

Assessing the Treated Concrete-Polymer-Modified Repair Mortars Interface via Ultrasonic, Thermal, and Permeability Analysis

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Abstract

This study aims to provide a comprehensive evaluation of concrete repair interfaces, extending beyond traditional mechanical strength tests to assess key durability-related aspects. The influence of substrate surface preparation and polymer modification on bond continuity, thermal compatibility, and permeability is investigated. The methodology involves creating composite specimens with as-cast, wire-brushed, or sandblasted surfaces, and repairing them using both plain and polymer-modified mortars. The resulting interfaces are characterized using ultrasonic pulse velocity (UPV), coefficient of thermal expansion (CTE), and water permeability analysis. The results demonstrate that sandblasting with polymer modification yields superior performance. This approach leads to a 12.99% increase in UPV, achieving an “Excellent” bond classification. It also produces a 27.06% reduction in CTE at 80°C and a 76.1% decrease in the water permeability coefficient. The findings confirm that aggressive surface preparation enhances mechanical interlock, while polymer modification improves adhesion. Consequently, this combined approach is essential for durable, high-performance repairs.

Keywords: polymer-modified mortar, surface roughness, ultrasonic pulse velocity, thermal expansion, permeability

1. Introduction

The global deterioration of concrete structures, driven by environmental, chemical, and mechanical stresses, necessitates the development of effective measures to preserve structural integrity and serviceability [1]. In response, polymer-modified mortars (PMMs) have emerged as a superior alternative to traditional materials, as the incorporation of polymers refines the mortar's microstructure, thereby reducing permeability and enhancing durability [2]. However, the long-term success of any repair hinges critically on the quality of the bond between the existing concrete substrate and the new mortar [3]. This region, known as the interfacial transition zone (ITZ), is a complex microstructural area that, despite being only micrometers thick, frequently acts as the weakest link in the repaired system [4]. The properties of the ITZ are highly sensitive to factors such as substrate roughness and moisture condition, and a deficient interface can therefore create a preferential pathway for the ingress of deleterious substances, accelerating renewed deterioration and defeating the purpose of the repair [4-5].

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The condition of the substrate surface before repair is therefore decisive. Substrate preparation is an essential engineering process designed to remove all deteriorated and contaminated concrete to expose a sound and stable base. Techniques such as abrasive sandblasting or mechanical grinding are employed to clean the surface and to impart a specific roughness profile [6]. This topography is instrumental in promoting mechanical interlocking, as it allows the fresh repair material to key into the substrate's valleys and pores, forming a robust physical connection [7]. In addition, a well-profiled surface increases the contact area, which enhances the physical bond and provides more sites for chemical bonding as hydration products from the repair mortar interact with the prepared substrate [8].

Although extensive research has established a strong correlation between surface preparation and bond strength, the quantification of this relationship has predominantly relied on mechanical tests such as slant shear and splitting tensile tests. This singular focus has created a significant knowledge gap. A high pull-off value indicates good adhesion at a single point in time, but it does not necessarily reflect the overall quality and long-term durability of the interface. There remains a critical lack of understanding regarding how these surface treatments influence other vital interfacial properties, such as their continuity, homogeneity, and, most importantly, their transport characteristics. A mechanically strong interface may still possess a highly porous microstructure that acts as a preferential pathway for water and aggressive ions, such as chlorides. This can accelerate reinforcement corrosion and undermine the long-term durability of the repair, a critical aspect that simple adhesion tests fail to capture [9].

A comprehensive evaluation of the ITZ should therefore integrate assessments of its structural integrity, permeability, and physical compatibility. Non-destructive techniques such as UPV offer a powerful method for assessing the quality and homogeneity of the bond, as the wave velocity is highly sensitive to defects such as voids and microcracks [10]. This enables a holistic assessment of the entire bonded area [6-11]. However, structural continuity alone does not guarantee durability. Measuring transport properties, such as water permeability, provides a direct assessment of the ITZ's resistance to the ingress of aggressive agents, offering critical insights into long-term service life prediction beyond mechanical strength alone [7, 9, 12].

In addition to structural continuity and permeability resistance, thermal compatibility represents another key factor. A mismatch in the CTE between the substrate and repair material induces significant stresses during thermal cycling, which may lead to fatigue and debonding [13]. Therefore, quantifying the CTE is essential for predicting the performance under realistic environmental conditions [14].

This study addresses a critical gap in concrete repair evaluation, where existing research has predominantly focused on mechanical bond strength while overlooking crucial durability-related metrics. The paper provides a holistic characterization of the repair interface by systematically investigating the influence of surface preparation and polymer modification on bond continuity (via UPV), water permeability, and thermal compatibility (CTE). This multi-faceted approach moves beyond simple adhesion tests to offer a more comprehensive and accurate prediction of the long-term performance and durability of repaired structures. The primary objectives of this investigation are:

- (1) To evaluate the effect of different surface preparation methods (as-cast, wire brushing, and sandblasting) on the homogeneity and continuity of the concrete-mortar interface using the non-destructive UPV technique.
- (2) To quantify the influence of these surface preparation techniques on interfacial durability by measuring their water permeability, thereby assessing their resistance to the ingress of deleterious substances.
- (3) To determine the impact of surface preparation on the physical compatibility of the composite system by measuring the CTE and evaluating its response to thermal stresses.

2. Experimental Methods

This section outlines the experimental program designed to evaluate the interface performance between concrete substrates and polymer-modified repair mortars. The methodology encompasses the selection of raw materials, the application of different surface preparation techniques, and the casting of composite specimens. Furthermore, it details the analytical techniques employed to assess bond quality, including UPV for continuity, thermal expansion tests for compatibility, and water penetration tests for permeability. These integrated procedures ensure a rigorous characterization of the repair system's durability and structural integrity under various conditions.

2.1 Constituent materials and their properties

To ensure the direct applicability of the findings to local construction methodologies, this investigation exclusively utilized materials procured from regional suppliers. The properties of each material were characterized in accordance with the relevant British Standards (BS). The primary binding agent for both the concrete substrate and the repair mortar was an ordinary Portland cement (OPC) obtained from the Al-Etihad Al-Arabi factory in Zliten, Libya. A detailed summary of its chemical composition and physical properties, which comply with the requirements of BS 882:1992, is presented in Table 1.

Table 1 Chemical and physical properties of cement

Chemical composition (mass %)	
Silicon dioxide (SiO ₂)	21.02
Aluminium oxide (Al ₂ O ₃)	6.10
Ferric oxide (Fe ₂ O ₃)	3.00
Calcium oxide (CaO)	59.88
Magnesium oxide (MgO)	1.66
Sodium oxide (Na ₂ O)	0.17
Potassium oxide (K ₂ O)	1.02
Sulfur oxide (SO ₃)	1.98
LOI (Loss on Ignition)	0.50
Physical properties	
Standard consistency (%)	32.00
Initial setting time (hr: min)	2:40
Final setting time (hr: min)	5:41
Soundness (Le Chatelier, mm)	1.00
Compressive strength @ 28 days (MPa)	42.00
Specific gravity	3.16

The aggregates consisted of both coarse and fine fractions. The coarse aggregate was a crushed stone with a maximum nominal particle size of 14 mm, while the fine aggregate was a natural sand sourced from the Misrata region. Both aggregates underwent evaluation of their physical and mechanical properties, and sieve analysis confirmed that their particle size distributions were within the acceptable grading limits specified in BS 882:1992. These key characteristics are detailed in Table 2. Potable tap water, meeting the quality specifications of Libyan standard LS 82/1997, was employed for all concrete and mortar mixtures. For the creation of the polymer-modified mortar, the formulation was enhanced with the inclusion of Sika Latex, an acrylic-based emulsion selected for its known ability to improve adhesion and waterproofing performance.

Table 2 Physical and mechanical properties of aggregates

Property	Coarse aggregate	Fine aggregate
Specific gravity (SSD)	2.68	2.66
Water absorption (%)	0.43	0.28
Fineness modulus	-	2.29
Bulk density (kg/m ³)	1,528	1,644
Fine material content (%)	-	0.40

2.2 Mix formulation and specimen fabrication

The experimental methodology commenced with the formulation of two primary mixtures: a concrete substrate representing existing concrete elements, and a cementitious mortar for repair applications. The substrate concrete was engineered using the absolute volume method to achieve a target 28-day compressive strength of 30 MPa. The mix proportion was a 1:2:4 ratio (cement:sand:gravel) with a water-to-cement (w/c) ratio of 0.47, as shown in Table 3. To ensure consistent workability across all batches, the concrete's slump was carefully maintained within the 55-70 mm range. For the repair layer, two distinct mortar formulations were developed. The first was a conventional cement mortar with a 1:3 cement-to-sand ratio and a w/c ratio of 0.45. As detailed in Table 3, the sand used in these formulations is the same natural fine aggregate described in Section 2.1.

Table 3 Mix proportions for concrete substrate and repair mortar

Mixture type	Component	Quantity
Concrete substrate (kg/ m ³)	Cement	396
	Water	185
	Fine aggregate	450
	Coarse aggregate	1,344
Repair mortar (per batch. kg)	Cement	10
	Sand	20
	Water	4.5
	Sika Latex	0.4

The second formulation was a polymer-modified mortar incorporating Sika Latex, an acrylic-based bonding agent, to augment its adhesive and waterproofing properties. In this modified mixture, the Sika Latex emulsion was used as a partial substitute for the mixing water. The specimen fabrication was carried out in several stages. Initially, the concrete substrate blocks were cast and cured for 28 days. After curing, the bonding surfaces were prepared using three different techniques: control surface (CS), wire brushing (WB), and sandblasting (SB). The repair mortar was subsequently applied to the prepared substrates to form composite specimens.

The substrate conditions, casting process, and final specimen configuration are illustrated in Fig. 1. Three surface preparation conditions are considered: CS, WB, and SB. The CS specimens are left in their as-cast condition, while WB and SB treatments are applied to introduce moderate and high levels of surface roughness, respectively. These surface preparation methods are adopted to evaluate the effect of interface roughness on the bonding performance between the substrate concrete and repair mortar.

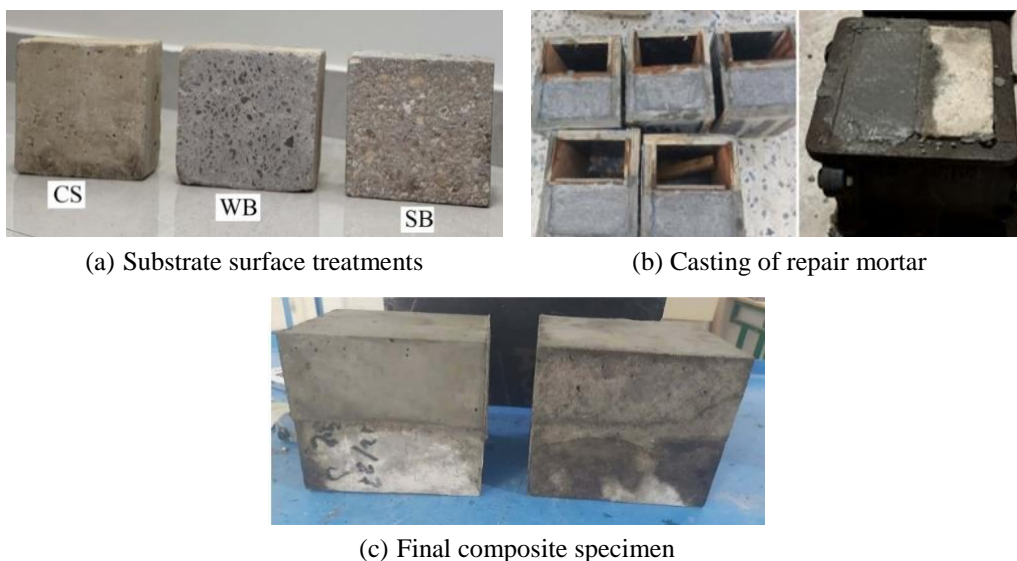


Fig. 1 Specimen preparation stages

Subsequently, the composite specimens were formed by applying the repair mortars onto these prepared substrates. Each of the three surface preparation groups (CS, WB, and SB) was further divided into two sets. The first set was repaired using plain, conventional mortar. The second set was repaired using polymer-modified (Sika Latex) mortar. This approach yielded six unique combinations of specimens, designated as CS, WB, and SB for the plain mortar, and CS-Si, WB-Si, and SB-Si for the Sika-modified mortar. The composite specimens were demolded 24 hours and then subjected to a final 28-day water curing regimen to ensure complete cement hydration and promote the full development of the bond at the interface.

2.3 Testing procedures

UPV testing was conducted in accordance with BS 1881 on 150 mm cubic specimens to assess the quality and homogeneity of the bond interface. The measurements were performed in direct transmission mode using a digital ultrasonic device (James Instruments V-Meter MK IV) equipped with 50 mm in diameter transducers operating at a frequency of 54 kHz. Measurements were taken in a direction parallel to the bond interface between concrete substrates and the cement mortar, in two perpendicular directions. The test measures the transmission time of an UPV through the material. The UPV was calculated using the path length (L), which explicitly refers to the longitudinal direction of the specimen, as indicated in Fig. 2(a), and the transmission time (T).

To ensure a robust comparative analysis, additional UPV measurements were conducted on the individual components of the composite system. Specifically, transit times were recorded with the sensors positioned entirely (100% surface contact) on the concrete substrate and entirely (100% surface contact) on the repair mortar sections. These measurements serve as upper and lower benchmarks, allowing for a precise quantification of how the interfacial zone's quality deviates from the monolithic properties of its constituent materials. This tripartite measurement approach (100% substrate, 100% mortar, and 50/50% interface) provides a comprehensive profile of the acoustic impedance and structural continuity across the repair system.

$$UPV = \frac{L}{T} \quad (1)$$

The coefficient of linear thermal expansion (CTE) was measured according to ASTM E 831 on 150 mm composite cubes. Steel discs were glued to opposite faces of the specimens to serve as reference points (Fig. 2(b)). The specimens were subjected to two controlled heating cycles, reaching temperatures of 50°C and 80°C, with measurements recorded after 1, 3, and 24 hours for each cycle. Prior to thermal testing, all specimens were oven-dried to a constant mass to ensure that the measured expansion was purely thermal and not influenced by varying internal moisture levels or pore water pressure. The change in length (ΔL) was measured using a high-precision digital gauge, and the CTE (α) was calculated as:

$$\alpha = \frac{(\Delta L / L_0)}{(T_2 - T_1)} \quad (2)$$

where ΔL is the change in length, L_0 is the initial length (150 mm), T_1 is the initial room temperature, and T_2 is the final temperature (50°C or 80°C).

The water permeability of the composite specimens was determined following the EN 12390-8 (Fig. 2(c)). The 150 mm cubic specimens were subjected to a water pressure of 5 bar for 72 hours. After testing, the specimens were removed and split open. The depth of water penetration was measured, and the coefficient of permeability (K_w m/s) was calculated to quantify the resistance of the composite system to water ingress.

$$K_w = \frac{d^2 v}{2ht} \quad (3)$$

where d is the depth of water penetration, v is the porosity, h is the applied water pressure head, and t is the duration of the test.

$$v = \frac{M_{sat} - M_{dry}}{\rho_w V_{specimen}} \quad (4)$$

where M_{sat} is the mass of the saturated-surface-dry specimen (kg), M_{dry} is the mass of the oven-dry specimen (kg), ρ_w is the density of water (approx. 1000 kg/m³), and $V_{specimen}$ is the bulk volume of the specimen (m³).

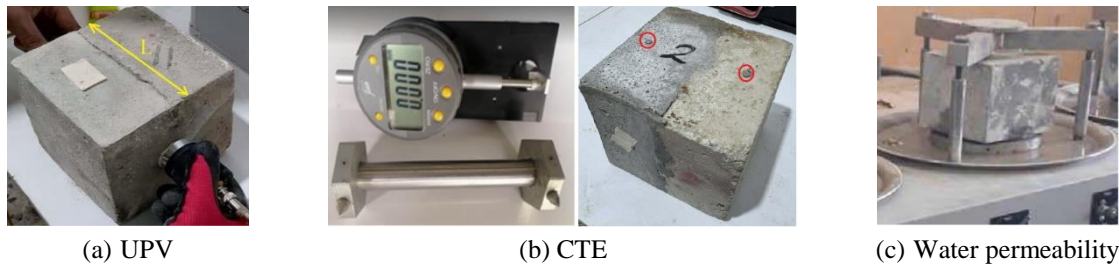


Fig. 2 Characterization of composite specimens through various experimental tests

3. Results and discussion

This section presents the experimental findings obtained from the UPV, CTE, and water permeability tests. The results are discussed in light of the influence of various surface preparation techniques and polymer modification on the interfacial performance. By correlating these parameters, the study evaluates bond continuity and durability at the concrete-mortar transition zone. Detailed comparisons between control and treated specimens are provided to identify the most effective repair strategy for ensuring long-term structural integrity.

3.1 Evaluating ultrasonic pulse velocity test results

This study employed the UPV technique as a non-destructive testing (NDT) method to evaluate the quality of the ITZ between a concrete substrate and a new cementitious repair mortar. The calculated velocity is influenced by material properties such as density, homogeneity, and elasticity. The presence of voids, micro-cracks, or discontinuities within the wave's path will impede its propagation, resulting in a lower velocity [15]. By directing the ultrasonic pulses parallel to the bond interface, the integrity of the connection between the substrate-overlay connection can be effectively assessed. The investigation focuses on the impact of the surface preparation (roughness) and the inclusion of a Sika Latex polymer bonding agent.

The UPV results conducted parallel to the interface are visualized in Fig. 3. A positive correlation between the intensity of surface preparation and the resulting pulse velocity, indicating an improvement in bond quality. The CS established a baseline average velocity of 4.034 km/s. The application of a Sika Latex bonding agent to an unprepared surface (CS-Si) resulted in a minor velocity increase to 4.077 km/s, representing a modest improvement of 1.07% over the control group. A more substantial enhancement was observed with mechanical surface roughening. The WB specimens achieved an average velocity of 4.330 km/s, a significant 7.34% increase compared to the CS group. The addition of WB-Si slightly elevates the velocity to 4.340 km/s, marking a 7.58% increase over the baseline.

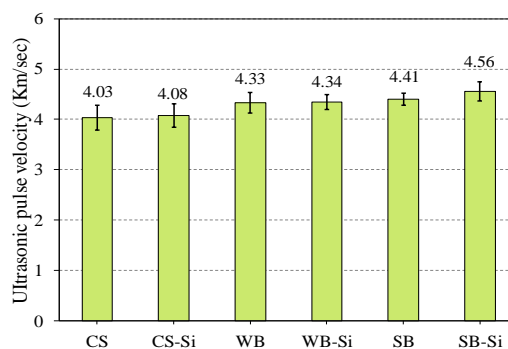


Fig. 3 UPV results for different surface treatments

The most effective surface preparation method was sandblasting. The SB specimens recorded a high average velocity of 4.408 km/s, which is 9.27% greater than that of the CS. The best performance was achieved by combining sandblasting with the Sika Latex additive (SB-Si), which yielded the highest average velocity of 4.558 km/s, corresponding to a remarkable 12.99% improvement over the control specimens. This exceptional value is particularly noteworthy as it surpasses the velocity of the substrate concrete itself by 2.42%, suggesting that the interface is no longer the weakest plane in the composite system.

To further investigate the correlation among the substrate, interface, and mortar regions, Table 4 summarizes the UPV values for the monolithic sections and the interface. The average UPV for the 100% substrate region was 4.450 km/s, while the 100% plain mortar and 100% polymer-modified mortar regions yielded 3.980 km/s and 4.120 km/s, respectively. For the SB-Si specimens, the interface velocity (4.558 km/s) exceeds the velocity of both the mortar and the substrate. This indicates that the synergy between aggressive sandblasting and polymer modification creates a denser transition zone. Conversely, in the CS (control) specimens, the interface velocity (4.034 km/s) remained significantly lower than the substrate benchmark, confirming that without proper surface treatment, the interface acts as a discontinuity that impedes wave propagation.

Table 4 Comparative UPV data for substrate, mortar, and interface regions

Region of interest	Sensor positioning	Material/Treatment	Average UPV (km/s)
Substrate region	100% on substrate	Concrete (30 MPa)	4.450
Mortar region	100% on mortar	Plain mortar	3.980
Mortar region	100% on mortar	Sika-modified mortar	4.120
Interface (baseline)	50% sub / 50% mortar	CS (control)	4.034
Interface (optimized)	50% sub / 50% mortar	SB-Si (sandblasted + sika)	4.558

The positive impact of surface roughening, particularly via wire brushing and sandblasting, can be attributed to the removal of the weak, porous laitance layer from the substrate surface. This process exposes the stronger, more durable aggregate and matrix beneath. Furthermore, it creates a textured and irregular topography that significantly enhances the mechanical interlock between the old concrete and the new mortar. The mortar can penetrate the crevices and undulations of the prepared surface, forming a robust physical key. This improved interlocking minimizes the formation of voids and air pockets at the interface, creating a more continuous and solid medium for ultrasonic wave transmission. A denser and more homogeneous ITZ facilitates faster wave propagation, hence leading to higher UPV readings [15].

The superiority of sandblasting over wire brushing indicates that a more aggressive and deeply profiled surface texture leads to a more effective mechanical bond. The role of the Sika Latex additive, while generally positive, appears to be synergistic with mechanical preparation. Sika Latex is a polymer emulsion that, when added to mortar, improves its adhesive properties and reduces permeability. It acts as a chemical bonding agent, promoting a stronger connection at the microscopic level.

On an unprepared surface (CS-Si), its effect was limited, likely because it could not overcome the deficiencies of the weak laitance layer. However, when applied to a mechanically prepared surface (WB-Si and SB-Si), it complemented the enhanced mechanical interlock with improved chemical adhesion. This dual-action mechanism explains the superior performance of the SB-Si specimens.

According to the concrete quality classification provided in Table 5 [16], the results can be interpreted to assess the integrity of the bond. The measured velocities for all specimen groups, which range from 4.034 km/s to 4.558 km/s, place their quality between “Good” (3.5-4.5 km/s) and “Excellent” (>4.5 km/s). Specifically, the control (CS) and latex-only (CS-Si) specimens are categorized as having a “Good” quality interface. The mechanically prepared specimens, including those treated by wire brushing (WB, WB-Si) and sandblasting alone (SB), also fall firmly within this “Good” rating, although they trend towards the upper limit of the category. Most significantly, the SB-Si group, with an average velocity of 4.558 km/s, exceeds the threshold for the “Excellent” classification.

This result confirms that combining an aggressive surface preparation, such as sandblasting, with a polymer bonding agent can enhance the integrity of the repair interface. These findings are consistent with the broader scientific literature. Kothari et al. [17] and Fan et al. [18] both concluded that increasing substrate surface roughness enhances the bond with new concrete overlays, which is reflected in higher UPV measurements due to improved mechanical and physical interlocking. Similarly, Santos et al. [19] demonstrated through numerical modeling that UPV wave velocity at an interface is directly proportional to its degree of roughness, further validating the methodology and conclusions of this study.

Table 5 Classification of concrete quality based on UPV [16]

UPV (km/s)	Condition
> 4.5	Excellent
3.5 - 4.5	Good
3.0 - 3.5	Questionable
2.0 - 3.0	Poor
< 2.0	Very Poor

3.2 Analysis and interpretation of thermal expansion results

The CTE of concrete is a critical parameter that governs its structural behavior and long-term performance under thermal loading. It is defined as the measure of the relative change in material dimensions in response to temperature variations, and dictates the extent to which concrete expands upon heating and contracts upon cooling. These volumetric changes can induce significant internal thermal stresses, potentially leading to cracking and deformation that compromise structural stability. Consequently, consideration of the CTE in the design phase is essential to prevent damage from unrestrained expansion and contraction [20]. The impact of thermal effects can be mitigated either by selecting materials with a low CTE or by incorporating design details that accommodate movement. Published literature indicates that the CTE for conventional concrete typically ranges from $7.2 \times 10^{-6}/^{\circ}\text{C}$ to $14.4 \times 10^{-6}/^{\circ}\text{C}$, depending on its constituent materials [21].

Fig. 4 and Fig. 5 present the results from subjecting the composite specimens to temperatures of 50°C and 80°C, respectively, over exposure periods ranging from 1 to 24 hours. A consistent and predictable trend was observed across all specimen groups: the measured CTE increased proportionally with the duration of thermal exposure at both temperature levels. This behavior can be attributed to the progressive attainment of thermal equilibrium, allowing for full dimensional change. More significantly, the results further demonstrate that surface preparation has a profound influence on the thermal compatibility of the composite system. A clear hierarchy emerged, wherein the SB specimens consistently exhibited the lowest CTE values, followed by the WB specimens. In stark contrast, the untreated CS specimens displayed the highest CTE, indicating inferior thermal performance.

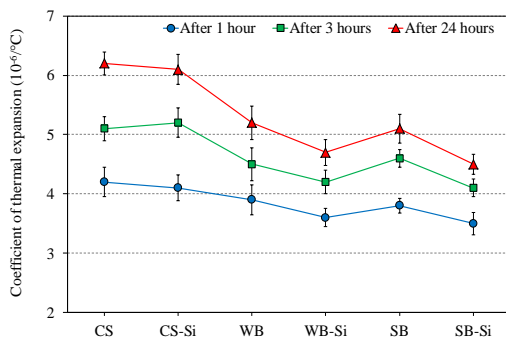


Fig. 4 The CTE for the investigated specimens at 50°C over various time intervals

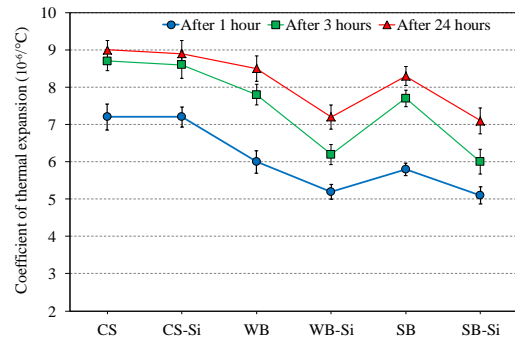


Fig. 5 The CTE for the investigated specimens at 80°C over various time intervals

The addition of Sika Latex had a nuanced effect. For the untreated control specimens (CS-Si), the polymer admixture showed a negligible impact on reducing the CTE. However, its contribution became significant when combined with mechanically prepared surfaces. This suggests a synergistic effect between the physical topography of the substrate and the

chemical properties of the polymer. The Sika Latex, which forms a polymer film within the cementitious matrix, likely functions as a thermal-insulating and crack-bridging agent. Its effectiveness, however, appears to be contingent on a roughened surface, which enhances adhesion and allows the polymer film to form a more continuous and well-anchored layer at the interface. This improves the composite's response to thermal stress. In contrast, on a smooth, as-cast surface, the polymer's ability to create a cohesive and restraining bond is diminished.

Fig. 6 illustrates the relative reduction in CTE after 24 hours of heating, benchmarked against the standard CS specimens. At 50°C, the relative reductions in CTE were approximately 1.11% for CS-Si, 5.56% for WB, 20.0% for WB-Si, 7.70% for SB, and 21.11% for SB-Si. At 80°C, the corresponding reductions reached approximately 1.61%, 16.13%, 24.19%, 17.74%, and 27.06%, respectively. These results clearly indicate that the efficacy of surface roughening techniques, particularly sandblasting, in enhancing thermal compatibility is amplified at elevated temperatures, at least within the conditions of this study.

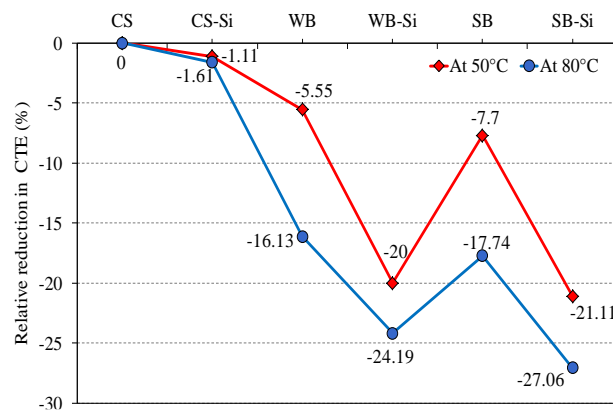


Fig. 6 Relative reduction in CTE as a function of substrate surface roughness after 24 hours at 50°C and 80°C

The interpretation of these findings should consider the fundamental factors affecting the CTE of concrete, including the type and quantity of aggregate and cement, mix proportions, and concrete age [22]. In this investigation, these variables were held constant across all specimens, thereby isolating the substrate surface roughness as the primary independent variable. Therefore, the observed variations in the composite CTE can be primarily attributed to the quality of the ITZ created by the different surface treatments.

The superior bond strength previously observed in specimens with roughened surfaces—particularly those treated with sandblasting and wire brushing—is associated with enhanced mechanical interlocking [23]. This improved bond is expected to create a more continuous and homogeneous ITZ, as the repair mortar can more effectively fill the substrate's voids and undulations.

The presence of voids, microcracks, and poor adhesion at the interface is the primary mechanism responsible for the higher CTE observed in the CS specimens. The ITZ in a composite system is inherently a point of weakness that negatively affects its engineering properties, including its resistance to thermal stresses. When the bond is weak and the interface is porous, the system cannot act as a monolithic unit. Instead, the voids and discontinuities allow greater differential movement between the substrate and the repair mortar upon heating.

These air-filled spaces can accommodate the differential expansion between the two layers, leading to a larger overall measured expansion of the composite specimen compared to a homogeneous, well-bonded concrete. Consequently, the measured CTE reflects not only the intrinsic material expansion but also the mechanical slip and movement occurring within the porous interface. Furthermore, while these air-filled spaces accommodate differential movement, it is important to note that the dry state of the specimens in this study prevents the added complexity of moisture migration or vapor pressure within these voids.

Conversely, effective surface preparation mitigates this effect. By creating a high-profile and torturous surface, sandblasting promotes strong mechanical interlocking that physically restrains this differential movement. The resulting continuous and well-compacted ITZ enhances the load transfer mechanism between the layers, allowing the composite to behave more cohesively, akin to a single monolithic material [24]. This restraint against interfacial movement leads to a lower overall measured CTE for the composite system. As a result, the voids and discontinuities that permit exaggerated expansion are minimized, improving thermal compatibility.

The porosity, voids, and weak adhesion between the substrate and the repair mortar contribute to an increased CTE in the composite specimen. This is due to the inherent differences in the thermal properties of the two layers and the ability of a porous interface to accommodate differential thermal movements. However, this phenomenon can be significantly curtailed through proper substrate surface preparation.

Despite these effects, all measured CTE values in this study, with the highest recorded value being approximately $9.5 \times 10^{-6}/^{\circ}\text{C}$, remain within the acceptable range specified by ACI 318-19, which suggests an upper limit of around $12 \times 10^{-6}/^{\circ}\text{C}$. This indicates that improving surface roughness through techniques such as sandblasting and wire brushing not only enhances bond strength but also improves thermal performance by reducing porosity and promoting interfacial continuity. These findings highlight the importance of surface treatment in optimizing both the structural and thermal performance of composite concrete systems, particularly in applications exposed to frequent thermal cycling.

3.3 Analysis of permeability test results

The results of the water permeability test for the concrete specimens are presented in Table 6. The depth of water penetration is a critical indicator of a concrete's resistance to fluid ingress. According to established standards [25], concrete is classified as “impermeable” when the water penetration depth is less than 50 mm, and as “impermeable under aggressive conditions” when the depth is below 30 mm.

Table 6 Water permeability test results

Surface preparation	Water penetration depth (mm)	Permeability coefficient (K_w) ($\times 10^{-10}$ m/s)
CS	92.0 ± 4.0	6.18 ± 0.50
CS-Si	81.0 ± 6.0	4.80 ± 0.60
WB	75.2 ± 5.0	4.20 ± 0.60
WB-Si	49.4 ± 2.0	2.03 ± 0.30
SB	70.0 ± 2.0	3.69 ± 0.25
SB-Si	45.0 ± 3.0	1.48 ± 0.30

The data reveal that the surface preparation method of the concrete substrate has a pronounced effect on water penetration depth. Based on the classification criteria, specimens WB-Si (49.4 mm) and SB-Si (45.0 mm) can be categorized as impermeable, as their average penetration depths are below the 50 mm threshold, indicating improved water resistance. In contrast, the control sample CS (92 mm), along with CS-Si (81 mm), WB (75.2 mm), and SB (70 mm), exhibited penetration depths exceeding 50 mm and are therefore classified as “permeable” under these test conditions. These trends, reflecting the combined benefits of surface roughening and polymer modification, are illustrated in Fig. 7, which shows the variation in penetration depth among the different sample types.

A more quantitative analysis can be performed by examining the permeability coefficient, which represents the rate of fluid flow through the porous medium. As shown in Table 6, the permeability coefficients were recorded as 6.18×10^{-10} , 4.80×10^{-10} , 4.20×10^{-10} , 2.03×10^{-10} , 3.69×10^{-10} , and 1.48×10^{-10} m/s for the CS, CS-Si, WB, WB-Si, SB, and SB-Si specimens, respectively.

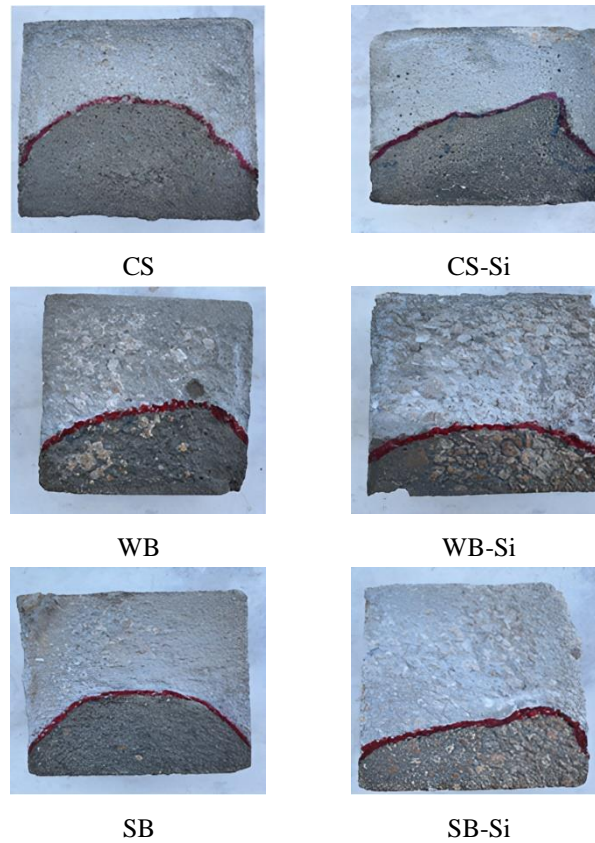


Fig. 7 Depth of water penetration at the concrete substrate-cement mortar interface following the permeability test

Compared to the CS, all other samples demonstrated a reduction in permeability. This reduction was 22.3% for CS-Si, 32.0% for WB, 67.2% for WB-Si, 40.3% for SB, and 76.1% for SB-Si. These relative improvements are graphically represented in Fig. 8. The data indicate that while surface roughening alone (WB and SB) lowers permeability, its combination with Sika Latex modification (WB-Si and SB-Si) yields a synergistic effect, leading to the most significant performance gains.



Fig. 8 Relative reduction in the K_w , compared to the reference specimen

The contribution of the Sika Latex admixture can be observed from the results. Its inclusion reduced the permeability coefficient by 22.3% in the untreated surface (CS vs. CS-Si), 51.7% in the wire-brushed samples (WB vs. WB-Si), and 59.9% in the sandblasted samples (SB vs. SB-Si). This demonstrates that the polymer modification is increasingly effective as the surface roughness increases. Based on these results, the combination of sandblasting followed by repair with a polymer-modified mortar (SB-Si) emerges as the most effective strategy for minimizing water permeability at the bond interface.

The underlying mechanism for this enhanced performance is twofold. First, mechanical surface roughening, achieved through wire brushing or sandblasting, creates a more complex and tortuous interfacial topography. This increased roughness enhances the mechanical interlock between the old substrate and the new repair mortar by increasing the frictional forces and

the effective bonding area. This intricate interface creates a longer, more convoluted path for water to travel, thereby increasing the resistance to penetration [26]. Second, the addition of Sika Latex contributes at the microstructural level. The polymer particles form a film within the mortar matrix, which helps to block capillary pores and reduce the overall porosity. At the ITZ, these polymers improve the bond quality by densifying the microstructure and reducing microcracks, leading to a less permeable interface [27].

The findings of this study are consistent with the observations reported by Ding et al. [27], who investigated the influence of substrate treatment on the permeability of the bond interface between strain-hardening cementitious composite (SHCC) and normal concrete (NC). Their study compared three surface conditions: untreated, wire-brushed, and corrugated. They concluded that interface water resistance was critically dependent on surface roughness, with the wire-brushed surface exhibiting the lowest average permeability coefficient (1.69×10^{-12} m/s), followed by the corrugated surface (3.98×10^{-12} m/s), and finally the untreated surface (7.81×10^{-12} m/s). These results support the principle that creating a rougher, more engaged surface is crucial for achieving a low-permeability bond.

Although the permeability coefficients obtained in the present study (ranging from 1.48×10^{-10} to 6.18×10^{-10} m/s) are higher than the values reported by Ding et al. and the typical range for high-performance concrete (10^{-11} – 10^{-12} m/s) [6], they consistently demonstrate the same trend: surface preparation is a key factor in controlling the durability and permeability of concrete repair interfaces. The sandblasting technique, by creating the most aggressive and intricate surface profile, provides improved resistance to water ingress, and this effect is further enhanced by polymer modification.

4. Conclusions

This study provides a comprehensive evaluation of the concrete-mortar repair interface, focusing on the synergy between surface preparation and polymer modification. Based on the experimental results, the following conclusions are drawn:

- (1) Substrate surface preparation is the most critical factor influencing repair quality. Aggressive mechanical treatments, specifically sandblasting, are more effective than wire brushing or as-cast surfaces by creating a robust mechanical interlock.
- (2) The inclusion of a polymer-modifying admixture (Sika Latex) demonstrates a profound synergistic effect with surface roughness. While its impact on smooth surfaces is marginal, it significantly enhances chemical adhesion and densifies the ITZ on roughened substrates.
- (3) The combination of sandblasting and polymer-modified mortar (SB-Si) consistently yielded superior performance across all durability metrics. This approach resulted in a 12.99% increase in UPV, achieving an “Excellent” bond quality classification.
- (4) Thermal compatibility is improved through proper surface treatment, with SB-Si specimens showing a 27.06% reduction in the CTE at 80°C, indicating a more monolithic behavior under thermal stress.
- (5) Water resistance was significantly enhanced, with the SB-Si group achieving a 76.1% decrease in the water permeability coefficient. This highlights the effectiveness of the combined method in blocking ingress pathways for deleterious substances.
- (6) A holistic evaluation involving ultrasonic pulse velocity (UPV) and transport properties is essential for predicting the long-term performance of repairs, as mechanical strength alone does not guarantee durability.

This study is limited by its controlled laboratory conditions, which lack real-world stressors such as freeze-thaw cycles and sustained loading. In addition, regional material sourcing and the use of a single polymer modifier may limit the generalizability of specific numerical data. Future research should focus on long-term durability under aggressive field

conditions, broader combinations of admixtures and preparation methods like hydrodemolition. Finally, integrating cost-benefit analyses and correlating non-destructive findings with traditional mechanical tests may support the development of predictive models for the service life of repaired structures.

Abbreviations and Symbols

ACI	American Concrete Institute	ASTM	American society for testing and Materials
BS	British standards	α	Coefficient of thermal expansion
SSD	Specific gravity	OPC	Ordinary Portland cement
Si	Sika Latex	LOI	Loss on ignition
w/c	Water to cement ratio	UHPFC	Ultra-high-performance fiber-reinforced concrete

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Conflicts of Interest

The authors declare no conflict of interest.

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