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Effect of Human Hair Fibers on the Performance of Concrete Incorporating High Dosage of Silica Fume

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Abstract: Sustainable development in structural materials is currently getting attention all around the world. Solid waste, building and demolition waste, natural resources, and their reuse are the most obvious strategies for achieving sustainability in the construction industry. Solid waste human hair fiber (HHF) with a diameter of 70 µm and a length of 30–40 mm is used as a fiber, having a dosage of 0%, 1%, 1.5%, 2%, 3%, 4%, and 5%, while silica fume (SF) with a dosage of 0%, 5%, 10%, 15%, 20%, 25%, and 30% is used as a cement substitute. A drop of 50 mm to 75 mm slump was witnessed for the water–cement ratio used in the M20 mix design of concrete. The concrete's mechanical properties, such as compressive, split tensile, and flexural strength, were determined after 28 days of water curing. The concept of the response surface methodology (RSM) for optimizing human hair fiber concrete (HHFC) and SF substitution was used, which was validated by the polynomial work expectation. The model is statistically significant when the fluctuation of the analysis of variance (ANOVA) is analyzed using a p-value with a significance level of 0.05. The test results showed that the use of 2% human hair as fiber and 15% SF as a cementitious additive or cement replacement considerably improved the strength of concrete. The compressive, flexural, and split tensile strengths of HHFC improved by 14%, 8%, and 7%, respectively, which shows the significance of human hair and the partial replacement of cement with SF. Moreover, SEM analysis was carried out to study the microstructure of the concrete matrix.

Keywords: low-carbon sustainable concrete; human hair fiber; silica fume; ANOVA; RSM; SEM; solid waste

Citation: Akbar, M.; Umar, T.; Hussain, Z.; Pan, H.; Ou, G. Effect of Human Hair Fibers on the Performance of Concrete Incorporating High Dosage of Silica Fume. *Appl. Sci.* **2023**, *13*, 124. https://doi.org/10.3390/app13010124

Academic Editors: Alessandro Arrigoni and Tanvir Qureshi

Received: 15 November 2022
Revised: 15 December 2022
Accepted: 15 December 2022
Published: 22 December 2022

1. Introduction

Concrete, a material developed millennia ago, is used to construct the vast majority of modern constructions. However, after the discovery of Portland cement in the early 1800s, the term was widely employed. Nonetheless, in recent years, rigorous study and progressive work in academia and industry have given hope to a new, innovative, and eco-friendly material [1]. New cementitious binders, with optimal mix designs and enhanced casting methods, have reduced the carbon footprint of cement while also increasing its strength [2,3].

Concrete cracks are unavoidable, and they should be repaired for long-term durability. The main reason for this is that only small cracks can heal completely [4]. A structure's service life mainly depends on the durability properties of the concrete. Concrete's long-term durability has always been a source of concern for researchers and structural engineers. The research community agrees that the durability of concrete is primarily affected by various cracks that form due to multiple types of loads during its service life. These flaws allow hazardous substances such as alkalis, sulfates, and chlorides to permeate the concrete structure, eventually causing concrete deterioration [4–6]. Different reinforcements are utilized to reduce cracks and minimize damages; fiber reinforced concrete (FRC) performs better than plain concrete. Because concrete is a weaker material when subjected to tensile stresses; various fibers such as synthetic, natural, and steel fibers are used to improve their flexural and tensile properties. [6–10] Microfibers (human hair fibers) are added to the concrete mixture because they control the formation of many small cracks. Macrofibers are used to bridge macro cracks, allowing for reducing crack widths from micro to macro [11–13]. Combining the two types of fibers could be a novel way to increase the durability of concrete constructions [14–16].

The current human population is almost 7.7 billion people, and it is estimated that 6.9×10^5 tonnes of hair are produced each year. Human hair fiber is composed of around 80% protein, which contains a high sulphur content generated by the amino acid cysteine, which distinguishes it from other keratin proteins. Keratin is a laminated complex that contributes to the hair's cylindrical structure, strength, durability, elasticity, and functioning. At the molecular level, hair strands have an incredibly stiff structure that provides mechanical resistance and flexibility [17–19]. In SF, having a dense structure helps reduce the voids in the concrete matrix. Daniel et al. showed that silica-enhanced concrete had 24–38% less voids than control mix. Test results further explained that SF-based concrete's performance was better in compressive strength, pore structure, water sorptivity, and surface radon exhalations [20]. S. Bhanja and B. Sengupta et al., [21] studied SF enriched concrete using mercury intrusion porosimetry (MIP) and isothermal calorimetry experiments, respectively, to examine the microstructure and hydration kinetics. Field emission scanning electron microscopy (FE-SEM) was also used to analyze the influence of SF addition on the concrete matrix's microstructure. The results showed that porosity decreased, and compressive strength, flexural strength, and split tensile strength improved.

Concrete's dense matrix promotes excellent durability capabilities, possibly the material's most significant advantage. This durable concrete allows structures to survive longer, reduces repair costs, and contributes to more sustainable infrastructure. Sustainable resources such as SF, fly ash, and carbon black, among others, can be used to densify concrete matrix [22]. To corroborate this, the performance of M20-grade concrete was studied using human hair fiber (HHF) in various percentages ranging from 0% to 5%. Ref. [23] discovered that SF matrix has a considerable increase in chemical resistance to most salts and acids. In SF concrete, mechanical erosion resistance improved slightly. Ref. [24] investigated compressive and tensile strengths. They discovered that the mechanical characteristics with SF addition are not constant and that the optimal replacement ratio is dependent on the water–cement (w/c) ratio of the concrete matrix. The tests revealed that split tensile and flexural strengths improved the most. Ref. [25] concluded that the chloride diffusion coefficient in concrete was found to be lower when the water-to-binder ratio was reduced and SF was added at a dosage of 10%. The impact of human hair as a fiber in concrete has been studied extensively. To evaluate the performance of concrete HHF as a fiber and SF as a cementitious material has been incorporated in different percentages. Fresh concrete properties such as slump were evaluated, as were hardened properties such as flexural, compressive, and split tensile strengths after 7, 14, and 28 days of curing. Secondly, to offer something concrete that could aid in overcoming environmental issues, waste products such as human hair fiber at 2% were incorporated. Furthermore, as a cementitious material, up to 30% of cement is replaced with SF. To the best of the authors 'knowledge, most researchers have investigated the mechanical properties of human hair fiber-reinforced concrete [15,26]. On the other hand, this study addresses both mechanical and statistical aspects of the investigation, making it unique. This research contributes to the United Nations' Sustainable Development Goals (SDGs) 9 (Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation) and 12 (Ensure sustainable consumption and production patterns), targeting goals 9.1, 9.4, 9.5, 12.2, 12.5, and 12.a, respectively [27]. These targets specifically focus on sustainable and resilient infrastructures, adoption of clean and environmentally friendly technologies, enhanced scientific research, efficient use of natural resources, reducing waste generation through recycling and reuse, and by supporting developing countries to strengthen the research capabilities to move towards sustainable consumption and production.

Research Significance

This study shows that solid waste human hair can be used as a fiber to improve the concrete performance by improving the mechanical properties such as compressive, split tensile, and flexural strength. Moreover, the silica fume also helps in improving the microstructure of concrete matrix by densification and CSH formation. This research also indicates that SF improves the mechanical properties of concrete by incorporating human hair fibers. The RSM for optimization provides a forecast indication of concrete properties. The optimization results are also conditionally approved. In addition, the expectation method is used to predict the HHFC and SF findings, demonstrating its usefulness. Unlike previous research, our study adds to the literature by investigating a wide variety of results using the RSM technique and filling the gap in the literature given in Table 1.

Table 1. Author study contribution table.

Author(s)	Human Hair Fiber Concrete	Lab Experiment	SEM Analysis	RSM Anova	Methodology	Reference
Balachandar, M et al., 2019	HHF Concrete	√	×	×	Laboratory testing	[17]
Manjunatha et al., 2021	HHF Concrete	√	×	×	Laboratory testing	[18]
Meghwar, S.L et al., 2020	HHF Concrete	√	×	×	Laboratory testing	[19]
Shohag, J.M.R.I et al., 2022	SF-enhanced Concrete	√	×	×	Laboratory testing	[28]
This Research Work	HHF, Silica fume Concrete	√	√	√	Laboratory testing/ SEM/ RSM	

2. Materials and Method

2.1. Materials and Mix Proportioning

The fine aggregates were sieved using a 4.75 mm sieve according ASTM Standard [29] to study the properties of fine aggregates. The chemical composition of cement and SF, which was provided by a local manufacturer and used in the experimental study, is depicted in Table 2. Table 3 shows the properties of the fine aggregates, such as fineness modulus, bulking modulus, water absorption, and specific gravity values. A 20 mm size coarse aggregate was used. Human hair fiber waste is inherited from discarded solid waste, household items, etc. For this experimental study, different human hair fiber lengths are used. The human hair fiber of 30 mm to 40 mm in length and 70 µm diameter is blended with concrete. Furthermore, solid waste could offer an environmentally friendly alternative to standard or conventional M20 concrete. The percentage of human hair fiber incorporated in concrete is 0%, 1%, 2%, 3%, 4%, and 5%. Superplasticizer (polycarboxylate based) was used to improve the workability of concrete. The SF is used as a cementitious additive in the concrete with different percentages of 0%, 5%, 10%, 20%, 25%, and 30%, as it helps to improve the concrete workability and mechanical properties. The cement used in this experimental program was ordinary Portland cement of 43 Grade [29].

Table 2. Chemical Composition of Cement and Silica Fume.

Oxide (%)	OPC-Type 1	SF
CaO	65	0.25
SiO_2	17.15	95
Na_2O	1.86	0.1
MgO	1.74	0.4
Al_2O_3	5.6	0.2
K_2O	1.19	1.2
Fe_2O_3	3.21	0.05
SO_3	2.66	0.1
TiO_2	0.32	-
P. size µm	20 ± 1	0.2

Table 3. Properties of Aggregates.

Property	Fine Aggregate	Coarse Aggregate	Range	Standard
Aggregate particle size	Less than 4.75 mm	20 mm nominal size	4.75 mm to 20 mm	ASTM: C192/C 192M-06
Specific gravity	2.65	2.72	2.5 to 3.0	AASHTO T 85-88
Fineness modulus	2.7	4.3	2.5 to 5.0	AASHTO T 85-88

2.2. Mixing and Casting Procedure

The percentage of HHFC in the modified high-volume SF concrete was calculated using design expert software design of experiment (DOE). According to the RSM study, the proportion of HHF ranged from 0 to 5%, while the percentage of SF ranged from 0 to 30%. As illustrated in Table 4, a total combination with various percentages of HHFC and SF was created. The concrete ingredients were dry mixed for three minutes, followed by wet mixing for an additional three minutes, SP was then added, and the final mixing required no less than 4 min. Following that, the properties of fresh concrete were determined. A 150 mm × 300 mm cylinder and a 100 mm × 100 mm × 500 mm prismatic beam were then made from the fresh concrete mixture. The compressive strength, split tensile strength, and flexure strength of HHFC was measured and assessed for each mixture. The loading rate was set at 3.0 kN/s, and the hardened cubes were tested at 7, 14, and 28 days for each combination, with three specimens tested for each test and the average results reported. The prismatic beams measuring 100 mm × 100 mm × 500 mm were made for the ASTM three-point loading bending test [29,30].

Table 4. Defining Cases for Each Mix Design Samples.

Mix Design	Cement Kg/m^3	Fine Aggregate Kg/m^3	Coarse Aggregate Kg/m^3	Water Kg/m^3	Human Hair Fiber Kg/m^3	Silica Fume Kg/m^3	Superplasticizer Kg/m^3	Slump Test
C1	383	727	1103	191.6	0	0	4.5	50 mm
C2	383	727	1103	191.6	1.91	0	4.5	48 mm
C3	383	727	1103	191.6	3.83	0	4.5	46 mm
C4	383	727	1103	191.6	5.75	0	4.5	45 mm
C5	383	727	1103	191.6	7.85	0	4.5	41 mm
C6	383	727	1103	191.6	9.5	0	4.5	38 mm

Table 4. *Cont.*

Mix Design	Cement Kg/m^3	Fine Aggregate Kg/m^3	Coarse Aggregate Kg/m^3	Water Kg/m^3	Human Hair Fiber Kg/m^3	Silica Fume Kg/m^3	Superplasticizer Kg/m^3	Slump Test
C7	383	727	1103	191.6	11.41	0	4.5	32 mm
C8	383	727	1103	191.6	13.32	0	4.5	27 mm
C9	383	727	1103	191.6	15.23	0	4.5	22 mm
C10	383	727	1103	191.6	17.14	0	4.5	19 mm
C1	383	727	1103	191.6	7.85	0	4.5	45 mm
C1-SF5	363.85	727	1103	191.6	7.85	19.15	4.5	-
C1-SF10	383	727	1103	191.6	7.85	38.3	4.5	-
C1-SF15	325.55	727	1103	191.6	7.85	57.45	4.5	-
C1-SF20	306.4	727	1103	191.6	7.85	76.6	4.5	-
C1-SF25	287.25	727	1103	191.6	7.85	95.75	4.5	-
C1-SF30	268.10	727	1103	191.6	7.85	114.9	4.5	-

2.3. Testing Program

In this research work, two tests were performed on fresh concrete specimens (slump test and compaction factor test) for studying the rheological properties of concrete, and other concrete specimens were tested to study the mechanical properties (compressive strength, flexural strength, split tensile strength) performed in accordance with ASTM: C192/C 192M-06 shown in Table 5. Initially, suitable concrete was designed by checking the workability at different dosages. The slump tests showed that after 2% of human hair, there was an amalgamation and balling effect. Therefore, a dosage of 2% human hair fiber was recommended in this experimental program. The cylinders utilized were 150 mm × 300 mm in size, with a beam size of 100 mm × 100 mm × 500 mm. Both normal concrete and human hair fiber concrete specimens were cast.

Table 5. Tests for measuring properties of materials.

Sr.No	Test	Standard
1	Soundness Test of Cement	ASTM C187-16
2	Setting Time of Cement	ASTM C403
3	Fineness Modulus of Sand	ASTM C136
4	Abrasion Value of Coarse Aggregates	ASTM C 535
5	Crushing Strength and Impact Value of Coarse Aggregates	ASTM D5821
6	Flakiness, Elongation, and Angularity No. of Course Aggregates	ASTM D 4791
7	Specific Gravity and Water Absorption of Coarse Aggregates	ASTM D7172-14
8	Slump Test	ASTM C143
9	Compression Test	ATSM C39
10	Flexural Test	ASTM C1161-18
10	Split Tensile Test	ASTM C496
12	Scanning Electron Microscopy (SEM)	ASTM C1723-16
13	RSM	Design Expert

2.4. Response Surface Method

RSM may be a measurable procedure utilized to create mathematical models that depict one or more responses within the series of one or more input variables [25,28,31]. The RSM design a polynomial relationship between the response and the input factors, counting their effect and the significance of the demonstration. This demonstration can be utilized to expect and optimize the mix design response. The development of the statistical model begins with the collection of experimental data, followed by the selection of an appropriate model to fit the data. The fitting ability of the model suggests its adequacy. The computer program Design-Expert v11 designed the experiment layout plan, numerical equations, and response optimization [32–34]. An examination of variance tool (ANOVA) is utilized to design the interaction between input factors and their impact on the response [35–37]. The reactions examined in this work are compressive strength ($y1$), splitting tensile strength ($y2$), and flexure strength ($y3$). The factors that control these responses are SF ($x1$) and human hair fiber ($x2$).

3. Results and Discussion

3.1. Compressive Strength

3.1.1. Human Hair Fiber Concrete Compressive Strength

The compressive strength test is performed on all specimens using an electrically driven automated compression testing machine with a 1000 kN capacity, as described in the methodology section, after 7, 14, and 28 days of curing. The test results were compared with a control mix design without human hair fiber, as presented in Table 4. The test results of control specimens are depicted in the following figures for compressive, flexural, and split tensile strength test results, which help us to study the positive influence of human hair fibers. When human hairs are included in the various percentages shown in Table 4, the primary criterion determines their concrete structural applicability. The results of all the test specimens' compressive strength tests are shown in Figure 1. The strength of the concrete increases as the curing period progresses. From C1-HHFC-1 to C5-HHFC-2.5, strength gain is noted at each curing phase. This improved compressive strength could be due to the crack-bridging effect of HHF. Similarly, a dramatic drop in compressive strength is found at C6-HHFC-3 dosages of 3% to 5%. Except for C4-HHFC-2, all of the mixes meet the strength requirements of M20-grade concrete. The decrease in compressive strength after a threshold of 2% HHF is due to the amalgamation of human hair fibers, which causes a decrease in the bond strength of the concrete matrix [15,28]. Compared to C1-HHFC-0, C5-HHFC-2% achieves the maximum compressive strengths of 13.72, 16.45, and 20.04 MPa at 7, 14, and 28 days of curing, respectively. According to these test results, the optimum use of human hair in concrete is 2% to acquire higher strength without altering the strength parameters of structural applications of concrete. Previous studies also confirmed the positive influence of hair fiber in concrete [18,31].

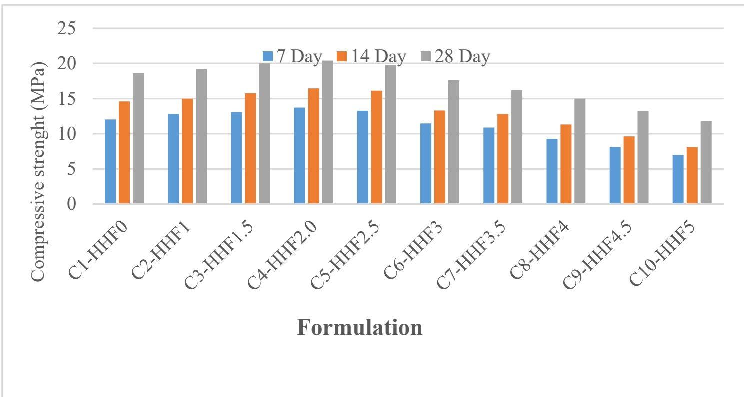


Figure 1. Compressive strength of concrete human hair fiber.

3.1.2. Effect on HHFC Compressive Strength with Replacement of Cement by Silica Fume

The replacement of cement with supplementary raw materials (human hair as a fiber) and cement with SF causes the concrete to behave differently. Figure 2 shows that the initial (7, 14, and 28 days) strength of SF concrete mix with 5%, 10%, 15%, 20%, 25%, and 30% replacement of cement has the highest strength among all other formulations and that the final (28 days) strength of SF concrete mix with a 15% replacement of cement has relatively more strength than HHFC concrete mix. As a result, compared to merely HHFC concrete, SF helps improve the final strength of HHFC concrete. The compressive strength of the concrete mix decreases up to 20% (28 days) with 30% SF substitution by cement, and the compressive strength of concrete C3-SF-20 decreases the compressive strength of the HHFC specimen. The SF of up to 15% helps to increase the compressive strength by aiding the pozzolanic effect [32]. Moreover, a higher dosage 30% of SF also plays a key role in decreasing the compressive strength by limiting the pozzolanic reaction. The mechanical properties of the HHFC with the addition of 15% SF, on the other hand, tend to improve.

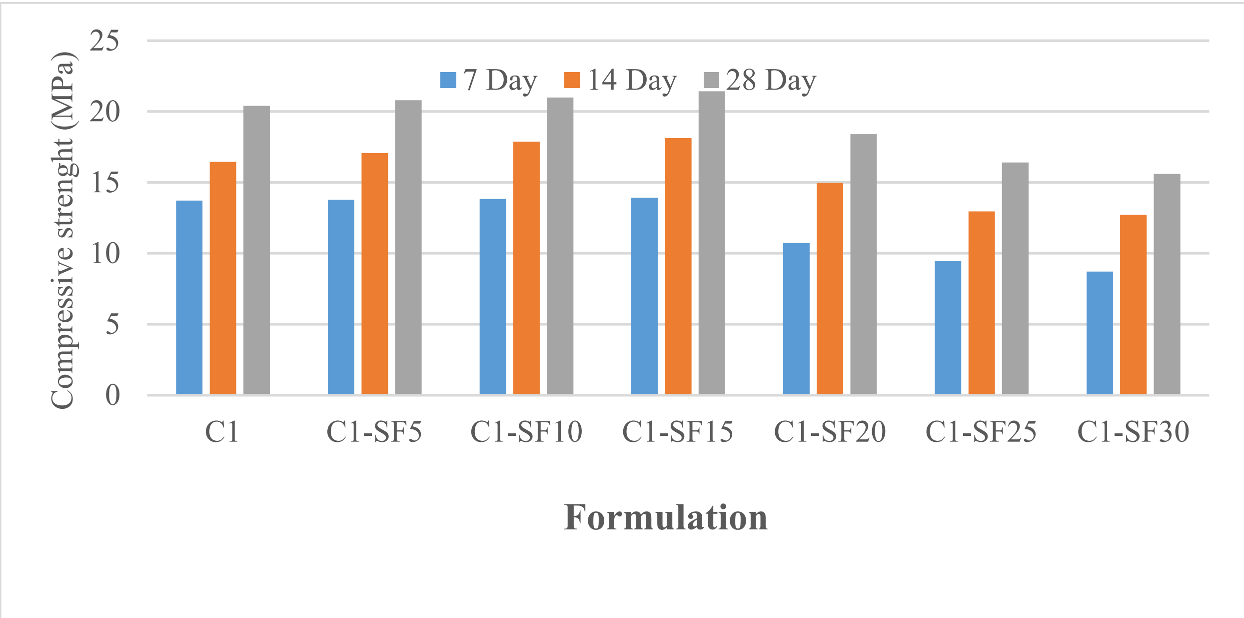
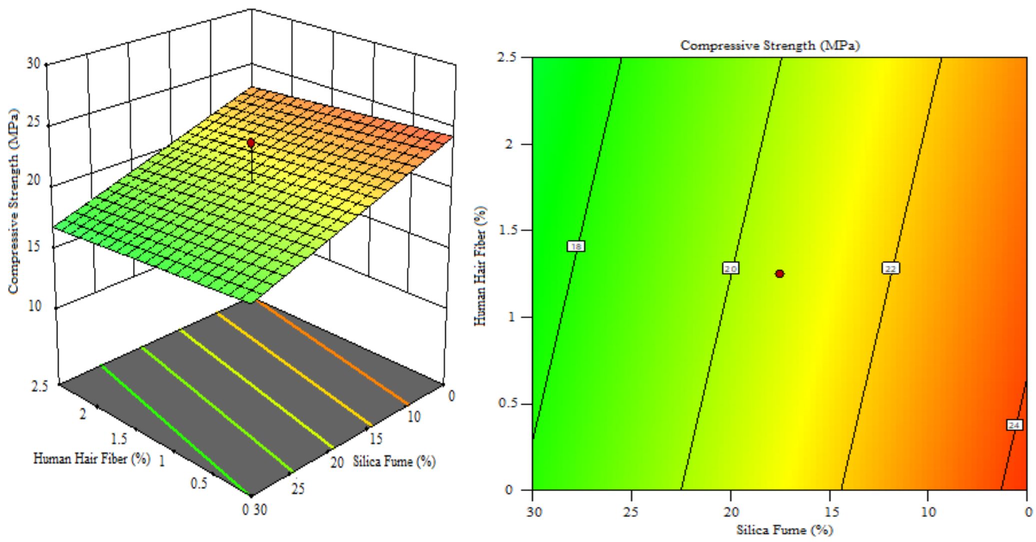


Figure 2. Compressive strength of concrete human hair fiber with Silica fume.

3.1.3. Effect on HHFC Compressive Strength with Replacement of Cement by Silica Fume Using RSM

The red zone represents a higher strength region, whereas the green region represents a lower strength region of HHFC strength, as shown in the 2D contour plot in Figure 3b. The red zone has the highest compressive strength value, and the green and blue regions have the lowest compressive strength values. For HHFC and SF, the highest compressive strength was 21.5 MPa at 2% and 15%, respectively. The contours' slanted appearance showed a weak interaction between the factors (percentages of HHFC and SF). According to the 3D response surface plot in Figure 3a, the compressive strength reduces dramatically as the SF concentration increases [38].



(**a**) (**b**)

Figure 3. (**a**) 3D surface diagram for compressive strength; (**b**) 2D contour for compressive strength.

3.2. Flexural Strength

3.2.1. Human Hair Fiber Concrete Flexural Strength

Concrete specimens (100 × 100 × 500 mm) were cast to test the flexural strength at 7, 14, and 28 days of curing, as depicted in Table 4. A universal testing machine (UTM) having a loading capacity of 1000 Kn was used. Figure 4 shows that flexural strength improves over time as HHF content and curing time increases. A dramatic decrease in strength is noted at each curing period for the 3 percent and 5 percent human hair dosages of C6-HHFC-3. Compared to the reference C6-HHFC-3, the maximum strength gains for C5-HHFC-2 (2% human hair) are 1.56, 1.96, and 2.62 MPa at 7, 14, and 28 days of curing for M20 grade concrete, respectively. The best dose of human hair fiber in concrete for structural purposes was discovered to be 2 % based on the flexural strength test findings [39].

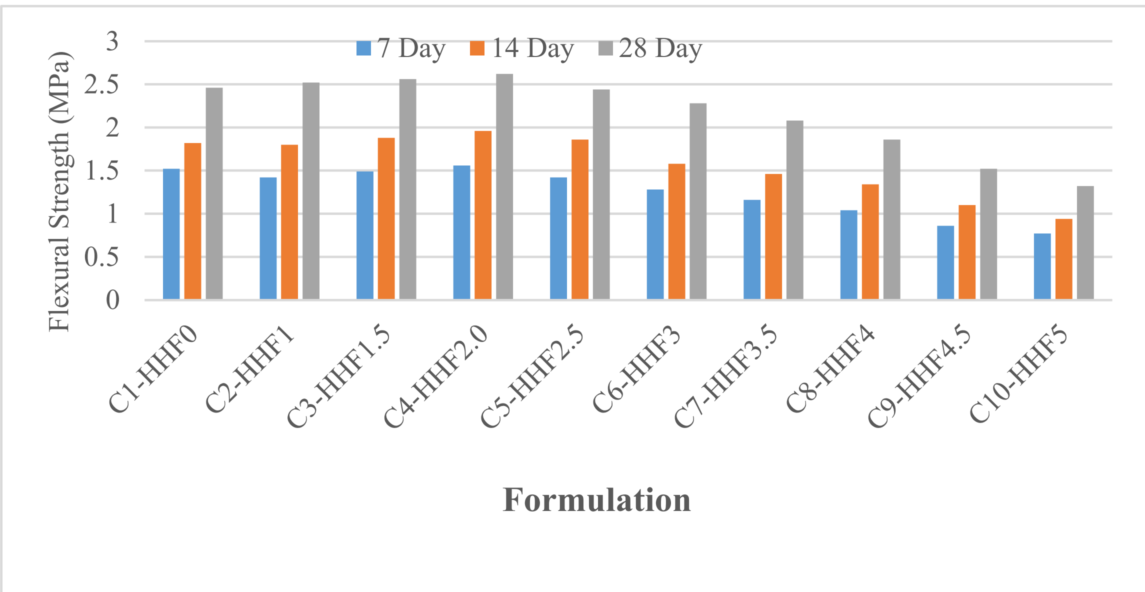


Figure 4. Flexural strength of concrete human hair fiber.

3.2.2. Effect on HHFC Concrete Flexural Strength with Replacement of Cement by Silica Fume

Figure 5 depicts the behavior of HHFC concrete when 15% of the cement is replaced with secondary raw materials (SF). Figure 5 demonstrates that the initial flexural strength of SF concrete mixes at 15% cement replacement causes an increase in flexural strength. Still, it also reveals that the concrete mix's end (28 days) flexural strength at 15% cement replacement exhibits relatively higher strength than the HHFC mix. In Figure 5, the flexural strength of concrete reduces by 20–40% (28 days) when the percentage of SF is replaced up to 30% by the weight of cement. However, it displays identical strength to the control specimen at 15% SF replacement. Another reason for the improvement in the flexural strength of concrete is possibly because of the filling of the pore's mechanism of SF. During the hydration process of concrete, SF liberates $Ca(OH)_2$ that causes the increase in strength [32]. Other than SF, the fibers also play a key role in the enhancement of flexural strength [37]. The fibers bridge the cracks at the flexure zone and prolong the cracking scenario, which ultimately increases the compressive strength. The flexural strength of the concrete also follows the compressive strength trend. For an SF dosage of 15%, the trend of flexural strength was positive [21].

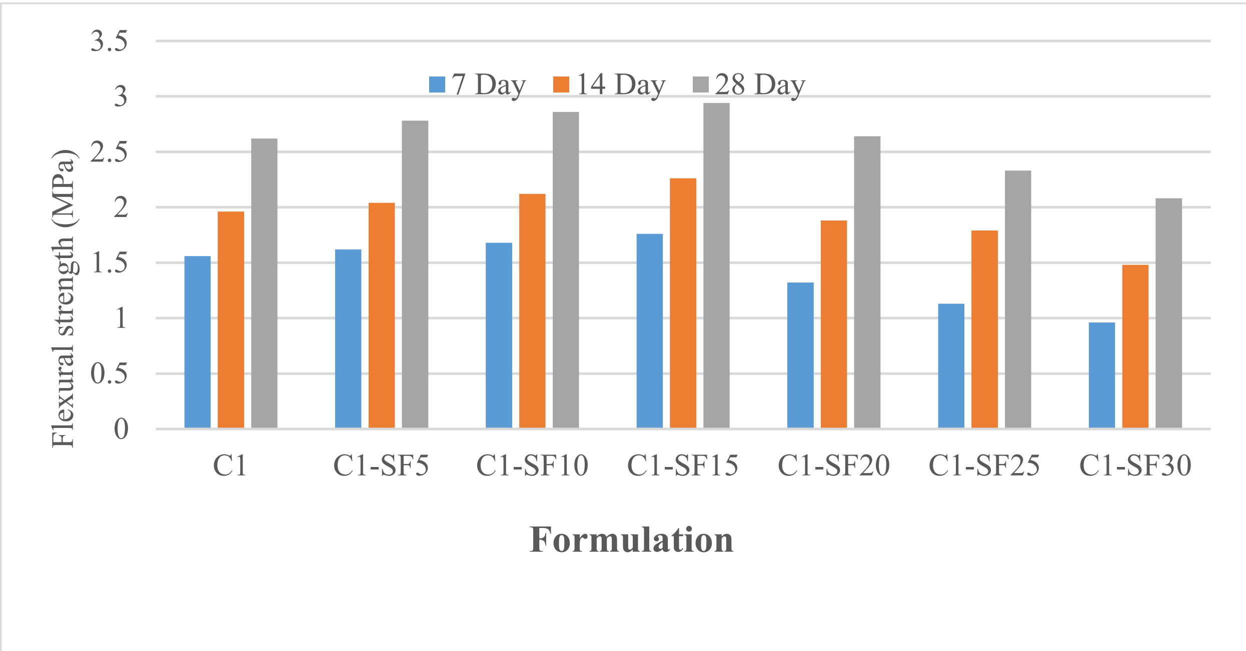


Figure 5. Flexural strength of concrete human hair fiber with silica fume.

3.2.3. Effect on HHFC Flexural Strength with Replacement of Cement by Silica Fume Using RSM

Figure 6 shows the RSM-generated 2D contour and 3D response surface diagrams for flexural strength (a,b). At 2% HHFC and 15% SF content, the highest flexural tensile strength of 2.94 MPa was achieved. However, the slope of the HHFC variable in this model is rather steep, indicating that even small changes in the amounts of HHFC and SF will result in a significant change in flexural tensile strength. When HHFC is fixed, adding more SF to the design mix lowers the flexural tensile strength. This justification supports the straight-line contour plot, which shows how each proportion of the red, green, and blue regions is evenly spread over the plot.

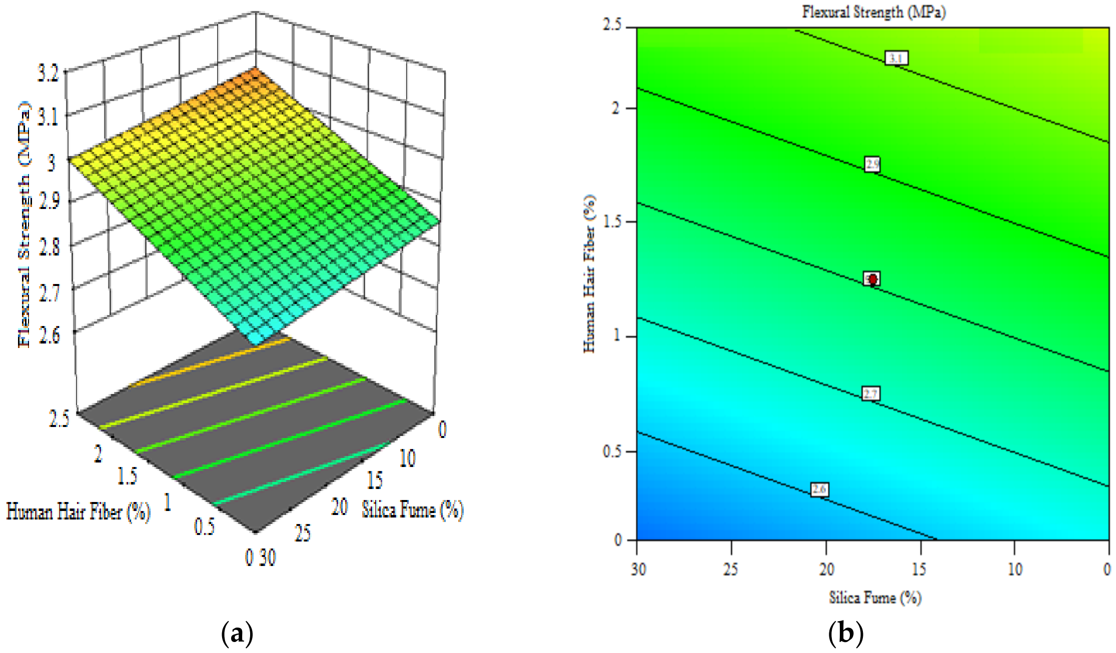


Figure 6. (**a**) 3D surface diagram for flexural strength; (**b**) 2D contour for flexural strength.

3.3. Split Tensile Strength

3.3.1. Human Hair Fiber Concrete Split Tensile Strength

For cylindrical test specimens, split tensile strength is computed using universal testing equipment with a capacity of 1000 kN. It's also one of the most important tests used to determine the strength and performance of concrete when varying percentages of human hair are added. C5-HHFC-2 reached a maximum strength of 1.4, 1.76, and 2.44 MPa at 7, 14, and 28 days of curing, respectively, for a 2% dosage of human hair, as shown in Figure 7. From C6-HHFC-3 to C10-HHFC-5, there is a 25% strength reduction after HHFC 3% to 5%. According to the split tensile test results, the ideal dose of human hair in concrete for increasing the strength of M20-grade conventional concrete is 2%.

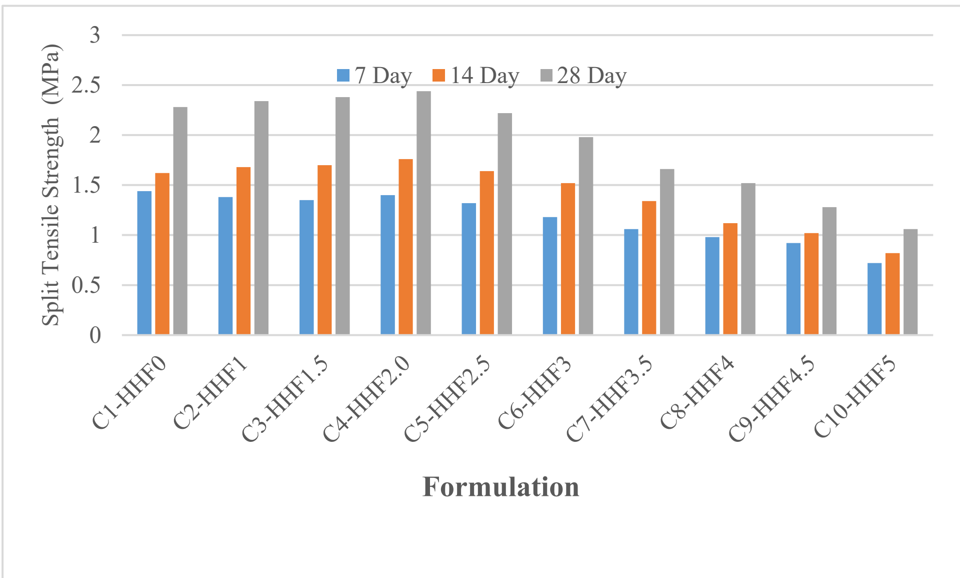


Figure 7. Split tensile strength of concrete human hair fiber.

3.3.2. Effect on HHFC Concrete Split Tensile Strength with Replacement of Cement by Silica Fume

When cement is substituted by SF 5–30% as secondary cementitious materials, a split tensile strength test is performed to evaluate the result of split tensile strength using ASTM Code C496/C496M-15 for concrete cylinders of size 150 × 300 mm at 7, 14, and 28 days each (SF). The HHFC's split tensile strength was lower than the control concrete mix. The tensile behavior of all concrete mixes is shown in Figure 8 under various combinations. The SF improves the bond strength of concrete due to its high specific area and the pozzolanic activity of the SF. The split tensile strength of HHFC concrete follows the patterns of flexural strength since the major part of this strength is offered by the fibers [38,39].

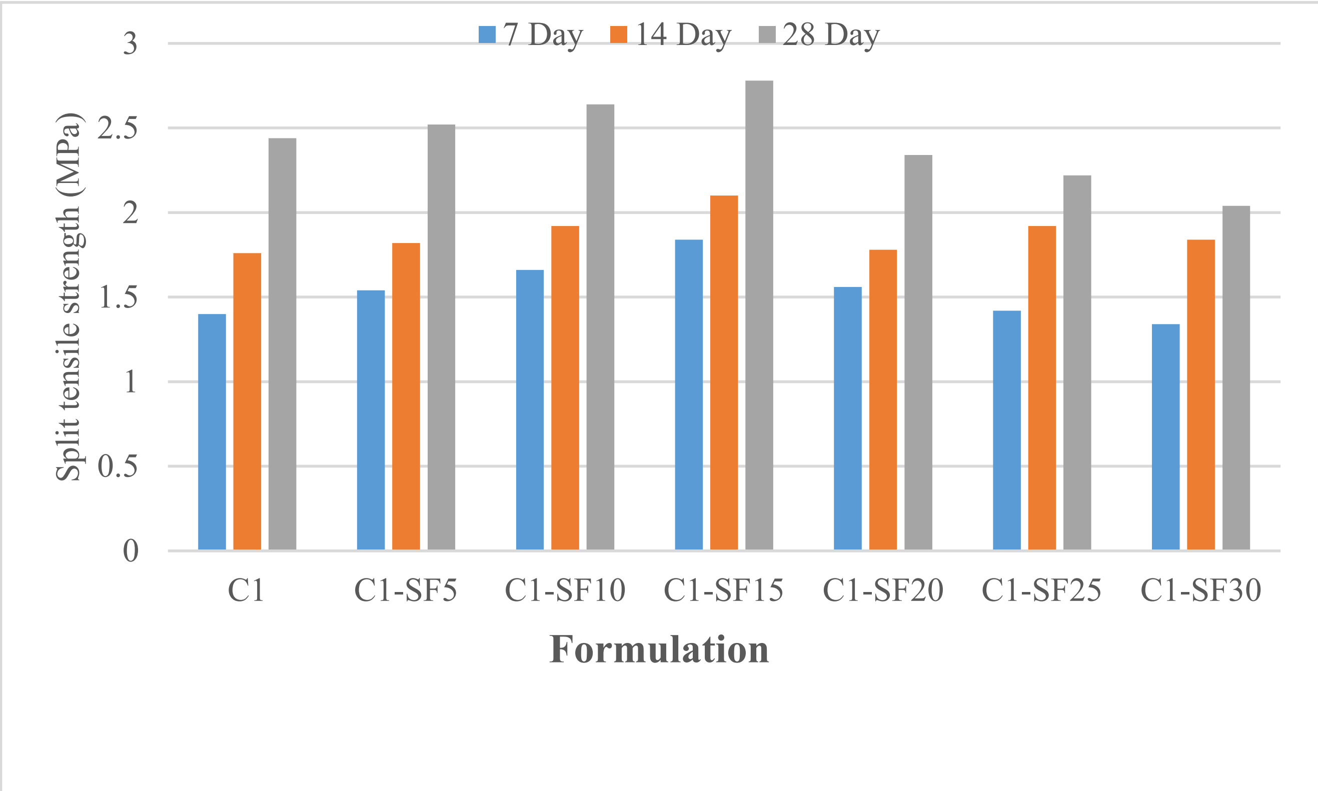


Figure 8. Split tensile strength of concrete human hair fiber with silica fume.

3.3.3. Effect on HHFC Concrete Split Tensile Strength with Replacement of Cement by Silica Fume Using RSM

The highest splitting tensile strength, 2.5 MPa, was determined using the 2D contour and 3D response surface plots shown in Figure 9a,b. The model constructed from the parameters is excellent and appropriate, as evidenced by the observation. On the splitting tensile strength model, the semi-elliptical lines in the contour diagram presented in Figure 10 demonstrate a fair relationship between the human hair fiber and SF. The splitting tensile strength dropped as the amount of SF increased, as shown in the 3D surface diagram.

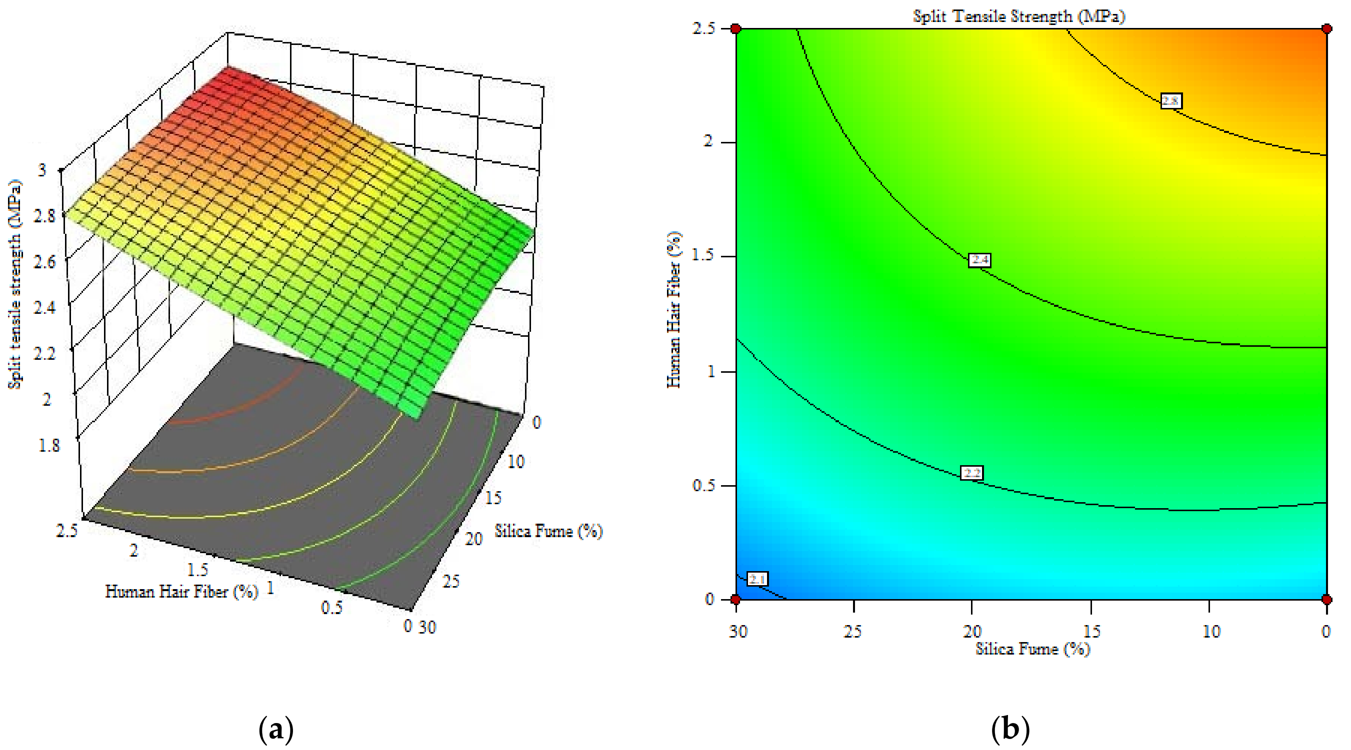


Figure 9. (**a**) 3D surface diagram for split tensile strength; (**b**) 2D contour for split tensile strength.

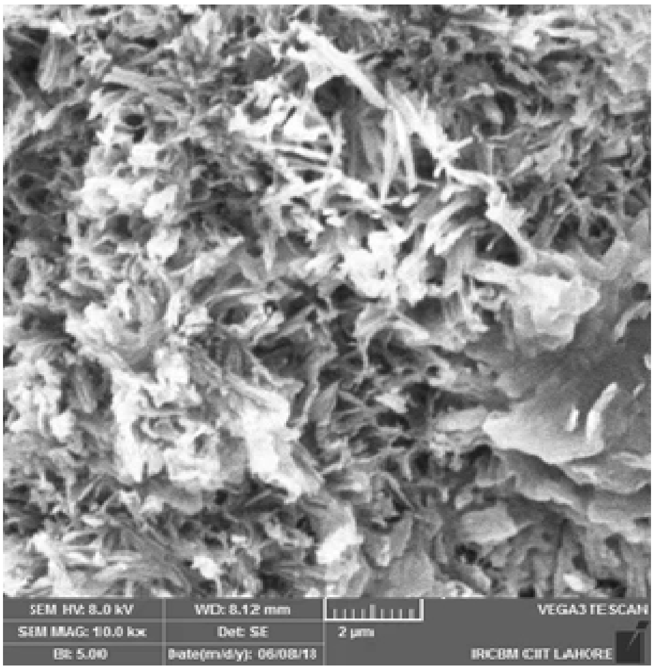


Figure 10. SEM of human hair fiber concrete.

3.4. SEM of Human Hair Fiber and Silica Fume

The bulk density of SF varies between 130–430 Kg/m^3. When coal is burned at a temperature of 1600 °C (2912 °F), SF is produced. It's divided into two classes by ASTM [29]. SF, Class F, is a siliceous substance with pozzolanic properties that are widely utilized. To further understand the microstructure of the HHFC, a scanning electronic microscopy (SEM) examination was performed, as shown in Figures 10 and 11. It aided in the comprehension of C-S-H formation mechanisms as well as the identification of flaws in the interfacial transition zone (ITZ), voids, and internal micro porosity. Both with HHFC and SF augmented concrete, SEM data in Figure 10 shows evidence of C-S-H formation, indicating satisfactory hydration. However, the composition in Figure 11 appears to be denser, which could be owing to increased C-S-H formation. Concrete performance was improved by both cement-based C-S-H and SF-based C-S-H forms. The internal spaces formed by free voids of unhydrated cement particles were filled with the human hair fiber, which improved the durability of the concrete matrix. Cement and SF-based C-S-H assist in the densification of concrete mortar, while HHF aids in the filling of voids, improving the overall durability of concrete. To avoid agglomeration, choosing the right fiber ratio is crucial. A ratio of 2% human hair fiber and 15% SF by weight is recommended based on the test results of the current study.

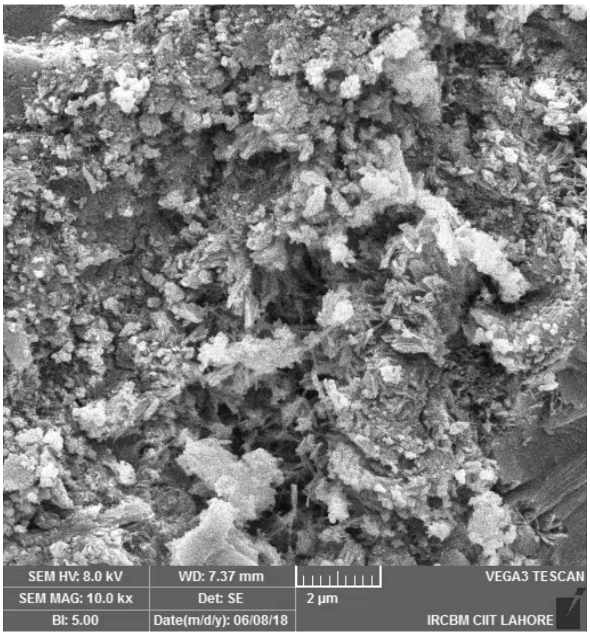


Figure 11. SEM of human hair fiber concrete incorporation silica fume.

4. Anova

4.1. Anova Analysis

In this work, the effects of human hair fiber and SF particles and their mechanical strength properties were modeled using RSM. In order to verify the effectiveness, a total of 13 mix designs were developed based on the first mix design proposed by the RSM, as shown in the table below. The influence of two independent factors, the combination of 2% HHF (B) and 15% SF on HHFC strength is investigated (A). An analysis of variance was used to establish the model's significance (ANOVA). The compressive strength of the model has an F value of 21.5 MPa, the flexural strength is 2.94 MPa, and the split tensile strength is 2.78 MPa, as indicated in the table. A high F-number denotes the model's relevance and appropriateness. These figures show that all models are significant. The model's F-number has a 0.01 percent risk of being affected by noise. Models with p-values less than 0.05 are considered essential. The results are shown in Tables 6 and 7. Table 7 shows that the model's coefficient of determination, also known as R-square (R2), is approximately 0.82, indicating dependability. The adjusted R2 and the predicated R2 have a variance of less than 0.2. This suggests that the modified R2 and the projected R2 are reasonably consistent. The signal-to-noise ratio measurement is also a minimum need for optimal (Adeq) accuracy.

Table 6. ANOVA Analysis of the Response Models.

Model	Source	Sum of Squares	df	Mean Square	F-Value	*p*-Value	Significance of the Model
Compressive Strength	Model	139.90	3	46.63	5.82	0.0124	Significant
	A-Cement	130.41	1	130.41	16.28	0.0020	
	B-Human Hair Fiber	5.40	1	5.40	0.6746	0.4289	
	C-Silica Fume	5.01	1	5.01	0.6259	0.4456	
	Residual	88.13	11	8.01			
	Cor Total	228.03	14				
Split Tensile Strength	Model	6.24	3	2.08	5.59	0.0141	Significant
	A-Cement	0.2982	1	0.2982	0.8013	0.3899	
	B-Human Hair Fiber	3.40	1	3.40	9.15	0.0116	
	C-Silica Fume	2.54	1	2.54	6.83	0.0241	
	Residual	4.09	11	0.3722			
	Cor Total	10.34	14				
	Model	6.24	3	2.08	5.59	0.0141	Significant
	A-Cement	0.2982	1	0.2982	0.8013	0.3899	
Flexural Strength	Model	0.8897	9	0.0989	7.50	0.0117	Significant
	A-Marble Powder	0.6440	1	0.6440	48.89	0.0004	
	B-PP Fiber	0.0179	1	0.0179	1.36	0.2880	
	C-Cement	0.0005	1	0.0005	0.0394	0.8492	
	Residual	0.0790	6	0.0132			
	Lack of Fit	0.0789	5	0.0158	159.28	0.0601	Significant
	Pure Error	0.0001	1				

Table 7. Models′ validation.

Model Terms	Compressive Strength	Split Tensile Strength	Flexural Strength	Source	Sequential *p*-Value
Std. Dev	2.83	0.1207	0.6101	Linear	<0.0001
Mean	20.59	2.33	9.81	Linear	<0.0001
C.V%	13.74	5.18	6.22	Linear	<0.0001
R^2	0.8852	0.8720	0.8674	Linear	<0.0001
Adj. R^2	0.8672	0.8520	0.8210	Linear	<0.0001
Pred. R^2	0.8642	0.8487	0.8143	Linear	<0.0001

4.2. Optimization and Experimental Validation

Multiple response optimization approaches are used to create the validation combination design. If the goal is to maximize reaction and mechanical strength, this answer gives four options. It is suggested that you select the option that meets your highest expectations. Experimental validation has been performed on the RSM equations. One technique to validate the model is to plot the residual normal plot, which is a straight line. As a result, if all points are almost parallel to the normal line, the predicted value will produce more accurate results than expected. The validity of the model and the capacity to select the appropriate extraction parameters based on the response outcomes are determined using normal residual plots. Table 8 shows the experiment and RSM results to summarize optimization mix results. The mean and standard deviation show that 2% HHFC and 15% SF, 21.5 MPa compressive strength, 2.94 MPa flexural strength, and 2.78 MPa split tensile strength can be achieved.

Table 8. Summary of Optimization Mix.

Sample	Human Hair Fiber (HHF %)	Silica Fume (SF %)	Compressive Strength (MPa)	Flexural Strength (MPa)	Splitting Tensile Strength (MPa)
1	2	15	21.45	2.94	2.78
2	2	15	21.44	2.94	2.78
3	2	15	21.45	2.96	2.8
4	2	30	15.6	2.08	2.02
Mean	-	-	19.985	2.75	2.595

5. Conclusions

The goal of this study was to investigate the mechanical properties of human hair fiber concrete made with human hair as a fiber and SF as a cementitious additive to find a solution to the adverse effects of high cement usage in the construction industry, which is one of the significant sources of pollution. The following conclusions can be drawn from the findings:

- Using human hair in concrete enhances the ductility of the material by minimizing the formation of macro cracks by crack bridging effect.
- Test results suggest that using 2% human hair fiber and replacing 15% of the cement with SF produces the best flexure, compression, and split tensile strengths.
- The optimum fiber and SF dosages were found to be 2% and 15%, respectively, based on experimental and RSM results. Due to the amalgamation of fibers, the results at larger dosages were conflicting.
- To see if the predictive models were statistically significant, researchers utilized a two-way ANOVA with a significance level of less than 0.05 p-value. The residual error and pure error from the lack of fit are insignificant. The adjusted and expected R2 indicate that the predictive model accurately reflects the variable-response relationship and is suitable for testing.
- A linear equation was proposed to relate the compressive strengths of SF and human hair fiber in human hair fiber concrete. The RSM model and equations utilized to calculate human hair fiber concrete's compressive, split tensile, and flexural strengths were accurate. The prediction model results validate the experimental data, revealing a slight variance.
- The use of human hair and silica fume could reduce the environmental impact of concrete; however, a lifecycle assessment should be carried out to assess the actual potential environmental benefits.

Author Contributions: Conceptualization, M.A.; methodology, M.A.; software, M.A. and Z.H. validation, M.A. and Z.H.; formal analysis, M.A.; investigation, M.A.; resources, T.U.; data curation, Z.H. and T.U.; writing—original draft preparation, M.A., Z.H. and T.U.; writing—review and editing, H.P. and G.O.; visualization, M.A.; supervision, H.P. and G.O.; project administration, H.P. and G.O. All authors have read and agreed to the published version of the manuscript.

Funding: This paper was supported by the Second Tibetan Plateau Scientific Expedition and Research Program (STEP) (Grant No. 2019QZKK0902) and the National Natural Science Foundation of China (Grant No. 42077275). It was also supported by the Youth Innovation Promotion Association of the Chinese Academy of Sciences (2018405).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data are available on request to the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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