CONSTRUCTION
E-ISSN: 2785-8731
VOLUME 3, ISSUE 2, 2023, 300 – 307
DOI: https://doi.org/10.15282/construction.v3i2.10071

RESEARCH ARTICLE

Characterisation of Steel Fiber Reinforced Concrete: Ductility and Service Life

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ABSTRACT - Plain concrete is a brittle material with low tensile strain and strength capacities. Steel fiber reinforced concrete (SFRC) has gained prominence as an innovative construction material, offering improved tensile and flexural properties over conventional concrete. Singapore Standards, “SS 674: Fiber concrete- Design of fiber concrete structures” just launched recently to offers a comprehensive structure for enhancing comprehension of Fiber-Reinforced Concrete. This study presents a comprehensive characterization of SFRC, focusing on both its mechanical properties particularly residual strength. Following this, a series of experimental works are conducted to assess the residual tensile strength under flexural loading behavior of SFRC specimens. Examining the tensile strength and residual strength of SFRC to assess its material strength and behaviour after being subjected to a load will help engineers comprehend the material's strengths and weaknesses. At 40 kg/m^3 fibers content shows an increase of residual strength with a strain hardening behaviour observed as compared to the 20 kg/m^3 and 30 kg/m^3 fibers content. In conclusion, this study offers a holistic characterisation of SFRC, encompassing mechanical properties with higher residual strength. The outcomes provide scientific understanding and practical insights of SFRC for engineers and practitioners seeking to optimise the use of SFRC to enhance structural longevity and reduce maintenance costs.

ARTICLE HISTORY

Received	:	12th June 2023
Revised	:	15th Oct. 2023
Accepted	:	06th Dec. 2023
Published	:	21st Dec. 2023

KEYWORDS
Flexural bending,
Steel fibers,
First crack,
Residual strength,
Resilient and sustainable,

1.0 INTRODUCTION

Steel fibers is the most common fiber used for concrete industry namely of Steel Fiber Reinforced Concrete (SFRC) with advanced engineering properties. With the increasing complexity of underground construction projects, the requirements of many projects may beyond the capabilities of basic reinforced concrete [1]. The need for diverse types of concrete in construction industry has grown due to the varying demands of contemporary projects. SFRC is an alternative to normal reinforced concrete that enhances the strength of weaker aspects of concrete, such as tensile strength or brittleness, by including fibers [2]. Concrete is a composite material consisting of cement, water, coarse particles, and fine aggregates. It possesses high compressive strength but relatively low tensile strength. Concrete is widely recognised as a brittle substance that has a limited ability to withstand stretching forces. In order to address the low tensile strength of concrete, the commonly used approach is to include steel reinforcement bars into the concrete. These bars are responsible for bearing the tensile stresses that the concrete face undergoes when it is subjected to tension [3].

Extensive research has been conducted during the 20th century on conventional reinforced concrete, establishing it as a highly utilised and comprehensively studied material in the building sector. The introduction of steel fibers plays a pivotal role in fortifying the tensile strength of SFRC. Traditional concrete, when subjected to tension, is prone to the initiation and propagation of cracks. However, the steel fibers in SFRC act as a network of micro-reinforcements, strategically bridging these cracks and effectively distributing tensile stresses across the material. This transformative mechanism not only prevents uncontrolled crack propagation but also significantly improves the concrete's ability to withstand tension. Moreover, SFRC offers the added advantage of potentially reducing or even eliminating the need for traditional steel rebars in concrete structures. This innovation addresses challenges like rebar congestion and limited spacing for traditional reinforcements commonly encountered during the construction phase. By mitigating these issues, SFRC presents a more efficient and time-saving approach to construction. In response to these challenges, fiber-reinforced concrete, such as SFRC, emerges as a solution to streamline construction processes while maintaining structural integrity. By mitigating issues like rebar congestion and addressing limited spacing for traditional reinforcements, SFRC offers a more efficient and time-saving approach to construction, making it a promising choice for contemporary construction projects [1]. As the construction industry continues to evolve, the utilization of SFRC presents an opportunity to enhance construction efficiency, reduce labor-intensive practices, and meet the diverse demands of modern infrastructure projects. The utilisation of fiber reinforced concrete seeks to address the limitations of time and labor-intensive construction while maintaining the structural integrity of the building [1]. This study aims to bridge this gap by systematically characterising SFRC and investigating its residual strength under flexural loads.

This paper is organized as follows: Section 2 presents development of SFRC. Section 3 explains the overall methology which includes research design, testing dan data analysis. Section 4 discusses the experimental results and analysis. Section 5 concludes the findings of this study.

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2.0 LITERATURE REVIEW

Steel fiber-reinforced concrete (SFRC) is a composite material consisting of a cementitious matrix incorporating with various types of fibers. These fibers, which can be made of materials such as steel, glass, synthetic, or natural fibers, are added to the concrete mix to enhance its mechanical properties [3]. The addition of fibers to the concrete mix improves the tensile, flexural, and impact strength of the concrete. Depending on the type and dosage of fibers used, FRC can exhibit enhanced toughness, crack resistance, and durability compared to traditional concrete reinforced concrete. Short and discrete threads are incorporated into the concrete mixture, similar to other components, and are evenly distributed throughout the structure, creating discontinuous fibers that are randomly oriented [4]. The stochastic arrangement of fibers is highly efficient in managing cracks in concrete, thereby enhancing the ductility of elements reinforced with fibers. Various types of fibers, such as glass, synthetic, natural, and steel fibers, are utilised in the sector. The predominant fiber utilised is steel fiber. SFRC has been widely utilised in various projects in underground tunneling construction such railway, highway and sewage system [5]. The primary purpose of incorporating SFRC is to enhance crack control, a material characteristic in which SFRC outperforms conventional reinforced concrete. The utilisation of SFRC has been limited to projects solely focused on crack control concerns and has not been widely employed for structural design purposes. The building sector has not completely capitalised on the advantages of SFRC, which include simplified construction processes, enhanced crack management, and reduced labour requirements [2,5]. One of the primary factors contributing to this is the absence of documented guidelines for designing SFRC. The limited understanding of the material characteristics of SFRC impedes its application in projects due to the uncertainty surrounding its structural behaviour post-construction [6].

Poor dispersion of fibers can adversely affect the concrete performance [7]. The dispersion of fibers in concrete is a significant challenge in the field of concrete technology [8]. Steel fibers are commonly added to concrete mixes to enhance the material's mechanical properties, such as tensile strength, toughness, and ductility [9]. Various methods have been developed to check the dispersion of steel fibers in concrete, including adjusting the matrix rheological properties, flow induction, and the wall effect. Vibrational mixing has also been studied as a method to improve the dispersion uniformity and performance of steel fiber reinforced lightweight aggregate concrete. Additionally, the use of silane as an admixture has been shown to improve the dispersion of steel fibers in steel-fiber-reinforced mortar [10]. The dispersion of steel fibers in concrete has been extensively studied, with a scientifically designed mixture shown to reduce the cost of steel fiber dosage and improve fiber dispersion [11]. The orientation of fibers in concrete can be improved by up to 80% through flow induction and the wall effect, which increases the bending strength, tensile strength, and toughness of concrete matrix. Further characterization of fiber dispersion in three-dimensional space is required, and factors such as aggregate or reinforcement must be considered in theoretical simulation results on fiber orientation. The use of hooked steel fibers has been shown to display a strain hardening load-displacement behavior with substantially enhanced ductility in concrete fiber reinforced cementitious composites [5,6].

Established standards developed by RILEM (International Union of Laboratories and Experts in Construction Materials, Systems, and Structures) in 2003 have played a pivotal role in advancing the understanding and application of SFRC [12]. This has facilitated the study and involves a detailed analysis of crack development and propagation, typically assessed by calculating the Crack Mouth Opening Displacement (CMOD) after the first crack behavior. CMOD is a critical parameter that provides insights into the post-cracking behavior of concrete, including its ability to maintain load-carrying capacity and resist further cracking [13]. Currently, there is no existing Eurocode available for reference in the design of SFRC. Singapore standard SS 674 was published in 2021 with great anticipation of the stakeholders in construction industry [14]. The standard provides a classification on the residual strength obtained from CMOD 0.5 mm, 1.5 mm, 2.5 mm and 3.5 mm respectively, utilising a material for structural design without a designated code poses a significant risk, thus making it imperative for the engineer to prioritise their comprehension of the material in order to effectively design the structure. This study is to provide a comprehensive analysis of the material properties of SFRC and its residual strength under flexural loading, as specified by the SS 674 standard [14].

3.0 METHODOLOGY

3.1 Research Design

Ordinary Portland Cement (OPC, CEM I 42.5N), fine and coarse aggregates, steel fibers, chemical admixtures were used as the concrete constituent materials. Two types of chemical admixtures were used namely; polycarboxylate-based superplasticizer and retarder. The results are summarized in Table 1, the particle grading distribution curves of fine and coarse aggregates are shown in Figure 1. The selected type of steel fibers steel fiber of length (L) 60, diameter (D) 0.75mm with aspect ratio (L/D) of 80 provided by SCAMCEM has been used in this mix. The concrete mix design and characteristic of steel fiber is shown in Table 2.

Table 1. Properties of Ordinary Portland Cement

Properties	OPC
Specific gravity	3.15
Specific surface area (m^2/kg)	365
SiO_2 (%)	21.0
Al_2O_3 (%)	5.3
Fe_2O_3 (%)	3.4
CaO (%)	65.0
MgO (%)	1.5
SO_3 (%)	0.3
Na_2O (%)	0.5
K_2O (%)	0.3

Table 2. Mix proportions of the SFRC

Materials	Volume
OPC	380 kg/m^3
Water	165 kg/m^3
Coarse Aggregate	965 $kg/\ m^3$
Fine Aggregate	820 $kg/\ m^3$
Superplasticizer	1365 ml/m^3
Retarder	1705 ml/m^3
Fiber 1	20 $kg/m^{3,}$
Fiber 2	30 $kg/m^{3,}$
Fiber 3	40 kg/m^3

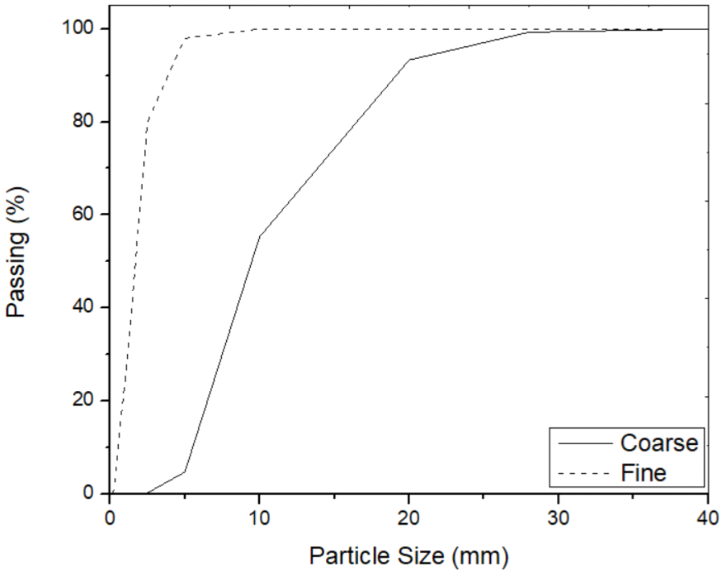

Figure 1. Particle size distribution of fine and coarse aggregates

3.2 Experimental Testing

Each casting consists three 150x150x550 mm beams. After beam casting, the samples were compacted using a vibrating rod. The flexural strength under bending of the beams was tested at 28 days of age, and an LVDT device was used to measure the crack mouth opening displacement (CMOD). The specific properties of fiber concrete that are required for the design of fiber-reinforced concrete include the characteristic residual flexural (tensile) strengths, $f_{R,1}$, $f_{R,3}$ and $f_{R,4}$, at a crack-mouth-opening displacement of 0.5, 2.5 and 3.5 mm respectively (see Fig. 2), determined from beam tests according to BS EN 14651 at the age of 28 days. The characteristic residual strengths can be obtained from the following equation,

$$f_{R,ik} = f_{R,im} – k_{n\sigma} \ (i = 1, 2, 3, 4) \tag{1}$$

where $f_{R,ik}$ is the characteristic value, $f_{R,im}$ is the mean value, σ is the standard deviation, and kn is a statistical factor depending on the number of specimens, n in the test series, as given in SS 674:2021 [14]

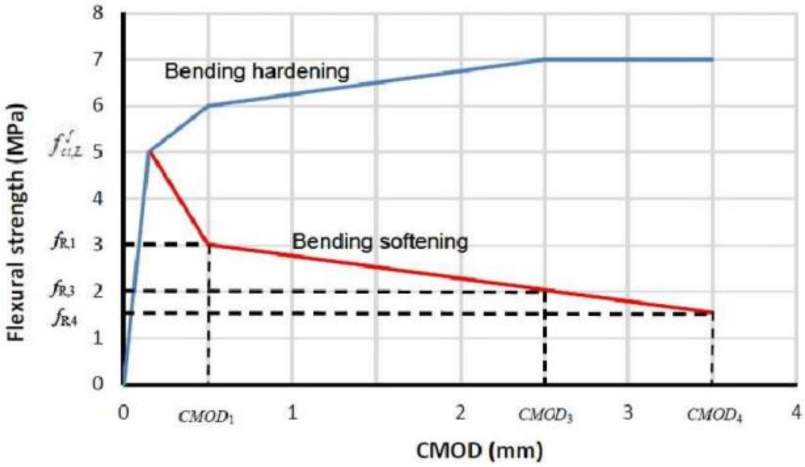

Figure 2. Relation between flexural strengths and CMOD adapted from BS EN 14651 [13]

4.0 EXPERIMENTAL RESULTS AND ANALYSIS

This study examines the performance of SFRC under flexural bending conditions by using the given equation (1). Table 3 showed the characteristic residual strengths, $f_{R,1}$, $f_{R,3}$ and $f_{R,4}$, at a CMOD of 0.5, 2.5 and 3.5 mm respectively. The results showed that increasing the dosage from 20 kg/m^3 to 30 kg/m^3 resulted in a decrease in residual flexural tensile strength. The absence of a well-dispersed network of fibers (in Fig.7) across the concrete matrix in beam with 30 kg/m^3 diminishes the bridging effect that steel fibers provide, which is crucial for maintaining residual strength after initial cracking. This poor dispersion of fibers due to agglomeration of fibers, leading to localized areas with reduced fiber reinforcement in the concrete [2]. Theoretically, a concrete mix's flexural tensile strength can be improved by adding more steel fibers to it. Nevertheless, there is an ideal dose for getting the intended results because the relationship between the amount of steel fiber and the characteristics of concrete is not linear. Variations in the volume content of fibers can cause problems with workability, uneven dispersion of fibers within the concrete mix, and fiber balling or agglomeration [2,16]. The presence of strain softening in all samples, with dosages of 20 kg/m^3 and 30 kg/m^3, indicates an uneven distribution of steel fibers inside the samples. The decrease in residual strength as shown in Figure 3 and Figure 4, after the first cracks all the beams experienced bending softening behaviour. a decrease in load-carrying capacity due to the gradual propagation and widening of cracks. The softening behavior is associated with the gradual pull-out of steel fibers from the matrix and the development of larger cracks [16]. This might be ascribed to insufficient steel fibers during the casting procedure, where the poor workability of the SFRC potentially leading to inadequate flow of SFRC.

The dosage of 40 kg/m^3 demonstrates a superior residual strength as compared to the dosages of 20 kg/m^3 and 30 kg/m^3. As shown in Figure 5, the beams with 40 kg/m^3 fibers after the first crack, SFRC demonstrates strain hardening [3,17]. This means that, even after cracking, the material continues to deform and carry additional load, resulting in an increase in tensile strain. Furthermore, two samples exhibited a strain hardening response when subjected to a dose of 40 kg/m^3. As shown in Figure 8, the presence of steel fibers helps in controlling crack widths and distributing tensile stresses, contributing to improved residual strength the SFRC exhibits enhanced post-cracking behavior compared to plain concrete, attributed to the bridging and reinforcing effect of steel fibers.

As shown in Figure 6 and Figure 7, an uneven distribution of fibers, resulting in localised areas that lack adequate reinforcement. This uneven distribution increases vulnerability to cracking and decreases flexural strength. The beam specimen with a larger fiber content (shown in Fig. 8) exhibits enhanced bridging capabilities and achieves a greater residual strength. The enhancements in crack management and material integrity resulted in improved performance as compared to a lower concentration of fibers. The strain hardening effect illustrates the uniform distribution of fibers within the concrete and their complete engagement during fracture, leading to an increased residual flexural tensile strength of the specimen. It is desirable for all SFRC materials to have a strain hardening response, as this is regarded as the most favourable type of reaction. The predominant failure mechanisms observed in most samples can be ascribed to fiber pull-out. This phenomenon arises when the bond between the fiber and concrete is inadequate to withstand the exerted pull-out force, leading to ineffective engagement of the fibers. The load-deflection graphs of all tested materials consistently exhibit a significant amount of ductility following the initial crack formation in the tension zone of the material [18]. The fibers play a crucial role in providing a "bridging" function. The steel fibers function as dispersed reinforcement inside the concrete matrix, effectively impeding the formation and spread of cracks [19,20]. The initial fracture occurs when the applied force surpasses the tensile strength of the concrete, resulting in the commencement of cracks. Within the context of SFRC, the steel fibers effectively hinder the spread of these cracks, hence enhancing the concrete's performance after cracking.

Table 3. Mix proportions of the designated concretes

Volume of fiber, kg/m^3	Specimens	$f_{R,1}$ (MPa)	$f_{R,3}$ (MPa)	$f_{R,4}$ (MPa)
20	Beam 1	2.59	2.77	2.75
20	Beam 2	2.32	2.16	2.18
20	Beam 3	2.28	2.92	2.92
30	Beam 1	1.84	1.62	1.60
30	Beam 2	1.82	1.81	1.80
30	Beam 3	2.06	1.88	1.88
40	Beam 1	2.51	4.61	4.61
40	Beam 2	2.74	4.71	4.73
40	Beam 3	3.30	4.31	4.31

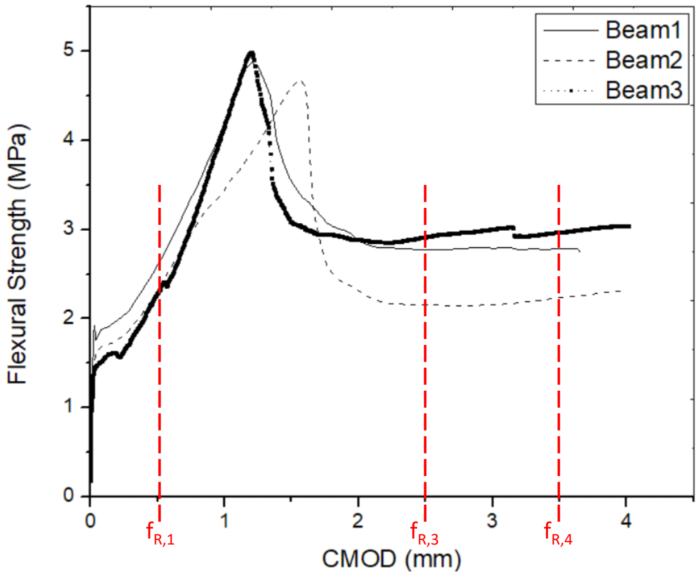

Figure 3. SFRC beams with 20 kg/m^3 under flexural testing

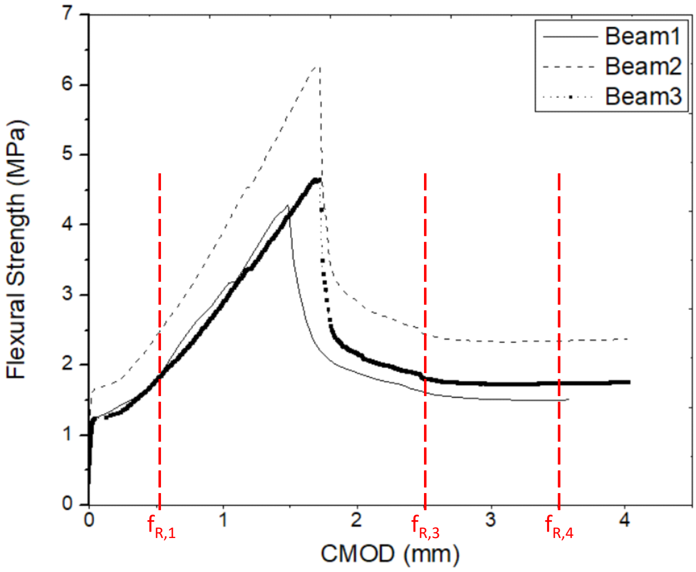

Figure 4. SFRC beams with 30 kg/m^3 under flexural testing

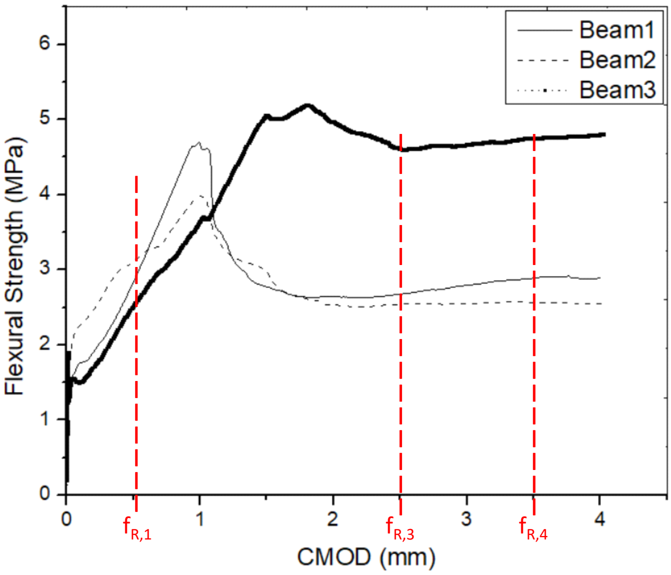

Figure 5. SFRC beams with 40 kg/m^3 under flexural testing

Figure 6. CMOD crack of the beam specimen with 20 kg/m^3

Figure 7. CMOD crack of the beam specimen with 30 kg/m^3

Figure 8. CMOD crack of the beam specimen with 40 kg/m^3

5.0 CONCLUSION

The residual strength of flexural beam was significantly stronger reaction observed in the 40 kg/m^3 dosage SFRC, in comparison to the 20 kg/m^3 or 30 kg/m^3 dosage. The predominant failure mode observed in the majority of samples is fiber pull-out, when the fibers fail by being pulled out from the surrounding material. The most prominent specimens exhibiting strain hardening behaviour did not exhibit failure, as the fibers continued to maintain the integrity of the concrete beam even after the test was terminated. This suggests that the strength of the link between the matrix and steel fibers is crucial. As long as the fibers remain securely embedded in the matrix, it can tolerate significant tensile stress.

The optimal dose for the ongoing project's structure remains undetermined due to the inconclusive results and the unsatisfactory quality of the test samples. Therefore, additional deliberations regarding enhancing the quality and attaining more definitive outcomes will occur prior to determining the appropriate dosage to be employed. Moreover, the analysis of remaining strength following the emergence of early fractures showcased the ability of SFRC to uphold structural soundness and withstand additional deterioration. The study highlights the efficacy of steel fibers in strengthening both the flexural strength of concrete and its ability to prevent fracture initiation and improve residual strength. The ability of SFRC to delay and control crack formation is a key advantage, enhancing the overall structural performance and durability of the material.

6.0 AUTHOR CONTRIBUTIONS

The experiments were performed and analysed by B.J.W.Teh and Y.Y.Too under the guidance and supervision of Y.J. Kum and J.L.G.Lim

7.0 FUNDING

The support provided by Universiti Kebangsaan Malaysia in the form of a research grant vote number GGPM-2023-078 is highly appreciated.

8.0 DATA AVAILABILITY STATEMENT

The data used to support the findings of this study are included within the article.

9.0 ACKNOWLEDGEMENT

The authors would like to thank the Real Point Sdn Bhd for providing the chemical admixtures and SIT Construction materials laboratory for providing the testing facilities.

10.0 CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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