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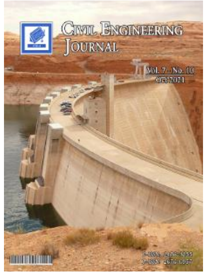

Impact of Length and Percent Dosage of Recycled Steel Fibers on the Mechanical Properties of Concrete

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Abstract

The global rapid increase in waste tyres accumulation, as well as the looming social and environmental concerns, have become major threats in recent times. The use of Recycled Steel Fiber (RSF) extracted from waste tyres in fiber reinforced concrete can be of great profitable engineering applications however the choice of suitable length and volume fractions of RSF is presently the key challenge that requires research exploration. The present experimental work aims at investigating the influence of varying lengths (7.62 and 10.16 cm) and dosages (1, 1.5, 2, 2.5, 3, 3.5, and 4%) of RSF on the various mechanical properties and durability of concrete. Test results revealed that the varying lengths and dosages of RSF significantly affect the mechanical properties of concrete. The improvements in the compressive strength, splitting tensile strength, and Modulus of Rupture (MOR) of RSF reinforced concrete observed were about 26, 70, and 63%, respectively. Moreover, the RSF reinforced concrete showed an increase of about 20 and 15% in the yield load and ultimate load-carrying capacity, respectively. The durability test results showed a greater loss in compressive strength and modulus of elasticity and a smaller loss in concrete mass of SFRC. Based on the experimental findings of this study, the optimum dosages of RSF as 2.5 and 2% for the lengths 7.62 and 10.16 cm lengths, respectively are recommended for production of structural concrete.

Keywords: Recycled Steel Fiber; Reinforced Concrete Beam; Mechanical Properties; Microstructure; Durability.

1. Introduction

In recent times, the extensive use of scrap tyres as fuel and dumping material across the globe has resulted in a rapid increase in persistent organic pollutants (POPs). This consequently has created serious repercussions for the natural environment and human health. In the past, several research studies revealed the critical effects of the stockpiling of non-degradable scrap-tyres as well as its use as a fuel in different manufacturing factories for the environment [1, 2]. Due to the lack of long-term sustainable goals as well as environmental protection measures the waste tyres are openly dumped in landfill areas and thereby resulting in wastage of useful land. Besides, the burning activity of scraped tyres in the open space is highly toxic and adversely affects human life. According to recent statistics, more than one billion tyres become scrap material after the end of their service life, in which more than half

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of its amount is wasted by either dumping at landfill sites without any proper treatment or by burning in free space [3]. The situation with regards to air pollution is more worsen in developing countries. Taking the example of Pakistan, in recent times the inferior air quality in some of the rural areas has become a source of serious concern for the government as it critically affects public health and their daily life activities. To effectively deal with the growing scrap tyres waste the development of suitable recycling techniques has become greatly essential. During the past decades, multiple techniques have been tried by researchers to develop consensus and encouragement of reuse of scrape-tyres in building construction and in rubber manufacturing industries [4, 5]. The development of rubberized concrete is one such material that has offered numerous benefits and applications due to its improved mechanical performance and high sustainability [6, 7]. Besides, the concept of rubber aerogel has shown excellent sound and thermal insulation abilities thereby resulting in effective and efficient recycling of waste tyres [8].

The waste tyres are majorly comprised of steel fibers that if properly extracted will result in numerous profitable engineering applications especially for the construction industry [9]. Recently, the trend of using recycled steel fibers (RSF) extracted from the scrap tyres in the fabrication of sustainable and green structural concrete has obtained greater attention from both researchers and practitioners [10-12]. In past, several research studies were carried out to assess the mechanical properties of concrete prepared with RSF extracted from used tyres and reported promising results. For instance, the experimental findings of Masmoudi and Bouaziz (2016) and Micelli et al. (2019) [13, 14] revealed that the use of RSF enhanced the mechanical properties of concrete while having very little or negligible effects on its durability and other environmental related issues. Furthermore, the experimental study by Fauzan et al. (2018) [15] revealed that the addition of RSF reduced the width and depth of cracks in concrete which eventually minimized the effect of different concrete harmful chemical agents. The benefits of using steel fibers extracted from waste tyres in the concrete mix, in terms of flexural and compression strength were also reported by Suleman et al. (2021), Liew & Akbar (2020) and Tu'ma and Aziz (2019) [16-18]. However, it has been also reported that the use of high-volume fractions of SF negatively affects the fresh state properties of the concrete matrix which creates difficulty in compaction and consequently leads to high porosity in concrete, high susceptibility to crack opening, and durability issues [13, 14, 19].

In comparison with the virgin steel fibers, the recycled steel fibers can result in identical mechanical properties of concrete composites, especially in terms of post-cracking behavior and toughness of concrete matrix while at the same time the latter is economical [12, 20, 21]. In general, the overall increase in the mechanical performance of steel fiber reinforced concrete (SFRC) in terms of post cracking strength, shear strength, fatigue, and dynamic resistance is associated with the uniform dispersion of steel fibers (SF) in concrete matrix which greatly depends on the length and dosage of SF [10, 22, 23]. Available literature revealed that in conventional normal strength concrete the dosage of SF (up to 0.26% by volume) can be added to ensure the adequate workability of the matrix along with uniform dispersion of SF. In some cases, the percentage of SF can be further increased to 0.46% by volume of concrete, by using a planetary mixer [2]. Previous research studies have shown that the utilization of commercial SF remarkably enhanced the flexural strength, shear strength, ductility, toughness, and resistance to post cracking of concrete mass [24, 25]. Furthermore, the increase in toughness and resistance to post cracking reduces the brittle behavior of concrete which is mainly attributed to the crack bridging action of SF which controls the crack origination and propagation and thereby results in an improved post cracking resistance [26]. On the contrary, some researchers concluded that an increase in the percentage of SF especially beyond 2% adversely affects the compression strength of concrete [27]. Moreover, in terms of the durability of concrete, several issues have been reported with the inclusion of SF in concrete [28, 29]. Generally, the incorporation of SF in concrete reduces the workability which causes difficulty in compaction and thereby results in a weak quality concrete matrix [30, 31]. Literature available also indicates that the size and the number of cracks in a unit concrete area have a great effect on the durability of concrete [32, 33]. This can be controlled via the proper selection of length and dosage of SF however, to know further about it a detailed research exploration regarding the optimum selection of length and dosage of SF is inevitably needed. Furthermore, the length of fiber plays an important role to resist the tensile stress during the widening of cracks and greatly depends on the embedded length of fiber in concrete. The only length of fiber is not enough for proper crack arresting while the number of fibers crossing the crack is also important. Keeping in view the previous research studies, it is necessary to experimentally evaluate the effect of length and percent dosage of RSF in concrete.

In this study, a new and effective recycling technique for the utilization of RSF in the production of structural concrete extracted locally from waste tyres in Pakistan was investigated through laboratory experimentation. More explicitly, the RSF having two different lengths of 7.62 and 10.16 cm and percentages 1, 1.5, 2, 2.5, 3, 3.5, and 4% were incorporated in the normal strength concrete and their performances were evaluated in terms of compressive strength, splitting tensile strength, modulus of rupture, and flexural strength. Furthermore, to assess the fiber-matrix interaction, the microstructure study was performed on small concrete representative samples via the scanning electron microscope (SEM). Lastly, the durability performance of steel fiber reinforced concrete (SFRC) cylindrical specimens was assessed in an acidic environment for a period of 56, 90, and 120 days.

2. Materials and Methods

2.1. Materials

In order, to develop an optimum design for the SFRC in terms of strength and cost effects the locally available concrete constituent materials were used in the current study. The materials were first physically and mechanically characterized at the concrete laboratory of the Civil Engineering Department of the University of Engineering and Technology (UET), Peshawar, Pakistan as per the standard procedures of ASTM [34, 35], before their use in concrete preparation. The schematic program showing experimental details is displayed in Figure 1.

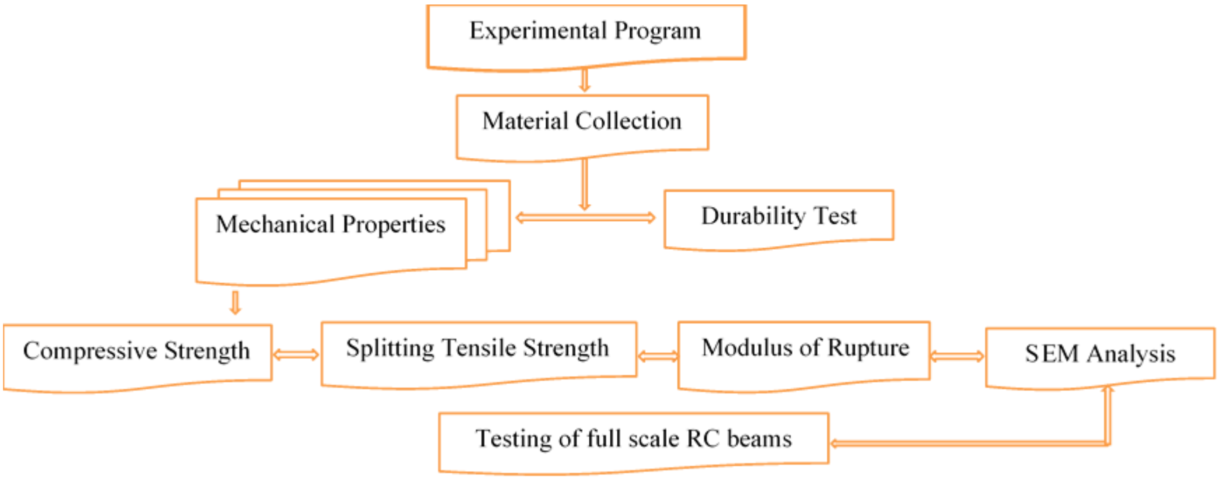

Figure 1. Schematic diagram showing details of the experimental program

The cement, sand, and coarse aggregate ratio of 1:2:4 and constant water to cement ratio i.e., 0.65 was used in the fabrication of all concrete specimens. The detail of materials used in this study is given in the following sections.

2.1.1. Steel Fibers Extracted from Scrap-tyres

In this research study, manually extracted RSF from the waste tyres of automobiles as shown in Figure 2 was used as reinforcement material in concrete. In Pakistan, the manual extraction of SF from used tyres is a common practice used for these scrap materials. The diameter of SF was 0.939 millimeters while its average tensile strength and percent elongation were determined as 996.15 MPa and 1.33%, respectively which conforms to ASTM A370 [36]. Two types of RSF having lengths equal to 7.62 and 10.16 cm and percentages 1, 1.5, 2, 2.5, 3, 3.5, and 4% (by weight replacement of concrete) were selected and their effects on the mechanical performance and durability of concrete were assessed.

Figure 2. Sample of RSF extracted from waste tyres of automobiles

2.1.2. Cement

The ordinary Portland cement (OPC) having type-I and complying with [37], was used with a fineness of 97%, and specific gravity 3.12 was used in the preparation of the concrete specimens. The OPC for the current research study was provided by a local cement manufacturer in Peshawar, Pakistan.

2.1.3. Coarse Aggregates

The normal concrete coarse aggregate of crushed stone with a particle size of 20 millimeters was used. The physical properties of coarse aggregate determined at the laboratory are shown in Table 1 and the gradation curve in Figure 3.

Table 1. Physical properties of coarse aggregate

Property	ASTM Specification	Values
Sieve analysis	ASTM C136 [38]	well graded
Moisture content	ASTM C566 [39]	0.22%
Specific gravity	ASTM C127 [34]	2.6
Water absorption	ASTMC127 [34]	1.24%

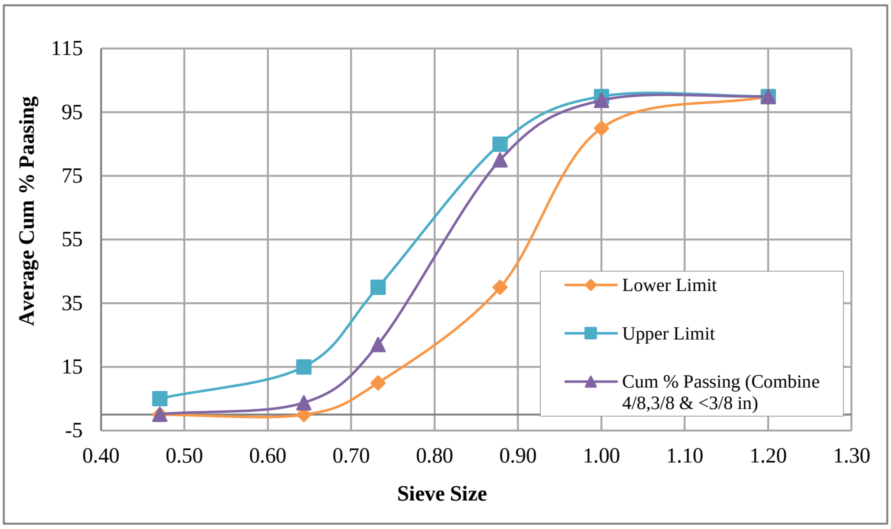

Figure 3. Gradation curve of coarse aggregate

2.1.4. Fine Aggregate

The natural fine aggregate having the physical properties tabulated in Table 2 were used. The physical properties were determined at the concrete laboratory as per the standard procedures of ASTM [35] and are shown in Table 2 and Figure 4.

Table 2. Physical properties of natural fine aggregate

Test	ASTM Specification	Values
Specific gravity	ASTM C128 [35]	2.76
Water absorption	ASTM C128 [35]	3.14%
Fineness modulus	ASTM C136 [38]	2.90
Moisture content	ASTM C70 [40]	2.45%

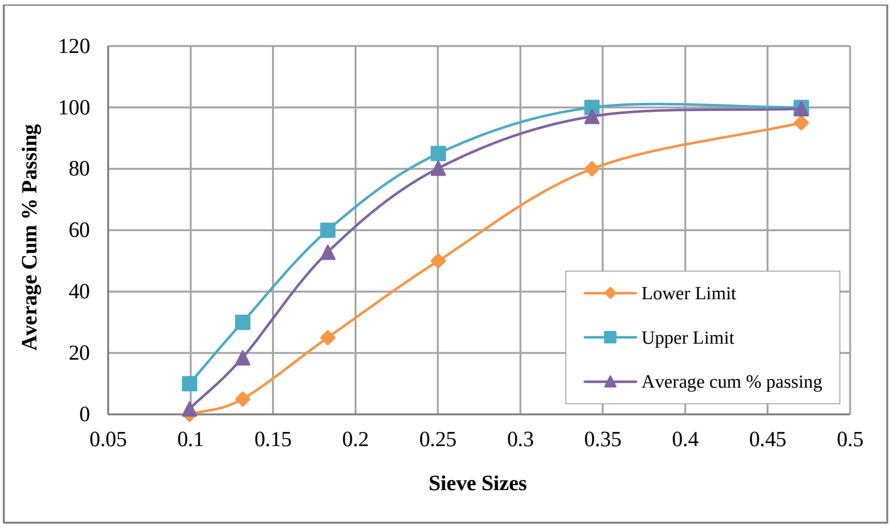

Figure 4. Gradation curve of fine aggregate

2.2. Methods

In total, 460 concrete cylinders having a diameter of 152.4 millimetres and a height of 304.8 millimetres were cast in the laboratory. The specimens were removed from the moulds after 24 hours of casting and were placed in a water curing tank at controlled laboratory conditions for a period of 28 days. The cured specimens were then tested under various experimental setups for assessing their mechanical properties. The details of the laboratory testing procedure are as follows.

2.2.1. Specimens for Compression and Split Tensile Tests

To evaluate the compressive and splitting tensile strength of SFRC, five concrete cylinders were prepared for each combination which resulted in a total of 140 cylinders having RSF as 1, 1.5, 2, 2.5, 3, 3.5, and 4% for both the chosen lengths. For comparison purposes, 20 control specimens for compressive and splitting tensile strength tests were also prepared with no steel fibers in them. The experimental setup made for the compressive strength test and splitting tensile strength test are shown in Figures 5(a) and 5(b).

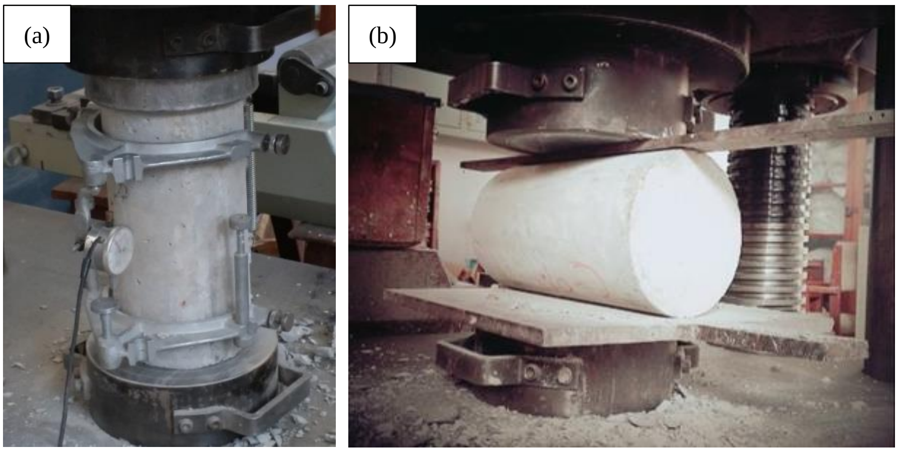

Figure 5. Experimental setup for a) compression and b) splitting tensile strength

2.2.2. Durability Test

In order to assess the durability performance of RSF reinforced concrete, 180 cylinders were prepared and immersed in the H_2SO_4 solution (having a concentration of 5%) for 56, 90, and 120 days. The performance of all concrete samples was evaluated in terms of loss in compressive strength, loss in mass, and loss in modulus of elasticity and was compared to control samples cured in water for 28 days. A similar procedure for durability assessment was also carried out by Joorabchian (2010) and Subathra (2018) [41, 42].

2.2.3. Modulus of Rupture Test

In this research study, the plain cement concrete beams were fabricated to assess the tensile strength of concrete in terms of modulus of rupture because the test setup for the direct tension test is difficult and the stress concentration in the gripping devices may affect the test results (H. Nilsson et al., 2004). For evaluation of modulus of rupture, a total of 75 SFRC beams having width, depth, and length dimensions of 10.16, 10.16, and 35.56 cm, respectively were constructed and tested under third point loading as per the ASTM standard procedure [43]. For both the RSF lengths i.e., 7.62 and 10.16 cm, five SFRC specimens comprising of varying proportions of steel fibers were prepared.

2.2.4. Flexural Strength Test

To examine the flexural behavior of SFRC, four beams with 145.40×288.60×2286 mm dimensions were constructed with a suitable combination of materials as described in section 2.1 and shown in Figure 6. The beams were designed as normal RC beams with a minimum steel reinforcement ratio as per the provision of the ACI 318 code [44]. It is important to mention that in the current study the minimum reinforcement was provided due to economic aspects and with the aim to judge the failure pattern at minimum loads as per the previous experience of the author [45]. All the beams were constructed and tested according to ASTM standard procedure [43]. The experiment procedure implemented for measuring flexure strength is shown in Figure 7. Three linear variable displacement transducers (LVDTs) were attached at the bottom face at the region of maximum bending moment of the SFRC beams and the load was applied with third point loading criteria. Two control beams designated as CB1 and CB2 were constructed without RSF while the other two steel fiber reinforced concrete beams designated as SFRB1 and SFRB2 were constructed with 2.5% content of RSF. The choice of selection of 2.5% dosage of RSF was made after careful assessment of the overall mechanical performance of SFRC reinforced with varying dosages and lengths of RSF.

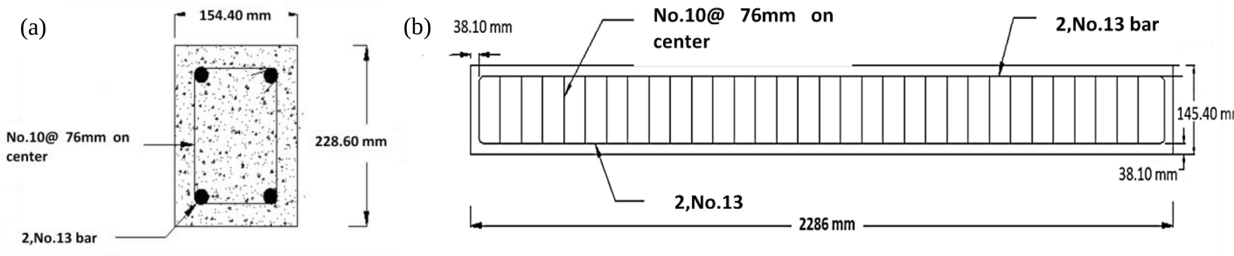

Figure 6. Beam dimensions a) x-section and b) long section

Figure 7. Loading setup and arrangements of linear variable displacement transducers (LVDTs) for full-scale recycled steel fiber reinforced concrete beam.

3. Results and Discussion

3.1. Compressive Strength

The compressive strength test results of control and RSF reinforced concrete beams are shown in Figure 8. Test results revealed that the percentages of RSF and their lengths, both affect the compressive strength of SFRC. For instance, with the use of 7.62 cm length of RSF, the compressive strength of concrete increased with the increase in the percentage of RSF. The maximum compressive strength was achieved at 2.5% dosage which was almost 26% greater than that of the control specimen. However, with the further increase of RSF dosage (beyond 3.0%) the compressive strength slightly decreased. Similar trends were also observed in the case of 10.16 cm length of RSF. The samples with 10.16 cm long RSF showed maximum compressive strength at 2% dosage, which was about 18% higher in comparison to the strength of the control specimen. However, with higher dosages of 10.16 cm RSF (greater than 3.0%), the compressive strength of SFRC was reduced. The decrease in the compressive strength of SFRC in the case of high dosage and greater length of RSF could be associated with the lower workability of concrete mix which resulted in a weak quality matrix with unwanted pores and cavities. The experimental findings of Micelli et al. (2019) [14] also indicated loss in a concrete slump of SFRC with the use of higher dosages of SF. Furthermore, the current experimental values are in close agreement with the previous works [27, 46].

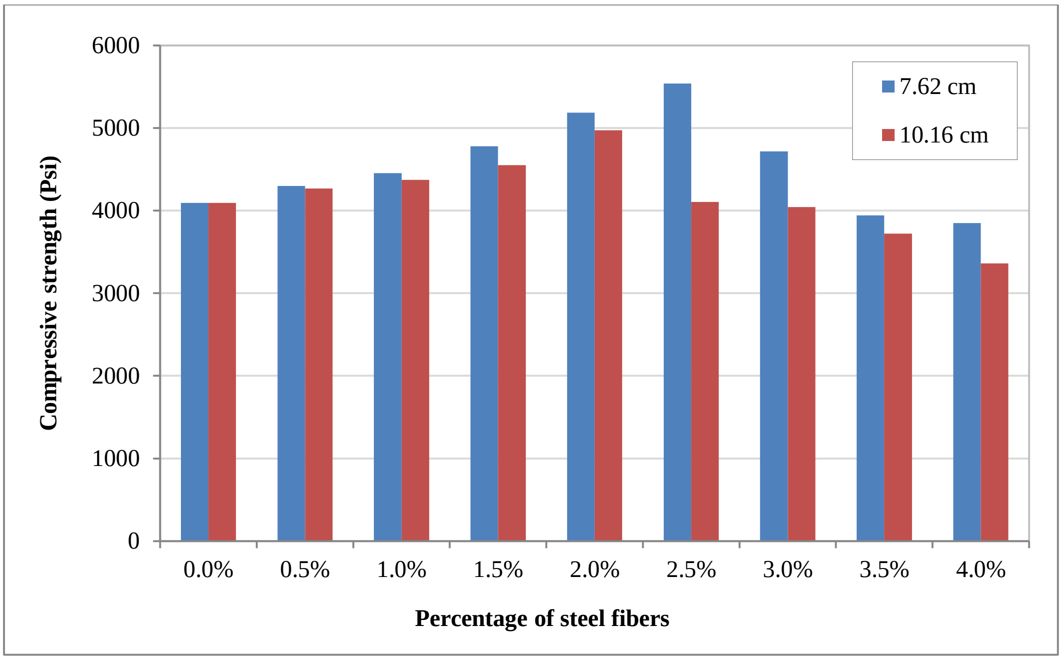

Figure 8. Compressive strength test results of control and SFRC containing various dosages of RSF

3.2. Stress-strain Relationship of Concrete

The stress-strain relation in compression plays an important role in the design and analysis of concrete elements and hence these were experimentally studied in the current study. Figure 9 and 10 shows the stress-strain relationship of control and SFRC cylinders. It can be seen that by introducing the RSF in concrete, the stiffness increased up to certain limits. The maximum stiffness was recorded at 2.5% dosage of RSF. By adding RSF more than 2.5 %, the SFRC behaved in a ductile manner which could be possibly due to the presence of voids resulted from the low workability of concrete mix and secondly due to the presence of a high amount of steel fibers which prevent the opening and propagation of cracks caused by the porous concrete mass. The greater values of strain at a high percentage of RSF showed that the steel fibers can play an effective role in a ductile manner which is evidence of bridging of fibers between the cracked inter-surfaces of concrete.

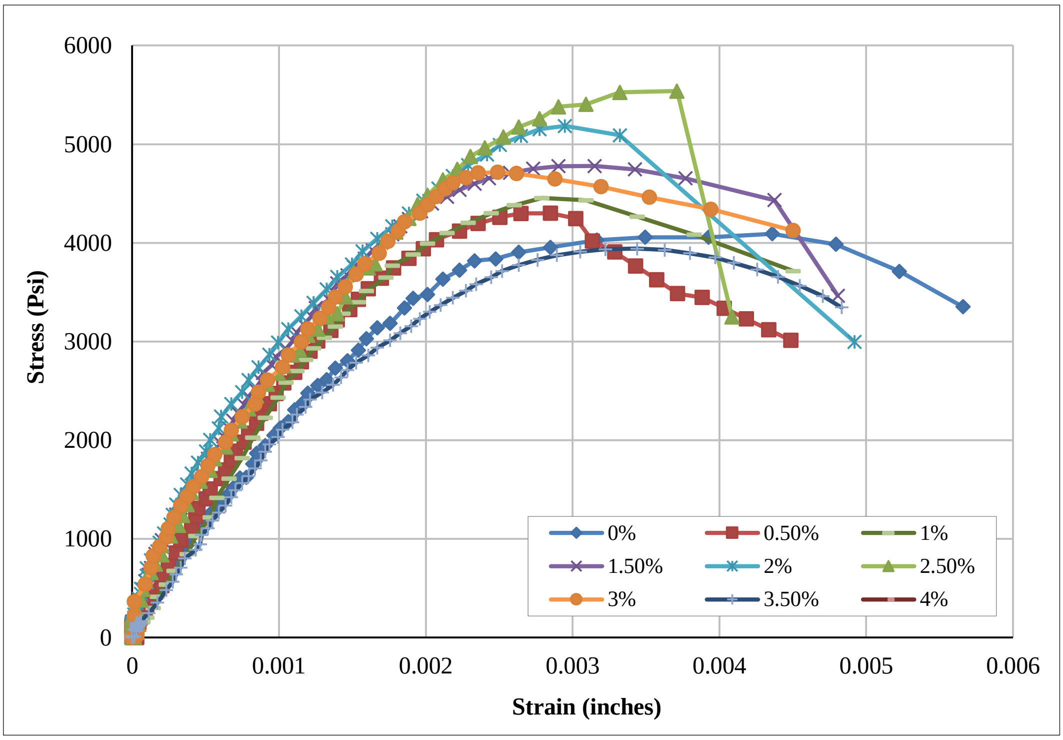

Figure 9. Stress-stain relationship of concrete with 7.62 cm long fibers

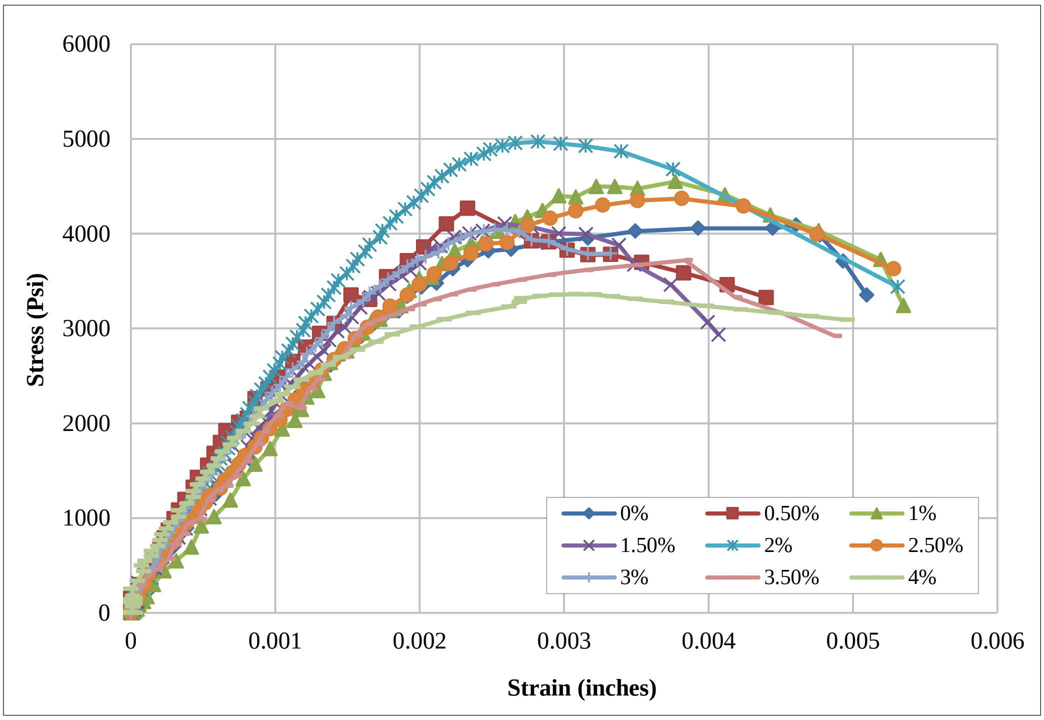

Figure 10. Stress-stain relationship of concrete with 10.16 cm long fibers

3.3. Splitting Tensile Test

The splitting tensile test was carried out to assess the performance of SFRC in terms of load-bearing capacity in tension. The tensile capacity of plain concrete is one of the important parameters for evaluating its mechanical performance. Figure 11 depicts the effect of varying dosages and lengths of RSF on the split tensile strength of SFRC. It is obvious from the test results that split tensile strength is enhanced with the increase of RSF dosage. The maximum splitting tensile strength was achieved with a 10.16 cm length and at 3.5% RSF dosage. Fibers with a length of 7.62 cm revealed lower split tensile strength as compared to that of the 10.16 cm length of RSF. The reduction in the splitting tensile strength beyond 3.5% dosage for both lengths of RSF is due to the porous microstructure resulted from the low workability of concrete. The maximum enhancement in the splitting tensile strength for 7.62 cm and 10.16 cm long RSF was about 58 and 70%, respectively. Overall, the splitting tensile capacity of SFRC significantly increased with the inclusion of RSF dosage in the range 0-3.5% for both lengths. Here, it could be said that, owing to the fiber reinforcing mechanism the RSF offered resistance to cracks widening and propagation as shown in Figure 12, and consequently lead to the improved tensile loading capacity of SFRC. Furthermore, the relation between splitting tensile strength test results and compressive strength test results of the current study is in the range of empirical equation i.e. 6 to $8\sqrt{f_c'}$ given by Darwin et al. (2016) [47].

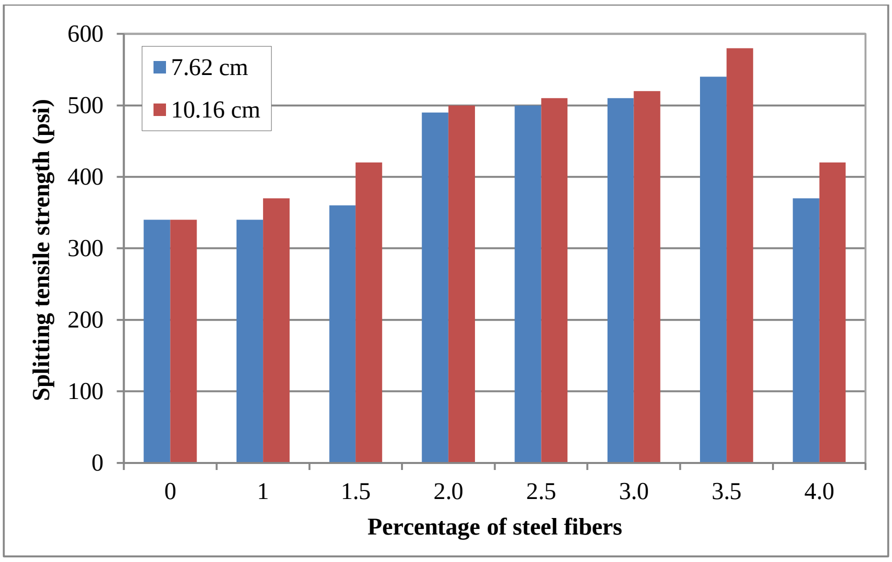

Figure 11. Splitting tensile strength of control and SFRC

Figure 12. Failure of concrete cylinders a) without RSF and b) with RSF

3.4. Modulus of Rupture Strength

Figure 13 shows the test results of beam specimens tested for modulus of rupture strength according to ASTM C78 [43]. The modulus of rupture (MOR) strength increased with an increase in the dosage of RSF for both the lengths of RSF up to 3.5% dosage. In comparison to the control specimen, the maximum percentage improvement in the MOR for 7.62 and 10.16 cm lengths of RSF was about 56 and 63%, respectively. It was observed that the dosage of RSF equal to 3.5% and more, made hurdles in the compaction of concrete mass which resulted in the reduction of MOR strength.

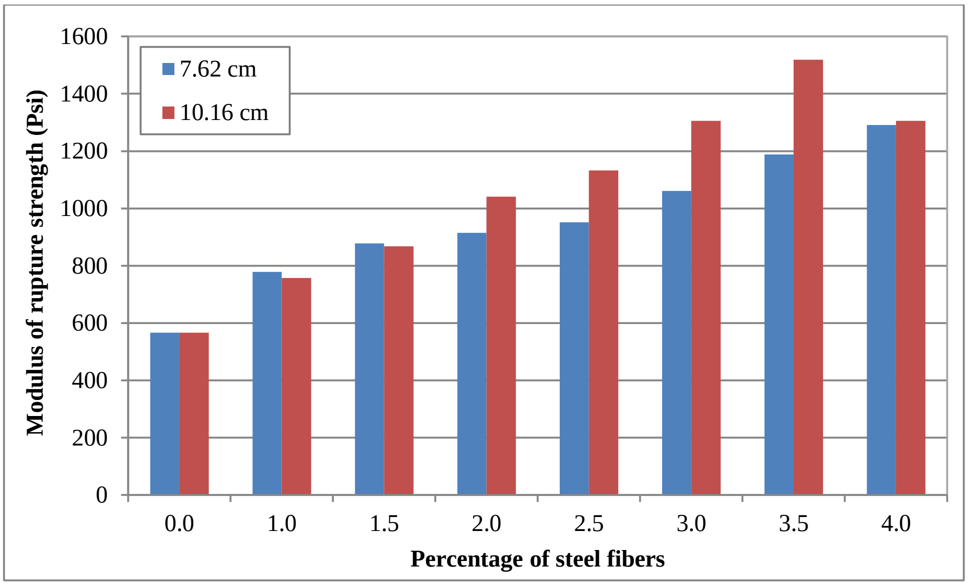

Figure 13. Modulus of rupture strength of control and RSF reinforced concrete

As shown in Figure 14 (a)-(b), the presence of RSF in concrete makes it capable to withstand larger cracks before the rupture which is majorly due to the fibers bridging action between the two fractured concrete parts and thereby reduce the chances of brittle failure. This bridging action also helps in mitigating the widening of cracks at post-yield status which results in the improved ultimate strength. Furthermore, at an RSF dosage of 3.5% and length of 10.16 cm, the flexural capacity was at its peak however the failure pattern was converted from flexural to shear failure. It can be seen in Figure 14 (c) that the 45-degree shear crack initiated in the maximum shear zone of the SFRC beam.

Figure 14. Failure of a) Plain concrete beam b) Beam with steel fibers less than 3.5% and c) Beam with steel fibers of 3.5%

3.5. Flexural Capacity

In order to assess the flexural loading capacity, full-scale concrete beams were tested in the laboratory for positive bending with third point loading criteria according to the ASTM C78 [43]. Keeping in view the workability issue at constant water to cement ratio (w/c) and the impact of RSF on the other mechanical properties of SFRC as evaluated previously, an optimum proportion of RSF i.e., 2.5% with a length of 7.62 cm was decided for the improvement of the flexural capacity of RC beams. The test results shown in Figure 15 reveal that the overall flexural performance of RSF reinforced concrete beams i.e., SFRCB1 and SFRCB2 are better than the control beam i.e., CB1 and CB2. The first crack in both SFRCB1 and SFRCB2 was a flexural crack initiated in the maximum flexural region at a load of 4.5 kips and 4.9 kips, respectively while in the control specimen the first crack was started at an average load of 3.8 kips. This shows that in the presence of RSF the elastic behavior of the beam is enhanced by more than 19 %. After the initiation of the first flexural crack, the SFRCB sustained about 10-12% more load as compared to that of CB. The addition of RSF in concrete increased the pre-cracking and post-cracking stiffness which could be due to the reduced width of cracks, and tensile stresses resisted by the RSF, comparable with the previous study [48]. The failure pattern of the SFRC beam and the crack arresting phenomenon is shown in Figure 16 (a)-(b). Overall, the average yield load of SFRCB was 20% greater than the CB thereby depicting good efficiency of fiber reinforced concrete beam at the post crack region. The SFRCB failed in a ductile manner with a uniform flexural pattern of cracks. The average increase in the ultimate load capacity was 15% more as compared to control beam specimens which were compatible with results reported by [48, 49]. Due to the presence of shear reinforcements and a low percentage of RSF, no shear failure was observed in the beams as otherwise seen in the modulus of rupture test.

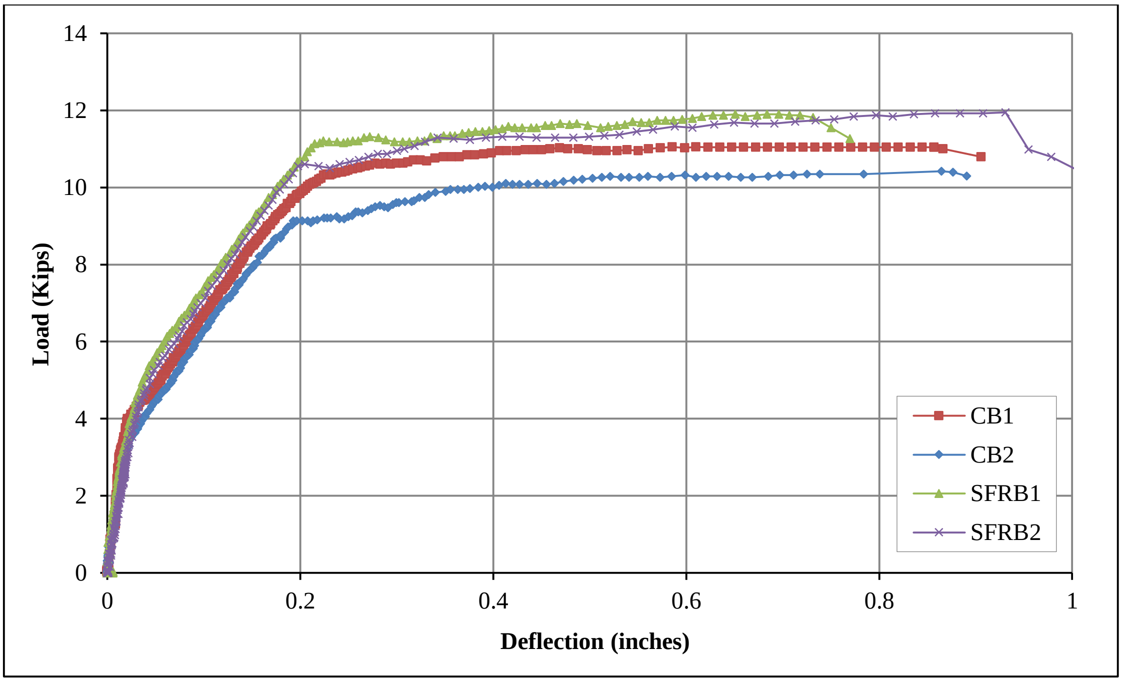

Figure 15. Load vs. deflection curve of control and SFRC beams

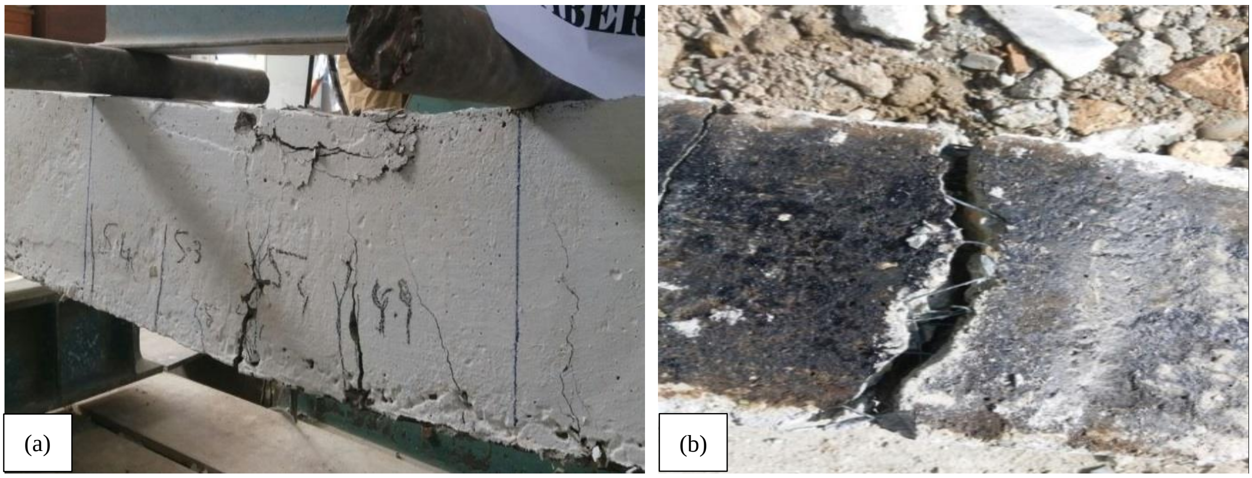

Figure 16. Failure of a) SFRC beam, b) crack bridging action of RSF at the tensile face of RC beam

3.6. Microstructure Observation

To examine the fiber-matrix interaction in the SFRC, the microstructure observation was made on a small concrete representative sample via the scanning electron microscope (SEM) which is one of the modern sophisticated technologies used for microstructural analysis by many researchers. The concrete with a high percentage of RSF, resulted in porous concrete as shown in Figure 17 (a). This indicates that the high percentage of RSF caused an increase in the volume of voids in concrete mass which eventually affected the mechanical properties of SFRC. This was also verified from the experimental results that the mechanical properties decreased when RSF percentage was increased beyond 2.5%. The arresting of cracks has been shown in Figure 17 (b) which supports the statement of the crack arresting mechanism by steel fibers. Furthermore, Figure 17 (c) shows the uniform dispersion of RSF which is the important parameter in the mechanical behavior of fibrous concrete. The interface interaction between steel fibers and concrete mass is shown in Figure 17 (d) which indicates excellent bonding between the RSF and the adjacent concrete mass.

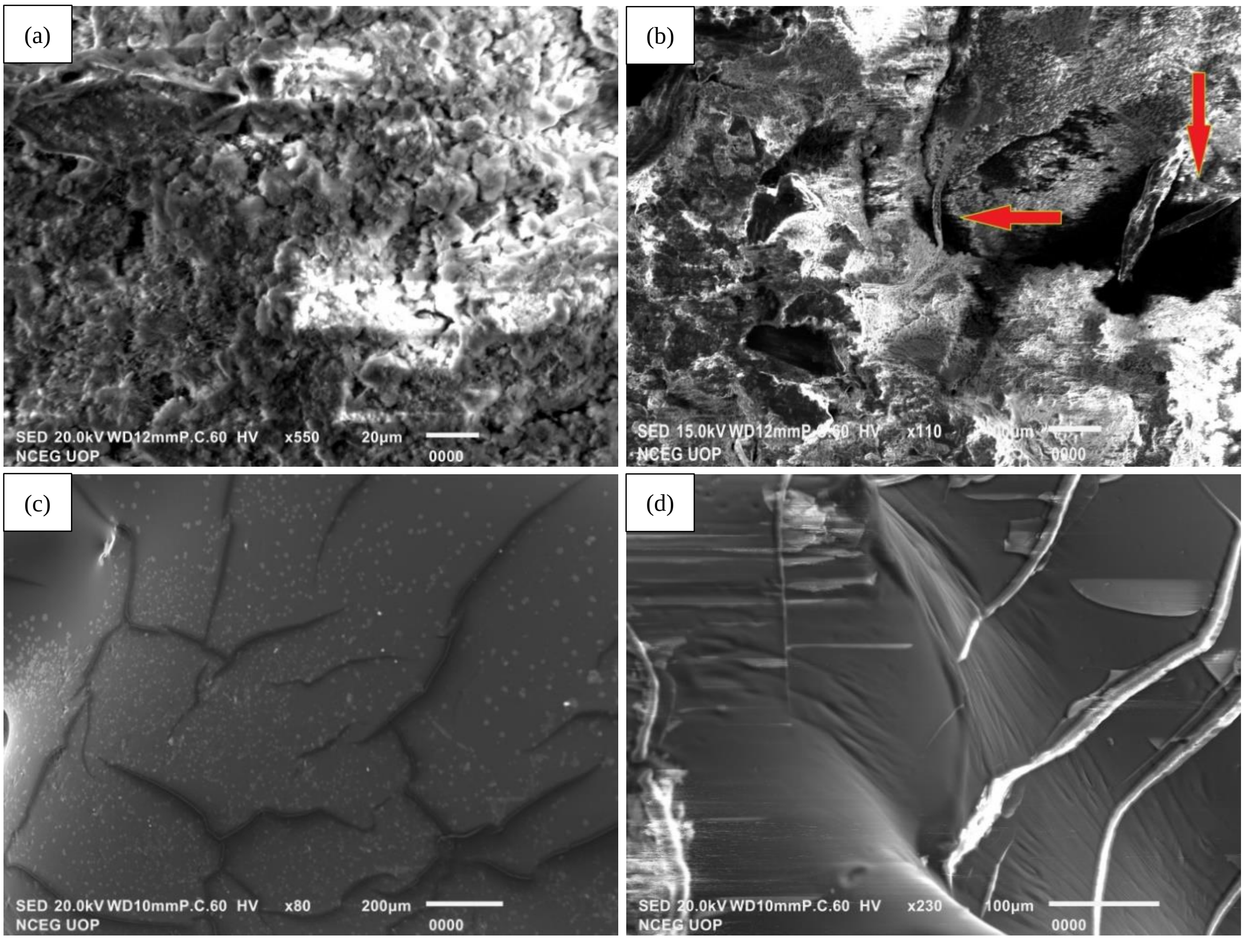

Figure 17. SEM micrographs of SFRC after testing

3.7. Durability Test

It is well known that concrete matrix composition is alkaline and its exposure to the acidic medium may cause the loss in its cohesiveness, increase in porosity, and loss of weight. In general, the acid attack critically affects the ability of the cement to bind together the aggregate of concrete mass [42]. In the current study, the durability of SFRC was assessed by evaluating the following physical and mechanical properties of concrete. For the assessment of durability, another batch of 180 concrete cylinders was cast and immersed in the acid solution. Out of 180 cylinders, 45 concrete cylindrical specimens were used as control specimens cured in water for 28 days while the remaining 135 concrete cylindrical specimens were tested after immersion in a 5% solution of H_2SO_4 for 56, 90, and 120 days. After exposure to an acidic environment, the mechanical properties of the concrete specimens were assessed as follows.

3.7.1. Loss in Compressive Strength

The loss in compressive strength of SFRC specimens for 7.62 cm and 10.16 cm lengths of steel fibers is shown in Figure 18 and Figure 19, respectively. The control and SFRC specimens were kept in the acid solution for three different periods of 56, 90, and 130 days after 28 days curing in water and were tested for compression after their completion of the curing period. The loss in compressive strength with 120 days immersion in acid solution was greater than the 56 and 90 days immersion. As expected, the compressive strength of control sample slightly decreased after exposure to the acid solution. However, in the case of fibrous concrete, a significant loss in the compressive strength was noticed in comparison to that of the control sample. It can be concluded that the presence of steel fibers in concrete has an adverse effect on the long-term compressive strength when exposed to acid attack which eventually decreases the durability of SFRC. The maximum loss in compressive strength of 56, 90, and 120 days immersion was 41, 53, and 71%, respectively for 7.62 cm length of steel fiber and 37, 52, and 56% for the 10.16 cm length of steel fibers. Comparing with control specimens the average loss in compressive strength was greater by 15, 13, and 23% for 7.62 cm length of steel fibers and 11, 12, and 13% for 10.16 cm length of steel fibers, respectively. The loss in compressive strength also depends upon the length of steel fibers. As shown in Figures 18 and 19, the losses in compressive strength with 7.62 cm length of steel fibers are greater as compared to the 10.16 cm length of steel fibers.

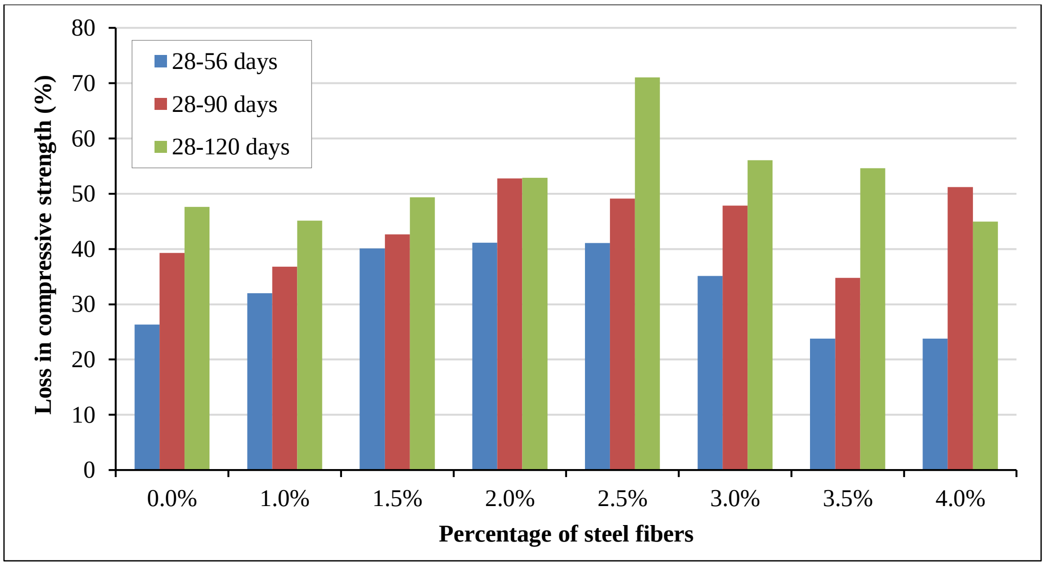

Figure 18. Loss in compressive strength of concrete with 7.62 cm length of RSF

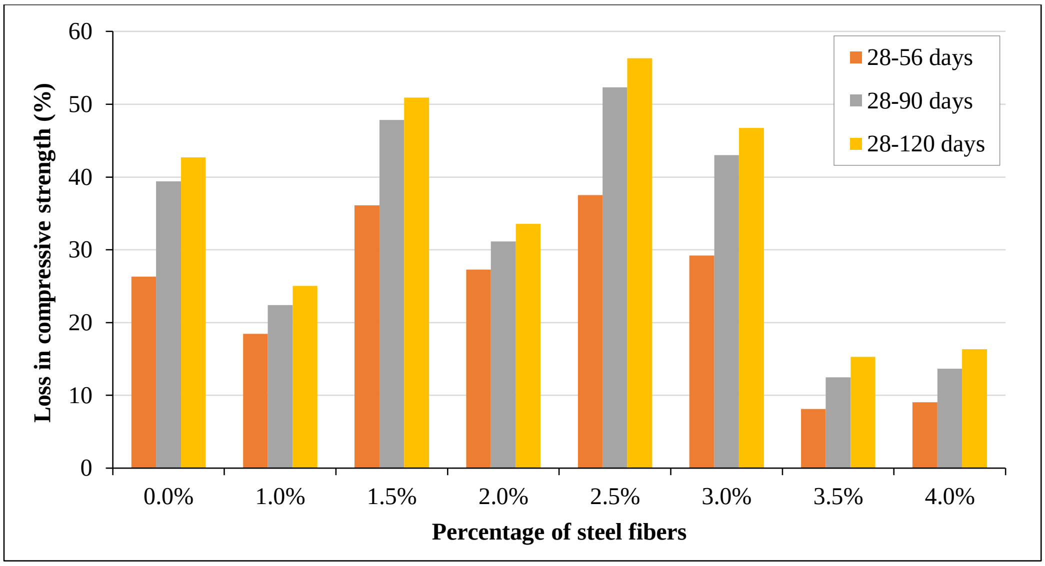

Figure 19. Loss in compressive strength of concrete with 10.16 cm length of RSF

3.7.2. Loss in Modulus of Elasticity

The modulus of elasticity of control and RSF reinforced concrete specimens is shown in Figure 20. Test results reveal that with an increase in the immersion time in acidic solution the percentage loss in the modulus of elasticity of concrete increased. The maximum loss in the modulus of elasticity was recorded for the 120 days immersion in acidic solution. Furthermore, it can be seen that the loss in the modulus of elasticity of RSF reinforced samples is greater than that of the control sample at all exposures. This could be attributed to the porous microstructure in the case of RSF reinforced concrete samples.

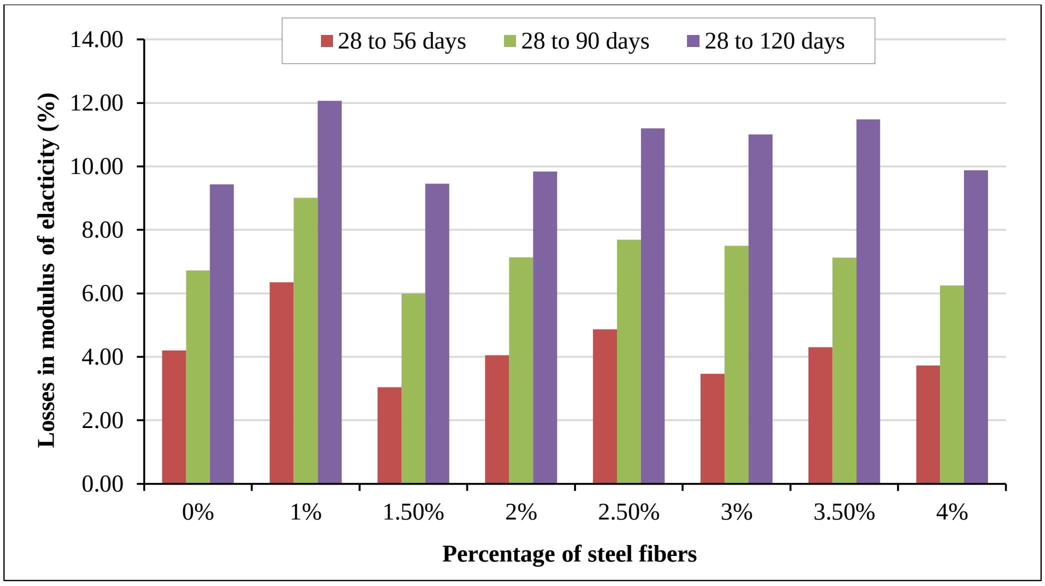

Figure 20. Loss in modulus of elasticity of concrete with 10.16 cm length of RSF

3.7.3. Loss in Mass

Figure 21 shows the variation in the mass of concrete after immersion in 5% of H_2SO_4 solution. The effect of length of RSF did not contribute much to the mass loss as like other properties of SFRC, therefore a single graph is shown for both the lengths of steel fibers. The mass at 56 days and 90 days immersion in acid solution increased as compared to the relative mass at 28 days curing in water. This can be due to the expansion of concrete volume as the reaction of acid take place with the alkali matter of concrete. Due to the increase in concrete volume, the weight/mass is eventually increased which is in close relation to the previous study by Joorabchian (2010) [41]. The samples did not lose much weight in the presence of RSF as they resist the propagation and widening of micro-cracks introduced by acid attack. In other words, minimizing the width and depth of cracks decreased the porosity of SFRC.

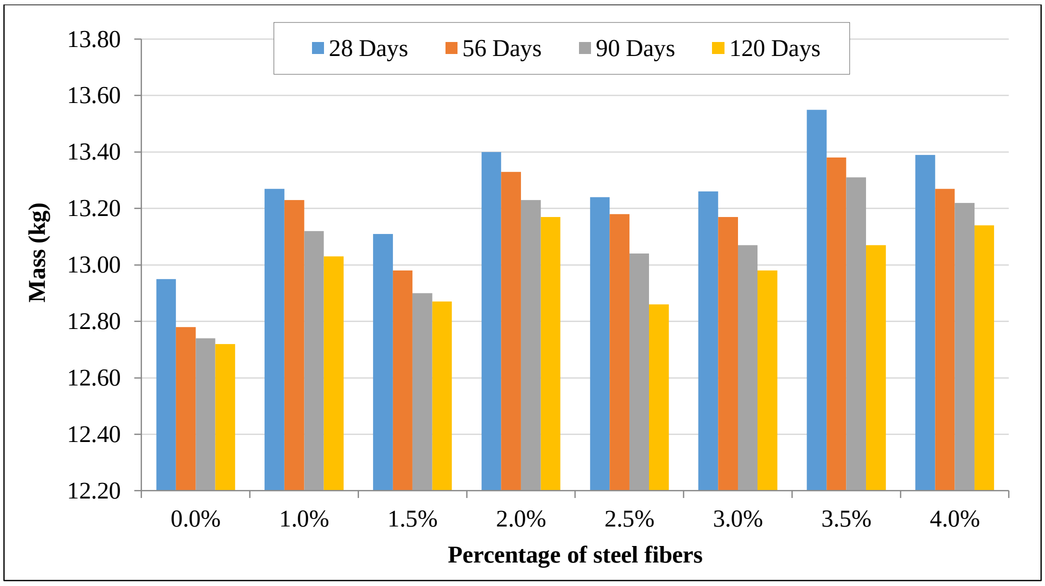

Figure 21. Loss in mass of control and SFRC concrete specimen

3.7.4. Visual Inspection of Specimen

Figure 22 shows the impression of corrosion on the surfaces of RSF reinforced concrete cylinders after taking off from the acid solution. Notably, the surface of cylinders showed a slight color change from grey to yellowish and surprisingly did not deteriorate and spoil when immersed in the acid solution for the specified time which indicates that the 5 % of H_2SO_4 solution did not affect the surface texture of SFRC. This implies that the SFRC could be utilized in building structures exposed to low and moderate acidic conditions. However, the durability of SFRC can further be enhanced by reducing the porosity of concrete by adding suitable admixtures namely silica fume, fly ash, etc. to improve the workability of concrete mix which will further enhance the mechanical properties of SFRC.

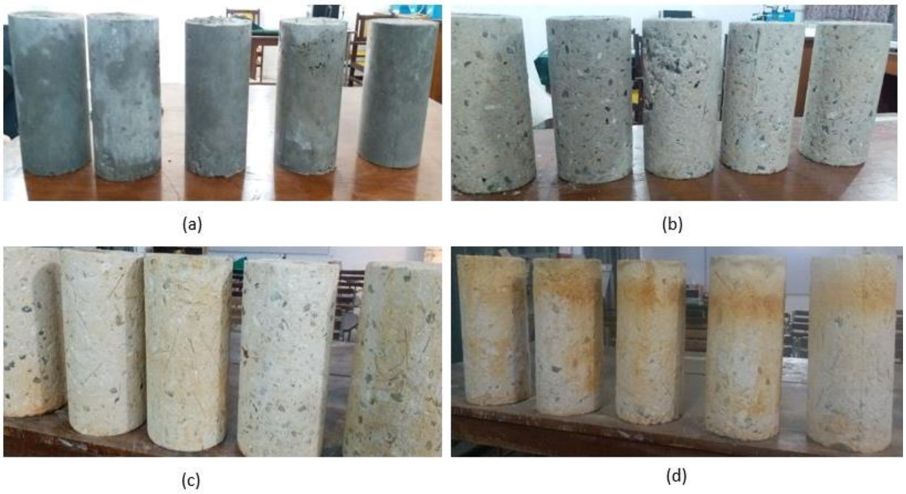

Figure 22. a) 28-days curing in water b) immersion in the acid solution for 56 days c) for 90 days d) and for 120 days

4. Conclusions

Based on the above detailed experimental findings of the current research study the following conclusion can be drawn.

- The lengths and percentages of RSF used in the current study varyingly affected the mechanical properties of SFRC;
- In the case of 7.62 cm length of RSF, the dosage of about 2.5% depicted a maximum increase of about 26% in the compressive strength of SFRC while the 10.16 cm long RSF showed a maximum improvement of about 18% in the compressive strength at 2% dosage;
- The splitting tensile strength of SFRC was significantly enhanced for both lengths of RSF. The maximum enhancements noted with 7.62 cm and 10.16 cm long RSF were about 58 and 70%, respectively;
- The full-scale reinforced concrete beams with conventional flexural and shear reinforcement, provided with 2.5% dosage and 7.62 cm length of fibers behaved elastically and enhanced its flexural capacity by 10-12%. The beams did not show shear failure cracks and failed in a ductile mode due to the remarkable crack bridging ability of RSF which prevented the opening and widening of micro and macro cracks;
- The incorporation of high dosages of RSF (above 2.5%) changed the failure mode of SFRC beams from flexure to shear which indicated the over-reinforced behavior and hence not recommended for structural concrete;
- From the SEM micrographs, it was noted that the RSF made excellent bonding with the adjacent host concrete matrix and helped in concrete crack resisting after the application of flexural loading;
- The durability test results showed a loss in both concrete compressive strength and modulus of elasticity with the increasing exposure of acidic medium. To protect concrete integrity and overcome a very minute chance of durability issue, the SFRC used in the current study is recommended only for structural elements which are not directly exposed to extreme weather effects;
- Based on the experimental evidence of this research work the RSF extracted from used tyres can be utilized in structural concrete with 7.62 cm length and 2.5% dosage by weight of concrete.

5. Nomenclature

ACI	American Concrete Institute	ASTM	American Society for Testing and Materials
CB	Control Beam	FRC	Fiber Reinforced Concrete
ISFRC	Industrial Steel Fiber Reinforced Concrete	LVDTs	Linear Variable Displacement Transducers
MOR	Modulus of Rupture	OPC	Ordinary Portland Cement
POPs	Persistent Organic Pollutants	RC	Reinforced Concrete
RSF	Recycled Steel Fiber	SEM	Scanning Electron Microscope
SF	Steel Fiber	SFRC	Steel Fiber Reinforced Concrete
SFRCB	Steel Fiber Reinforced Concrete Beam		

6. Declarations

6.1. Author Contributions

Conceptualization, A.G., B.A. and W.A.; methodology, A.G., B.A. and M.J.I.; validation, A.G., B.A. and W.A.; formal analysis, A.G., B.A. and M.J.I.; investigation, A.G., B.A. and M.J.I.; resources, A.G. and B.A.; data curation, A.G., M.J.I. and W.A.; writing—original draft preparation, A.G., M.J.I. and W.A.; writing—review and editing, A.G., W.A., K.S. and E.A.K.; visualization, A.G., K.S., M.H.J. and E.A.K.; supervision, A.G. and B.A.; project administration, A.G. and B.A.; funding acquisition, A.G. and B.A. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in article.

6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6.4. Conflicts of Interest

The authors declare no conflict of interest.

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