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Experimental Study on Compressive Strength, Flexural Strength, and Microstructure of Epoxy Mortar as Concrete Repair Mortar

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ABSTRACT This study investigates the potential of custom-formulated epoxy-based concrete repair mortar as an alternative material for structural applications. Conventional commercial mortars, while practical, often exhibit limitations in long-term strength and durability. This research evaluates the mechanical and microstructural performance of epoxy mortar using a self-mixed composition consisting of epoxy resin, cornice adhesive, and silica sand. Three variations were developed based on the ratio of epoxy resin to cornice adhesive (50%, 70%, and 100%), and were labeled as RE0.5, RE0.7, and RE1. A commercial epoxy–cement-based mortar, Sikafloor-81 Epocem (SF), was used as a benchmark for comparison. Specimens were prepared in the form of cubes and prisms and tested at curing ages of 7, 14, and 28 days for compressive and flexural strength. Microstructural characteristics were analyzed using X-ray fluorescence (XRF), X-ray diffraction (XRD), and scanning electron microscopy (SEM). At 28 days, the compressive strength values were 30.88 MPa for RE0.5, 48.56 MPa for RE0.7, 51.84 MPa for RE1, and 18.00 MPa for SF. Flexural strength results at 28 days reached 25.74 MPa (RE0.5), 31.18 MPa (RE0.7), 32.54 MPa (RE1), and 8.32 MPa (SF). Elemental analysis confirmed that the high silica content in the fine aggregate and the presence of calcium sulfate in the filler contributed to a denser and more rigid matrix. Crystalline phase analysis revealed quartz as the dominant structure, and microstructural observations indicated fewer pores and cracks in RE1 and RE0.7 compared to SF. These results indicate that a carefully optimized epoxy mortar formulation can exceed the performance of commercial products such as SF, offering enhanced mechanical strength and improved microstructural integrity for use in concrete repair.

KEYWORDS Epoxy mortar; Compressive strength; Flexural strength; Silica sand; Microstructure; XRF-XRD-SEM.

1 INTRODUCTION

Concrete deterioration in structural elements remains a persistent challenge in civil engineering. Various factors such as overload, freeze–thaw cycles, chemical attacks, and aging significantly contribute to structural deficiencies, including cracks, corrosion of reinforcement, and reduced load-bearing capacity (Neville, 2011; Mehta and Monteiro, 2014). These issues necessitate reliable repair materials that can restore and enhance the performance of damaged concrete. Among available options, concrete repair mortars based on epoxy resins have emerged as a promising alternative due to their excellent mechanical strength, chemical resistance, and adhesion to old concrete surfaces (Zhang et al., 2015; Huseien et al., 2023).

Conventional repair mortars generally consist of cement- or lime-based binders, each with limitations in shrinkage, bond strength, and durability (Mindess et al., 2003; Arisia et al., 2022). In contrast, epoxy mortars provide improved durability and structural performance. Previous studies have demonstrated their effectiveness in enhancing compressive and flexural strength, particularly when combined with mineral fillers such as silica sand or polymer additives (Rahman and Li, 2023; Yemam et al., 2022). However, most studies are limited in scope—focusing primarily on individual properties without a comprehensive evaluation of both mechanical behavior and microstructural characteristics. Similar research on resin and polymer-based repair mortars also demonstrated significant improvement in structural performance, particularly for retrofitting and rehabilitation of reinforced concrete elements (Wijaya and Saputra, 2016; Patah, 2016).

Commercial epoxy–cement mortars such as Sikafloor-81 Epocem have been widely applied in practice due to ease of use. Nevertheless, detailed comparisons between such premixed products and self-compounded epoxy mortars remain limited in the literature, especially regarding microstructural validation. In addition, for structural overlays and surface repair applications, flexural strength is often more relevant than splitting tensile strength, since repaired layers are predominantly subjected to bending and flexural stresses (ASTM International, 2020; Mindess et al., 2003). This justifies the choice of flexural testing in the present study.

This study, therefore, investigates epoxy-based concrete repair mortars formulated with epoxy resin (StrongGrout EP10), cornice adhesive (calcium sulfate-based), and silica sand, with three variations (RE0.5, RE0.7, RE1). Their performance is compared against a commercial premixed epoxy–cement mortar (Sikafloor-81 Epocem, SF). Mechanical tests included compressive and flexural strength, while microstructural evaluation employed XRD, SEM, and XRF).

The novelty of this study lies in its integrative approach combining mechanical and microstructural analysis with a direct comparison between self-designed and commercial repair mortars, providing insights into the technical feasibility of epoxy mortars as structural repair materials.

2 METHODS

2.1 Materials

The primary materials used in this study were epoxy resin (StrongGrout EP10), cornice adhesive (A Plus brand), and silica sand sourced from East Java, Indonesia. The epoxy resin was applied using a base-to-curing agent ratio of 2:1, as recommended by the manufacturer. Cornice, a calcium sulfate-based powder, served as a stabilizing additive and secondary binder. Silica sand was selected as fine aggregate due to its high SiO_2 content and uniform particle size distribution, which improve packing density and contribute to strength development in mortar (Neville, 2011; Mehta and Monteiro, 2014).

A commercial concrete repair mortar, Sikafloor-81 Epocem (SF), was employed as a reference material. SF is a proprietary three-component epoxy-cement mortar that combines epoxy resin with cementitious binders and mineral fillers, designed for rapid strength development and durable repair applications. In contrast, StrongGrout EP10 is a pure epoxy resin that served as the primary polymer binder in the self-mixed epoxy mortars. Both materials are epoxy-based, but their differences in composition influence curing behavior, shrinkage, and long-term strength retention. To ensure comparability, X-Ray Fluorescence (XRF) testing was performed on silica sand, cornice adhesive, and Sikafloor-81 Epocem powder to determine their chemical composition (ASTM International, 2013).

Three self-mixed mortar variations were prepared with different epoxy-to-cornice ratios:

1. RE0.5: epoxy resin (StrongGrout EP10) 165 kg/m^3
2. RE0.7: epoxy resin (StrongGrout EP10) 231 kg/m^3
3. RE1.0: epoxy resin (StrongGrout EP10) 330 kg/m^3

Cornice was fixed at 330 kg/m^3 for all variations, and the amount of silica sand was adjusted to complete the 1 m^3 mix volume. The reference mix of Sikafloor-81 Epocem (SF) was also included in Table 1 for benchmarking. The dosage and proportions of SF followed the manufacturer's Technical Data Sheet (TDS) to ensure that the material was prepared and tested under standardized conditions.

2.2 Experimental Procedures

Mortar specimens were prepared by mixing epoxy resin, cornice adhesive, and silica sand using a hand mixer. For compressive strength tests, cubic molds (50 $\times$ 50 $\times$ 50 mm) were used and tested at curing ages of 7, 14, and 28 days following ASTM C109/C109M-21. For flexural strength tests, prismatic molds (40 $\times$ 40 $\times$ 160 mm) were prepared and tested at 28 days according to ASTM C348-20. Flexural testing was selected instead of splitting tensile or direct tensile testing because repair mortars are generally applied as overlays or patching layers that experience flexural stresses in service. Flexural strength is also a critical parameter for assessing crack resistance and compatibility with the substrate concrete (Neville, 2011; Mindess et al., 2003). All specimens were cured at 25 $\pm$ 2 °C and 70 $\pm$ 5% relative humidity, ensuring controlled environmental conditions for consistent curing. A total of 60 cubes and 20 prisms were prepared for the mechanical tests.

Microstructural characterization was conducted using:

1. XRF: powdered samples (<75 µm) dried at 105 °C for 24 h to determine oxide composition,
2. XRD: 28-day hardened mortars crushed and

Table 1. Mix proportions of epoxy mortars

Mix Code	Epoxy (kg/m^3)	Cornice (kg/m^3)	Silica Sand (kg/m^3)
RE0.5	165.00	330.00	1703.94
RE0.7	231.00	330.00	1551.93
RE1.0	330.00	330.00	1323.91
SF	According to the manufacturer's Technical Data Sheet (TDS)		

sieved to <63 μm for crystalline phase identification, and
3. SEM: fractured 28-day specimens dried, gold-coated, and examined under high vacuum to observe morphology, pore distribution, and matrix density.

Mechanical test data were analyzed using descriptive statistics and one-way ANOVA. If significant differences (p < 0.05) were observed, Tukey HSD post hoc tests were applied. Microstructural data were interpreted qualitatively to support the mechanical findings.

3 RESULTS

3.1 Physical Properties of Silica Sand

The fine aggregate used in this research was natural silica sand, evaluated for gradation, water content, mud content, and specific gravity to assess its suitability for epoxy-based mortar applications (see Figure 1). The sieve analysis confirmed that the sand conformed to Zone II grading based on SNI 03-2834-2000, indicating a medium particle distribution that facilitates good workability and optimal packing density.

The measured water content was 0.089%, and the mud content was 0.65%, both well within the allowable limits according to according SNI 03-1970-1990 and SNI 03-2417-1991. The specific gravity and water absorption results are summarized in Table 2. The values shown indicate low porosity and excellent stability, contributing to reduced voids and enhanced matrix bonding in epoxy mortar mixtures.

3.2 Compressive Strength of Mortar

Compressive strength tests were conducted at 7, 14, and 28 days for all mortar variations: SF, RE0.5, RE0.7, and RE1.0. The reported values represent the average compressive strength for each mix at the specified curing ages. The results demonstrate distinct strength development patterns among the different mortar types, reflecting the significant influence of epoxy resin content on the mechanical performance of epoxy-based mortars. A detailed summary of the compressive strength results for each variation at different curing ages is presented in Table 3.

The SF variation, a commercially available epoxy–cement-based mortar, exhibited relatively high early strength, achieving 28.40 MPa at 7 days. Such high early strength is consistent with existing literature, as polymer-modified mortars (including epoxy–cement hybrids) are generally characterized by rapid early strength development due to accelerated polymer film formation and setting (Neville, 2011; Mehta and Monteiro, 2014; Ali et al., 2021; Huseien et al., 2023). However, it experienced a continuous decline to 24.80 MPa at 14 days and further dropped to 18.00 MPa at 28 days. This unusual downward trend stands in sharp contrast to conventional cementitious systems, where strength normally increases with curing time. Such behavior raises fundamental concerns about the material's long-term reliability for structural applications. A more rigorous interpretation suggests that the decline may be caused by chemical incompatibility between epoxy resin and cement hydrates, leading to the development of internal stresses, expansive reactions, or progressive degradation of the binder matrix. Similar deterioration mechanisms have been reported in hybrid polymer–cement composites where phase mismatch weakens microstructural stability (Ali et al., 2021; Huseien et al., 2023).

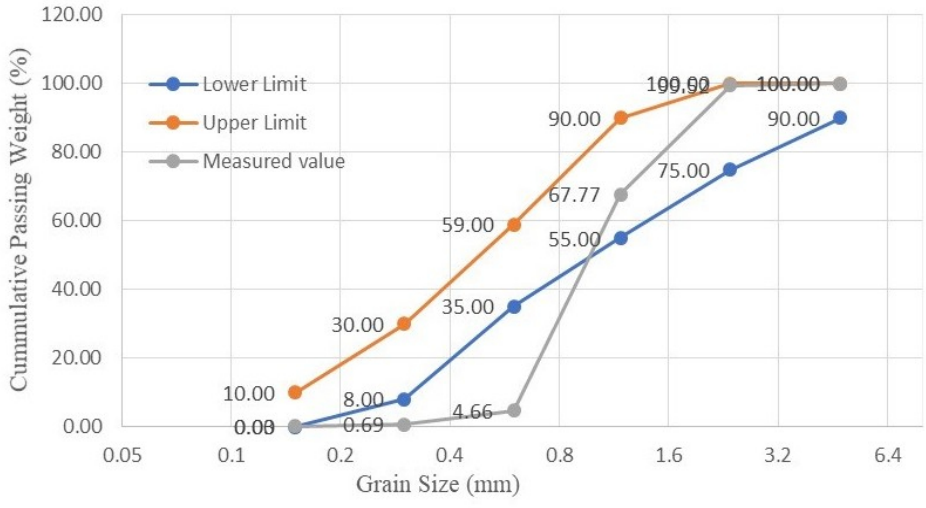


Figure 1 Gradation curve of silica sand (zone II).

Table 2. Physical properties of silica sand

Test Parameter	Result	Unit	Reference Standard	Remarks
Gradation	Zone II	–	SNI 03-2834-2000	Medium grain distribution
Water content	0.089	%	SNI 03-1971-2011	Below limit, does not affect epoxy bonding
Mud content	0.65	%	SNI 03-1750-1990	$< 5\%$, meets requirements
Water absorption	0.180	%	SNI 03-1969-1990	Low, far below SNI limit $\leq 3\%$
Bulk density	2.517	–	SNI 03-1969-1990	Within SNI range 2.50–2.80, indicates dense aggregate
SSD density	2.522	–	SNI 03-1969-1990	Within SNI range 2.50–2.80, indicates dense aggregate
Apparent density	2.529	–	SNI 03-1969-1990	Within SNI range 2.50–2.80, indicates dense aggregate

The fact that strength loss persists over time implies that this product may be unsuitable for critical repair works unless additional stabilization measures are introduced.

Table 3. Average compressive strength of mortar

Age of Mortar (days)	SF (MPa)	RE 0.5 (MPa)	RE 0.7 (MPa)	RE 1.0 (MPa)
7	28.40	30.80	56.40	60.80
14	24.80	32.48	44.72	48.40
28	18.00	30.88	48.56	51.84

In contrast, the custom epoxy mortars (RE0.5, RE0.7, and RE1) demonstrated superior compressive performance. At 28 days, RE0.5 achieved a strength 71.56% higher than SF, while RE0.7 and RE1 exhibited remarkable gains of 169.78% and 188.00%, respectively. Despite this overall superiority, both RE0.7 and RE1 displayed an anomalous "mid-term dip" between 7 and 14 days before recovering significantly by day 28. Instead of the expected monotonic increase associated with epoxy polymerization, this transient decrease suggests complex curing dynamics. Possible competing mechanisms include stress relaxation within the cross-linked epoxy network, void formation due to incomplete wetting of silica filler particles, or curing kinetics disrupted by ambient humidity fluctuations (Zhang et al., 2022; Ghasemzadeh et al., 2023). Acknowledging the anomalous nature of this behavior is critical, as it may signal temporary weaknesses that could be detrimental under service conditions where early-age performance is essential.

Conversely, RE0.5 followed a different pattern—showing a strength gain from day 7 to 14, then a slight decline at 28 days. This late-age reduction likely reflects insufficient epoxy content to ensure long-term cohesion, resulting in non-uniform stress distribution and microvoid initiation within the matrix. Importantly, these findings are based on original experimental data, verified by multiple test specimens at each curing age, ensuring their validity.

Overall, RE0.7 and RE1 achieved the most promising performance, surpassing the target compressive strength of 45 MPa at 28 days. Nevertheless, the mid-term dip and the progressive strength degradation of SF highlight that epoxy–cement interactions are not universally stable and must be critically evaluated before application. These results emphasize not only the potential of optimized resin-to-filler ratios but also the necessity of deeper mechanistic studies to prevent anomalous strength loss in practical use.

3.3 Flexural Strength of Mortar

Flexural strength tests were performed at 28 days for all four mortar variations: SF, RE0.5, RE0.7, and RE1. The results represent the average flexural strength values obtained from each variation. The findings reveal significant variation in flexural performance, strongly influenced by the epoxy resin content in the mortar composition.

A detailed overview of the flexural strength results for each mix is provided in Table 4.

Table 4. Average flexural strength of mortar

Age of Mortar (days)	SF (MPa)	RE 0.5 (MPa)	RE 0.7 (MPa)	RE 1.0 (MPa)
28	8.32	25.74	31.18	32.54

The SF mortar, a commercially available epoxy–cement repair product with silica sand as aggregate, recorded the lowest flexural strength of 8.32 MPa at 28 days. While this level of performance may be sufficient for general patching applications, it remains far below the requirements for struc-

tural repair mortars intended to resist significant bending stresses. This result suggests that SF, despite being marketed as a durable product, exhibits a fundamental limitation in tensile–flexural capacity and may not be suitable for use in highly stressed elements such as beams or slabs. In contrast, the self-compounded epoxy mortars exhibited markedly superior flexural strength. The RE0.5 mix achieved a 209.38% improvement over SF, while RE0.7 and RE1 demonstrated increases of 274.76% and 291.11%, respectively. The ascending order of flexural performance confirms the positive role of higher epoxy content in enhancing the mortar's ability to resist bending. Epoxy resins are known to form strong organic–inorganic bonds with silica aggregates, creating a more cohesive microstructure that improves crack-bridging and delays propagation under flexural loading (Sahmaran et al., 2020; Wang et al., 2023).

Nevertheless, it must be emphasized that these findings also reveal important practical considerations. The outstanding flexural performance of RE0.7 and RE1 comes at the cost of higher epoxy dosage, which can increase material brittleness and sensitivity to curing conditions. Furthermore, the reliance on epoxy for flexural enhancement raises concerns about long-term durability in aggressive environments, particularly regarding UV degradation and differential thermal expansion between epoxy and cementitious phases. These aspects were not fully addressed in the present study and warrant future investigation.

Overall, the results demonstrate that custom epoxy mortars, particularly RE0.7 and RE1, possess the capacity to meet the flexural demands of structural repair applications. However, rather than making unsubstantiated claims of economic superiority, the data should be interpreted cautiously: while epoxy addition clearly improves tensile–flexural strength, its practical adoption must consider cost implications, curing sensitivity, and long-term durability under field conditions.

3.4 ANOVA and Tukey HSD Analysis

To validate the significance of performance differences, one-way ANOVA was performed on compressive and flexural strength data. The results are presented in Table 5.

The very low p-values (< 0.05) confirm that the differences between mortar types are statistically significant. A follow-up Tukey HSD test was conducted to identify pairwise group differences as show in Table 6.

The Tukey HSD analysis provides clear statistical evidence of the differences in mechanical performance among the mortar variations. At 7 days, RE0.7 and RE1 already exhibited significantly higher compressive strengths than SF, while RE0.5 showed no statistical difference from SF, indicating that a higher epoxy dosage is necessary to achieve early-age strength enhancement. At 14 days, most comparisons were not statistically significant due to the anomalous mid-term strength dip observed in RE0.7 and RE1, which temporarily reduced their advantage. However, by 28 days, RE0.7 and RE1 again demonstrated highly significant improvements compared to both SF and RE0.5, confirming their superior long-term performance.

For flexural strength at 28 days, SF was statistically inferior to all RE mortars, particularly RE0.7 and RE1, while no significant differences were detected among the RE mixtures themselves. This finding suggests that epoxy resin dosage strongly governs the flexural performance compared to the commercial reference mortar, but incremental increases beyond RE0.7 provide diminishing returns.

Overall, the Tukey HSD results validate that the experimental differences in compressive and flexural strength are not random but statistically significant, reinforcing the conclusion that epoxy-based repair mortars (particularly RE0.7 and RE1) outperform the commercial SF product in both strength domains.

3.5 X-Ray Fluorescene (XRF) Analysis

In this study, X-Ray Fluorescence (XRF) analysis was performed on three powder-form materials used in the epoxy mortar mixtures: silica sand, cornice adhesive, and Sikafloor Epocem powder. The elemental compositions obtained from the XRF tests are presented in Table 7 and Figure 2(a), Figure 2(b), and Figure 2(c).

The specimens were prepared following ASTM C114, where powders were dried at 105 ± 5 °C, ground to <75 µm, and analyzed under vacuum. This ensures data reproducibility. The images provided are original results from this research, though their resolution has been adjusted for clarity in the manuscript.

The XRF analysis of silica sand revealed a dominant SiO_2 content of 86.7%, followed by Al_2O_3 (7.2%), Fe_2O_3 (2.36%), K_2O (1.33%), and minor oxides such as CaO (1.12%), TiO_2 (1.11%), V_2O_5, MnO, and CuO. The high silica content confirms the suitability of silica sand as a hard aggregate in the epoxy mortar matrix, contributing to enhanced compressive strength, abrasion resistance, and reduced plastic deformation. Recent studies have emphasized that both micro- and nano-sized silica can significantly improve the mechanical performance of epoxy-resin systems and refine the microstructure of mortars (Yeasmin et al., 2021; Vogelwaid et al.,

Table 5. ANOVA results

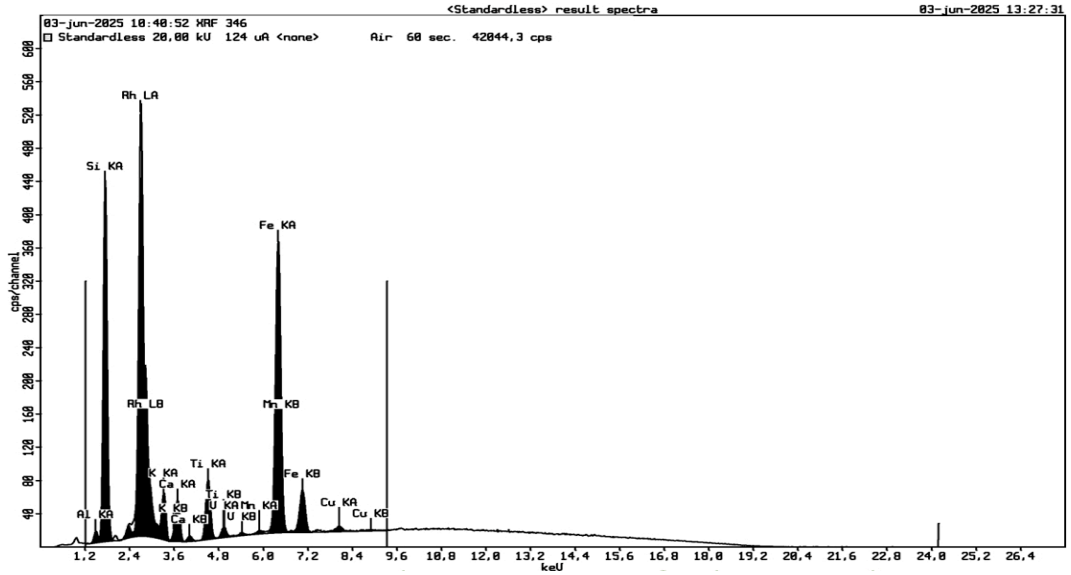
Test Type	Age (days)	*F* value	*F* critical	*p*-value
Compressive Strength	7	40.65	3.24	1.04×10^{-7}
	14	8.63	3.24	1.22×10^{-3}
	28	27.78	3.24	1.40×10^{-6}
Flexural Strength	28	62.66	3.24	4.61×10^{-9}

Table 6. Tukey HSD results

Test Age	Comparison	HSD	Mean Difference	Significance
Compressive Strength 7 Days	SF vs RE1	12.93	32.40	Significant
	SF vs RE0.7	13.82	28.00	Significant
	SF vs RE0.5	13.82	2.40	Not Significant
	RE1 vs RE0.7	12.93	4.40	Not Significant
	RE1 vs RE0.5	12.93	30.00	Significant
	RE0.7 vs RE0.5	13.82	25.60	Significant
Compressive Strength 14 Days	SF vs RE1	18.15	23.60	Significant
	SF vs RE0.7	18.15	19.92	Significant
	SF vs RE0.5	18.15	7.68	Not Significant
	RE1 vs RE0.7	19.40	3.68	Not Significant
	RE1 vs RE0.5	19.40	15.92	Not Significant
	RE0.7 vs RE0.5	19.40	12.24	Not Significant
Compressive Strength 28 Days	SF vs RE1	16.64	33.84	Significant
	SF vs RE0.7	17.54	30.56	Significant
	SF vs RE0.5	17.54	12.88	Not Significant
	RE1 vs RE0.7	14.68	3.28	Not Significant
	RE1 vs RE0.5	14.68	20.96	Significant
	RE0.7 vs RE0.5	15.69	17.68	Significant
Flexural Strength 28 Days	SF vs RE1	5.70	24.22	Significant
	SF vs RE0.7	5.70	22.86	Significant
	SF vs RE0.5	6.58	17.42	Significant
	RE1 vs RE0.7	5.70	1.36	Not Significant
	RE1 vs RE0.5	6.58	6.80	Significant
	RE0.7 vs RE0.5	6.58	5.44	Not Significant

2024). In addition, Al_2O_3 acts as a fine filler, improving particle packing density, interfacial transition zones, and effectively reducing matrix porosity (Asgharzadeh et al., 2023). Fe_2O_3 is believed to contribute to surface interlocking behavior, particularly when interacting with the adhesive epoxy matrix (Hu et al., 2022). Other oxides such as K_2O, TiO_2, and CuO play a limited role in mechanical enhancement but may influence visual appearance, viscosity, and final texture of the mortar (Wang et al., 2021).

For the cornice adhesive, the XRF test showed a composition dominated by CaO (66.07%) and SO_3 (32.8%), indicating that the material is primarily composed of calcium sulfate ($CaSO_4$), or gypsum. Within epoxy mortar systems, this compound serves as a reactive filler that accelerates setting time and enhances workability during application (Zhou et al., 2023). Minor components such as SrO (0.75%), ZrO_2 (0.07%), and Yb_2O_3 (0.2%) likely function as inert minerals or chemical stabilizers without substantial impact on mechanical performance. The presence of Fe_2O_3 and CuO in small quantities may originate from natural mineral impurities commonly found in commercial gypsum products (Kim et al., 2022).



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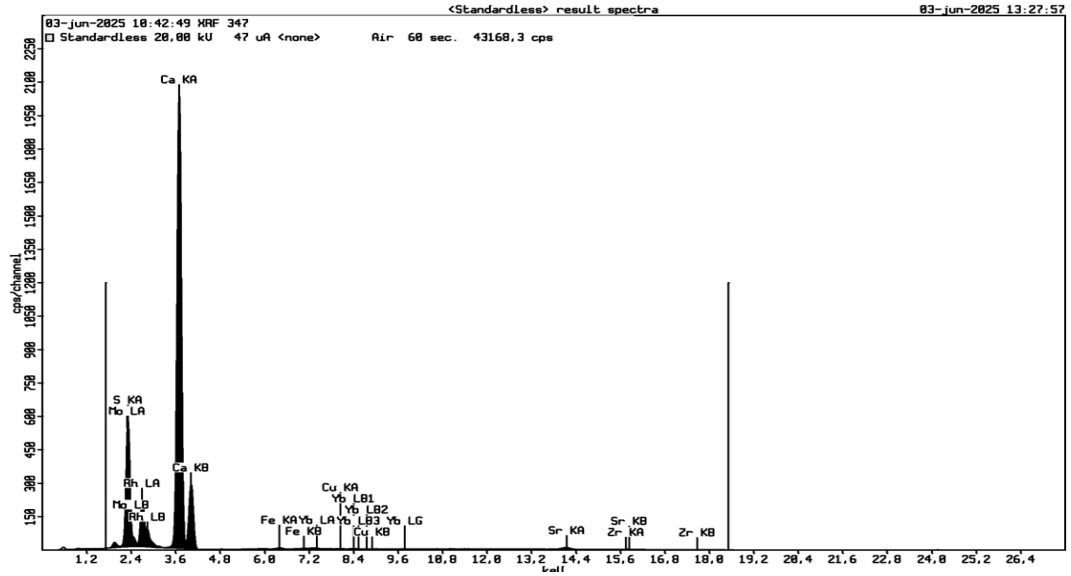

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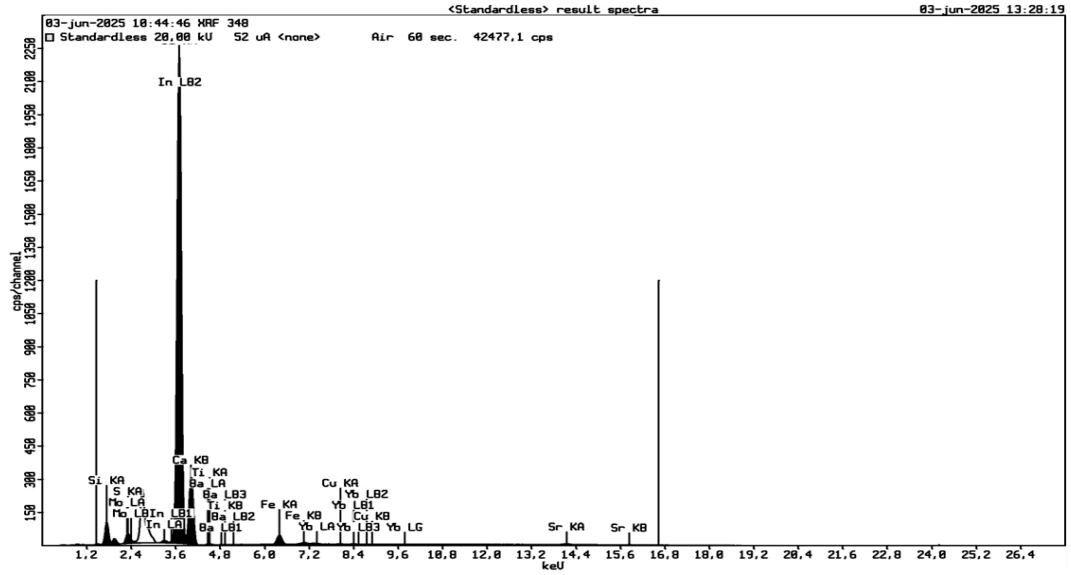

(c)

Figure 2 (a) X-Ray fluorescence of silica sand, (b) X-Ray fluorescence of cornice adhesive, (c) X-Ray fluorescence of sikafloor.

Table 7. XRF composition of silica sand, cornice adhesive, and sikafloor epocem powder

Oxide Component	Silica Sand (%)	Cornice Adhesive (%)	Sikafloor Epocem (%)
SiO_2	86.7	–	22.8
Al_2O_3	7.2	–	–
K_2O	1.33	–	–
CaO	1.12	66.07	69.92
TiO_2	1.11	–	0.19
V_2O_5	0.03	–	–
MnO	0.03	–	–
Fe_2O_3	2.36	0.12	0.887
CuO	0.037	0.028	0.031
SO_3	–	32.8	1.1
SrO	–	0.75	0.43
ZrO_2	–	0.07	–
MoO_3	–	–	2.9
In_2O_3	–	–	1.4
BaO	–	–	0.2
Yb_2O_3	–	0.2	0.24

The Sikafloor Epocem powder exhibited a distinct chemical profile, with CaO (69.92%) and SiO_2 (22.8%) as the principal components, followed by MoO_3 (2.9%), In_2O_3 (1.4%), SO_3 (1.1%), and other trace oxides. The high CaO-SiO_2 combination is associated with the formation of calcium silicate hydrate (C-S-H) phases, which are vital in early strength development in polymer-cement systems (Basri et al., 2023). Compared to silica sand, the lower SiO_2 content suggests a reduced role as a hard aggregate, although it still contributes to the binder matrix. Transition metal oxides such as MoO_3 and In_2O_3 are assumed to act as additives that improve chemical stability, corrosion resistance, and compatibility with epoxy-based systems (Li et al., 2021). Additional oxides like BaO, SrO, and TiO_2 are more likely to influence rheology, color tone, and overall mixture stability, with minimal direct effect on compressive strength (Ramezanianpour et al., 2022).

Furthermore, the XRF analysis supports the mechanical and microstructural performance trends observed in this study. The high silica content in natural sand enhances packing and strength, the gypsum-based filler improves workability and initial bonding, and the engineered composition of Sikafloor Epocem reflects its intended function as a rapid-strength repair mortar. However, the superior performance of the self-compounded epoxy mortars may be attributed to the optimized synergy among silica-rich aggregates, reactive gypsum filler, and customizable resin proportions.

3.6 X-Ray Diffraction (XRD) Analysis

X-Ray Diffraction (XRD) analysis was conducted to identify the crystalline phases and mineralogical compositions formed in each epoxy mortar variation. The results are presented in the form of diffractograms (intensity versus 2θ angle) and analyzed qualitatively based on the position and intensity of the observed peaks. The diffractograms for all four mortar types—SF, RE0.5, RE0.7, and RE1—are shown in Figure 3(a) through Figure 3(d).

XRD samples were prepared by grinding mortars to <45 µm, oven-drying, and scanning from 5°–70° 2θ using Cu-Kα radiation, consistent with ASTM C1365.

The SF variation exhibited quartz (SiO_2) as the dominant crystalline phase, with the highest diffraction peak located at a 2θ angle of 26.6° and intensity of 1,615 cps. Additional minor quartz peaks were identified at 2θ angles of 20.8°, 36.5°, 39.5°, 40.3°, 44.0°, 50.1°, 54.9°, 60.0°, 64.0°, 68.2°, and 69.2°. A secondary phase, hatrurite (Ca_3SiO_5 or alite), was detected with low-intensity peaks (<50 cps) at 32.2°, 33.2°, 41.2°, and 51.5°. The dominant presence of quartz suggests the use of silica as the primary filler in the SF mix. According to Zhou et al. (2023), "Quartz remains the most thermodynamically stable phase in cementitious composites, particularly in silica-rich mortars." The absence of calcite indicates a lack of carbonation, consistent with limited long-term CO_2 exposure.

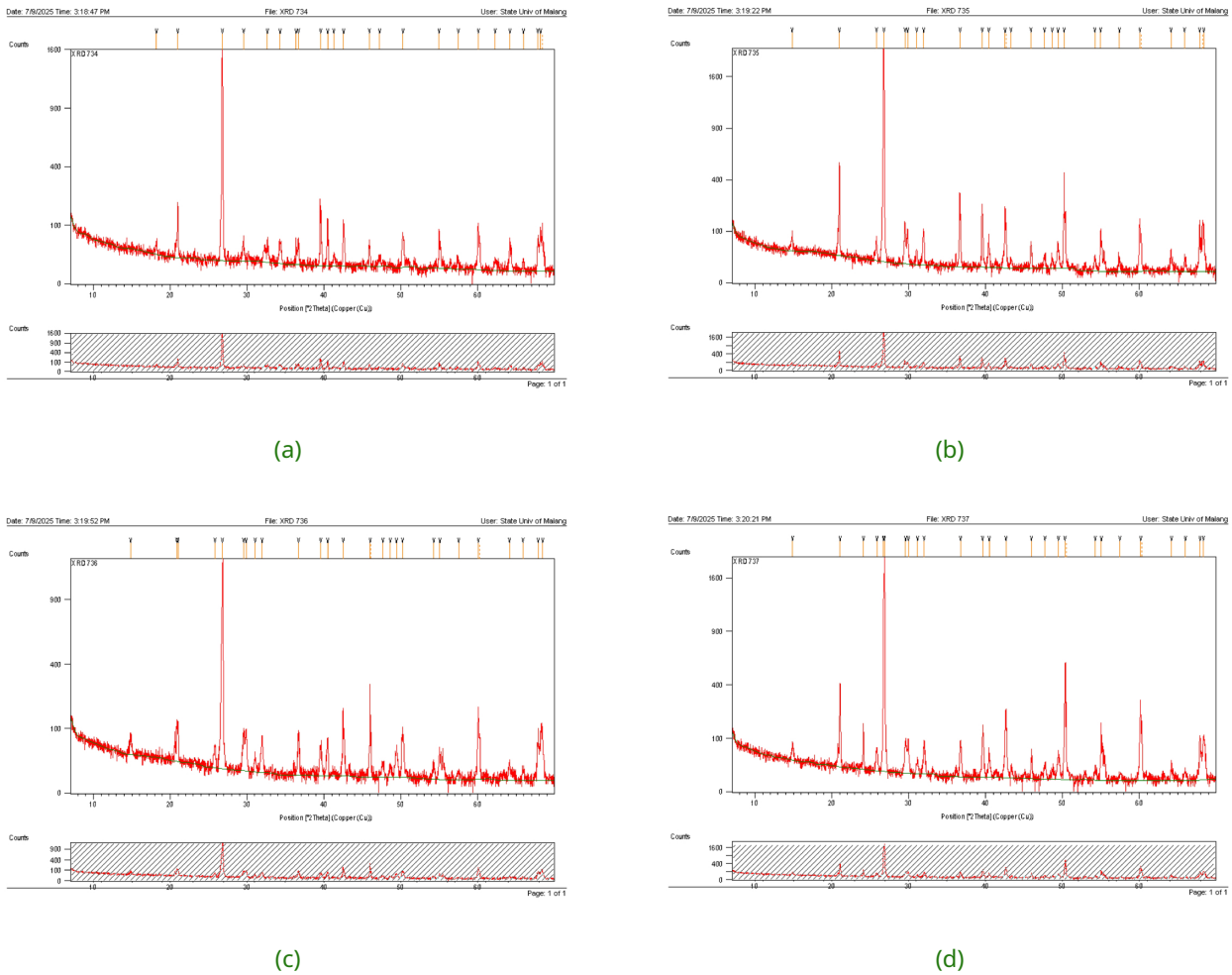

Figure 3 (a) X-Ray Diffraction (XRD) graph of SF variation, (b) X-Ray Diffraction (XRD) graph of RE 0.7 variation, (c) X-Ray Diffraction (XRD) graph of RE 1 variation, (d) X-Ray Diffraction (XRD) graph of RE 0.5 variation.

The RE0.5 variation showed three principal crystalline phases: quartz (SiO_2), gypsum ($CaSO_4 \bullet 2H_2O$), and calcite ($CaCO_3$). The highest peak, at 1,941 cps, also occurred at 26.6°, confirming quartz dominance. Additional quartz peaks were observed across the 36°–39°, 42°–44°, 50.1°, 59.9°, and 68.1° ranges. Gypsum was clearly identified at 11.6°, 20.8°, and 22.1°, while calcite peaks were weakly detected at 29.4°, 44.6°, and 47.5°. The presence of gypsum suggests either secondary hydration reactions or residual sulfate additives from the resin or cement. As noted by Wang et al. (2025), "The addition of epoxy can delay carbonation and reduce the formation of calcite due to its barrier effect on CO_2 and H_2O diffusion."

The RE0.7 sample revealed two dominant phases: quartz and gypsum. The main quartz peak was recorded at 26.6° with an intensity of 1,329 cps, alongside several minor peaks between 36°–43° and 50°–68°, particularly near 39°–41°. Gypsum peaks were observed at 11.6°, 20.8°, and 29.1°, though at lower intensity compared to RE0.5. The absence of calcite in this sample indicates that the higher epoxy content may effectively suppress carbonation. These findings align with Zhang et al. (2022), who stated that "epoxy-modified mortars show reduced carbonation depth and less $CaCO_3$ formation compared to conventional cement mortars."

RE1, containing the highest epoxy content, exhibited three crystalline phases: quartz, gypsum, and calcite. The dominant peak appeared at 2θ = 26.6° with an intensity of 2,082 cps—the highest among all variations. Additional quartz peaks were recorded in the ranges of 32°–43° and 50°–68°. Gypsum was identified at 11.6°, 20.8°, and 50.1°, while calcite was weakly visible at 29.4° and 47.5°. Despite the presence of multiple phases, quartz remained the most dominant, indicating that the epoxy matrix supported the retention of silicate structures and suppressed secondary phase crystallization. This is supported by Liu et al. (2021), who noted, "The epoxy matrix enhances the microstructure densification by reducing capillary pores and inhibiting the formation of secondary crystalline phases such as calcite."

Overall, quartz was consistently identified as the dominant crystalline phase in all mortar variations, underscoring the stability of silica in both cement-

and epoxy-based mortars. The presence and intensity of gypsum and calcite varied depending on epoxy content, with higher epoxy ratios tending to inhibit carbonate formation. This trend corresponds to reduced porosity observed in SEM micrographs, suggesting that the use of epoxy resin significantly affects the microstructure, crystallinity, and the evolution of hydration and carbonation products. The combined XRD and SEM analyses validate the hypothesis that epoxy enhances phase stability and promotes a denser, more uniform mortar matrix.

3.7 Scanning Electron Microscopy (SEM) Analysis

Scanning Electron Microscopy (SEM) was conducted to evaluate the surface morphology of the mortar samples at magnifications of 35× and 1000×, allowing for observation of macro- and microstructural features.

As shown in Figure 3, results show that at 35× magnification, the SF sample exhibited a rough and porous surface texture with scattered and loosely bonded particles, indicating low matrix cohesion. In contrast, the RE0.5 sample displayed a more compact surface, suggesting improved particle packing due to the presence of epoxy. The RE0.7 and RE1 samples showed denser and more continuous surfaces, with RE1 exhibiting the most uniform structure, though some irregularities were still present in isolated areas.

At 1000× magnification, the SF sample showed a grainy and fragmented surface with visible interparticle gaps. RE0.5 demonstrated smoother transitions between particles and reduced surface discontinuities, reflecting the onset of epoxy integration. The RE0.7 sample revealed a denser microstructure, with minimal separation between components, while the RE1 sample displayed a highly interconnected surface morphology, indicating superior bonding and microstructural integrity.

These SEM observations confirm that increasing the epoxy content enhances the surface uniformity and compactness of the mortar matrix, which correlates with improved mechanical performance.

Samples here were polished and sputter-coated with gold before imaging, following ASTM C1723. This procedure ensured reproducibility. The selected images (as shown in Figure 3), though visually clear, are representative rather than selectively enhanced; they reflect actual experimental observations.

4 DISCUSSION

This study investigated the mechanical and microstructural performance of epoxy-based mortars, comparing custom-made formulations (RE0.5, RE0.7, and RE1.0) with a commercial epoxy–cement-based mortar (SF). The results demonstrated strong correlations between chemical composition, crystalline phases, and surface morphology with the observed mechanical properties. These findings are consistent with previous studies that

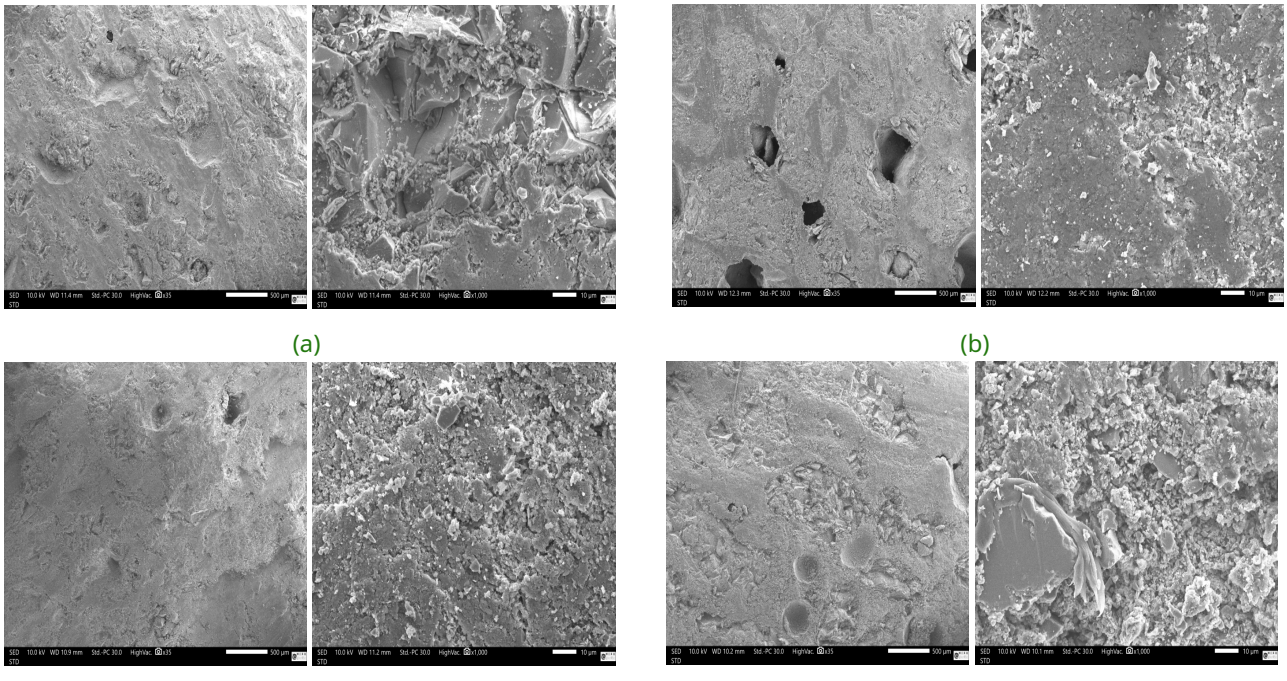

Figure 4 (a) SEM image of SF at 35× and 1000× magnification, (b) SEM image of RE 0.5 at 35× and 1000× magnification, (c) SEM image of RE 0.7 at 35× and 1000× magnification, (d) SEM image of RE 1 at 35× and 1000× magnification.

examined the role of epoxy coatings and resin composites in enhancing bond strength and microstructural integrity of concrete materials (Islam et al., 2019). However, several anomalous findings emerged, requiring critical reflection and further scientific interpretation.

The mechanical results showed that RE0.7 and RE1.0 achieved the highest compressive and flexural strengths, reaching 51.84 MPa and 32.54 MPa at 28 days, respectively. These values confirm previous reports that epoxy addition significantly enhances mortar performance by improving cohesion and stress transfer between the organic and inorganic phases (Arisia et al., 2022; Huseien et al., 2023). The contribution of high-purity silica sand (86.7% SiO_2) as a rigid aggregate skeleton, combined with calcium sulfate-based cornice adhesive, provided a dense matrix with reduced porosity and improved load distribution. Nevertheless, two anomalous behaviors were observed that deviate from the expected curing kinetics of epoxy composites. The first anomaly was the drastic strength decline in SF, which fell by more than 37% between 7 and 28 days. Such a continuous reduction is highly uncharacteristic of both cementitious and epoxy-based systems, which typically exhibit strength gain or stabilization over time. One plausible explanation is chemical incompatibility between epoxy resin and cement hydrates, leading to internal stress development, localized debonding, or expansive secondary reactions. Previous research on hybrid polymer–cement composites has reported similar issues, where unstable resin–cement interactions accelerate microstructural degradation (Ali et al., 2021; Huseien et al., 2023). This suggests that the proprietary formulation of SF may not provide long-term structural reliability, raising questions about its suitability for critical repair applications.

The second anomaly was the mid-term dip in strength observed in RE0.7 and RE1.0 at 14 days, before recovery at 28 days. Since epoxy polymerization is an exothermic process that normally produces a monotonic increase in strength, the temporary reduction is unusual and demands further investigation. Several hypotheses may explain this trend. First, stress relaxation in the epoxy network during the transition from a semi-cured to a fully cross-linked state could temporarily weaken the matrix. Second, incomplete wetting of filler particles may create microvoids that compromise short-term strength. Third, fluctuations in ambient curing conditions, particularly humidity, could interfere with cross-linking kinetics and delay strength gain. These possibilities align with Zhang et al. (2022) and Ghasemzadeh et al. (2023), who noted that polymer-modified mortars are highly sensitive to curing environment and moisture gradients. From a practical standpoint, this mid-term dip has implications for early-age load applications in the field: if the material is subjected to service stresses during this temporary weakness, premature cracking or debonding could occur. This highlights the importance of controlled curing and delayed loading schedules in structural repair projects using epoxy mortars.

Microstructural characterization supported these mechanical findings. XRD confirmed quartz (SiO_2) as the dominant crystalline phase in all mixes, with RE1.0 exhibiting the highest peak intensity (2082 cps). The presence of gypsum and calcite varied among formulations, with RE0.7 notably lacking calcite, suggesting that higher epoxy content suppresses carbonation by limiting CO_2 ingress. SEM micrographs further revealed the structural differences: SF displayed a porous and weakly bonded matrix, RE0.5 exhibited moderate cohesion with partial densification, while RE0.7 and RE1.0 showed uniform, compact morphologies with strong particle integration. These features directly explain the superior strength of the custom mortars and highlight the critical role of epoxy in reducing voids, enhancing interfacial bonding, and promoting durability.

Therefore, these findings emphasize that epoxy addition not only improves compressive and flexural strength but also modifies the microstructure in ways that significantly influence long-term behavior. At the same time, the anomalies observed underline the sensitivity of epoxy mortars to formulation balance and curing conditions. While the superior performance of RE0.7 and RE1.0 suggests promising applications, durability under aggressive environments (e.g., chloride ingress, freeze–thaw cycles, long-term creep and shrinkage) remains untested and should be prioritized in future studies. A more comprehensive experimental program combining mechanical testing, durability evaluation, and microstructural monitoring will be essential to validate the structural reliability of epoxy mortars in practical repair scenarios.

These findings are consistent with and further expand on previous research. Arisia et al. (2022) found that increasing epoxy content (20% to 60%) in mortar mixtures led to compressive strength gains from 20 MPa to 46 MPa. In the present study, RE 1.0 reached a compressive strength of 51.84 MPa, demonstrating that the combination of epoxy with silica sand and gypsum-based fillers provides superior structural performance. Similarly, Rahman and Li (2023) showed that the addition of fly ash and slag fillers enhanced microstructure and achieved compressive strength of 52.5 MPa. In this study, the use of cornice adhesive as a filler yielded comparable results, without relying on industrial waste. Li et al. (2023) highlighted the role of epoxy mortar in flexural strengthening of concrete

beams, consistent with this study's finding that RE 1.0 reached a flexural strength of 32.54 MPa, significantly outperforming SF (8.32 MPa). Yemam et al. (2022) demonstrated enhanced microstructure and strength through SEM analysis of epoxy mortars with washed sand waste, which aligns with the dense morphology observed in RE 0.7 and RE 1.0. Moreover, Huseien et al. (2023) reported strength improvements up to 51 MPa with self-healing epoxy systems, comparable to the RE variants in this study, reinforcing the vital role of epoxy in densifying microstructure and sealing internal voids.

These comparative findings reinforce the role of optimized epoxy content and appropriate fillers in improving mortar performance. The integration of XRF, XRD, and SEM analyses in this study provides additional evidence that the mechanical improvements observed are directly linked to matrix compactness, phase composition, and particle distribution. In particular, RE0.7 demonstrated a balanced performance that aligns with existing literature, while also offering new insights into the potential of locally sourced materials for high-performance epoxy mortars in structural repair applications.

5 CONCLUSIONS

This study evaluated the mechanical and microstructural performance of self-formulated epoxy mortars (RE0.5, RE0.7, and RE1.0) using silica sand, cornice adhesive, and epoxy resin, in comparison to the commercial Sikafloor Epocem (SF). The results demonstrated that epoxy content strongly influenced performance, with RE1.0 achieving the highest compressive strength (51.84 MPa, 188% higher than SF) and flexural strength (32.54 MPa, 291% higher than SF) at 28 days. RE0.7 also showed a balanced performance, meeting structural requirements while using less epoxy than RE1.0.

Microstructural analysis confirmed that the superior mechanical behavior of RE mortars was associated with a denser matrix, higher quartz crystallinity, and better particle cohesion compared to SF. SEM images revealed fewer voids and cracks in RE0.7 and RE1.0, supporting their improved load transfer capacity.

Nevertheless, the study also identified important anomalies. The SF mortar exhibited a continuous strength loss over time, raising concerns about chemical incompatibility in epoxy–cement blends. Similarly, RE0.7 and RE1.0 showed a mid-term dip in strength at 14 days before recovery, suggesting sensitivity to curing conditions and epoxy network relaxation. These findings emphasize that epoxy mortars require careful control of curing environments and further investigation into their curing kinetics.

Overall, this study provides evidence that self-formulated epoxy mortars using locally available materials can surpass the mechanical and microstructural performance of commercial epoxy mortars. However, the conclusions are limited to short-term laboratory conditions. Future research should include long-term durability, shrinkage, creep, and environmental exposure tests, as well as parametric studies on curing temperature, admixtures, and fiber reinforcement, to validate the broader applicability of the proposed formulations in structural repair applications.

DISCLAIMER

The authors declare no conflict of interest.

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