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Effects of Different Fiber Dosages of PVA and Glass Fibers on the Interfacial Properties of Lightweight Concrete with Engineered Cementitious Composite

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Abstract: The bond strength at the interface zone between two concrete sections plays a critical role in enhancing long-term durability, ensuring that both materials perform homogeneously. Ensuring compatibility at the interfaces between repair and concrete materials is one of the most challenging aspects of constructing composite systems. Despite various studies, a comprehensive understanding of the engineered cementitious composite (ECC) bonding mechanism at the repair interface is still limited. The objective of this research is to identify the interfacial properties between lightweight concrete (LWC) and engineered cementitious composite (ECC) with varying fiber dosages of polyvinyl alcohol (PVA) and glass fibers under different surface roughness conditions. The study tested LWC-ECC specimens in direct shear using slant shear and bi-surface shear tests, recording the maximum shear stress at failure. Two grades of LWC—normal-strength lightweight concrete (NSLW) and high-strength lightweight concrete (HSLW)—were used as substrates, while the ECC overlays contained varying fiber dosages: 2% PVA, 1.5% PVA with 0.5% glass, 1.0% PVA with 1.0% glass, and 0.5% PVA with 1.5% glass. The surface conditions considered included grooved and as-cast substrates. The results indicated that the highest bond strength was achieved by specimens with 1.5% PVA and 0.5% glass fiber, with a maximum shear strength of 24.05 MPa for grooved HSLW substrates. Interface roughness had minimal impact on shear strength for NSLW substrates but significantly affected HSLW substrates, with bond strengths varying from 13.81 MPa to 24.05 MPa for grooved surfaces. This study demonstrates the critical role of fiber dosage and surface roughness in enhancing the bond performance of composite materials.

Keywords: engineered cementitious composite; polyvinyl-alcohol fiber; bi-surface shear test; roughness surfaces; slant shear test; substrate concrete



Citation: Al-Baghdadi, H.M.; Kadhum, M.M. Effects of Different Fiber Dosages of PVA and Glass Fibers on the Interfacial Properties of Lightweight Concrete with Engineered Cementitious Composite. *Buildings* **2024**, *14*, 2379. <https://doi.org/10.3390/buildings14082379>

Academic Editors: Bo Wang, Rui Guo, Muye Yang, Weidong He and Chuntao Zhang

Received: 24 May 2024

Revised: 22 July 2024

Accepted: 24 July 2024

Published: 1 August 2024



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1. Introduction

The bond strength at the interface zone between two concrete sections plays a critical role in enhancing long-term durability and ensuring that both materials perform homogeneously. This bond ensures the effective transfer of loads between the concrete layers in a composite section, enabling it to resist applied loads and stresses over an extended period [1]. The strength of the bonding area between two types of concrete is primarily influenced by four factors: the compressive strength of the weaker concrete, the stresses within the bonding area, the roughness of the bonding area, and the presence of shear reinforcement crossing the interface [2]. Additionally, bond strength is determined by cohesion and friction at the material boundary, which contributes to shear force and shear resistance [3].

Lightweight concrete (LWC) is known for its low density and high performance in terms of both strength and durability, particularly high-strength LWC. When dealing with composite structural members that combine lightweight and normal concrete, it is crucial to assess the material properties and behavior at the lightweight-to-normal concrete interface.

Differential shrinkage may not be a significant concern when LWC is used as a repair layer thanks to its self-curing properties, which reduce shrinkage [4].

Recent studies have highlighted the potential of using environmentally sustainable composites to enhance the properties of lightweight aggregate concrete (LAC). For instance, Suparp et al. [5] demonstrated that the axial load capacity of LAC can be significantly improved by using sustainable composites [5]. Similarly, Sirisonthi et al. [6] conducted a full-scale load test on precast post-tensioned continuous girders, providing insights into the load-deformation behavior of such systems under service and ultimate loading conditions [6]. The use of glass fiber reinforced polymer (GFRP) rods for the remediation of punching shear failure has also been investigated, showing promising results in enhancing the structural integrity of concrete slabs [7]. Moreover, Ullah et al. [8] explored the effect of partial replacement of e-waste as a fine aggregate on the compressive behavior of concrete specimens, highlighting the potential of alternative materials in improving concrete performance [8].

Ultra-high-performance fiber concrete is characterized by low porosity and excellent mechanical properties, including high tensile and compressive strength. Ultra-high-performance fiber concrete is ideal for rehabilitating and strengthening structures exposed to high mechanical and severe environmental loads, while normal structural concrete can be used for areas subjected to moderate exposure [9]. This combination enhances structural performance in terms of durability and life cycle costs [10]. Ensuring compatibility at the interfaces between repair and concrete materials is one of the most challenging aspects of constructing composite systems. This compatibility significantly impacts the overall structural behavior of the repaired structure [11]. Despite various studies, a comprehensive understanding of the bonding mechanism at the repair interface is still lacking [12]. For instance, studies on steel fiber-reinforced concrete have shown that steel fibers can improve interface bond strength and ductility in repaired structures, albeit slightly [13].

Engineered cementitious composite (ECC) are a new generation of high-performance fiber-reinforced cementitious materials with high flexibility and moderate fiber content. ECC materials using polyvinyl alcohol (PVA) fibers with a fiber volume fraction of no more than 2% have shown tensile strain capacities of between 3 and 5%. This high deformation capacity is due to the development of multiple microcracks rather than the continuous opening of a single crack [14]. The ECC's high fracture toughness and controlled crack width make it an ideal material for improving the serviceability and durability of infrastructure. ECC has been successfully applied in various structural elements, including embankments, bridge deck overlays, and connecting beams in high-rise buildings [15].

ECC's properties also make it suitable for repairing and modernizing concrete buildings. Potential applications include new structures requiring high energy absorption, impact resistance, and controlled crack width [16,17]. Studies have demonstrated that pseudo-ductile cement composite is an effective and durable material for concrete repair. The bond between pseudo-ductile cement composite and sufficiently cured concrete is strong, often leading to bond failure within the concrete substrate under shear or traction stresses [18].

Experimental studies on the bond strength between ECC layers and regular concrete substrates with varying surface textures have shown that ECC significantly enhances bond strength. This is particularly evident in compressive loading scenarios where ECC-coated concrete's bond strength is higher than that of substrate concrete [19]. ECC's ability to withstand tensile stresses makes it an excellent material for repairing structures prone to cracking due to low tensile strength [20].

Several researchers have explored the application of ECC in strengthening reinforced concrete structures, including beams, columns, and beam-column joints. The introduction of ECC into structural members results in the formation of multiple small cracks on tensile surfaces, leading to a ductile failure mode without reducing the load capacity of the member. These studies have shown that the bond strength between ECC and concrete, including interfacial tensile and shear strengths, is sufficient to transfer forces from the original

reinforced concrete structure to the ECC layer [21]. The slant shear test (see Figure 1a), in particular, has proven to be an effective method for assessing bond strength, often yielding higher bond strength values compared to other tests [22]. To evaluate the bond performance between different concrete interfaces, various test methods exist, such as the pull-off test, splitting tensile test, direct shear test (see Figure 1b), and slant shear test [19,20].

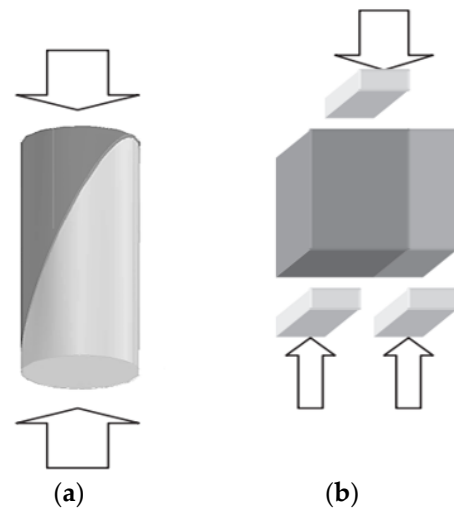


Figure 1. Specimen tests of bond strength: (a) slant shear and (b) direct shear (bi-surface).

2. Research Significance

This research addresses gaps in the use of polyvinyl alcohol (PVA) and glass fibers in engineered cementitious composite (ECC) for lightweight concrete (LWC) are addressed, offering significant contributions to both academic research and civil engineering practices. It shows how fiber dosages affect ECC's mechanical properties, provides new guidelines for optimizing composite interfaces, and introduces innovative, sustainable construction practices. The aim of this research is to identify the interfacial properties between LWC and ECC with different fiber dosages of PVA and glass fibers, along with varying degrees of roughness. In order to evaluate ECC effectiveness and suitability as repair materials for retrofitting reinforced concrete structures, LWC-ECC specimens were tested in direct shear using the slant shear test and bi-surface shear test, and the maximum shear stress at failure was recorded. Also, two grades of LWC (normal-strength lightweight concrete (NSLW) and high-strength lightweight concrete (HSLW)) were used as substrates, while for the overlay, ECC mixes contained various types and dosages of fibers (2% PVA, 1.5% PVA with 0.5% glass, 1.0% PVA with 1.0% glass, and 0.5% PVA with 1.5% glass fibers) were used. Grooved and as-cast substrate surface conditions were considered. Furthermore, this research investigates the relationship between surface roughness and bond strength for the LWC-ECC specimens with different types and dosages of fibers, along with two types of interface treatments—namely, as-cast and grooved surfaces.

3. Experimental Work

3.1. Apparatus and Measurement Techniques

The slant shear test was conducted using cylindrical molds with dimensions of 75 mm in diameter and 150 mm in height. The molds were cut at an inclination angle of 30 degrees to create the slant interface, as shown in Figure 2. This apparatus allowed compressive loads to be applied to the inclined surface, simulating real-life shear and compressive stresses at the bond interface. The elliptical area of the slant surface was calculated for stress determination. For the bi-surface shear test, cubic molds measuring 150 mm × 150 mm × 150 mm were used. The molds were designed to contain two-thirds of the LWC substrate and one-third of the ECC overlay material, as shown in Figure 2. Three thick steel plates with dimensions of 100 mm × 33 mm × 25 mm were used to facilitate direct shearing between

the different concrete composites. The setup ensured symmetrical load application to simulate realistic shear stress conditions. Two surface preparation methods were employed to achieve the desired surface roughness: as-cast and grooved surfaces. Grooves inclined at approximately 45 degrees were created using special cutting discs designed for hard stone. This preparation ensured good interlock between the concrete surface and the ECC layer. The surfaces were cleaned with water and compressed air to remove any dust and debris and then left to dry before the ECC overlay application. A 2000 kN capacity digital compression testing machine was utilized to apply loads at a constant rate of 2 kN/s. This machine was employed for both the slant shear test and the bi-surface shear test to evaluate the bond strength between the LWC substrates and the ECC overlays. The machine's setup ensured precise load application and measurement throughout the testing process.

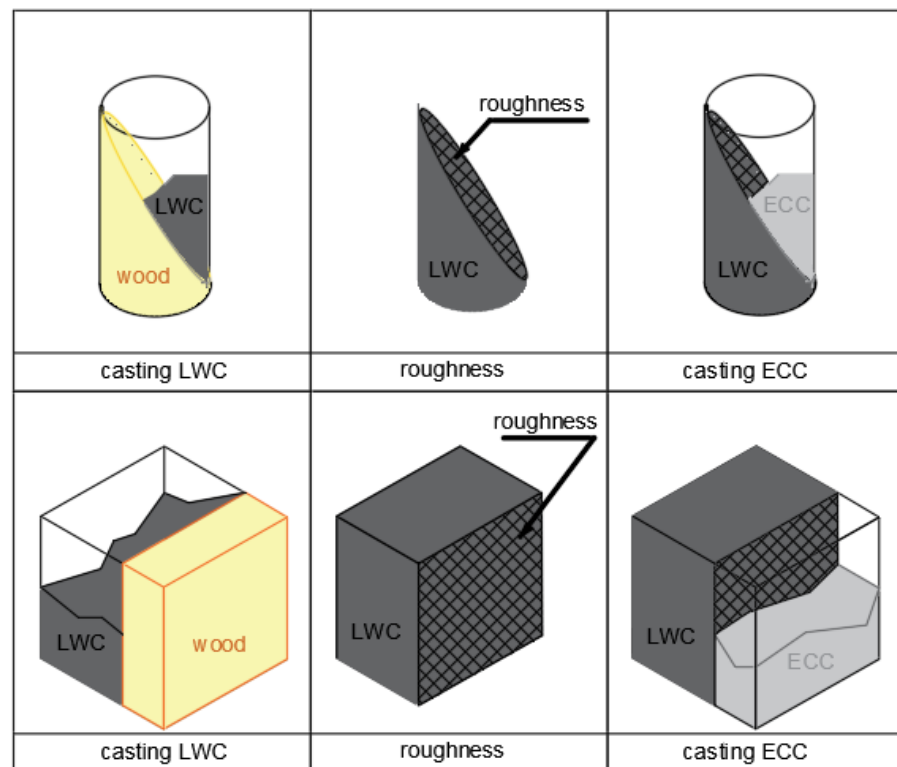


Figure 2. Preparation of composite specimens (slant shear and the bi-surface shear).

3.2. Materials

In all mixes (LWC and ECC), ordinary Portland cement was used in this study. The cement was tested to ensure conformity with No. 5/1984 standard [23]. The physical and chemical properties of the fine aggregate are listed in Table 1 in accordance with No. 45/1984 standard [24] and ASTM C128 standard [25]. Uniformly sized lightweight aggregates (0.475–1 cm) were used in this study. These aggregates are made from porous ceramic materials with uniformly small closed-cell pores and firmly sintered, durable exterior surfaces. The particle volume increases significantly during production due to swelling when the lightweight aggregates are produced from clay mineral raw materials, as shown in Figure 3. This process involves burning the materials in rotary kilns at temperatures between 1100 and 1200 °C. The sieve analysis of the lightweight aggregate was conducted to ensure it met the limits specified in ASTM C330-17a, 2017 [26], as shown in Table 2. Table 3 presents the physical and chemical properties of the lightweight aggregate tested by a manufacturer. Due to its high-water absorption capability, the lightweight aggregate was soaked in water for hours to prevent it from absorbing water during mixing. After soaking, the aggregate was spread out in laboratory air until the surface dried, resulting in a saturated surface dry state, as recommended by ACI 211.2-98 [27].

Table 1. Sand physical and chemical properties.

Size of Sieve (mm)	Cumulative Passing %	Limits of IQS No. 45/1984 as in (Zone 2)	Physical Properties	Test Results
10	100	100	Specific gravity	2.65
4.75	92	90–100	Absorption	0.92%
2.36	81	75–100	Fine material passing from the sieve (75 µm)	2.50%
1.18	73	55–90	Fineness modulus	2.68
0.6	55	35–59		
0.3	24	8–30	Chemical properties	
0.15	7	0–10	Sulfate content	0.35%

**Figure 3.** Lightweight aggregate.**Table 2.** Grading of used lightweight aggregate.

Size of Sieve (mm)	Cumulative Passing (%)	Limits of ASTM C330-17a, 2017
12.5	100	100
10	99	80–100
8	66	-
6	44	-
4.75	7	5–40
2.36	2	0–20
1.18	0	0–10

Table 3. Physical and chemical properties of lightweight aggregate.

Chemical Properties	
Chemical Composition	Percentage by Weight%
CaO	3.78
SiO ₂	61.58
Al ₂ O ₃	16.99
Fe ₂ O ₃	7.62
MgO	2.56
SO ₃	0.19
Na ₂ O	1.03
Loss on Ignition	0.2
Physical Properties	
Properties	Test Results
Specific Gravity	1.2
Absorption	12%
Bulk density Kg/m ³	700

Silica fume consists of extremely tiny spherical particles with diameters ranging from 0.1 to 0.2 μm . In this research, silica fume was used as a partial replacement (15% by weight) for cement to enhance the microstructure of the cement paste, increasing its resistance to external influences. The technical data for the silica fume includes Form—Powder, Color—Grey, Density—0.55 to 0.7 kg/L, and Chloride content—<0.1% [28]. A high-performance concrete superplasticizer based on modified polycarboxylic ether, MasterGlenium 54, was also used. A proportion of 3.5% was employed to achieve acceptable flow properties for ECC. Table 4 provides the technical description of MasterGlenium 54 [29].

Table 4. Technical description of MasterGlenium 54 [29].

Chemical Basis	Aqueous Solution of Modified Polycarboxylic Ether
Color	Whitish to straw
Specific gravity	1.07
PH	5–7
Chloride content	None
Toxicity	Danger hazardous material.
Fire	Not fire-propagating

The PVA fibers used in this study are 12 mm in length and 39 μm in diameter. The fiber's nominal tensile strength, stiffness, and density are 1600 MPa, 40 GPa, and 1300 kg/m³, respectively. Figure 4 displays the PVA fibers used in this research. Table 5 provides the technical properties of the PVA fibers according to a manufacturer. Another type of fiber used in this study is glass fiber (GF). The properties of the glass fibers are shown in Table 5. Figure 5 displays the glass fibers used in this research.

Table 5. Properties of PVA and glass fibers *.

Fiber	Fiber Length (mm)	Diameter μm	Tensile Strength (MPa)	Young's Modulus (GPa)	Fiber Elongation (%)	Density (kg/m ³)
PVA	12	39	1600	40	10-Apr	1.3
GF	12	-	2200	80	0–4	2.78

* Manufacturer Properties.

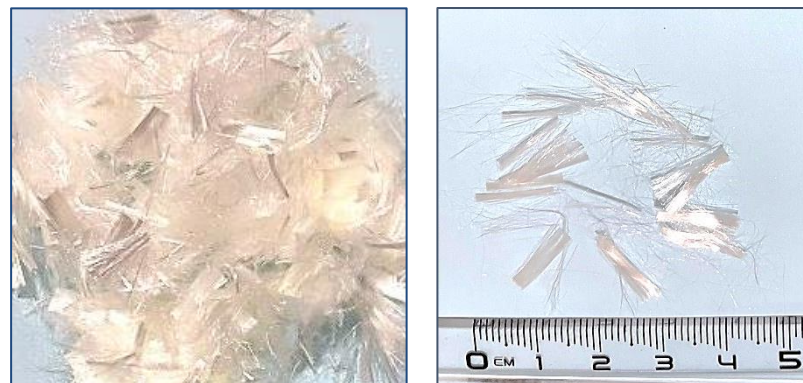


Figure 4. PVA fiber geometry.

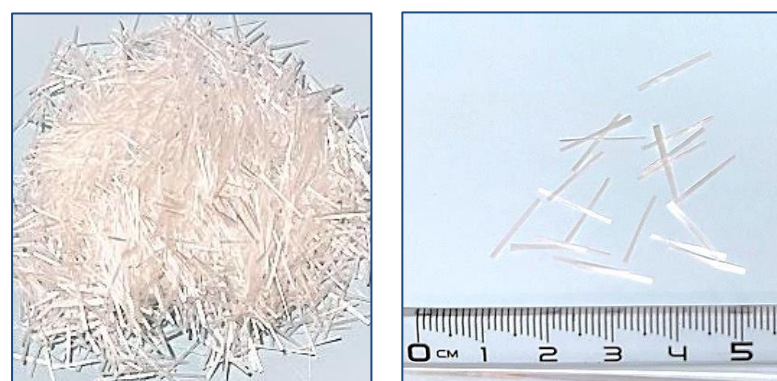


Figure 5. Glass fiber geometry.

Moreover, the fly ash used in this study complies with BS 3892-1 [30] and BS EN 450-1 [31]. The specific gravity of the fly ash is 2.70 g/cm^3 , and its Blaine-specific surface area is $2970 \text{ cm}^2/\text{g}$. The chemical properties of the fly ash are presented in Table 6.

Table 6. Chemical analysis of fly ash (Type F).

Chemical Composition	% by Weight
Al_2O_3	24.62
SiO_2	48.53
CaO	9.49
Fe_2O_3	7.59
K_2O	2.51
MgO	2.28
Na_2O	1.18
SO_3	2.48
Loss on ignition	1.69
28 d activity index	90%

3.3. Detailed Composition and Mixing Procedures

For substrate concrete mixes, the mix proportions for the NSLW and HSLW were designed to achieve a compressive strengths of 30 MPa and 50 MPa at 28 days, following ACI Committee 211.2-98 [32] and ACI 211.4R-08 [33] guidelines, respectively. To attain the necessary strength, a variety of trial mixes were tested; the specific mix ratios for NSLW and HSLW are listed in Table 7.

Table 7. LWC design mixes.

ID	Cement Kg/m ³	Sand Kg/m ³	Lightweight Aggregate Kg/m ³	Silica Fume Kg/m ³	Water Kg/m ³	SP (%) *	W/C
NSLW	478	667	440	0	153	1.1	0.32
HSLW	550	678	400	81	160	1.7	0.25

* SP by wt. of cm.

For overlay concrete mixes, ECC has been optimized using micromechanics to achieve high tensile ductility and tight micro-crack width while keeping the fiber content low (2% by volume) [34]. For ECC, the maximum grain size of 250 μm with an average size of 110 μm of fine aggregates was used to ensure a homogeneous mix. Many trial mixes were prepared to achieve the optimal properties for ECC mortars, with a mini-slump flow range of 240–260 mm, ensuring easy and complete penetration of the mortars through the concrete mold specified for repair.

Table 8 presents the typical mixture design of ECC adopted in this study, which exhibits self-consolidating casting properties. All proportions are given for materials in the dry state. Four different ECC mixes with various types and percentages of fibers (PVA and glass) were used as overlay materials. To account for material heterogeneity, a maximum fiber content of 2% by volume, which is greater than the calculated critical fiber content needed to achieve strain-hardening, is typically used in the mix design. Different percentages of glass fiber volume fractions were added to the ECC mix and PVA fibers, creating hybrid fiber composites. Therefore, the ECC-P2.0-G0.0, ECC-P1.5-G0.5, ECC-P1.0-G1.0, and ECC-P0.5-G1.5 mixes included 2% PVA fiber, 1.5% PVA + 0.5% glass fiber, 1.0% PVA + 1.0% glass fiber, and 0.5% PVA + 1.5% glass fiber, respectively.

Table 8. ECC Mix ID.

Mix ID	C/C	F/C	S/C	W/C	HRWR/C	PVA Fiber (%)	Glass Fiber (%)	Total (%)
ECC-P2.0-G0.0	1	1.2	0.8	0.56	0.012	2.0	0.0	2
ECC-P1.5-G0.5	1	1.2	0.8	0.56	0.012	1.5	0.5	2
ECC-P1.0-G1.0	1	1.2	0.8	0.56	0.012	1.0	1.0	2
ECC-P0.5-G1.5	1	1.2	0.8	0.56	0.012	0.5	1.5	2

C: cement, F: fly ash, S: sand, W: water.

3.4. Specimen Preparation and Curing Regimes

Composite specimens consisting of NSLW and HSLW substrates with various ECC overlay materials were prepared and tested. Slant shear and bi-surface shear tests were used to evaluate the interface bond strength at 28 days. For the slant shear test, the specimens were 75 $\times$ 150 mm cylinders with an inclination angle (α) of 30°, measured relative to the vertical axis [22]. For the bi-surface shear test, the specimens were 150 mm cubes, with two-thirds of the cube consisting of the NSLW and HSLW substrates and one-third consisting of the ECC overlay material [35].

To prepare the LWC substrate concrete specimens, wooden cylinders were cut at the specified slanted dimension, and wooden cubes were cut to a height of 150 mm with a base size of 50 $\times$ 150 mm, as shown in Figure 6. First, the cylindrical molds were filled halfway, and the cubic molds were filled two-thirds of the way with the cast LWC substrate. The fresh LWC mixtures were left in the molds for 24 h. Afterward, the samples were de-molded and cured in water for 28 days.



Figure 6. Wood slices for (a) slant shear and (b) bi-surface shear test.

To obtain quantitative surface roughness parameters for the LWC surfaces of the specimens, both grooved and as-cast surface methods were used to create a rough surface that ensures a strong bond between the concrete substrate and the repair material. This is crucial to ensure that the ECC repair material contributes to bearing part of the stresses. Special discs for cutting hard stones were used to make grooves inclined in opposite directions at an angle of approximately 45 degrees, ensuring good interlock between the concrete surface and the ECC layer. After the roughening process was completed, a final cleaning process was performed using water extrusion followed by compressed air to ensure no dust remained. The specimens were then left to dry before the ECC repair material was applied, as shown in Figure 7. NSLW and HSLW were used as reference interfaces, as listed in Table 9.



Figure 7. Interface roughness (a) half cylinder grooved and as cast surface and (b) two-thirds of the cube grooved and as cast surface.

Beushausen et al. [36] emphasized the necessity of reaching saturated surface dry conditions at the LWC-substrate interface before overlay application by soaking the interface. The purpose of this is to allow the mixed water from the fresh layer to pass into the dry LWC substrate when a new layer is applied. The LWC substrate overlay surfaces were moistened and subsequently dried using a damp towel. The saturated surface dry slanted cutting specimens were positioned in cylinder molds with the bevel side facing upward, and the overlay materials were poured on top of the LWC substrate concrete to complete these cylinders. Similarly, the saturated surface dry bi-surface cutting specimens were placed in cube molds and covered with overlay material on one-third of the cubes. A total of 16 groups of specimens are listed in Table 9, and in each group three specimens were prepared.

Table 9. Specimen identification.

Specimen ID	Substrate Concrete Mix	Overlay Concrete Mix	Interface Roughness
N-E-P2.0-G0.0-G	NSLW	ECC-P2.0-G0.0	Grooved surface
N-E-P1.5-G0.5-G	NSLW	ECC-P1.5-G0.5	Grooved surface
N-E-P1.0-G1.0-G	NSLW	ECC-P1.0-G1.0	Grooved surface
N-E-P0.5-G1.5-G	NSLW	ECC-P0.5-G1.5	Grooved surface
H-E-P2.0-G0.0-G	HSLW	ECC-P2.0-G0.0	Grooved surface
H-E-P1.5-G0.5-G	HSLW	ECC-P1.5-G0.5	Grooved surface
H-E-P1.0-G1.0-G	HSLW	ECC-P1.0-G1.0	Grooved surface
H-E-P0.5-G1.5-G	HSLW	ECC-P0.5-G1.5	Grooved surface
N-E-P2.0-G0.0-A	NSLW	ECC-P2.0-G0.0	As cast surface
N-E-P1.5-G0.5-A	NSLW	ECC-P1.5-G0.5	As cast surface
N-E-P1.0-G1.0-A	NSLW	ECC-P1.0-G1.0	As cast surface
N-E-P0.5-G1.5-A	NSLW	ECC-P0.5-G1.5	As cast surface
H-E-P2.0-G0.0-A	HSLW	ECC-P2.0-G0.0	As cast surface
H-E-P1.5-G0.5-A	HSLW	ECC-P1.5-G0.5	As cast surface
H-E-P1.0-G1.0-A	HSLW	ECC-P1.0-G1.0	As cast surface
H-E-P0.5-G1.5-A	HSLW	ECC-P0.5-G1.5	As cast surface

3.5. Load Application and Monitoring

Slant shear tests were performed according to ASTM C882 [22]. Specimens were tested using a standard compression apparatus, as shown in Figure 8a. The loading was applied as recommended in ASTM C39 [37]. The maximum load values were recorded, and the applied stress (σ_o) required to produce bond rupture was determined using Equation (1):

$$\sigma_o = P / A_e. \quad (1)$$

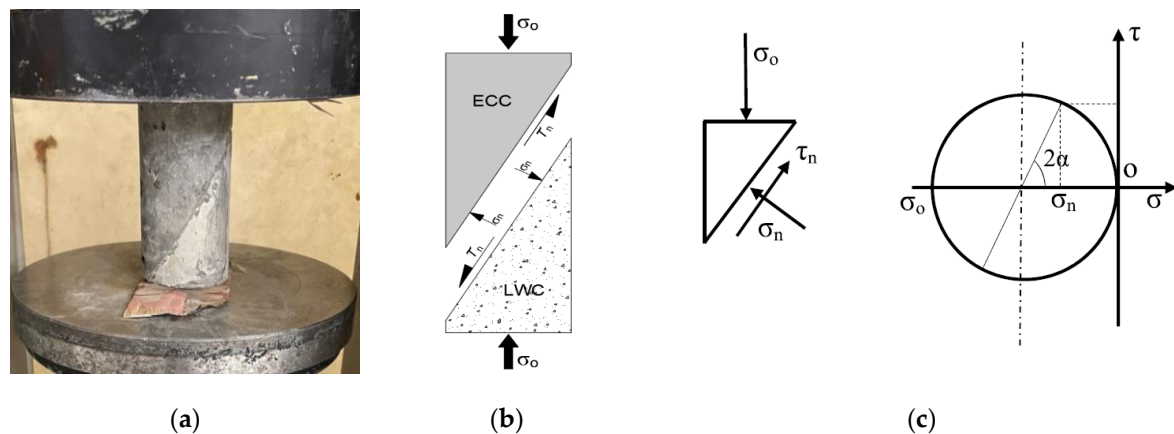


Figure 8. Slant shear test (a) and compression test (b) stresses developed at the interface, and (c) Mohr–Coulomb circle.

In Equation (1), P is the maximum applied load, and A_e is the elliptical area of the slant surface [38]. The maximum applied stress is a combined measure of the shear and compressive strength of the bond (Figure 8b), which are represented by Equation (2) and Equation (3), respectively.

$$\tau_n = \sigma_o \cos \alpha \quad (2)$$

Equation (2) calculates the normal shear stress acting on the interface. This shear stress component is derived from the overall stress and the angle of inclination, factoring in the geometric orientation of the bond interface.

$$\sigma_n = \sigma_o \sin 2\alpha \quad (3)$$

Equation (3) determines the normal compressive stress at the interface. This equation emphasizes the influence of the inclination angle on the compressive stress experienced by the interface, which is critical for evaluating the capacity of the interface to resist compression. In Equations (2) and (3), $\alpha = 30^\circ$, while τ_n and σ_n are the shear and compressive stresses acting on the bond plane, respectively. τ_n and σ_n are related in form, as in Equation (4) [39].

$$\tau_n = c + \mu \sigma_n = c + \tan \phi \cdot \sigma_n, \quad (4)$$

where c , μ , and ϕ are cohesion, coefficient of friction, and internal friction angle of the bond, respectively. Equation (4), known as the Mohr–Coulomb failure criterion, links the shear stress with the compressive stress. The parameters c (cohesion) and μ (coefficient of friction) are material properties that describe the adhesive and frictional contributions to the interface strength. This equation integrates the effects of both shear and compressive stresses to provide a comprehensive view of the failure mechanics at the interface.

To determine the average shear bond strength between two types of concrete, Momayeza et al. [21] proposed the bi-surface shear test method used in this research. This test is straightforward to perform and provides consistent results. The samples comprised two-thirds LWC and one-third repair materials (ECC), as shown in Figure 9. Three thick steel plates with dimensions of $100 \times 33 \times 25$ mm were used to facilitate direct shearing between the interfaces of the different concrete composites. A 2000 kN digital testing machine was used to apply a constant loading rate of 2 kN/s to all bi-surface specimens. The bi-surface shear strength values were determined using Equation (5).

$$\tau_v = Pv / (2 \times Av), \quad (5)$$

where τ_v = bi-surface shear bond strength (MPa), Pv = ultimate load indicated by the testing machine (N), Av = area of interface in shear (mm^2). The average of two shear force values was used to evaluate the direct shear strength. Figure 9 shows the testing machine and test setup.



Figure 9. Bi-surface shear test and test setup.

4. Results and Discussion

4.1. Concrete Mechanical Properties of LWC and ECC

For evaluating the material properties of NSLW and HSLW at 28 days, nine samples were prepared for each type of concrete. Three samples were used to determine the compressive strength, three for flexural strength, and three for splitting tensile strength. The mechanical properties of NSLW and HSLW are summarized in Table 10. For ECC materials with different types and dosages of fibers, the average compressive strength at 28 days was obtained from the average results of three cube samples ($70 \text{ mm} \times 70 \text{ mm} \times 70 \text{ mm}$) tested for compression. Additionally, four prismatic samples of each type of ECC were tested to determine the flexural strength at 28 days. Micromechanics is a branch of mechanics applied at the material constituent level, capturing the mechanical interactions between

the fiber, mortar matrix, and fiber/matrix interface. The matrix heterogeneities in ECC, including defects, sand particles, cement grains, and mineral admixture particles, range in size from the nanoscale to the millimeter scale. The ingredients and mix proportions have been optimized to satisfy multiple cracking criteria. Specifically, the type, size, amount of fiber, matrix ingredients, and interface characteristics are tailored for multiple cracking and controlled crack width. ECC incorporates fine silica sand with a sand-to-binder ratio (S/B) of 0.36 to maintain adequate stiffness and volume stability. The ECC mix has a water-to-binder (W/B) ratio of 0.26 to balance fresh and hardened properties. The binder system is defined as the total amount of cementitious material (i.e., cement and Type F fly ash) in ECC. The particle size of all matrix components is properly graded to achieve self-consolidating fresh properties [40]. The mechanical properties of the ECC materials with various types and dosages of fibers are summarized in Table 10.

Table 10. Mechanical properties of substrate and overlay concretes.

Mix ID	Compressive Strength (MPa)	Flexural Strength (MPa)	Splitting Tensile Strength (MPa)
NSLW	29.3	3.8	3.6
HSLW	56.2	6.8	4.5
ECC-P2.0-G0.0	78.7	21.5	14.1
ECC-P1.5-G0.5	81.3	23.3	15.7
ECC-P1.0-G1.0	76.0	20.7	15.0
ECC-P0.5-G1.5	59.5	19.8	13.6

4.2. Bond Strength—Slant Shear Test and Bi-Surface Test

Previously, various test methods have been reported to estimate bond strength [41–44]. These tests can be classified into the following categories: (1) direct tension tests, (2) direct shear tests (bi-surface tests), (3) indirect tensile tests (split tensile tests), (4) shear and compression tests (inclined shear tests), (5) withdrawal tests, and (6) three-point bending tests. Among these, the direct shear and oblique cut tests are widely used due to their ease of preparation, cost-effectiveness, and consistent results [42,43]. Many standards and codes also approve slant shear and Bi-surface tests to define bond strength [38,45]. Therefore, in this study, these methods were employed to determine the bond strength between different concrete substrates and overlays. The bond strength values of the composite LWC substrate-ECC overlay specimens were determined using slant shear and bi-surface shear tests. These values represent the average bond strengths, as listed in Tables 11–14.

Table 11. Slant shear bond strength and failure modes for NSLW concrete substrate.

Specimen ID	$\sigma\sigma$ (MPa)	Ave. $\sigma\sigma$ (MPa)	COV (%)	τ_n (MPa)	σ_n (MPa)	Failure Mode
N-E-P2.0-G0.0-G	10.8	10.58	7.6	9.16	1.7	C
N-E-P2.0-G0.0-G	9.5					C
N-E-P2.0-G0.0-G	11.44					C
N-E-P1.5-G0.5-G	11.95	12.75	4.9	11.04	1.96	B
N-E-P1.5-G0.5-G	12.83					B
N-E-P1.5-G0.5-G	13.47					D
N-E-P1.0-G1.0-G	10.12	9.5	5.3	8.22	1.48	C
N-E-P1.0-G1.0-G	8.89					C
N-E-P1.0-G1.0-G	9.49					C
N-E-P0.5-G1.5-G	5.81	6.25	5.0	5.41	1.06	C
N-E-P0.5-G1.5-G	6.45					C
N-E-P0.5-G1.5-G	6.49					C
N-E-P2.0-G0.0-A	9.12	9.05	4.0	7.83	1.48	C
N-E-P2.0-G0.0-A	9.45					C
N-E-P2.0-G0.0-A	8.58					C

Table 11. Cont.

Specimen ID	σ_o (MPa)	Ave. σ_o (MPa)	COV (%)	τ_n (MPa)	σ_n (MPa)	Failure Mode
N-E-P1.5-G0.5-A	11.02	10.81	3.7	9.36	1.72	B
N-E-P1.5-G0.5-A	10.25					C
N-E-P1.5-G0.5-A	11.16					B
N-E-P1.0-G1.0-A	6.85	7.23	6.0	6.26	1.21	C
N-E-P1.0-G1.0-A	7					C
N-E-P1.0-G1.0-A	7.84					C
N-E-P0.5-G1.5-A	4.89	5.4	8.1	4.67	0.93	C
N-E-P0.5-G1.5-A	5.35					C
N-E-P0.5-G1.5-A	5.96					C

Table 12. Slant shear bond strength and failure modes for HSLW concrete substrate.

Specimen ID	σ_o (MPa)	Ave. σ_o (MPa)	COV (%)	τ_n (MPa)	σ_n (MPa)	Failure Mode
H-E-P2.0-G0.0-G	18.12	17.58	2.3	15.22	2.49	B
H-E-P2.0-G0.0-G	17.5					C
H-E-P2.0-G0.0-G	17.12					C
H-E-P1.5-G0.5-G	23.75	24.05	0.9	20.82	3.26	B
H-E-P1.5-G0.5-G	24.15					B
H-E-P1.5-G0.5-G	24.25					B
H-E-P1.0-G1.0-G	14.81	15.3	2.9	13.24	2.57	B
H-E-P1.0-G1.0-G	15.2					B
H-E-P1.0-G1.0-G	15.89					C
H-E-P0.5-G1.5-G	11	11.25	4.1	9.74	1.81	B
H-E-P0.5-G1.5-G	10.85					B
H-E-P0.5-G1.5-G	11.9					B
H-E-P2.0-G0.0-A	9.63	9.39	6.3	8.13	1.55	B
H-E-P2.0-G0.0-A	8.58					B
H-E-P2.0-G0.0-A	9.96					B
H-E-P1.5-G0.5-A	12.95	13.81	4.5	11.95	2.27	B
H-E-P1.5-G0.5-A	14.12					C
H-E-P1.5-G0.5-A	14.36					C
H-E-P1.0-G1.0-A	7.85	8.23	3.5	7.13	1.56	B
H-E-P1.0-G1.0-A	8.55					B
H-E-P1.0-G1.0-A	8.29					B
H-E-P0.5-G1.5-A	4.75	4.86	2.1	4.21	0.96	B
H-E-P0.5-G1.5-A	5					B
H-E-P0.5-G1.5-A	4.83					B

Table 13. Bi-surface bond strength and failure modes for NSLW concrete substrate.

Specimen ID	σ_o (MPa)	Ave. σ_o	COV (%)	Failure Mode
N-E-P2.0-G0.0-G	7.1	6.8	10.4	B
N-E-P2.0-G0.0-G	5.8			C
N-E-P2.0-G0.0-G	7.5			B
N-E-P1.5-G0.5-G	7.6	7.9	2.4	B
N-E-P1.5-G0.5-G	8.1			D
N-E-P1.5-G0.5-G	7.9			D
N-E-P1.0-G1.0-G	6.3	5.9	4.4	C
N-E-P1.0-G1.0-G	5.8			B
N-E-P1.0-G1.0-G	5.7			B

Table 13. Cont.

Specimen ID	σ_o (MPa)	Ave, σ_o	COV (%)	Failure Mode
N-E-P0.5-G1.5-G	4.0	4.3	23.9	C
N-E-P0.5-G1.5-G	5.6			C
N-E-P0.5-G1.5-G	3.2			C
N-E-P2.0-G0.0-A	5.5	6.0	9.5	C
N-E-P2.0-G0.0-A	5.6			C
N-E-P2.0-G0.0-A	6.8			B
N-E-P1.5-G0.5-A	7.0	6.9	1.7	B
N-E-P1.5-G0.5-A	6.8			C
N-E-P1.5-G0.5-A	6.9			B
N-E-P1.0-G1.0-A	5.1	4.9	5.9	C
N-E-P1.0-G1.0-A	4.5			C
N-E-P1.0-G1.0-A	5.0			C
N-E-P0.5-G1.5-A	3.7	3.7	15.8	C
N-E-P0.5-G1.5-A	4.5			C
N-E-P0.5-G1.5-A	3.0			C

Table 14. Bi-surface bond strength and failure modes for HSLW concrete substrate.

Specimen ID	σ_o (MPa)	Ave σ_o	COV (%)	Failure Mode
H-E-P2.0-G0.0-G	9.8	10.0	8.0	B
H-E-P2.0-G0.0-G	9.1			B
H-E-P2.0-G0.0-G	11.0			B
H-E-P1.5-G0.5-G	14.0	13.1	6.5	B
H-E-P1.5-G0.5-G	13.2			B
H-E-P1.5-G0.5-G	12.0			B
H-E-P1.0-G1.0-G	9.8	10.3	3.5	B
H-E-P1.0-G1.0-G	10.5			B
H-E-P1.0-G1.0-G	10.6			B
H-E-P0.5-G1.5-G	7.4	7.3	10.2	C
H-E-P0.5-G1.5-G	8.1			B
H-E-P0.5-G1.5-G	6.3			C
H-E-P2.0-G0.0-A	5.8	6.2	6.0	C
H-E-P2.0-G0.0-A	6.7			B
H-E-P2.0-G0.0-A	6.1			C
H-E-P1.5-G0.5-A	9.4	9.1	2.4	B
H-E-P1.5-G0.5-A	9.0			B
H-E-P1.5-G0.5-A	8.9			B
H-E-P1.0-G1.0-A	6.1	6.2	11.8	B
H-E-P1.0-G1.0-A	5.4			B
H-E-P1.0-G1.0-A	7.2			B
H-E-P0.5-G1.5-A	3.4	3.9	15.8	C
H-E-P0.5-G1.5-A	4.7			B
H-E-P0.5-G1.5-A	3.5			C

From the slant shear test results, the applied stress (σ_o) on the interfacial bond was calculated by dividing the maximum force at bond failure obtained from compression loading by the elliptical area (A_e) using Equation (1). For the bi-surface shear test, the bonding shear strength was calculated by dividing the maximum applied force by the bonded surface area using Equation (5). Figure 10 presents the average slant shear strengths, and Figure 11 presents bi-surface shear strengths for grooved and as-cast surfaces for NSLW and HSLW at 28 days of age.

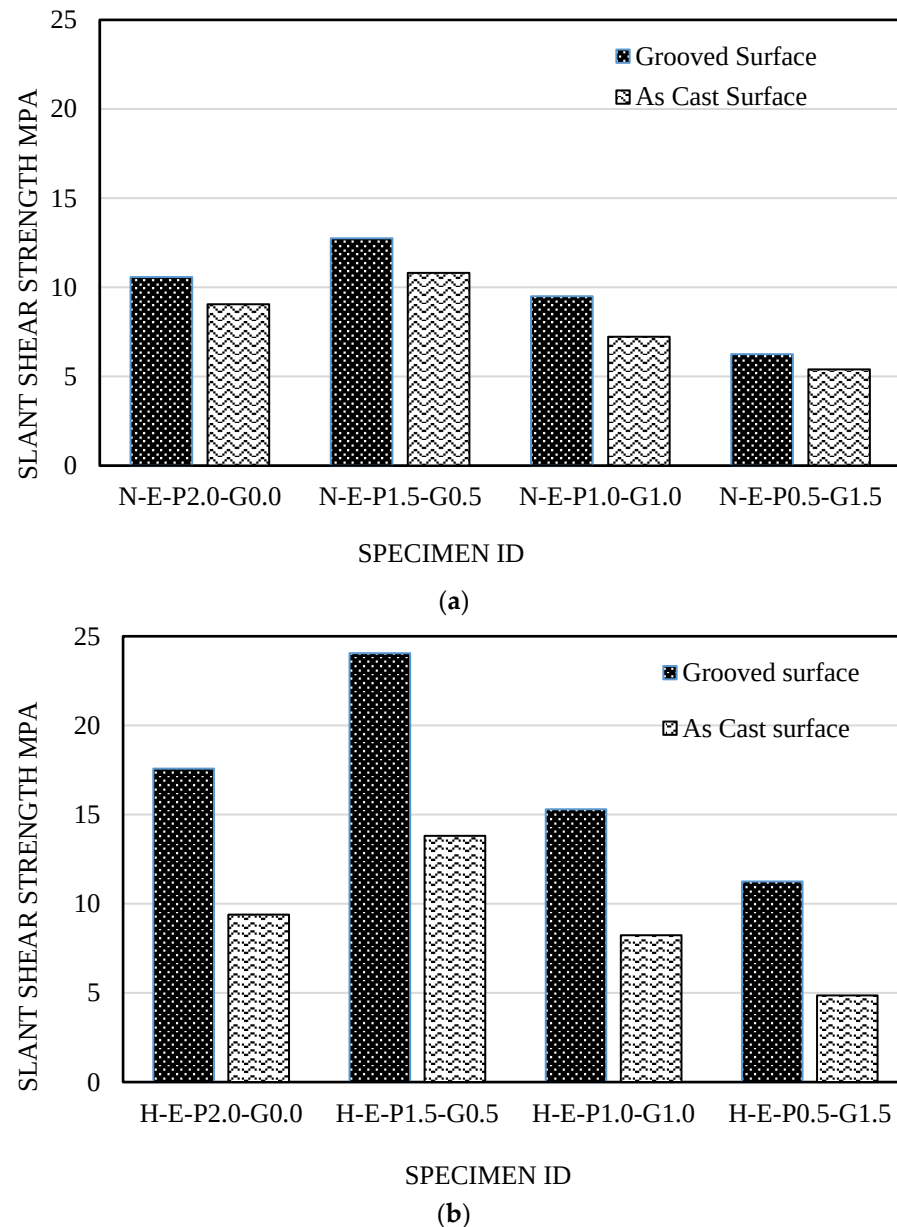
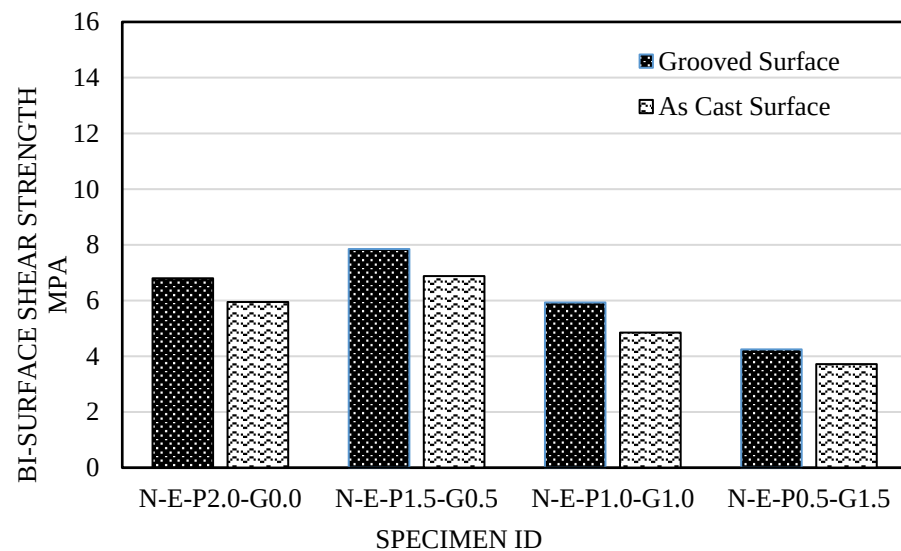


Figure 10. Slant shear bond strengths with grooved and as-cast surfaces for (a) NSLW substrate and (b) HSLW substrate.

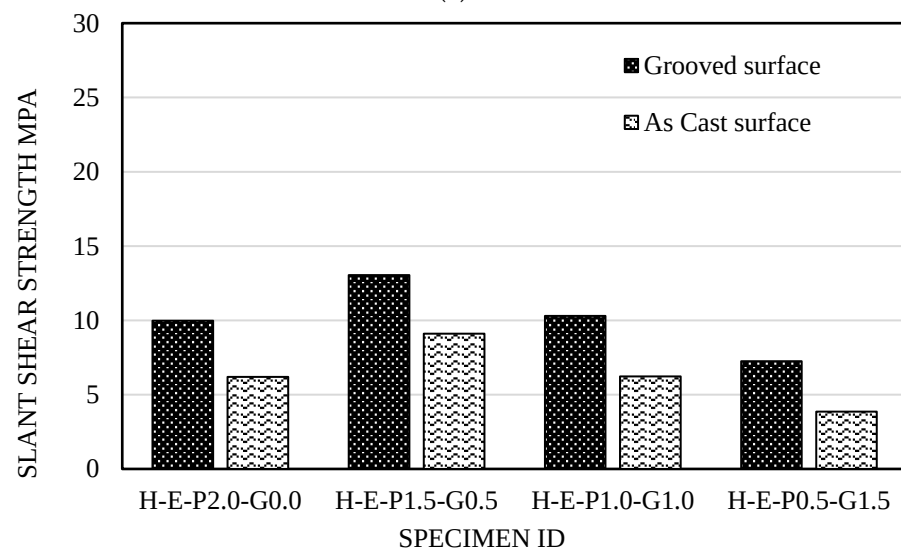
The figures indicate that the bond strengths measured by the slant shear method were higher than those measured by the bi-surface shear method for all ECC repair materials and surface preparations for both NSLW and HSLW substrates. This is attributed to the higher friction forces and interlock resulting from the high compressive stresses in the slant shear test, which increases the shear failure load [21].

Among all the NSLW and HSLW substrate-ECC specimens, the N-E-P1.5-G0.5 and H-E-P1.5-G0.5 specimens exhibited the highest bond strengths at 28 days. The bond quality decreased in the following order: N-E-P2.0-G0.0, N-E-P1.0-G1.0, N-E-P0.5-G1.5, H-E-P2.0-G0.0, H-E-P1.0-G1.0, and H-E-P0.5-G1.5. The decrease in bond strength with higher glass fiber content can be primarily attributed to the formation of voids within the ECC matrix. Increasing the volume of glass fibers tends to disrupt the uniformity of the cementitious matrix due to their rigid and non-pliable nature compared to more flexible fibers like polyvinyl alcohol (PVA). Glass fibers, when added in larger quantities, can create localized areas of weak matrix density due to poor particle packing and increased air entrapment during mixing. The formation of these voids is critical as they act as

stress concentrators within the composite material, significantly weakening the interfacial transition zone between the ECC and the LWC substrate. Voids reduce the effective contact area through which load and stresses can be transferred between the ECC overlay and the concrete substrate. As a result, the mechanical interlocking necessary for optimal bond strength is compromised, leading to reduced overall adhesion.



(a)



(b)

Figure 11. Bi-surface shear bond strengths with grooved and as-cast surfaces for (a) NSLW substrate (b) HSLW substrate.

The increase in PVA fibers leads to a stronger bond with the cement matrix due to the fibers' interaction with the $\text{Ca}(\text{OH})_2$ compound. This interaction forms complex clusters with metal hydroxide, which can create a consistency that reduces the ability to fill the pores on the substrate surface [46]. Conversely, an increase in glass fibers results in the formation of voids in the cement matrix, reducing adhesion and bond strength between the overlay and the original concrete.

Figures 10a and 11a show that the quality and roughness of the adhesion surface of the ECC repair material minimally affect NSLW. The results were similar for grooved and as-cast surfaces in both slant shear and bi-surface shear tests, respectively. The adhesion

strength of ECC was such that failure occurred in the NSLW (substrate layer). Several studies have concluded that the bond strength between two materials is highly influenced by the degree of roughness of the substrate surfaces [47–49]. In this study, to obtain quantitative surface roughness parameters for the LWC surfaces of the specimens, both grooved and as-cast surface methods were used to create a rough surface that ensures a strong bond between the concrete substrate and the repair material. This is crucial to ensure that the ECC repair material contributes to bearing part of the stresses. The effect of surface roughness on bond strength is significant for NSLW in both tests. Figures 10 and 11 show that grooved specimens have a markedly higher bond strength than as-cast surface specimens. This is due to the better interlock provided by the grooved surfaces between the ECC and the LWC substrate, especially in HSLW.

Based on the investigation of PVA and glass fibers on the interfacial properties of lightweight concrete with engineered cementitious composite, a comparison of the test results from the present study with past research is warranted. Reference [50] by Chuanqing Fu et al. focused on corrosion's impact on bond strength and cracking in cement mortar and PVA-ECC, highlighting the complex interactions between material degradation and mechanical properties under corrosive conditions. This complements this study on the mechanical impact of fiber content in non-corrosive environments. Hui et al. [51] examined the dynamic compressive strength of steel fiber-reinforced concrete under cyclic conditions, underscoring the importance of fiber content, similar to these findings on how fiber variations influence ECC's bond strength and integrity. Hui et al. [52] explored the mechanical properties of polypropylene fiber cement mortar under different loading speeds, relevant to our interest in fiber dosage effects under static conditions, suggesting a further investigation into dynamic behaviors. These studies collectively enrich the understanding of fiber-reinforced composites' performance across various conditions, aligning with and expanding upon our research on fiber dosage's structural impacts.

4.3. Failure Mode—Slant Shear Test and Bi-Surface Test

The bond quality between the lightweight concrete (LWC) substrate and the engineered cementitious composite (ECC) overlay can be effectively evaluated by analyzing the locations and types of failure. These failures, documented through visual inspections, are categorized into four distinct modes. Type A: Interfacial Bond Failure—This type of failure, where the bond interface itself fails without material adherence from either the substrate or overlay, was not observed in our experiments. Type B: Interface Failure with Thin Layer Detachment—This mode is characterized by the detachment of thin layers of the LWC substrate that remain adhered to the ECC, indicative of moderate bond strength. Representative images are displayed in Figures 12 and 13. Type C: Interfacial Failure with Thick Layer Detachment—Here, a substantial layer of the LWC substrate remains attached to the ECC, suggesting a robust bond. This type is illustrated in Figures 14 and 15. Type D: Complete Substrate Failure—This most substantial bond type results in the complete structural failure of the substrate, while the overlay remains intact. This scenario is depicted in Figures 16 and 17. Most failures, particularly in the normal-strength lightweight concrete (NSLW) during both slant shear and bi-surface tests, occurred within the substrate itself, showing no cracks in the ECC overlay across both as-cast and grooved surfaces. However, the failures in high-strength lightweight concrete (HSLW) with as-cast surfaces generally stemmed from inadequate friction at the interface between the substrate and the ECC.

In specific cases, such as with the N-E-P1.5-G0.5 and H-E-P1.5-G0.5 samples, interface failures followed internal substrate fractures or occurred wholly within the substrate, demonstrating an exceptionally strong bond strengths of 12.75 MPa and 24.05 MPa, respectively. These observations highlight the critical role of mechanical interlocking and substrate conditions in influencing bond efficacy.



Figure 12. Slant shear typical failure mode B—Interface failure with a thin layer on the substrate.



Figure 13. Bi-surface typical failure mode B—Interface failure with a thin layer on the substrate.



Figure 14. Slant shear typical failure mode C—Interfacial failure with a thick layer of the substrate.



Figure 15. Bi-surface typical failure mode C—Interfacial failure with a thick layer of substrate.



Figure 16. Slant shear typical failure mode D—Complete substrate failure.

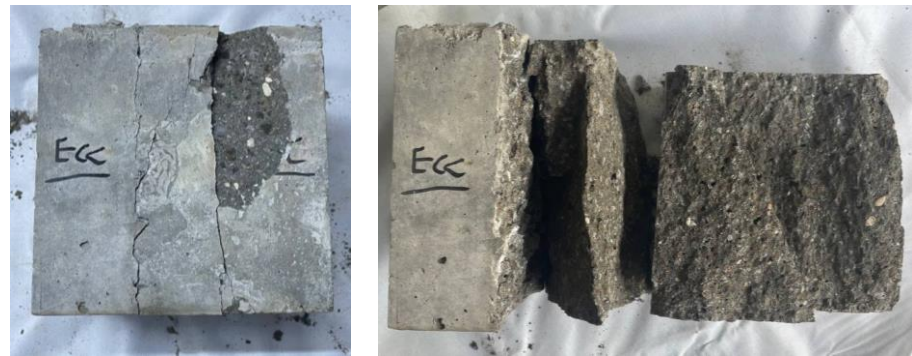


Figure 17. Bi-surface typical failure mode D—Complete substrate failure.

In this study, it was observed that higher concentrations of fibers, particularly glass fibers, are associated with increased porosity within the interfacial transition zone. This increase in porosity is attributed to the disruption caused by the fibers to the packing density of the cement matrix, resulting in the formation of voids and gaps at the interface. Conversely, it was found that optimal dosages of polyvinyl alcohol (PVA) fibers enhance the density of the interfacial transition zone by promoting better interactions between the fibers and the matrix, thereby reducing porosity and enhancing bond strength.

Regarding surface roughness, it was found that higher roughness levels lead to a more mechanically interlocked interfacial transition zone. Rougher substrate surfaces provide greater mechanical anchorage points for the ECC, which decreases the porosity of the interfacial transition zone through improved contact and interlocking at the micro-level. This enhancement in physical bonding contributes to reduced porosity at the interface, which is correlated with increased shear transfer capacity and higher overall bond strength.

4.4. Friction Coefficient

The calculated values of the coefficient of friction (μ) for the studied specimens are summarized in Table 15. The results indicate an increase in the μ values for the grooved surface specimens compared to the as-cast specimens for both NSLW and HSLW substrates. For HSLW, the μ values ranged from 2.101 to 1.375 for grooved specimens and 1.246 to 0.361 for as-cast specimens. These results suggest that the increase in μ is due to the type of substrate surface preparation and the interlock effects between the concrete substrate and the overlay. The highest μ values were observed in specimens H-E-P1.5-G0.5 (2.383) and N-E-P1.5-G0.5 (1.626) with grooved surfaces, which is consistent with the previously mentioned adhesion strength results.

Table 15. Coefficient of friction (μ).

Specimen ID	μ	Specimen ID	μ
N-E-P2.0-G0.0-G	1.4	H-E-P2.0-G0.0-G	2.1
N-E-P1.5-G0.5-G	1.6	H-E-P1.5-G0.5-G	2.4
N-E-P1.0-G1.0-G	1.5	H-E-P1.0-G1.0-G	1.1
N-E-P0.5-G1.5-G	1.1	H-E-P0.5-G1.5-G	1.4
N-E-P2.0-G0.0-A	1.3	H-E-P2.0-G0.0-A	1.2
N-E-P1.5-G0.5-A	1.4	H-E-P1.5-G0.5-A	1.3
N-E-P1.0-G1.0-A	1.2	H-E-P1.0-G1.0-A	0.5
N-E-P0.5-G1.5-A	1.0	H-E-P0.5-G1.5-A	0.4

The fiber dosage within the ECC mix plays a pivotal role in modifying the friction coefficient by directly affecting the surface texture and the microstructure of the ECC when it interfaces with the LWC substrate. Increasing the dosage of fibers, particularly polyvinyl alcohol (PVA) fibers, contributes to an involved and more irregular surface topology at the microscopic level. These fibers, due to their high tensile strength and

stiffness, create micro-anchoring points within the ECC, which protrudes slightly at the interface, enhancing mechanical interlocking with the LWC substrate. As fiber content increases, these micro-anchoring points become more prevalent, effectively increasing the roughness at the microscale, even if the macroscopic surface appears smooth. This increase in microscopic roughness enhances the friction coefficient by providing more points of resistance against sliding, thereby improving the shear transfer capacity across the interface.

The differences in the μ values are significant and can be attributed to the effect of surface roughness on the adhesion surface of HSLW compared to NSLW models. For HSLW, the impact of surface roughness is considerable, as shown in Figures 18 and 19, whereas, for NSLW, the effect of surface roughness is slight.

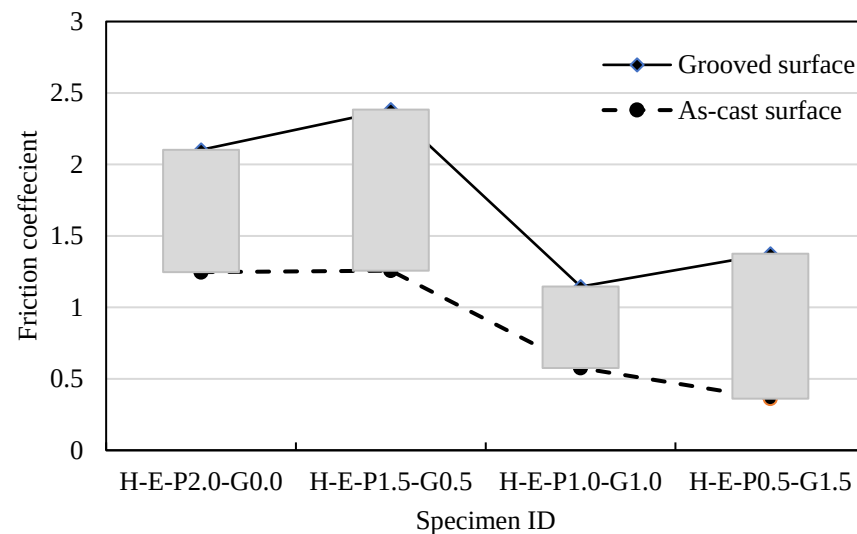


Figure 18. Friction coefficient values between grooved and as-cast surface for HSLW substrate.

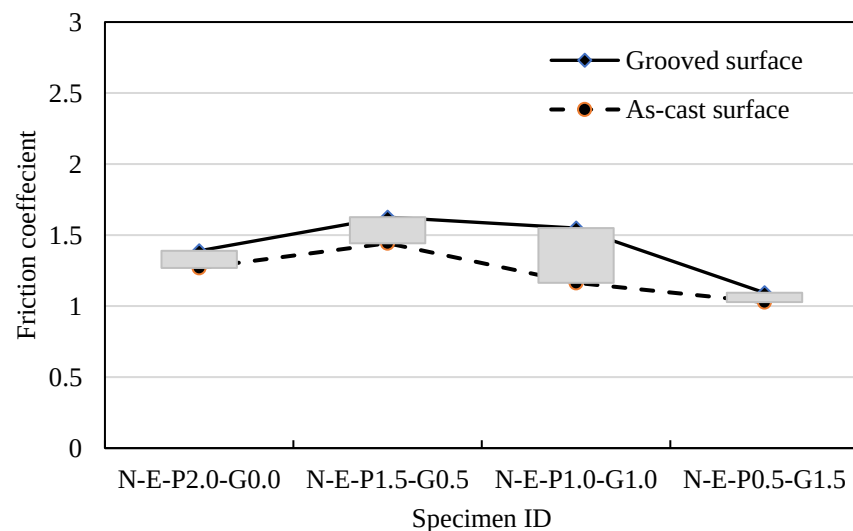


Figure 19. Friction coefficient values between grooved and as-cast surface for NSLW substrate.

This study observed a clear correlation between increased surface roughness and enhanced bond strength. Specifically, as surface roughness parameters increased, bond strength was proportionally enhanced. This relationship is attributed to the improved mechanical interlocking facilitated by more pronounced surface textures, which increases the effective contact area and frictional resistance between the Engineered Cementitious Composite (ECC) overlay and the LWC substrate. Statistical analyses, including regression models, indicated a positive correlation, showing that an increase in surface roughness

parameters significantly enhanced bond strength across various samples and test conditions. Additional data and graphical representations illustrating this relationship will be detailed in the revised manuscript, providing comprehensive insight into how surface roughness directly impacts the bond performance in fiber-reinforced composites.

5. Conclusions

In this research, each analyzed sample consisted of two types of concrete: the substrate LWC and the overlay ECC material. The ECC contained various types and percentages of fibers, specifically 2% PVA fiber, 1.5% PVA + 0.5% glass fiber, 1.0% PVA + 1.0% glass fiber, and 0.5% PVA + 1.5% glass fiber. Multiple factors were considered, including the testing methods and the roughness of the substrate surfaces at 28 days of age. The investigation aims to comprehensively understand how these variables influence the bond performance between the repair materials and LWC substrates. Based on the experimental investigation, the following conclusions were reached:

1. The absence of a high rough surface (as-cast surface) did not significantly affect the adhesion strength between the ECC matrix and the LWC, preventing interface failure. This strength can be attributed to the chemical interaction between active silicon dioxide from supplementary cementitious materials in ECC and $\text{Ca}(\text{OH})_2$ in mature concrete, forming secondary C–S–H. This phenomenon has been demonstrated in several prior studies, indicating that the material has a strong adhesion capacity, which varies depending on surface roughness.
2. Increasing the proportion of glass fibers beyond 0.5% while reducing PVA fibers in the ECC matrix reduces adhesion strength for both slant shear and bi-surface shear tests across different surface roughness levels (as-cast and grooved surfaces).
3. The bond strength is greatly affected by the test method employed. The bond strengths obtained from the slant shear test were significantly greater in both NSLW and HSLW types than those obtained from the bi-surface shear test. It is crucial to select bond tests that can accurately represent the shear stress experienced by structures in real conditions.
4. For the HSLW substrate, surface roughness significantly impacts the bond strength with the repair material (ECC). This effect is observed in both the slant shear and bi-surface shear tests.
5. The coefficient of friction is influenced by the properties and texture of the adhesive surface. When the surface was grooved, there was an increase in the coefficient of friction between both NSLW and HSLW types and the repair material ECC.

It is recommended that the initial findings related to curing age and fiber orientation in composite concrete systems be further explored. The effects of extended curing periods on the bond strength between normal-strength and high-strength lightweight concrete, when combined with engineered cementitious composite (ECC), are to be further investigated. Additionally, the influence of the alignment of polyvinyl alcohol (PVA) and glass fibers within the ECC matrix on mechanical properties and stress transfer should be explored. Further experimental and computational studies are also recommended to quantify the influence of porosity and microstructural characteristics of NSLW on the bonding behavior with ECC. Advanced imaging techniques like scanning electron microscopy (SEM) and micro-computed tomography (μCT) could provide deeper insights into the interfacial properties and clarify the role of surface roughness in different substrate types.

Author Contributions: Data curation, H.M.A.-B.; formal analysis, H.M.A.-B. and M.M.K.; investigation, H.M.A.-B.; methodology, H.M.A.-B. and M.M.K.; project administration, M.M.K.; resources, M.M.K.; supervision, M.M.K.; writing—original draft, H.M.A.-B.; writing—review and editing, M.M.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

LWC	Lightweight Concrete
ECC	Engineered Cementitious Composite
PVA	Polyvinyl Alcohol
NSLW	Normal-Strength Lightweight Concrete
HSLW	High-Strength Lightweight Concrete
GFRP	Glass Fiber Reinforced Polymer
CFRP	Carbon Fiber Reinforced Polymer
ASTM	American Society for Testing and Materials
MPa	Megapascal
mm	Millimeter
COV	Coefficient of Variation
E-waste	Electronic Waste

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