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Evaluating the Bond Performance of Conventional and Polymer-Modified Repair Mortars on Variously Prepared Concrete Substrates

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Abstract

The long-term performance of repaired concrete structures depends fundamentally on the quality of their constituent materials and interfaces. This study aims to investigate the bond between existing concrete substrates and new repair materials. A systematic experimental program is conducted to evaluate the integrated bond performance of conventional and polymer-modified mortars applied to concrete substrates with three surface preparation conditions (as-cast, wire brushing, and sandblasting). The interfacial behavior is assessed under slant shear, indirect tensile, and four-point bending tests. The results demonstrate that mechanical surface preparation is the dominant factor governing interfacial bond efficiency, with sandblasting consistently providing the greatest improvement. In contrast, polymer modification has a negligible effect on slant shear capacity but profoundly improves flexural bond strength. Overall, sandblasting is essential for achieving durable structural joints, while polymer modification prevents bond failure under significant flexural or tensile stresses, ensuring structural longevity.

Keywords: bond strength, concrete substrate, surface preparation, polymer-modified mortar

1. Introduction

The long-term performance, structural integrity, and service life of repaired concrete structures are fundamentally dependent on the quality of their constituent materials and the interfaces between them. In the context of infrastructure maintenance and rehabilitation, the bond between an existing concrete substrate and a newly applied repair material is an essential factor that, together with material compatibility and environmental conditions, ensures monolithic behavior. This interface, often referred to as the interfacial transition zone (ITZ), acts as a critical plane for stress transfer and is frequently the weakest link in a repaired composite system [1]. A deficient bond can lead to premature failure modes such as delamination, spalling, and cracking, thereby compromising the structural capacity and durability of the entire element. The failure of this bond is not only a structural concern but also a significant economic issue, as it necessitates repeated, costly interventions. Consequently, understanding and optimizing the factors that govern bond strength are fundamental to effective and sustainable concrete repair technology.

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The development of a robust and durable bond is challenged by a complex interplay of factors. A primary source of interfacial stress arises from the inherent incompatibility of the physical, mechanical, and chemical properties between the aged substrate and the fresh repair material. Differences in elastic modulus and thermal expansion coefficients can lead to significant stress concentrations at the interface, particularly under cyclic thermal loading [2]. Furthermore, volumetric changes induced by drying shrinkage create substantial shear and tensile stresses that the bond must resist during service [3]. The efficacy of the bond is also heavily influenced by the surrounding environmental conditions, which directly affect the curing process and the long-term durability of the interface [4]. Failure to account for these interacting mechanisms can compromise structural integrity, leading to the degradation of the repair.

Among the variables controlled by the practitioner, the preparation of the substrate surface before the application of the repair mortar is widely recognized as a fundamental prerequisite for achieving adequate adhesion. The primary aims of this preparation process are twofold: first, to remove deleterious materials, including laitance, dust, oils, and unsound concrete; and second, to create a specific surface profile. This roughness enhances the bond through mechanical interlocking, where the hardened repair material keys into the irregularities of the substrate, therefore enhancing resistance to applied forces [5].

Recent comprehensive studies have quantitatively highlighted the substantial impact of these surface preparation techniques across various advanced repair materials. For instance, investigations into the interfacial bond behavior between ultra-high-performance concrete (UHPC) and normal concrete substrates have demonstrated that appropriate surface roughening significantly elevates bond capacity and promotes cohesive failure within the substrate [6-7]. Similarly, the critical role of mechanical surface preparation has been further validated in systems utilizing advanced adhesives like graphene oxide (GO)-modified epoxies [8] and sustainable ambient-cured geopolymer mortars [9], where substrate roughness strongly influences the effectiveness of mechanical interlocking and the resulting bond strength. However, aggressive mechanical methods can risk introducing microcracks into the substrate [4], necessitating a critical balance between optimal roughness and the preservation of the near-surface zone's integrity.

Concurrently, the composition of the repair mortar plays a critical role in its ability to bond with the substrate [10]. To bridge the property gap between old and new materials, modern repair mortars are often modified with polymeric admixtures, such as styrene-butadiene rubber (SBR), ethylene vinyl acetate (EVA), or acrylic latexes. These polymers form a continuous film within the cementitious matrix and at the bond interface, which improves adhesion, increases flexibility, and enhances tensile strength by bridging microcracks [11]. Studies have shown that polymer latexes can increase the tensile bond strength of cement-based materials by approximately 30% to 40%, largely due to improved pore structure and chemical adhesion [12]. These findings are further supported by evidence that such polymer emulsions significantly enhance interfacial bonding properties by modifying the microstructure of the cementitious matrix, resulting in a denser and more cohesive material [13].

Recent comprehensive reviews and experimental evaluations validate that applying specific bonding agents alongside these polymer-modified mortars can effectively improve long-term adhesion and structural compatibility between new and old concrete interfaces [14-15]. To establish a quantitative baseline, recent advancements in mechanical surface preparation—particularly sandblasting—have been rigorously evaluated, with studies demonstrating that it can substantially enhance interfacial bond strength by 150% to 300% when compared to untreated, as-cast concrete surfaces [14]. Similarly, the application of chemical bonding agents at the interface has been shown to provide significant independent improvements in bond strength, yielding measured increases ranging from 25.4% to 36.8% [15].

Expanding on this, contemporary research has shown that the performance of these mortars can be optimized by incorporating micro-reinforcements. For example, investigations assessing the interfacial adhesion of modified slag repair overlays have confirmed that combining precise surface texturing with optimized mineral additives can elevate slant shear bond strength by as much as 215% [16]. Furthermore, the strategic incorporation of polymeric emulsions, such as SBR latex, has proven highly effective. Literature indicates that optimal SBR dosages of 10% to 15% have been reported to provide up to a 38% improvement in flexural bond strength and up to a 55% increase in tensile pull-off adhesion [17-18]. These modifications not only maximize the ultimate interfacial bond strength but also enhance energy absorption and mechanical resilience against debonding under applied stresses.

Despite these significant quantitative findings detailing the isolated benefits of surface profiling and specific polymer modifications, a critical gap in knowledge remains regarding their combined bond performance under complex structural loading environments. While recent investigations—such as full-factorial analyses of bond strength and studies on acrylic copolymer additions [18-19]—have begun to explore interactive effects, the majority of existing research is largely focused on confirming individual effects and is mainly limited to single-stress evaluations (predominantly standard slant shear or pull-off tests). These conventional approaches may not adequately capture the complex mechanical behavior and failure mechanisms of repairs under real-world, diverse loading conditions.

Specifically, limited information is available regarding the interaction between mechanical roughening techniques (such as sandblasting) and SBR polymer modification under multi-axial stress states. Evaluating this synergistic bond performance under flexural loading is especially critical, as bending stresses act as the primary drivers of premature interfacial debonding in spanning structural elements such as bridge decks and continuous beams. Consequently, this study aims to explicitly bridge this knowledge gap by comprehensively evaluating the integrated bond performance of conventional and polymer-modified mortars across systematically prepared substrates under a multi-test framework, providing a more comprehensive understanding of joint durability.

Therefore, the main scientific contribution of the present work is to bridge this knowledge gap by providing a multi-axial quantification of bond performance beyond conventional single-stress approaches. Specifically, this study establishes a novel, integrated evaluation framework by systematically isolating and quantifying the interactive mechanisms between high-profile mechanical topographies and polymer modifications under slant shear, indirect tensile, and flexural loading configurations. This multi-test approach delivers useful insights for optimizing structural joint integrity under complex, real-world stress conditions. The primary objectives of this study are:

(1) To experimentally quantify interfacial bond performance under distinct mechanical stress states utilizing a standardized multi-test suite, including slant shear (ASTM C882), indirect tensile (GB/T 50081-2019), and four-point bending (ASTM C78 / BS EN 12390-5) configurations.

(2) To evaluate the synergistic interactions between mechanical surface topographies and chemical polymer modifications, establishing empirical guidelines for achieving monolithic joint behavior in practical repair applications.

2. Materials and Methods

Ordinary Portland cement (OPC) produced by the Al-Etihad Al-Arabi factory in Zliten, Libya, was used as the primary binder. The cement's physical and chemical properties, determined through laboratory characterization, are summarized in Table 1, and the cement conforms to BS EN 197-1.

Table 1 Chemical and physical properties of OPC conforming to BS EN 197-1

Chemical composition (mass %)	
Silicon dioxide (SiO_2)	20.14
Aluminium oxide (Al_2O_3)	5.91
Ferric oxide (Fe_2O_3)	2.99
Calcium oxide (CaO)	62.9
Magnesium oxide (MgO)	1.59
Sodium oxide (Na_2O)	0.19
Potassium oxide (K_2O)	0.97
Sulfur oxide (SO_3)	2.13
Loss on ignition (LOI)	0.3

Table 1 Chemical and physical properties of OPC conforming to BS EN 197-1 (continued)

Physical properties	
Standard consistency (%)	30
Initial setting time (hr: min)	2:35
Final setting time (hr: min)	5:30
Soundness (Le Chatelier, mm)	1.00
Compressive strength at 28 days (MPa)	44*
Specific gravity	3.15

*Determined using 70.6 mm mortar cubes per BS EN 196-1 (1:3 mix, w/c = 0.50)

Both coarse and fine aggregates were tested in the laboratory for their physical and mechanical properties, with the results detailed in Table 2. These properties were evaluated in accordance with standard testing procedures, and sieve analyses confirmed that both aggregates were within the grading limits specified by BS EN 12620. Potable tap water (LS 82/1997) was used for all mixtures. A commercially available acrylic-based emulsion, Sika Latex, was used for the polymer-modified mortar.

Table 2 Physical and mechanical properties of aggregates conforming to BS EN 12620

Property	Coarse aggregate	Fine aggregate
Specific gravity (SSD)	2.72	2.67
Water absorption (%)	0.44	0.30
Fineness modulus	-	2.29
Bulk density (kg/m³)	1530	1629
Fine material content (%)	-	0.43

The concrete substrate was designed according to ACI 211.1 to achieve a target 28-day compressive strength of 30 MPa and a target slump of 80±25 mm. To ensure statistical reliability, three replicate batches were produced for each configuration. The optimized substrate mix proportions were established as follows: 396 kg/m³ of cement, 185 kg/m³ of water (w/c ratio of 0.47), 715 kg/m³ of fine aggregate, and 1091 kg/m³ of coarse aggregate.

Repair mortars were produced in two batches: a plain mortar and a polymer-modified version incorporating Sika Latex, a styrene-butadiene rubber (SBR) emulsion. The SBR forms a continuous film that bridges micro-defects at the ITZ. For the repair layer, a 1:3 cement-to-sand mortar with a w/c ratio of 0.45 was prepared, utilizing 10 kg of cement, 20 kg of sand, and 4.5 kg of water per batch. For the modified group, 0.4 kg of Sika Latex was added as a partial water replacement. The Sika Latex dosage was kept constant to isolate the chemical contribution of the polymer, allowing for a controlled comparison among different surface preparation conditions.

The fabrication of composite specimens followed a systematic two-stage procedure. First, following an initial 28-day curing period for the concrete substrates, the bonding surfaces were prepared using one of three distinct methods to achieve varying degrees of roughness: an untreated as-cast surface to serve as the control (CS), a mechanically abraded surface using a steel wire brush (WB), and a highly roughened surface prepared by sandblasting (SB), as shown in Fig.1. Second, the repair mortars were applied to these prepared surfaces to create the composite system. Prior to application, the substrate surfaces were pre-wetted to achieve a saturated surface dry (SSD) condition to prevent the absorption of mixing water from the fresh repair mortar. The mortar was then cast onto the substrate and compacted using a vibrating table to eliminate entrapped air and ensure dense interfacial consolidation.

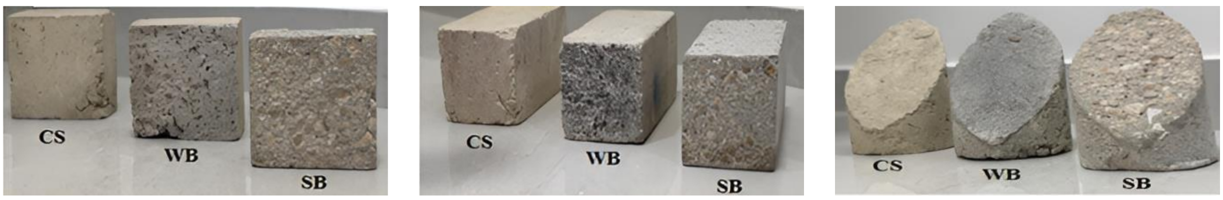


Fig. 1 Visual comparison of different concrete surface preparation techniques

To investigate the interaction between surface texture and material composition, each treatment group was further divided into two subgroups: one repaired with plain mortar (CS, WB, SB) and the other with Sika-modified mortar (CS-Si, WB-Si, SB-Si), resulting in six unique configurations. To ensure statistical reliability, three replicate specimens were prepared for each configuration. Following casting, all composite specimens were demolded after 24 hours and subjected to a final 28-day water curing period, resulting in a substrate age of 56 days at the time of mechanical testing.

The bond strength was evaluated using the slant shear test on composite cylindrical specimens (100 mm diameter, 200 mm height), following the methodology reported in [9]. This size was chosen instead of the 75 × 150 mm ASTM C882 standard to accommodate the substrate's 14 mm maximum aggregate, preventing scale effects. The interface was inclined at 30° to the longitudinal axis (Fig. 2(a)). Uniaxial compression was applied at 0.50 MPa/s until failure. The slant shear bond strength (f_{ss}) was calculated from the maximum load (P_{max}) using the equation below [20]:

$$f_{ss} = \frac{P_{\max}}{A_c} \sin(30°) \times \cos(30°) \tag{1}$$

where A_C is the cross-sectional area of the cylinder.

The flexural performance of the composite beam specimens (100 × 100 × 400 mm) was evaluated using a four-point bending test adapted from BS EN 12390-5 and ASTM C78 (Fig. 2(b)). Loading was continued until failure to determine the flexural strength (Modulus of Rupture, F) according to the equation below. This test assesses the ability of the bond interface to transfer tensile stresses induced by bending. The testing procedure was carried out following the methodology established in [21] for evaluating multilayered cementitious systems.

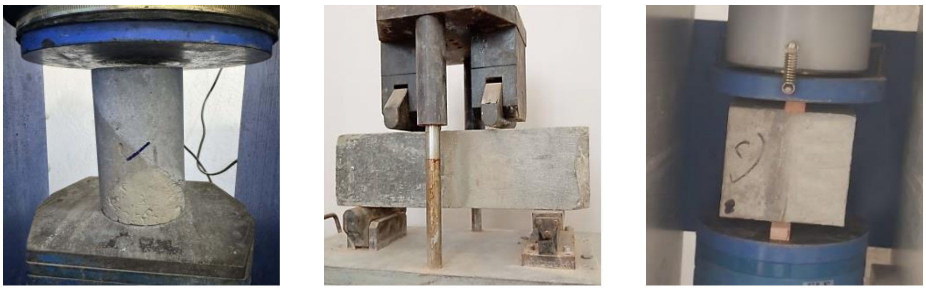
$$F = \frac{PL}{bd^2} \tag{2}$$

where P is the maximum applied load, L is the span length, b is the width of the specimen, and d is the depth of the specimen (as per standard mechanics of materials and ASTM C78).

To evaluate the interfacial tensile bond strength, an indirect tensile (splitting) test was conducted in accordance with the Chinese standard GB/T 50081-2019, utilizing a methodology adapted from Luo et al. [2]. Specifically, 100 mm composite cubes were subjected to a compressive line load along the vertical joint line perpendicular to the bond plane (Fig. 2(c)). This loading configuration induces a relatively uniform transverse tensile stress across the vertical interface, directly pulling the repair mortar away from the substrate and ultimately precipitating a splitting failure at the bond line. The interfacial tensile bond strength (F_t) was calculated by:

$$F_t = \frac{2P}{A_{bond}} \tag{3}$$

where P is the maximum applied load at failure, and A_{bond} is the cross-sectional area of the bonded interface (100 mm × 100 mm).



(a) Slant shear (b) Four-point bending (c) Indirect tensile

Fig. 2 Characterization of composite specimens through various experimental tests

To ensure the reliability and reproducibility of the experimental results, all mechanical tests—including slant shear, four-point bending, and indirect tensile tests—were performed on multiple replicate specimens for each group. The experimental data reported in this study represent the mean values of these replicates. Furthermore, the variability of the test results is illustrated in the corresponding graphs using error bars, which represent the standard deviation of the measurements.

3. Results and Discussion

This section presents and discusses the experimental findings obtained from the comprehensive multi-test suite evaluating the interfacial bond performance between the concrete substrate and the repair mortars. The mechanical behavior of the composite systems is analyzed across three distinct loading configurations: slant shear, splitting tensile, and four-point bending tests. Furthermore, the macroscopic engineering properties are correlated with microstructural observations using scanning electron microscopy (SEM) to examine the densification of the ITZ. Through this systematic approach, the interactive effects of mechanical surface topographies and chemical polymer modifications are quantified to provide insights into the optimization of structural joints.

3.1 Evaluating slant shear bond strength test results

The results of the slant shear bond strength test are shown in Fig. 3. This test configuration simulates the combined compressive and shear stress states frequently encountered in critical structural applications, such as column jacketing, the rehabilitation of load-bearing walls, and the repair of bridge piers. The results demonstrate that surface preparation is a primary factor influencing the bond strength between the old concrete substrate and the new mortar layer. A clear trend of increasing bond strength is observed with increasing surface roughness achieved by the preparation technique (from as-cast to wire brushing to sandblasting).

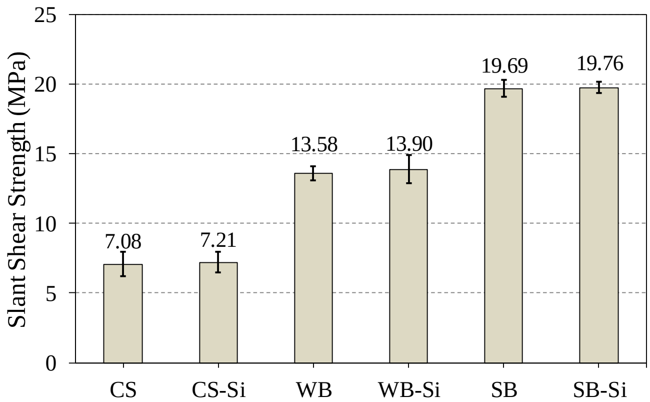


Fig. 3 Comparison of slant shear strength for specimens with various surface treatments and polymeric admixtures

This profound enhancement can be attributed to the physical transformation of the ITZ. Aggressive mechanical profiling effectively eradicates the inherently weak surface laitance layer and exposes the sound, uncarbonated concrete matrix alongside the coarse aggregates. This creates a highly irregular, tortuous topography with pronounced surface asperities. Under the complex combined compressive and shear stress state inherent to the slant shear test, this roughened profile enhances macroscopic mechanical interlocking. Furthermore, the increased effective interfacial area promotes frictional resistance across the interlocking asperities, thereby improving resistance to sliding along the structural bond plane.

The control specimens with an untreated surface (CS) yielded the lowest slant shear strength, recording a value of 7.08 MPa. This value serves as the baseline for comparison. In contrast, specimens with surfaces prepared by wire brushing (WB) exhibited a significantly higher strength of 13.58 MPa, representing a 91.8% increase over the control group. The most substantial improvement was achieved with the sandblasted specimens (SB), which reached a slant shear strength of 19.69 MPa. This corresponds to a 178.1% increase compared to the untreated surface.

The analysis reveals that the addition of Sika Latex (Si) had a marginal to negligible impact on the slant shear strength across all surface conditions. For the untreated control specimens, the addition of Sika Latex (CS-Si) resulted in a strength of 7.21 MPa, a minor increase of only 1.8% compared to the CS specimen (7.08 MPa). A similar trend was observed for the surface-prepared specimens. The wire-brushed specimen with Sika Latex (WB-Si) showed a strength of 13.90 MPa, a slight improvement over the 13.58 MPa of the WB specimen without the admixture. Similarly, the sandblasted specimen with Sika Latex (SB-Si) achieved the highest overall strength of 19.76 MPa, but this was only slightly higher than the 19.69 MPa recorded for the SB specimen. The relative strength increases due to the Sika admixture were approximately 2.4% for the wire-brushed group and only 0.35% for the sandblasted group.

These experimental results indicate that while bonding agents may offer some benefit on smooth or poorly prepared surfaces, their contribution becomes insignificant when proper surface preparation is performed. The dominant factor for achieving high bond strength in this specific test is the mechanical interlock created by surface texturing, which is more influential than the chemical adhesion benefits provided by the polymer additive in this context. Because the slant shear test applies a combined compressive and shear stress, the high normal forces effectively mobilize the interfacial friction of the roughened substrate. This stress state reduces the relative contribution of the micro-crack bridging and adhesive tensile enhancements typically provided by the SBR polymer, explaining its negligible impact here. This aligns with findings from Harris et al. [22], who also noted that surface preparation has a paramount effect on bond and adhesion, particularly when using high-performance repair materials.

The ACI 546.3R-14 (Guide to Materials Selection for Concrete Repair) [23] provides guidelines for the minimum acceptable bond strength for repair systems. According to this ACI guide, summarized in Table 3, the acceptable range for slant shear strength after 28 days of curing is 12.41 MPa to 20.68 MPa.

Table 3 Minimum acceptable slant shear strength (ACI 546.3R [23])

Days	Slant shear strength (MPa)
1	2.76 – 6.9
7	6.9 – 12.41
28	12.41 – 20.68

Comparing the experimental results to the ACI 546.3R-14 standard, it is evident that the control specimens (CS and CS-Si), with strengths of 7.08 MPa and 7.21 MPa, fall significantly below the minimum 28-day requirement of 12.41 MPa. Conversely, all mechanically prepared specimens (ranging from 13.58 MPa to 19.76 MPa) comfortably exceed this minimum threshold, suggesting that mechanical roughening is sufficient to guarantee a robust bond without the necessity of chemical admixtures.

To evaluate the effectiveness of the bond, the failure patterns resulting from the slant shear test are typically classified into four main categories [24]. These modes provide qualitative insight into the location of the weakest plane within the composite specimen. These include Type A: interfacial failure (a complete debonding at the transition zone); Type B: interfacial failure and substrate cracking or minor substrate damage; Type C: interfacial failure and substrate fracture; and Type D: complete substrate failure with a good interface.

The visual analysis of the failure modes for the tested specimens, as illustrated in Fig. 4, provides additional support for the quantitative strength data by pinpointing the location of the weakest plane across the composite system. The control specimens (CS and CS-Si) exhibited a Type A failure, characterized by a clean and complete debonding directly at the interface. This is consistent with their low shear strength values (7.08 and 7.21 MPa) and confirms that the bond itself was the weakest link. In contrast, the wire-brushed specimens (WB and WB-Si) displayed a Type B failure, where the failure involved the interface but also caused minor cracking and damage to the substrate surface, indicating a notable enhancement in bond quality.

(a) CS (Type A) (b) CS-Si (Type A) (c) WB (Type B)

(d) WB-Si (Type B) (d) SB (Type D) (e) SB-Si (Type D)

Fig. 4 Typical failure modes of slant shear specimens evaluating joint interface vs. substrate failure planes

The sandblasted specimens (SB and SB-Si), which yielded the highest bond strengths, demonstrated the most favorable failure pattern, Type D. This mode was defined by a complete failure within the substrate material itself, leaving the bond interface intact and demonstrating that the bond was stronger than the substrate. This transition from purely interfacial debonding (Type A) to complete parent-material fracture (Type D) is highly relevant to bond characterization; it qualitatively confirms that effective surface profiling shifts the critical failure plane away from the interface, indicating that the joint line is no longer the weakest plane in the composite system.

3.2 Evaluating splitting tensile bond strength test results

The splitting tensile test directly quantifies the true interfacial tensile bond strength (F_t) of the composite joint line. This direct quantification is achieved by testing 100 mm composite cubic specimens with their old-to-new concrete interface positioned vertically along the loading plane. When the compressive line load is applied, it induces a uniform transverse tensile stress acting directly perpendicular to this vertical interface, pulling the repair layer cleanly apart from the substrate. Consequently, the recorded failure load (P) represents the absolute tensile capacity sustained by the ITZ, which is mathematically calculated across the cross-sectional area of the bonded interface (A_{bond}) using Eq. (3).

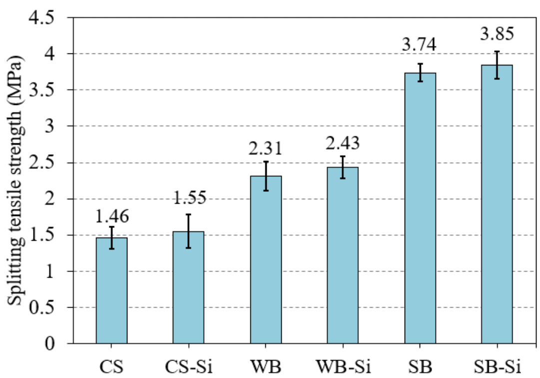


Fig. 5 Comparison of splitting tensile strength for specimens with various surface treatments and polymeric admixtures

The results presented in Fig. 5 demonstrate a clear relationship between the surface preparation technique, the resulting bond strength, and the observed failure mechanism. Specifically, higher bond strengths were associated with a shift from clean interfacial debonding to cohesive fracture within the substrate.

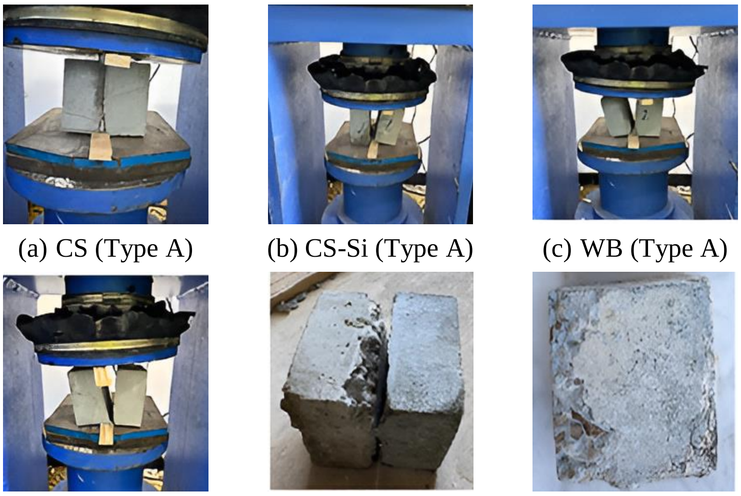
A comprehensive analysis reveals that all mechanical surface preparation methods yielded a measured enhancement in bond strength compared to the untreated control sample (CS), which established a baseline tensile strength of 1.46 MPa. The application of Sika Latex as a bonding agent on an untreated surface (CS-Si) resulted in only a marginal increase in strength to 1.55 MPa, representing a 5.8% improvement. This suggests that the chemical adhesion provided by the polymer modification alone is insufficient to substantially enhance the bond without adequate surface profiling.

In contrast, mechanical treatments were more effective. The wire-brushed samples (WB) achieved a tensile strength of 2.31 MPa, a notable 58.4% increase over the control. The synergistic effect of combining wire brushing with Sika Latex (WB-Si) resulted in a minor increase in the strength to 2.43 MPa, corresponding to a 66.25% enhancement, which indicates that while the primary contribution comes from mechanical roughening, this slight variation between WB and WB-Si likely falls within the inherent statistical scatter of the concrete testing, suggesting no clear structural benefit from the polymer bonding agent under these conditions.

The most significant improvements were observed with sandblasting. The sandblasted samples (SB) exhibited a tensile strength of 3.84 MPa, an increase of 162.3% relative to the control. The addition of Sika Latex to the sandblasted surface (SB-Si) yielded the highest strength of all series at 3.85 MPa, a 162.8% increase. Consistent with the slant shear results, this indicates that the addition of the polymer modifier has a marginal to negligible impact when combined with mechanical surface preparation. The minor numerical difference between the SB and SB-Si specimens likely represents normal statistical scatter rather than a definitive structural advantage. This demonstrates that sandblasting creates a superior substrate topography for bonding, and its transformative mechanical effect largely outweighs any potential contribution from the polymer bonding agent.

According to the bond quality classification proposed by Sprinkel and Ozyildirim [25], the quantitative results can be categorized into qualitative scales for practical assessment. The control sample (CS), with a measured strength of 1.46 MPa, falls within the qualitative “Good” range (1.4–1.7 MPa). However, both the wire-brushed (WB) and sandblasted (SB) samples, with strengths of 2.31 MPa and 3.85 MPa, respectively, exceed the 2.1 MPa threshold and can be classified as “Excellent.” This qualitative classification underscores the efficacy of these mechanical treatments in improving bond quality and durability.

The analysis of the failure modes provides crucial insight into the mechanics of the bond (Fig. 6). The control (CS) and wire-brushed (WB) specimens predominantly exhibited Type A failure, characterized by a clean split along the bond interface. This mode indicates that the bond strength, while improved in the WB case, remains the weakest link in the composite system. Conversely, the sandblasted specimens (SB and SB-Si) consistently demonstrated Type B failure. In this mode, the fracture initiates at the interface but propagates into the substrate concrete, causing partial cohesive failure of the original material. This is a highly desirable outcome, as it signifies that the interfacial bond strength is greater than or at least equal to the tensile strength of the substrate itself; the bond is no longer the weakest plane in the composite system. This clear distinction in failure modes directly corroborates the quantitative strength data, confirming the superiority of the bond achieved through sandblasting.



(a) CS (Type A) (b) CS-Si (Type A) (c) WB (Type A)

(d) WB-Si (Type A) (e) SB (Type B) (f) SB-Si (Type B)

Fig. 6 Failure patterns under indirect tensile test: (A) interfacial debonding and (B) cohesive failure in the substrate

Furthermore, regarding the testing methodology illustrated in Fig. 6, utilizing the indirect tensile test for a textured interface inherently captures a friction-dependent component. While the test exerts tension, the complex, non-planar separation forces the interlocking aggregates to engage and resist sliding. Consequently, the measured values represent the combined effect of tensile adhesion and frictional resistance associated with surface roughness, rather than a pure tensile stress.

The exceptional performance of the sandblasted surfaces can be attributed to two primary mechanisms. Firstly, sandblasting creates a high-amplitude surface profile by eroding the weaker cement paste matrix and exposing the coarse aggregate. This enhances mechanical interlock, as the repair mortar physically keys into the rough, undulating topography.

Although the splitting tensile test primarily evaluates the interface’s resistance to direct perpendicular separation (Mode I tensile fracture), the purely frictional component of the bond is inherently complex to isolate. However, because of the highly irregular topography created by sandblasting, the interfacial separation is not perfectly planar. Consequently, localized frictional resistance may develop along the interlocking micro-asperities during the initial stages of loading. This localized friction restricts micro-slip and works synergistically with the mechanical interlock to significantly enhance the overall tensile load transfer capability across the expanded effective surface area. Secondly, this process improves chemical adhesion by exposing fresh, uncarbonated aggregate and cement paste surfaces. This allows for more effective diffusion and growth of hydration products from the repair mortar into the substrate, forming a stronger, more integrated chemical bond [26].

These findings are in strong agreement with existing literature. Harris et al. [22] reported that surface treatments like sandblasting and wire brushing significantly enhanced the bond between conventional and ultra-high-performance concrete, with treated samples achieving tensile strengths of 4.1 MPa, which aligns with the performance observed in this study. Furthermore, the results are also consistent with the conclusions of Tayeh et al. [27], who investigated the interface between normal concrete and an ultra-high-performance fiber reinforced concrete (UHPFC) overlay.

Their study confirmed that sandblasting produced the highest bond strength and that the failure modes observed were similar to those in the present investigation, reinforcing the conclusion that robust mechanical surface preparation is a fundamental prerequisite for achieving a durable and reliable concrete repair. Furthermore, by validating these findings across multiple testing methodologies (slant shear, splitting tensile, and flexural), the current study helps address the critical gap identified in the literature review. It provides a broader understanding of how mechanical preparation synergizes with polymer modification under diverse stress states, moving beyond the single-loading evaluations commonly reported in previous studies.

3.3 Evaluating flexural bond strength test results

While flexural testing for concrete bond assessment remains a developing approach requiring further validation, it offers a distinct operational advantage due to its simplicity [28]. The four-point bending test was used to evaluate the interfacial flexural bond strength (F) across the composite transition zone. Under this loading configuration, the induced mid-span bending generated maximum tensile stresses perpendicular to the vertical joint interface. Crucially, the experimental failure was consistently localized as a clean, brittle fracture precisely at the old-to-new concrete joint line, without inducing premature slippage or damaging the parent materials. This distinct failure pattern suggests that the interface served as the weakest plane under flexure, meaning the ultimate recorded load (P) directly represents the flexural bond capacity of the composite system.

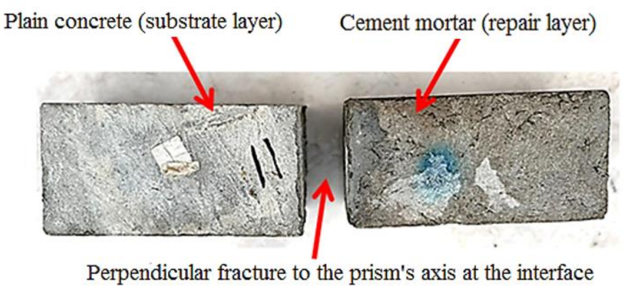


Fig. 7 A typical failure mode for specimens subjected to a bending test

As illustrated by the visual evidence in Fig. 7, this highly consistent failure pattern manifested as a clean crack occurring perpendicularly to the longitudinal axis of the prism, resulting in the separation of the composite beam into two separate prism segments. The nature of the fracture suggests that the bond itself failed in tension before either the substrate or the repair material could reach its own ultimate flexural capacity.

These observations closely align with the findings of Oktavia et al. [29], who reported that surface texturing techniques led to similar perpendicular separation at the concrete layer interface, confirming that failure under flexural loading is strongly localized to this critical zone. However, it is important to note that this failure mechanism is inherently dependent on the relative strengths of the constituent materials; under different conditions—such as a significantly higher bond strength or a weaker substrate—the failure plane might shift away from the interface.

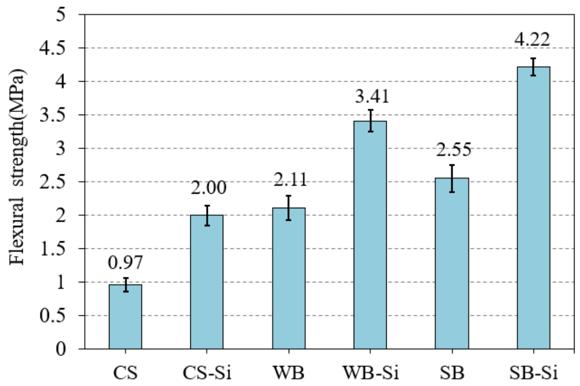


Fig. 8 Comparison of flexural strength for specimens with various surface treatments and polymeric admixtures

The quantitative results of the flexural bond strength, visualized in Fig. 8, illustrate the effect of different surface preparation methods. The control specimen (CS), which received no surface treatment and contained no admixture, serves as the baseline, exhibiting a mean flexural strength of 0.966 MPa. Both mechanical surface preparation techniques demonstrated a substantial improvement in flexural bond strength compared to the baseline. Specifically, the wire-brushed specimens (WB) achieved an average flexural strength of 2.11 MPa, representing a significant increase of approximately 118.4% over the control, while the sandblasted specimens (SB) yielded an even higher average strength of 2.55 MPa, corresponding to a remarkable 164.0% improvement.

Concurrently, the inclusion of Sika Latex, an SBR polymer emulsion, had a significant positive impact on the flexural bond strength across all specimen groups. When added to the untreated surface specimens (CS-Si), the flexural strength increased to 2.004 MPa, an increase of 107.5% over the baseline control (CS). The synergistic effect of combining mechanical surface preparation with the polymer admixture was even more pronounced. For the wire-brushed specimens, the addition of Sika Latex (WB-Si) elevated the strength to 3.41 MPa, while the sandblasted specimens with Sika Latex (SB-Si) reached an outstanding average flexural strength of 4.22 MPa.

Comparing this highest-performing group (SB-Si) to the baseline control group (CS), the total increase in flexural strength is a remarkable 336.8%. The results indicate that the SBR polymer modifier provides an essential toughening mechanism that is particularly beneficial under flexural loading, successfully bridging micro-defects at the interfacial transition zone (ITZ) that may not be fully compensated by mechanical interlocking alone.

The observed improvements in flexural strength can be attributed to distinct physical and chemical mechanisms. While the categorical nature of the applied surface treatments in this study precludes the development of continuous empirical mathematical equations, the experimental data reveal a strong, direct proportional relationship between the flexural strength enhancements and the capacity gains observed in both the slant shear and indirect tensile tests.

The effectiveness of surface roughening, particularly sandblasting, stems from the creation of a high-profile, tortuous surface topography. As noted by previous research, a controlled level of surface roughness is beneficial; as roughness increases, so does the effective surface area available for bonding [30]. This increased surface area, combined with the angular micro-topography, promotes a strong mechanical interlock between the substrate and the new repair mortar. The Sika Latex admixture enhances performance through a different, complementary mechanism. As a polymer modifier, it forms a continuous polymer film throughout the cement matrix as it cures, which significantly enhances the adhesive bond (chemical adhesion) and improves the intrinsic material properties of the repair mortar itself, particularly its toughness.

The outstanding results of the SB-Si group are a clear demonstration of synergy. The sandblasting provides a superior mechanical key, while the Sika Latex provides enhanced chemical adhesion and a tougher mortar matrix. This dual-action approach—optimizing both the physical interface and the chemical bond—is what leads to a composite beam with a bond strength that, in this case, was over four times that of the untreated specimen. The fact that sandblasted specimens exhibited flexural strength greater than even the polymer-modified but untreated specimens (SB at 2.55 MPa vs. CS-Si at 2.004 MPa) highlights the importance of establishing a sound mechanical connection at the bond line.

To further elucidate the fundamental mechanisms driving the exceptional mechanical performance of the SB-Si group, a microstructural analysis of the ITZ was conducted using SEM. As depicted in the SEM micrograph (Fig. 9), the boundary between the existing concrete substrate and the polymer-modified repair mortar is characterized by a highly tortuous, deeply interlocking profile. This pronounced macro- and micro-surface roughness is a direct consequence of the sandblasting preparation, which removed the weak surface laitance layer and exposed a sound, highly irregular topography.

Crucially, the micrograph reveals a relatively dense, homogenous, and continuous interfacial bond line. Unlike typical concrete repairs where the ITZ acts as a highly porous and micro-cracked weak plane, the interface here exhibits profound cohesion. The incorporation of the Sika Latex polymer admixture plays a vital role in this microstructural densification; the polymer particles coalesce during hydration to form a continuous flexible film that may penetrate the micro-crevices of the roughened substrate. This film helps reduce capillary pores, bridges micro-defects, and binds the new mortar securely to the old matrix. This synergistic combination of aggressive mechanical interlocking and polymer-driven chemical adhesion physically transforms the ITZ into a highly cohesive transition zone. Overall, the SEM observations are consistent with the macroscopic mechanical findings, providing microstructural evidence that helps explain why the SB-Si composite exhibited the highest bond capacities across all applied stress states—including slant shear, splitting tensile, and flexural tests—and promoted a transition of the failure plane away from the interface.

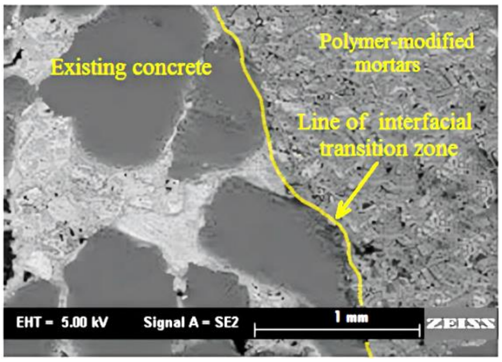


Fig. 9 SEM micrograph illustrating the dense ITZ of the SB-Si composite specimen

4. Conclusions

This study evaluated the interfacial bond performance of conventional and polymer-modified repair mortars applied to concrete substrates with different surface preparation conditions using a multi-test approach. Based on the experimental results, the following conclusions can be drawn:

(1) Sandblasting (SB) emerged as the most dominant factor, significantly increasing slant shear bond strength by 178.1% (to 19.69 MPa) and splitting tensile bond strength by 162.3% (to 3.84 MPa) over untreated surfaces. This finding demonstrates that aggressive mechanical profiling is a key requirement for a successful repair, safely surpassing ACI minimum requirements.

(2) While SBR polymer addition (Sika Latex) showed a negligible impact on both interfacial shear bond capacity (<2.5% increase) and splitting tensile bond strength when combined with aggressive mechanical preparation, it substantially improved the flexural bond performance. Modifying untreated surfaces with SBR increased flexural bond strength by 107.5%, indicating that polymer modification is particularly beneficial for interfaces subjected to bending.

(3) Combining aggressive mechanical profiling with polymer modification (SB-Si) yielded the highest overall interfacial bond capacity. This dual-action approach increased the ultimate flexural bond strength by a 336.8% (to 4.22 MPa) compared to the baseline control, suggesting that the chemical adhesion provided by polymer modification alone is insufficient without adequate surface texturing.

(4) Effective surface profiling altered the composite failure mechanism at the joint interface. Sandblasting successfully redirected the failure plane from premature interfacial debonding (Type A) to cohesive fracture within the parent substrate (Type D in shear, Type B in tension), therefore contributing to a more reliable composite joint.

Overall, the findings highlight that achieving durable concrete repairs requires a balanced combination of mechanical surface topographies and polymer modifications tailored to the specific structural loading conditions. For practical applications, sandblasting is recommended for preparing concrete surfaces in critical structural repairs to maximize mechanical bond strength, while polymer admixtures like Sika Latex are particularly beneficial when the interface is subjected to significant flexural or tensile stresses. Future studies are recommended to investigate the long-term durability of these composite joints under severe environmental exposure, cyclic fatigue loading, and varying polymer dosages to establish more comprehensive guidelines for field applications.

Abbreviations and Symbols

ACI	American Concrete Institute	ASTM	American Society for Testing and Materials
BS	British Standards	CS	Control surface
ITZ	Interfacial transition zone	OPC	Ordinary Portland cement
SBR	Styrene-butadiene rubber	SB	Sandblasted
Si	Sika Latex	UHPFC	Ultra-high-performance fiber-reinforced concrete
w/c	Water-to-cement ratio	WB	Wire brushed
f_t	Splitting tensile strength	f_{ss}	Bond shear strength
F	Modulus of rupture	LOI	Loss on ignition

Conflicts of Interest

The authors declare no conflict of interest.

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