Istraživanja i projektovanja za privredu
ISSN 1451-4117
DOI:10.5937/jaes0-47765
www.engineeringscience.rs

publishing

Journal of Applied Engineering Science
Vol. 22, No. 3, 2024
Original Scientific Paper
Paper number: 22(2024)3, 1220, 554-563

MECHANICAL ANALYSIS ON TEST SAMPLES MADE IN CONCRETE REINFORCED WITH STEEL FIBERS

Saieth Baudilio Chaves Pabón*, Miguel Angel Ospina García, Miguel Angel Bonet León

Nueva Granada Military University, Faculty of Distance Education, Cajicá, Cundinamarca, Colombia
saieth.chaves@unimilitar.edu.co

Steel fibers have been used for improving the behavior of structural concrete elements for a long time ago. This paper shows the main results from the flexural test of steel fiber reinforced concrete beams, that is to say, flexural strength and toughness. The results were compared with those from the flexural test of reinforced concrete beams with steel bars and plain concrete beams. Steel fiber did not increase the flexural strength and toughness of beams when compare with reinforced beams with steel bars but it does improve the behavior of steel fiber reinforced concrete beams for failure control and gradual mechanics which allows caution about upcoming collapse.

Keywords: flexural strength, toughness, steel fiber, steel bar

1 INTRODUCTION

Concrete, being a brittle material, has low tensile strength and low deformation capacity, as a result, the mechanical behavior of concrete is directly influenced by crack propagation. Concrete in service can exhibit failure through cracks that develop due to brittleness [1]. To improve the properties of concrete, such as low stress and low deformation capacity, a number of techniques have been developed such as reinforcing with steel bars and concrete reinforced with metallic fibers.

Reinforcing bar concrete is mainly based on the bonding mechanism between steel bars and concrete. The characteristics of the steel-concrete interface are influenced by a wide range of parameters related to steel and concrete, in addition to the interactions between them. This diversity of aspects, detailed in the study by Carvalho et al, in heterogeneities throughout the steel-concrete interaction influencing, among other aspects, the steel-concrete adhesion [2].

In the same way, the Fiber concrete, which is defined as concrete containing randomly oriented dispersed fibers [3], has been used to reinforce cementitious material since ancient times. The properties of the concrete matrix and fibers greatly influence the mechanical behavior and performance of this type of concrete. The properties of major influence on the behavior of this material include fiber stiffness, bond between fiber and concrete matrix, fiber concentration, fiber geometry, fiber orientation, fiber distribution and fiber aspect ratio [4].

Currently, there have been several studies where steel fibres have been included in hydraulic concrete, among them, the study by Zeibek and company [5], who developed an experimental study to explore the effect of fibre content on the fresh and hardened state of concrete, and observed an improvement in the mechanical properties of concrete with the increase of the volume fraction of steel fibre. In other studies, steel fibres were used to amplify the mechanical properties of concrete with excellent results on its mechanical properties [6, 7]. In research by [8], in order to obtain the desired good concrete quality, they replaced the steel reinforcement by steel fibres partially or completely. In studies of [9, 10, 11, 12, 13], industrial steel fibres, recycled steel fibres or hybrid fibres (industrial and recycled) were used as reinforcement. In other research [14, 15, 16], concrete was made with recycled aggregates, which generally have properties of lower density and higher brittleness compared to natural aggregates, attributed to residual mortar on the surface, and additionally the mechanical properties and durability of recycled aggregate concrete are generally inferior to those of natural aggregate concrete, and although efforts were devoted to improve the physical properties by physical or chemical treatments, limitations emerged. However, this material has limitations, similar to normal concrete.

All of the above, this served to generate this theme and was developed in a quantitative research project, with experimental work aims initially to characterize and differentiate reinforcing bars and metallic fibers according to the available literature; once this review stage is performed, experimental analyses will be developed on concrete specimens with reinforcing bars and metallic fibers to identify the main differences of these mixtures in terms of mechanical properties, allowing to demonstrate that steel fibers have acceptable mechanical behavior.

2 METHODOLOGY

The experimental phase of this study consisted of the measurement of characteristic parameters of the materials from tests at the Materials Laboratory of the Universidad Militar Nueva Granada. For definition of the mechanical parameters, the tests of tensile strength of steel under the terms of ASTM A-706 [17], compressive strength of concrete [18] and flexural strength of reinforced with concrete steel fibers [19] and reinforced with concrete steel bars [20].

Table 1 shows the experimental program carried out, which includes the implemented standards describing the procedure and the number of samples to obtain the results. It should be clarified that the results shown in this study correspond to an average of 5 samples per test performed.

Table 1. Matrix of laboratory tests; SC* plain concrete, SFRC* concrete reinforced with steel fibers, SBRC** concrete reinforced with steel bars.

Test	Standard NTC (ASTM)	Type of specimen	Number of steel samples		
Tensile in structural rebars	NTC 3353 y NTC 2289 (ASTM A 706 y ASTM A 370)	60 cm long steel bar	3		
TESTING OF PLAIN CONCRETE AND REINFORCED CONCRETE			CS*	SFRC**	SBRC**
Compressive strength of concrete specimens	NTC 673 (ASTMC - 39)	Cylindrical 15 cm x 30 cm	3	3	N/A
Bending in beams loaded in middle thirds	NTC 2871 (ASTM - C 1609)	Beams 15 cm x 15 cm x 60 cm	2	2	N/A
		Beams 10 cm x 13 cm x 90 cm	N/A	2	2

2.1 Test configuration

Figure 1 shows the configuration of the tests performed in this study. Figure 1.a. shows the configuration of the tension tests to determine the design parameters for the steel used. In this test, electrical deformation meters were used to obtain the unit stress-strain curve shown in Figure 1. Figure 1.b. shows the test setup described in ASTM C - 39 to determine the strength of concrete with cylindrical specimens of 30 cm in height and 15 cm in diameter.

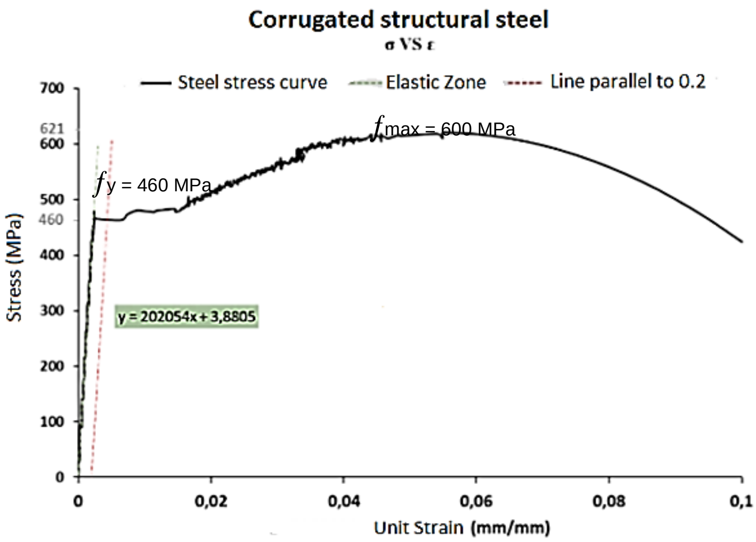

Fig. 1. Stress vs. strain curve for steel used as reinforcement

Fig. 2. Laboratory test configuration

Finally, Figure 1.c shows the assembly carried out for the flexural tests on beams with their corresponding instrumentation. It should be clarified that some of the beams had structural steel reinforcement; for this reason, conventional beams with a cross section of 15 cm x 15 cm were not used, but rather beams with a cross-section of 10 cm x 13 cm and a length of 90 cm were built, which allowed the concrete to have enough space to cover all the spaces. However, the flexural tests of all beams were performed with the same loading conditions and span spacing as shown in Figure 5.

2.2 Flexural design of rebar-reinforced concrete beams

2.2.1 Design method

In order to predict the maximum flexural strength of the beams used in this study, the type of failure and pre- and post-test behavior, the elastic design method [21], was used, without using safety factors, strength reduction or increased loads.

2.2.2 Design conditions and limitations

- The loading conditions were given by the provisions of ASTM C 1609. In these standards, the flexural strength test is performed with a load applied in the middle thirds of a span between single supports of 450 mm as shown in Figure 5.
- There are certain limitations unique to the equipment and materials used in this investigation. The maximum load that can be applied by the MTS landmark equipment of the Structures Laboratory of the Universidad Militar Nueva Granada is 85 kN.
- Additionally, the maximum cross-section dimensions of the beams were 15 cm base by 15 cm height. The maximum diameter of the bars and the strength of the concrete is given by the maximum load experienced by the beams and their limitations as mentioned above.

2.2.3 Available materials

The materials used for the aggregates are river pebbles and sand, while the cement is general-purpose gray cement. The forms used are made of dense, non-absorbent, and waterproofed wood to avoid altering the water/cement ratio of the concrete. The characteristics and dosages of the materials are listed in Table 2 and illustrated in Figure 3. For the design, the specified compressive strength (f'c) was set at a minimum of 17 MPa, by the minimum structural concrete requirements in Colombia.

Table 2. Materials used in the research.

Material	Description	Dosage x m^3 Concrete
Coarse aggregate	River gravel TM 3/4" and TMN 1/2".	792,2 kg
Fine aggregate	Well graded river sand	861,4 kg
Cement	general use GU	302,3 kg
Corrugated structural steel	Bars #3 as longitudinal and transverse reinforcement	0,996 kg / m
Steel fiber	Lenght 35 mm, L/d 65 fy = 1200 MPa	25 kg
standard formliners	Beams 5 cm × 15 cm × 60 cm metalic cylinder specimens de 15 cm ×30 cm	5 beams and 5 Cylinders
Pre-fabricated formliners	Formliners wood 10 × 13 × 90 cm	5 formliners

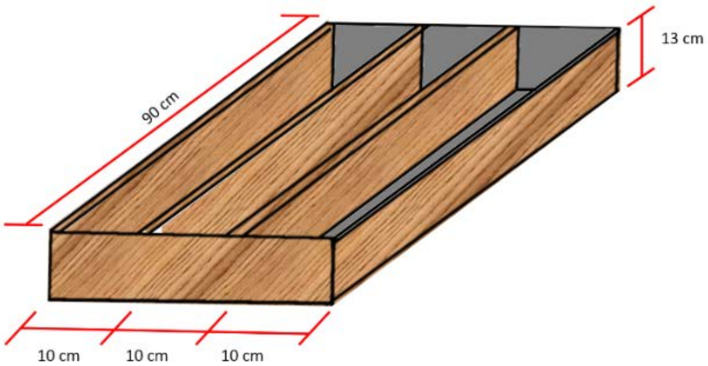

Fig. 3. Wooden formwork for rectangular section beams

2.2.4 Estimation of the maximum load

To calculate the maximum design load, the following initial conditions were taken into account: 1) the minimum amount of reinforcing steel that could be used is As = 143 mm^2, which can be supplied by two 9,5 mm diameter #3 bars (see Table 2). 2) According to the NSR - 10 standard, the value of the working steel amount was obtained by obtaining 2 bars #3 in the section for a reinforcement area of 143 mm^2 [22]. The amount of steel (ρ) was obtained with the following equation:

$$\rho = \frac{As}{b*d} \qquad (1)$$

Where:

As= area of reinforcing steel, mm^2

b = base of beam section, mm

d = height minus steel overlay, mm (40 mm overlay)

$$\rho = \frac{143mm^2}{100\ mm*90\ mm} = 0{,}016 \qquad (2)$$

2.2.5 Concrete mix design criteria

Different theoretical concrete strengths were evaluated to estimate the value of the maximum load experienced by the reinforced beams that met the above-mentioned criteria. Therefore, the following hypothesis was established: since the neutral axis of the beam with the greatest depth is at 45 mm and the resistant moment must be equal to the acting moment, for a concrete with a compressive strength (f'c) of 10 MPa; a steel with (f'u) of 621 MPa and a steel amount of 0,016, applying the elasticity theory, a load of 44,8 kN is obtained, which corresponds to 52% of the equipment's capacity.

2.3 Design review

Design verification corresponds to the estimation of the theoretical maximum load in order to meet the conditions and limitations presented in section 2.1.4 [19].

2.3.1 Exploded view of the beam

Loading conditions. The maximum load applied with the equipment was 44.8 kN under the conditions shown in Figure 4.

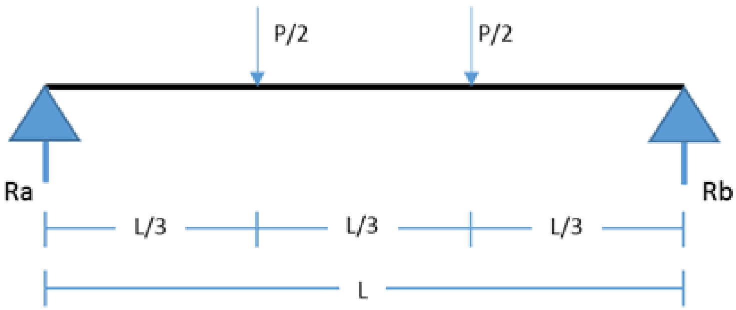

Fig. 4. Free body diagram - Loading conditions for bending test.

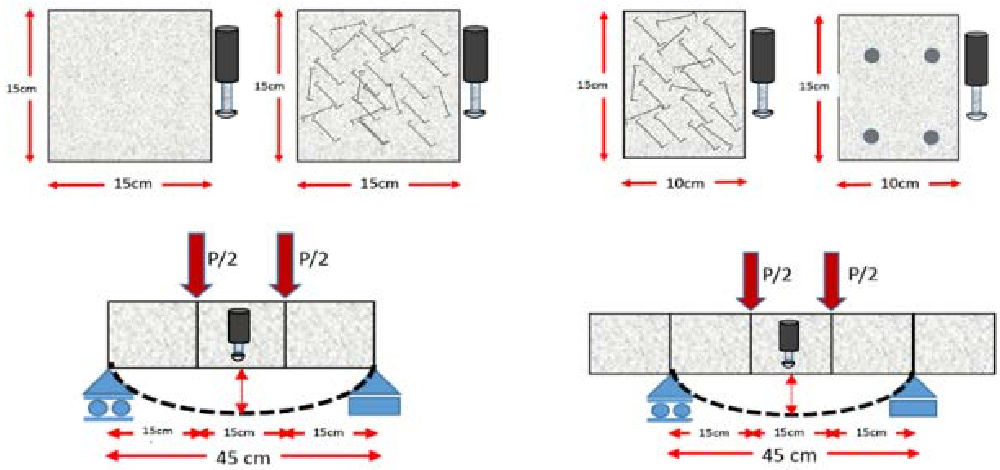

Fig. 5. Test conditions for conventional beams and structural beams

The dimensions and loading conditions required by the ASTM C 1609 standard are summarized in Figure 4 a and b. and Figure 3.

Force diagrams and applicable equations. The shear force diagram for the beams is shown in figure 6.

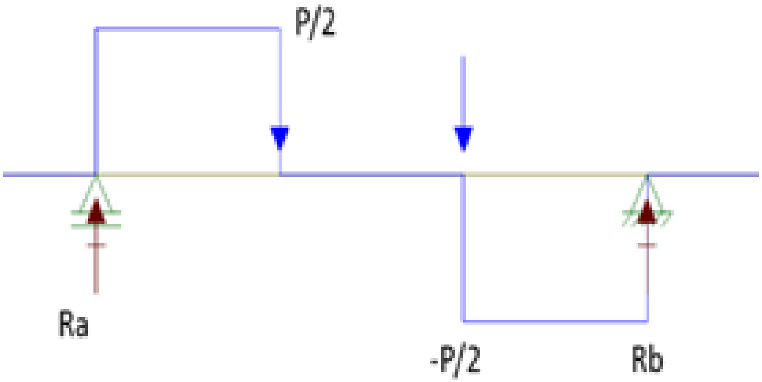

Fig. 6. Shear force diagram. Source: FTO software

According to this shear diagram the shear force (V) with force summation and equilibrium condition can be calculated:

$$\sum F_Y = R_A - p + R_B \tag{3}$$

$$V_{máx} = R_B = \frac{p*\frac{L}{2}}{L} = \frac{p}{2} \tag{4}$$

Figure 7 shows the bending moment diagram.

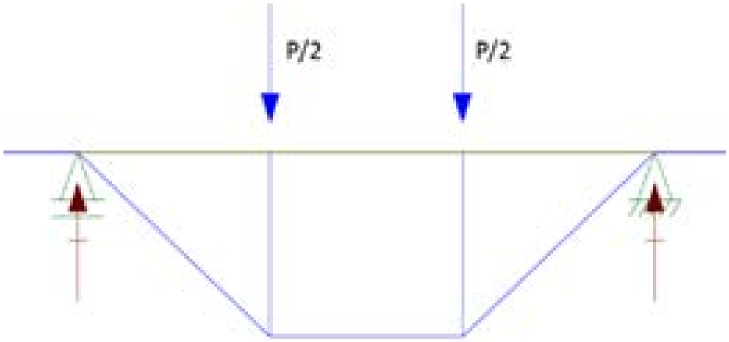

Fig. 7. Moment diagram. Source: FTOOL software

The maximum bending moment (Mmax) is obtained from the sum of moments as shown below:

$$\sum M_A = -\left(\frac{P}{2} * \frac{L}{3}\right) - \left(\frac{p}{2} * \frac{2L}{3}\right) + R_B * L = 0 \tag{5}$$

$$M_{máx} = \frac{P_{max}*450mm}{6} \tag{6}$$

2.3.2 Material constants and section dimensions

The beam cross-section dimensions are shown in Illustration 7 based on the criteria in section 2.2.1 [19].

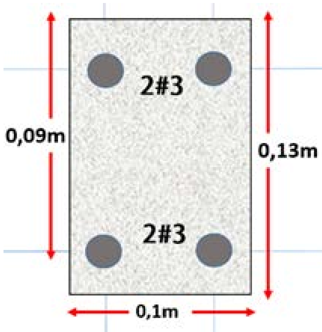

Fig. 8. Design beam dimensions

Materials constant for design. Based on laboratory results and experimental properties of materials, in Table 3.

Table 3. Design properties of the materials.

Steel area		
Parameter	Value	SI Units
Bar Designation	3	N/A
Nominal diameter	9.5	mm
Nominal Area	71	mm^2
No. of bars used	2	unit
Total steel area	143	mm^2
Rectangular beam section		
Base of beam b	100	mm
Beam height h	130	mm
Design distance d	90	mm
Modulus of elasticity of concrete (Ec)	16	GPa
Modulus of elasticity of steel (Es)	202	GPa
Results		
Theoretical failure	44.8	kN

Based on the theory of elasticity and applying equation 4 of the book “Estructuras de concreto 1” [21], which establishes that the balanced amount can be obtained with the following equation:

$$\rho_{bal} = \frac{K}{2r} \tag{7}$$

Where: K = depth constant of neutral axis (dimensionless).

R = f'c/fy ratio (dimensionless).

The calculated balanced amount is $\rho_{bal} = 0.0018$, because $\rho > \rho_{bal}$, the beam was considered over-strengthened, which is consistent with the type of failure observed in the flexural test specimens.

3 EXPERIMENTAL RESULTS AND DISCUSSION

The results obtained from the mechanical characterization tests of the materials used and the mechanical characterization tests are presented below. Additionally, an analysis is made based on the reference literature.

3.1 Compressive test results

Compressive strength tests were performed on the plain concrete and steel fiber concrete mixtures and the results are shown in Table 4.

Table 4. Compressive strength results of the mixes.

	SC			SFRC	
	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2
Maximum load (kN)	206	194,0	193,0	92,1	87,2
Compressive Strength (MPa)	11,2	10,6	10,5	11,4	10,8
Compressive Strength (PSI)	1625	1530	1516	1656	1568

The results of the compression tests indicated that the average strength values increased by 3.73% with the addition of steel fibers (see Table 4). This observation aligns with the findings of Aslani & Nejadi, who reported that the strength of concrete reinforced with steel fibers can increase between 0% and 15% when using a dosage of 25 kg/m^3 [23]. The tests were conducted after 7 days of concrete curing due to laboratory availability constraints.

3.2 Flexural behavior

With respect to flexural strength, Table 5 shows the results for the three types of mixes and figure 9 shows the average strengths as a function of the type of mix.

According to Table 5, the SBRC beams presented higher flexural strength, approximately three times more than the strength of the SFRC beams and about four times more than the strength of the SC beams.

Table 5. Results of flexural strength and modulus of rupture (MOF)

Condition	SC		SFRC		SBRC	
Load Maximum (kN)	20,4	20,5	14,22	15,5	45,2	42,7
Modulus of rupture (MPa)	2,43	2,61	3,61	4,05	11,43	10,92
MR Average (MPa)	2,52		3,83		11,18	
Tenacity (T_{150})	0.67		39.03		88.7	

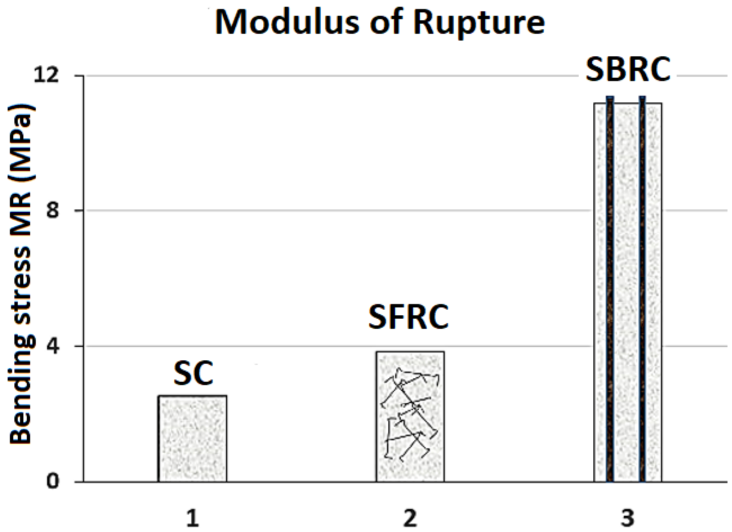

Fig. 9. Flexural strength or modulus of rupture.

Similarly, Table 5 and figure 10 show the toughness also obtained from the flexural tests of the beams. From the values presented in this table and the graphical representation, the effect of the conventional steel reinforcement on the energy absorption of the concrete can be observed. The toughness obtained in the SBRC beam was approximately 130 times the concrete toughness, while the addition of steel fibers to the SC allowed the increase of the toughness up to 50 times the SC toughness.

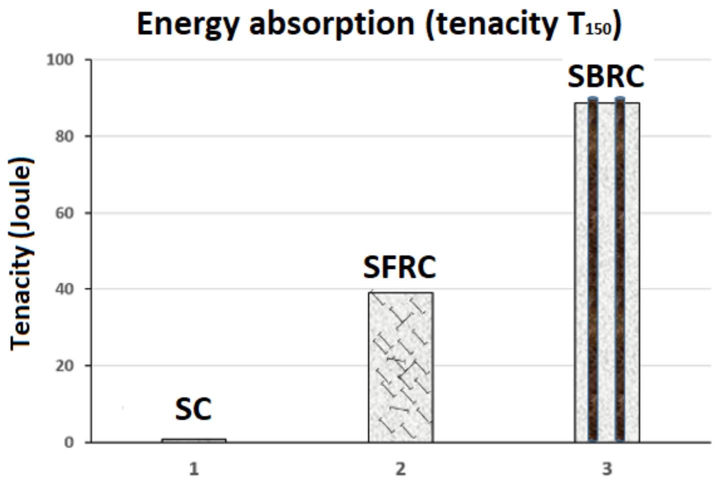

Fig. 10. Toughness of SC, SFRC and SBRC beams.

Figure 11 shows the bending stress-strain curve measured in the beams. This graph shows that in spite of the evident increase in the tenacity of the SBRC, the SFRC has a more stable behavior after reaching its maximum strength, which differs from the behavior obtained for the SBRC where abrupt jumps in the curve are observed, corresponding to abrupt detachments of the concrete.

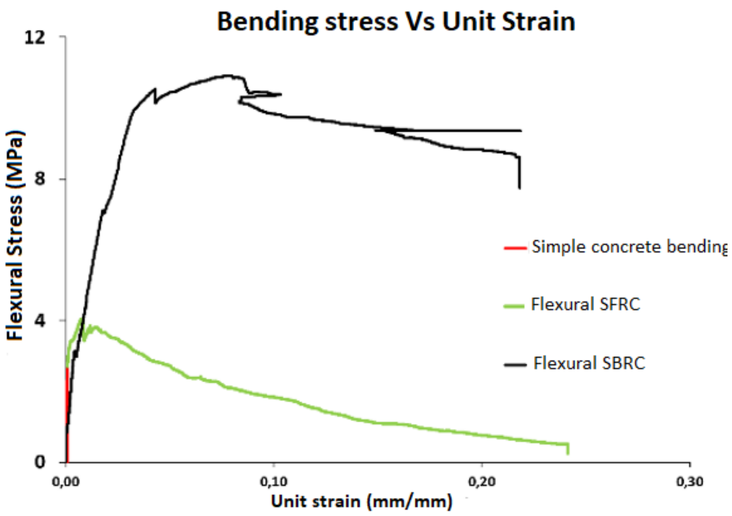

Fig. 11. Flexural stress-strain curves.

In general, SBRC exhibited higher bending capacity because the steel bars are positioned in the zone where the element is subjected to bending. Therefore, the bars bear most of the bending stresses of the element. In contrast, the steel fibers in SFRC are randomly distributed throughout the concrete matrix, and their influence on the deflection zone of the element is indirect, resulting in lower bending strength. As shown in Figure 11, the SBRC mix is the strongest in terms of flexural strength because the reinforcement is located precisely where flexural stress occurs, making this sample stronger than the SFRC. However, the sample reinforced with fibers has the advantage of being evenly distributed throughout the section, which might improve its performance under dynamic loads. Finally, concrete must be reinforced because plain concrete lacks plasticity and does not exhibit linear elastic behavior, making reinforced concrete necessary.

3.3 Flexural failure type

In the samples evaluated, cracking was adequate, showing a ductile behavior in the beams, as shown in Figure 12; this type of failure starts with a crack in the lower part of the beam where the maximum bending moment occurs. The crack is gradually transferred to the upper face, preventing the failure of the element.

Fig. 12. Type of failure observed in the SFRC beams

On the other hand, the SBRC beams presented a compression failure, as can be seen in Figure 13. In this illustration it can be seen that the cracks in the upper part of the beam are larger than the lower cracks indicating that the stresses were concentrated in compression due to the fact that the beam was over-reinforced. This is also evident in the right image of figure 13 where it can be seen that the top bars suffered excessive buckling allowing the concrete to detach precipitously.

Fig. 13. Failure observed in beams

4 CONCLUSIONS

In this study, the main results of flexural tests performed on SC, SFRC and SBRC beams were presented. The results were compared in order to create more confidence in the use of steel fiber reinforced concrete (SFRC) for civil constructions. The main conclusions of this study are presented below:

- It was concluded that steel fibers do not replace conventional steel reinforcement since the flexural strength the SFRC beams was on average 29% of the flexural strength of SBRC beams. However, steel fibers could be an excellent complement to concrete reinforcement with bars, since they would allow a better behavior of the concrete under dynamic and cyclic loads.
- Although the toughness of the beams with SFRC was 43% of the toughness of the beams with SBRC it was evident that the behavior of the beams with SFRC was more stable because there were no abrupt jumps in the stress-deflection curve caused by concrete spalling, contrary to the concrete with steel bars, where there are jumps in the curve, which causes more serious damage due to concrete spalling.
- The use of steel fibers contributes to avoid excessive concrete spalling because the steel is present in almost all the concrete matrix, and occupies spaces where structural steel is not present.
- The failure mode of the SFRC beams showed that the cracking of the elements was gradual and controlled, which is an advantage because it allows predicting the failure of the element.
- The inclusion of steel fibers in the concrete also slightly increased the initial flexural stiffness of the beams compared to the stiffness of the SBRC beams.

As a recommendation for further studies, the design of sub-reinforced beams needs to be performed to analyze if the failure has such a difference in the stress vs. deflection curves. It is also important to observe the behavior of a concrete using the two materials, because the amounts of steel bars will decrease.

5 ACKNOWLEDGMENT

The authors mention that this paper is a product of the research project with code INV-DIS-3767, of the year 2022, whose title is "Estudio del comportamiento mecánico y físico del concreto con adición de bioprecipitación de carbonato de calcio ($CaCO_3$) mediante el empleo de cepas bacterianas ", and financed by the Universidad Militar Nueva Granada through the Vicerrectoría de Investigaciones.

6 REFERENCES

[1] Harmsen, T. (2005). *Diseño de estructuras de concreto armado*. Fondo Editorial Pontificia Universidad Católica de Perú.

[2] Carvalho, E., Ferreira, E., Cunha, J., Rodríguez, C., & Maia, N. (2017). Experimental investigation of steel-concrete bond for thin reinforcing bars. *Latin American Journal of Solids and Structures, 14*(11), 1932-1951. https://doi.org/10.1590/1679-78254116

[3] Hameed, R., Turatsinze, A., Duprat, F., & Sellier, A. (2009). Metallic fiber reinforced concrete: Effect of fiber aspect ratio on the flexural properties. *Journal of Engineering and Applied Sciences, 5*(4), 67-72. https://www.semanticscholar.org/paper/METALLIC-FIBER-REINFORCED-CONCRETE%3A-EFFECT-OF-FIBER-Hameed-Turatsinze/ab10a1b64e19e18112ed074acd8febc7578d908e

[4] Li, B., Zhang, W., Xie, H., & Yang, X. (2018). Effects of fiber type, volume fraction, and aspect ratio on the flexural and acoustic emission behaviors of steel fiber reinforced concrete. *Construction and Building Materials, 181*, 474-486. https://doi.org/10.1016/j.conbuildmat.2018.06.065

[5] Zeybek, Ö., Gül, M., & Koçak, Y. (2022). Performance evaluation of fiber-reinforced concrete produced with steel fibers extracted from waste tire. *Frontiers in Materials, 9*. https://doi.org/10.3389/fmats.2022.1057128

[6] Anil, N. (2018). Mechanical properties of steel fiber reinforced self-compacting concrete. *International Journal of Engineering Technologies, 4*, 33-40. https://doi.org/10.19072/ijet.340259

[7] Jabir, H. A., Mohamed, A., & Ali, S. (2020). Experimental tests and reliability analysis of the cracking impact resistance of UHPFRC. *Fibers, 8*(12), 74. https://doi.org/10.3390/fib8120074

[8] Rashid, K., & Balouch, N. (2017). Influence of steel fibers extracted from waste tires on shear behavior of reinforced concrete beams. *Structural Concrete, 18*(4), 589-596. https://doi.org/10.1002/suco.201600194

[9] Caggiano, A., Folino, P., Lima, C., Martinelli, E., & Pepe, M. (2017). On the mechanical response of hybrid fiber reinforced concrete with recycled and industrial steel fibers. *Construction and Building Materials, 147*, 286-295. https://doi.org/10.1016/j.conbuildmat.2017.04.160

[10] Domski, J., Katzer, J., Zakrzewski, M., & Ponikiewski, T. (2017). Comparison of the mechanical characteristics of engineered and waste steel fiber used as reinforcement for concrete. *Journal of Cleaner Production, 158*, 18-28. https://doi.org/10.1016/j.jclepro.2017.04.165

[11] Hu, H., Papastergiou, P., Angelakopoulos, H., Guadagnini, M., & Pilakoutas, K. (2018). Mechanical properties of SFRC using blended manufactured and recycled tyre steel fibres. *Construction and Building Materials, 163*, 376-389. https://doi.org/10.1016/j.conbuildmat.2017.12.116

[12] Carrillo, J., Lizarazo-Marriaga, J., & Lamus, F. (2020). Properties of steel fiber reinforced concrete using either industrial or recycled fibers from waste tires. *Fibers and Polymers, 21*, 2055-2067. https://doi.org/10.1007/s12221-020-1076-1

[13] Simalti, A., & Singh, A. P. (2020). Comparative study on direct shear behavior of manufactured and recycled shredded tyre steel fiber reinforced self-consolidating concrete. *Journal of Building Engineering, 29*, 101169. https://doi.org/10.1016/j.jobe.2020.101169

[14] Lu, B., Shi, C., Cao, Z., Guo, M., & Zheng, J. (2019). Effect of carbonated coarse recycled concrete aggregate on the properties and microstructure of recycled concrete. *Journal of Cleaner Production, 233*, 421-428. https://doi.org/10.1016/j.jclepro.2019.05.350

[15] Zhan, B. J., Xuan, D. X., Zeng, W., & Poon, C. S. (2019). Carbonation treatment of recycled concrete aggregate: Effect on transport properties and steel corrosion of recycled aggregate concrete. *Cement and Concrete Composites, 104*, 103360. https://doi.org/10.1016/j.cemconcomp.2019.103360

[16] Shi, C., Wu, Z., Cao, Z., Ling, T. C., & Zheng, J. (2018). Performance of mortar prepared with recycled concrete aggregate enhanced by CO2 and pozzolan slurry. *Cement and Concrete Composites, 86*, 130-138. https://doi.org/10.1016/j.cemconcomp.2017.10.013

[17] ASTM International. (2016). *ASTM A706/A706M Standard Specification for Deformed and Plain Low-Alloy Steel Bars for Concrete Reinforcement*. West Conshohocken, PA.

[18] ASTM International. (2021). *Standard test method for compressive strength of cylindrical concrete specimens*. West Conshohocken, PA.

[19] ASTM International. (2010). *ASTM C1609 Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading)*.

[20] ASTM International. (2021). *ASTM C78/C78M-21 Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)*. West Conshohocken, PA.

[21] Franco Segura, J. I. (2002). *Estructuras de concreto 1*. Universidad Nacional de Colombia.

[22] Asociación Colombiana de Ingeniería Sísmica. (2010). *Reglamento Colombiano de Construcción Sismo Resistente NSR-10*.

[23] Aslani, F., & Nejadi, S. (2012). Bond behavior of reinforcement in conventional and self-compacting concrete. *Advances in Structural Engineering, 15*(12), 2033-2051. https://doi.org/10.1260/1369-4332.15.12.2033

Paper submitted: 17.11.2023.

Paper accepted: 07.08.2024.