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VALORIZATION OF RECYCLED FIBERS IN HIGH-PERFORMANCE CONCRETE: AN EXPERIMENTAL AND SUSTAINABLE APPROACH

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Within the framework of sustainable development in the construction sector, the valorization of industrial waste in concrete formulation has emerged as a strategic approach to reducing production costs while minimizing environmental impact. This research presents a comparative study investigating the effects of waste plastic fibers derived from recycled PET strapping and steel fibers recovered from tire waste on the properties of high-performance concrete. To achieve this objective, the physical, mechanical, and durability properties of high-performance concrete mixtures incorporating 0.5% and 1% of recycled strapping fibers and recycled steel fibers were examined and compared with those of high-performance concrete containing conventional steel fibers. The experimental results revealed that the incorporation of recycled steel fibers progressively decreased the workability of high-performance concrete, whereas recycled strapping fibers enhanced it. Moreover, fiber-reinforced high-performance concrete exhibited higher compressive and flexural strengths, particularly when conventional steel fibers and recycled steel fibers were used, while recycled strapping fibers had an insignificant effect on flexural strength. Specifically, the compressive strength increased by 22.40%, 21.85%, and 7.63% for high-performance concrete incorporating steel fibers, recycled steel fibers, and recycled strapping fibers, respectively. The findings also indicated that recycled fiber incorporation reduced drying shrinkage of high-performance concrete. However, the resistance to acid attacks was reduced.

Keywords: high-performance concrete, waste, strapping fibers, steel fibers, properties

HIGHLIGHTS

- Effects of recycled plastic straps fibers and recycled steel fibers on HPC were studied.
- Recycled fibers improved the compressive strength of HPC.
- Fiber addition reduced drying shrinkage in HPC.
- Recycled fibers lowered HPC resistance to acid attack.

NOMENCLATURE

HPC: High-performance concrete
RSF: Recycled steel fibers
PSF: Plastic straps fibers
DS: Siliceous dune sand
G1: Gravel 3/8
SP: Superplasticizer
UPV: Ultrasonic pulse velocity
SF: Conventional steel fibers
PF: Plastic fibers
PC: Portland cement
CS: Crushed carry sand
G2: Gravel 8/16
CHPC: Control high-performance concrete

1 Introduction

The increasing demand for sustainable and high-performance infrastructure has fostered the development of High-Performance Concrete (HPC), characterized by superior mechanical strength, enhanced durability, and a dense microstructure [1]. However, the continuous improvement of the mechanical properties and durability of HPC remains a significant challenge, particularly when local materials and recycled industrial waste are incorporated to promote sustainable construction [2]. For this reason, the incorporation of fibers, whether steel or synthetic, into concrete mixtures has proven particularly effective in enhancing tensile strength, crack resistance, toughness, and post-cracking behavior [1–4]. Conventional steel fibers (SF), first used in the 1960s, have demonstrated beneficial effects on the rheological, mechanical, physical, and durability properties of concrete [3,4]. Aydin [5] reported that incorporating SF into self-compacting concrete improved its mechanical properties. Alabduljabbar et al. [6] observed that adding 2% SF increased the tensile and compressive strengths by 91.40% and 13.40%, respectively. Khaloo et al. [7] found that the presence of SF in the concrete mixture negatively affected workability and compressive strength but increased tensile strength by 28%. A similar trend was reported by De Figueiredo and Ceccato [8] and Iqbal et al. [9], who indicated that SF had an insignificant effect on the elastic modulus and compressive strength, while improving tensile strength. Olivito and Zuccarello [10] also noted that the inclusion of SF enhanced the ductile behavior of concrete.

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On the other hand, numerous studies have investigated the use of fibers derived from recycled tire waste [11-14]. Leon et al. [15] incorporated recycled steel fibers (RSF), recovered from waste tires, into concrete mixtures and observed a reduction in workability and mechanical strengths. However, they also reported that RSF-reinforced concrete exhibited improved ductility and post-cracking behavior. Centonze et al. [16] found that concrete reinforced with RSF showed a 23% increase in compressive strength and enhanced matrix toughness. Similar trends were reported by Zia et al. [17] and Aiello et al. [18], who further noted that RSF-reinforced concrete demonstrated good energy absorption capacity and residual strength. Köroğlu [19] used RSF in self-compacting concrete and observed improvements in compressive, split-tensile, and flexural strengths, with greater improvements observed in the latter two properties. Su et al. [20] reported that the incorporation of RSF in concrete reduced drying shrinkage by 9% and enhanced freeze–thaw resistance. Medina et al. [21] investigated the durability of rubberized concrete containing RSF and reported improved resistance to acid attack.

The use of plastic fibers (PF), derived from bottles, containers, and bags, in concrete mixtures has also been investigated in several studies [22]. These studies reported a reduction in the workability of PF-reinforced concrete [23-25]. However, this reduction remains acceptable within an appropriate dosage range [22]. Aziz and Kuhair [26] observed that adding 0.5% and 0.75% PF increased compressive strength by 2.9% and 5%, respectively. They further reported that the mixture containing 1% PF exhibited the greatest increase in flexural strength by 12.5%. Alhadithi et al. [27] incorporated PF into self-compacting concrete and recorded increases of 70% and 17% in flexural strength and elastic modulus, respectively, when 1.5% PF was used. Gu and Ozbakkaloglu [28] found that compressive strength increased with PF content up to 1%, beyond this dosage, it tended to decrease. Similar findings were reported by [23, 29-31]. Kim et al. [32] observed that both compressive strength and elastic modulus decreased with increasing PF content, although its ductility improved. Likewise, Silva et al. [33] highlighted an enhancement in the toughness of PF-reinforced concrete. Wong et al. [34] found that PF-reinforced concrete exhibited chloride permeability comparable to that of conventional concrete. However, its freeze–thaw resistance was significantly improved by the inclusion of PF. Fode et al. [35] also reported that adding 0.5% PF significantly reduced chloride ion migration. Vijaya et al. [29] concluded that incorporating PF reduced both weight loss and compressive strength degradation of self-compacting concrete under aggressive environmental conditions, with an optimum PF content of approximately 1%.

1.1 Research significance

HPC has undergone continuous development through the use of advanced materials, including supplementary cementitious materials and fiber reinforcement. In this regard, the reuse of waste materials to improve the properties of HPC represents an innovative and sustainable approach. Plastic waste and used tires currently pose a major environmental challenge. According to [36], more than 350 million tons of plastics are produced annually, a significant portion of which ends up in oceans or landfills, where their degradation can take several centuries. Similarly, nearly 1.5 billion tires are discarded each year worldwide, creating a substantial amount of waste that is difficult to manage and potentially harmful to the environment [37,38]. In this context, utilizing these wastes materials as fibers for HPC offers two major advantages: reducing the environmental footprint while improving the mechanical performance of the concrete.

Over the past few decades, several experimental studies have investigated the reuse potential of RSF derived from waste tires in concrete. These studies mainly focused on mechanical properties such as compressive strength, flexural strength, and ductility. However, there remains a significant gap in understanding the durability performance of RSF-reinforced concrete, particularly in the case of HPC. The present study provides a comprehensive experimental investigation of the fundamental properties of HPC incorporating RSF, aiming to address this research gap.

In addition, several studies have examined the properties of concrete modified with PF derived from bottles, containers, and bags, highlighting that the performance of PF-reinforced concrete depends on the type and nature of the fibers used. However, a limited number of studies have investigated the effect of polyethylene terephthalate fibers derived from plastic strapping waste on the properties of concrete. After use, the plastic strapping material is generally discarded, generating solid waste that contributes to environmental issues, including disposal challenges, visual pollution, and the blockage of waterways. The present research investigates the feasibility of reusing plastic strapping fibers (PSF) to enhance the mechanical and durability properties of HPC. To provide a comprehensive assessment of their performance, a comparative analysis of HPC reinforced with RSF, PSF, and conventional SF is conducted.

2 Materials and methods

2.1 Materials used

2.1.1 Cement

A Portland cement (PC) of type CEM II/A-L 52.5, manufactured by CILAS (Lafarge Cement Company), was used in this experimental research. The physical and mechanical properties of PC used are detailed in Table 1, and its chemical composition is presented in Table 2.

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Table 1. Physical properties of PC

Physical Properties	PC	Standards
Initial setting time [min]	181	NA 230
Final setting time [min]	228	NA 230
Specific gravity	3.07	EN 196-6
Loss in ignition [%]	2.9	NA 5042
Specific surface [cm²/g]	4308	NA 231
Expansion [mm]	0.5	NA 230
Compressive strength at 2 days [MPa]	29.80	NA 234
Compressive strength at 28 days [MPa]	59.10	NA 234
Flexural strength at 2 days [MPa]	5.84	EN 196-1
Flexural strength at 28 days [MPa]	8.44	EN196-1

Table 2. Chemical Composition of PC

Element [%]	PC
CaO	61.35
Al_2O_3	4.74
Fe_2O_3	3.27
SiO_2	19.93
MgO	1.01
Na_2O	0.21
Chloride	0.06
K_2O_3	0.41
SO_3	2.92
C_4AF	10.05
C_3A	8.26
C_2S	10.57
C_3S	65.30

2.1.2 Aggregates

Siliceous dune sand (DS, 0/1), collected from Oued El Zhor (Skikda, Eastern Algeria), and crushed quarry sand (CS, 0/4), obtained from the Constantine quarry, were employed as fine aggregates in this investigation (Fig.1). The physical characteristics of the fine aggregates are summarized in Table 3, while their particle size distributions are presented in Fig. 2.

Two types of crushed gravel, designated as G1 (3/8) and G2 (8/16), both sourced from the Constantine quarry, were used as coarse aggregates. The physical properties of the coarse aggregates are also provided in Table 3, and their particle size distributions are illustrated in Fig. 2

Fig.1. Aggregates used

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Table 3. Properties of aggregates used

Properties	G1	G2	CS	DS	Standards
Density [g/cm³]	2.69	2.69	2.64	2.64	EN 1097-6
Sand equivalent [%]	–	–	74	78	EN 933-8
Water absorption [%]	1.28	1.18	1.40	0.94	EN 1097-6
Fineness modulus	–	–	2.79	1.65	EN 933-1
Micro-Deval [%]	14.3	15.5	–	–	EN 1097-1
Los Angeles [%]	28.1	27.1	–	–	EN 1097-2

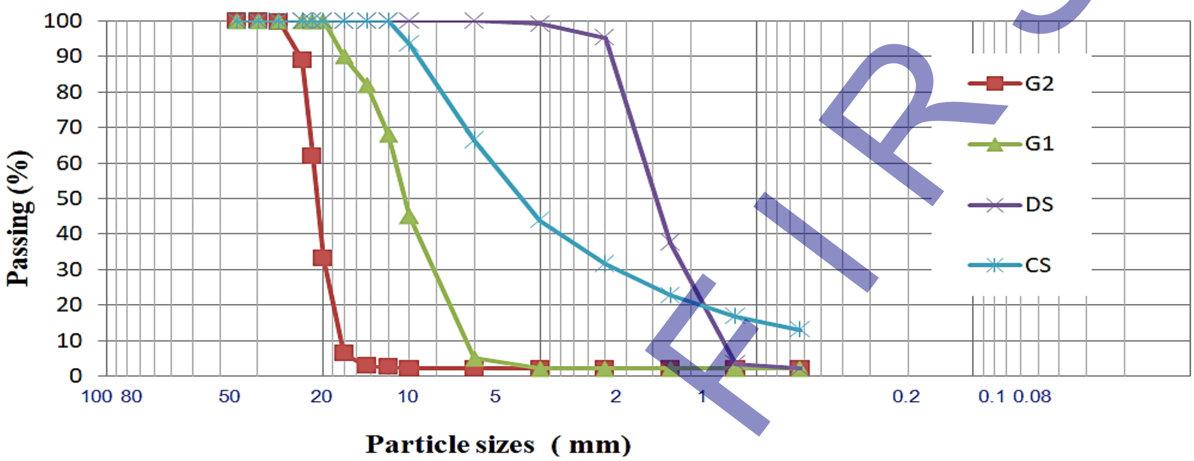

Fig. 2. particle size curves of aggregates used

2.1.3 Fibers

Three types of fibers were used in this study: conventional steel fibers (SF), recycled steel fibers (RSF), and recycled plastic straps fibers (PSF). SF, commercially known as Metal Products MPZGB35/0.55 (Fig. 3), was manufactured by Metal Products B.V. (Netherlands). These drawn SF are supplied in glued bundles, facilitating their uniform dispersion in the concrete mix and preventing fiber balling during mixing. The adhesive dissolves easily in the mixing water. The main physical and mechanical properties of the SF are presented in Table 4. PSF were obtained from waste packaging straps composed of polyethylene terephthalate (PET). These fibers exhibited a smooth surface and generally originate from industrial and commercial waste such as pallet strapping or brick bindings. The recycling process includes several stages: collection and washing to remove impurities (glue, dust, oils, etc.); mechanical cutting into controlled dimensions; and final drying and conditioning. The PSF were used directly after cutting, without any additional thermal or chemical treatment (Fig. 3), to ensure a cost-effective and environmentally sustainable approach. Their main properties are summarized in Table 4. RSF recovered from waste tires of light vehicles were used. These tires contain high-strength steel cords that provide rigidity and mechanical performance. The recycling process involves collection and mechanical shredding to separate rubber, textiles, and steel; magnetic extraction of the steel fibers; cleaning through sieving and washing to remove residual rubber; and final cutting and sizing to achieve the desired fiber dimensions. RSF presented a relatively smooth surface with minor surface irregularities resulting from the tire recycling process. The RSF were used without any chemical modification (Fig. 3), maintaining a sustainable and economical approach. The properties of the RSF are listed in Table 4.

Fig. 3. Fibers used

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Table 4. Properties of the fibers used

Fiber Type	Length [mm]	Diameter or Width [mm]	Aspect Ratio	Density [kg/m³]	Tensile Strength [MPa]
SF	35	0.55	64	7850	1221
PSF	35±5	2±0,5	15.5	1345	306
RSF	35±5	0.3	115	7894	856

2.1.4 Admixture

In this study, the superplasticizer used (SP) is Sika Viscocrete-665, a new-generation SP belonging to the family of modified polycarboxylate ethers. This high-performance SP is designed to provide a significant water reduction while maintaining excellent workability of fresh concrete. The main properties of SP used are summarized in Table 5.

Table 5. Properties of SP used

Properties	Value
Chemical base	Modified polpolycarboxylate
Appearance	Brown liquid
Density (20°C)	1,085 ± 0,015
PH	5 ± 1
Sodium oxide equivalent (Na_2O-eq.)	≤ 1,0 %
Chloride content	≤ 0,1 %

2.2 Mix preparation and tests

The Dreux–Gorisse method was employed to determine the coarse-to-fine aggregate ratio of the control HPC mixture (CHPC). The PC and water contents were fixed at 420 kg/m³ and 173 L/m³, respectively. The SP was added at 0.85% of the PC weight to ensure adequate workability without increasing the water content. Subsequently, 0.5% and 1% of SF, PSF, and RSF were incorporated into the HPC mixtures by volumetric substitution of aggregates, in order to assess their influence on the properties of the formulated HPC (Table 6).

To ensure proper homogeneity of the fiber-reinforced HPC mixtures, all solid components were first mixed for three minutes, followed by the addition of water and SP, and further mixing for an additional three minutes. The fresh HPC mixtures were then cast and compacted in standard steel molds in accordance with NF P18-405. All specimens were compacted using a vibrating table. Vibration was applied for approximately 15 s, until adequate compaction was achieved. After 24 hours, the specimens were demolded and cured in water at 23 °C and 100% relative humidity until the testing age. For each test, three specimens were tested, and the reported results correspond to the average value obtained from the three measurements.

Table 6. Fiber-reinforced HPC mixtures composition

Mixtures	DS [kg/m³]	CS [kg/m³]	G1 [kg/m³]	G2 [kg/m³]	PC [kg/m³]	Water [kg/m³]	SP [kg/m³]	Fibers [kg/m³]
CHPC	192	739	195	707	420	173	3.57	00
HPCSF0,5	189.14	728.01	192.10	696.60	420	173	3.57	27.16
HPCSF1	86.27	717.02	189.19	686.20	420	173	3.57	54.32
HPCPF0,5	191.51	737.12	194.50	705.22	420	173	3.57	4.65
HPCPF1	191.02	735.23	194	703.22	420	173	3.57	9.30
HPCRSF0,5	189.12	727.95	192.08	696.54	420	173	3.57	27.31
HPCRSF1	186.24	716.90	189.16	686.08	420	173	3.57	54.62

In the fresh state, the workability, density, and air content were measured in accordance with standards NF EN 12350-2, NF EN 12350-6, and NF EN 12350-7, respectively. To evaluate the mechanical performance of the formulated HPC mixtures, compressive strength tests were carried out on 150 mm cubic specimens at 7, 28, 90, and 180 days, following NF EN 12390-3. Flexural strength was determined on 70 × 70 × 280 mm prisms at 7, 28, 90, and 180 days, according to NF EN 12390-5. Capillary water absorption tests were conducted on 70 × 70 × 280

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mm prisms at 28 days in accordance with NBN B 15-215, while the water absorption by immersion was evaluated on 150 mm cube specimens in accordance with ASTM C642 standard. The shrinkage of HPC mixtures was measured to evaluate the longitudinal deformation caused by drying and moisture loss. The test was conducted on 70 × 70 × 280 mm prisms in accordance with ASTM C596. Chemical resistance tests were performed on 100 mm cubic specimens following ASTM C267-96. After 28 days of water curing, the specimens were removed, surface-dried, and then immersed in acid solutions prepared at a concentration of 5%. Two types of aggressive environments were considered: hydrochloric acid (HCl) and sulfuric acid (H_2SO_4), both prepared by diluting concentrated laboratory-grade acids with distilled water. The pH of each solution was initially adjusted to approximately 1.0 ± 0.2 and maintained throughout the exposure period. The specimens were fully submerged in the acid baths and stored at a constant temperature of 23 ± 2 °C. To preserve the aggressiveness of the medium, the acid solutions were renewed every 14 days. The exposure durations were set at 90 and 180 days. At the end of each period, the specimens were rinsed with distilled water, surface-dried, and tested to evaluate their residual compressive strength loss.

3 Results and discussion

3.1 Workability

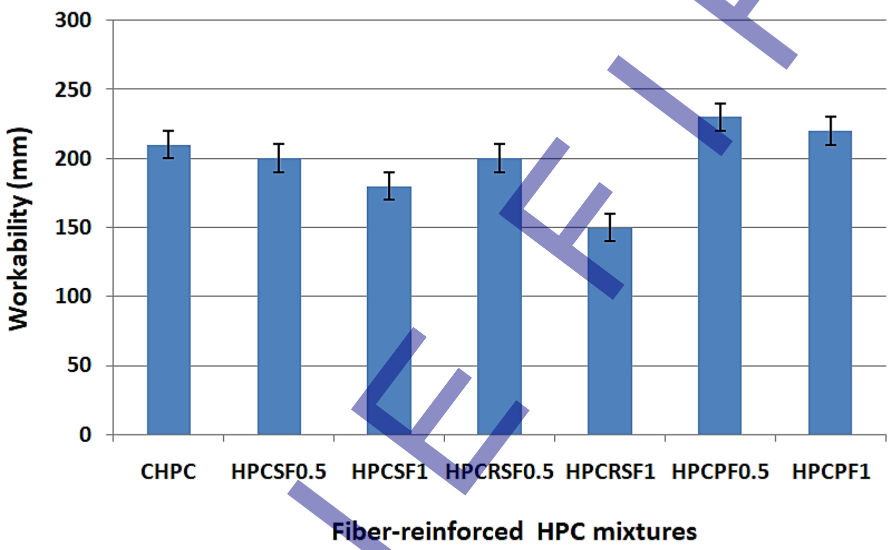

Fig. 4. Workability of fiber-reinforced HPC mixtures

Fig. 4 illustrates the workability of HPC mixtures incorporating SF, PSF, and RSF. A progressive reduction in workability was observed with increasing contents of SF and RSF. The incorporation of 1% SF and RSF decreased the slump from 210 mm to 180 mm and 150 mm, respectively. This reduction can be attributed to the high stiffness, elongated shape, and rough surface of these fibers, which increase internal friction between aggregates and the cement paste, thereby limiting particle mobility and reducing flowability. Moreover, the formation of a rigid interlaced network within the fresh mix further restricts fluid movement [16, 39-42]. Centoze et al. [16] noted that the irregular geometries of the RSF enhance inter-particle friction and the tendency of fibers to cluster, resulting in lower workability. In contrast, HPC mixtures containing PSF exhibited higher workability compared with the control HPC. The HPCPF0.5 mixture, containing 0.5% PSF, showed the greatest increase in workability, with an improvement of 9.52%. This enhancement is explained by the flexibility and lower surface roughness of PSF, which promote better dispersion and reduce internal friction, as noted by Yoo and Banthia [41], Ochi et al. [43], and Fraternali et al. [44].

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3.2 Air content

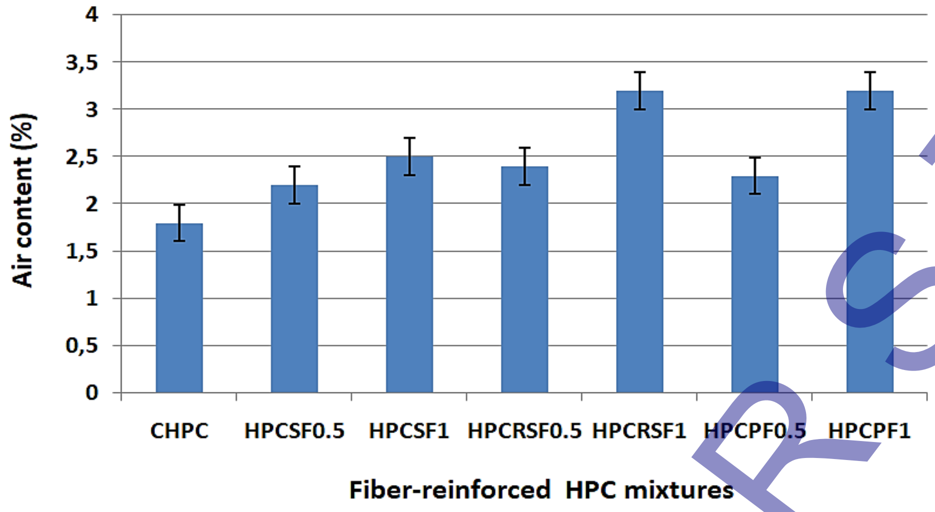

Fig. 5. Air content of fiber-reinforced HPC mixtures

Fig. 5 shows that the incorporation of fibers leads to an overall increase in the air content of HPC mixtures. The extent of this increase depends on both the type and content of fibers used. This trend can be explained by the presence of fibers within the HPC matrix, which create preferential zones for air entrapment during mixing, as noted by Bentur et al. [45]. Among all mixtures, HPC containing 1% PSF and RSF exhibited the highest increase in air content, by up to about 77.8% compared with the control HPC. This trend can be attributed to the elongated geometry and low density of PSF, which favor the retention of micro-air bubbles and reduce the efficiency of vibration compaction [46]. Moreover, the irregular shape and rough surface texture of RSF contribute to additional air-trapping zones within the matrix, further increasing the overall entrapped air volume [47].

3.3 Fresh density

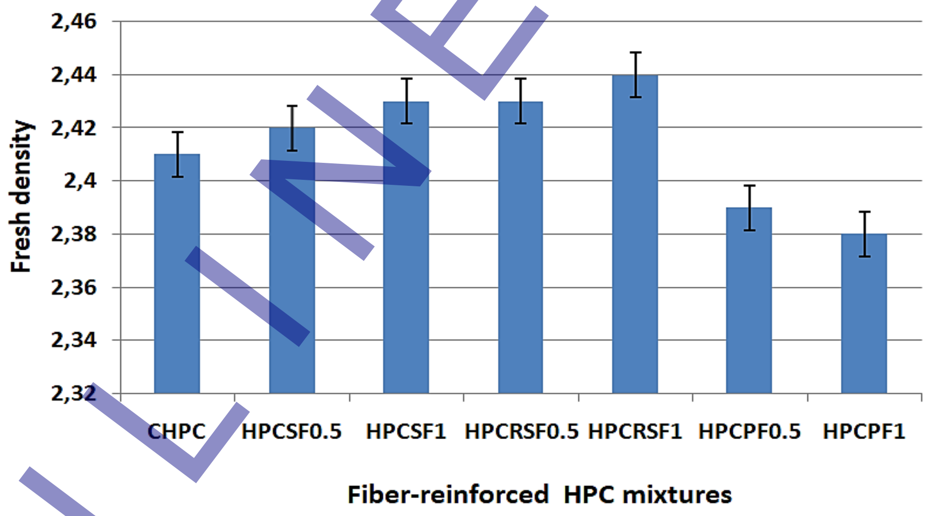

Fig. 6. Fresh density of fiber-reinforced HPC

The results presented in Fig. 6 indicate that the incorporation of fibers influences the fresh density of HPC, primarily depending on the intrinsic density of the fibers used [48]. The HPC mixtures reinforced with RSF exhibited the highest fresh density, followed by those containing SF. This trend can be attributed to the relatively high specific gravity of RSF and SF, typically exceeding 7.80 g/cm³ [49,50]. The incorporation of 1% RSF and SF increased the density by approximately 1.24% and 0.82%, respectively. In contrast, the addition of 1% PSF resulted in a reduction in density of about 1.65%, owing to the much lower specific gravity of PSF compared with mineral aggregates [51]. Overall, the incorporation of fibers in HPC led to only minor variations in density, ranging from +1.24% to -1.65%. These results suggest that appropriate selection and dosage of fibers can enhance the mechanical and durability properties of HPC without significantly affecting its density.

3.4 Compressive strength

Fig. 7 presents the compressive strength results of HPC mixtures incorporating SF, PSF, and RSF. The analysis reveals a significant improvement in compressive strength depending on both the fiber type and dosage. HPC mixtures reinforced with 1% SF and RSF exhibited the highest compressive strengths, particularly at longer curing ages. In contrast, the optimal performance of PSF-reinforced HPC was achieved with 0.5% fiber content. At 180

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days, the incorporation of 1% SF and RSF increased compressive strength by 21.85% and 22.40%, respectively, compared with the control HPC mixture. The addition of 0.5% PSF resulted in a moderate improvement of 7.63%, whereas increasing the PSF content to 1% led to a slight increase in compressive strength by 2.21% compared with the control HPC.

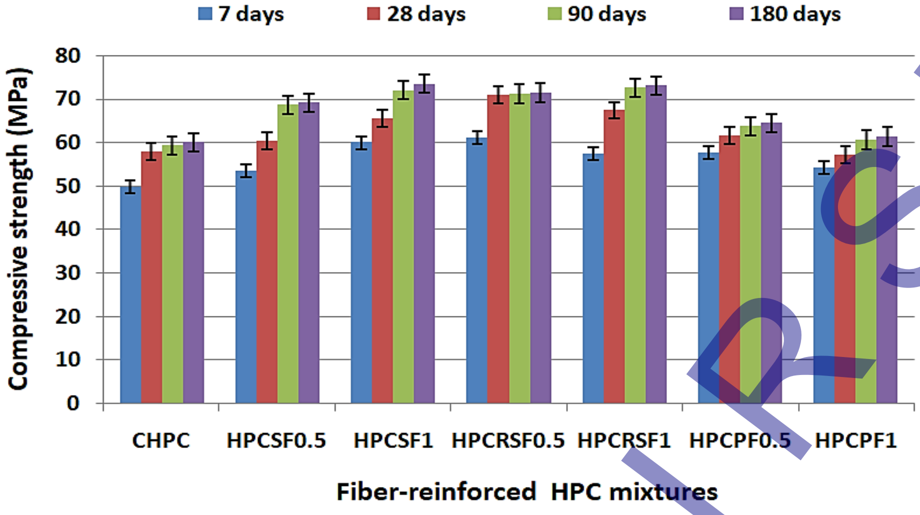

Fig. 7. Compressive strength of fiber-reinforced HPC mixtures

The enhancement of compressive strength observed in SF- and RSF-reinforced mixtures has been reported in the literature [16, 41, 42, 45]. This improvement is attributed to the strong mechanical bond and effective stress transfer between the steel fibers and the cementitious matrix, which promote a more uniform distribution of internal stresses, inhibit the initiation and propagation of microcracks, and contribute to the gradual densification of the microstructure during hydration [52].

The improvement in compressive strength of concrete containing PF has also been reported by several researchers [37,44,53]. This enhancement is generally attributed to the good dispersion of PF within the cementitious matrix, which contributes to a more homogeneous microstructure. The flexible nature of PF allows them to bridge microcracks during the early stages of loading, delaying their propagation and thus improving the post-cracking behavior and apparent compressive strength. Ochi et al. [37] and Fraternali et al. [44] also reported that the low water absorption of PF helps maintain the effective water-to-cement ratio, favoring a denser and more cohesive matrix. However, other studies have observed a slight decrease in compressive strength with increasing PF content [32, 54]. This reduction is mainly associated with the hydrophobic surface and low stiffness of polymer fibers, which limit bonding with the cement paste. Furthermore, excessive fiber content may lead to agglomeration and air entrapment, increasing porosity and weakening overall matrix cohesion [32].

3.5 Flexural strength

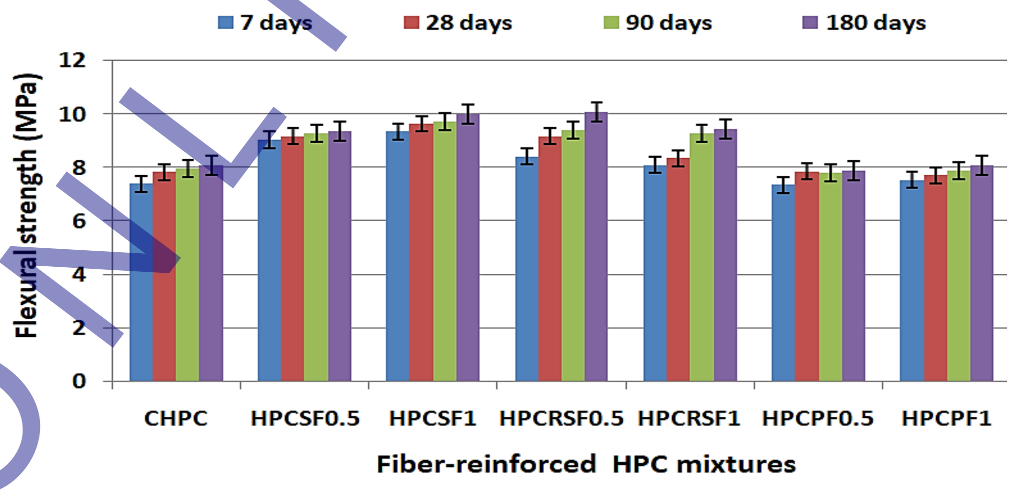

Fig. 8. Flexural strength of fiber-reinforced HPC mixtures

Fig. 8 presents the flexural strength results of fiber-reinforced HPC mixtures. Similar to the compressive strength behavior, a significant improvement in flexural strength was observed for HPC incorporating SF and RSF. The addition of 1% SF increased the flexural strength by 23.91%, while the inclusion of 0.5% RSF resulted in a 25.03% increase compared with the control HPC mixture. The enhancement in flexural strength of HPC containing SF and RSF has been reported by [3, 41, 42, 55, 56]. This improvement is primarily attributed to the strong bonding between steel fibers and the cementitious matrix, which enables efficient stress transfer across the matrix–fiber interface. During loading, the fibers act as crack-bridging elements, arresting the initiation and propagation of

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microcracks and enhancing the post-cracking ductility of the composite. Moreover, the high tensile strength and stiffness of steel fibers contribute to an effective redistribution of tensile stresses within the matrix, thereby increasing the flexural strength and toughness of HPC [3, 41, 57].

However, the HPC mixtures reinforced with PSF exhibit no measurable improvement and even show a neutral or slightly negative effect, depending on curing age. The incorporation of 0.5% PF led to a slightly lower value by 2.23% compared with the reference HPC, while 1% PF resulted in a similar value. The reduction in flexural strength of concrete containing PF has also been reported by several authors [37, 58-62], who attributed it to the low stiffness and tensile strength of plastic fibers compared with steel fibers.

3.6 Ultrasonic pulse velocity (UPV)

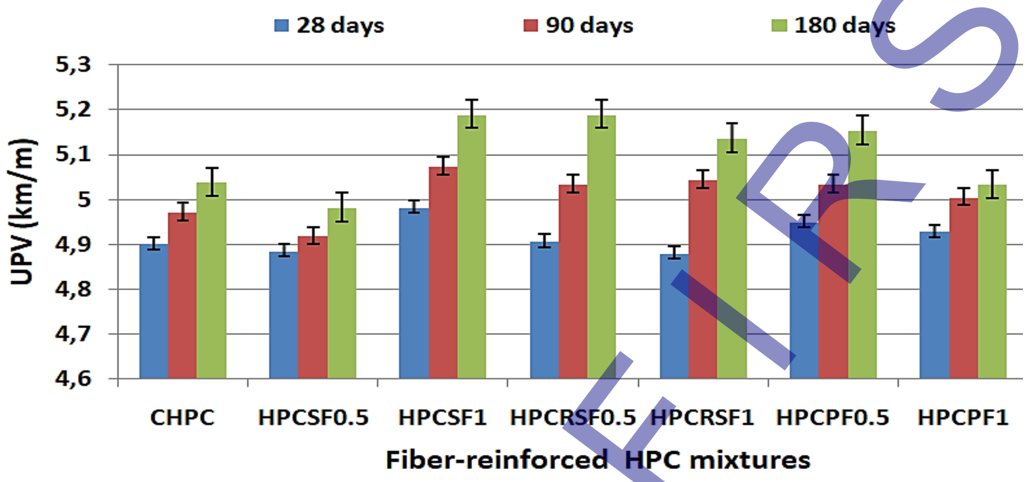

Fig. 9. UPV of fiber-reinforced HPC mixtures

Ultrasonic Pulse Velocity (UPV) testing is a non-destructive method used to evaluate the compactness, homogeneity, and internal quality of concrete. The propagation velocity of ultrasonic waves depends directly on the density and continuity of the cementitious matrix. Higher velocities indicate a denser and more homogeneous material, whereas lower velocities reveal internal voids, discontinuities, or microcracks [63]. As shown in Fig. 9, although mixtures HPCSF0.5 and HPCPF1 exhibit slightly lower UPV values than the control HPC, all other fiber-reinforced HPC mixtures display higher UPV values. This improvement indicates a denser and more cohesive internal structure due to the incorporation of fibers, as reported by Abdulrehman et al. [64] and Gebretsadik et al. [65]. The maximum increase in UPV by about 3% at 90 days was observed for HPC mixtures containing 1% SF and 0.5% RSF. According to ASTM C597, which classifies concrete as very good quality when UPV exceeds 4.5 km/s, all fiber-reinforced HPC mixtures formulated in this study can be categorized as high-quality concretes with excellent internal compactness.

3.7 Water absorption

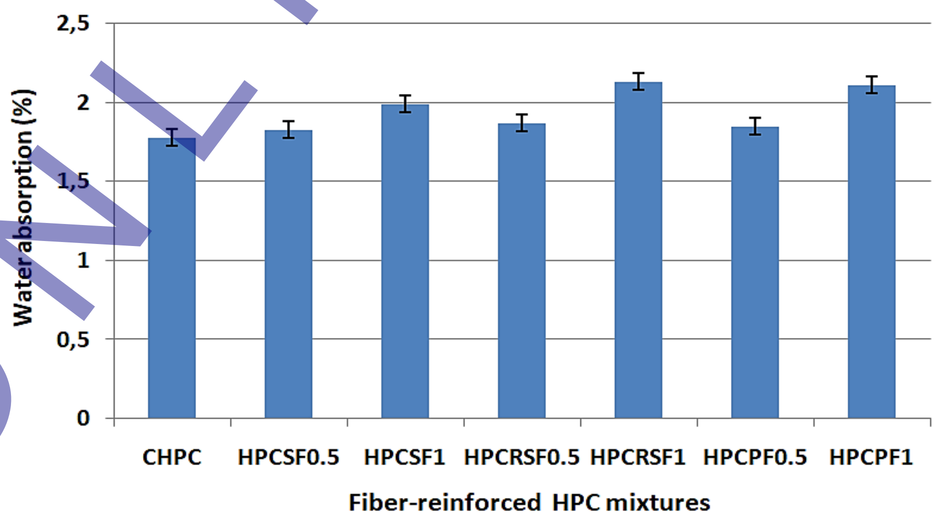

Fig. 10. Water absorption by immersion of fiber-reinforced HPC mixtures

Fig. 10 presents the water absorption by immersion results of the fiber-reinforced HPC mixtures. A gradual increase in water absorption with increasing fiber content is observed, regardless of the fiber type. The incorporation of 1% SF, RSF, and PSF led to increases in water absorption of 11.79%, 19.66%, and 18.53%, respectively. Similar trend was reported by [64, 66,67], and was attributed to the higher air content in fiber-reinforced concretes and the formation of more porous interfacial transition zones (ITZ) surrounding the fibers [3,

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68]. It should be noted that all fiber-reinforced concrete mixtures exhibited comparable water absorption values up to a fiber content of 0.5%. However, when the fiber content exceeded 0.5%, the RSF-reinforced concrete exhibited the highest water absorption, followed by the PF-reinforced concrete, whereas the SF-reinforced concrete showed the lowest water absorption. According to the CEB-FIP Model Code, concrete with water absorption values below 3% is classified as being of good quality. Based on this criterion, all fiber-reinforced HPC mixtures in this study can be considered of good quality, despite the slight increase in water absorption.

Figure 11 illustrates the capillary water absorption of the formulated fiber-reinforced HPC mixtures. These results reveal that water absorption through capillarity increases over time for all fiber-reinforced HPC mixtures. However, the magnitude of absorption depends on both the type and dosage of fibers incorporated. Similar to the results obtained from the water absorption by immersion test, all reinforced HPC mixtures follow the same trend in capillary absorption behavior. The highest water absorption values are observed for the mixtures containing 1% fibers, indicating an increase in the rate of water uptake with higher fiber content. At a fiber content of 1%, RSF-reinforced concrete continued to exhibit the highest water absorption, whereas PF- and SF-reinforced concrete showed comparable water absorption values. These results confirm that the presence of fibers increases the porosity around the interfacial transition zone (ITZ), as reported by Afroughsabet and Ozbakkaloglu [3] and Haruna et al. [68].

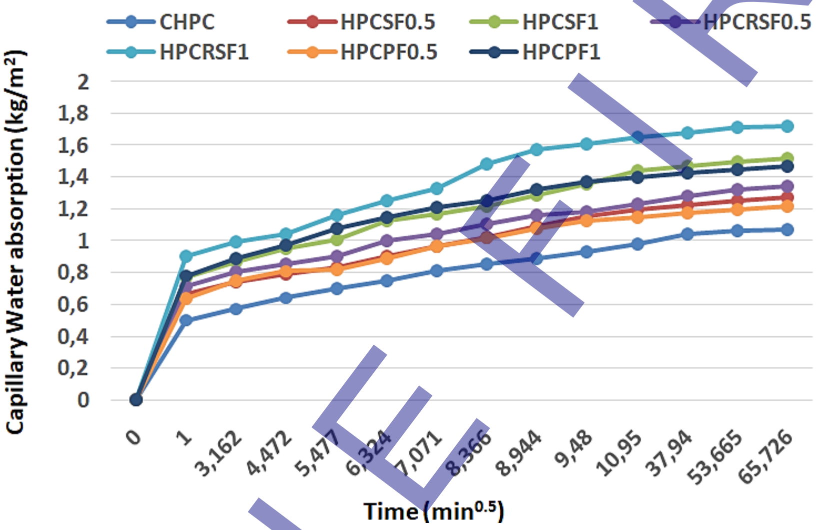

Fig. 11. Capillary water absorption of fiber-reinforced HPC mixtures

3.8 Drying shrinkage

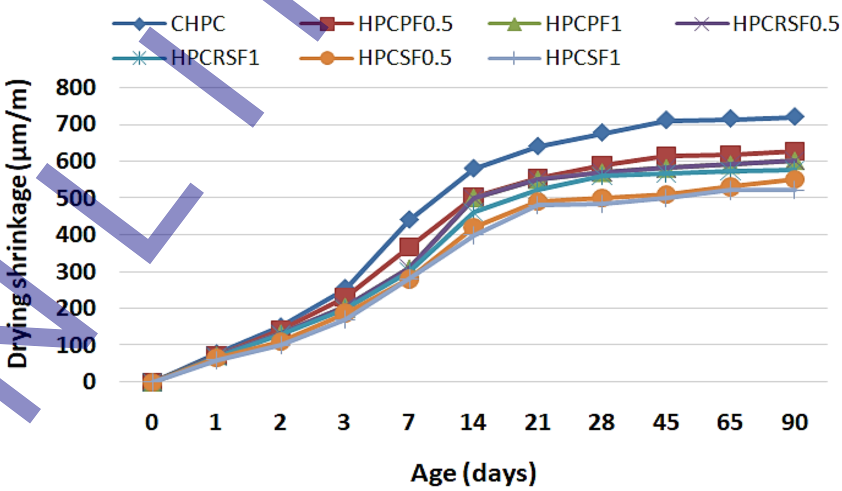

Fig. 12. Drying shrinkage of fiber-reinforced HPC mixtures

Fig. 12 illustrates the drying shrinkage behavior of the fiber-reinforced HPC mixtures. A distinct beneficial effect of incorporating SF, RSF, and PSF is observed, as all fiber-reinforced mixtures exhibit reduced drying shrinkage compared to the control HPC. After 90 days, the control mixture (CHPC) shows a drying shrinkage value of 720 µm/m, whereas the mixtures containing 1% SF, RSF, and PSF record shrinkage values of 522 µm/m, 570 µm/m, and 600 µm/m, respectively. These values correspond to reductions of 16.66%, 20.83, and 27.50% relative to the control HPC, confirming the effectiveness of fiber addition in mitigating drying shrinkage in HPC. The reduction of drying shrinkage in HPC containing fibers is attributed to the restraining of microcrack formation and the limitation of volumetric contraction during moisture loss [69-73]. Choi et al. [69] reported a nearly linear reduction in drying

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shrinkage with increasing fiber content in self-compacting concrete, confirming the efficiency of fibers in mitigating drying-induced deformations.

3.9 Chemical attack resistance

3.9.1 Resistance to hydrochloric acid attack resistance

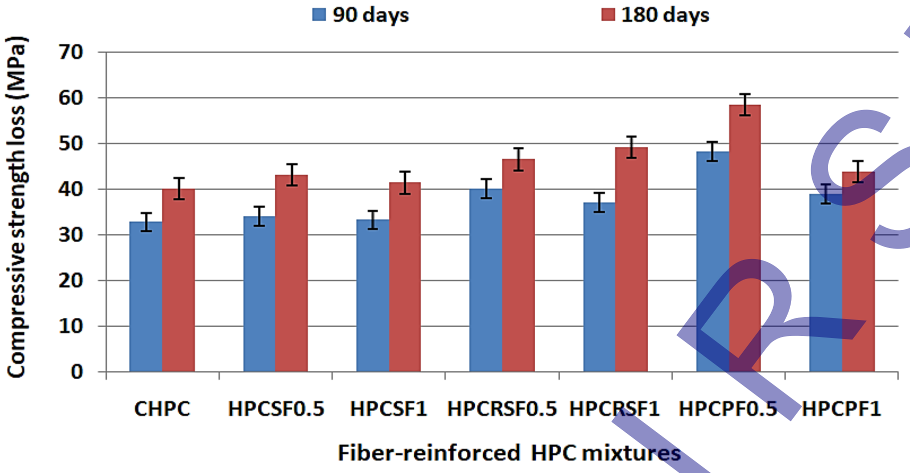

Fig. 13. Compressive strength loss of fiber-reinforced HPC mixtures immersed in HCl solution

Fig. 13 illustrates the compressive strength loss of fiber-reinforced HPC immersed in hydrochloric acid (HCl) solution. It is evident that all mixtures exposed to HCl experienced a significant decrease in compressive strength, and this loss intensified with longer exposure duration. The inclusion of fibers appears to have an adverse effect on the HPC resistance to acid attack, as all fiber-reinforced HPC exhibited greater strength loss than the control HPC. Among the fiber types, SF-reinforced concrete demonstrated the lowest reduction in compressive strength, whereas RSF- and PSF-reinforced HPC showed higher losses. After 180 days of immersion, the HPC containing 1% SF exhibited a 3.29% reduction in compressive strength compared to the control HPC, while mixtures containing 1% RSF and PSF recorded reductions of 22.96% and 9.40%, respectively. This trend has also been reported by several researchers [74-77]. Kos et al. [77] observed that the incorporation of SF and PF in concrete exposed to acidic environments did not enhance its acid resistance and led to higher strength loss compared with plain concrete. Marcos-Meson et al. [75] further reported that exposure of SF-reinforced concrete to acid solutions resulted in greater deterioration of its mechanical performance due to the increased permeability and water absorption of concrete.

3.9.2 Resistance to sulphuric acid attack

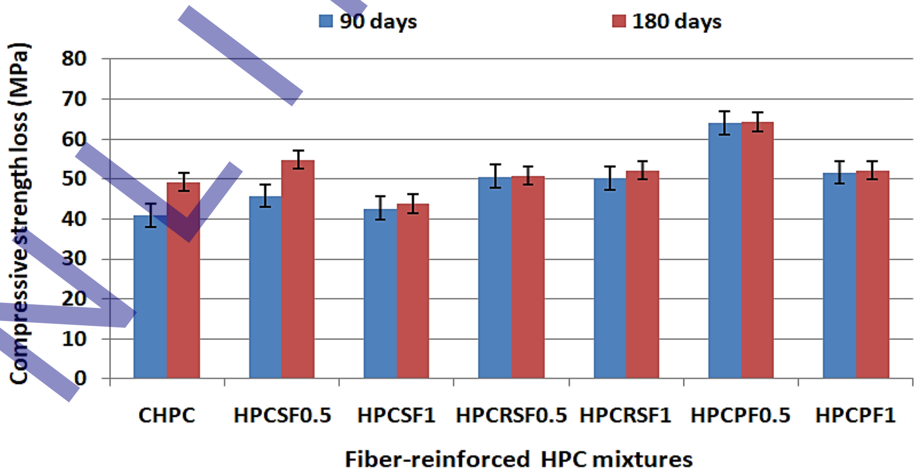

Fig. 14. Compressive strength loss of fiber-reinforced HPC mixtures immersed in H_2SO_4 solution

Fig. 14 presents the compressive strength loss of fiber-reinforced HPC mixtures immersed in sulfuric acid (H_2SO_4) solution. The fiber-reinforced HPC mixtures exhibited behavior similar to those exposed to HCl solution. Except for the mixture containing 1% SF (HPCSF1), all fiber-reinforced HPCs showed greater final compressive strength loss than the control HPC. This trend confirms the unfavorable effect of fiber incorporation on the acid resistance of HPC [78-80]. These observations are consistent with the results of water absorption and air content tests, which increased with higher fiber content in the HPC composition and consequently facilitated the penetration of acid into the HPC matrix.

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4 Conclusions

This study investigated the effect of the incorporation of SF, RSF, and PSF on the physic-mechanical and durability properties of HPC. Based on the experimental findings, the following key conclusions can be drawn:

The incorporation of fibers significantly affects the rheological and physical properties of HPC. Workability is primarily governed by the intrinsic characteristics of the fibers, where the rigidity and surface roughness of SF and RSF reduce HPC mobility, while the flexibility and smooth texture of PSF slightly enhance it. The presence of fibers also promotes higher air content, particularly in mixtures containing PSF and RSF, due to the formation of preferential zones for air entrapment during mixing. Conversely, fiber addition has only a minor effect on the fresh density of HPC, which mainly depends on the specific gravity of the fibers.

Regarding mechanical strengths, the incorporation of fibers enhances both the compressive and flexural strengths of HPC, particularly when SF and RSF are used. This improvement is mainly attributed to the strong interfacial bond and efficient stress transfer between steel fibers and the cementitious matrix, which promote crack bridging and stress redistribution. PSF also contributes to a moderate gain in compressive strength at optimal contents. However, its low stiffness and weak interfacial adhesion limit its effectiveness in improving flexural behavior and may even reduce performance when used in excess.

The incorporation of fibers leads to a slight increase in both total and capillary water absorption of HPC, mainly due to the higher air content and the formation of more porous interfacial transition zones around the fibers. Despite this increase, all mixtures maintained water absorption values below 3%, indicating that the fiber-reinforced HPC still exhibits good overall quality.

The incorporation of SF, RSF, and PSF effectively reduces the drying shrinkage of HPC. This improvement is mainly attributed to the fibers' ability to restrain micro-crack formation, limit volumetric contraction, and enhance stress redistribution during moisture loss. Among the studied mixtures, SF showed the greatest shrinkage reduction, confirming its efficiency in controlling drying-induced deformations.

The incorporation of fibers into the concrete mixture was found to adversely affect its resistance to chemical attack, particularly in the case of waste-derived fibers. The increase in porosity facilitates the ingress of aggressive ions into the concrete matrix, leading to greater losses in compressive strength.

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6 References

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7 Conflict of interest statement

The authors declare no conflict of interest.

8 Author contributions

Rachid Kebout: conceptualization, methodology, software, formal analysis, investigation, writing – review & editing. Rachid Djebien: conceptualization, methodology, validation, writing – review & editing, supervision, project administration. Riad Derabla: validation, writing – review & editing, supervision, project administration.

9 Data availability statement

There is no data set associated with the study.

10 Supplementary materials

There are no supplementary materials to include.

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