The Effect of the Hydrophilic and Hydrophobic Behavior of Polymeric Fibers on Some Properties of Reactive Powder Concrete

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ABSTRACT

This study compares the interface bonding properties of Polyvinyl Alcohol (PVA) fibers and Polypropylene (PP) fibers with a Reactive Powder Concrete (RPC) matrix. The chemical composition and microstructure of the reaction were characterized using Scanning Electron Microscopy (SEM) to understand the influence of PVA and PP fibers on their surrounding matrix. The Interfacial Transition Zone (ITZ) between the fibers and the RPC matrix was examined in detail. The hydrophilic and hydrophobic behavior of PVA and PP fibers affected the tensile strain capacity and flexural strength properties of the concrete mixes. Two strength grades of RPC mixes were used (30 MPa and 60 MPa, both with 1% fiber content of PVA or PP). The PVA fibers showed superior bonding with the RPC matrix compared to the PP fibers. The 60 MPa PVA mix achieved the highest strain capacity of 13.8%. The 30 MPa PVA mix had a maximum flexural strength enhancement of 4.3%, while the 60 MPa PVA mix demonstrated a 23% increase. Such enhancement can broaden the use of RPC with PVA fibers in structural members subjected to tensile and flexural stresses, while its significant strain capacity lessens the likelihood of microcrack formation.

Keywords-reactive powder concrete; hydrophilic polymer fibers; hydrophobic polymer fibers; scanning electron microscopy; flexural strength; tensile strain capacity

I. INTRODUCTION

RPC has compressive strength reaching 200 MPa, and its constituents may be the reason behind its workability, holding exceptional static and dynamic strengths, good durability, high tensile capacity, and low shrinkage. Its microstructure is organized by particle gradation to achieve maximum compactness. The tensile strength can be improved by incorporating fibers that act as micro-reinforcements, which help prevent crack formation [1]. These fibers can withstand additional tensile loads until they are pulled out of the matrix. Fine materials, such as quartz, silica fume, cement, and sand, play a crucial role in enhancing RPC durability and mechanical properties [2]. Polymers interact with water in distinct ways, classifying them as either hydrophilic or hydrophobic. Hydrophilic polymers, meaning "water-loving," readily interact with water and can dissolve in it due to hydrogen bonding. In contrast, hydrophobic polymers repel water molecules and do not dissolve in water [3, 4]. Table I highlights the key differences between hydrophilic and hydrophobic substances.

TABLE I. HYDROPHOBIC AND HYDROPHILIC MAIN CHARACTERISTICS

Category	Hydrophobic	Hydrophilic
Definition	Hydrophobic means water-resistance	Hydrophilic means water-loving
Water molecules	Repel water molecules	Attract water molecules
Interaction with water	Do not interact with water or dissolve in water	React and dissolve in water
Polarity	Non-Polar molecules	Polar molecules

In this research, PVA fibers act as hydrophilic materials, whereas PP fibers act as hydrophobic materials. The SEM images in [5] reveal that micro-cracks smaller than 50 μm were effectively arrested by polymer fibers. This controlled crack development contributed to enhanced flexural properties in the concrete. Concrete mixes incorporating steel mesh and polymer fibers have demonstrated potential for applications in impact-prone environments [6]. Authors in [1] demonstrated that increasing cement fibers in the mixes to achieve homogeneity, increases strain capacity and provides a good bond among matrix and fibers; this performance is obvious for 60 MPa mixes containing 450 kg/m^3 cement. Concrete exhibits tensile strain-hardening behavior, allowing it to sustain high loads even at elevated strain levels while maintaining multiple crack widths below 60 µm at a maximum fiber volume fraction of 2%. Polymeric fiber surface coating has a great effect on the nanoscale (the order of 10–100 nm) on the fiber/matrix interface properties and the matrix properties [7]. SEM images further indicate that silica fume effectively reduces porosity and enhances the formation of calcium silicate hydrate, a key hydration product. Incorporating up to 15% silica fume improves both the microstructural integrity and mechanical properties of the concrete. This improvement results from filler effects and the reaction between silica fume and calcium hydroxide, which reduces the latter's presence in the mix [8]. The hydrophilic nature of PVA fibers plays a critical role in minimizing drying shrinkage strains. Comparisons between PVA and PP fiber mixes over short- and long-term periods show that PVA mixes exhibit lower shrinkage strains than their PP counterparts [9]. The crack-bridging ability of the fibers, combined with fiber strength and fiber-to-matrix interface adhesion, is a key factor in determining the ultimate tensile strength of the concrete [7]. The intentional structuring of fiber, matrix, and interface properties ensures a cooperative load-bearing mechanism in the composite material [9]. Effectively managing the fiber-to-matrix interface is crucial for preserving ductility under high loading rates [4, 7]. This research aims to investigate tensile strain and flexural strength performance in RPC with two strength levels: 30 MPa and 60 MPa, both reinforced with 1% PVA or PP fibers. SEM is applied in this research to clarify the microstructural behavior of the RPC.

II. MATERIALS

The following materials were used along with their specifications:

- Cement: Type I cement was utilized, meeting the ASTM C150 requirements [10]. Two cement content levels were adopted: 300 kg/m³ for 30 MPa concrete and 450 kg/m³ for 60 MPa concrete.
- Sand (Fine Aggregate): The sand's sieve grading and key characteristics comply with Iraqi Standards I.Q.S NO. 45 and fall within Zone Two [11].
- Silica Fume: The strength activity index of the silica fume is 120%, conforming to ASTM C1240 [12].
- Polymeric fibers: PP and PVA fibers were used. Their characteristics are detailed in Table II. Additionally, a PVC solution was applied to reduce porosity and enhance concrete density.
- Polyvinyl chloride (PVC): Pure PVC is white, brittle solid, and insoluble in alcohol but slightly soluble in tetrahydrofuran. It melts when heated between 100°C and 260°C, allowing it to bind on its own. Due to this property, molten PVC can be utilized as a binder, and when mixed with materials like bitumen, it enhances binding properties.

A center-point loading test was conducted on 100 × 100 × 400 mm concrete prisms following ASTM C293-2002 [13] to assess flexural strength. Tensile strain capacity tests were performed on 100 × 100 × 400 mm prisms [13]. Cracks were observed to have developed once the tensile strain of the concrete exceeded its strain capacity. The load indicators stopped recording upon the first crack at which point tensile strain was measured using a strain gauge. A Field Emission Scanning Electron Microscope (FE-SEM) was used to analyze the microstructural features of concrete containing different polymer fiber types. The RPC mix proportions are listed in Table III. The mixing and sample preparations were conducted according to ASTM C192 [14].

TABLE II. CHARACTERISTICS OF POLYMERIC FIBERS

Characteristics	Polymer fiber	
	PVA	PP
Affinity	Hydrophilic	Hydrophobic
Length (mm)	12	12
Elongation (%)	6	10
Color	Light yellow	White
Diameter (µm)	0.039	0.032
Density (kg/m^3)	1300	910
Shape	Straight	Straight
Elastic Modulus (GPa)	42.8	36
Tensile Strength (MPa)	1620	600 - 700

TABLE III. MIX PROPORTIONS BY WEIGHT

RPC	Cement (kg/m^3)	Sand (kg/m^3)	SF (kg/m^3)	PVC solution (kg/m^3)	w/b (%)
30 MPa	300	850	30	140	0.35
60 MPa	450	850	45	140	0.27

*w/b: water to binder ratio

III. RESULTS AND DISCUSSION

The test results for flexural strength and tensile strain capacity for the RPC mixes are presented in Table IV.

TABLE IV. RESULTS OF THE MIXES

Age (days)	30P	30V	60P	60V
	Flexural strength (MPa)			
28	9.36	9.54	12.48	14.37
60	10.78	11.20	13.20	15.00
90	11.90	12.70	13.37	15.62

*30P: 30 MPa PP, *30V: 30MPa PVA, *60P: 30 MPa PP, *60V: 30MPa PVA

From Table IV and Figure 1, it is evident that reinforcing RPC 30MPa with PVA fibers results in a higher flexural strength than reinforcing it with PP fibers. This is attributed to the higher tensile strength of PVA fibers (1620 MPa) compared to PP fibers (700 MPa). The enhanced performance of PVA fiber-reinforced mixes is due to the stronger bond between the fibers and the matrix. This bond is improved by the chemical ionic coating on PVA fibers, which helps regulate their hydrophilic properties and prevents them from excessively absorbing mixing water. The percentage enhancement when using PVA fibers compared to PP fibers is shown in Figure 2.

Table V presents the tensile strain capacity of the different concrete mixes. The results indicate that PP fibers exhibit a lower strain capacity than PVA fibers, despite their high tensile strength. This behavior is primarily due to the hydrophobic nature of PP fibers, which leads to a weaker fiber/matrix bond compared to PVA fibers, as illustrated in Figure 3.

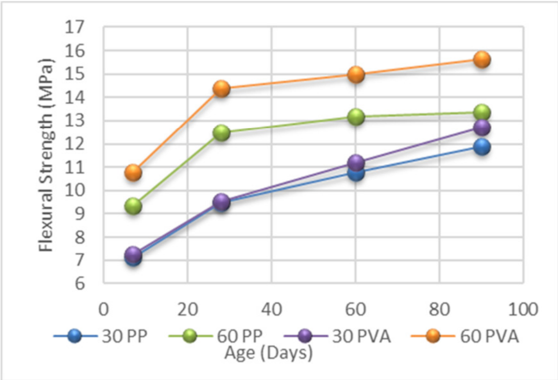

Fig. 1. Flexural strength of RPC mixes of/with PP and PVA.

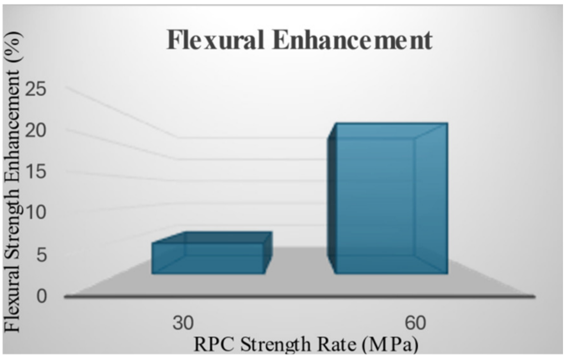

Fig. 2. Percentage (%) enhancement in the flexural strength of PVA fibers compared to PP fibers.

TABLE V. TENSILE STRAIN CAPACITY RESULTS

Mix	30P	30V	60P	60V
Strain (%)	9	9.9	12.3	13.8

*30P: 30 MPa PP, *30V: 30MPa PVA, *60P: 30 MPa PP, *60V: 30MPa PVA

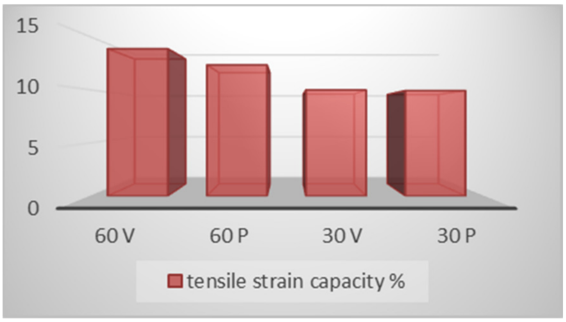

Fig. 3. Tensile strain capacity at 28 days.

IV. MICROSTRUCTURAL BEHAVIOR OF REACTIVE POWDER CONCRETE

The results indicate that PVA fibers exhibit superior performance in concrete mixes compared to PP fibers, primarily due to the ionic coating on PVA fibers, which enhances chemical bonding with the cement matrix. The behavior of these polymeric fibers is supported and confirmed by the following SEM images presented in Figures 4-6. Figure 4 depicts the bonding interface between PP fibers and the cement matrix at 5 μm magnification. Figure 5 portrays the surface characteristics of PP fibers.

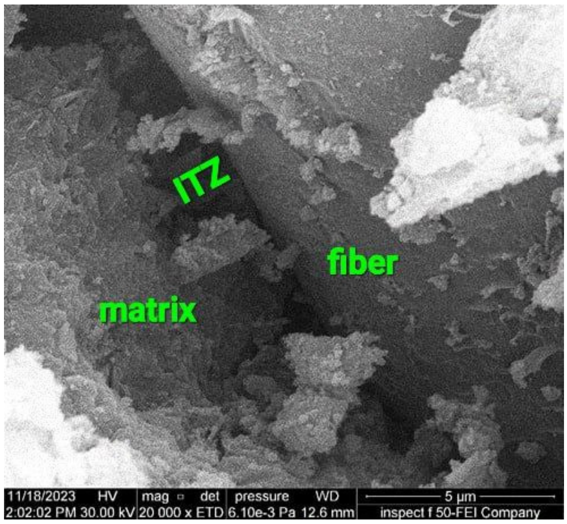

Fig. 4. Bond between matrix and PP fibers (hydrophobic material).

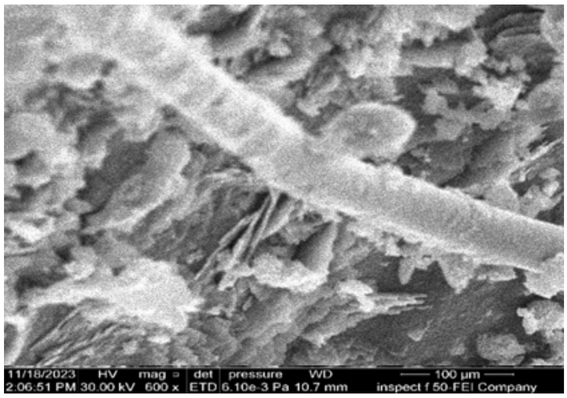

Fig. 5. PP fiber at 100 μm level, no coating since it is a hydrophobic material.

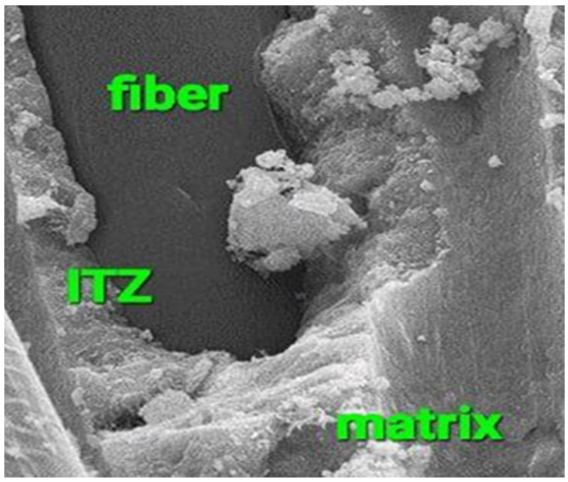

Fig. 6. Bond between matrix and PVA fibers (hydrophilic material).

Figure 6 exhibits the bonding behavior of PVA fibers with the matrix, emphasizing their ionic coating, which significantly improves the ITZ, leading to enhanced flexural strength and tensile strain capacity.

Overall, the addition of polymeric fibers in RPC substantially enhances its mechanical properties, particularly flexural strength. These findings align with previous research conclusions [7, 15].

V. CONCLUSIONS

This study extends previous research on the impact of polymeric fibers on Reactive Powder Concrete (RPC). In [2, 3], the mechanical properties of polymer fiber-reinforced mortars or bendable concrete were explored, while in [3, 7] the influence of Polyvinyl Alcohol (PVA) fibers on concrete performance was examined. However, a direct comparison of PVA and Polypropylene (PP) fibers in RPC at the microstructural level (below 50 μm) remains unexplored.

This research investigates the role of polymeric fiber affinity toward water in microstructural behavior and its subsequent impact on tensile strain capacity and flexural strength. The enhancement in tensile properties due to fiber addition is validated through Scanning Electron Microscopy (SEM) imaging, supporting the potential use of PVA fiber-reinforced RPC in structural applications subject to tensile and flexural stresses. Furthermore, its high strain capacity reduces the likelihood of microcrack formation, contributing to improved durability. The following conclusions can be extracted from the results:

- RPC (60 MPa) with 1% PVA fibers exhibits higher flexural strength and tensile strain capacity compared to PP fiber-reinforced mixes.
- The hydrophilic nature of PVA fibers, coupled with their ionic coating, results in a strong fiber-matrix bond.
- Concrete mix performance depends on fiber type. Mixes containing PVA fibers demonstrate greater flexural strength than those with PP fibers.
- In 30 MPa mixes, PVA fibers improve flexural strength by 4.3% compared to PP fibers. In 60 MPa mixes, PVA fibers lead to a 23% increase in flexural strength over PP fiber-reinforced mixes.
- The superior performance of PVA fibers is attributed to their ionic coating and high elastic modulus, which enhance flexural capacity and tensile strain resistance in RPC.
- SEM images confirm these findings, highlighting the differences in fiber-matrix interaction between PVA and PP fibers.

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DATA AVAILABILITY

Data will be made available upon request.

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