Effects of Fibers on the Interfacial Shear Strength of a Two-Layer Bi-Material Polymer Concrete System

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Abstract

This study presents a comprehensive experimental investigation into the enhancement of interfacial shear strength at the bond interface between old and new concrete layers using polypropylene (PP) fibers and acrylic resin. Given that weak interface performance is a persistent challenge in multilayer concreting and repair operations, particularly when casting delays are unavoidable, this research addresses the necessity of developing material-based solutions capable of improving bond integrity under practical construction conditions. Three placement configurations were examined: monolithic casting (Type A), cold joint with initial set (Type B), and construction joint with final set (Type C). Unlike previous studies that typically evaluated modifiers independently, this work introduces an integrated fiber–polymer strategy and quantifies its performance across varied execution scenarios, thereby emphasizing its innovative and application-oriented contribution. Key variables included PP fibers (12 mm) at 0–1.2% and acrylic resin at 0–7% by weight of cement. Cubic specimens (150×150×150 mm) were tested in direct shear at 7, 14, and 28 days. Results indicated a strong dependence of modifier efficiency on placement conditions. In Type A specimens, the use of 0.7% fibers increased shear strength by 23%. In Type B, while 3% resin alone had negligible effect, its combination with 1.2% fibers improved strength by 11%. Most notably, in Type C, the synergistic application of 0.4% fibers and 3% resin produced a remarkable 71% improvement in interfacial shear strength. These findings demonstrate that the hybrid fiber–polymer system, through crack bridging and enhanced adhesion, provides a robust enhancement mechanism. Overall, the study establishes a scientifically grounded and practically scalable modification method that effectively mitigates the inherent weaknesses of delayed-placement interfaces and offers significant benefits for concrete repair, retrofitting, and layered construction.

Keywords

Interfacial shear strength; Concrete interface; Polypropylene fibers; Acrylic resin; Cold joint; Concrete repair

1. INTRODUCTION

Concrete, as the most fundamental and widely used construction material globally, is extensively utilized in a myriad of civil, infrastructural, and repair projects such as bridges, buildings, dams, and pavements. This material has long held a distinguished position in civil engineering due to the broad abundance and accessibility of its raw materials, relatively low production cost, adequate durability, high formability in its fresh state, and significant load-bearing capacity in its hardened state [1–3]. The ease of production and design flexibility have made concrete an economical and efficient choice for diverse construction needs. However, one of the most significant inherent weaknesses of concrete is its brittleness and low resistance to tensile and shear stresses. This often necessitates the use of steel reinforcement to compensate for this deficiency, leading to the formation of microcracks and, ultimately, a reduction in the service life of structures [4–6] .These cracks not only compromise the structural aesthetics but also pave the way for the ingress of destructive agents (such as moisture and chloride ions). This can lead to progressive deterioration and a significant reduction in the structure's load-bearing capacity. This issue becomes particularly critical in the connection zone or interface—specifically, the interfacial layer of two-layer concrete—where the bond between the old and new layers is of paramount importance [7–9]. To enhance the performance of the connection zone and increase its shear strength, numerous studies have focused on methods such as surface roughening, application of epoxy adhesives, use of composite materials, and concrete-modifying additives [10–12]. While these approaches have been effective to varying degrees in enhancing the bond and durability of the interface, each also possesses specific limitations and implementation challenges. Consequently, the need to find more efficient and economical solutions for strengthening this critical zone has always been emphasized. One novel and promising approach in this area is the simultaneous use of reinforcing fibers and modifying polymers, which can significantly improve the mechanical properties and surface adhesion at the concrete interface [13–15]. This synergistic combination, by leveraging the advantages of both materials, is capable of increasing both the tensile and shear strength of the concrete and significantly enhancing the bond between the old and new layers. This leads to the formation of a more integral and durable bond. Polypropylene (PP) fibers have gained significant attention in recent research due to their low density, high chemical resistance, and ability to control microcracks in concrete [16–18]. The use of these fibers is considered a practical and effective approach, not only due to their favorable physical and chemical properties but also because of their ease of mixing and uniform dispersion within the concrete matrix. By forming a network throughout the concrete, these fibers enhance the transfer of tensile and shear stresses and inhibit crack propagation. This mechanism plays a vital role, particularly during the initial stages of concrete hardening and under cyclic or impact loads, significantly contributing to increased flexibility and resistance to brittle failure [19,20].

Furthermore, PP fibers can act as an effective reinforcing agent, enhancing the shear strength of concrete at the interface of layers, particularly under cyclic loading [6,21,22]. This characteristic is particularly crucial in structures subjected to dynamic or cyclic loads, as the fibers create a bridging mechanism that inhibits crack propagation at the interface and significantly contributes to preserving structural integrity in the long term. This leads to enhanced durability and an extended service life of the structure under severe service conditions. On the other hand, acrylic polymers, as additives for modifying the rheological behavior and adhesion of concrete, possess suitable properties such as high flexibility, adequate chemical durability, and the ability to improve the bond between concrete layers [23,24]. These polymers enhance the workability and finishability of fresh concrete by modifying its properties, which is crucial in repair applications and layer bonding. Furthermore, their ability to form strong bonds with the old substrate significantly improves interlayer adhesion. The use of acrylic resins in combination with cementitious systems leads to the formation of polymer films within the concrete matrix. These films not only increase mechanical strength but also reduce water absorption and permeability. By filling pores and reducing concrete porosity, these polymer films contribute to the improvement of its strength properties. Moreover, by creating a barrier against the ingress of aggressive agents such as chloride and sulfate ions, they significantly enhance the durability and stability of concrete in corrosive environments. This reduction in permeability is one of the most important advantages of using acrylic polymers in concrete employed in high-humidity areas or those exposed to chemicals [25–27].

Some studies have demonstrated that the use of these resins in the interface zone of two-layer concrete significantly enhances shear strength and reduces bond degradation under harsh environmental conditions. This improvement in shear strength, resulting from enhanced cohesion and the creation of a stronger bond surface between the old and new concrete layers, is crucial for ensuring the integral performance of the structure and preventing shear-induced failure. Furthermore, the ability of these resins to mitigate bond degradation under severe environmental conditions-such as freeze-thaw cycles, exposure to corrosive chemicals, or extreme variations in humidity and temperature-demonstrates the long-term durability and stability of this type of connection. These benefits substantially contribute to extending the service life of rehabilitated structures and ensuring their satisfactory performance against environmental degrading agents, proving the high potential of these materials in civil engineering applications [28–30]. The simultaneous combination of polypropylene (PP) fibers and acrylic resin as a novel approach for enhancing the performance of the interface zone in two-layer concrete has garnered significant attention in recent years. The interface zone, as the stress transfer region between different concrete layers, plays a determining role in the structural integrity and resistance against applied loads. Weakness in this zone can lead to premature failure and reduced structural durability; therefore, improving the mechanical properties and bond strength of the interface using modifying additives has always been a key objective in advanced material design. Various studies have demonstrated that the use of polymers and fibers, either separately or in combination, in the mortar or surface layer can lead to improved shear strength or enhanced bond durability. For instance, the use of mortar containing epoxy resin has resulted in a significant improvement in the bond properties and shear strength of the interface zone [31].

Furthermore, studies on engineered materials with high deformability, such as Engineered Cementitious Composites (ECC), have shown that these materials can enhance the shear performance of the interfacial layer by increasing energy absorption capacity and preventing stress concentration. On the other hand, results from investigating the behavior of recycled aggregate concrete in the interface layer indicate that adding modifying compounds such as fibers and polymers can reduce bond failure and lead to increased stability at the boundary between the layers. In parallel to these investigations, some studies have specifically focused on the role of fiber additives in modifying the interface zone. According to the obtained results, the use of acrylic polymers leads to improved internal cohesion, reduced porosity, and increased concrete strength in the interface zone [32]. Investigation into the combined use of PP fibers and acrylic resin has demonstrated that this hybrid system not only leads to a significant increase in shear strength but also alters the failure mechanism, resulting in a more ductile and tougher behavior at the failure zone [33].

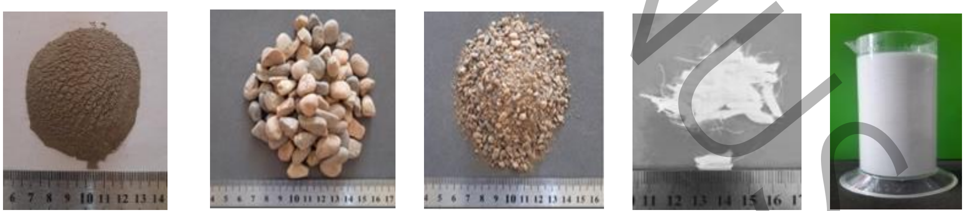
Furthermore, studies on engineered materials with high deformability, such as Engineered Cementitious Composites (ECC), have shown that these materials can enhance the shear performance of the interfacial layer by increasing energy absorption capacity and preventing stress concentration. On the other hand, results from investigations on the behavior of recycled-aggregate concrete in interface layers indicate that incorporating modifying compounds such as fibers and polymers can reduce bond failure and improve stability at the boundary between layers. In parallel, specific studies have focused on the role of fiber additives in modifying the interface zone: for instance, Saberi Varzaneh and Naderi (2022) reported through experimental and finite element analyses that the use of fibers and acrylic polymers significantly enhances the mechanical properties and bond strength between repair mortars and concrete substrates, while Saberi Varzaneh and Naderi (2023) demonstrated that fiber-reinforced mortars improve interface performance and durability under pre-stress conditions [30,34]. Moreover, recent investigations on the interface between concrete and epoxy-modified mortars have highlighted that testing methods, including splitting tensile and direct shear tests, influence the measured interfacial mechanical properties, emphasizing the importance of considering appropriate experimental approaches when evaluating interlayer behavior [35]. According to these findings, the use of acrylic polymers and fibers is associated with improved internal cohesion, reduced porosity, and increased concrete strength in the interface zone, thereby providing a reliable strategy for enhancing bond performance in layered and repaired concrete structures.

Based on previous research findings, it is evident that the use of modifying materials can play an effective role in enhancing the performance of the interface zone. However, a precise assessment of the synergistic effects between fibers and polymers on improving the mechanical properties of the interface requires more extensive laboratory investigations. Therefore, the present study was designed and conducted to investigate the simultaneous effect of polypropylene fibers and acrylic resin on the shear strength of the interface in two-layer concrete. To this end, numerous specimens with different mix designs, including the separate and combined use of reinforcing components, were prepared. The shear strength of these specimens was then tested using the direct single-sided shear method to evaluate the performance of the interface zone under realistic loading conditions. The resulting findings can contribute to the development of efficient solutions for enhancing the durability, stability, and integrity of multi-layer concrete structures under real service conditions.

2. MATERIALS AND METHODS

2.1. Materials

In this research, various materials such as cement, aggregate, polypropylene fibers, and polymer were used, which are presented in the Figure 1.



(a) (b) (c) (d) (e)

Figure 1: Materials used in the present study (a) Type II cement, (b) coarse aggregate, (c) fine aggregate, (d) PP fibers, (e) polymer.

2.1.1. Cement

The cement used in the present study was Type II Portland cement conforming to ASTM C150/C150M-23 [36] .
This cement is used for producing concrete where moderate heat of hydration is essential and exposure to sulfates is expected to be at a moderate level. Due to the limited aluminate phase and lower tricalcium silicate content in this cement, which are responsible for the aforementioned specific properties, the initial and final compressive strength of its standard mortar is lower than that of Type I Portland cement. The chemical specifications of this cement are provided in Table 1 as defined by the standard ASTM C150/C150M-23.

Table 1. Chemical specifications of Type II Portland cement [37].

Chemical Parameters	Value(%)
CaO	63
Sio2	20.4
Al2O3	4.9
Fe2O3	3.9
MgO	1.7
SO3	2
NaO2+K2O	0.9
Loss on ignition (LOI)	1.5
Specific gravity	3.12

2.1.2. Aggregate

The fine and coarse aggregates used in this research consisted of both crushed and river-origin materials. The coarse aggregate had a maximum size of 20 mm, and the fine aggregate had a maximum size of 9.5 mm. The utilized sand had maximum particle sizes of 19 mm and 4.75 mm, an apparent specific gravity of 2420 kg/m³, and a water absorption of 1.5%. The gradation curve for these materials was obtained through sieve analysis conducted in accordance with ASTM C136, ASTM D422, and ASTM C33 standards, and is presented in the Figure 2. The solid lines indicate the mean particle size distributions, while the dashed lines represent the upper and lower permissible limits [38,38–40].

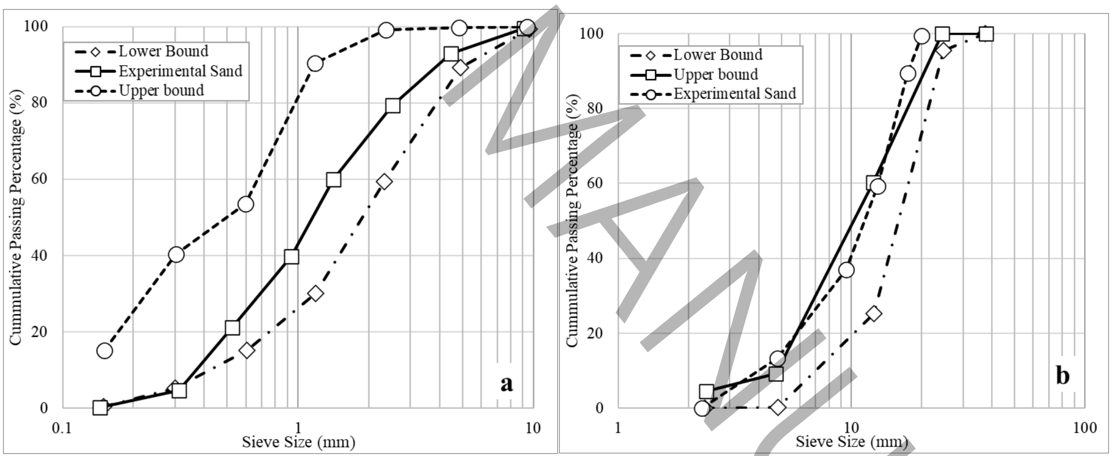


Figure 2: Particle size distribution curves for sand and gravel: (a) coarse and (b) fine aggregate

2.1.3. Fiber

Polypropylene fibers were used in this research. Unlike steel, these fibers are not affected by weather conditions, the alkaline environment of concrete, or the presence of moisture. Since these fibers are immune to corrosion and rust, concrete containing them exhibits long-term durability and strength. The geometric parameters of the fiber, including length, equivalent diameter (or thickness), and aspect ratio, are presented in Table 2.

Table 2. Physical and chemical properties of the polypropylene fibers used [41]

Parameters	Characteristics
Physical State	Solid fibrous
Color	White
Specific Gravity (gr/cm³)	0.91
Melting Point (°C)	160
Tensile Strength (MPa)	445
Elasticity Modulus (GPa)	5
Length (mm)	12

Diameter (mm)	0.091
Aspect ratio (L/D)	131.9

2.1.4. Polymer

In this study, the styrene-acrylic polymer (SA-12), which is a widely used concrete admixture with numerous applications in the construction industry, was employed. This polymer is an emulsion based on acrylic resin that effectively enhances the tensile strength, flexural strength, abrasion resistance, adhesion, and durability of concrete, plaster, or lime, and can help prevent cracking (reference to be added). This polymer can be evaluated according to ASTM C1059, C1042, and C1440 standards [42–45]. The specifications of the polymer used are provided in Table 3 as defined by the standard ASTM C1059.

Table 3. Physical and chemical properties of the polymer [43]

Parameters	Characteristics
Physical State	Viscous liquid
Chloride Ion	None
Specific Gravity (gr/cm³)	1.05 ± 0.05
Color	Milky white
pH	6.5 ± 1

2.2. Preparation of Concrete Specimens

For the fabrication of concrete specimens, the required materials including cement, aggregates (sand and gravel), and fibers were precisely weighed according to the mix design. Dry mixing of the raw materials was carried out for one minute in a laboratory mixer. Subsequently, water and polymer were gradually added, and mixing continued until complete homogeneity was achieved (approximately 3-5 minutes). After measuring the slump, the concrete mixture was cast and compacted into standard cylindrical and cubic molds in accordance with the standard. The specimen surfaces were finished and kept in an environment with over 90% relative humidity for 24 hours. The specimens were then demolded and cured fully saturated in a water tank at a temperature of 23 ± 1.7°C. All procedures for specimen fabrication and curing conformed to ASTM C192/C192M (to be referenced). During casting, the molds were lubricated and filled accordingly: Type A specimens were completely filled, whereas for Type B and Type C, only half of the mold was initially filled, with the remaining half cast after a specified time interval. Figure 3 illustrates a view of the partially filled molds for Type B and Type C specimens, and Figure Y shows the fully cast specimens. At the age of 28 days, the specimens were removed from the tank, surface-dried with a cotton cloth, and their weight and dimensions were determined. Finally, they were subjected to direct shear testing [46].

Figure 3. Concrete specimen preparation and curing: (a) Mold preparation and casting procedure for Type A, B, and C (half-filled for Type B and C); (b) Partially filled molds for Type B and C; (c) Fully cast specimens; (d) Specimens curing in a water tank under full saturation.

2.3. Concrete Mix Design

A series of tests were conducted to investigate the effects of the polymer on the shear strength behavior of fiber-reinforced concrete. The mass proportions of the constituents were selected based on preliminary trial mixes aimed at achieving adequate workability, cohesiveness, and uniform dispersion of the additives. The adopted replacement levels also fall within the commonly recommended ranges reported in previous studies (e.g., [47,48]). Three water-to-cement ratios (0.40, 0.45, and 0.50) were employed to account for the variation in water demand caused by the inclusion of the additives and to maintain comparable workability among different mixtures. The experimental program is presented in the Table 4.

2.4. Laboratory Experiments

The laboratory experiments conducted for this research were divided into two main categories: tests on fresh concrete and tests on hardened concrete.

2.4.1. Fresh Concrete Tests

A slump test was performed to measure the rheological behavior-specifically, the workability and consistency-of the fresh concrete. The slump test was carried out in accordance with ASTM C143/C143M standard. In this test, fresh concrete was placed into a slump cone with top and bottom diameters of 100 mm and 200 mm, respectively, and a height of 300 mm.

Table 4: Mix designs used for fabricating the concrete specimens

Row	Mix Design ID	Cement (kg/m³)	Water (kg/m³)	Coarse Aggregate (kg/m³)	Fine Aggregate (kg/m³)	Fiber & Additive Type	W/C	Fibers & Additives (kg/m³)	Density (kg/m³)
1	Control Sample 1	350	140	510	1406	-	0.4		2406.0
2	Control Sample 2	350	175	510	1315	-	0.5		2350.0
3	Control Sample 3	350	192.5	510	1268	-	0.55		2320.5
4	pp 0.4%	350	175	510	1312.8	PP	0.5	1.4	2349.5
5	pp 0.7%	350	175	510	1310	PP	0.5	2.45	2347.5
6	pp 1%	350	175	510	1308	PP	0.5	3.5	2346.5
7	pp 1.2%	350	175	510	1306	PP	0.5	4.2	2345.5
8	Poly 3%	339.5	175	510	1297	SA-12	0.5	10.5	2332.0
9	Poly 5%	332.5	175	510	1286	SA-12	0.5	17.5	2321.0
10	Poly 7%	325.5	175	510	1274	SA-12	0.5	24.5	2309.0
11	0.4%pp+3%poly	339.5	175	510	1294	PP-SA-12	0.5	1.4-10.5	2330.5

The fresh concrete was placed into the conical mold in three layers, with the height of each layer being approximately one-third of the total slump cone height (h). Each layer was compacted by 25 strokes of a standard tamping rod. After compacting the third layer, the slump cone was carefully lifted vertically upwards, without any shock or rotation, after approximately 10 seconds. The difference in height between the mold and the displaced concrete specimen was recorded as the slump value [26].

2.4.2. Tests on Hardened Concrete (Shear Strength)

The direct shear test is a key and validated method for evaluating the shear strength of concrete specimens, particularly at the interface or bond between fresh and hardened concrete layers. In this method, loading is applied such that shear stresses are directly imposed on the shear plane, enabling the investigation of internal cohesion, crack propagation, and the performance of additives such as polypropylene fibers and polymers under shear stresses [49,50]. Among the most important international standards in this area is ASTM C882, known as the "Standard Test Method for Bond Strength of Epoxy-Resin Systems Used with Concrete by Slant Shear." This method is primarily used to assess the bond performance between two concrete layers or between concrete and repair materials. Furthermore, the EN 12615:2004 standard from the European Committee for Standardization introduces a test method for the shear bond strength of repair and protection systems for concrete [51]. In the present study, a direct shear method was employed to evaluate the shear strength of cubic specimens. Due to its accuracy and simplicity of execution, this method allows for the direct analysis of the effects of various compositions, including polypropylene fibers and acrylic resin.

For conducting the shear strength tests - including direct shear strength, interfacial shear strength, and single-plane shear strength - a pair of special steel grips for 150×150×150 mm cubic specimens was designed and manufactured. This apparatus enabled the precise transfer of concentrated force to the predefined shear surface. It should be noted that, due to the configuration of the loading system, the shear rupture plane is intentionally predetermined, and the specimen is forced to fail along this controlled interface. This inherent characteristic of the test method allows for consistent evaluation of the material response along a fixed shear plane, while it does not represent a naturally developed failure path in the concrete. A view of the grips used in the experiments is shown in Figure 4.

Figure 4: Image of the manufactured steel grips for performing the shear test: (a) the shear grip mold, (b) the placement of the shear grip mold and the concrete specimen inside it within the compressive strength jack.

To perform the shear test, specimens were fabricated similarly to those for compressive strength testing (150×150×150 mm cubes). After 7 and 28 days of curing under fully saturated conditions, the specimens were placed into the shear test mold. The mold, containing the concrete specimen, was then positioned in the compressive testing machine. The machine applied a compressive force to the upper grip.

The shear strength is defined as the maximum force sustained by the concrete prior to failure. It can be calculated using Equation (1):

$$\tau_v = \frac{F_v}{A_v} \quad (1)$$

Where F_v is the maximum vertical load applied to the concrete before shearing (N), A_v is the sheared cross-sectional area of the concrete (mm²), τ_v is the shear strength of the concrete (MPa).

3. Results and Discussion

3-1. Physical Properties of Fresh Concrete

To investigate the effects of additives on workability, specimens with fiber contents ranging from 0% to 1.2% and polymer contents from 0% to 7% were fabricated. The control specimen (CS) in this study was defined as concrete containing no additives (neither polymer nor fibers). The results are presented in the Figure 5.

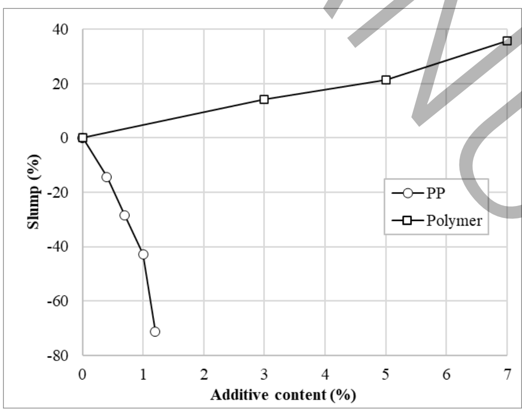


Figure 5. Effects of Fiber and Polymer Additives on Concrete Workability (Slump Test)

As observed in this figure, the workability of concrete decreased with increasing fiber content. This phenomenon aligns well with findings from other researchers [52,53]. The maximum reduction in concrete workability due to the presence of fibers was approximately 70% compared to the control concrete (containing no fibers or polymer). This can be attributed to the increased specific surface area of the fibers and their higher water absorption. This effect can lead to greater internal friction within the mixture and a consequent reduction in workability. A decreased slump in fiber-reinforced mixtures can result in inadequate fiber distribution if the mix design is not properly controlled. To compensate for the loss of fluidity in mixtures containing fibers, the use of super plasticizing water-reducing agents is recommended, a point also emphasized in standards such as ASTM C494/C494M [54].

For a comparative analysis between different additives, concrete was produced using the optimal percentages obtained from the shear strength tests, as well as a sample containing the optimal fiber-polymer combination. The results are presented in the Figure 6.

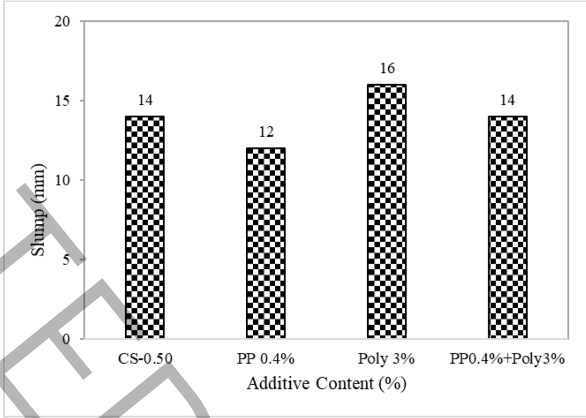


Figure 6: Comparison of Slump Values for Different Mix Designs

As illustrated in this figure, the incorporation of fibers resulted in an approximately 14% reduction in concrete workability compared to the control mix. This reduction in fluidity is attributed to the increased internal friction between fibers and cement particles, as well as the partial absorption of mix water by the fibers. In contrast, the inclusion of polymer led to an increase in concrete workability of approximately 14%. This enhancement in fluidity stems from the inherent lubricating property of polymer resins and their effect on reducing the surface tension of water in the concrete mixture. The use of water-soluble polymers can improve the flowability and compatibility of fresh concrete. A significant observation is that the presence of polymer in the fiber-reinforced concrete mitigated its workability loss, resulting in a workability level comparable to that of the control mix. This finding indicates that the negative effect of fibers on concrete fluidity was neutralized by the positive effect of the polymer. While enhancing the mechanical properties of concrete, this hybrid combination of additives can also effectively maintain the initial fluidity of the concrete.

3-2. Tests on Hardened Concrete

This research investigated the combined effect of acrylic resin and polypropylene fibers on the shear behavior of the interfacial transition zone in hardened concrete. Concrete specimens were prepared as 150×150×150 mm cubes and, after a minimum curing period of 28 days under moist conditions, were subjected to a direct shear test. These tests were conducted to analyze the behavior of cold joints, assess the bond between concrete layers, and examine the role of polymer and fiber additives in enhancing shear strength. To study the effects of the concrete placement method, three main procedures were evaluated: monolithic casting (A), delayed casting after initial setting (B), and delayed casting after final setting (C). The details of these procedures are provided in Table 5.

Table 5. Classification of Hardened Concrete Specimens Based on Layer Placement Method and Type of Shear Test

Group Type	Test Designation	Description
A	Direct Shear Strength of Monolithic Specimen	Concrete was placed continuously in a single stage, resulting in a fully monolithic specimen.
B	Single-Plane Shear Strength of Specimen (Initial Set)	The second concrete layer was placed with a one-hour time interval after the first layer to investigate the effect of time delay on interlayer bonding
C*	Single-Plane Shear Strength of Specimen (Final Set)	The second layer was placed after the first layer had completely hardened; this category includes various mixtures of concrete modified with fibers, polymer, or a simultaneous combination of both materials.

* In Group C, the specimens were cast in two layers. Initially, half of the mold was filled with ordinary concrete. After this section had fully hardened, the second half of the mold was completed using one of the concrete mixtures containing fibers, polymer, or a combination of both. This method was designed to simulate cold joint conditions, investigate the

effects of layered concrete placement, and evaluate the performance of modifying materials in enhancing interlayer bond, reducing the vulnerability of the joint interface, and exploring potential applications in strengthening and rehabilitating concrete structures.

Since the microstructural parameters such as the Interfacial Transition (ITZ) were not experimentally quantified in this study, their influence on the measured shear response cannot be directly validated. Accordingly, references to ITZ densification in the following analysis should be interpreted as potential mechanisms inferred from macroscopic behavior and supported by trends reported in the literature.

3-2-1. Influence of W/C on the Shear Strength of the Interfacial Layer

To investigate the effects of the water-to-cement ratio (W/C) on the shear strength of the interfacial layer, concrete specimens with W/C ratios of 0.4, 0.5, and 0.55 were tested at different ages of 7, 14, and 28 days. The results are presented in the Figure 7.

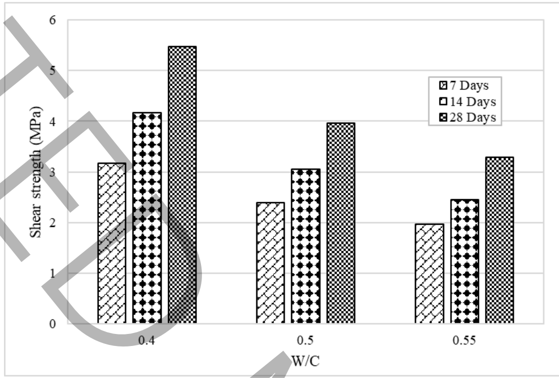


Figure 7. Effects of W/C on the Shear Strength of CS concrete

As observed in the figure 5, the water-to-cement ratio (w/c) is a determining parameter for the shear strength of the interfacial layer. Specimens with a w/c ratio of 0.4 demonstrated the highest shear strength compared to other mixtures, a finding consistent with results reported by Mehta & Monteiro (2014) [4]. This phenomenon enhances shear strength, particularly in the critical interfacial zone, through several interconnected mechanisms. The fundamental basis for this improvement is reduced porosity and increased microstructural density. By reducing the water-to-cement ratio to an optimal value (0.4 in this study), the concentration of cement particles per unit volume increases, leading to the formation of a denser and more homogeneous cement paste structure after hydration. This compaction may influence the ITZ, a region generally considered the weakest part of concrete owing to its higher porosity and the tendency for water to accumulate during casting. At lower w/c ratios, the thickness and porosity of this critical zone are significantly reduced, consequently creating a stronger physical and chemical bond between the cement matrix and the aggregate surface. This enhanced bond facilitates more effective stress transfer and ultimately improves resistance to shear failure, which often concentrates in this zone. In contrast, increasing the w/c ratio beyond this optimal value significantly weakened the shear strength. Specifically, increasing the w/c ratio from 0.4 to 0.55 led to a sharp decline of approximately 39% in the shear strength of the interfacial layer. This considerable reduction is likely associated with higher porosity in the cement paste, with the effect being more pronounced in areas corresponding to the ITZ [22]. Excess water in the mixture, after hydration, leads to the formation of more micropores and capillary channels, which weaken the microstructural cohesion and transform the interfacial zone into a critical region prone to failure. Consequently, the capacity for shear stress transfer in this area is severely diminished. It is noteworthy that an excessively low ratio (below 0.35) can have adverse effects due to reduced workability and inadequate compaction. In addition to the w/c ratio, the data indicated a positive and continuous influence of increasing curing age on the shear strength of all specimens, regardless of their w/c ratio. This phenomenon is directly related to the ongoing cement hydration process. As hydration progresses, secondary products like Calcium Silicate Hydrate (C-S-H) may accumulate within the paste and in areas corresponding to the ITZ, potentially lowering the overall porosity. This process leads to increased microstructural density and bond strength at the interface. Therefore, even specimens with high w/c ratios exhibited improved shear strength with increased curing age, although their absolute strength never reached the level of specimens with the optimal w/c ratio (0.4). For the tests in this research, the water-to-cement ratio was set at 0.5 to ensure the necessary concrete workability without using water-reducing admixtures (such as polycarboxylates) [24].

3-2-2. Influence of Fibers on Concrete Shear Strength

This study investigated the effect of adding polypropylene (PP) fibers on the direct shear strength of concrete specimens with a water-to-cement ratio of 0.5. Cubic specimens measuring 150×150×150 mm were prepared with different percentages of PP fibers (by weight of cement) and tested. The obtained results are presented in Figure 8.

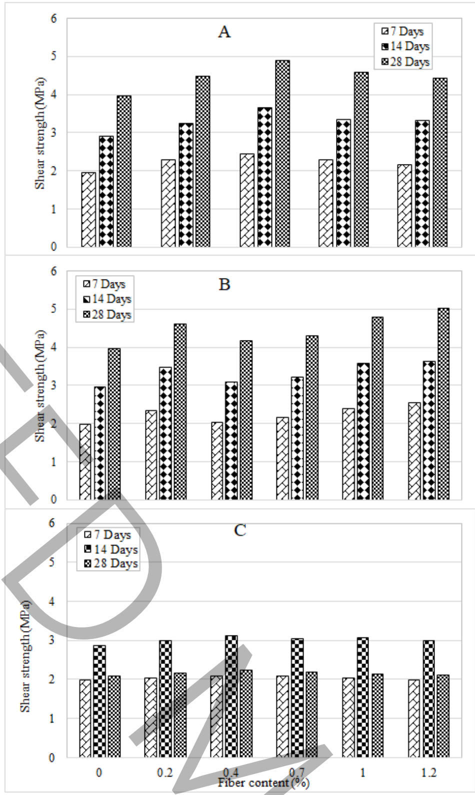


Figure 8. The effect of fibers on the shear strength of the concrete interfacial layer.

Based on the chart data, the shear strength of the interfacial layer follows an ascending trend with an increase in polypropylene fiber content from 0% to 0.7% by weight [4]. Specimens tested at 7, 14, and 28 days also exhibited a continuous growth in shear strength, indicating the sustained positive influence of fibers as hydration progresses. Within this range, the maximum shear strength was recorded for the specimen containing 0.7% fibers, representing a 23% increase compared to the control specimen (without fibers). This performance enhancement is primarily attributed to the multifaceted role of fibers in reinforcing internal mechanisms. Fibers create a "bridging effect" across micro-cracks, preventing stress concentration and promoting a more uniform distribution of shear stresses throughout the concrete volume [24]. This mechanism simultaneously leads to increased fracture toughness and greater energy absorption before ultimate failure. Furthermore, the interconnected fiber network enhances internal cohesion and strengthens the bond between the cement paste and aggregates, facilitating more effective stress transfer and acting as an internal reinforcement system. Another possible contributing factor is the improved behavior of regions commonly associated with the ITZ; the presence of fibers may reduce paste shrinkage and form a flexible micro-network, which can help limit microcracking and potentially enhance the bond between the cement paste and aggregates. However, as the fiber content increased from 0.7% to 1.2%, the trend of shear strength improvement reversed, and a relative decrease was observed. This phenomenon can be mainly attributed to the reduced workability and fluidity of fresh concrete due to the increased fiber volume [3]. Decreased workability can lead to incomplete compaction and the formation of weak points in the concrete microstructure, especially in the sensitive interfacial zone. Additionally, the risk of fiber balling and non-uniform distribution at high percentages can create stress concentration points, ultimately undermining cohesion and shear strength. Moreover, at very high percentages, fibers may act as independent stress concentration points rather than reinforcing the matrix, becoming initiation points for cracks themselves. Consequently, the incorporation of polypropylene fibers up to an optimal dosage (0.7% in this study) results in noticeable enhancement of interfacial shear strength and concrete toughness through fiber-bridging and increased internal cohesion. A potential improvement in regions associated with the ITZ may also contribute to this behavior. Nevertheless, higher fiber contents negatively affect workability and homogeneity, ultimately reducing performance. Therefore, the utilization of these fibers must be accompanied by careful review and optimization of the mix design to achieve a desirable balance between the properties of fresh concrete (workability) and hardened concrete (shear strength and toughness).

Figure (Type B) illustrates the variation in shear strength at the interfacial layer of two-layer concrete specimens with delayed casting (simulating a cold joint). In this configuration, the bottom layer consists of ordinary concrete (OC), and the top layer contains varying percentages of polypropylene (PP) fibers. This experiment aimed to simulate practical repair conditions and evaluate the shear performance of the connection between existing concrete (at the end of initial setting) and fresh fiber-reinforced concrete. According to the results, the presence of fibers generally led to increased interfacial shear strength compared to the control specimen (without fibers), which aligns with previous studies [50,55]. However, the trend of strength variation with increasing fiber content was non-linear, demonstrating an optimization behavior. Specifically, increasing the fiber content from 0% to 0.2% caused an approximately 16% increase in strength. Yet, with a further increase in fibers to 0.7%, the shear strength decreased, approaching the strength level of the control specimen. This unexpected decline at the intermediate percentage is primarily due to the significant reduction in the fluidity and workability of the fresh concrete, leading to inadequate compaction and insufficient penetration into the surface roughness of the underlying layer. Furthermore, the non-uniform distribution and balling of fibers at this percentage create stress concentration points, while the high apparent density of fibers impedes effective mechanical interlock and engagement of aggregates across the joint, forming a fiber-rich soft layer at the interface that directly reduces resistance to sliding and shear. Ultimately, with a further increase in fibers to 1.2%, the maximum shear strength reached approximately 5 MPa (equivalent to a 27% increase compared to the control), a significant improvement at the optimal percentage, attributable to mechanisms such as enhanced mechanical interlock, increased surface friction, and crack bridging and restraint by the uniform fiber network. These results clearly demonstrate that achieving maximum fiber efficiency in improving cold joint performance is highly dependent on reaching an optimal percentage and uniform fiber distribution to avoid execution challenges at intermediate percentages and realize structural benefits at higher percentages. As observed in the Type C chart, specimens containing fibers in the range of 0% to 0.4% showed a negligible increase in shear strength of about 4% compared to the control specimen (without fibers). However, as the fiber percentage increased from 0.4% to 1.2%, a declining trend in shear strength began, such that at 1.2% fiber content, the strength of the fiber-reinforced specimen nearly decreased to the level of ordinary concrete (control). This behavior occurred under conditions where the second concrete layer was placed after the first layer had reached its final set. In such a scenario, the possibility of establishing a strong chemical bond between the two layers, which is the primary mechanism for shear transfer, heavily depends on direct contact and the penetration of fresh cement paste into the surface roughness of the hardened first layer. The presence of fibers, especially at high percentages, fundamentally weakens this bond through two mechanisms: firstly, by significantly reducing the workability of the second concrete layer, it hinders the effective penetration of cement paste into the surface micropores of the first layer, preventing proper adhesion. Secondly, the non-uniform distribution and balling of fibers near the interface physically act as a separating layer, disrupting the direct contact between the cement matrix of the new layer and the existing concrete. Consequently, in this specific execution scenario, the usual benefits of fibers, such as crack bridging, are unable to compensate for the strength reduction due to the fundamental weakening of the primary bond at the interface, ultimately leading to a decline in the shear performance of the system.

3.2.3. Influence of Polymer on Concrete Shear Strength

To investigate the effect of polymer resins on the mechanical performance of concrete, this study employed acrylic resin as a polymer modifier at different percentages (3%, 5%, and 7% by weight of cement), partially replacing cement in the mix design. Cubic specimens measuring 150×150×150 mm were prepared and subjected to direct shear strength testing after 7, 14, and 28 days of curing. The results are presented in Figure 9.

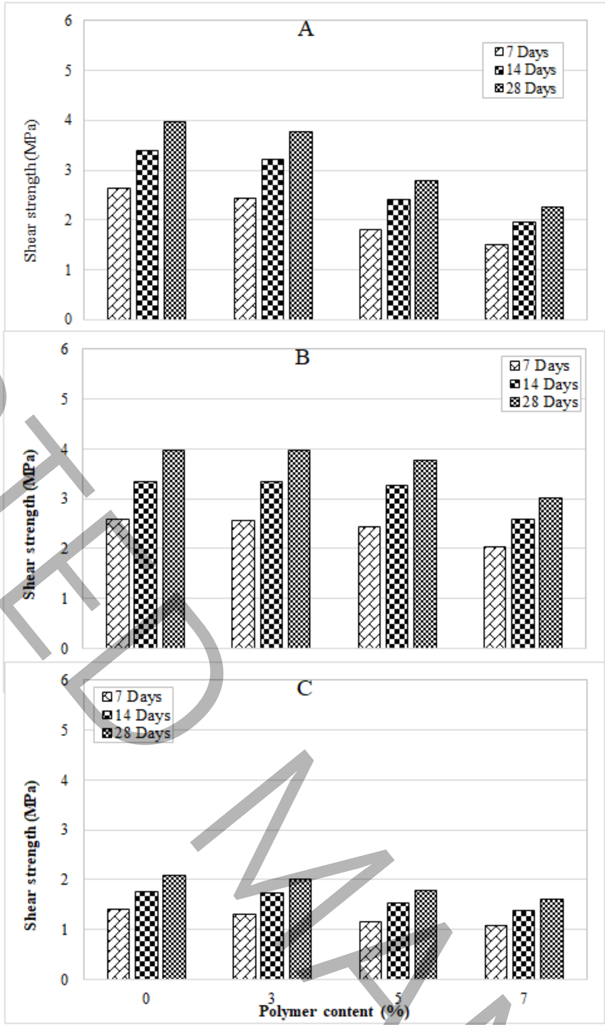


Figure 9. Direct shear strength of 28-day specimens containing polymer

As observed in Figure 8A, the incorporation of polymer led to a reduction in the shear strength of concrete. At the highest dosage level (7%), the shear strength of the specimens decreased by approximately 42% compared to the control specimen. However, using the resin at a 3% level showed the least strength reduction (approximately 4%) and can be considered as a preliminary optimum value. The observed reduction in shear strength can be attributed to several factors, including interference of organic resins with the cement hydration process, increased porosity in the cementitious matrix, and the formation of weak layers in the interfacial transition zone between the paste and aggregate [4]. Furthermore, the presence of the resin may reduce the cohesion between the paste components and aggregates, consequently weakening the bond strength at shear interfaces [56,57]. Despite this mechanical reduction, acrylic resin offers benefits such as improved durability, reduced water absorption, and enhanced adhesion to various surfaces; characteristics that justify its use in corrosive environments and the design of lightweight elements [51,58]. These results align with previous studies and emphasize the necessity of optimizing the resin content to achieve a suitable balance between the mechanical properties and durability of concrete [19,59].

As illustrated in Figure 8B, the addition of polymer up to approximately 3% by weight had no significant effect on shear strength, with its strength remaining comparable to that of the control concrete. However, increasing the resin content to 7% resulted in a notable reduction in shear strength of approximately 24% compared to the control. This phenomenon can be attributed to several factors: firstly, the increased polymer concentration may reduce friction and mechanical interlock at the interface of the two layers. Secondly, by filling voids and reducing surface roughness, polymers diminish the mechanical engagement between particles in the joint region. Previous studies have also indicated that while some polymer additives improve durability and reduce permeability, they may adversely affect the shear strength at the interface ([49,55]. In summary, the results of this section demonstrate that the uncontrolled use of polymer resins in the joint area can lead to weakened interlayer bonding and reduced shear strength. Therefore, careful attention to the dosage and application conditions of polymer resins is essential in concrete strengthening and repair projects.

As seen in Figure 8C, the presence of polymer resulted in decreased shear strength. The addition of polymer to concrete from 0% to 7% led to a reduction in shear strength of approximately 23% compared to the control specimen. This decline in shear strength can be ascribed to several factors: reduced contact surface roughness due to the resin presence, impeded effective penetration of fresh cement paste particles into the hardened layer, and diminished internal friction and mechanical interlocking in the connection zone. Previous studies have also shown that although the use of polymers in repair or bilayer applications may enhance some local concrete properties, in the absence of adequate surface preparation or the use of stronger adhesive resins such as epoxy, the bond at the interface can be significantly compromised [49,55]. Consequently, it can be concluded that in layered applications, the use of polymer alone cannot provide adequate performance in improving the shear strength of the interface, unless the method of applying the second layer, the preparation of the base concrete surface, and the type of resin are selected with precise engineering consideration. This issue further underscores the importance of considering the chemical and mechanical interaction of the resin with the hardened concrete surface.

3.2.4. Combined Effect of Fibers and Polymer on Concrete Shear Strength

This section investigates the simultaneous effect of polymer and fibers on the shear strength of the concrete interfacial layer. Concrete specimens containing optimal percentages of fibers and polymer (Polymer=3%, PP=0.4%) were prepared and subjected to direct shear strength testing at different curing ages of 7, 14, and 28 days under fully saturated conditions. For comparison, control specimens (without additives), fiber-only specimens, and polymer-only specimens were also prepared. The results of these tests are presented in Figure 10.

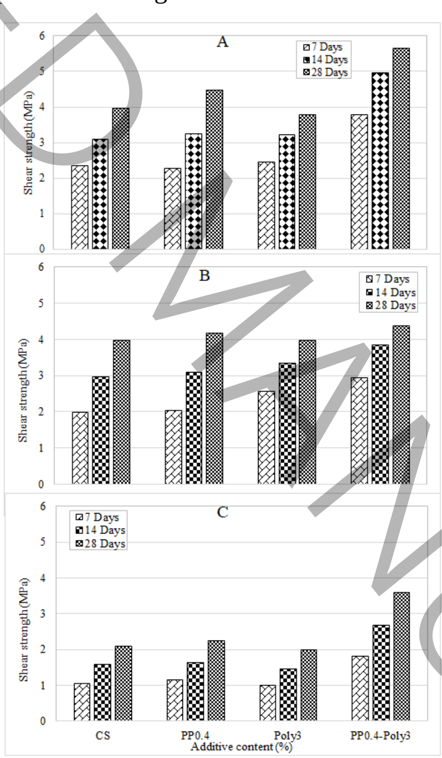


Figure 10. Direct shear strength of 28-day specimens containing polymer and fibers

Based on the data from Figure 9A, composite specimens containing acrylic resin and polypropylene fibers showed significant improvement in direct shear strength. While the separate use of acrylic resin resulted in an approximately 5% reduction, and the use of polypropylene fibers alone led to a 13% increase in shear strength compared to the control specimen, the simultaneous application of both materials produced a 29% increase in direct shear strength and an approximately 42% increase in interfacial strength. This notable improvement stems from the synergistic effect of the two materials, where fibers compensate for the weakness induced by the polymer in the cement matrix through crack-bridging mechanisms, while the polymer enhances stress transfer to the fibers by improving adhesion and chemical cohesion. This finding aligns completely with previous studies emphasizing significant improvement in shear behavior and mechanical strength of concrete through combined use of modified resins and polymer fibers [60,61]. Furthermore, this combination enhances interlayer cohesion and increases shear strength, potentially improving the behavior of critical regions such as joints and areas commonly associated with the ITZ, which broadens its applicability in the strengthening and repair of concrete structures [57].

As observed in Figure 9B, the results of direct shear tests at the interface between hardened concrete (OC) and fresh concrete containing a combination of acrylic resin (3%) and polypropylene fibers (0.4%) are presented compared to control specimens and polymer-only specimens. The data indicate that using polymer alone had no significant effect on shear strength; while adding fibers alone and the simultaneous combination of fibers and polymer led to approximately 6% and 11% increases in interface shear strength relative to the control specimen, respectively. This notable performance improvement can be attributed to the synergistic effect of the two materials; the acrylic resin enhances cohesion at the interface by filling pores and reducing surface water absorption, while the polypropylene fibers increase the resistance of the contact area between the two layers by creating mechanical interlock, controlling crack propagation, and effective stress distribution [49,50]. Additionally, the presence of fibers prevents stress concentration at the cold joint and enhances the stability of the connection between layers [55]. These findings confirm that the combined use of fibers and polymer as modifying materials can provide an effective solution for enhancing durability, cohesion, and shear performance at cold joints and connection surfaces in concrete structures.

Figure 9C shows the effect of modifying materials in the second layer on the shear performance of the contact surface. The specimen containing 3% polymer alone resulted in a 4% reduction in interfacial shear strength compared to the control specimen, a phenomenon caused by the formation of a smooth polymer layer and weakened mechanical interlock at the contact surface [49]. In contrast, specimens containing 0.4% fibers alone showed a 7% increase in shear strength. The performance peak was related to the simultaneous combination of polymer and fibers, which was accompanied by a 71% increase in shear strength compared to the control specimen. This remarkable improvement indicates a synergistic effect between the two materials; the polypropylene fibers enhance cohesion and effective stress transfer at the interface simultaneously through mechanical interlock, crack control, and uniform stress distribution, while the acrylic resin fills pores and improves contact surface uniformity [50,55]. These findings demonstrate that although individual use of polymer may have negative effects on surface cohesion, its combined application with fibers not only compensates for this weakness but can also serve as an effective strategy in projects involving strengthening, rehabilitation, and connection of precast concrete elements.

4. **CONCLUSION**

This study investigated the combined effects of polypropylene fibers and acrylic resin on the shear strength of the concrete interface. Tests were conducted on cubic specimens measuring 15×15×15cm under three distinct casting scenarios (Type A: continuous, monolithic casting; Type B: two-layer casting with the second layer placed after the first layer reached initial set and Type C: two-layer casting with the second layer placed after the first layer reached final set). The independent variables were the water-to-cement ratio (W/C=0.40, 0.50, 0.55), fiber content (0–1.2%), and polymer (acrylic resin) content (0–7%). Direct shear tests were performed at curing ages of 7, 14, and 28 days to capture the time-dependent development of the cementitious matrix. The main findings of the study are summarized as follows:

The findings of this study demonstrate that the mechanical and fresh-state behavior of concrete incorporating polypropylene fibers and acrylic resin is highly dependent on the mixture design parameters and, more critically, on the placement conditions. The slump test results confirmed that the water-to-cement ratio, fiber dosage, and polymer content govern the rheology of fresh concrete. While higher W/C ratios improved workability, this enhancement may adversely affect the mechanical response of hardened concrete. Polypropylene fibers reduced slump through increased internal friction and water entanglement, whereas acrylic resin improved mixture fluidity and served as an effective compensating agent when used in combination with fibers. These observations emphasize that achieving a practical balance between workable mixtures and favorable hardened properties requires careful optimization of additive combinations.

In monolithic specimens (Type A), fibers at the optimal level of 0.7% improved shear strength by approximately 23% through crack-bridging actions and increased internal cohesion. Any influence related to regions such as the ITZ is considered only as a potential mechanism, given that the imposed shear plane of the experimental setup does not allow direct evaluation of local microstructural effects. In layered systems, the role of placement conditions became even more pronounced. When the second layer was placed after initial setting (Type B), an optimal fiber content of 1.2% resulted in a 27% increase in shear strength, primarily due to enhanced mechanical interlock and friction at the interface. In contrast, when concreting was performed after final setting (Type C), even high fiber contents failed to produce significant improvement, mainly due to reduced workability, fiber segregation, and the inherently weakened interlayer bond in delayed placement scenarios. Therefore, the practical use of fibers requires simultaneous control over fiber content, workability, and uniform dispersion to avoid interlayer bond degradation, particularly in non-monolithic applications.

The influence of acrylic resin exhibited a dual-effect behavior. High polymer contents (7%) led to considerable reductions in shear strength - up to 42% in monolithic specimens and 23–24% in layered configurations - primarily due to interference with hydration, increased porosity, and diminished frictional resistance along the imposed shear plane. A limited dosage of 3% proved to be optimal, causing only a minor strength reduction (4%) and maintaining acceptable performance. Placement methodology again played a decisive role; the interlayer bond in bilayer systems depended strongly on the resin type and surface condition, indicating that polymer alone cannot compensate for deficiencies in execution quality. Consequently, optimal polymer dosages must be selected with respect not only to material behavior but also to project-specific construction conditions, especially where layered concreting is unavoidable.

A major outcome of this research is the demonstration of the superior performance achieved through the combined use of acrylic resin (3%) and polypropylene fibers (0.4%). Under monolithic placement, this combination produced synergistic improvements, yielding 29% and 42% increases in direct and interfacial shear strengths, respectively, compared with the control mix - substantially higher than the 13% gain from fibers alone and the 5% reduction from polymer alone. In layered systems, the combined system improved shear strength by 11% under initial-set placement (Type B) and by an exceptional 71% under final-set placement (Type C). These results indicate that the hybrid use of fiber and polymer compensates for the individual limitations of each additive and provides a robust modification approach for both monolithic and delayed-placement concrete.

From a practical perspective, the outcomes highlight that optimized fiber–polymer systems can significantly enhance the reliability of concrete structures, particularly in strengthening, rehabilitation, and field conditions involving unavoidable delays between layers. From a research perspective, the study provides quantitative evidence on how synergistic material modifications can mitigate the weaknesses associated with imposed shear planes and interlayer bonding. Although microstructural mechanisms—such as potential influences in regions associated with the ITZ—cannot be directly confirmed due to the nature of the shear test setup, discussing them as plausible mechanisms helps contextualize the observed macroscopic behavior without overstating their role.

Overall, the results underscore the importance of integrated mixture optimization, controlled placement conditions, and balanced additive dosages in achieving enhanced shear performance in both monolithic and layered concrete applications.

5. SUGGESTIONS FOR FUTURE DEVELOPMENT:

It is recommended that future research investigate the effects of surface preparation, different types and quantities of resins (epoxy, polyurethane, etc.), as well as the impact of dynamic or cyclic loading on the performance of connections. This will provide more comprehensive execution guidelines for the use of fiber- and polymer-modified concrete in real-world civil engineering conditions.

6. ACKNOWLEDGMENTS

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