

Microstructural Characterization of Hybrid Polypropylene-Glass Fibre Reinforced Concrete Using Scanning Electron Microscopy

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Abstract: Concrete is a brittle cementitious material with limited tensile strength and a tendency to develop microcracks and propagate cracks under mechanical and environmental loading. The incorporation of fibres can improve crack control and enhance the integrity of the cementitious matrix. The present study experimentally investigates the microstructural characteristics of hybrid polypropylene (PP) and glass fibre reinforced concrete with different total fibre volume fractions and fibre combinations. Plain cement concrete was considered as the reference mixture, while hybrid fibre mixtures were prepared with total fibre contents of 0.25%, 0.50%, 0.75%, and 1.00%, incorporating different proportions of PP and glass fibres. Scanning Electron Microscopy (SEM) was employed to examine fibre dispersion, fibre-matrix interaction, interfacial transition zone characteristics, crack bridging, matrix compactness, and void formation. The microstructural observations indicate that the incorporation of hybrid fibres improves crack interruption and matrix continuity compared with plain concrete. Glass fibre-rich mixtures showed effective bridging and arrest of comparatively larger cracks, whereas polypropylene fibres contributed primarily to the control of fine microcracks. Balanced PP-glass combinations exhibited comparatively uniform fibre dispersion and multi-scale crack-bridging behaviour. Increasing fibre content generally improved crack control and matrix refinement; however, at higher fibre dosages, localized fibre crowding, overlapping, and entrapped voids were observed, particularly in polypropylene-rich mixtures. The study demonstrates that the microstructural performance of hybrid fibre reinforced concrete depends on both the total fibre volume fraction and the relative proportion of PP and glass fibres. The findings provide a basis for identifying suitable hybrid fibre combinations for improving the microstructural integrity, crack resistance, and potential durability of concrete.

Keywords: Hybrid Fibre Reinforced Concrete, Polypropylene Fibre, Glass Fibre, Scanning Electron Microscopy, Microstructure, Fibre Dispersion, Fibre-matrix Interface, Interfacial Transition Zone

1. Introduction

Concrete is extensively used in construction because of its high compressive strength, versatility, and durability; however, its relatively low tensile strength and brittle behaviour make it susceptible to crack initiation and propagation. The incorporation of discrete fibres into concrete is an effective approach for improving crack resistance, toughness, and post-cracking behaviour. Fibres restrict crack development

through stress transfer and crack-bridging mechanisms, although their effectiveness depends on fibre type, dosage, geometry, orientation, dispersion, and interaction with the surrounding cementitious matrix [21]. Consequently, microstructural characterization is important for understanding the mechanisms governing the behaviour of fibre-reinforced concrete.

Polypropylene (PP) fibres are widely used because

of their low density, chemical stability, and ability to restrict microcracking. Their contribution to concrete is predominantly physical rather than chemical. PP fibres have been reported to reduce permeability and capillary porosity through pore-blocking effects while improving tensile, flexural, and durability characteristics at appropriate dosages [23]. The fibre-matrix interface is particularly important because the naturally smooth and hydrophobic surface of PP fibres may restrict adhesion with cement paste. Surface modification increases fibre roughness, improves mechanical interlocking, and promotes better interaction with the surrounding matrix [15]. However, excessive PP fibre content can produce weak interfacial regions and connected pores when the available cement paste is insufficient to adequately surround and disperse the fibres [15]. The surrounding matrix also influences fibre effectiveness; mineral additions can refine harmful capillary pores and partially compensate for fibre-associated pore formation, resulting in a denser microstructure [10].

Glass fibres provide a different reinforcing mechanism because of their relatively high tensile strength and stiffness. Appropriate glass fibre incorporation can form a distributed reinforcing network within the cementitious matrix, improving crack bridging and stress transfer. Improvements in tensile strength, flexural strength, and impermeability have been associated with suitable glass fibre distribution [8, 11]. Microstructural observations have shown strong fibre-matrix adhesion and deposition of cement hydration products on fibre surfaces at appropriate fibre contents [3]. Uniformly distributed fibres can restrict crack propagation and improve the internal pore structure. In contrast, excessive glass fibre content may result in non-uniform distribution, fibre agglomeration, increased porosity, and reduced matrix homogeneity [3].

Comparative investigations of glass and PP fibre reinforced concrete have demonstrated that fibre effectiveness depends strongly on both fibre dosage and characteristics of the cementitious matrix [12]. Optimum fibre contents have been found to vary with water-to-binder ratio, indicating that an optimum dosage identified for one concrete matrix cannot necessarily be applied to another. Glass fibres can provide comparatively greater stiffness and resistance to crack opening, whereas the flexibility and deformation capacity of PP fibres make them effective in controlling finer cracks and maintaining post-cracking integrity [12].

Hybrid fibre reinforcement combines different fibre types to exploit complementary mechanisms at different stages and scales of cracking. Hybrid systems can improve crack resistance when fibres possessing different stiffnesses, deformation capacities, and bonding characteristics act simultaneously within the matrix [4, 16, 20]. In a PP-glass hybrid system, PP fibres can contribute to the restriction of fine microcracks, while the comparatively stiffer glass fibres can bridge developing cracks and provide additional resistance to

crack propagation. Such complementary behaviour offers the possibility of multiscale crack control. However, successful hybridization depends on uniform dispersion and adequate fibre-matrix bonding.

Fibre volume fraction is therefore a critical parameter governing the microstructural effectiveness of hybrid fibre reinforced concrete. At lower and moderate fibre contents, individual fibres can be adequately surrounded by cement paste and dispersed throughout the matrix, facilitating stress transfer and crack bridging. Increasing fibre content provides additional potential crack-bridging locations; however, it also increases the probability of fibre-fibre interaction, overlapping, entanglement, agglomeration, and entrapped air. Excessive PP fibre addition has been associated with weak interfacial regions and increased pores [15], while high glass fibre contents have similarly produced fibre agglomeration and a more porous matrix [3]. Thus, increasing fibre volume fraction does not necessarily result in continuous improvement, and an optimum fibre combination is required to achieve effective crack control without compromising matrix compactness.

Scanning electron microscopy (SEM) provides an effective means of examining these mechanisms at the microscale. SEM enables direct observation of fibre embedment, fibre pull-out, interfacial gaps, debonding, fibre surface characteristics, microcracks, crack bridging, voids, fibre dispersion, and matrix compactness. Previous microstructural investigations indicate that uniform fibre distribution and intimate fibre-matrix contact favour efficient crack bridging and stress transfer, whereas fibre clustering, interfacial gaps, and increased void formation reduce reinforcement efficiency [3, 10, 15, 23].

Although PP and glass fibres have been extensively investigated individually, systematic microstructural studies examining different PP-to-glass fibre proportions over progressively increasing total hybrid fibre volume fractions remain comparatively limited. Previous investigations have predominantly emphasized mechanical and durability performance, with microstructural observations generally serving as supplementary explanations. Consequently, the effects of hybrid fibre proportion and total fibre content on fibre dispersion, fibre-matrix interaction, crack bridging, pull-out behaviour, interfacial integrity, void formation, and matrix compactness require further investigation.

The present study therefore investigates the microstructural characteristics of hybrid polypropylene-glass fibre reinforced concrete using SEM. Different total fibre volume fractions and PP-to-glass fibre proportions are examined to evaluate fibre distribution, fibre-matrix bonding, crack bridging, fibre pull-out, microcracking, void formation, and matrix compactness. The investigation aims to identify the microstructural mechanisms associated with effective hybridization and to determine how increasing fibre content modifies the internal structure and fibre-matrix interaction of PP-glass hybrid fibre reinforced concrete.

2. Methodology

2.1. Experimental Programme

The experimental programme investigated the influence of hybrid polypropylene (PP) and glass fibres on the microstructural characteristics of concrete. Plain cement concrete (PCC) was used as the control mixture, while hybrid fibre concrete was prepared with different total fibre volume fractions and PP-to-glass fibre proportions. The study included mix preparation, casting, curing, and scanning electron microscopy (SEM). The effects of fibre dosage and proportion were evaluated by comparison with PCC.

2.2. Materials

Ordinary Portland Cement (OPC) of 43 grade conforming to IS 8112:2013 was used as the primary binder. The cement had a specific gravity of 3.12 and a standard consistency of 30%. Natural river sand conforming to Zone II requirements of IS 383:2016 was used as the fine aggregate, while crushed granite aggregate with a nominal maximum size of 20 mm was used as the coarse aggregate. The specific gravities of the fine and coarse aggregates were 2.64 and 2.75, respectively, and their water absorption values were below 1%. Potable water was used for both concrete mixing and specimen curing.

To achieve the required workability at the adopted water-to-binder (W/B) ratio, a polycarboxylate-based superplasticizer was incorporated at a dosage of 0.8% by weight of cement.

Alkali-resistant (AR) glass fibres with a length of 24 mm and a zirconia content exceeding 16% were used as one of the reinforcing fibres. The fibres consisted of chopped monofilament strands with diameters ranging from approximately 14 to 20 μm . Their tensile strength and elastic modulus were 1.6-1.8 Gigapascal (GPa) and 70-75 GPa, respectively. The relatively high stiffness of the glass fibres, together with their resistance to the alkaline environment of the cementitious matrix, makes them suitable for bridging cracks and restricting microcrack propagation.

Macro-synthetic Fiber-Tuff polypropylene (PP) fibres were used as the second fibre type. These fibres were 54 mm long, with an equivalent diameter of approximately 0.8-0.9 mm. Their tensile strength ranged from 550 to 650 Megapascal (MPa), while the elastic modulus ranged from 5 to 9 GPa. The embossed fibre surface provides improved mechanical anchorage with the surrounding cementitious matrix. Owing to their relatively low density and flexible nature, PP fibres can become distributed in different orientations within the concrete and contribute to crack control and post-cracking integrity.

Both glass and PP fibres were incorporated on a volume-fraction basis. Before the addition of water, the fibres were gradually dry-mixed with the aggregates to promote uniform dispersion and minimize fibre clustering during concrete production. The hybrid fibre system was selected to utilize the complementary characteristics of the two fibre types: the comparatively stiff glass fibres provide resistance to crack opening and propagation, whereas the more deformable

PP fibres contribute to crack control and post-cracking deformation capacity. Their combined incorporation was therefore intended to improve fibre bridging and maintain the integrity of the concrete matrix after cracking.

2.3. Fibre Volume Fraction and Mix Proportions

PCC and hybrid PP-glass fibre mixtures were prepared with total fibre volume fractions of 0.25%, 0.50%, 0.75%, and 1.00%. Three PP-to-glass fibre combinations were considered at each dosage: glass-rich, balanced, and PP-rich. This enabled evaluation of the effects of total fibre content and fibre proportion. Table 1 below shows different total volume fractions and varying proportions of glass and polypropylene in each volume fraction.

Table 1. Hybrid Fibre Combinations.

Mix	PP (%)	Glass (%)	Total (%)
PCC	0.000	0.000	0.000
M1	0.070	0.180	0.250
M2	0.125	0.125	0.250
M3	0.180	0.070	0.250
M4	0.125	0.375	0.500
M5	0.250	0.250	0.500
M6	0.375	0.125	0.500
M7	0.190	0.560	0.750
M8	0.375	0.375	0.750
M9	0.560	0.190	0.750
M10	0.250	0.750	1.000
M11	0.500	0.500	1.000
M12	0.750	0.250	1.000

2.4. Concrete Mix Preparation

The required quantities of cement, aggregates, water, PP fibre, and glass fibre were measured according to the selected mix design. Cement, fine aggregate, and coarse aggregate were initially dry-mixed to obtain uniformity. Water was gradually added while mixing continued. Glass fibre followed by PP fibre was added progressively to minimize fibre balling, clustering, and non-uniform distribution. Mixing continued until a uniform mixture was obtained, followed by determination of fresh concrete workability.

2.5. Casting of Specimens

Fresh concrete was placed into clean moulds coated with a suitable release agent. The concrete was placed in layers and adequately compacted to remove entrapped air while avoiding excessive compaction that could cause fibre segregation or preferential orientation. The surface was levelled and finished, and specimens were labelled according to their respective fibre combinations.

2.6. Curing of Specimens

After casting, specimens were kept undisturbed under laboratory conditions for approximately 24 h and then demoulded. They were subsequently placed in a normal water-curing tank under similar curing conditions. Specimens were removed at predetermined testing ages of 28 days.

2.7. SEM Sample Preparation

Representative fragments were collected from hardened concrete specimens to examine the cementitious matrix, fibre-matrix interfaces, cracks, and pores. Samples were cut to suitable dimensions, dried, and prepared to provide appropriate observation surfaces. They were mounted on SEM stubs and, where required, coated with a conductive material. Care was taken to minimize artificial cracks and damage to the fibre-matrix interface.

2.8. Scanning Electron Microscopy

SEM was used to examine the microstructural characteristics of PCC and hybrid fibre concrete at approximately 50 $\times$, 500 $\times$, 1000 $\times$, and 5000 $\times$ magnifications. Lower magnifications were used to observe fibre distribution, pores, and larger cracks, while higher magnifications were used to examine fibre-matrix interfaces, ITZ characteristics, microcracks, hydration products, interfacial gaps, fibre surfaces, and pull-out cavities. Observations focused on fibre dispersion, fibre-matrix interaction, crack development, crack bridging, matrix compactness, void formation, and fibre clustering. The hybrid mixtures were compared with PCC to identify changes associated with fibre dosage and PP-to-glass fibre ratio.

3. Results and Discussion

The microstructural analysis offered crucial evidence supporting the enhanced performance of hybrid fibre-reinforced concrete. With increasing fibre dosage, significant improvements were observed in fibre dispersion, ITZ refinement, crack bridging, and matrix densification. Glass fibres when combined with polypropylene, contributed to multi-scale reinforcement. Glass fibres effectively restrained major cracks, while polypropylene controlled microcracks and improved uniformity.

3.1. Plain Concrete Microstructure (Baseline PCC)

The SEM images of plain cement concrete serve as a baseline to understand the inherent limitations of unreinforced concrete. These include the presence of microcracks, porous interfacial transition zones (ITZ), and loosely packed hydration products that compromise durability. Figure 1 presents the SEM images of plain cement concrete (PCC), which serve as the reference microstructure for comparison with the fibre-reinforced concrete mixes discussed in the subsequent sections.

As a reference point, the plain cement concrete (PCC) sample exhibited a microstructure typical of unreinforced hardened concrete, with several features underscoring its vulnerabilities. At low magnification (on the order of 50X), the PCC showed a relatively random distribution of voids and initial microcracks. Small air voids were present in the matrix, and fine cracks could be seen emanating from the aggregate-paste interfaces due to drying shrinkage or specimen preparation. There was no internal mechanism to restrain these cracks; thus, even at moderate magnification one could observe uninterrupted crack paths traversing the cement paste. The interfacial transition zones around coarse aggregates appeared as porous, weak regions (visible at around 500X). In these zones, the cement paste was noticeably more loosely packed, with observable micro-voids and a lack of dense hydration product, consistent with the known porous nature of the ITZ in plain concrete. Moving to higher magnification (1000X), the micrographs revealed growing microcracks and disconnected hydration crystals in the matrix. Cracks in the plain concrete tended to propagate freely and continuously through the paste once initiated, indicating low tensile resistance and ineffective crack arrest at the microscopic level. At the highest magnifications (5000 $\times$), the PCC matrix showed a highly porous gel structure - the calcium-silicate-hydrate (C-S-H) matrix looked "open" and cavernous, with many capillary pores visible. This is indicative of a less compact hydration structure, which correlates with higher permeability. Overall, the SEM examination of plain concrete confirmed its inherent microstructural weaknesses: a porous matrix, weak ITZ, presence of microcracks, and absence of any reinforcing element to impede crack growth. These characteristics help explain why plain concrete has relatively poor durability and brittle failure behaviour. This baseline will be contrasted with the fibre-reinforced cases, where we expect to see improvements in each of these aspects.

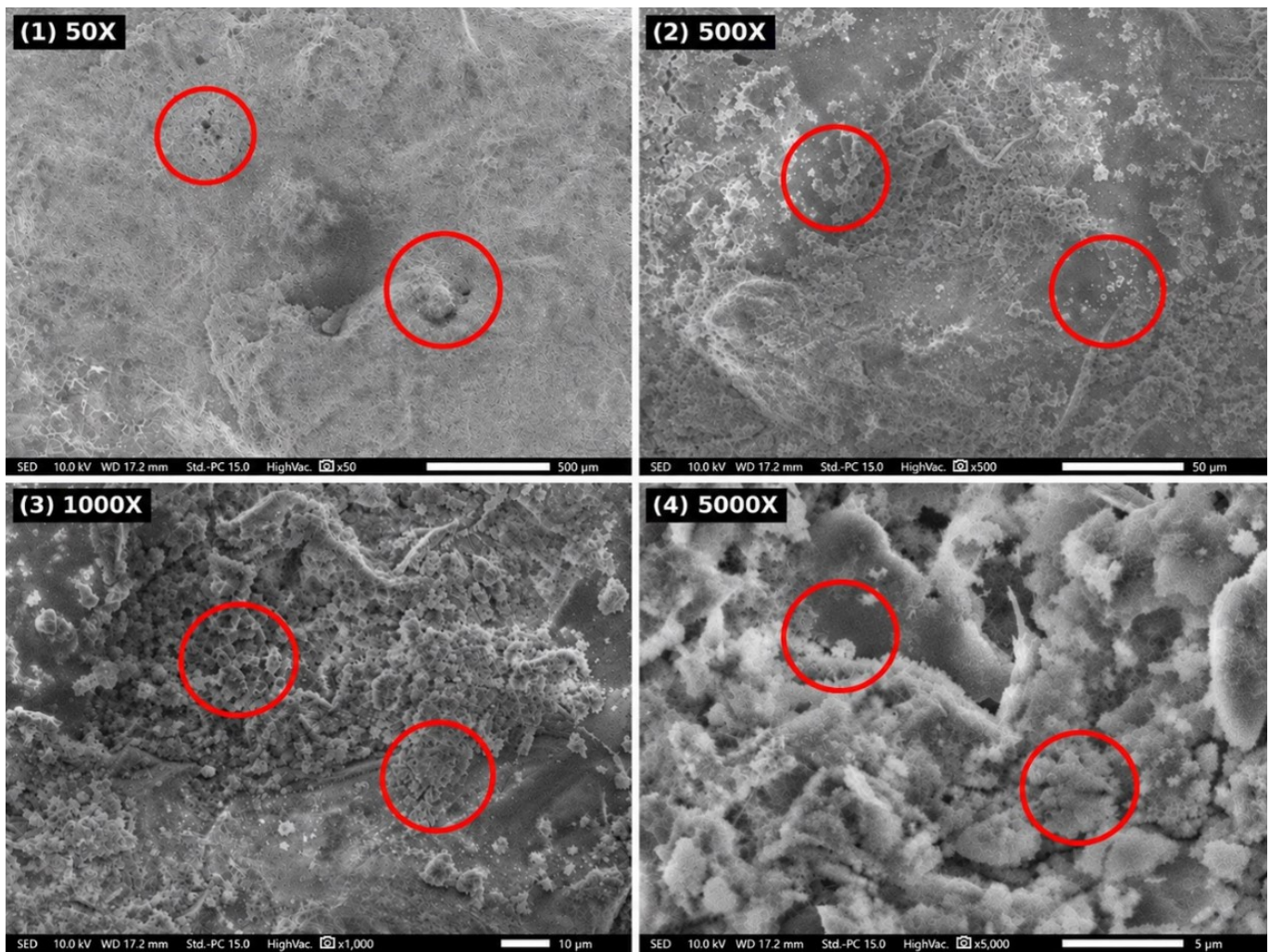


Figure 1. Scanning Electron Microscope (SEM) images of plain cement concrete (PCC) at magnifications of 50 $\times$, 500 $\times$, 1000 $\times$, and 5000 $\times$.

3.2. Micro Structural Studies - Polypropylene and Glass

Following the baseline SEM analysis of plain cement concrete (PCC), detailed imaging was conducted on hybrid mixes with polypropylene (PP) and glass fibres to evaluate microstructural changes. The observations focus on fibre dispersion, ITZ quality, crack bridging, and matrix porosity across different fibre volume fractions.

3.2.1. Effect of 0.25% Total Fibre Volume

At 0.25% total fibre content of M1, SEM analysis revealed distinct improvements over plain concrete. As shown in Figure 2, the SEM images illustrate the fibre-matrix interaction and the microstructural characteristics of the hybrid fibre-reinforced concrete at different magnifications.

Figure 2 shows the microstructural characteristics of the hybrid concrete containing 0.25% total fibres of M1. At 50 $\times$, the matrix appears relatively uniform and compact, indicating satisfactory fibre distribution without evident large-

scale fibre clustering. At 500 $\times$, the highlighted region shows a fibre embedded within the surrounding cementitious matrix, with close fibre-matrix contact and limited interfacial separation. At 1000 $\times$, the circled region indicates fibre interaction with a developing microcrack, suggesting a crack-bridging mechanism that can restrict crack opening and propagation. At 5000 $\times$, the matrix surrounding the fibre appears comparatively dense, with closely packed hydration products and limited micro-voids. Collectively, the observations indicate satisfactory fibre dispersion, fibre-matrix interaction, and microcrack control at this fibre dosage.

Fibre Dispersion: Fibre-reinforced samples exhibited excellent distribution at 50 $\times$ magnification. In the glass-rich mix of M1, rigid glass fibres were well spaced within the cement matrix. The balanced mix of M2 displayed uniform random orientation of fibres across the field. Even in the PP-dominant mix of M3, fibre separation remained satisfactory with no clumping observed, due to the low total volume of 0.25%.

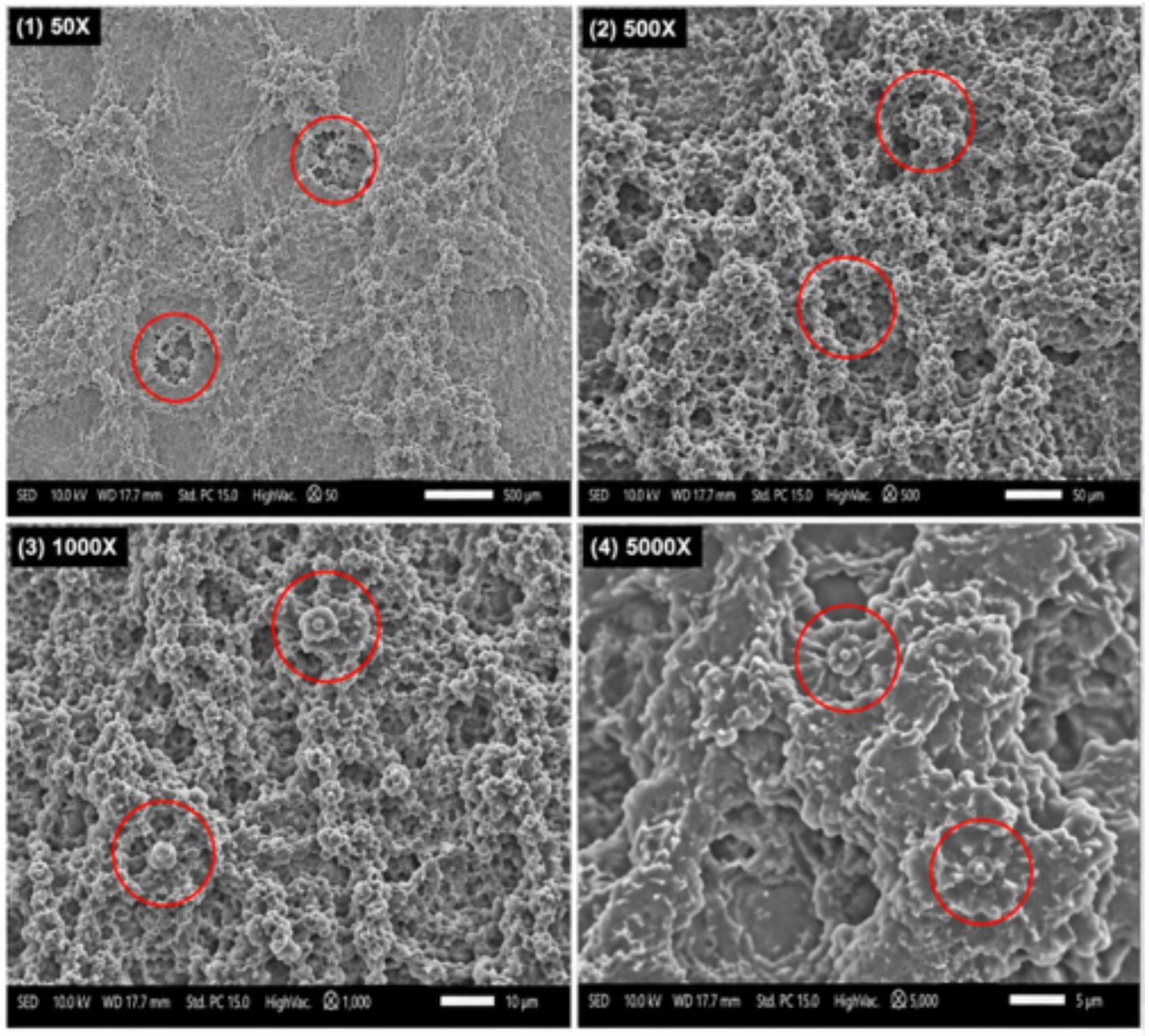


Figure 2. SEM images of hybrid fibre-reinforced concrete containing 0.25% total fibre content of M1 at 50X, 500X, 1000X, and 5000X magnifications.

ITZ and Matrix Density: All three mixes demonstrated improved ITZ quality over PCC. At 150x and 500x, fibre-matrix interfaces were visibly tighter, with fewer interfacial voids. The glass-rich mix displayed compact ITZs around the rough-surfaced glass fibres, while the PP-rich mix also showed densified paste near flexible PP fibres. The balanced mix showed a harmonious transition at the aggregate and fibre interfaces, with enhanced paste packing around both fibre types.

Crack Bridging: At 1000x magnification, multiple fibres were seen intercepting and terminating cracks. Glass-rich mixes demonstrated strong crack-bridging by stiff fibres, effectively stopping propagation. The PP-rich and balanced mixes offered additional fine crack control due to the flexibility of PP fibres. All mixes showed reduced crack continuity, with

narrower crack widths and shorter lengths compared to plain concrete.

Void Content: Across all 0.25% mixes, SEM images revealed low porosity. The matrix appeared denser with fewer micro-voids. No fibre pull-out cavities or clustering-related voids were visible. Even in mixes with higher PP content, the microstructure remained refined, avoiding any signs of fibre-induced defects.

Summary: At just 0.25% total fibre content, hybrid PP-glass concrete displayed remarkable microstructural refinement. All mixes showed uniform fibre dispersion, improved ITZ bonding, reduced cracking, and decreased pore volume. Glass-rich mixes provided robust ITZ densification and crack blocking, while PP-rich combinations excelled in fine crack control. The balanced M2 mix demonstrated the most

harmonious blend of both behaviours, confirming the value of even low-dose hybridization

3.2.2. Effect of 0.5% Total Fibre Volume

At 0.5% total fibre content of M5, SEM images revealed major microstructural enhancements relative to plain concrete.

As shown in Figure 3, the SEM images illustrate the fibre-matrix interaction and the microstructural characteristics of the hybrid fibre-reinforced concrete at different magnifications.

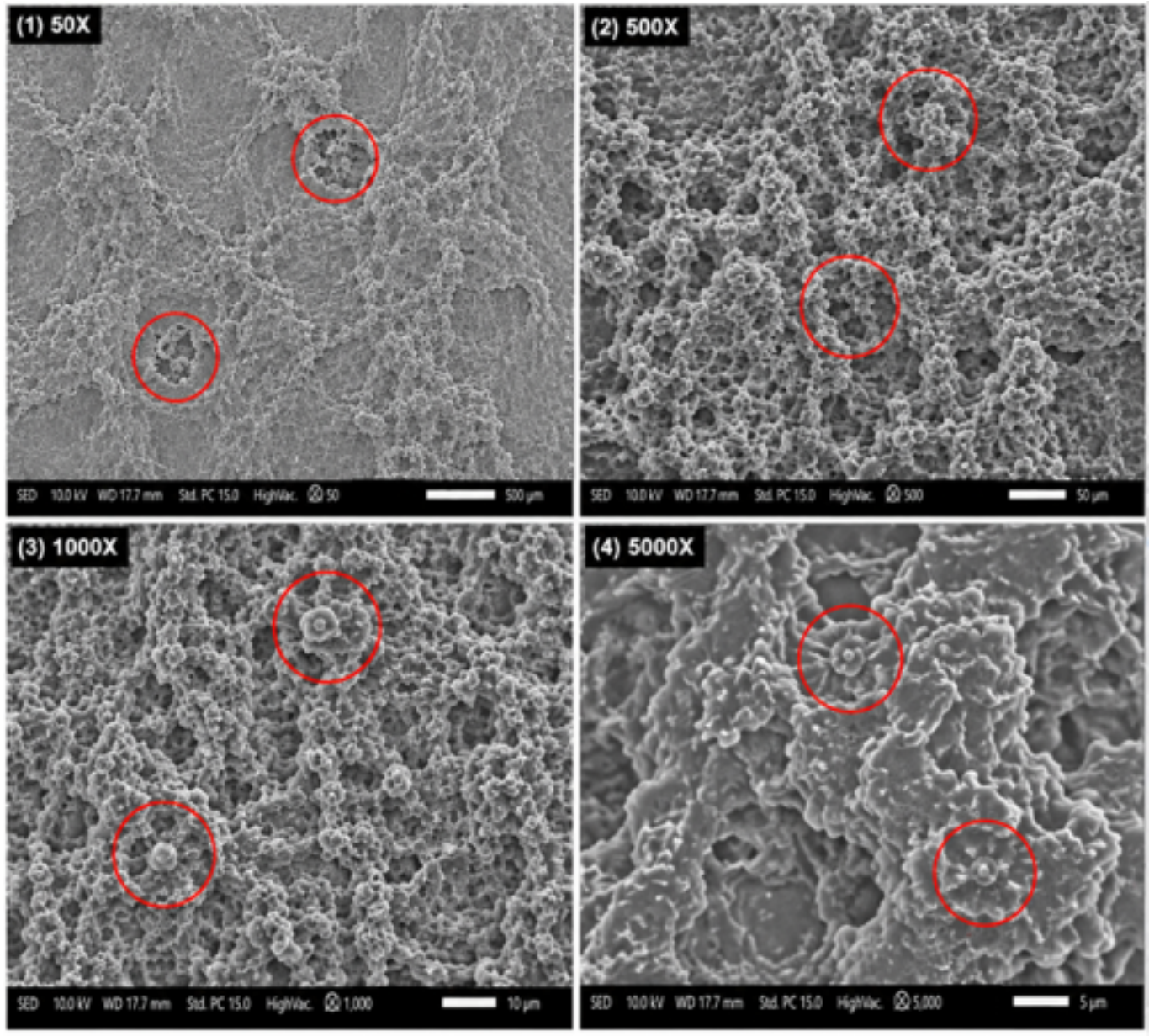


Figure 3. SEM images of hybrid fibre-reinforced concrete containing 0.5% total fibre content of M5 at 50X, 500X, 1000X, and 5000X magnifications.

Figure 3 shows the microstructural characteristics of hybrid concrete containing 0.50% total fibres of M5. At 50 exttimes , the microstructure appears relatively homogeneous, with no prominent fibre clustering or large discontinuities, indicating satisfactory fibre dispersion. At 500 exttimes , the fibre-matrix interfacial region appears comparatively compact and continuous, with limited separation between the embedded

fibre and surrounding matrix. At 1000 exttimes , the highlighted regions indicate effective fibre interaction with microcracks, suggesting crack bridging and restriction of crack propagation. At 5000 exttimes , a closely packed matrix with relatively few visible micro-voids is observed, indicating improved matrix compactness. Overall, the micrographs suggest that the balanced PP-glass fibre combination provides

favourable fibre distribution, fibre-matrix interaction, crack control, and matrix compactness at this fibre dosage

Fibre Dispersion: Fibre density was significantly higher at 50 exttimes magnification. The balanced mix M5 displayed optimal distribution, with no clumping and uniform fibre orientation. In the glass-rich mix of M4, glass fibres were well spread, although a few minor PP fibre clusters were observed. In the PP-rich mix of M6, PP fibres dominated the matrix, with slight unevenness in spacing but still no fibre balling.

ITZ and Matrix Density: All three mixes showed robust improvement in ITZ. In the glass-rich mix, ITZ around glass fibres was especially dense due to better mechanical interlocking. The balanced mix maintained uniform ITZ densification across the matrix. In the PP-rich mix, ITZ densification was localized near PP fibre zones, still superior to PCC but less consistent than in balanced or glass-rich combinations.

Crack Bridging: SEM at 1000 exttimes revealed extensive crack bridging. The glass-rich mix effectively intercepted cracks with stiff fibres, halting their growth. The balanced mix benefited from dual action - glass fibres bridged large cracks, while PP fibres restrained fine ones. In the PP-rich

mix, flexible PP fibres increased crack tortuosity, resulting in shorter, more distributed cracks.

Void Content: Void density remained low across all mixes. The glass-rich and balanced mixes displayed minimal micropores and no fibre pull-out gaps. The PP-rich mix showed a slightly higher number of isolated voids, likely due to increased fibre volume and flexibility-related spacing issues.

Summary: At 0.5% fibre content, microstructural refinement was prominent. The glass-rich mix demonstrated excellent ITZ and crack control. The balanced mix combined uniform dispersion and multi-scale bridging. The PP-rich mix showed efficient crack dispersion and flexibility-induced confinement. All mixes outperformed PCC by a wide margin in porosity, crack resistance, and ITZ quality.

3.2.3. Effect of 0.75% Total Fibre Volume

At 0.75% total fibre content of M9 SEM analysis continued to show improved microstructure but also revealed early signs of fibre interaction effects. As shown in Figure 4, the SEM images of M9, illustrate the fibre-matrix interaction and the microstructural characteristics of the hybrid fibre-reinforced concrete at different magnifications.

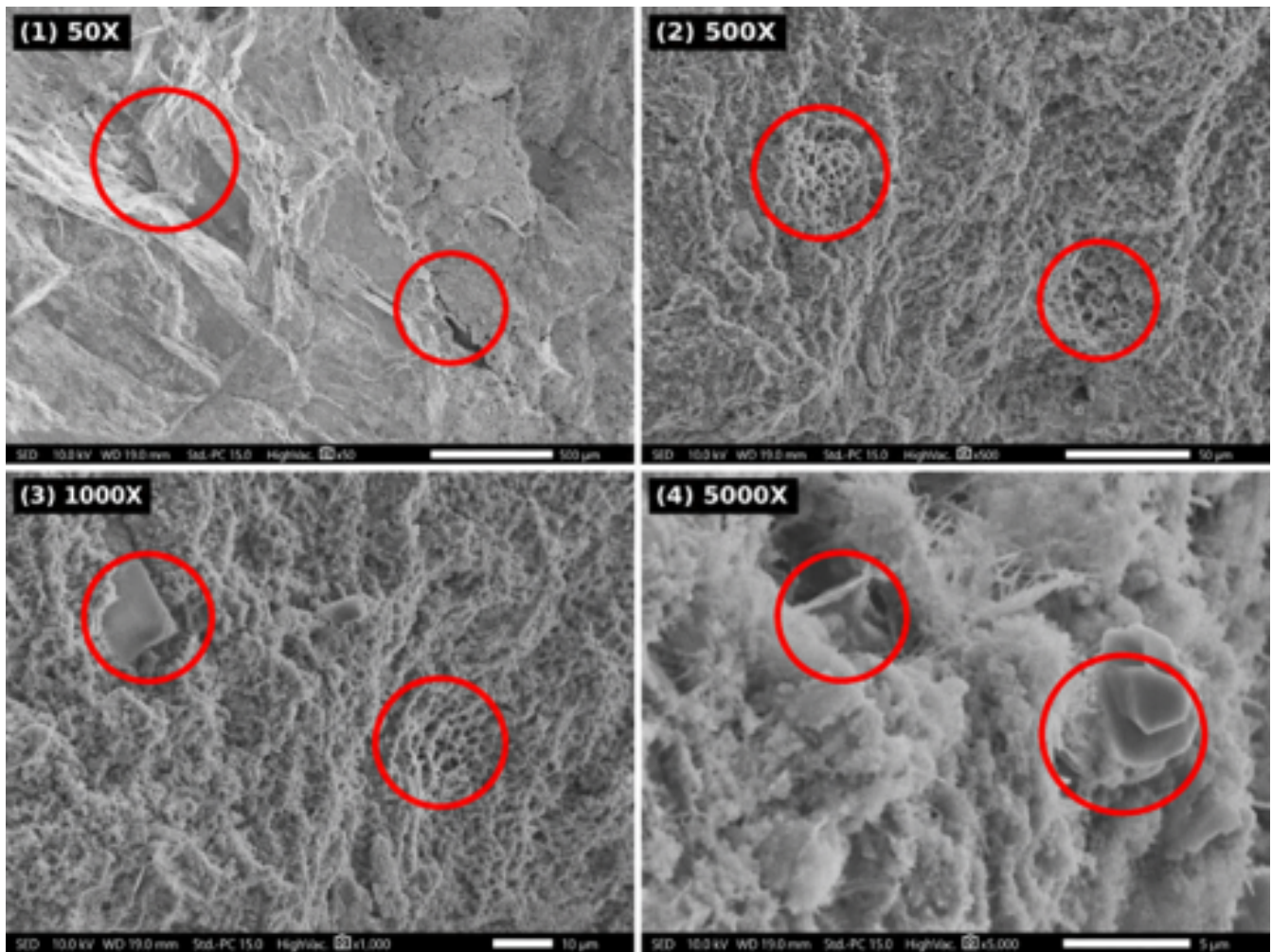


Figure 4. SEM images of hybrid fibre-reinforced concrete containing 0.75% total fibre content of M9 at 50X, 500X, 1000X, and 5000X magnifications.

Figure 4 shows the microstructural characteristics of hybrid concrete containing 0.75% total fibres of M9. At 50 exttimes, the fibres appear generally well distributed throughout the matrix, although minor PP fibre bundling is evident in localized regions. At 500 exttimes, the fibre-matrix interfacial region appears improved and relatively compact, but with slight non-uniformity around some fibres. At 1000 exttimes, the highlighted regions indicate that PP fibres interact with developing microcracks, contributing to crack arrest and bridging, while the stiffer glass fibres can assist in restricting wider crack propagation. At 5000 exttimes, the matrix appears relatively dense with limited visible micro-voids, although localized heterogeneity is present. Overall, the PP-rich hybrid combination provides satisfactory fibre dispersion, fibre-matrix interaction, and microcrack control, with minor fibre bundling indicating the beginning of dispersion-related limitations at the higher fibre content.

Fibre Dispersion: Fibre density was high at this dosage. The balanced mix of M8 showed the best dispersion. The glass-rich mix of M7 had good distribution of glass fibres but slight PP clustering in certain areas. The PP-rich mix of M9 began to show fibre crowding and occasional overlapping, although no serious balling occurred.

ITZ and Matrix Density: ITZ remained compact in all mixes. The glass-rich mix still exhibited strong bonding at fibre-matrix interfaces. The balanced mix showed uniform matrix densification. In the PP-rich mix, although ITZ remained better than PCC, localized resin-rich areas around PP fibres suggested minor over-saturation of fibre surface zones, slightly reducing densification consistency.

Crack Bridging: Crack control remained effective. In the glass-rich mix, glass fibres provided robust crack interruption. The balanced mix showed excellent multi-scale bridging again. The PP-rich mix had superior fine crack tortuosity, but longer fibres occasionally overlapped, creating minor stress risers in rare cases.

Void Content: Porosity stayed low in all mixes. However, in the PP-rich mix, a few overlapping fibre clusters caused localized compaction issues. The balanced and glass-rich mixes showed no such defects, maintaining a compact, void-free matrix.

Summary: At 0.75%, hybrid fibre mixes achieved excellent crack control, ITZ bonding, and densification. The balanced mix offered the best compromise, with minimal dispersion issues and highly uniform structure. Glass-rich mix retained its ITZ advantage. PP-rich mix had exceptional crack control but started showing minor crowding effects, suggesting that 0.75% may be close to the optimal fibre threshold for uniform dispersion.

3.2.4. Effect of 1.0% Total Fibre Volume

At 1.0% total fibre content, SEM analysis revealed the maximum fibre influence, with the benefits beginning to

plateau and minor drawbacks becoming apparent. As shown in Figure 5, the SEM images of M1 illustrate the fibre-matrix interaction and the microstructural characteristics of the hybrid fibre-reinforced concrete at different magnifications.

Figure 5 shows the microstructural characteristics of hybrid concrete containing 1.0 total fibres of M11. At 50 exttimes, both fibre types appear widely distributed throughout the matrix, although minor localized fibre clustering is evident due to the relatively high total fibre content. At 500 exttimes, the fibre-matrix interfacial regions appear relatively compact and continuous, indicating satisfactory contact between the fibres and surrounding cementitious matrix. At 1000 exttimes, the highlighted regions indicate extensive fibre interaction with developing cracks, suggesting effective crack bridging and restriction of crack propagation by the combined action of PP and glass fibres. At 5000 exttimes, the matrix appears dense and compact with limited visible micro-voids and relatively good interfacial integrity. Overall, the balanced PP-glass combination at 1.0% total fibre content exhibits favourable fibre distribution, fibre-matrix interaction, crack-bridging characteristics, and matrix compactness, although minor fibre clustering indicates the importance of adequate mixing and dispersion at higher fibre contents.

Fibre Dispersion: At 50 exttimes magnification, fibre crowding was evident. Clustering and overlapping increased across all mixes. Uniformity declined, particularly in PP-rich configurations, though glass-rich mixes managed slightly better distribution due to fibre stiffness. Fibre-rich zones and fibre-lean regions were more common.

ITZ and Matrix Density: ITZ bonding was still better than in PCC but not as refined as in lower dosages. Overlapping fibres occasionally disrupted the matrix continuity. In glass-dominant areas, strong ITZ was visible, but in PP-dense regions, paste saturation and minor voids affected bonding slightly.

Crack Bridging: Overall porosity remained controlled. However, internal fibre overlaps led to denser local areas and small entrapped air pockets in others. Slight increase in observable pores compared to 0.75% fibre mixes.

Void Content: Overall porosity remained controlled. However, internal fibre overlaps led to denser local areas and small entrapped air pockets in others. Slight increase in observable pores compared to 0.75% fibre mixes

Summary: At 1.0% fibre volume, the SEM analysis showed that while microcrack control and matrix refinement continued, uniformity of dispersion decreased. Glass-rich zones maintained good performance; PP-rich zones faced overlap challenges. Matrix densification slightly reduced due to crowding. Thus, 1.0% dosage appears to mark the upper boundary of efficient hybrid fibre use without significant compromise in uniformity.

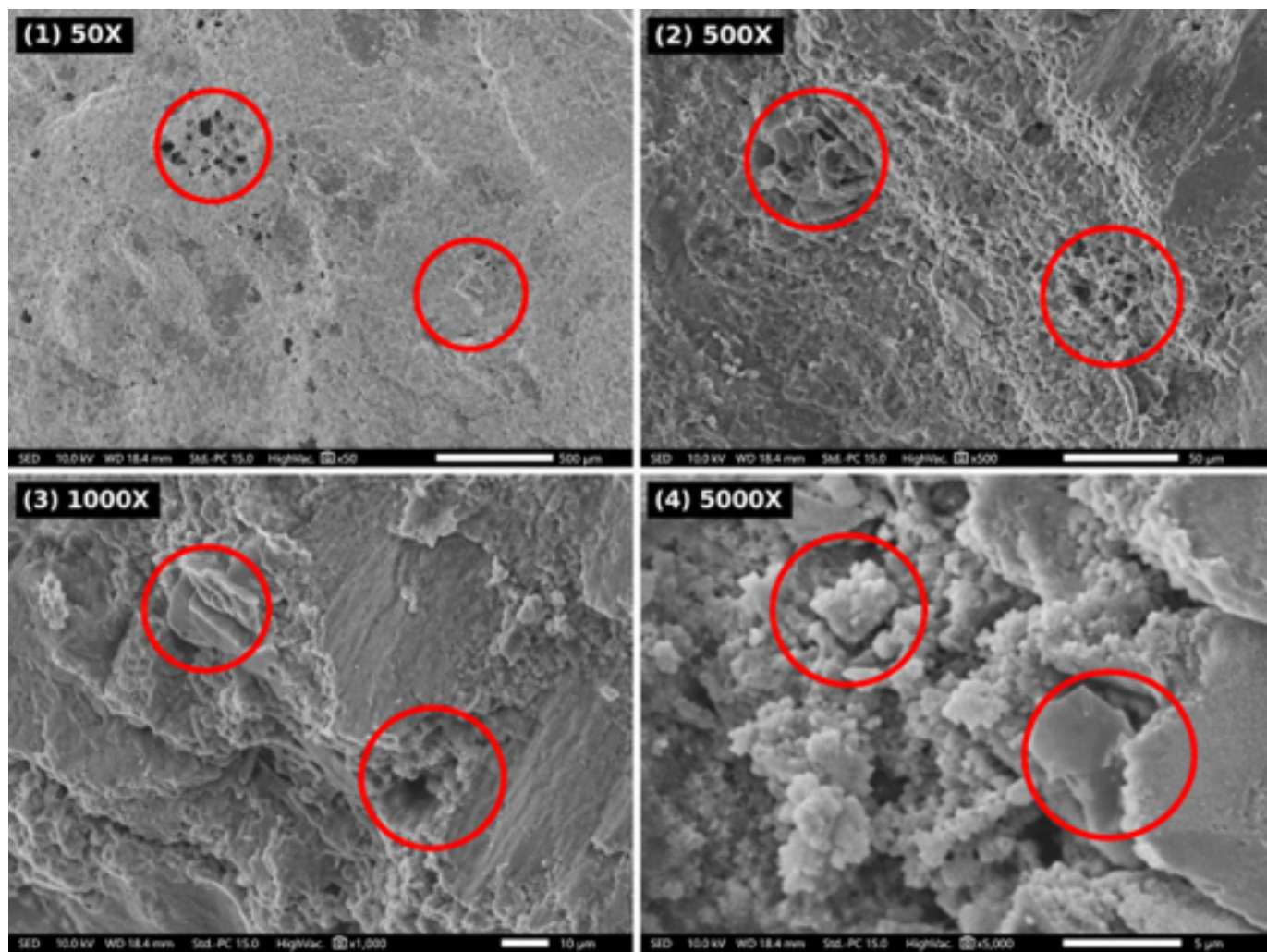


Figure 5. SEM images of hybrid fibre-reinforced concrete containing 1.0% total fibre content of M11 at 50X, 500X, 1000X, and 5000X magnifications.

3.2.5. Progressive Improvement with Fibre Dosage

A consistent trend is evident: as total fibre content increases from 0.25% to 1.0%, the matrix becomes denser and more crack resistant. Hybrid fibres offer multi-scale reinforcement-glass fibres control major cracks and strengthen the ITZ, while PP fibres mitigate microcrack formation and assist in dispersion. Uniform fibre distribution is crucial; clustering in high-PP mixes (0.75% and 1.0%) can compromise local quality, while balanced and glass-rich mixes maintain homogeneity. Overall, the 1.0%

mixes-especially the balanced and glass-rich ones-deliver superior microstructural integrity, with compact ITZs, minimal porosity, and near-complete crack suppression. These findings highlight the synergy of hybrid fibres and the importance of proper mix design and fibre management at high dosages. Below Table 2 presents a comparative SEM summary of the hybrid fibre-reinforced concrete mixes highlighting their key microstructural properties including fibre dispersion, ITZ characteristics, crack control, matrix density, and the corresponding expected durability.

Table 2. Comparative SEM Summary for Hybrid Fibre-Reinforced Concrete Mixes (Polypropylene and Glass Fibre Combinations).

Mix (PP% & G%)	Fibre Dispersion	ITZ Characteristics	Crack Bridging / Crack Control	Matrix Density / Voids	Expected Durability (Microstructural Inference)
Plain Concrete (0% fibres)	– (no fibres)	Weak, porous ITZ around aggregates	Uncontrolled crack propagation (no bridging)	Porous matrix; loosely packed hydration gel	Low (baseline; high permeability and crack risk)
0.07% PP & 0.18% G (0.25% total)	Uniform fibre distribution; no clumping	Strong, compact ITZ, notably around glass fibres	Fibres bridge cracks, arresting crack growth	Dense matrix; very few micro-voids	High (significantly improved over PCC due to refined structure)
0.125% PP & 0.125% G (0.25% total)	Uniformly dispersed fibres	Refined ITZ throughout; both fibre types contribute	Cracks intercepted by fibres; improved crack pattern	Compact hydration structure; minimal porosity	High (improved overall durability from reduced cracks and porosity)
0.18% PP & 0.07% G (0.25% total)	Predominantly PP fibres, well distributed	ITZ improved near fibres; moderate densification	Microcracks bridged by PP fibres; limited glass bridging	Moderately dense matrix; small voids visible	Moderate–High (better than PCC, slightly less refined than glass-rich mix)
0.125% PP & 0.375% G (0.50% total)	Glass-rich dispersion; glass fibres densely interspersed, with minor PP clustering	Densified ITZ, especially around glass fibres; strong fibre–matrix bond	Excellent crack bridging by plentiful glass fibres; crack deflection evident	Tightly packed matrix; minimal voids	Very High (dense microstructure and superior crack control)
0.250% PP & 0.250% G (0.50% total)	Homogeneous fibre distribution; no clumps	Uniformly refined ITZ around both PP and glass fibres	Effective bridging by both fibre types; cracks greatly contained	Highly compact matrix; hardly any voids	High (well-rounded improvement in durability and strength)
0.375% PP & 0.125% G (0.50% total)	PP-rich distribution; generally uniform with slight local clustering	Moderately densified ITZ near fibres; some non-uniform patches	Some crack bridging; PP controls microcracks with fewer glass fibres for large cracks	Semi-dense matrix; a few dispersed small voids	Moderate (notably improved over PCC, but less than glass-heavy mix)
0.19% PP & 0.56% G (0.75% total)	High fibre content; well distributed overall with minor clusters	Significantly densified ITZ; glass-dominant mix yields tight interfaces	Strong crack bridging by many glass fibres; PP aids microcrack control	Dense matrix; virtually no new voids	High (excellent durability expected from highly refined microstructure)
0.375% PP & 0.375% G (0.75% total)	Very high fibre content; mostly uniform with minor clustering	ITZ uniformly dense around fibres; both types equally present	Extensive crack bridging at multiple scales; PP and glass fibres act synergistically	Dense, well-packed matrix; negligible void content	High (significant microstructural improvements across the board)
0.56% PP & 0.19% G (0.75% total)	PP-heavy fibre content; mostly well dispersed with minor PP fibre bundles	Improved ITZ, but slightly less uniform due to fewer glass-rich zones	Good crack control; PP arrests microcracks with moderate bridging of larger cracks	Dense matrix overall; no obvious voids	Moderate–High (markedly better than PCC, although the glass-heavy mix is more optimal)
0.25% PP & 0.75% G (1.00% total)	Extremely fibre-rich; glass fibres prevalent with minor clustering	Very strong ITZ around abundant glass fibres; excellent fibre–matrix bond	Outstanding crack bridging; cracks rarely propagate without interception by glass fibres	Very dense matrix; minimal additional voids despite high fibre content	High (maximized crack resistance and matrix densification; top durability)
0.50% PP & 0.50% G (1.00% total)	Extremely fibre-rich; both fibre types pervasive with minor mixed-fibre clusters	Uniformly strong ITZ throughout; high fibre presence within the matrix	Extensive fibre bridging; cracks spanned by both PP and glass fibres	Dense matrix; practically no significant voids with good mixing	High (very high durability due to refined microstructure; requires careful mixing)
0.75% PP & 0.25% G (1.00% total)	Extremely fibre-rich; PP fibres dominant with some PP clustering	ITZ improved but less optimal; limited glass reinforcement and some local weak spots	Microcracks well controlled by PP; limited glass bridging for larger cracks	Dense matrix but with some voids due to fibre clustering and air entrapment	Moderate (better than PCC, but compromised by voids and diminishing returns at high PP content)

Note: Observations are qualitative summaries derived from SEM imaging. Expected durability is inferred from microstructural features such as porosity and crack presence. A high rating indicates a microstructure with greater resistance to ingress and crack growth, whereas a moderate rating indicates remaining microstructural concerns.

4. Conclusion

The SEM investigation demonstrated that hybrid polypropylene (PP) and glass fibres significantly improved the microstructural characteristics of concrete compared with PCC through enhanced fibre-matrix interaction, crack control, ITZ quality, and matrix compactness. Glass fibres were particularly effective in bridging larger cracks, while PP fibres controlled finer microcracks, demonstrating complementary multi-scale reinforcement. At 0.25% total fibre volume, glass-rich M1 exhibited strong ITZ and crack blocking, PP-rich M3 effectively controlled fine microcracks, while balanced M2 provided the most uniform overall microstructure. At 0.50%, glass-rich M4 showed excellent ITZ and larger-crack bridging, PP-rich M6 improved fine-crack control but exhibited slight local unevenness, whereas balanced M5 achieved uniform dispersion and effective multi-scale crack bridging. At 0.75%, glass-rich M7 maintained strong fibre-matrix bonding and crack interruption, while PP-rich M9 provided effective microcrack control but showed initial fibre crowding and overlapping. Balanced M8 exhibited superior dispersion, uniform ITZ densification, effective multi-scale crack bridging, and negligible void formation. At 1.00%, glass-rich M10 retained strong ITZ and crack-bridging characteristics, and balanced M11 provided effective combined crack control; however, fibre crowding and overlapping increased, particularly in PP-rich M12, resulting in localized voids and reduced matrix uniformity. Considering all twelve hybrid mixes, M8 was identified as the optimum overall mix, providing the best balance of fibre dispersion, ITZ quality, multi-scale crack control, and matrix compactness without the dispersion-related limitations observed at higher fibre content. Thus, effective hybridization depends on both fibre dosage and proportion rather than merely increasing total fibre content.

Abbreviations

AR	Alkali-Resistant
C-S-H	Calcium-Silicate-Hydrate
EDS	Energy-Dispersive X-ray Spectroscopy
GPa	Gigapascal
G-GRC	Graded Glass Fiber Reinforced Concrete
ITZ	Interfacial Transition Zone
MPa	Megapascal
OPC	Ordinary Portland Cement
PCC	Plain Cement Concrete
PGRC	Polymer Glass Fibre Reinforced Concrete
PP	Polypropylene
PP-GF	Polypropylene-Glass Fiber
SEM	Scanning Electron Microscopy
W/B	Water-to-Binder
XRD	X-ray Diffraction

Author Contributions

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Conflicts of Interest

The authors declare no conflicts of interest.

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