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Investigating the Impact of Stainless Steel Shavings Fibers 316L on Enhancing the Properties of High-Flow Sand Concrete in the Long-Term

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ABSTRACT

Industrial metallic waste is a focus in civil engineering research, leading us to utilize it as building materials. High-Flow Sand Concrete (HFSC) has an economical cost, acceptable mechanical properties, and high workability. However, its drawback is the development of cracks, mitigated through the incorporation of fibers. To maximize the advantages, stainless steel shavings waste was utilized as fibers, specifically opting for Stainless Steel Fiber 316L (SSF-316L). The samples of HFSC were reinforced with SSF-316L fiber shavings at doses of 0.25%, 0.50%, 0.75%, 1.00%, 1.50%, and 2.00% by mass of concrete over 90 days During our research, we conducted tests to study the influence of SSF-316L on three properties (physical, mechanical and durability). Among the physical tests there is the determination of the air content, slump and density), at the level of the mechanical properties (we cite the compression, bending and traction tests), as for the durability we exposed our specimens to acid and sulfate, at the end the HFSC specimens were examined under a scanning electron microscope (SEM). The results show that there is a relative improvement in these three properties (physical, mechanical and durability).

1. INTRODUCTION

In the progress of the industry, there has been a rise in the production of by- products. These come in the form of industrial waste, including those from the chemical sector, mining, and the production of construction materials [1, 2]. The industrial pollutants significantly contribute to contamination primarily due to their slow decomposition process. The steel industry involves a multitude of operations that generate enormous volumes of atmospheric emissions (CO_2), liquid discharges and solid waste [3].

Nowadays, research in the field of civil engineering is focused on finding alternative construction materials. This concern has sparked growing interest in the recycling of waste from industry and the search for additives capable of improving both the mechanical and environmental properties of materials [4].

High-flow sand concrete is an economical and flexible choice in terms of design, but it has drawback is "the appearance of cracks" [5]. According to the description provided in the book "Sablocrate" [6]: Fibers are primarily utilized to minimize early age shrinkage; dosage and nature are very important parameters to ensure the effectiveness of this addition. If we want to improve ductility, we can use steel fibers.

To preserve its advantages and avoid this problem, high-flow sand concrete reinforced with steel fibers is used. This type of concrete is characterized by its potential to flow and fill voids without the need for vibration or leveling [7-9]. Additionally, it contains steel fibers that improve its physical, mechanical, and physicochemical properties. This concrete is utilized in various fields of civil engineering and construction, including columns, bridges, tunnels, foundations, load-bearing walls, concrete slabs, precast concrete elements, lightweight concrete structures, and shotcrete.

Many past research works have primarily concentrated on using types of waste steel chips in general in reinforcement, without specifying the exact type of steel used [10-12].

The new aspect of this study specifically focuses on a particular type, namely INOX 316L (stainless steel) chips. This material is well known for its features and high quality [13]. This alloy is by melting a variety of elements, mostly iron, chromium, nickel, and molybdenum, at temperatures over 1500℃. A minor amount of carbon is also melted. This alloy belongs to the austenitic stainless steel family; nickel makes up the majority of its composition, ranging from 6% to 21%. These steel kinds can be employed at high temperatures and are suitable for welding and hardening. Their ability to withstand corrosion is what makes them unique [14], especially in chemical and marine conditions. Excellent mechanical qualities are also displayed by the 316L stainless steels, which typically have yield strengths between 170 and 310 MPa and tensile strengths between 485 and 620 MPa. The kind of heat treatment used and the way the parts are assembled affect these values. Their remarkable ductility [15] allows them to tolerate deformations before breaking, in contrast to carbon steel reinforcement. 316L stainless steel is not just a substance. It is an essential component for businesses where dependability and durability are necessary. Because of its unique qualities, it is essential for innovations and helps to build infrastructure that is more sustainable and safer. Furthermore, 316L encourages sustainable development initiatives as a recyclable material, which helps to create a more accountable sector [16].

There is not much research that has been done on the use of 316L stainless steel chips in concrete. Although some research carried out on the effect of stainless steel fibers on concrete has led to positive results in terms of improving the durability and mechanical performance of the material. For instance, Bareiro et al. [17] in their work looked at the thermomechanical behavior of refractory concrete based on alumina and reinforced with stainless steel fibers using different shapes. So, the different types of stainless steel fiber, such as knurled, corrugated and straight were used in the investigation.

A rich research program based on experimental tests with numerical simulations was carried out on fibers. To do this, direct traction, compression, three-fold bending and fiber tearing tests were carried out at temperatures ranging from 25 to 1,200°C in order to obtain the residual mechanical values.

Through the results obtained we see that those of bending showed that the behavior of the knurled fiber reinforcement was always superior and this at all temperatures due to its higher adhesion with the matrix. The results of experimental tests have proven that the reinforcement provided by the fibers benefits the pre-peak and post-peak behavior of refractory concretes. The impact of the fibers on the shape of the softening curve makes it possible to predict the final fracture behavior of the composites.

Yang et al. [18] studied the adhesion performance between carbon fiber (CF) reinforced coral aggregate concrete (CAC) and stainless steel reinforcing bars (SSR). In this study, 63 samples of CF-reinforced CACs embedded with (SSR) were subjected to tension. All samples developed a pull-out pattern, and further analysis showed that the CAC strength, c/d (c is the thickness of the. CAC lid and d is the diameter of the SSR), d/la (a is the bond length) has an approximately linear relationship with the bond strength, while the CF content has an approximate parabolic relationship with the bond strength Based on the results cited above, a bond strength formula emerges from regression statistics. Furthermore, the proposed bond lengths are given by a reliability analysis based on the bond force formula. On the other hand, corrections were made to the thick-walled cylinder model regarding the properties of CAC and SSR to theoretically derive the bond force, and the results confirmed that the theoretical value matches well. to the experimental value.

Wang et al. [19] incorporated stainless steel fibers (SSF) into reactive powder concrete (RPC) to make aligned conductive RPCs (enhanced by an L-shaped device) and distributed in random directions. The aspect ratio of SSFs was varied from 30 to 150, and their content ranged from 0.2% to 1.2% by RPC volume. CPP curing ages spanned from 7 to 60 days. Electrical resistivity performance was evaluated through electrical resistance and AC impedance spectroscopy, along with studying ultrasound speed and piezo-resistivity. Mechanical tests, including compressive strength, flexural strength, and toughness, were conducted on samples cured for 60 days. High-resolution images were produced to analyze SSF dispersion and orientation. It was found that ultrasonic speed and electrical resistance of SSF-RPC increased quadratically with curing age. The percolation threshold for SSF-RPC was determined to be 0.4% SSF content. RPC with higher aspect ratio and well-aligned fibers demonstrated better conductivity, piezo-resistiveness, and mechanical performance. The conductive mechanism of SSF-RPCs was explained by the conduction patterns of three series-connected electrical components. Image analysis revealed that SSFs with a higher aspect ratio were more evenly distributed within the RPC, and the L-shaped device significantly enhanced fiber alignment.

Li and Aoude [20] studied the impact of stainless steel (SS) reinforcement on the flexural behavior of high-strength reinforced concrete beams under static and blast loads. They tested beams made with high-strength concrete and Grade 520 MPa, SS bars using a shock tube for blast loads and quasi-static conditions. The study also examined the influence of steel fibers on shear and flexural responses. SS bars improved blast resistance in beams with stirrups by increasing capacity and reducing displacements. Fibers further enhanced blast performance, reducing displacements and increasing damage tolerance. In beams without stirrups, fibers could not fully replace transverse steel but did increase shear capacity. Numerical simulations using 2D finite element modeling provided accurate predictions for static and blast conditions.

Zhang et al. [21] found that corrugated fibers (CO-F) provide the most significant enhancement in the compressive, splitting, shear, and flexural strengths of SFRC, with hooked fibers (HE-F) being moderately effective and straight fibers (ST-F) showing the least improvement. Ran et al. [22] supported these findings, noting that the effects varied with different fiber dosages.

Regarding the use of steel waste in concrete, the research work of Djebri et al. [11] consisted of incorporating metal shavings into the concrete at a rate of 0.5% by volume. The authors concluded that the inclusion of metal shavings in the concrete improved its compressive and tensile strengths and helped to reduce cracks.

This study is specified by the methodology adopted. Tests were carried out to see the impact of stainless steel chip fibers on improving the performance of high flow rate sand concrete. These tests tested its physical properties such as density, air content and slump, as well as its mechanical properties including compressive strength, tensile strength, flexural strength and split tensile strength. The same goes for chemical properties, especially the effects of sulfuric acid and hydrochloric acid on mass loss. Additionally, microstructural analysis (SEM) of these mixtures in a deep manner provided crucial information.

This research contributes to the development of economical and eco-friendly construction materials by utilizing industrial waste to enhance the properties of high-flow sand concrete. It also opens new horizons for future research on the effects of steel fibers (with precise type determination) on concrete. This study is part of a series of detailed studies that we conducted for each type of industrial waste and its use in high-flow sand concrete.

2. USED MATERIALS

In this study, the following materials were utilized to produce high-flow sand concrete reinforced with stainless steel fiber (316L):

- Sand (S): Class 0/2 sand, with a density of 2.6 g/cm^3 and an equivalent sand content of 78.80%, sourced from a quarry located in Oued Z'hor, Skikda, Algeria.

- Cement (C): Sulfate-resistant cement (SRC), also known as NA 442. CEM I 42.5 N SR3, from the Moukaoum Plus brand, LAFARGE ALGERIE, Algeria. This cement, with a density of 3.1 g/cm^3 and a Blaine fineness of 3450 cm^2/g, underwent detailed chemical analysis as presented in Table 1.
- Fine limestone (FL): Type ALCAL F15, with a density of 2.7 g/cm^3 and chemical analysis outlined in Table 1, was sourced from the El-Kheroub unit of the National Aggregates Company (ENG) in Constantine, Algeria.
- Silica fume (SF): Marketed under the name SILTEK and provided by the TEKNACHEM company in Sidi Bel Abbes, Algeria. This silica fume, with a density of 0.3 g/cm^3 and chemical analysis as detailed in Table 1, was utilized in the study.
- Water reducer (SP): A super high water-reducing plasticizer, viscocrete 665, from Sika-El Djazair, with a density of 1.085 g/cm^3 and a dry extract content of 32%.
- Mixing water (W): tap water.
- Fiber: Stainless steel shaving fiber (SSF-316L), with a density of 7.9 g/cm^3, was procured from the Algerian Equipment and Machine Tools Company (ALEMO), situated in El Kheroub, Constantine.

Table 1. The chemical analysis of C, FL and SF

Designation (%)	Cement	FL	SF
CaO	62.28	55.94	0.50
$CaCO_3$	--	99.61	--
SiO_2	23.20	0.04	95.01
Fe_2O_3	5.40	0.02	1.00
Al_2O_3	4.67	0.03	0.50
MgO	1.70	0.20	1.00
SO_3	1.70	0.02	0.01
Na_2O	0.15	0.05	--

These fibers, which came from shavings of spare parts, were sorted and chopped into lengths of 25 to 40 mm, with 0.75 to 2 mm of breadth projecting from them, as shown in Figure 1. The morphological characteristics of the SSF-316L, including their length, width, percentage of content, and distribution, are also shown in Table 2. Table 3 elaborates on the chemical characteristics of stainless steel 316L.

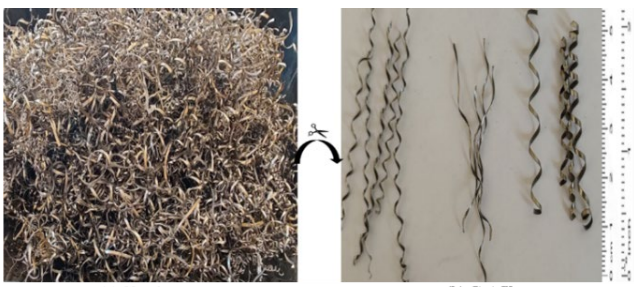

Figure 1. 316 L stainless steel

Table 2. SSF-316L morphology

Length (mm)	Width (mm)	Fibre Content (%)
25 to 30	0.75 to 1.25	12
	1.25 to 2.00	5
30 to 35	0.75 to 1.25	27
	1.25 to 2.00	8
35 to 40	0.75 to 1.25	39
	1.25 to 2.00	9

Table 3. The chemical analysis of SSF-316L

Designation (%)	Fe	Cr	Ni	Mo	C	Mn
SSF-316L	59.5	19.0	15.0	3.0	0.1	2.0

Figure 2 is SEM-EDS cartography, which combines the spatial resolution of a scanning electron microscope with the power of X-ray spectroscopy. By scanning an electron beam across the specimen surface, the green color represents the calcium (Ca) element. It is the principal component of calcium carbonate ($CaCO_3$), commonly known as fine limestone, and the blue color represents the silicon (Si) element. It is the principal component of silicon dioxide (SiO_2), commonly known as silica.

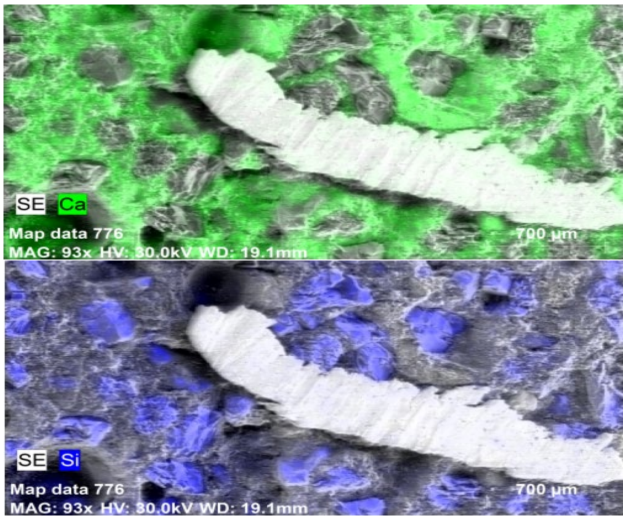

Figure 2. SEM-EDS Cartography of Ca and Si

Figure 3 shows the SSF-316L fiber shavings via SEM-EDS cartography. The specimen surface is scanned by the electron beam, with light blue indicating the iron (Fe) element, pink representing the chromium (Cr) element, and light green standing for the nickel (Ni) element. These are the principal components of SSF 316L.

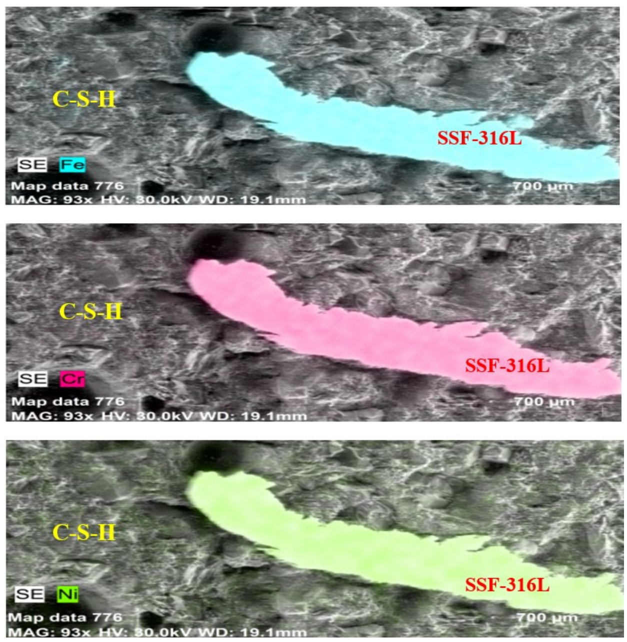

Figure 3. SEM-EDS Cartography of Fe, Cr and Ni

3. INVESTIGATIONAL METHODOLOGY

The preparation of the mixture has been formulated to achieve a compressive strength of 30 MPa using a W/C ratio of 0.60, this is important for the implementation and production of high fluidity sand concretes. Using the Sablocrete approach [6], we developed the mix design for sand concrete. After conducting many laboratory trials, we made small adjustments to the theoretical results to arrive at the values reported in M0.

The control sample (M0) consists of high-flow sand concrete without stainless steel fibers (SSF-316L), while six other samples (M1, M2, M3, M4, M5, and M6) were prepared with the incorporation of 0.25%, 0.5%, 0.75%, 1.0%, 1.5%, and 2.0% of stainless steel fibers (SSF-316L) by mass, respectively. The study's scope was increased to ensure result accuracy, and the ratios selected were based on previously published research findings [23-25]. The detailed mix design proportions are shown in Table 4.

Sand, cement, fine limestone, and silica fume are first added to a mixer. They are mixed for 1 minute until a uniform dry mixture is obtained. Water and superplasticizer are then gradually added and mixed with the constituents for another 2 minutes, in accordance with the NF EN 12350-1 standard [26]. When using high-flow sand concrete with SSF-316L, it is added after the water and superplasticizer are added to the mix.

After the mixing operation, we measured the slump values, density and air content of the newly mixed concrete according to the guidelines in Table 5 so that its physical characteristics could be verified.

Next, the samples were put in lubricated molds in a lab setting (20°C, 50% ± 5% relative humidity (RH)). The solidified concrete specimens were unmolded after one day and stored until the test in water at a temperature of 20°C. For each blend, three specimens underwent the measurements, and the average values are given.

Table 5 lists the many tests, together with the standards, specimen dimensions, and equipment needed, that are utilized for high-flow sand concrete reinforced with SSF-316L in both the fresh and hardened phases [26].

Table 4. Mix design proportions

Mix kg/m^3	M0	M1	M2	M3	M4	M5	M6
Fibre%	0.00	0.25	0.50	0.75	1.00	1.50	2.00
S	1267	1267	1267	1267	1267	1267	1267
C	450	450	450	450	450	450	450
FL	100	100	100	100	100	100	100
SF	50	50	50	50	50	50	50
W	270	270	270	270	270	270	270
SP	3.6	3.6	3.6	3.6	3.6	3.6	3.6
Fibre mass	0.00	5.34	10.69	16.03	21.37	32.06	42.74

Table 5. Norms, specimen dimensions of the concrete

Concrete Properties	Norms	Specimens Dimensions
Physical		
Slump	NF EN 12350-2	Abrams cone, 30 cm tall
Density	NF EN 12350-6	(15×15×15) cm^3
Air content	NF EN 12350-7	1L Air Entrainment Meter
Mechanical		
Compressive strength	NF EN 12390-3	(10×10×10) cm^3
Flexural tensile strength	NF EN 12390-5	(7×7×28) cm^3
Split tensile strength	NF EN 12390-6	(15×15×15) cm^3
Chemical		
Sulfuric acid	NF EN 206-1	(7×7×7) cm^3, 5% H_2SO_4
Hydrochloric acid	NF EN 206-1	(7×7×7) cm^3, 5% HCL
Microstructure SEM	---	1cm^2

4. RESULTS AND DISCUSSION

4.1 Physicals properties

Standard test methods outlined in Table 5 were utilized to conduct tests on physical properties. During the sag test, we proceeded by filling the Abrams cone with the mixture, then we lifted it constantly, and we measured each time the corresponding sag height. In the density test, both the void mold (M_v) and the filled mold (M_f) were weighed, with the volume of the mold (V) known (15×15×15) cm^3. Eq. (1) was then used to compute the results. The air content in the high-flow sand concrete was measured using a 1-liter air entrainment meter device.

$$\rho = \frac{(Mv - Mf)}{V} \tag{1}$$

Table 6 shows the impact of SSF-316L on the workability of fresh high-flow sand concrete. The slump value for the M0 mix was 215 mm. It increased by 13.95% for the M1 (0.25%) and M4 (1.00%) mixes. The reason for the result is that evenly dispersed 316L stainless steel fibers improve the mixture's homogeneity and consistency and strengthen the concrete's cohesiveness by strengthening the bond between the fibers, sand, and cement matrix. This configuration makes the concrete easier to deal with by making the pumping and placing operation easier.

It is evident that the inclusion of SSF-316L in mixes M2, M3, and M5 resulted in decreased workability. Furthermore, an increase in the SSF-316L content led to additional reduction in workability in mix M6, indicating a potential alteration in the properties of fresh concrete that could affect its strength and performance post-hardening [27, 28].

As the SSF 316L shavings fibers content rises in HFSC, the density gradually increases after 0.50%. At the peak percentage of 2.00%. Indeed, the shape, size, dispersion, and bulk density of SSF-316L shaving fibers can affect the concrete's apparent density.

Table 6 demonstrates how the air concentration in both mixtures M1 and M6 decreases when fibers are present. This suggests that fibers can be incorporated into the concrete matrix at rates of 0.25% and 2% to effectively disperse the fibers, improving the concrete's interaction with its constituent parts and minimizing air gaps. Compared to carbon fibers, stainless steel fibers (SSF) are recognized for their strong interfacial connection, durability, and capacity for dispersal within the concrete matrix. On the other hand, the air content in M5 has stabilized, and the compositions of M2, M3, and M4 concrete have increased.

Table 6. Physicals properties of the mixtures

Mixtures	Slump (mm)	Density (g/dm^3)	Air Content (%)
M0 (0.00%)	215	2091	6.2
M1 (0.25%)	245	2108	5.6
M2 (0.50%)	215	2091	6.8
M3 (0.75%)	210	2092	7.0
M4 (1.00%)	245	2093	7.2
M5 (1.50%)	220	2106	6.2
M6 (2.00%)	195	2120	5.8

As evidenced by the results reported in the literature [29], the authors reinforced concrete using two distinct types of fibers: waste metal fibers (WMF) obtained from a local lathe workshop byproduct, which had an irregular shape; and waste polypropylene fibers (WPF) obtained from polypropylene storage bags, which had a straight shape and behaved differently from the fiber-reinforced sand concretes in this study.

Researchers found that adding waste fibers to a cement matrix can be difficult when mixing and consolidating the fibers, particularly when there is a large volume proportion of irregularly shaped and complicated fibers, such as the fibers (WMF) used. In addition, compared to concrete reinforced with WMF fibers, the addition of WPF fibers had no discernible effect on workability and was easy to consolidate. Additionally, they came to the conclusion that adding fibers to the cement matrix upsets the granular skeleton and that, in order to achieve the proper workability and compactness of the fiber-reinforced concrete (FRC), the composite material's proportions must be re-optimized [30].

4.2 Mechanical properties

Mechanical property tests were performed by standard test methods specified in Table 5. The samples were submerged in water at 20°C until the day of the test.

4.2.1 Compressive strength

Table 7 illustrates how the addition of SSF-316L to high-flow sand concrete first increased and subsequently lowered its compressive strength. It is determined that 0.25% of SSF-316L is its ideal content. The compressive strength (fc) of mix M1 was 23.21% greater than that of reference mix M0. There are numerous causes for this growth, including: First, the high-flow sand concrete's micropores were filled with fine limestone and silica gasses; Secondly, the addition of SSF-316L enhanced its density while reducing air content (as indicated in Figure 4 and Figure 5, respectively, limiting the formation of micro-cracks [31]. Furthermore, by dispersing stresses throughout the concrete matrix, 316L stainless steel fibers in concrete act as tiny reinforcement bars and help avoid cracks.

Table 7. Mechanical properties of the mixtures in 90 days

Mixtures (MPa)	Compressive Strength (fc)	Flexural Tensile (ft)	Split Tensile (fs)
M0 (0.00%)	33.38	4.32	3.89
M1 (0.25%)	41.13	5.14	4.04
M2 (0.50%)	34.22	5.23	4.12
M3 (0.75%)	31.24	5.32	4.27
M4 (1.00%)	26.90	5.69	4.35
M5 (1.50%)	29.08	5.71	4.67
M6 (2.00%)	32.89	6.15	5.92

On the one hand, this can reduce the width and propagation of cracks. The compressive strength of this concrete was improved by the uniform distribution and the strong adhesion to the aggregates and the cement matrix. On the other hand, increasing the SSF-316L content does not cause a systematic improvement in the compressive strength of high-rate sand concrete, since excess SSF-316L hinders the mixing process and d homogenization of fibers, which causes a negative effect on workability [27].

The best results were obtained at 1.2% by volume, using the substitution method, according to Ndayambaje's research [32], which examined the evolution of compressive strength in concrete mixes incorporating various percentages of steel fibers extracted from abandoned tires. On the other hand, when waste polypropylene fibers were added, the samples' compressive strength increased in comparison to the control mix that lacked steel fibers [33].

4.2.2 Flexural and split tensile strength

As detailed in Table 7, Raising the content of SSF-316L led to enhancement in both flexural (ft) and split tensile (fs) strength [34]. The best mix for both strengths, M6, was determined to be 2.0%. Bending strength saw an increase of 52.18%, and split tensile strength improved by 42.36% compared to the reference mix M0. The improvement of fibres in split tensile strength can be attributed to their ability to serve as stitches between two cracked parts, to transfer the stresses and improve tensile capacity [27]. Additionally, this improvement attributed to the excellent properties of SSF-316L, with its corrugated shape playing an important role, as supported by the Fox study [21, 22].

Xu et al. [35] found has demonstrated that increasing fibre content reduces the average distance between fibres, and the increased fibres shared the load, consequently reducing the average bonding stress between the fibres and the matrix.

The decrease in bonding stress effectively restricts crack expansion, thereby enhancing both flexural and splitting tensile strength.

Furthermore, Kalpana and Tayu [4] found that the addition of steel waste substantially improves the mechanical properties of concrete, particularly impacting on tensile and flexural properties compare to compressive property. This finding corroborates our study's results [4, 36, 37].

4.2.3 Relationship between properties in the fresh and hardened state

There is a link between the mechanical characteristics, air content, and density of concrete following the addition of SSF-316L shaving fibers, as illustrated in Figure 4 and 5. It is seen that SSF-316L was added to mix M1 at a rate of 0.25%, seems to an increase in density and a reduction in air content, leading to enhancement in compressive, flexural and split tensile strengths.

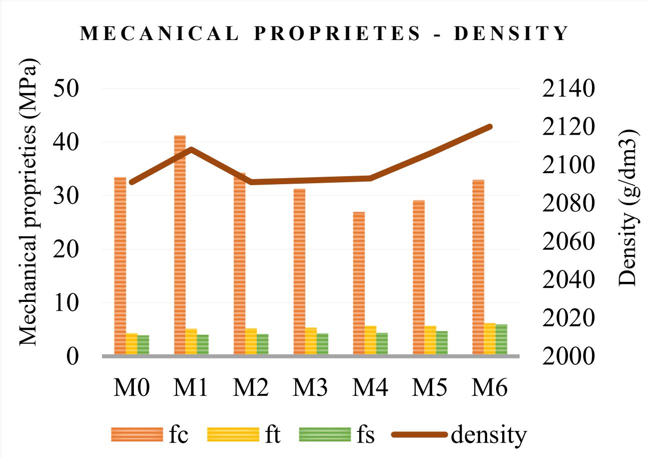

Figure 1. Mechanical proprieties and density of the mixtures

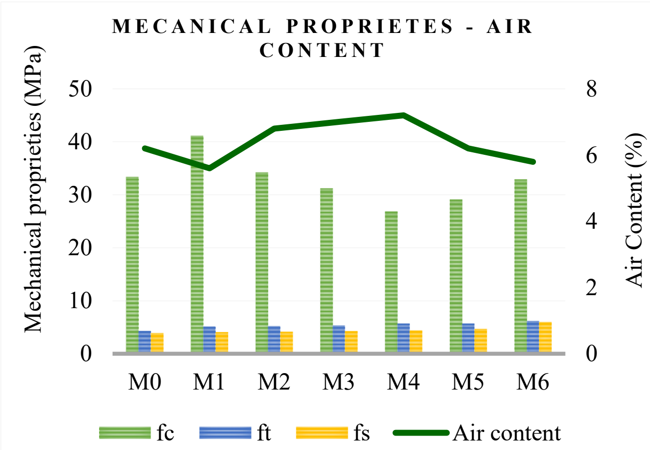

Figure 2. Mechanical proprieties and air content of the mixtures

4.3 Chemical properties

4.3.1 Sulfuric acid

A study was conducted to assess the durability of samples exposed to 5% water concentration sulfuric acid for 90 days by examining the weight loss caused by attack [25].

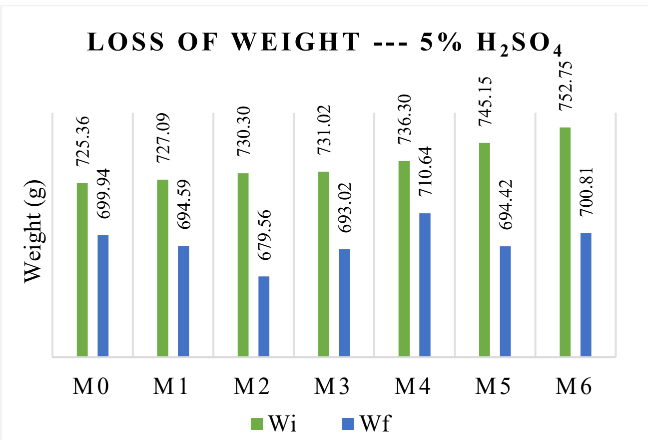

Figure 3. Chemical properties (H_2SO_4) of the mixtures

Based on the results obtained in Figure 6, the best combination to withstand sulfuric acid is M0, without SSF 316L, this is attributed to the quality of the sulfate-resistant cement (SRC). It was found that the mix closest to it is M4, with a 1% SSF 316L content. In mix M4, the weight loss percentage for the high-flow sand concrete was 3.50%, matching what was observed in mix M0. This is because the fibers made of stainless steel help to reinforce the concrete structure and prevent cracking brought on by sulfate assault. Concrete constructions that exhibit porosity are vulnerable to material degradation as a result of external substance penetration [38].

The mechanical qualities of both steel- and polypropylene-reinforced concretes improve as the fiber content of the concrete rises, providing an adequate solution. This is because fibers have the capacity to limit the spread of cracks, lessen the amount of stress concentrated at the tips of cracks, and slow down the rate at which cracks expand [39].

4.3.2 Hydrochloric acid

Research was conducted to assess the durability of samples exposed to a 5% water concentration of hydrochloric acid for 90 days. The objective of the research was to study the decrease in weight due to this attack.

According to the results shown in Figure 7, it is evident that the high-flow sand concrete reinforced with SSF-316L exhibits resistance to acid attack compared to mix M0, resulting in less weight loss. Among the different ratios, mix M5 reinforced with 1.5% of SSF-316L by weight demonstrated the highest resistance against acid attack. These results agree with those found by Dsouza Nithin et al. [25]. Stainless steel fibers are more resistant to corrosion in an atmosphere containing chlorides, which can corrode conventional steels. By doing this, concrete's mechanical qualities can be preserved and its longevity increased. Moreover, adding 316L stainless steel fibers to concrete can lessen its permeability, which will stop chloride from penetrating the concrete structure.

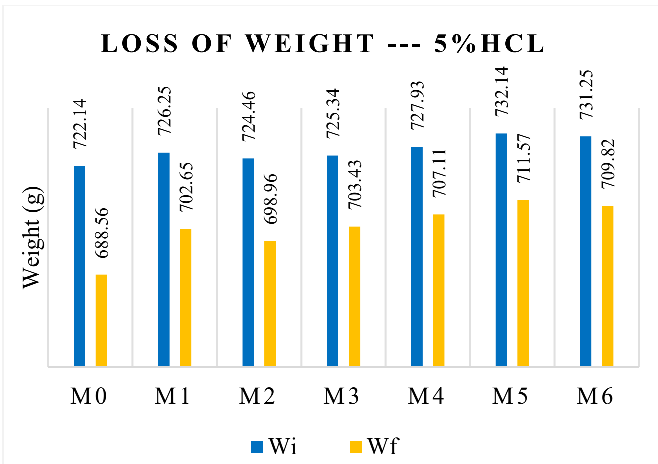

Figure 4. Chemical properties (HCl) of the mixtures

4.4 SEM testing

After the mechanical tests mentioned above, the specimens were cut into small discs measuring 10 mm in diameter and 2mm, in thickness. Following they were cleansed with water and drying in an oven. The microstructure of the specimens was observed and imaged using a FEI Quanta 650 FEG scanning electron microscope (SEM).

A scanning electron microscope (SEM) be used to examine specimens analyzing their structure and physical proprieties within a scale of 50 μm to 1 mm. By comparing Figure 8 representing the reference mix M0, to Figure 9 illustrating the enhanced mix M1 containing high flow sand concrete reinforced with 0.25% SSF 316L by mass, differences in diameter and number of pores are apparent.

The incorporation of SSF 316L into mix M1 led to a reduction in pore diameter and quantity. This led to a 9.67% reduction in air content and a 17 kg/cm^3 increase in the density of the mixture. As a result, there was an improvement in the mechanical properties of the high-flow sand concrete.

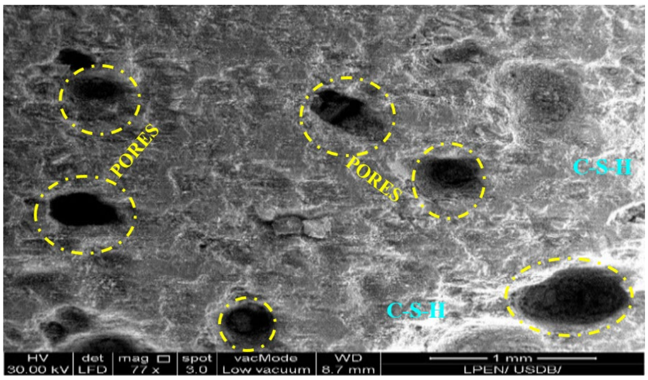

Figure 5. SEM of the mix M0

Figure 9 shows a cross section of a specimens from mix M1. The SSF-316L fibers have irregular edges blending well with C-S-H (calcium silicate hydrate). This enhanced bonding and cohesion between the sand concrete and the fibers explain the progressively increasing flexural and split tensile strength results.

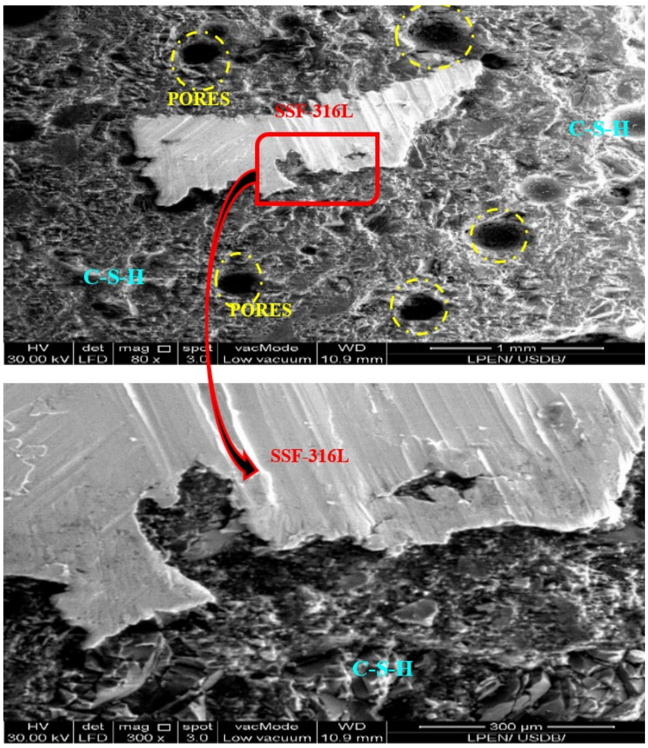

Figure 6. SEM of the mix M1

Additionally, Figure 10 illustrates a longitudinal section of a sample from the same mix M1. It is apparent that the SSF-316L fibers do not have smooth surfaces like standard steel fibers, but they have graduated protrusions which enhance their adhesion with the cementitious matrix. As a result, this enhances the cohesion between the high flow sand concrete and the SSF-316L.

Sun et al. [40] found that SSF fibers mainly play a bridging role through the bonding force and friction force formed by the hydration reaction between the fiber and the cementitious matrix.

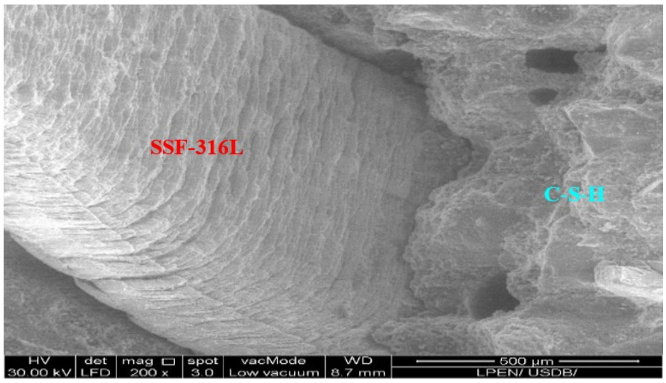

Figure 7. SEM of the mix M6

5. CONCLUSIONS

In this study, the effect of SSF-316L shavings fibers on the strength and durability properties of high-flow sand concrete (HFSC) was investigated. Based on the experimental study, the following conclusions were drawn:

-Adding SSF-316L fibers at 0.25% to HFSC in mix M1 increases workability. After this percentage, workability decreases relatively. A minimum slump of 50 mm was observed for mix M6 with 2% reinforcement compared to mix M1.

-An increase in density and a decrease in air content were observed with the addition of 0.25% SSF-316L shavings fibers into HFSC in mix M1. This resulted in a maximum compressive strength of 41.13 MPa at 90 days.

-The maximum 90 day flexural and split tensile strengths of 6.15 MPa and 5.92 MPa, respectively, were obtained at a fiber dose of 2% in the mix M6. The improvement in tensile strength is due to the mechanical properties that distinguish SSF-316L, including density and high tensile strength, and this explains the maximum density at that ratio.

-The enhancement in flexural and split tensile strength can be due to effective load sharing by the SSF-316L fibers due to stretching and straining under tensile stresses. Moreover, the corrugated nature of the fibers (CO-F) also played a role, in strengthening the HFSC.

-Regarding its exposure to chemical attack, the mixtures adding SSF-316L fibers showed lower resistance to sulfuric acid compared to the reference concrete M0. But when SSF-316L fibers were added, their resistance to hydrochloric acid grew, which prevented them from losing as much weight as M0. The concrete performed much better in chloride settings thanks to the stainless steel fibers SSF-316L, which increased corrosion resistance, reduced cracking, and increased long-term durability.

-The SEM microscopy shows the details of the edges defining SSF-316L fibers, enhancing their adhesion to the cementitious matrix. Additionally, the diameter and number of pores in M1 were found to be lower than in M0, confirming the positive impact of SSF-316L fibers on improving HFSC properties.

-Generally speaking, the incorporation of SSF-316L chip fibers into HFSC has a positive effect on its properties. However, this statement is only true with a specific (optimal) fiber dosage.

-By adding 316L stainless steel shavings, which are obtained from industrial waste, to concrete as fibers, the composite material gains durability and corrosion resistance as well as improved mechanical qualities.

-By recycling materials that would otherwise be thrown away, the use of 316L stainless steel shavings is in fact innovative in and of itself, helping to promote environmental sustainability.

-It is difficult to draw definitive conclusions regarding the long-term durability of 316L stainless steel fiber reinforced concrete due to the lack of research work on this aspect and the absence of concrete results.

-Future plans must ensure low cost and little environmental impact while maximizing the number, form, and distribution of 316L stainless steel fibers within concrete.

-Validating the outcomes of the initial experiments, long-term research should be conducted to evaluate performance under different environmental and climatic circumstances. The performance of 316L stainless steel fibers in relation to other metallic and non-metallic fiber types, as well as their possible combinations for particular applications, should be further investigated in research.

-It is imperative to incorporate multidisciplinary methodologies that encompass materials scientists, structural engineers, sustainability specialists, and economists in order to comprehensively assess the technological, financial, and ecological consequences of 316L stainless steel fibers in concrete.

-Expand the research to compare the performance of 316L stainless steel fibers with other types of fibers, both metallic and non-metallic, as well as their potential combination for specific applications. Collaborate with materials scientists, structural engineers, sustainability experts, and economists to integrate multidisciplinary approaches in order to assess the environmental, technological, and economic aspects of 316L stainless steel fibers in concrete in a comprehensive manner. This will help validate the initial experimental results.

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