
Research article

Impact of fiber types on the performance of sustainable modified self-compacting concrete

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Abstract: The rising demand for sustainable materials has created a need to decrease cement consumption while enhancing concrete performance. This study assessed the effect of fiber types on the characteristics of sustainable self-compacting concrete with 20% metakaolin as a partial cement replacement. Different types of fibers (carbon, hooked micro steel, and polyvinyl alcohol), at volume fractions of 0.25%, 0.5%, 0.75%, 1.0%, 1.25%, and 1.5%, were used to prepare 19 mixtures, in a total of 171 specimens. The compressive strength, splitting strength, flexural strength, modulus of elasticity, ultrasonic pulse velocity, and microstructural characteristics were tested. The optimum fiber content was found to be different for the different properties evaluated. The highest compressive strength and dynamic modulus were obtained at 0.75% fiber content, while the highest flexural and splitting tensile strength were obtained at 1.0%; beyond that, properties deteriorated due to fiber agglomeration. Hooked micro steel fibers showed the highest ultrasonic pulse velocity of 4580 m/s, the highest increase in flexural strength (72.7%), splitting tensile strength of 77.1%, and compressive strength of 17.1%, also recording the highest dynamic modulus of elasticity of 39.7 GPa among all mixtures. The polyvinyl alcohol fibers performed best in crack-control, with the splitting tensile strength rising by as much as 54.3% over the reference mixture. The results indicate that the role of fiber type in stress transfer properties, crack-bridging mechanism, and performance of sustainable self-compacting concrete is critical.

Keywords: self-compacting concrete; carbon fibers; micro steel fibers; polyvinyl alcohol fibers; microstructural characteristics

1. Introduction

The growing construction industry has increased the demand for conventional concrete, resulting in the overuse of natural resources and causing many environmental problems [1]. Cement production is known to be one of the largest contributors to carbon dioxide emissions worldwide, contributing about 5%–8% of the total global emissions [2,3]. This environmental cost has led to significant research in the development of sustainable construction materials to reduce cement use while delivering the same or better concrete performance [4]. Self-compacting concrete (SCC) has become a superior and sustainable option, as it can flow under gravity without vibration. SCC has a variety of benefits, such as enhanced filling capacity, passing capacity, and less labor demand, and it is applicable in complex structural components and heavily reinforced areas [5,6]. However, the large amount of paste and the low coarse aggregate fraction needed in SCC make it more prone to changes in the materials, especially the addition of supplementary cementitious materials and fiber reinforcements, as the formulation of optimized excavatable cement-treated materials using a new punching test apparatus [7]. Benefits notwithstanding, both traditional concrete and SCC have brittle nature and low tensile strength, which restricts their ability to resist crack formation and propagation [8,9]. The latter can be addressed by introducing the use of fibers in the concrete matrix [10,11]. It has been shown that fiber-reinforced concrete is an effective solution for enhancing tensile strength, ductility, toughness, and post-cracking behavior [12]. Such composites are not only determined by the presence of fibers but also by their type, mechanical properties, geometry, and bonding characteristics with the cementitious matrix [13,14]. The efficiency of fiber reinforcement is mainly determined by its capacity to bridge cracks, to distribute internal stresses, and to improve the integrity of the cementitious matrix. When the material is loaded, microcracks start to form, and fibers bridge the cracks and delay their propagation, narrow their width, and change the failure mode of the material from brittle to ductile [15,16].

The efficiency of this mechanism is dependent on fiber geometry, mechanical properties, dispersion, and the quality of the fiber–matrix interfacial bond; all of which are responsible for controlling the efficiency of stress transfer and post-cracking behavior [17,18]. Significant research efforts have also been conducted in recent years on engineered cementitious composites and ultra-high performance concrete, which have confirmed that optimized fiber–matrix interaction can lead to multiple microcracking, increase the integrity of the structure, and greatly improve the overall mechanical performance and durability of cementitious composites [19]. Hooked micro steel fibers (HMSF) have high tensile strength and mechanical anchorage, which enhances the load-carrying capacity and stiffness of the fibers after cracking and improves their crack-bridging capacity, thus showing the highest improvement in post-cracking load-carrying capacity and stiffness among all fibers investigated [20]. Chopped carbon fibers (CCF), with high elastic modulus and small diameter, can effectively control the initiation of microcracks; in the early stage of loading, the stress can be transferred to other points, which makes the strength and stiffness of the composite material balanced [21,22]. Polyvinyl alcohol fibers (PVAf), on the other hand, bond well with the cementitious matrix, allowing for efficient stress transfer and crack-width control, as well as enhanced ductility and

damage tolerance [23]. The different fiber–matrix interaction mechanisms of each fiber type therefore determine the mechanical and structural behavior of fiber-reinforced SCC.

Recent studies have tried to come up with sustainable SCC by adding supplementary cementitious materials and fiber reinforcement to improve environmental performance and mechanical behavior. Rojo-López et al. (2022) [24] investigated sustainable SCC mixtures with different ratios of metakaolin and limestone filler, where binary and ternary binder systems were evaluated. The ternary system with 15% metakaolin outperformed the others, striking the best balance between fresh properties, mechanical strength, durability, and environmental impact. The study demonstrated the importance of metakaolin in refining the microstructure and improving the interfacial transition zone (ITZ), thereby improving the overall performance of SCC to achieve a maximum compressive strength of 44 MPa at 28 days of age. Bede Odorčić and Kravanja (2022) [25] investigated the effectiveness of metakaolin at various ratios (5%–15%) as a partial replacement for cement and hybrid fibers in SCC. Their results indicated that the addition of 15% metakaolin, hooked steel fibers, and synthetic microfibers enhanced compressive strength by up to 31% compared to the control mix. Nevertheless, the research also established that the addition of metakaolin and fiber dosage can negatively affect workability, and optimizing the mix design is important. Moreover, Ahmed et al. (2023) [26] examined the concept of incorporating sustainability and fiber reinforcement, experimenting with SCC using recycled concrete aggregate, metakaolin, and PVA fibers. A blend of 20% metakaolin and 22% fly ash gave satisfactory fresh properties and enhanced structural behavior, though with a slight reduction in compressive strength. PVAF greatly enhanced crack control and flexural stiffness, which suggested its capability to enhance ductility and crack resistance in sustainable SCC systems.

Regarding the fiber type effect, Khaloo et al. (2014) [27] examined SCC reinforced with HMSF at different volume fractions. The experimental outcomes indicated that the addition of steel fiber content significantly enhanced splitting tensile strength, flexural performance, and toughness, and reduced workability. This work found that steel fibers enhance post-cracking behavior and load capacity. Moreover, Siddique et al. (2016) [28] explored SCC with huge quantities of fly ash and hooked steel fibers. The researchers found that sustainable SCC containing a high level of fly ash can work satisfactorily when reinforced by steel fibers, even though the compressive strength is slightly lowered. Notably, with fibers added, crack resistance and durability were enhanced. Yehia et al. (2016) [29] thoroughly investigated steel, synthetic, and hybrid fibers in SCC, focusing on mechanical and durability characteristics. The experiment established that the type of fiber plays a major role in crack spread, permeability, and microstructural behavior. Fiber-reinforced mixtures were found to be more durable and reduce chloride penetration in all the mixtures, which is significant in improving mixture performance in the long term. Ahmad and Umar (2018) [30] looked at the effect of synthetic fibers in SCC with glass and PVAF. The researchers found that PVAF was more effective in controlling cracks and ductility, whereas glass fibers were more effective in enhancing mechanical strength. The experiment found that various types of fibers have varying performance advantages depending on the property required. In addition, carbon fibers, although not widely utilized, have demonstrated potential in SCC applications. Safiuddin et al. (2018) [31] investigated carbon fiber–reinforced SCC and discovered that a low fiber content (0.25%) produced the best results, increasing tensile strength and toughness while maintaining acceptable workability. But with increasing fiber content, compressive strength and flowability were reduced considerably because of the agglomeration of fibers.

More recently, Zamani et al. (2023) [32] investigated sustainable SCC using recycled fine aggregates as well as steel and PVA fiber. The results indicated that 1.5% hooked steel fibers provided

the best overall performance in terms of strength, impact resistance, and energy absorption. The study also confirmed that fiber reinforcement significantly enhances the ductility and toughness of sustainable SCC mixtures. Overall, studies have primarily investigated the influence of individual fiber types or hybrid fiber systems under different SCC mixtures, binder compositions, and experimental conditions. The replacement rates for supplementary cementitious materials have been widely distributed across the studies, and steel fibers have been generally compared to carbon fibers and polyvinyl alcohol fibers separately. This means that a direct comparison between CCF, HMSF, and PVAF under the same mix proportion and curing conditions is lacking, which makes it more challenging to differentiate the intrinsic contribution of each type. With this background, the present study aims to fill this gap by comparing chopped carbon fibers, hooked micro steel fibers, and polyvinyl alcohol fibers under the same mix proportions, curing conditions, and testing procedures in the same self-compacting concrete mixture with 20% metakaolin content.

In general, the research significance of this study presents a controlled and methodological comparison of chopped carbon fibers, hooked micro steel fibers, and polyvinyl alcohol fibers at the same volume ratios (0.25%, 0.50%, 0.75%, 1.00%, 1.25%, and 1.50%) in a sustainable self-compacting concrete matrix with 20% metakaolin used as a partial cement replacement. The research will close the gap in inconsistent comparative assessment by determining the most efficient type of fiber for improving crack control, as well as the overall behavior of the concrete. The results will help to design environmentally friendly and high-performing fiber-reinforced concrete and will offer real-world advice on the appropriate types of fibers to use in a sustainable building project.

2. Materials and methods

This section describes the raw materials and characteristics used in the study, as well as the mechanical properties tested and microstructures.

2.1. Raw materials

The sustainable self-compacting concrete used in this study was produced using ordinary Portland cement in accordance with IQS No. 5 (2019) [33]. Natural river sand with a maximum particle size of 4.75 mm was used as fine aggregate, complying with ASTM C33 (2016) [34]. Crushed coarse aggregate with a maximum size of 10 mm was utilized to ensure adequate flowability and passing ability of SCC mixtures, in accordance with ASTM C33 (2016) [34]. Water suitable for concrete production was used in accordance with IQS 1703 (2018) [35]. Metakaolin was added at a replacement level of 20% by weight of cement to improve the sustainability and microstructural characteristics of the concrete. This replacement rate was chosen according to previous studies, which have shown that 20% replacement with metakaolin leads to an optimum balance between sustainability, fresh properties, mechanical performance, and durability in self-compacting concrete [26]. High-purity metakaolin, supplied by BASF (Germany), had a median particle size (d_{50}) of approximately 3 μm , a whiteness of more than 85%, silica content of more than 52%, and alumina content of more than 40%. Metakaolin was heated to high temperature (about 750 $^{\circ}\text{C}$) to make it highly reactive as a pozzolana [36]. A high-range water-reducing admixture produced by Sika Company, conforming to ASTM C494 Type F [37], was used at a dosage of 1.5% by binder weight to achieve the required workability and flow characteristics of SCC. Three different types of fibers were employed in this

study: CCF, HMSF, and PVAF, as shown in Figure 1. The fibers were selected to have approximately similar lengths to allow a consistent comparison of their performance within the concrete matrix. The properties of the fibers, as obtained from the manufacturer's datasheets, are summarized in Table 1.

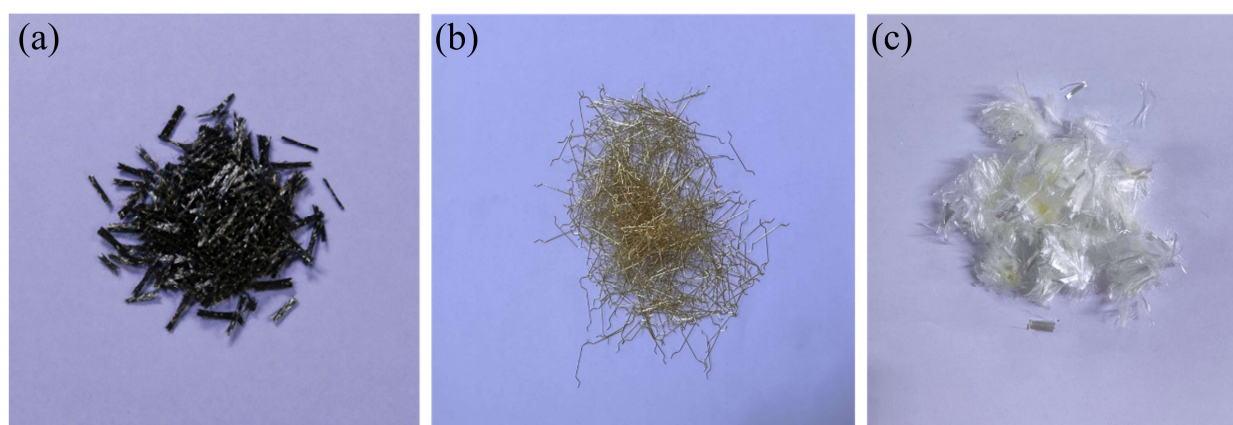


Figure 1. Types of fibers used in the experimental work: (a) CCF, (b) HMSF, and (c) PVAF.

Table 1. Characteristics of the fibers used from the product datasheet.

Kinds of fibers	CCF	HMSF	PVAF
Length (mm)	12	12	12
Diameter (mm)	0.007	0.2	0.04
Aspect ratio	1700	60	300
Tensile strength (N/mm ²)	3500–4000	1000–1200	1200–1600

2.2. Mix proportions

The trial-mix method was applied to determine the mix proportions of SCC mixtures in order to attain sufficient stability and flowability. The reference mixture was used, where 20% metakaolin was used as a partial replacement of cement. The water-to-binder ratio was 0.35, and the superplasticizer was 1.5% by weight of binder for all mixes. The proportions of the detailed blend are shown in Table 2. Nineteen mixtures were prepared, one of which was a control mix that did not have fibers, and the rest were fiber-reinforced mixes. CCF, HMSF, and PVAF were utilized at volume portions of 0.25%, 0.50%, 0.75%, 1.00%, 1.25%, and 1.50% for each type. These volume fractions were chosen to offer acceptable workability and mechanical property characteristics and to prevent fiber agglomeration at higher dosages, based on previous studies. Table 3 presents the codes and the ratios of fibers for each mix.

Table 2. SCC contents for 1 m³.

Material	Quantity (kg/m ³)
Cement	360
Metakaolin	90
Sand	950
Gravel	780
Water	158
High-range water-reducing	6.75

Table 3. SCC codes and content.

Code	CCF (kg/m ³)	HMSF (kg/m ³)	PVAF (kg/m ³)
SCC	0	0	0
C0.25	4.4	0	0
C0.5	8.8	0	0
C0.75	13.2	0	0
C1.0	17.6	0	0
C1.25	22	0	0
C1.5	26.4	0	0
S0.25	0	19.63	0
S0.5	0	39.25	0
S0.75	0	58.88	0
S1.0	0	78.5	0
S1.25	0	98.13	0
S1.5	0	117.75	0
P0.25	0	0	3.25
P0.5	0	0	6.5
P0.75	0	0	9.75
P1.0	0	0	13
P1.25	0	0	16.25
P1.5	0	0	19.5

2.3. Testing techniques

All self-compacting concrete mixtures with various types of fibers at various volume fractions were used in the experimental tests. Three specimens were prepared for each test for each mixture, and the average value is reported here. The dimension of the compressive specimen was taken as 100 × 100 × 100 mm, and the same specimen geometry was used for the ultrasonic pulse velocity (UPV) test. The UPV test was carried out as a non-destructive method for the evaluation of internal quality, internal homogeneity, and internal integrity of the concrete, in order to identify possible internal defects or voids and to correlate the above characteristics with the mechanical performance of the concrete. A splitting tensile strength test was conducted on cylindrical specimens (100 × 200 mm).

The dynamic modulus of elasticity and flexural strength were measured using prismatic specimens of dimensions $100 \times 100 \times 400$ mm. All specimens were cast and allowed to dry at room temperature for 24 h, then demolded and cured in water for 28 days. Upon curing, the specimens were subjected to the experimental test. Microstructural analysis was carried out to study the inner structure and the fiber–matrix interaction.

3. Results and discussion

This section presents and discusses the results obtained from the experimental program, as summarized in Table 4. Data include the effects of different fibers and ratios on the mechanical properties of sustainable self-compacting concrete.

Table 4. Experimental results for the concrete specimens.

Code	Slump test (mm)	Compressive strength (MPa)	Flexural strength (MPa)	Splitting tensile strength (MPa)	Dynamic modulus of elasticity (GPa)	Ultrasonic pulse velocity (m/s)
SCC	760	45.7 ± 0.9	5.5 ± 0.3	3.5 ± 0.1	34.2 ± 0.2	4220 ± 10
C0.25	755	47.1 ± 1.2	6.2 ± 0.35	4.1 ± 0.1	35.3 ± 0.5	4310 ± 15
C0.5	748	49.5 ± 1.1	6.8 ± 0.2	4.6 ± 0.15	36.5 ± 0.6	4430 ± 25
C0.75	740	50.8 ± 0.8	7.2 ± 0.3	5.0 ± 0.1	36.9 ± 0.5	4440 ± 30
C1.0	730	48.3 ± 1.1	7.4 ± 0.35	5.2 ± 0.15	35.2 ± 0.4	4220 ± 35
C1.25	718	46.7 ± 1.2	7.0 ± 0.3	4.8 ± 0.25	34 ± 0.55	4100 ± 20
C1.5	705	43.5 ± 0.5	6.8 ± 0.15	4.5 ± 0.2	33.6 ± 0.3	4050 ± 25
S0.25	750	48.2 ± 1.1	7.5 ± 0.1	4.8 ± 0.1	36.2 ± 0.2	4460 ± 15
S0.5	738	51.1 ± 0.7	8.5 ± 0.2	5.5 ± 0.5	38 ± 0.35	4470 ± 30
S0.75	725	53.5 ± 1.3	9.2 ± 0.35	6.0 ± 0.1	39.7 ± 0.3	4510 ± 10
S1.0	712	52.6 ± 1.2	9.5 ± 0.15	6.2 ± 0.2	38.4 ± 0.4	4490 ± 25
S1.25	695	49.3 ± 1.1	8.8 ± 0.1	5.8 ± 0.25	36 ± 0.65	4580 ± 30
S1.5	680	46.5 ± 0.9	8.2 ± 0.2	5.3 ± 0.1	34.5 ± 0.6	4220 ± 15
P0.25	754	46.7 ± 0.6	6.5 ± 0.35	4.2 ± 0.15	34.2 ± 0.5	4310 ± 15
P0.5	746	48.4 ± 1.2	7.2 ± 0.3	4.8 ± 0.2	35.4 ± 0.4	4450 ± 10
P0.75	736	49.1 ± 1.1	7.8 ± 0.25	5.2 ± 0.1	35.9 ± 0.4	4340 ± 30
P1.0	724	47.7 ± 0.8	8.0 ± 0.1	5.4 ± 0.25	34.6 ± 0.3	4280 ± 25
P1.25	710	45.8 ± 1.2	7.5 ± 0.35	5.0 ± 0.15	33 ± 0.7	4160 ± 30
P1.5	698	42.6 ± 1	7.0 ± 0.25	4.6 ± 0.1	31.9 ± 0.5	4090 ± 20

3.1. Slump test

The slump flow test was used to assess the fresh workability of all self-compacting concrete mixtures according to ASTM C1611 [38], and the results are presented in Table 4. The measured slump flow values were between 680 and 760 mm, which matches the European Federation for Specialist Construction Chemicals and Concrete Systems (EFNARC) [39] specification of 650–800 mm for

workability for SCC. The reference mixture had the highest slump flow value (760 mm), which belongs to the slump flow class 3, while all fiber-reinforced mixtures were found within the acceptable SCC range (slump flow class 3 is the lowest value of 660–750 mm, and the highest value of slump flow class 3 is 760–900 mm). The results indicate that the use of 20% metakaolin and 1.5% high-range water-reducing admixture (HRWRA) yielded sufficiently good flowability despite the use of the various types and dosages of fibers. The slump flow was found to decrease with the increase in fiber volume fraction for all types of fibers, which suggests that fiber addition had a negative effect on the fresh concrete flowability. This is mainly due to the increased internal friction between the aggregate particles and fibers, the higher specific surface area of aggregates, which requires more coating of cement paste, and the limitation of free movement in the cementitious matrix. The most significant decrease in workability was observed with hooked micro steel fibers, with the slump flow of the mixture decreasing from 750 mm at 0.25% fiber content to 680 mm at 1.5% fiber content, a decrease of around 10.5% relative to the reference fiber mixture. This is primarily attributed to the hooked geometry, stiffness, and mechanical interlocking of steel fibers, which significantly affect flow resistance during concrete deformation. The carbon fiber mixtures showed a relatively low loss, from 755 to 705 mm slump flow, a total decrease of about 7.2%. The reduction is due to the high aspect ratio and specific surface area of carbon fibers, which increase the amount of paste required and decrease the mobility of the fresh concrete, especially at higher fiber dosages where fiber interaction is more important. Likewise, polyvinyl alcohol fibers decreased the slump flow from 754 to 698 mm, which is around 8.2%. This behavior is primarily attributed to the hydrophilic properties of PVA fibers and their high interfacial interaction with the cementitious matrix, which causes higher water requirements and a decrease in the flowability of the fresh mixture. The workability of the mixes was progressively reduced with the increase in fiber content, but all investigated mixtures had a slump flow of more than the minimum recommended by EFNARC (2005). This indicates that the selected mixture proportions and superplasticizer dosage were able to overcome the negative effect of fiber incorporation and retain the self-compacting properties of all mixtures. The results also show that mixtures containing up to 1.25% fiber showed a high mechanical property and very good workability, while mixtures containing 1.5% fiber met the SCC requirements but had the lowest workability due to the increased resistance to flow through fiber interaction.

3.2. Compressive strength

The compressive strength results at 28 days, according to BS-EN 12390 (2019) [40], are presented in Table 4 and illustrated in Figure 2. The reference mixture had a compressive strength of 45.7 MPa. It is clear that the incorporation of fibers generally increased compressive strength up to an optimum level, after which it decreased due to fiber agglomeration and reduced workability, as shown by the trend of the curves in Figure 2. The compressive strength of carbon fiber mixtures increased as the fiber content increased up to 0.75%. The mixtures C0.25, C0.5, C0.75, C1.0, C1.25, and C1.5 recorded compressive strengths of 47.1, 49.5, 50.8, 48.3, 46.7, and 43.5 MPa, corresponding to increases of 3.1%, 8.3%, 11.2%, 5.7%, 2.2%, and –4.8%, respectively, compared to the reference mix. The maximum improvement at C0.75 can be attributed to improved microcrack control and stress distribution, whereas higher fiber content levels resulted in reduced strength due to poor dispersion and increased voids.

Compressive strength increased significantly in steel fiber mixtures. The mixtures S0.25, S0.5, S0.75, S1.0, S1.25, and S1.5 achieved compressive strengths of 48.2, 51.1, 53.5, 52.6, 49.3, and 46.5 MPa, representing increases of 5.5%, 11.8%, 17.1%, 15.1%, 7.9%, and 1.8%, respectively. The peak value was recorded at S0.75, as illustrated in Figure 2. This is attributed to the fact that steel fibers are very stiff and mechanically anchored, which effectively retard crack propagation and enhances load transfer. At extra fiber contents, the workability reduction led to fiber clustering, which led to a slight loss in compressive strength, which is a similar result to that of Otrowski et al. (2021) [41].

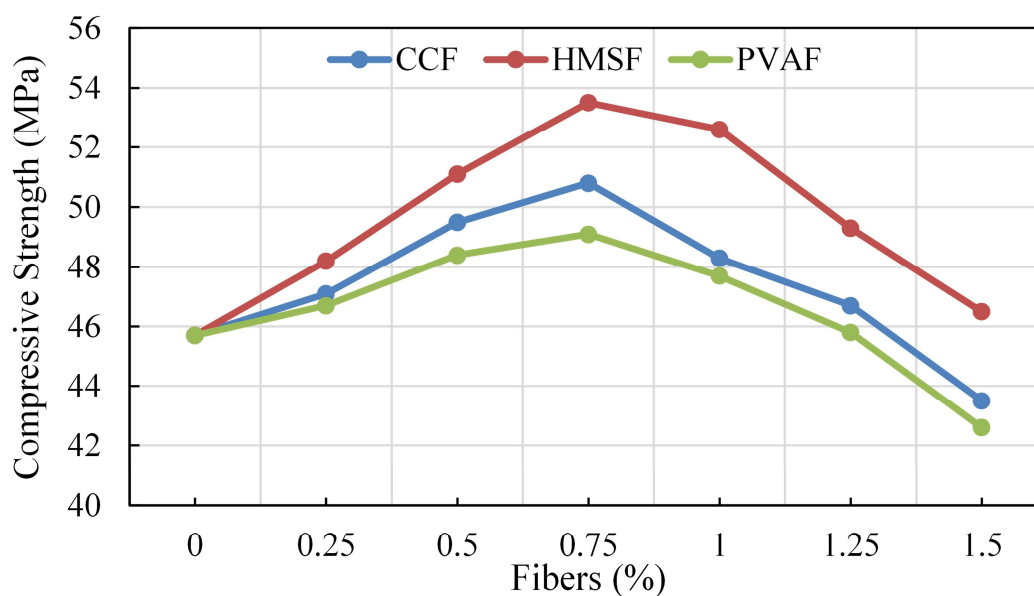


Figure 2. Relationship between compressive strength and fiber content.

The compressive strength of PVA fiber mixtures increased up to an optimal fiber content of 0.75%. The mixtures P0.25, P0.5, P0.75, P1.0, P1.25, and P1.5 recorded compressive strengths of 46.7, 48.4, 49.1, 47.7, 45.8, and 42.6 MPa, corresponding to increases of 2.2%, 5.9%, 7.4%, 4.4%, 0.2%, and -6.8%, respectively. The improvement at lower fiber contents is mainly due to strong fiber-matrix bonding and effective microcrack control, whereas higher fiber contents had a negative impact on workability and reduced compressive strength. Notably, the P1.5 mixture had a lower compressive strength than the reference SCC (45.7 MPa), indicating that there is a practical maximum amount of PVAF incorporation in the metakaolin-based self-compacting concrete and that the excess incorporation of PVAF may have a negative effect on the integrity of the matrix. Overall, the optimal fiber content for all fiber types was around 0.75%, which resulted in the highest compressive strengths. S0.75 outperformed all mixtures, increasing by 17.1%, followed by C0.75 (11.2%) and P0.75 (7.4%). The results clearly show that moderate fiber content increases compressive strength, but excessive fiber content reduces performance due to reduced workability and fiber agglomeration. The compressive strength test is presented in Figure 3.

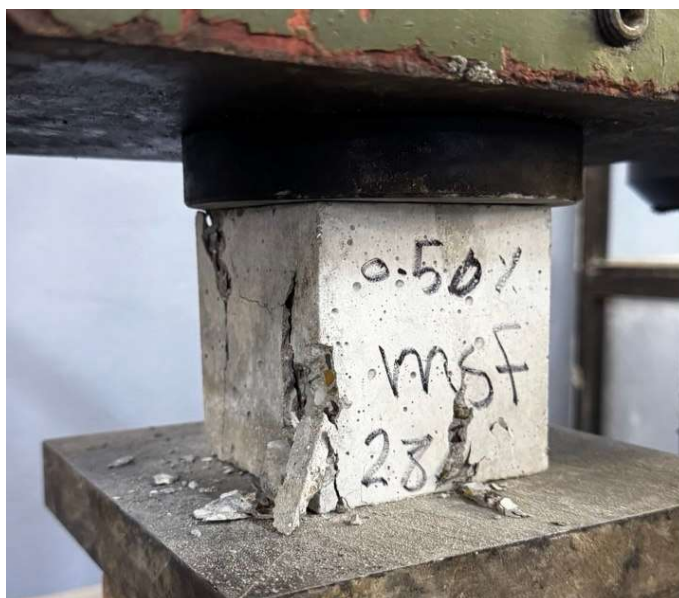


Figure 3. Compressive strength test for SCC reinforced with 0.5% HMSF.

3.3. Flexural strength test

The flexural strength results at 28 days according to ASTM-C78 (2017) [42] are presented in Table 4 and illustrated in Figure 4. The reference mixture exhibited a flexural strength of 5.5 MPa. It is evident that the inclusion of fibers significantly improved the flexural performance of all mixtures, with a clear increasing trend up to an optimum fiber content, followed by a reduction at higher fiber volumes, as illustrated by the curves in Figure 4. For carbon fiber mixtures, the flexural strength increased with increasing fiber content up to 1.0%. The mixtures C0.25, C0.5, C0.75, C1.0, C1.25, and C1.5 recorded flexural strengths of 6.2, 6.8, 7.2, 7.4, 7.0, and 6.8 MPa, corresponding to increases of 12.7%, 23.6%, 30.9%, 34.5%, 27.3%, and 23.6%, respectively, compared to the reference mix. The highest value was obtained at C1.0, which is due to the carbon fibers' ability to control microcrack propagation and improve stress distribution. There is further loss of flexural strength at this level, which is mainly due to fiber clustering and low workability, indicated by the downward trend in Figure 4.

The flexural strength of steel fiber mixtures increased the most amongst other types of fiber. The mixtures S0.25, S0.5, S0.75, S1.0, S1.25, and S1.5 achieved flexural strengths of 7.5, 8.5, 9.2, 9.5, 8.8, and 8.2 MPa, representing increases of 36.4%, 54.5%, 67.3%, 72.7%, 60.0%, and 49.1%, respectively. The highest value was at S1.0. This is greatly contributed to by the overall high stiffness and mechanical anchorage of steel fibers, which have high mechanical anchorage and crack bridging characteristics, and enhance post-cracking behavior. At higher fiber contents, the reduction in workability causes fiber agglomeration, resulting in a slight decrease in flexural strength.

Flexural strength increased significantly in PVA fiber mixtures. The mixtures P0.25, P0.5, P0.75, P1.0, P1.25, and P1.5 recorded flexural strengths of 6.5, 7.2, 7.8, 8.0, 7.5, and 7.0 MPa, corresponding to increases of 18.2%, 30.9%, 41.8%, 45.5%, 36.4%, and 27.3%, respectively. The optimum performance was achieved at P1.0. This behavior is mainly attributed to the strong fiber–matrix bonding and the ability of PVA fibers to effectively control crack width and improve ductility. However, excessive fiber content reduced workability and resulted in a decline in flexural strength.

Overall, the results indicate that the optimal fiber content for flexural strength was approximately 1.0% for all fiber types.

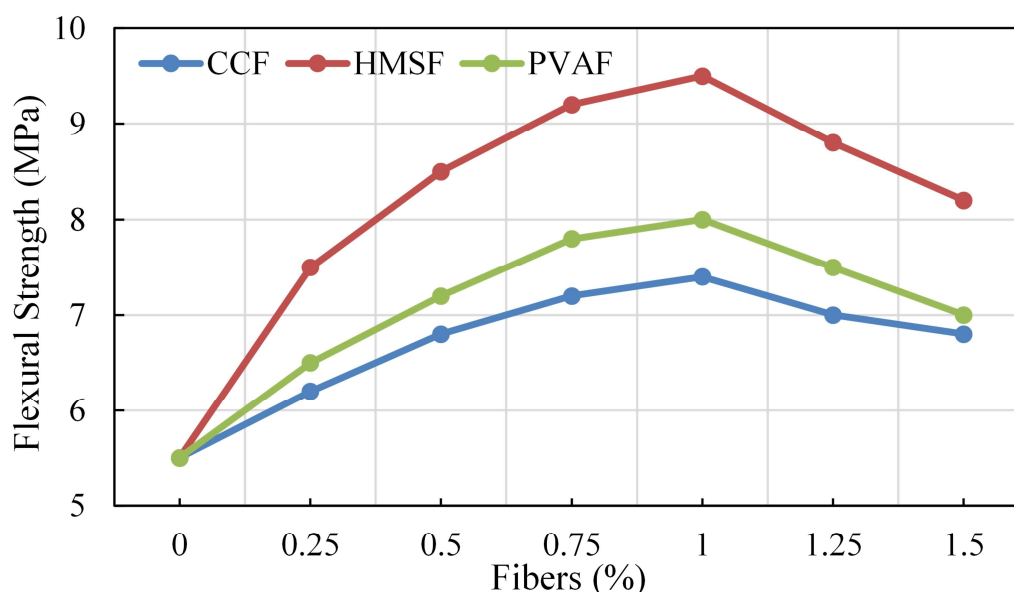


Figure 4. Relationship between flexural strength and fiber content.

The improved flexural performance also demonstrates the ability of the fiber-bridging mechanism and stress transfer across developing cracks to delay the propagation of cracks and improve the post-cracking behavior of the SCC mixtures. Among all mixtures, S1.0 exhibited the highest flexural strength with an increase of 72.7%, followed by P1.0 (45.5%) and C1.0 (34.5%), similar to the trend reported by Choi et al. (2023) [43].

3.4. Splitting tensile strength test

The splitting tensile strength results at 28 days, according to ASTM-C496 (2017) [44], are presented in Table 4 and illustrated in Figure 5. The reference mixture recorded a splitting tensile strength of 3.5 MPa. Overall, the fibers increased the splitting tensile strength of all fiber-reinforced mixtures, including the reference mixture, which proves the beneficial impact of fibers in postponing the occurrence of cracks and enhancing tensile stress transfer throughout the concrete mass. The trend of the curves in Figure 5 shows that the splitting tensile strength increased progressively with fiber content up to an optimum level, after which it declined due to reduced workability and possible fiber agglomeration. In the case of carbon fiber mixtures, the tensile strength of the mixture splits improved by 17.1%, 31.4%, 42.9%, and 48.6% from C0.25 to C1.0, respectively, over the reference mixture. After that, the values decreased slightly to 4.8 MPa for C1.25 and 4.5 MPa for C1.5, which still represent increases of 37.1% and 28.6%, respectively. The possibility of carbon fibers to inhibit the propagation of microcracks and to improve the redistribution of internal stress, as well as the decrease at higher levels of fiber content, can be explained by the fact that the fibers are better dispersed and have a less uniform matrix.

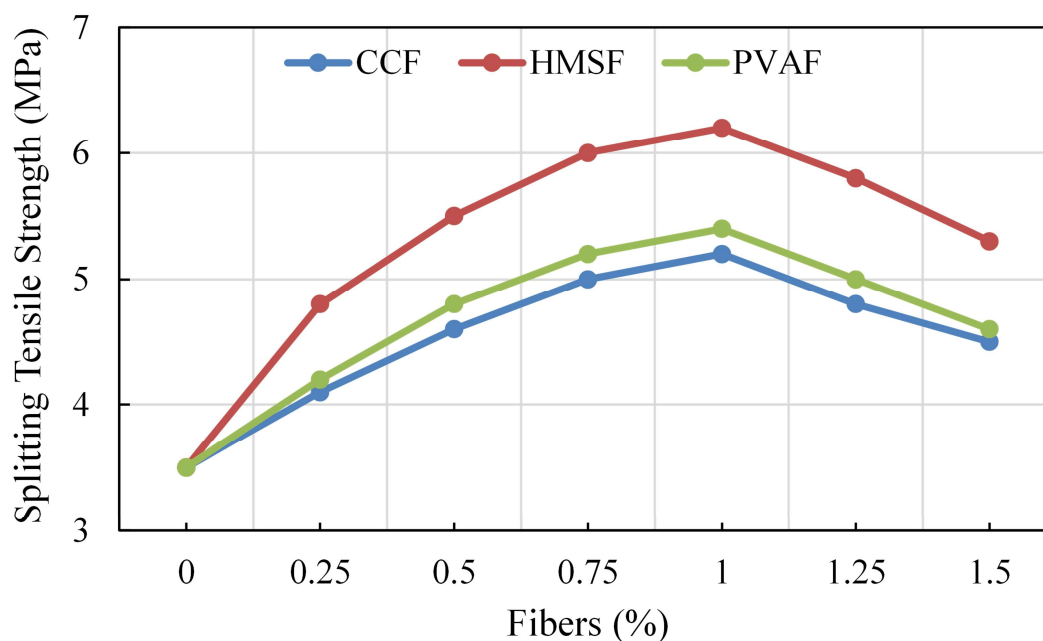


Figure 5. Relationship between splitting tensile strength and fiber content.

For hooked micro steel fiber mixtures, the greatest improvement in splitting tensile strength was observed among all fiber types. The mixtures S0.25, S0.5, S0.75, S1.0, S1.25, and S1.5 recorded splitting tensile strengths of 4.8, 5.5, 6.0, 6.2, 5.8, and 5.3 MPa, corresponding to increases of 37.1%, 57.1%, 71.4%, 77.1%, 65.7%, and 51.4%, respectively. The peak value was achieved for S1.0, as clearly shown in Figure 5. This excellent performance is largely explained by the high stiffness, tensile strength, and mechanical anchorage of steel fibers that enable them to bridge cracks in a better way and provide tensile stresses through the section that has been cracked. The decrease in the splitting tensile strength, beyond 1.0, can be attributed to the decrease in workability and more fiber contacts in the matrix.

For PVAF mixtures, the splitting tensile strength also followed an increasing trend up to 1.0% fiber content. The mixtures P0.25, P0.5, P0.75, P1.0, P1.25, and P1.5 achieved values of 4.2, 4.8, 5.2, 5.4, 5.0, and 4.6 MPa, representing increases of 20.0%, 37.1%, 48.6%, 54.3%, 42.9%, and 31.4%, respectively. The maximum value was recorded for P1.0. This improvement is mainly attributed to the strong fiber–matrix bond of PVAF, which enhances crack bridging and crack width control. However, excessive fiber addition negatively affected the mixture uniformity and workability, leading to a gradual decline in strength. Overall, the results demonstrate that the optimum fiber content for splitting tensile strength was approximately 1.0% for all fiber types. This improvement also indicates the effectiveness of the fiber-bridging mechanism and the transfer of tensile stress between the developing cracks, leading to an improvement in crack resistance by delaying crack initiation and limiting crack propagation. The superior performance of HMSF is due to its good mechanical anchorage, while that of PVAF is due to its high deformation capacity, which was more effective in controlling microcracks. Among all mixtures, S1.0 showed the highest splitting tensile strength with an increase of 77.1%, followed by P1.0 (54.3%) and C1.0 (48.6%). The pattern in Figure 5 corroborates the notion that moderate amounts of fiber addition have a significant positive effect on the tensile properties of sustainable self-compacting concrete, but with excessively high fiber addition, the effect is negative due

to worsened workability and fiber agglomeration, similar to the outcomes of Akhmetov et al. (2022) [45]. The splitting tensile strength test for SCC reinforced with 0.25% HMSF is shown in Figure 6.



Figure 6. Splitting tensile strength test for SCC reinforced with 0.25% HMSF.

3.5. Dynamic modulus of elasticity

The dynamic modulus of elasticity obtained at 28 days, according to ASTM C-215 (2014) [46], is shown in Table 4 and plotted in Figure 7. A dynamic modulus of elasticity of 34.2 GPa was measured in the reference mixture. Overall, the addition of fibers enhanced the dynamic modulus until an optimal fiber concentration was reached, after which it declined. This tendency shows that a moderate level of fiber addition led to a coherent and denser internal structure, whereas excessive levels of fiber content had a negative influence on the continuity of the matrix as it reduced the workability and agglomeration of fibers, as illustrated by the decreasing curves in Figure 7. In carbon fiber mixtures, the dynamic modulus of elasticity rose by 3.2%, 6.7%, and 7.9% in C0.25, C0.5, and C0.75, respectively, as compared with the reference mixture. After that, values decreased to 35.2 GPa for C1.0, 34.0 GPa for C1.25, and 33.6 GPa for C1.5, representing increases of 2.9%, a decrease of -0.6% , and a decrease of -1.8% , respectively. The maximum was attained at C0.75, and this can be explained by the fact that carbon fibers are in a position to increase the speed of propagation of stress-waves and increase the internal compactness of the matrix. Nevertheless, more fiber content must have led to worse dispersion and lowered uniformity, which adversely affected the dynamic modulus.

In the case of hooked micro steel fiber mixtures, the largest values of dynamic modulus were obtained for all types of fibers. The mixtures S0.25, S0.5, S0.75, S1.0, S1.25, and S1.5 achieved dynamic modulus values of 36.2, 38.0, 39.7, 38.4, 36.0, and 34.5 GPa, corresponding to increases of 5.8%, 11.1%, 16.1%, 12.3%, 5.3%, and 0.9%, respectively. The optimal value was found at S0.75, as is clearly shown in Figure 7. This excellent performance is explained by the high stiffness and elastic modulus of steel fibers, which enhance the rigidity of the concrete matrix and the transmission of

dynamic waves. In addition to the best fiber content, the decrease in the modulus is primarily linked to the lower workability and emergence of internal heterogeneity.

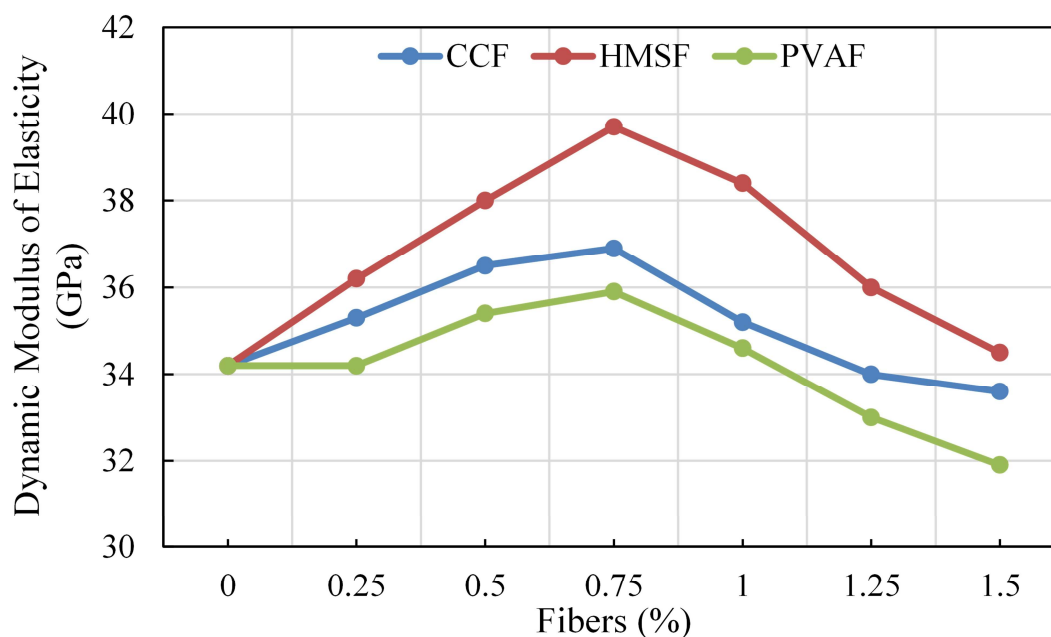


Figure 7. Relationship between the dynamic modulus of elasticity and fiber content.

The dynamic modulus of elasticity also improved at moderate fiber contents in the case of PVAf mixtures. The values were 34.2 GPa at P0.25, 35.4 GPa at P0.5, and 35.9 GPa at P0.75, with the corresponding percentage changes of 0.0%, 3.5%, and 5.0%, respectively, relative to the reference mixture. Thereafter, values decreased to 34.6 GPa for P1.0, 33.0 GPa for P1.25, and 31.9 GPa for P1.5, representing increases of 1.2% and decreases of -3.5% and -6.7%, respectively. The highest value was found for P0.75. The role played by the PVA fibers in controlling cracks and enhancing internal bonding at low-to-moderate fiber content can explain this behavior, but the addition of too much fiber decreased the uniformity of the matrix and had adverse impacts on stiffness.

In general, the findings reveal that the optimum fiber content to achieve the dynamic modulus of elasticity was about 0.75% across fiber types. Of all the mixtures, S0.75 had the highest dynamic modulus, which increased by 16.1%, followed by C0.75 (7.9%) and P0.75 (5.0%). Figure 7 validates the fact that moderate addition of fiber enhances the stiffness and internal integrity of the sustainable SCC, whereas excessive fiber content results in loss of dynamic modulus due to reduced workability and fiber agglomeration.

3.6. Ultrasonic pulse velocity test (UPV)

The ultrasonic pulse velocity results at 28 days are presented in Table 4 and illustrated in Figure 8. The reference mixture recorded a UPV value of 4220 m/s. In general, the inclusion of fibers improved the UPV values at low-to-moderate fiber contents, indicating enhanced compactness and internal integrity of the concrete matrix. However, at higher fiber contents, a reduction in UPV was observed due to increased voids and reduced workability, as reflected by the descending trend in Figure 8. For carbon fiber mixtures, the UPV increased from 4310 m/s for C0.25 to 4430 m/s for C0.5 and 4440 m/s

for C0.75, corresponding to increases of 2.1%, 5.0%, and 5.2%, respectively, compared to the reference mixture. Beyond this level, the UPV decreased to 4220 m/s for C1.0, 4100 m/s for C1.25, and 4050 m/s for C1.5, representing changes of 0.0%, -2.8%, and -4.0%, respectively. The enhancement at mid-range fiber contents is explained by improved crack management and matrix densification, and that at higher contents by the agglomeration of fibers and internal discontinuities that prevent wave propagation.

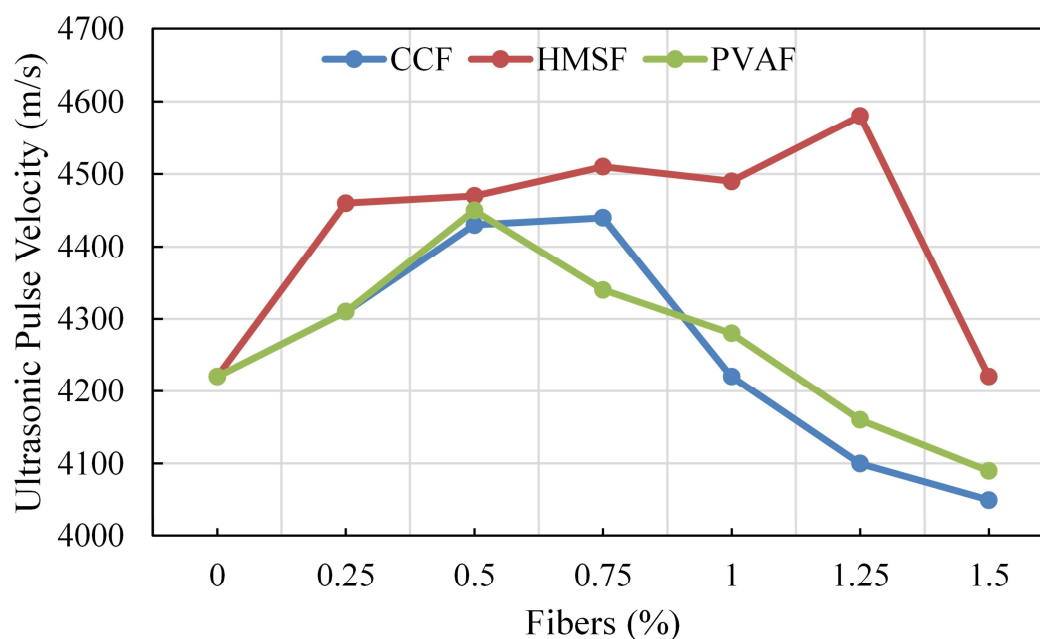


Figure 8. Relationship between velocity and fiber content.

For hooked micro steel fiber mixtures, the highest UPV values were observed among all fiber types. The mixtures S0.25, S0.5, S0.75, S1.0, S1.25, and S1.5 recorded UPV values of 4460, 4470, 4510, 4490, 4580, and 4220 m/s, corresponding to increases of 5.7%, 5.9%, 6.9%, 6.4%, 8.5%, and 0.0%, respectively. The peak value was achieved at S1.25, as shown in Figure 8. This high performance can mainly be attributed to the metallic characteristics of steel fibers, which are highly dense and capable of transmitting waves at high speeds; hence, the performance of the concrete matrix is excellent in the transfer of ultrasonic pulses. Moreover, the mechanical anchorage of the fibers is high in steel, thereby enhancing continuity of the matrix and minimizing internal defects at medium-degree fiber density. However, when the fiber content was increased to 1.5% (S1.5), the UPV reduced. This behavior may be attributed to the lower workability of the higher fiber dosages, which could have contributed to the agglomeration of the fibers and the formation of voids in the concrete matrix. This internal heterogeneity could have caused the observed reduction in UPV due to the effect it had on the transmission of ultrasonic waves.

In the case of PVA fiber mixtures, UPV demanded an increasing and decreasing pattern with respect to fiber content in the beginning. The mixtures P0.25, P0.5, P0.75, P1.0, P1.25, and P1.5 recorded values of 4310, 4450, 4340, 4280, 4160, and 4090 m/s, corresponding to increases of 2.1%, 5.5%, 2.8%, 1.4%, -1.4%, and -3.1%, respectively, compared to the reference mixture. The extreme UPV was recorded at P0.5. The initial development can be attributed to improved connection and crack control, while the decrease at higher fiber contents is due to increased porosity and lower

stiffness of PVAF, when compared with HMSF, which reduces wave transmission efficiency. Overall, the results indicate that the UPV is strongly influenced by fiber type and content, similar to the outcomes by Rao et al. (2016) [47]. The highest values were obtained with steel fiber mixtures due to their metallic nature and superior wave transmission capability. Moderate levels of fiber enhanced internal structure and continuity of the concrete, whereas fiber over-addition had a negative effect on UPV since there was greater heterogeneity and poor workability. The ultrasonic pulse velocity test for SCC reinforced with 0.75% PVA is shown in Figure 9.

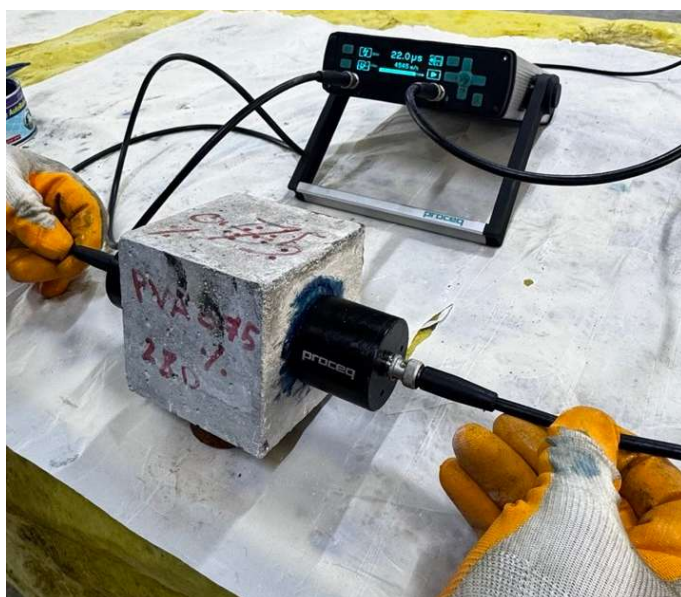


Figure 9. Ultrasonic pulse velocity test for SCC reinforced by 0.75% PVA.

3.7. Scanning electron microscopy (SEM)

The microstructural features of the mixtures studied were examined using SEM, and the characteristics of the interfacial transition zone and fiber–matrix interaction were qualitatively assessed to explain the mechanical response of the mixtures. The thickness of the ITZ and crack width were not quantified in the present study, but the SEM observation results are useful to support the experimental results. SEM analysis has been used successfully in recent research to account for the link between fiber–matrix bonding and the resulting enhancement of concrete performance, as well as the effect of matrix densification. The SEM images showed that there were obvious differences in the behavior of the three types of fibers at the microstructural level. The ITZs for all investigated mixtures are shown in Figure 10, with the SCC with hooked micro steel fibers having the densest and most compact ITZ. There were a few microvoids in the interface and good steel fiber–matrix bonding. This could be explained by the rough surface and hooked geometry of the steel fibers that ensured good mechanical anchorage within the hardened matrix and good stress transfer between the fibers and the matrix. The ability of the fibers to bridge microcracks, and hence to delay crack propagation, is thus attributed to the superior compressive strength, splitting tensile strength, flexural strength, and dynamic modulus results achieved with the HMSF mixes. The observations are in line with the conclusions by Imoh et al. (2025) [48], which indicated that improved mechanical anchorage contributes greatly to the load transfer mechanism and mechanical performance. Such enhancements owing to matrix

densification and refinement of the interfacial transition zone have also been observed in recent studies of metakaolin-modified concrete. The CCF mixtures also showed a relatively dense and homogeneous microstructure, as presented in Figure 11, compared to HMSF. The SEM images revealed that there were relatively few interfacial voids between the carbon fibers and the cementitious matrix, and that the carbon fibers were uniformly embedded in the matrix. Carbon fibers, however, do not have mechanical deformation or hooked ends, and their surface is smooth, so the bonding mechanism was not dominated by mechanical interlocking but was mainly dominated by the physicochemical bonding mechanism.

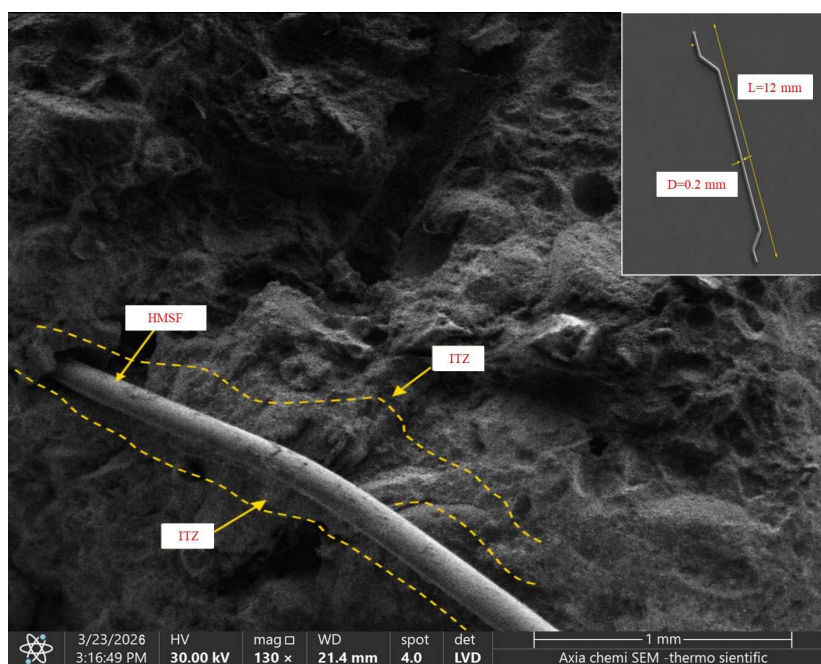


Figure 10. SEM image for SCC reinforced by HMSF at 200 $\times$.



Figure 11. SEM image for SCC reinforced by CCF at 4000 $\times$.

This bonding process was able to redistribute stresses and to delay the initiation of microcracks, but was not as effective as the bonding process in the case of HMSF. This is the reason that the CCF mixtures showed significant improvements in compressive, tensile, flexural strength, and dynamic modulus, but were slightly less than those for the HMSF mixtures. The same microstructural features have been correlated with better matrix continuity and better cementitious bond in sustainable concrete with supplementary cementitious materials. On the other hand, the PVAF mixtures showed relatively poor bond strength between the components as illustrated in Figure 12; these observations are in line with the conclusions by Imoh et al. (2025) [49]. The fibers seemed to be uniformly distributed in the matrix and to have good chemical compatibility with the hydration products in the surrounding matrix, but areas of both microvoids and fine microcracks were found around parts of the fiber–matrix interface. PVA fibers were relatively smooth and flexible and did not develop as much mechanical anchorage compared with steel fibers, which led to lower stress transfer efficiency across the ITZ.

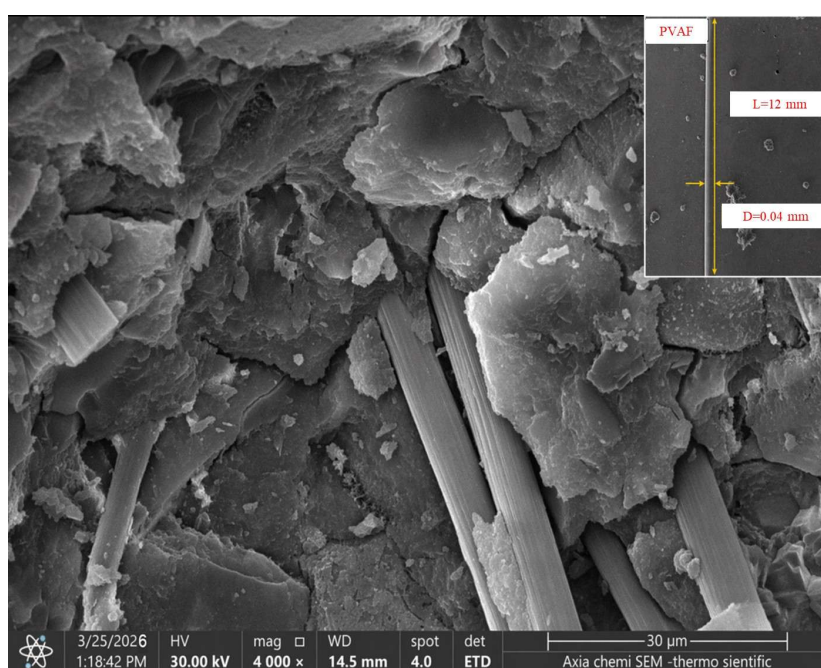


Figure 12. SEM image for SCC reinforced by PVAF at 2000 $\times$.

However, the good dispersion and deformation capacity of PVAF allowed for the control of the initiation and propagation of microcracks in an effective manner by distributing the localized stresses more evenly throughout the matrix. The PVAF mixtures, therefore, showed better crack resistance and ductility characteristics than the maximum compressive strength. The same correlations between fiber dispersion, crack control, and matrix continuity have been reported for recent microstructural studies on cementitious composites. In general, SEM observations confirmed that the mechanical properties of MSCC were strongly influenced by the quality of ITZ and the effectiveness of the fiber–matrix interaction. The highest mechanical performance was achieved by HMSF, which gave the best mechanical anchorage and crack-bridging ability, followed by CCF, which gave intermediate mechanical performance with better adhesive bonding and matrix densification. On the other hand, PVAF, although relatively lower in its mechanical anchorage, improved crack control and ductility due to its superior fiber dispersion. The qualitative microstructural observation results are in full

agreement with the experimental mechanical results and corroborate the influence of fiber geometry, surface properties, and the adhesion between fiber and cement paste on the overall performance of sustainable fiber-reinforced self-compacting concrete. These observations are in line with the conclusions by Imoh et al. (2025) [50].

4. Conclusions

From the experimental outcomes of this study, the following conclusions can be drawn:

1. The experimental results confirmed that the incorporation of fibers significantly influences the mechanical and physical properties of sustainable self-compacting concrete.
2. The optimum fiber dosage depended on the evaluated property, with 0.75% being optimal for compressive strength and dynamic modulus, while 1.0% was optimal for flexural and splitting tensile strengths.
3. The workability of all mixes was found to be satisfactory, and the slump flow values of the mixes were within the range of 680–760 mm, indicating that the incorporation of fibers up to 1.5% did not affect the self-compacting characteristics of the concrete.
4. The compressive strength results showed that all fiber types enhanced strength up to an optimum level, followed by a reduction at higher fiber contents. The optimal fiber content for compressive strength was found to be approximately 0.75% for all fiber types, with HMSF achieving the highest increase of about 17.1%, followed by CCF (11.2%) and PVAF (7.4%).
5. Fibers effectively resisted crack initiation and propagation, as evidenced by the improvements in splitting tensile and flexural strengths. The performance was best for 1.0% HMSF due to its excellent mechanical anchorage and best crack-bridging performance, while 1.0% PVAF offered the best crack control and ductile performance.
6. Dynamic modulus of elasticity increased with the addition of fibers at moderate dosages, with a maximum value obtained using 0.75% HMSF, due to the high stiffness of the steel fibers, and the improvement of fiber–matrix interaction, which increased the overall rigidity of the concrete.
7. The results of the UPV confirmed that the internal compactness and quality of the concrete matrix are enhanced by fiber addition at moderate dosages. HMSF mixtures exhibited the highest UPV values due to their metallic nature and superior wave transmission capability, while higher fiber contents resulted in reduced UPV due to increased voids and poor workability.
8. The SEM revealed that the performance of fiber-reinforced SCC is strongly governed by the quality of ITZ. The compact and best bonded ITZ with high mechanical interlocking was displayed by HMSF, and moderate bonding was observed in CCF and PVA fibers, which displayed weaker ITZ with greater porosity.
9. Overall, it was found that HMSF are the most effective reinforcement among the investigated fibers, followed by CCF and PVAF. In terms of practical use, it is suggested that the HMSF are used for structural applications that demand high strength and stiffness, while the CCF can be used for applications that need both strength enhancement and stiffness, with a focus on durability. PVAF, however, are more appropriate for applications where crack control, ductility, and corrosion resistance are a greater concern than maximum compressive strength.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Author contributions

Conceptualization and methodology: Samer S. Abdulhussein and Sura F. Alkhafaji; experimental work and data collection: Rawya A. Abduljabbar and Hussein K. Khalaf; data analysis: Samer S. Abdulhussein and Ala Z. Keblawi; writing—original draft: Sura F. Alkhafaji; writing—review and editing: Samer S. Abdulhussein and Ala Z. Keblawi; supervision: Samer S. Abdulhussein. All authors read and approved the final manuscript.

Conflict of interest

The authors declare no conflict of interest.

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