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Evaluation of bond strength and direct tensile strength of geopolymer mortar with concrete substrate using pull-off tests

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Abstract: In order to assess the dependability of externally reinforced concrete buildings, one must be familiar with the long-term performance of the interfacial transition zone (ITZ) between adhesive materials and the concrete substrate. Use sustainable geopolymer binders to enhance the mechanical capabilities and longevity of concrete components during strengthening and repair processes. In this investigation, the adhesive-to-concrete substrate binding strength was measured using a computerized pull-off strength tester (E142) in line with standard testing procedures. In place of epoxy, this study presents the findings and analysis of a pull-off test that used geopolymer mortar (GPM). Experimental and measurable data included failure mechanisms, bond strength, energy-dispersive X-ray spectroscopy, and scanning electron microscopy (SEM). The results revealed that in all tested specimens; failure occurred within the concrete substrate rather than at the adhesive interface. This indicates that both geopolymer mortar and epoxy resin successfully function as adhesive materials, ensuring strong bonding with concrete surfaces. Given its comparable performance, along with its eco-friendly and cost-effective nature, geopolymer mortar presents itself as a promising alternative to epoxy in rehabilitation and repair applications, contributing to the sustainability and longevity of concrete structures.

Keywords: Concrete substrate; Geopolymer mortar; External strengthening; Interfacial transition zone; Pull-Off Tests; Repairing.

List Abbreviations

Abbreviation	Definition
ITZ	Interfacial Transition Zone
GPM	Geopolymer Mortar
SEM	Scanning Electron Microscopy
EDX	Energy-Dispersive X-Ray
NDT	Nondestructive Test
PDT	Partial Destructive Testing
FRP	Fiber-Reinforced Polymer
CFRP	Carbon Fiber-Reinforced Polymer
SFRP	Steel Fiber-Reinforced Polymer
MK	Metakaolin
FA	Fly Ash

1. Introduction

One of the key characteristics used to evaluate concrete constructions is their compressive strength. Numerous studies have been conducted on the assessment of concrete strength using nondestructive test (NDT) methods, including the ultrasonic pulse velocity method, nail penetration testing methods, and rebound hammer. The nondestructive and inexpensive NDT techniques measure a test parameter (surface hardness, penetration resistance, elastic modulus, and sound velocity) [1-3]. It is not always the case that the coefficient of variation decreases with increasing data volume, as shown by the compression strength dispersion as measured by NDT methods using correlation curves [4]. Partial destructive testing (PDT), which examines the strength of concrete by drilling cores, may provide more precise results than non-destructive testing (NDT). Core drilling often destroys concrete samples, which may lead to an inaccurate assessment of the material's strength. Additionally, inhomogeneous concrete has the potential to generate eccentric load when compressed [5, 6]. When operated by trained professionals, commonly used NDT techniques—in contrast to the state-of-the-art PDT testing methods—should reliably estimate the in-place concrete strength utilizing portable equipment. The pull-off test method is one of several techniques for this purpose that have been documented in the literature [7-9]. A practical method to determine the strength of the connection, the pull-off test may be readily repeated in the field. To name a few potential applications, the pull-off test has been used to measure the tensile strength of concrete, the adhesive strength of coatings put on different substrates, and the binding strength of strengthening treatments on concrete surfaces. Applying the pull-off test to concrete may provide an idea of its near-surface tensile strength, which can be used to predict its compressive strength. Not only that but BS 1881-Part4 and ASTM C1583/C1583M are already standards [10-13]. A pull-off test's measurement of the tensile bond strength is commonly taken for granted when assessing the efficacy and performance of strengthening systems in the context of FRP composites, including CFRP-bonded concrete substrates [11, 14]. Independently, Bonaldo et.al. [15] studied SFRC's bonding strength pull-off performance. We studied the pull-off performance of the adhesives to estimate the bonding strength between the newly cast and old concrete, because the composite system is mortar-based and applied to a concrete substrate. Benzarti et al. [16] investigated how the adhesive connection between CFRP covers and concrete specimens behaved when subjected to accelerated hydrothermal ageing at 40°C and 95% relative humidity.

The concrete substrates (core samples) were tested for compressive strength in addition to shear and pull-off tests on the CFRP. Zhou et al. [17] investigated the binding behavior of FRP-to-concrete contacts in response to sulfate attacks. In both controlled laboratory and outdoor environments, Mata et al. [18] examined the FRP-concrete connection using the pull-off test approach. Research has been concentrating more on creating more efficient materials with improved cohesion and thermal resistance in order to overcome the problems with binding materials, such as poor cohesion brought on by material irregularities and the incapacity to tolerate high temperatures [19, 20]. One Among these is geopolymer. The potential of geopolymer to replace cement has drawn a lot of interest due to its equal or superior qualities to cement and its environmental friendliness [21, 22]. By combining alkaline solutions (such NaOH or KOH), geopolymer is created [23, 24]. Aluminosilicate source materials with a lower calcination temperature are often used, and these materials include metakaolin (MK), fly ash (FA), slag, and rice husk ash. This implies that less energy is used, and less carbon dioxide is released when geopolymer is made. One possible substitute for cement is geopolymer, which has several desirable qualities such as low shrinkage, rapid concretion, high early compressive strength, and increased fire resistance [25-27].

Due to the weakness of the interfacial transition zone (ITZ), this study aims to evaluate the bond strength and direct tensile strength of geopolymer paste on concrete surfaces using the pull-off test. Also, improve the ITZ between the concrete substrate and textile sheets or concrete layers to resist the shear failure expected in ITZ. The use of epoxy, as an organic polymer, introduces a heterogeneous nature compared to concrete, potentially leading to mismatches in thermal expansion and mechanical compatibility, which may induce stress concentrations at the ITZ. In contrast, geopolymer mortar exhibits chemical similarity to concrete, promoting a stronger and more compatible bond at the interface. Failure modes, bond strength, energy-dispersive X-ray (EDX) spectroscopy, and scanning electron microscopy (SEM) were experimented, measured, and analyzed.

2. Experimental setup Experimental procedure

2.1. Materials

2.1.1. Fly ash

The main source of aluminosilicate used in the geopolymer reaction was Class F's low calcium fly ash (FA), which conforms to ASTM C618 [28]. The average particle size of the FA used in this investigation was 28 microns. The ultimate qualities of the geopolymer mortar are heavily influenced by characteristics, which are listed in Table 1. FA contributes to the binding characteristics of GPM, enhancing its mechanical performance and durability.

2.1.2. Alkaline Solution (AS)

The alkaline solution (AS) serves as the activator for the geopolymerization process and consists of two primary components: sodium hydroxide solution (SHS) and sodium silicate solution (SSS). Sodium hydroxide pellets (99% purity, molecular weight 40) were obtained from El Nasr for Intermediate Chemicals and dissolved in tap water to prepare the SHS with a molarity concentration of 12 M. This solution was left 24 hours before use to stabilize the ambient temperature. The SSS was sourced from Egypt Global Silicates and had the following chemical composition: 60% water content, 9% Na_2O, and 31% SiO_3, with a molecular weight of 184–254 and a weight ratio of 1:2. The SHS and SSS were mixed at a mass ratio of 2.5 to produce the alkaline activator, which enhances the geopolymerization reaction and improves the material's adhesion and durability.

Table 1. Cementitious materials characteristics

Properties	Cement	Fly ash
Physical properties		
Specific gravity	3.15	2.50
Specific surface area (cm^2/gm)	3250	3950
Color	Gray	Light gray
Chemical compositions (%)		
SiO_2	20.30	61.06
Al_2O_3	6.46	28.55
Fe_2O_3	3.66	3.15

CaO	62.15	1.41
MgO	3.32	1.32
SO_3	2.51	1.06
K_2O	0.75	-
Na_2O	0.85	-

2.1.3. Geopolymer mortar (GPM)

Mostly made of fly ash and sand in a 1:3 ratio, and an alkaline solution, geopolymer mortar (GPM) is a high-performance, environmentally friendly adhesive and binder substance. Fly ash is activated using an alkaline solution made of sodium hydroxide (SHS) and sodium silicate (SSS) to prepare GPM, the liquid-to-binder ratio was chosen as 0.7 to achieve high fluidity. After adding fly ash and sand to the mixing machine, the pre-made alkaline activator is gradually added to start the mixing process. For around three minutes, the mixture is mixed until it reaches a uniform consistency. To guarantee the best mechanical qualities, the resultant paste is thereafter allowed to dry at room temperature (23 °C) and 50% relative humidity. All samples were cured at an ambient temperature of 23 °C and 50% relative humidity until the testing time. The 28-day average compressive strength was determined using six 50×50×50 mm cube samples. Table 2 shows the properties of adhesive materials corresponding to ASTM D7205-06 [29].

2.1.4. Epoxy polymer (EP) resin

The two-part product, Kemapoxy 165 adhesive mortar, is based on modified epoxy resin and has a suitable hardening mechanism. It was sourced from Chemicals Modern Building (CMB). This product conforms with ASTM C 881 [30] and has technical details that are detailed in Table 2 of the manufacturer's specifications.

2.2. Concrete substrate

In compliance with the necessities of EN 1504-4 [31], the standard for items and methods used in the maintenance and repair of concrete structures, the pull-off concrete for pull-off testing is MC (0,45), as stated in the reference concretes for testing section of EN 1766 [32]. There are 395/410 kg/m^3 of cement in Type MC (0.45) concrete, with a water-cement ratio of 0.45. To meet the standards of EN 197-1, the standard Ordinary Portland Cement (OPC) CEM I 42.5N was used, and its specifications are shown in Table 1 [33]. The specific gravity of crushed stone was 2.67 and that of sand was 2.63; these two types of aggregates, coarse and fine, were obtained from natural sources and included in the concrete mixture. The particle size distribution was determined according to EN 933-2 [34]. Median bonding strength of more than 2.5 N/mm^2 was shown by pull-off tests carried out in compliance with EN 1542 [35].

Table 2. Properties of EP resin and GPM matrix

Properties	Epoxy	Geopolymer
Color	Grey	Dark grey
Solid content	100%	100%
Density (g/cm^3)	1.95 ± 0.02	1.84
Mixing ratio (by weight)	12: 1	-
Compressive strength (N/mm^2)	80	35.6
Tensile stress (N/mm^2)	-	8.16
Flexural stress (N/mm^2)	> 40	-

Punching sheet strength (N/mm^2)	25	-
Adhesive strength (N/mm^2)	10.3	1.96

2.3. Preparation of test specimens

The foundation of the structure was made of 300 mm × 300 mm slabs of unreinforced concrete, each 100 mm thick. The slabs and specimens were covered with wet hessian bags for two days. After this curing period, the slab specimen was de-molded and kept in a typical lab environment. The casting surface, which is the top surface of the slab specimen, needed to be treated after 28 days of ageing on the concrete substrate. To create an uneven surface, a very thin layer of a concrete substrate must be removed before the top surface may be roughed. Additionally, garbage, oil, and grease are removed by this procedure as shown in the figure (Fig. 2a). It was possible to cast the new concrete overlay once the bond compound was applied, and the freshly mixed geopolymer mortar overlay was firmly fastened to the hardened concrete (Fig. 2b) in accordance with the procedures specified in Egyptian Code No. 203 [36]. Pull-off tests were carried out after the geopolymer mortar overlay had cured for about 28 days. The reason is that evaluations of pull-off strength are the purview of instrumental characteristics.

2.4. Pull-off bond test

Bond strength tests are often conducted on concrete, mortars, grouts, and repair and protection systems in accordance with the "BS EN 1542:1999 Products and systems for the protection and repair of concrete structures - Test methods- Measurement of bond strength by pull-off" benchmark. Pull-off bond tests were performed in this work using an E142 Digital pull-off strength tester Fig. 1 in compliance with BS EN 1542:1999 test method E, the specimens must have an adhesion test aluminum disc (Fig. 2) glued to their surface for the load to be gradually increased until failure. A partial core measuring 6 to 12 mm around the test zone is recommended. A core drill forms a circular core by attaching an aluminum disk to the specimen's surface. The use of a drill press allowed for the creation of 50 mm diameter cores. The core had a depth of 10 mm (Fig. 2c). Before applying the epoxy, the surface was cleaned, smoothed, and prepared using acetone and sandpaper. After the surface was prepared, Sikadur-30 epoxy glue was used to adhere the dolly to the core surface (Fig. 2d), and it was let to dry at room temperature for at least one day. According to EN 1542, As shown in the figure (Fig. 2e) the pull-off testing dolly must continue to operate under a continuous load at a constant speed of 0.05 ±0.01 MPa/s until it breaks.

Figure 1. E142 Digital pull-off strength tester

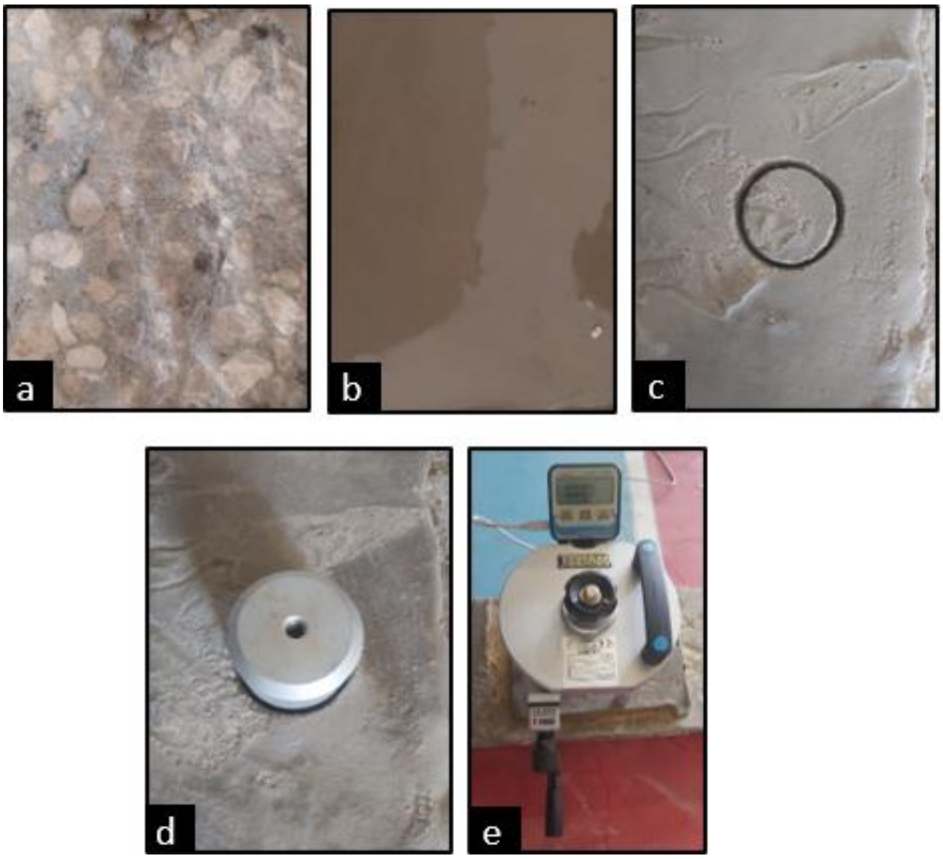


Figure 2. Experimental sequences of pull-off test of GPM overlay

3. Results & Discussion

3.1. Failure modes

A pull-off test was conducted on each sample surface to evaluate adhesive strength and observe failure modes. Each failure mode was carefully monitored, recorded, and classified according to BS EN 1542:1999, as summarized in Table 3. A visual examination for the proportion of each failure mode is required when there is a mixture of provided failure modes; for instance, if A/B= 40%, 10%, and 50%, then the breakdown is A/B= 40/10/10/50. To compare different adhesive materials, a concrete slab coated with Kemapoxy 165 was tested as a control sample, while another slab was coated with geopolymer mortar (GPM). Visual inspection revealed that both Adhesive material epoxy and geopolymer failed due to concrete substrate failure (Mode A), as illustrated in Fig. 3. That the geopolymer paste-to-concrete adhesion strength was greater than the tensile strength of the concrete itself is confirmed by this failure mode (Mode A), which indicates a strong and full binding between the GPM and concrete.

Table 3. Pull-off test failure modes classification according to BS EN 1542:1999

Failure Mode	Failure Type	Failure Description
A	CF*	Concrete substrate
A/B	AF**	ITZ (substrate and first layers)
B	CF*	First layer
B/C	AF**	ITZ (first and second layers)

C	CF*	Second layer
-/Y	AF**	ITZ (last and adhesive layers)
Y	CF*	Adhesive layer
Y/Z	AF**	ITZ (adhesive layer and the dolly (which is Z))

*CF: Cohesion failure; **AF: Adhesion failure

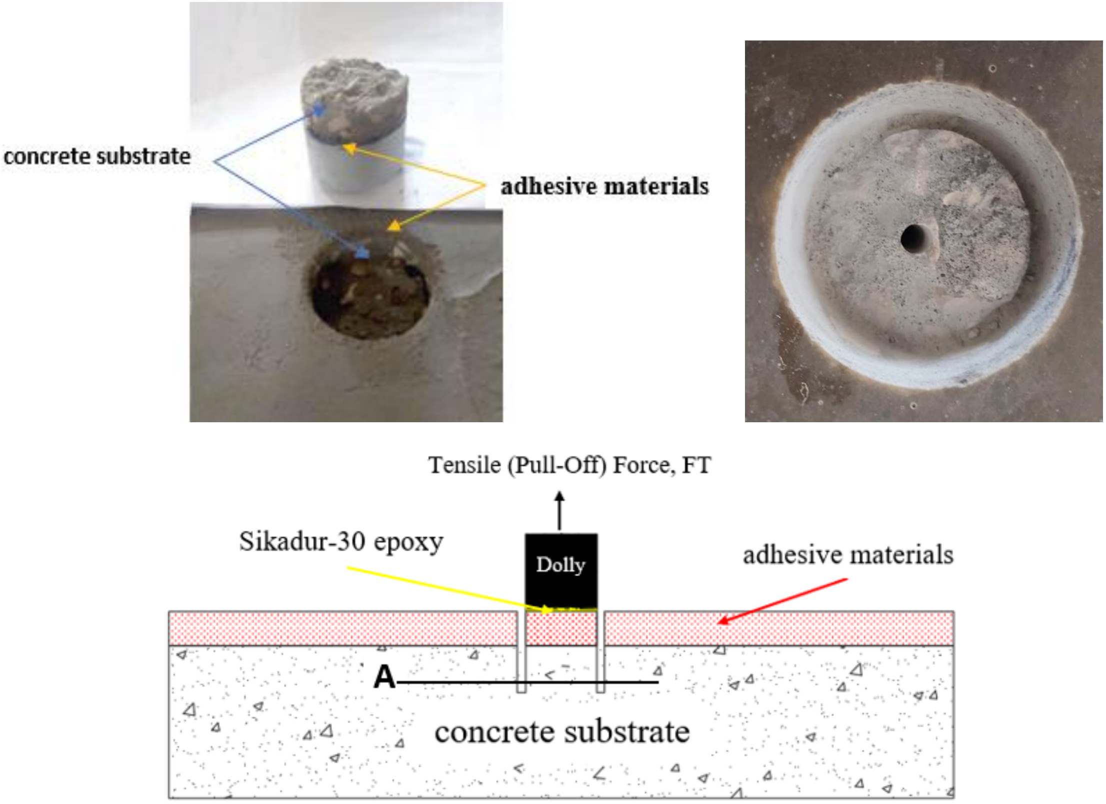


Figure 3. Failure modes of the pull-off test for of the specimens.

3.2. Pull-off bond strength

The findings of this study highlight the significant role that material type, application method, and curing conditions play in determining bond strength. Understanding these factors is crucial for improving construction and repair techniques. To assess the tensile bond strength, calculations were conducted following the BS EN 1542:1999 standard (Eq. 1). The results revealed that all bonded surfaces ultimately failed due to concrete substrate failure, demonstrating a strong adhesion between the Adhesive material and the concrete. According to Fig. 4 and Table 4, geopolymer mortar exhibited an adhesion strength of 1.96 MPa, while epoxy recorded a slightly higher value of 2.10 MPa. These results suggest that geopolymer mortar holds great potential as an eco-friendly and cost-effective alternative to epoxy in repair and rehabilitation applications for enhancing the durability and sustainability of concrete structures.

$$fh = 4F_h / \pi D^2 \qquad \text{(Eq. 1)}$$

Where:

(fh): bond strength (N/mm²)

(F_h): failure load (N)

(D): specimen diameter (mm)

Table 4. Typical mechanism of failure of the specimens

Adhesive materials	Failure mode	Average load (N)	Failure strength (N/mm²)
Epoxy (Kemapoxy 165)	A	4120	2.10
Geopolymer	A	3840	1.96

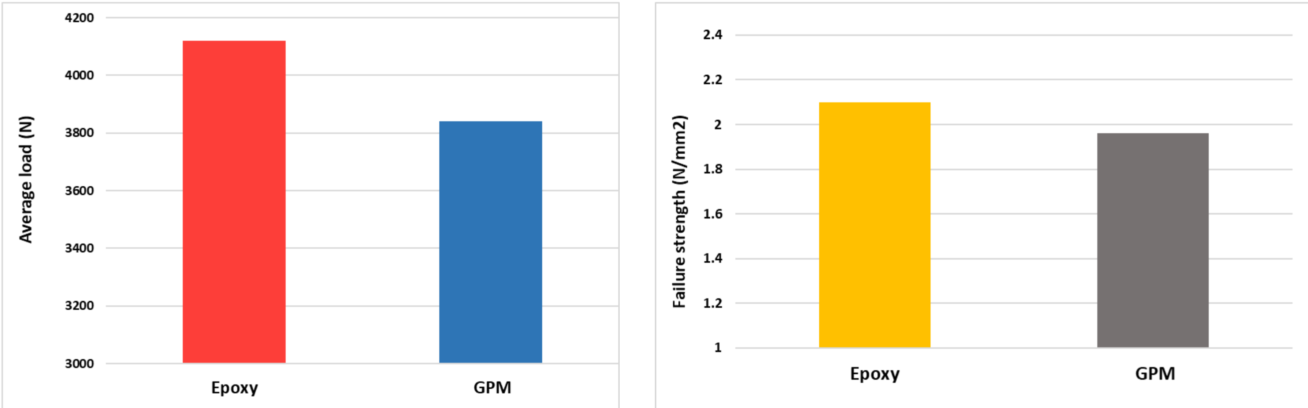


Figure 4. Average pull-off strength and Failure strength.

3.3. SEM and EDX Analysis

Microstructural analysis was conducted using SEM, and EDX was performed to quantify the elemental composition, focusing on Si, Al, Ca, Na, and Fe distributions, which are critical for geopolymer network formation. The material had an average particle size of 28 microns. and SEM imaging revealed a densely packed matrix with the formation of gel-like reaction products which promotes superior mechanical interlocking and densification at the interface. The presence of reactive aluminosilicate phases contributes to the formation of additional gel phases, refining the pore structure and improving adhesion strength. Moreover, the gradual development of geopolymer gel enhances the transition zone properties, reducing interfacial microcracking and improving overall bond durability. indicative in Fig. 5. Unreacted fly ash particles were partially encapsulated within the geopolymer network, contributing to heterogeneous phase distribution. A study was conducted on GPP using EDX spectroscopy, as seen in Fig. 6. Geopolymer matrices of 21.02% SiO_2, 3.04% Al_2O_3, 1.58% Fe_2O_3, and 8.3% CaO have excellent stress resistance characteristics, as seen by the EDX spectrum. While Na and K were present in trace levels in the GPP, Si and Al were their primary constituents [37, 38]. The strength growth was caused by the substantial creation of an aluminosilicate gel, as verified by the EDX spectra, which showed a high Si/Al ratio. The presence of calcium indicates the possibility of a partial gel consisting of calcium silicate and hydrate coexisting with the main geopolymer phase.

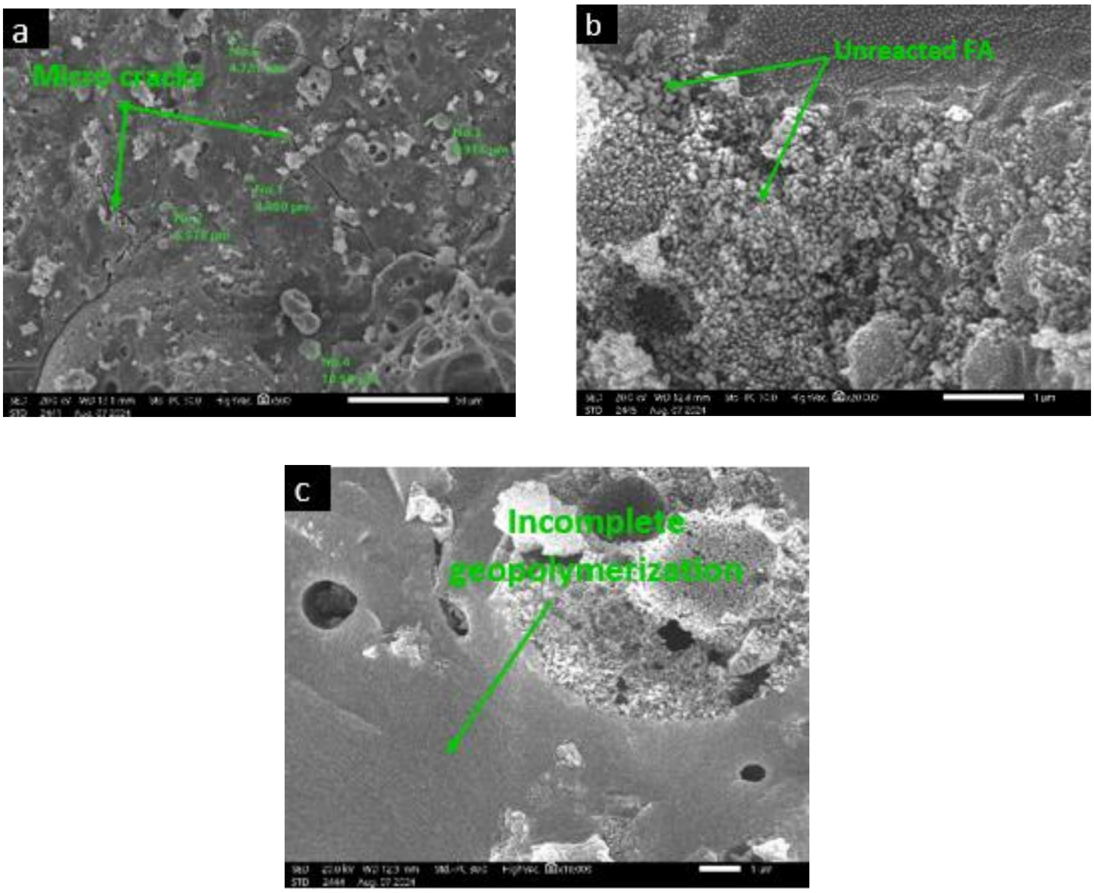
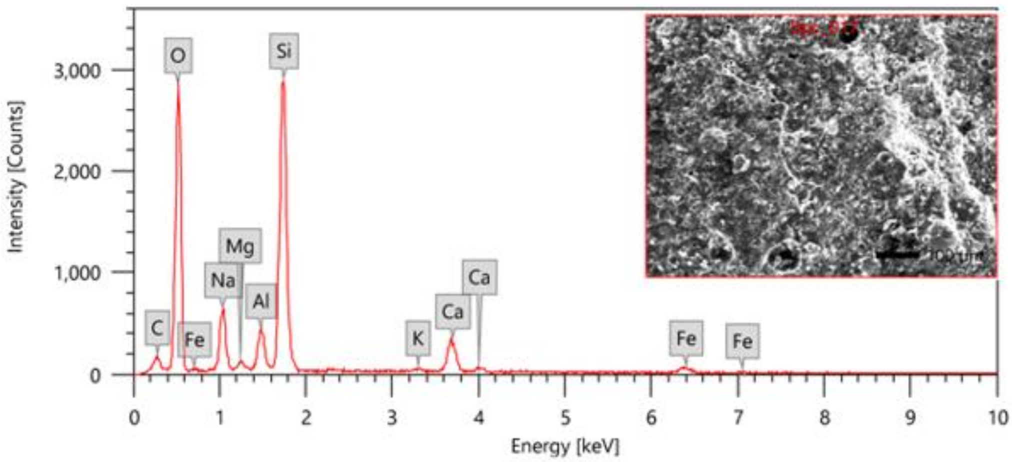


Figure 5. SEM analysis of GPM



Element	Line	Mass%	Atom%
C	K	8.92±0.18	13.73±0.28
O	K	53.16±0.38	61.43±0.44
Na	K	7.37±0.14	5.93±0.12
Mg	K	0.66±0.05	0.51±0.04
Al	K	3.04±0.08	2.09±0.06
Si	K	21.02±0.20	13.84±0.13
K	K	0.23±0.03	0.11±0.02
Ca	K	4.01±0.10	1.85±0.04
Fe	K	1.58±0.08	0.52±0.03
Total		100.00	100.00
Spc_017			Fitting ratio 0.0232

Figure 6. EDX analysis of GPM

3.4. Economic Feasibility

A cost analysis of GPM and epoxy resin was conducted, and the unit cost per kilogram of both materials was calculated, as presented in Table 5 and Fig. 7. The results indicate that the cost of geopolymer mortar is 74.43% lower compared to epoxy.

Table 5. Cost Analysis of Geopolymer Mortar and Epoxy Resin (USD/kg)

Materials	Geopolymer mortar (GPM)	Kemapoxy 165	Variation %
Rate (USD)	0.9	3.52	74.43

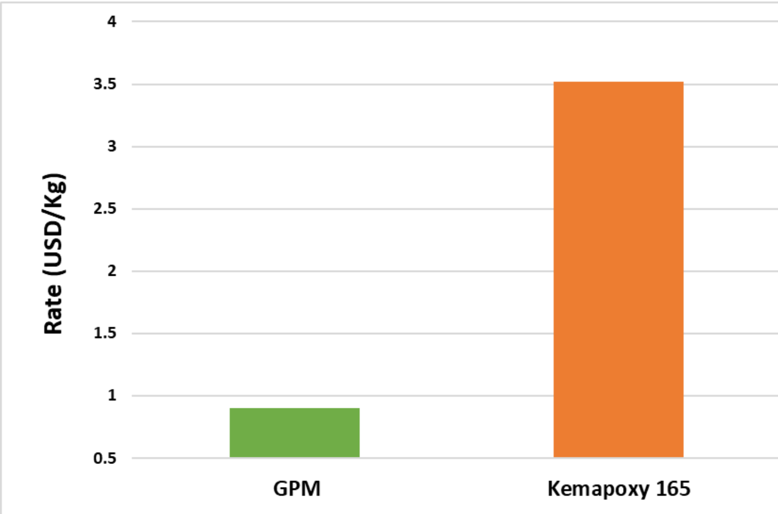


Figure 7: Cost Geopolymer Mortar and Epoxy resin.

4. Conclusions

In this study, the bond strength of geopolymer mortar was investigated as an alternative to epoxy-based adhesives and reinforcement materials, offering an environmentally friendly and cost-effective solution. The pull-off test was conducted using a pull-off device. The experimental results of the study led to the following conclusions:

- The ocular inspection revealed that the epoxy and geopolymer adhesive materials failed due to the concrete base, suggesting a strong link between the two.
- The strength growth was attributed to the substantial creation of aluminosilicate gel, as corroborated by the EDX spectra, which revealed a high Si/Al ratio.
- The observation of calcium in the material points to the coexistence of a partial C-S-H gel with the main geopolymer phase. Impurities compromising long-term durability were indicated by the detection of minor quantities of Fe and Mg.
- In its simplest form, the pull-off test is a dependable, time-honored method of gauging the in-situ strength of concrete and the binding strength of overlays to concrete substrates.

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