Journal of Building Engineering 64 (2023) 105543

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

Microstructural analysis of siderurgical aggregate concrete reinforced with fibers

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ARTICLE INFO

Keywords:
Eco-concrete
Siderurgical aggregates
Electric arc furnace slag
Fibers
Mechanical properties

ABSTRACT

The development of cracks in concrete structures is one of the significant issues with maintaining high strength after hardening. One way to prevent and control this problem is to use fibers. This paper investigates concrete containing electric arc furnace slag aggregates reinforced with fibers. The fibers used in this study are steel fibers and three kinds of polypropylene fibers; polyolefin fibers (modified polypropylene), polypropylene homopolymer, and high-toughness polypropylene. By checking the compressive and flexural strength of concretes made with fibers, it can be seen that the best results at 28 days are found for concrete with steel fibers, namely 62 MPa with 0.9% of fibers. On the contrary, the lowest values are for concrete containing polyolefin fibers, 51 MPa, and the same percentage of fibers. Additionally, under flexural strength testing, at the age of 28 days, the strength of these samples with 0.9% of fibers was 9.54 MPa, a value that is comparable to test concrete with the same percentage of steel fibers, 10.67 MPa, despite the low workability of concrete containing polyolefin fibers with a slump of 25 mm. Moreover, the boundary transition area analysis shows that the excellent connection between the fibers and cement paste near the siderurgical aggregate has caused no cracks in this area. In contrast, cracks can be observed in critical areas near the natural aggregates.

1. Introduction

The construction industry, one of the most critical consumers of natural raw materials globally, produces a lot of environmental pollution [1,2]. This sector consumes about 50% of raw materials and 40% available industrial energy [3–7]. One way to prevent this is to use value-added slag aggregates to manufacture concrete [8,9]. Slag is a waste of the iron and steel smelting process produced when steel is made. Slags are generally classified into iron-making slag (IMS) and steel-making slag (SMS). Electric arc furnace slag (EAFS) is one of the SMSs extracted from the valorization of furnace slags [10,11]. After valuation, a small amount of these wastes is converted into siderurgical aggregate (SA) used in concrete. However, there is still no strong will to use these wastes widely in the construction industry. For this reason, a large amount of this waste is stored in the open space in steel factories and causes environmental pollution [12]. Sustainable development-focused environmental regulations [13,14] require the minimization of industrial waste disposal and oblige reuse of those waste materials in many countries worldwide [2,15,16].

Concrete with SA aggregates replacing natural aggregates has shown excellent compressive strength (more than 60 MPa) [17–20]. Therefore, SA can be used in various structural applications, such as concrete production. Some examples are concrete sleepers, bal-

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https://doi.org/10.1016/j.jobe.2022.105543
Received 13 June 2022; Received in revised form 10 November 2022; Accepted 11 November 2022
Available online 24 November 2022

last, foundations, substrates [21,22], bricks, and tiles [20]. However, the quality of raw materials, production processes, and EAFS cooling significantly affect the number of elements such as iron, aluminum, and compounds related to these elements in this product [21,23,24]. Suppose the water-to-cement ratio in the mixture is kept constant because SA aggregates have high water absorption. In that case, there is a possibility of a shrinking phenomenon and cracks in the concrete [19,25,26].

Fibers in concrete reduce the growth of fine cracks caused by shrinkage and drying and minimize water and permeability in concrete [27]. Each type of fiber behaves differently in concrete. For example, polypropylene fibers (PP) improve concrete behavior against cracking [28]. Increasing the number of fibers in concrete causes the reduction or absence of cracks in concrete and increases the compressive and flexural strength of concrete [29–31]. PP fibers have been shown to work well with conventional concrete components and help increase concrete strength [32,33]. Fibers positively affect properties such as freeze/thaw, moist-dry, sulfates, and carbon dioxide in concrete [34]. However, there is no consensus on which fiber type is best for each application [35,36]. Due to the lack of comprehensive research on fiber-reinforced concrete with siderurgical aggregates, this research aimed to study the performance of four types of fibers in this type of concrete. This study will examine concrete mixes manufactured with 25% of this aggregate and different percentages of four kinds of fibers. The selected proportions of fibers for this study are 0.3, 0.6, and 0.9% by volume of concrete because research on the use of fibers in ordinary concrete has shown that a percentage of more than one percent of the volume of concrete has no significant effect on the compressive strength of concrete [37,38].

Many studies exist on fiber-reinforced concrete, but there is a knowledge gap regarding the behavior of different kinds of fibers (metal or polymers) on the mechanical properties of concrete using special aggregates. The study shows that polymer fibers present similar behavior to metallic fibers in flexural strength but not compressive strength. For this reason, as well as the low cost of this type of fiber, these fibers will be a suitable alternative to steel fibers in concrete members under bending. Moreover, the results show that the polymer fibers show good adhesion with the cement paste in the interfacial transition zone.

2. Materials and methods

The samples were made in the Isfahan University of Technology (IUT) materials laboratory. The pieces were made in the dimensions of 15*15*15 cm^3 and 10*10*35 cm^3 for the compressive and flexural strength tests. Overall, 78 standard cubic and prismatic concrete samples were prepared. Twenty-four hours after making the samples, they were placed in a water container until they reached the test age.

2.1. Cement and additive

The cement used was Ordinary Portland Cement (OPC) type II [39], with a density of 3.12 g/cm^3 and a Blaine-specific surface of 3000 cm^2/g. The superplasticizer (Sp) was based on polycarboxylate under the brand name MLS [40].

2.2. Aggregates

SA aggregate used in this study was obtained from EAF. Table 1 shows the chemical and physical properties of natural aggregates and SA obtained from Isfahan (Iran). The natural aggregates used were appropriately graded and presented standard characteristics [41], but SA aggregates, due to production in stone crusher factories, did not have appropriate grading. Figs. 1 and 2 show the grading chart of natural aggregates and SA and the aggregate sizes used.

2.3. Fibers

The behavior and performance of four types of fibers used in concrete, FST, FPP, FPL, and FSN, were studied. Fig. 3 shows the appearance of the fibers, all in the standard range [42,43]. Table 2 shows the technical specifications.

2.4. Mix proportions

This study used five different concrete mix proportions for each type of fiber (4) and one control concrete using SA. Previous research investigated different percentages of fine and coarse SA. According to the research goals, the highest resistance obtained was for 25% replacement of fine and coarse grain SA with natural aggregate [19]. Control siderurgical concrete (CSC) has a 25% replace-

Table 1
Materials properties.

Materials	Physical Properties				
	Apparent Density (g/cm^3)	Real Density (g/cm^3)	Water absorption (wt.%)	Porosity (vol%)	Los Angeles (%)
Limestone	2.62	2.67	1.53	4.70	20.47
SA	3.55	3.36	2.2	12.10	16.70
Materials	Chemical Properties				
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO
Cement	22.00	5.00	3.82	64.00	1.90
SA	25.80	4.90	31.80	28.60	6.30
Limestone	10.63	1.20	0.78	45.16	0.40

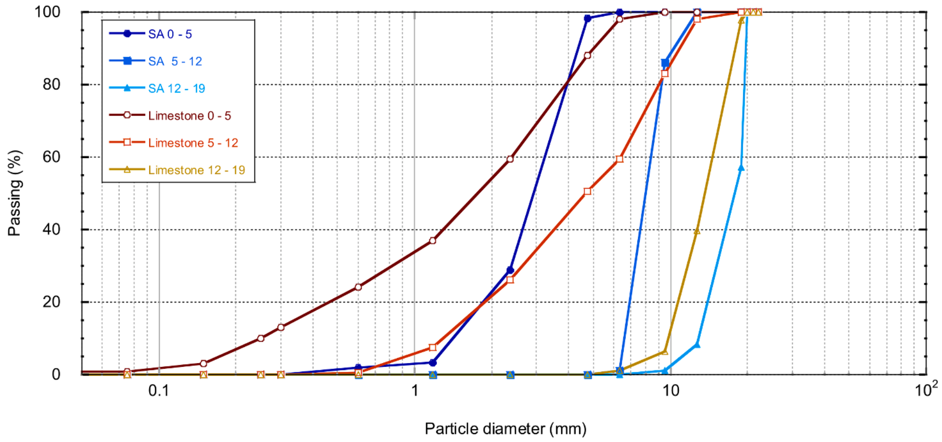


Fig. 1. Grading chart of natural aggregates and SA (0–5 mm), (5–12 mm), (12–19 mm).

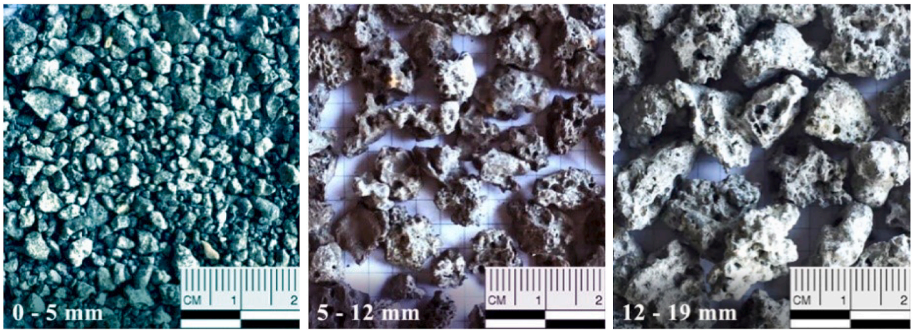


Fig. 2. Sizes of SA samples in the three categories used in this study.

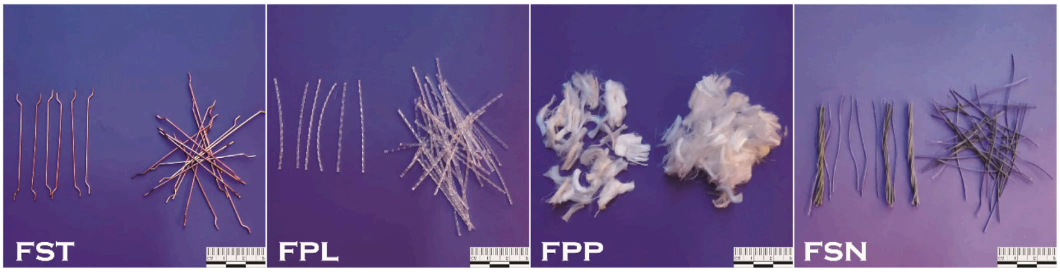


Fig. 3. The appearance of the fibers used in the reinforcement of concrete.

Table 2
Technical specifications of the fibers.

Material	Diameter (mm)	Length (mm)	Shape	Density (kg/m^3)	Tension strength (MPa)
FST	0.6	50	Two hooked heads	7850	1300
FPL	0.5	50	Serrated	900	480
FPP	0.07	12	Amorphous	910	285
FSN	0.3	50	Monofilament	910	600

ment of coarse and fine-grained SA. Table 4 contains the findings regarding CSC concrete's compressive and bending strength. According to the type of fibers and the percentage, categories were defined using steel (FST), high-toughness polypropylene (FSN), polypropylene homopolymer (FPL), and polyolefin fiber-(modified polypropylene) (FPP) fibers with incorporation percentages of 0.3%, 0.6%, and 0.9% by volume of concrete.

This study aims to analyze the behavior of concrete containing SA aggregates reinforced with fibers and the effect of these components on the mechanical properties at the ages of 7 and 28 days. The proposed mixing schemes are based on the weighted method and the recommendations provided by the standard [44,45]. Superplasticizer (Sp) was added to each mix at the final mixing stage. In some cases, increasing the percentage of fibers leads to an increment in SP to compensate for the decrease in fresh concrete workability. Sp was used at 0.8%, 1.0%, and 1.2% of cement wt and compensated by water/cement ratio reduction due to the SA's high water absorption [15]. Table 3 shows the mixed proportions used in this study.

3. Results and discussion

3.1. Fresh state concrete

Fig. 4 shows the slump of fresh concrete with a 0.45 w/c ratio and different fiber volume fractions (V_f). Concrete with 0.9% content of fibers and the maximum allowable use of Sp, i.e., 1.2%, still undergoes a sharp decrease in a slump. Adding fibers to the mixture in FST, FPL, and FSN categories, the slump increases due to the low percentage of these fibers (0.3) and the addition of 0.8% Sp in the mix. Although the amount of Sp used increased along with the percentage of used fibers, the workability of concrete did not sig-

Table 3
Mix design used for this study (kg/m^3).

Mix design											
Concrete	Type of fibers	Fibers (%. vol)	Cement	Water	Sp[a]	Limestone (mm)			SA (mm)		
						12–19	5–12	0–5	12–19	5–12	0–5
CSC		0.0	450	202	0.0	484	236	590	161	79	196
SCFST0.3	FST	0.3	450	202	0.8	484	236	590	161	79	196
SCFST0.6		0.6	450	202	0.8	484	236	590	161	79	196
SCFST0.9		0.9	450	202	0.8	484	236	590	161	79	196
SCFPL0.3	FPL	0.3	450	202	0.8	484	236	590	161	79	196
SCFPL0.6		0.6	450	202	1.0	484	236	590	161	79	196
SCFPL0.9		0.9	450	202	1.2	484	236	590	161	79	196
SCFPP0.3	FPP	0.3	450	202	0.8	484	236	590	161	79	196
SCFPP0.6		0.6	450	202	1.0	484	236	590	161	79	196
SCFPP0.9		0.9	450	202	1.2	484	236	590	161	79	196
SCFSN0.3	FSN	0.3	450	202	0.8	484	236	590	161	79	196
SCFSN0.6		0.6	450	202	1.0	484	236	590	161	79	196
SCFSN0.9		0.9	450	202	1.2	484	236	590	161	79	196

[a] Superplasticizer.

Table 4
Results for CSC [19].

Slump (mm)	170			Density (kg/m^3)	2511	
Compressive Strength (MPa)	7 Days 42.35	28 Days 59.47	90 Days 67.29	Flexural Strength (MPa)	7 Days 4.11	28 Days 4.44

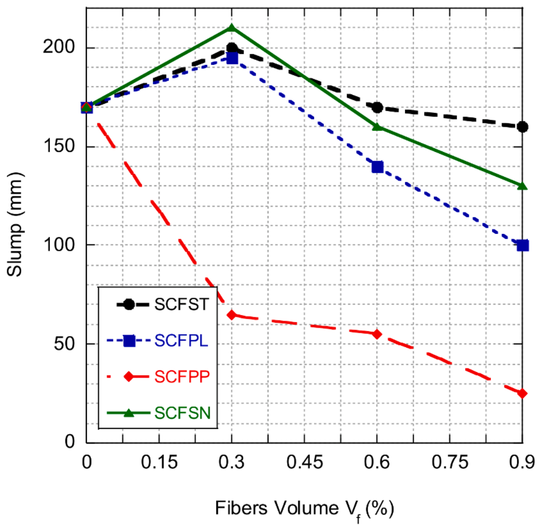


Fig. 4. Slump of fresh concrete with 0.45 w/c ratio and different volumes of fibers (V_f) used in concrete from 0.3% to 0.9% vol.

nificantly change [46]. As a result, given the constant water-cement ratio in mixing, raising the water-cement ratio is the only remaining method to increase the fluidity and workability of concrete [15,19]. It can be observed that the slump of all categories except for the category with 0.3% fiber is lower than that of the control mixture (CSC), which does not contain fibers or Sp. Among the studied categories, the SCFPP category, which contains FPP fibers, has the highest fiber-related decrease [47–49] and double the water absorption by SA [50,51]. Therefore, with the increase of the fibers volume, the workability of SCFST mix concrete was appropriate, and the SP did not need to be increased. However, in other categories, especially the SCFPP category, the need to increase SP was strongly observed; according to the factory's instructions, the maximum use limit was 1.2%.

3.2. Hardened concrete properties

3.2.1. Compressive strength

In Fig. 5, the results for compressive strength of the samples at 7 and 28 days' age were assessed. With the addition of 0.3% of fibers to the mix, the strength attained by all samples was less than CSC (50 MPa), except for the concrete containing SCFST with a strength of 52 MPa due to the inherent stiffness of steel, which helps withstand more Stresses [46]. In the other three categories (polypropylene fibers), at 7 and 28 days, when the Vf is increased from 0.3 to 0.9%, the compressive strength of concrete decreases. This behavior has also been reported in concrete samples containing natural aggregates and polypropylene fibers [52–55]. This decrease in compressive strength is related to the type of fibers used, not the change in the total from natural to SA [56,57]. The SCFPP category presents a very different downward trend to other samples, so for SCFPP0.9, at 28 days, compressive strength of 43 MPa was recorded, which is less than CSC, 54 MPa. The results show that when keeping the percentage of components in concrete constant, samples with polypropylene-based fibers present a decrease in compressive strength [55,56]. Fig. 5 shows the compressive strength for 7 and 28 days.

3.2.2. Flexural strength

Fig. 6 shows the flexural strength of the concrete at 7-day and 28-day ages and 0.3%–0.9% volume of fibers (Vf). At the age of 7 days, all samples had undergone an upward trend in strength. The lowest strength gain was for SCFPL fibers, and, as expected, the optimal flexural strength results were for SCFST. The inherent stiffness of steel fibers helps achieve flexural strength. Increasing the proportion of fibers used reduces the workability of concrete while maintaining its strength [58]. Considering the tensile strength values of the fibers, the behavior of threads in obtaining flexural strength is reasonable and understandable. However, only in the category of SCFPP, which has the lowest tensile strength, does this trend not apply, so FPP fibers with a tensile strength of 7.15 MPa have resulted in a very relative flexural strength with FST fibers.

With the increase in the percentage of fibers used in concrete at 7- and 28-day ages, the strength undergoes an upward trend. This gain increases with the increasing rate of fibers used up to SCFPL0.9, with 5.60 MPa, which reached 59% of the flexural strength of others of their category in terms of fiber consumption, SCFST0.9 with 9.51 MPa. This trend for the other two types, SCFPP0.9 and SCFSN0.9, is to attain 74 and 86% of the highest flexural strength. The increasing tendency in flexural strength changes at 28 days, and the attained strengths are very close to the maximum flexural strength recorded and more than 81% in all categories. The highest flexural strength obtained was for SCFST0.9, which attained a final 28-day resistance of 10.70 MPa. Considering that the process of increasing flexural strength in fiber-reinforced siderurgical concretes is very similar to that of concrete with natural aggregates

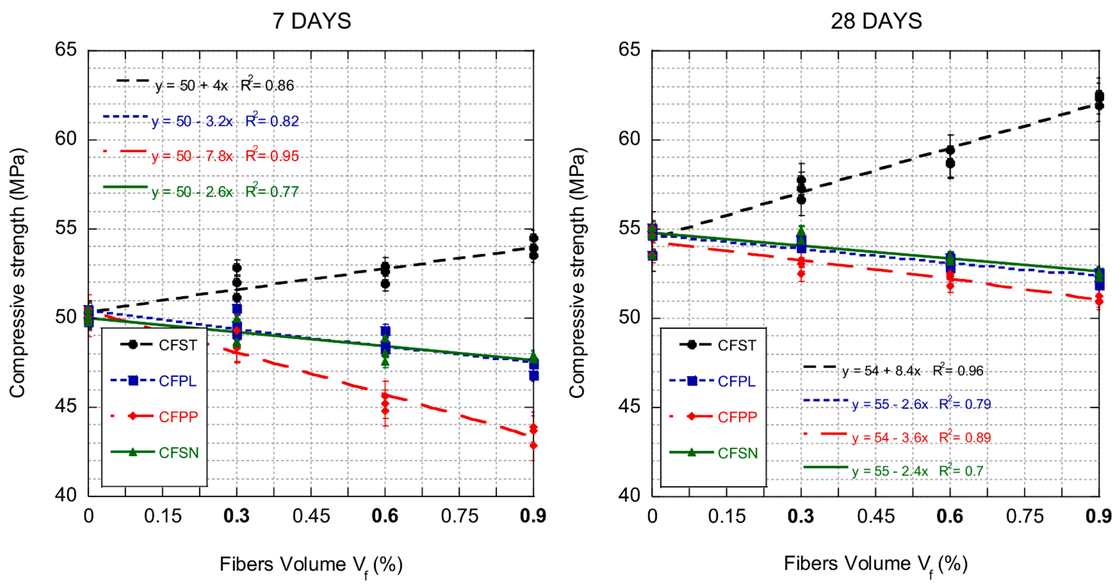


Fig. 5. Compressive strength with age for different volumes of fibers (V_f) used in concrete from 0.3% to 0.9% concrete vol.

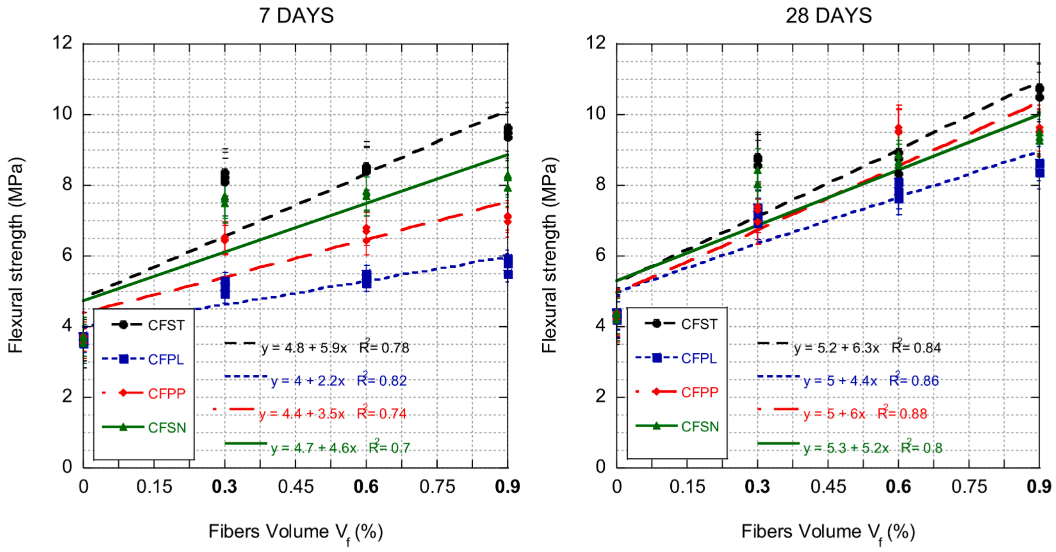


Fig. 6. Flexural strength with 7- and 28-day ages for the volume of fibers (V_f) used in concrete from 0.3% to 0.9% concrete vol.

[52–55], it can be concluded that SA displays good bonding with different types of male fibers in obtaining flexural strength [59,60]. Fig. 7 shows 28-day aged specimens broken in flexural strength tests: with 0.3% of fibers (a), 0.6% fibers (b), and 0.9% fibers (c).

3.3. Scanning electron microscopy analysis (SEM)

Scanning electron microscopy analysis (SEM) technology was used to investigate further the behavior of concrete components, which will be shown below. All photos used were taken of the samples after the flexural strength test. As shown in Fig. 8, despite the flexural strength test performed on the samples, there is still no complete separation between any category of fiber and cement paste, which demonstrates the excellent correlation between SA and fiber-paste bond.

Fig. 8-A shows that FST fibers have established adequate resistance to forces, and the connection between the paste and fibers has been maintained. Due to its uneven surface and high pore content, SA absorbs free water in concrete. As a result, fewer accessible water cavities remain around the fibers after the hydration process. In ordinary concrete, however, more accessible water remains due to the smooth surface of the natural aggregate. As a result, more cavities remain around the fibers, which creates a weak bond between the cement paste and the fibers [61]. In the case of FPL fibers, Fig. 8-C shows different behavior to FST fibers. The scratches on the body of this fiber indicate that it has withstood much force. Moreover, hydration produces residues on these fibers that indicate an adequate connection between these two concrete components. In this category, no separation between fibers and paste bonds is observed. Fig. 8-B shows all these details.

As shown in Fig. 8-C, no cracks are observed in the FPP fiber area. This demonstrates the connection between paste, FPP fibers, and SA. The full coverage of the surface of SA with paste and the complete adhesion of the fibers with paste explain the increase in flexural strength in the concrete containing FPP fibers. The performance of FPP fibers in strengthening concrete with natural aggregate and the reinforcement to obtain greater strength in concrete with SA is similar [52,53]. As is evident in Fig. 9, a perfect connection has been established between cement paste, SA, and FPP fibers. The accumulation of FPP fibers can be seen in the area close to SA. However, the trend around the natural aggregate is the opposite. The cracks created in the sample are in areas close to the bulk material without FPP fibers; this discontinuity between fibers, natural aggregate, and cement paste reduces the tensile strength of concrete [54,55].

In the case of FSN fibers, it can be seen in Fig. 8-D that FSN fibers, despite withstanding the loads that have led to the rupture of these fibers, still have a good bond with the cement paste, which is evidenced by the presence of hydration product residues on the body of FSN fibers. This connection has been such that there is no crack in the paste bond. In general, according to the results obtained, it can be concluded that SA shows a similar function to natural aggregate. In the discussion of the continuity between aggregate, cement paste, and fibers, the yield is much more acceptable than in the natural aggregate, demonstrating that it is an excellent alternative to this aggregate. Fig. 9 shows the accumulation of FPP fibers near the SA grain. The regular arrangement of FPP fibers near the SA has caused no cracks or porosity in this area, but cracks and porosity can be seen near the natural aggregates. The result demonstrates the suitability of FPP fibers in cement paste.

4. Conclusions

This article addresses the compressive and flexural behavior of SA concrete made with four conventional fibers. From the above discussion, the following conclusions can be drawn:

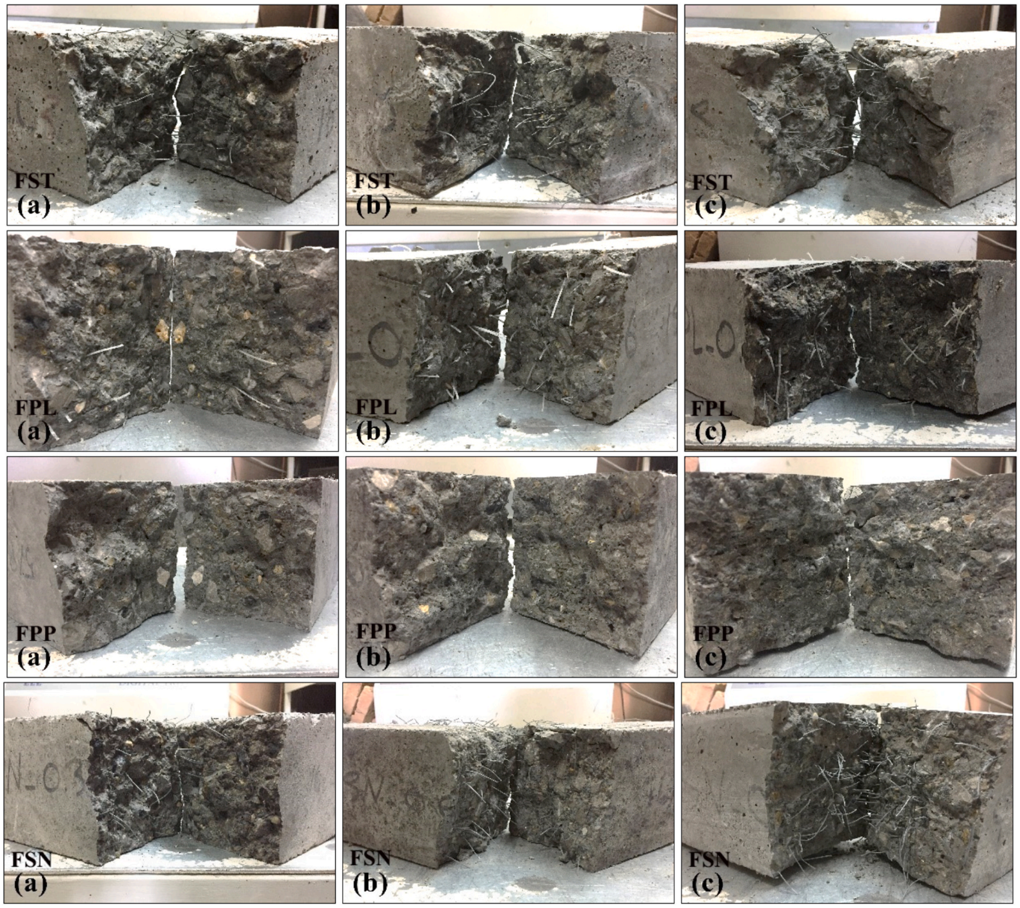


Fig. 7. 28-day aged specimens broken in flexural strength test: with 0.3% of fibers (a), 0.6% fibers (b), 0.9% fibers (c).

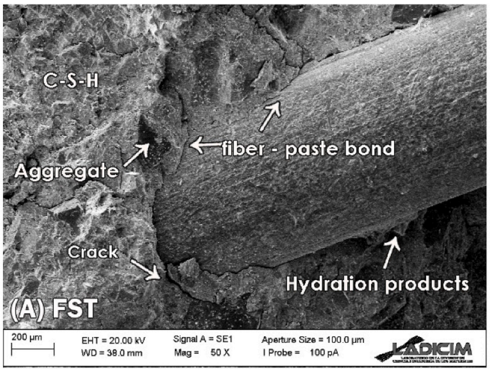
- Steel fibers have achieved the highest compressive and flexural strength results, with 62 and 10.7 MPa, respectively, and increases of 16 and 10% over the second place.
- Polypropylene fibers significantly reduce the workability and slump of fresh concrete. This reduction in slump increases with an increasing percentage of fibers. The most significant decrease is related to FPP fibers, with 25 mm in this category.
- The compressive strength is decreased when polypropylene fibers are used. The increased proportion of consumed fibers is directly related to this loss in strength. SCFPP0.9 fibers experience the most significant strength loss, which is 18% lower than CSC.
- Polypropylene fibers in FPP and FSN categories showed an outstanding performance in obtaining flexural strength in siderurgical concrete. However, the strength attained is similar to (about 86%) the strength obtained by steel fibers.
- A perfect bonding was observed between cement paste and polypropylene fibers in all categories. Moreover, even after breaking the concrete in the sample containing FPP and FSN fibers, no cracks were still seen in the paste bond.

Credit author roles conceptualization

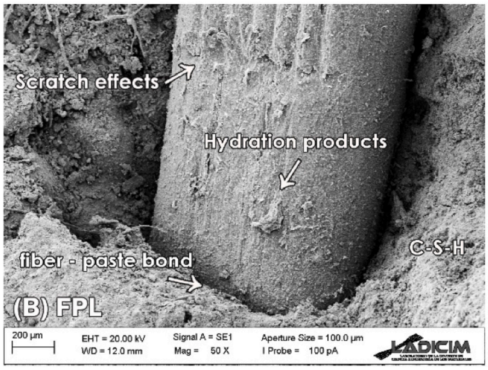
Conceptualization: Aghajanian, A.; Thomas, C.; Data curation: Aghajanian, A.; Thomas, C.; Behfarnia, K.; Formal analysis: Aghajanian, A.; Thomas, C.; Brand, A.S.; Cimentada, A.; Funding acquisition: Thomas, C.; Behfarnia, K.; Brand, A.S.; Cimentada, A.; Project administration: Aghajanian, A.; Thomas, C.; Resources: Thomas, C.; Brand, A.S.; Cimentada, A.; Supervision: Thomas, C.; Behfarnia, K.; Brand, A.S.; Cimentada, A.; Validation: Aghajanian, A.; Thomas, C.; Behfarnia, K.; Brand, A.S.; Visualization: Thomas, C.; Behfarnia, K.; Writing - original draft: Aghajanian, A.; Thomas, C.; Writing - review & editing: Aghajanian, A.; Thomas, C.; Behfarnia, K.; Brand, A.S.

Declaration of competing interest

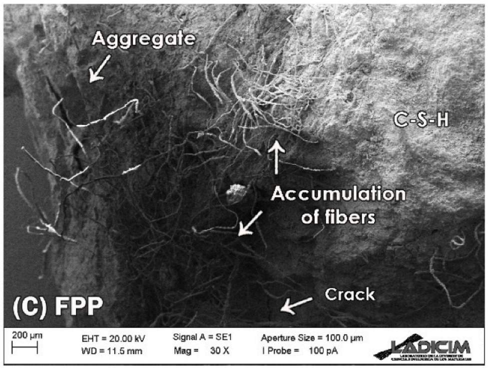
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.



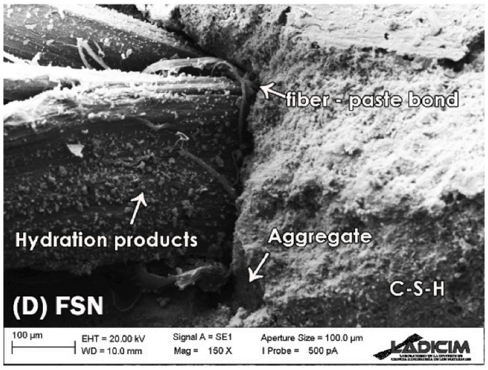
(A): micrograph of concrete containing FST fiber.



(B): micrograph of concrete containing FPL fiber.



(C): micrograph of concrete containing FPP fiber.



(D): micrograph of concrete containing FSN fiber.

Fig. 8. Micrograph of concrete containing fibers after the flexural test.

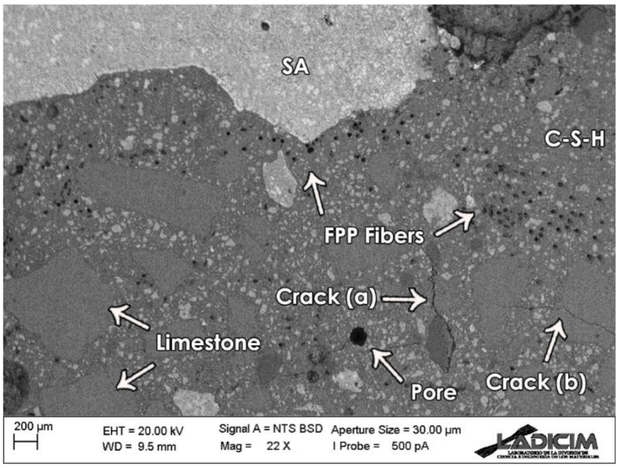


Fig. 9. The accumulation of FPP fibers near SA, Crack (a) is a crack through the bond between the cement paste and aggregate, and crack (b) is a crack through the aggregate.

Data availability

No data was used for the research described in the article.

Acknowledgments

The authors of this research would like to thank Isfahan University of Technology (Iran) for help with performing the required tests, Virginia Polytechnic Institute and State University (USA) for advice on the method used in the research, and the LADICIM Laboratory of the Division of Materials Science and Engineering of the University of Cantabria (Spain) for helping to take the scanning electron microscope photos.

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