion by creating a continuous polymeric phase across the interface, improving load transfer and chemical bonding [23]. The inclusion of **polypropylene fibers (0.2%)**, while not directly affecting bond chemistry, helped limit interfacial cracking and micro-slip under load. This effect is supported by Gesoglu et al, who found that fiber reinforcement reduces strain localization at weak points, enhancing bond durability under shear and fatigue conditions [24].

4. Conclusion

This study set out to investigate the mechanical performance and durability of **high-performance polymer repair concrete (HPPRC)** incorporating **sulfate-resisting cement (SRC)**, **supplementary cementitious materials (SCMs)**—namely **silica fume** and **ground granulated blast furnace slag (GGBS)**—alongside **epoxy resin** and **polypropylene fibers (PPF)**, under realistic, non-standard curing conditions. The research specifically aimed to evaluate the potential of such materials in producing **repair-grade concrete** suitable for structurally vulnerable or resource-limited environments.

1. **Slump test results**, ranging between 11 and 13.1 cm, confirmed acceptable workability across all mixes, aided by the use of a **superplasticizer at 1% of binder weight**, and demonstrated that even with increasing silica fume and GGBS content—which typically increase water demand—workability could be preserved within practical ranges.
2. In terms of **fresh density**, values between **2390 to 2430 kg/m³** were observed, indicating that the inclusion of epoxy and PPF did not significantly alter the bulk weight of the mix, maintaining suitability for structural repairs without imposing additional dead loads.
3. **Water absorption** results showed a decreasing trend with increasing SCM and epoxy content, dropping from **4.5% in M1** to **2.9% in M9**. This outcome supports

the conclusion that scms and epoxy both contribute to **pore refinement and matrix densification**, reducing the permeability of the concrete and improving durability—crucial for repairs in aggressive or moisture-prone environments.

4. **Compressive strength** values, recorded at **28 and 90 days**, increased with higher proportions of silica fume and GGBS, reflecting ongoing pozzolanic and latent hydraulic reactions. The strength improved from **24.8 mpa at 28 days to 33.2 mpa at 90 days** in the best-performing mix (M9). These findings demonstrate that the **long-term strength development** of polymer-modified concrete can rival or exceed traditional mixes even when cured in less-than-ideal environments.
5. **Flexural strength**, critical for tensile and bending resistance in overlays and slabs, showed similar trends, rising from **3.41 mpa (M1)** to **3.93 mpa (M9)** at 28 days and up to **4.40 mpa** at 90 days. The presence of silica fume and epoxy helped improve the **interfacial transition zone (ITZ)** and tensile resistance, while **polypropylene fibers** mitigated early microcracking and improved post-cracking behavior.
6. **Slant shear test**, which assessed bond strength between old and new concrete surfaces, confirmed the effectiveness of the mixes in repair applications. Values increased from **13.8 mpa at 28 days to 18.5 mpa at 90 days**, highlighting the **adhesive potential** of epoxy and the **compatibility enhancement** provided by scms. The fiber addition likely contributed to reduced interfacial slippage and stress concentration.
7. Collectively, these test results confirm the **synergistic and complementary roles** of epoxy polymers and scms in enhancing the mechanical and durability properties of HPPRC. More importantly, these results validate the feasibility of **field-deployable repair solutions** for humanitarian settings, where ideal laboratory curing conditions may not exist. This research underscores that scientifically informed concrete repair can be **both high-performing and compassionately engineered**, extending safety and resilience to communities in need.

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