Journal of Science and Technology in Civil Engineering, NUCE 2020. 14 (3): 84–95

INFLUENCE OF FIBER SIZE ON MECHANICAL PROPERTIES OF STRAIN-HARDENING FIBER-REINFORCED CONCRETE

Duy-Liem Nguyen[a,*], Thac-Quang Nguyen[b], Huynh-Tan-Tai Nguyen[a]

[a]*Faculty of Civil Engineering, Ho Chi Minh City University of Technology and Education, 01 Vo Van Ngan street, Thu Duc district, Ho Chi Minh city, Vietnam*
[b]*Faculty of Civil Engineering, Campus in Ho Chi Minh City, University of Transport and Communications, No. 450-451 Le Van Viet street, District 9, Ho Chi Minh city, Vietnam*

Article history:
Received 13/07/2020, Revised 05/08/2020, Accepted 10/08/2020

Abstract

This research deals with the influences of macro, meso and micro steel-smooth fibers on tensile and compressive properties of strain-hardening fiber-reinforced concretes (SFCs). The different sizes, indicated by length/diameter ratio, of steel-smooth fiber added in plain matrix (Pl) were as follows: 30/0.3 for the macro (Ma), 19/0.2 for the meso (Me) and 13/0.2 for the micro fiber (Mi). All SFCs were used the same fiber volume fraction of 1.5%. The compressive specimen was cylinder-shaped with diameter × height of 150 × 200 mm, the tensile specimen was bell-shaped with effective dimensions of 25 × 50 × 100 mm (thickness × width × gauge length). Although the adding fibers in plain matrix of SFCs produced the tensile strain-hardening behaviors accompanied by multiple micro-cracks, the significances in enhancing different mechanical properties of the SFCs were different. Firstly, under both tension and compression, the macro fibers produced the best performance in terms of strength, strain capacity and toughness whereas the micro produced the worst of them. Secondly, the adding fibers in plain matrix produced more favorable influences on tensile properties than compressive properties. Thirdly, the most sensitive parameter was observed to be the tensile toughness. Finally, the correlation between tensile strength and compressive strength of the studied SFCs were also reported.

Keywords: aspect ratio; strain-hardening; post-cracking; ductility; fiber size.

https://doi.org/10.31814/stce.nuce2020-14(3)-08

1. Introduction

Under serious mechanical and environmental loadings, e.g. earthquake, impact, blast load and marine environment, a civil infrastructure has revealed the hasty deterioration, and this might cause construction collapse, even damage to person. Clearly, there has been a great concern in improving the robustness, energy absorption capacity, crack resistance and durability of civil infrastructure. Strain-hardening fiber-reinforced concretes (SFCs) is a promising construction material because it has performed its superior mechanical properties, e.g., compressive strength possibly exceeding 80 MPa, post-cracking tensile strength exceeding 8 MPa, strain capacity exceeding 0.3% even though the SFCs were used a low volume content of fibers, less than 2.5% [1, 2]. Especially, SFCs could generate a strain-hardening behavior accompanied with multiple micro-cracks under tensile loadings [3, 4],

*Corresponding author. *E-mail address:* liemnd@hcmute.edu.vn (Nguyen, D.-L.)

this mechanism was considered as a superior property resulting in high mechanical and cracking resistance of SFCs. Fig. 1 shows a typical strain-hardening curves with 3 zones: linear-elastic zone, strain-hardening zone and crack opening zone [3].

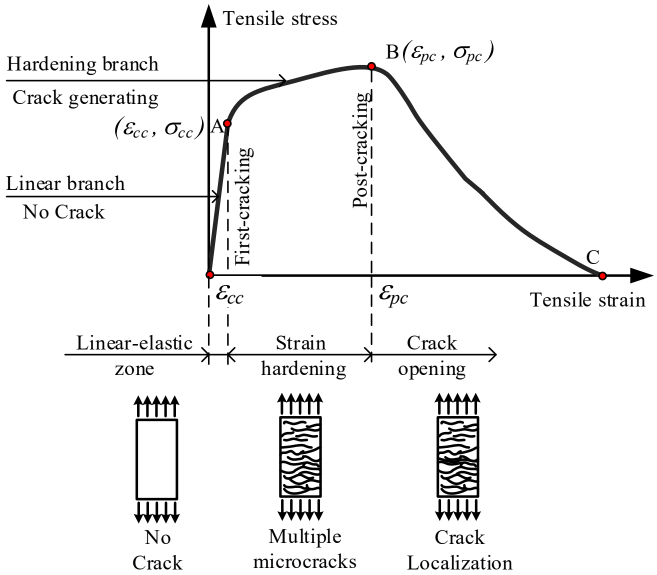


Figure 1. Typical strain-hardening response curve of SFCs

On the other hand, the mechanical properties of SFCs have been reported to be dependent much on fiber characteristics, e.g., fiber aspect ratio (length/diameter ratio), fiber size and shape, fiber volume content, fiber material [4–9]. Also, in the process of making SFCs, the fiber type and fiber content greatly affected the probability of heterogeneous fiber distribution and fiber flocculation governing workability and viscosity of a concrete mixture [6]. Despite the available references, the influencing factors regarding fiber characteristics should be thoroughly clarified. Two questions would be answered in this investigation: whether the order in terms of steel-smooth fiber size for enhancing compressive properties of SFCs was similar to that for enhancing tensile properties?; and, what significances in enhancing tensile and compressive parameters of SFCs using different reinforcing steel-smooth fiber sizes were? This situation led to the motivation for this experimental research. The main objectives of this research work are as follows: (i) to explore the sensitivity of macro, meso and micro fibers to tensile and compressive properties of SFCs, and (ii) to correlate the tensile strength to compressive strength of SFCs containing macro, meso and micro steel-smooth fibers. The study result is expected to provide more useful information for enlarging the application of SFCs in both civil and military infrastructures.

2. Experiment

2.1. Materials and preparation of specimens

Fig. 2 shows the experimental testing program while Tables 1 and 2 provide the composition of plain matrix of SFCs (Pl) and fiber features, respectively. Three types of steel-smooth fiber were used with their length/diameter ratios as follows: 30/0.3 for the macro (Ma), 19/0.2 for the meso (Me) and 13/0.2 for the micro fiber (Mi). All SFCs were added a same fiber volume fraction of 1.5%.

For the compressive test, the cylindrical specimen with its diameter × height of 100 × 200 mm was used with gauge length of 100 mm. For the tensile test, the bell-shaped specimen was used with effective dimensions of 25 × 50 × 100 mm (thickness × width × gauge length). The mixing detail of SFC mixture could be referred to previous study [7]. All specimens after casting were placed in a laboratory room for 2 days prior to demolding. After demolding, the specimens were water-cured at 25°C for 14 days. Next, the specimens were removed from the water tank and dried at 70°C in a drying oven for at least 12 h. All the specimens were tested at the age of 18 days.

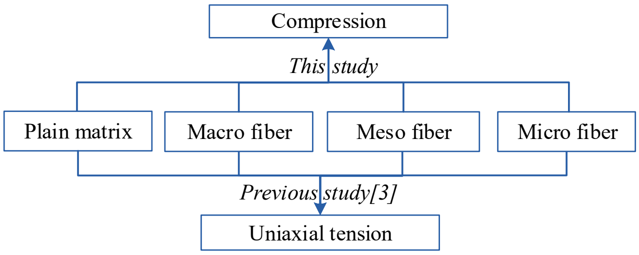


Figure 2. Experimental testing program

Table 1. Plain matrix composition of SFCs

Cement (Type III)	Silica fume	Silica sand	Fly ash	Superplasticizer	Water
0.80	0.07	1.00	0.20	0.04	0.26

Table 2. Fiber features

Notation	Diameter (mm)	Length (mm)	Aspect ratio (L/D)	Tensile strength (MPa)
Ma	0.3	30	100	2580
Me	0.2	19	95	2788
Mi	0.2	13	65	2788

2.2. *Experiment setup*

All specimens were tested using a universal test machine with applied displacement speed of 1 mm/min. The frequency of data acquisition under compression tests was 1 Hz. Fig. 3 presents the experimental setup for uniaxial tension and compression. Two and three linear variable differential

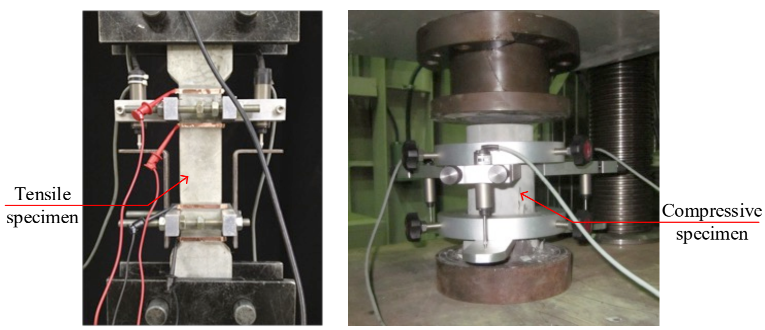


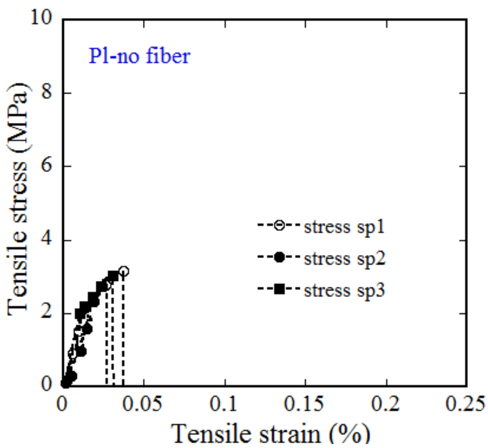
Figure 3. Experiment setup

transformers (LVDTs) were attached to tensile and compressive specimens, respectively. The average values from LVDTs were used to perform the response of stress versus strain curve.

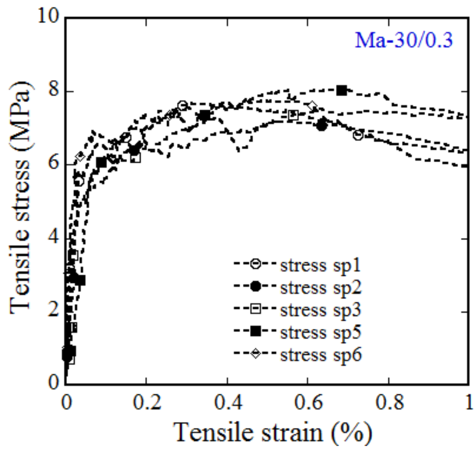
3. Experiment result and discussion

3.1. Tensile and compressive behaviors of SFCs

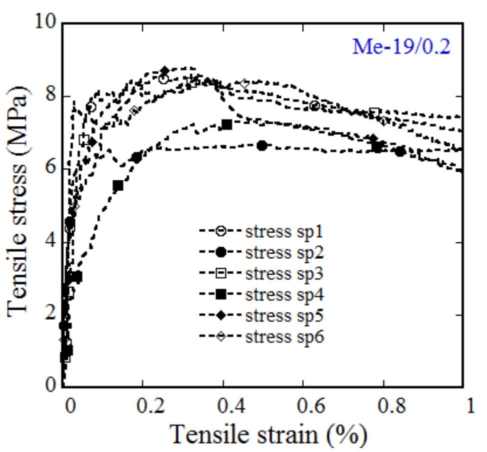
Fig. 4 shows the tensile stress versus strain response curves of SFCs. As shown in Fig. 4, the plain matrix revealed the strain-softening behavior while the SFCs added reinforcing fibers displayed the strain-hardening behaviors accompanied by multiple micro-cracks. The compressive stress versus strain responses of SFCs were presented in Fig. 5. As shown in Fig. 5, there were so many different profile curves according to SFC types: the profile curves were almost linear from the start of loading to their peaks. As shown in Fig. 4, the plain matrix revealed the strain-softening behavior while the SFCs added reinforcing fibers displayed the strain-hardening responses accompanied by multiple micro-cracks.



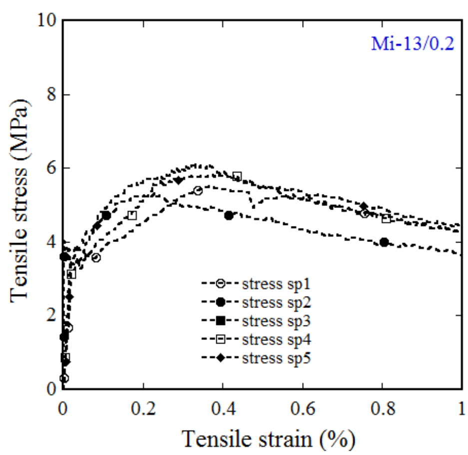
(a) Plain



(b) Macro

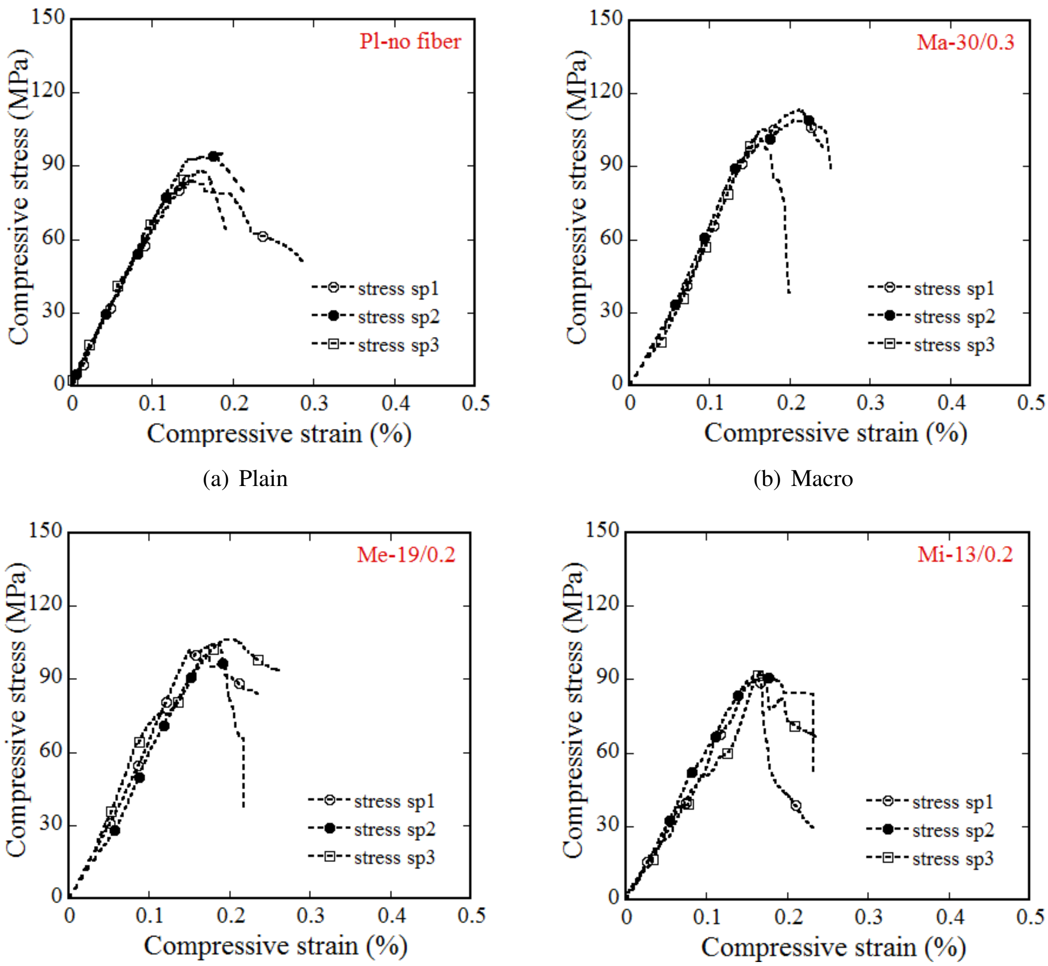


(c) Meso



(d) Micro

Figure 4. Tensile behaviors of SFCs



(a) Plain

(b) Macro

(c) Meso

(d) Micro

Figure 5. Compressive behaviors of SFCs

Tables 3 and 4 supply the average values of six investigated parameters, including tensile strength, tensile strain capacity, tensile toughness (Table 3), compressive strength, compressive strain capacity, compressive toughness (Table 4). Fig. 6 shows the comparison of mechanical properties of SFCs under tension and compression. As shown in Fig. 6, the addition of macro and meso fibers in plain matrix clearly enhanced all the investigated parameters, whereas there was a reduction in compressive strain capacity and compressive toughness of SFCs containing micro fibers. The reinforcing fibers embedded in the SFCs helped generate a mechanism of crack bridging [1, 3], and this mechanism resulted in the enhanced strengths in both tension and compression. Besides, the ineffectiveness of the micro fiber in enhancing mechanical properties of SFC would be discussed in Section 3.2. The macro fibers produced the best performance in most of the investigated parameters, under both tension and compression. This phenomenon could be explained through the highest aspect ratio of the macro fibers, equaling to 100, since the higher aspect ratio would produce the higher mechanical property of the composites [5, 10, 11]. In contrast, the micro fiber, having its lowest aspect ratio of 65, would produce the lowest mechanical property.

Table 3. Tensile parameters

Series	Tensile strength (MPa)	Tensile strain capacity (%)	Tensile toughness (MPa.%)
Pl	2.53	0.025	0.07
Ma	7.64	0.53	3.91
Me	8.05	0.38	3.30
Mi	5.69	0.33	3.19

Table 4. Compressive parameters

Series	Compressive strength (MPa)	Compressive strain capacity (%)	Compressive toughness (MPa.%)
Pl	89.01	0.165	8.66
Ma	113.20	0.193	11.45
Me	103.63	0.187	10.65
Mi	91.52	0.164	7.53

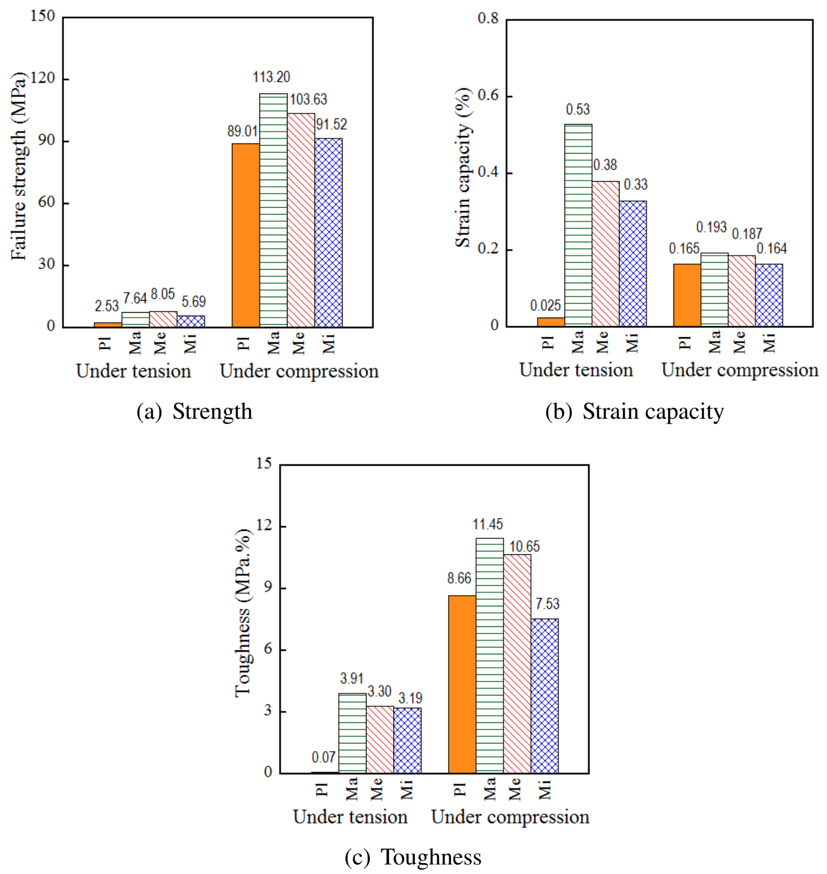
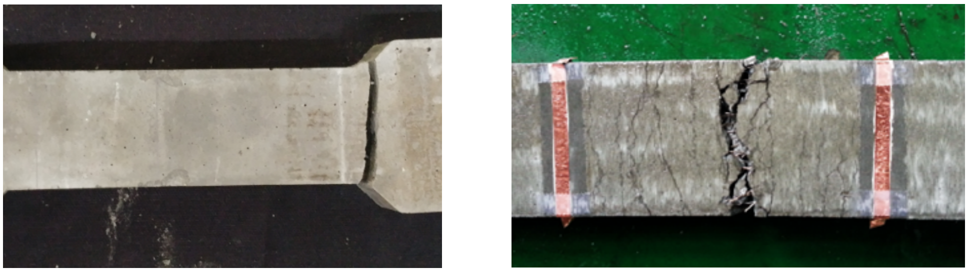
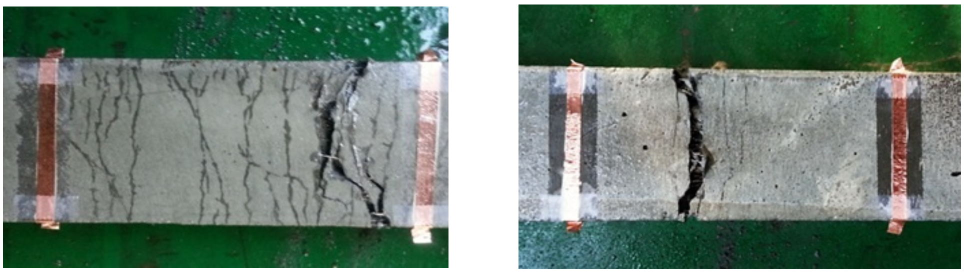


Figure 6. Comparison of mechanical properties of SFCs

Figs. 7 and 8 display cracking behaviors of SFCs under tension and compression, respectively. Under tension, the SFCs produced the multiple micro-cracks with the presence of the embedded fibers but single crack with no fibers. Under compression, the SFCs with the embedded fibers produced the local tensile cracks along the specimen height whereas there was a broken damage for the specimens without fiber.

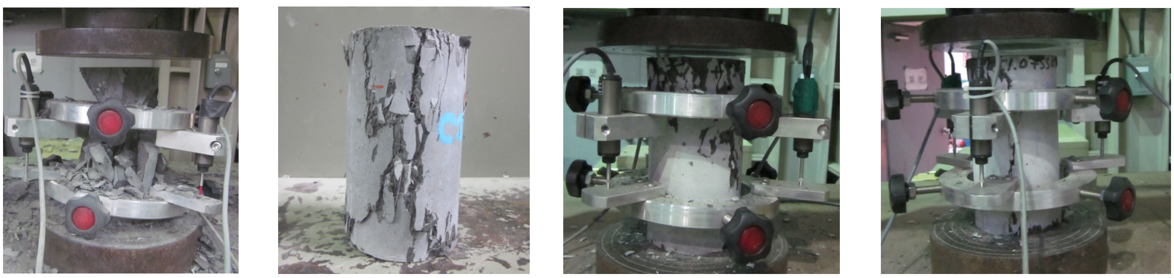


(a) Plain (b) Macro



(c) Meso (d) Micro

Figure 7. Cracking behaviors of SFCs under tension

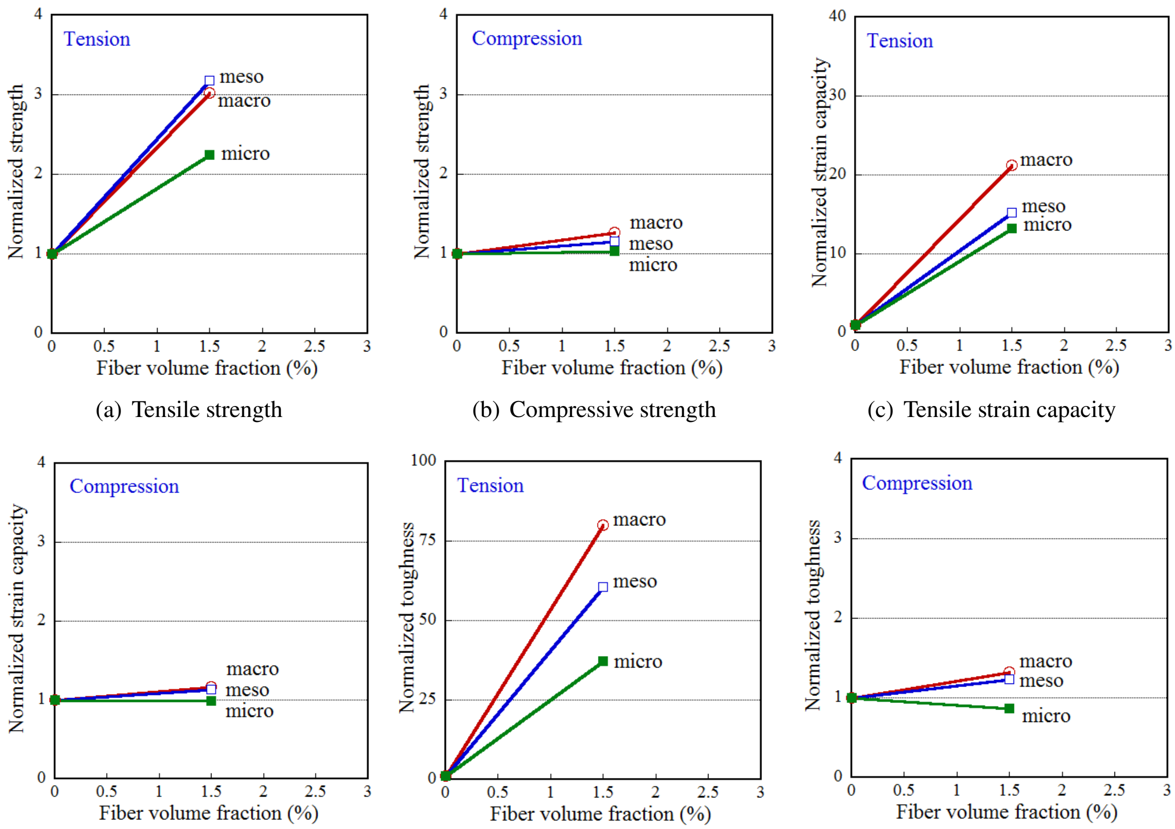


(a) Plain (b) Macro (c) Meso (d) Micro

Figure 8. Cracking behaviors of SFCs under compression

3.2. Sensitivities of fiber size to the studied mechanical properties of SFCs

To evaluate the sensitive significance of fiber sizes to tensile and compressive properties of SFCs, the strength, failure strain and toughness of each series were normalized by corresponding parameters of the plain matrix, as performed in Fig. 9. In this figure, the line with a higher slope revealed more sensitivity. Table 5 supplies the slope values of all curves of normalized parameter versus fiber content responses presented in Fig. 9. Generally, the addition of steel-smooth fibers in plain matrix produced more favorable influences on enhancing tensile properties than compressive properties. This could be attributed to the different failure-crack types in the tensile and compressive specimen although the crack bridging of the fibers could prevent crack propagation in both tension and compression. The failure of tensile specimen was dominated by fully fiber pull-out mechanism that was greatly influenced by the interfacial bond resistance of fiber-matrix, and the failure crack in this case was perpendicular to the direction of applied stress [12, 13]. On the contrary, the failure of compressive specimen was controlled by shear resistance or locally tensile resistance, with a failure crack not perpendicular to the direction of applied stress, as described in Fig. 10 [14].



(a) Tensile strength (b) Compressive strength (c) Tensile strain capacity

(d) Compressive strain capacity (e) Tensile toughness (f) Tensile toughness

Figure 9. Response of normalized parameter versus fiber content of SFCs

Table 5. Slope of normalized parameter versus fiber content response curves of SFCs

Series	Strength (MPa)		Strain capacity (%)		Toughness (MPa.%)	
	Tension	Compression	Tension	Compression	Tension	Compression
Ma	2.01	0.85	14.13	0.78	53.35	0.88
Me	2.12	0.77	10.13	0.75	40.30	0.82
Mi	1.50	0.69	8.80	−0.66	24.74	−0.58

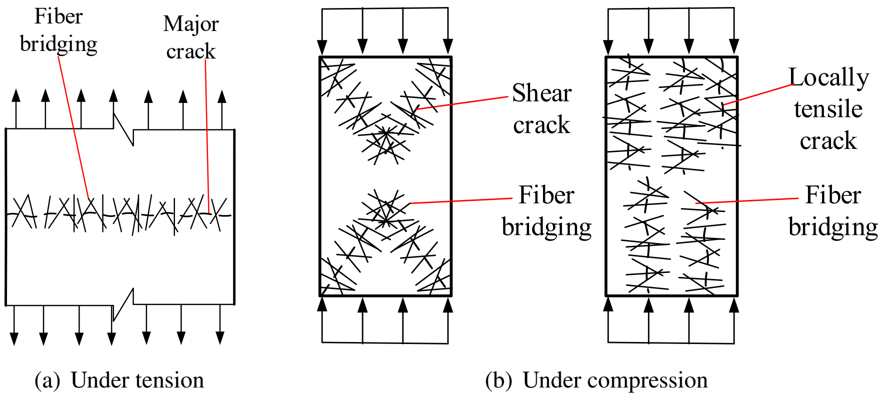


Figure 10. Failure crack under direct tension and compression

As shown in Table 5, the micro fibers produced the smallest slope in most of tensile and compressive parameters. Even for compressive strain and toughness, the micro fibers generated the reductions in mechanical properties, as shown in Figs. 6(b) and 6(c), and/or the negative slopes in Table 5. It could be stated that the worst favorable fiber type in enhancing tensile and compressive properties was the micro fibers. The reduction in compressive strain and toughness of SFC containing micro fiber was really unclear in comparison with plain matrix, and this tendency should be confirmed in a further study. The macro and meso fibers produced the favorable influences on tensile and compressive properties with positive slope. The highest slope was for tensile toughness produced from the macro fibers, i.e., the most sensitive parameter was tensile toughness. In general, the macro fiber was better than the meso with 5 parameters revealing higher values, only was worse than the meso with 1 parameter (tensile strength) revealing lower value. Fig. 11 shows the explanation for the worst favorable effect in enhancing mechanical properties of the micro fibers. As displayed in Fig. 11, the minimum embedded length (L_0) for developing full bond of fiber-matrix included 3 zones: the debonded length (L_d), the softening length (L_s), and the bonded length (L_b), the total of L_d and L_s was defined as the length of the damage zone. It was required a minimum embedded length (L_0) regarding to fiber diameter (d_f) in order to develop the bond of fiber-matrix [15], the aspect ratio of the micro fibers, equaling to 65, may be not enough for producing L_0 in pull-out mechanism, this resulted the low mechanical properties of SFCs. It was noted that the such explanation was for smooth fiber

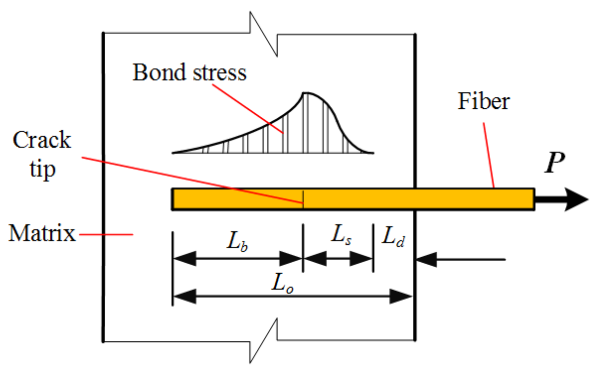


Figure 11. Minimum embedded length for developing fully bond of fiber-matrix

type, for other fiber types, e.g., twisted or hooked fiber types, it was required a furthur investigation to clarify.

3.3. Correlation between the tensile strength and compressive strength of SFCs

For ordinary concrete (OC), the direct tensile is often correlated with the compressive strength using a square root scale in a few standards. Eq. (1) presents the such correlation according to ACI 318 for OC [16]. The correlation between the tensile strength and compressive strength of SFCs may different from that of OC, this was because the tensile strength of SFCs was importantly improved with the use of reinforcing fibers in the concrete mixture. Some references were reported that a power relationship between the tensile strength and compressive strength of SFCs was valid [17, 18], whereas other references were still proposed a square root scale between them [19, 20], as displayed in Eq. (2). The coefficient (λ) in Eq. (2) would be drawn based on the data of experimental tests.

$$f_t = 0.33\sqrt{f'_c} \tag{1}$$

$$\sigma_{pc} = \lambda\sqrt{f'_{SFC}} \tag{2}$$

where f'_c is the compressive strength of OC using a cylindrical specimen of 150 × 300 mm, f_t is the tensile strength of OC, f'_{SFC} is the compressive strength of SFCs using a cylindrical specimen of 100 × 200 mm, σ_{pc} is the post-cracking tensile strength of SFCs.

Table 6. Coefficients in correlation between tensile and compressive strength of SFCs

Type of fiber	Tensile strength (MPa)	Compressive strength (MPa)	Coefficient (λ)
Plain	2.53	89.01	0.27
Ma	7.64	113.20	0.72
Me	8.05	103.63	0.79
Mi	5.69	91.52	0.59

Table 6 supplies the drawn coefficients, λ, for various fiber types as follows: 0.27 for Pl, 0.72 for Ma, 0.79 for Me and 0.59 for Mi. Comparatively, the order in term of λ was observed as follows: Pl < Mi < Ma < Me, this order was completely agreed with the order in term of tensile strength. Compared with OC, the SFCs containing the embedded fibers generated a higher λ, from 1.8 to 2.4 times, although the plain matrix produced a lower λ, only 0.8 times. The drawn coefficients of SFCs were spread out and significantly dependent upon the reinforcing fibers.

4. Conclusions

The experimental results supplied helpful information on the sensitivity of macro, meso and micro steel-smooth fibers to tensile and compressive properties of SFCs. The observations and conclusions can be listed as follows:

- The adding steel-smooth fibers in plain matrix of SFC produced more favorable influences on tensile properties than compressive properties.

- The micro fibers and macro steel-smooth fibers generally produced the smallest and highest sensitivity, respectively, for enhancement of tensile and compressive parameters of SFCs. The macro steel-smooth fiber could be employed for improving performances of reinforced concrete structures using SFCs.

- The most sensitive parameter of SFCs, among the six parameters investigated under tension and compression, was observed to be the tensile toughness.

- The coefficients in correlation between tensile and compressive strength of SFCs using a square root scale was scattered and higher than that of ordinary concrete.

Acknowledgements

This research was funded by the Vietnam National Foundation for Science and Technology Development (NAFOSTED) under grant number 107.01-2017.322. The authors are grateful for the financial support. The opinions expressed in this paper are those of the authors and do not necessarily reflect the views of the sponsors.

References

[1] Wille, K., Kim, D. J., Naaman, A. E. (2011). Strain-hardening UHP-FRC with low fiber contents. *Materials and Structures*, 44(3):583–598.

[2] Park, S. H., Kim, D. J., Ryu, G. S., Koh, K. T. (2012). Tensile behavior of ultra high performance hybrid fiber reinforced concrete. *Cement and Concrete Composites*, 34(2):172–184.

[3] Naaman, A. E., Reinhardt, H.-W. (2006). Proposed classification of HPFRC composites based on their tensile response. *Materials and Structures*, 39(5):547–555.

[4] Nguyen, D.-L., Lam, M. N.-T., Kim, D.-J., Song, J. (2020). Direct tensile self-sensing and fracture energy of steel-fiber-reinforced concretes. *Composites Part B: Engineering*, 183:107714.

[5] Choi, W.-C., Jung, K.-Y., Jang, S.-J., Yun, H.-D. (2019). The influence of steel fiber tensile strengths and aspect ratios on the fracture properties of high-strength concrete. *Materials*, 12(13):2105.

[6] Abdelrazik, A. T., Khayat, K. H. (2020). Effect of fiber characteristics on fresh properties of fiber-reinforced concrete with adapted rheology. *Construction and Building Materials*, 230:116852.

[7] Nguyen, D. L., Song, J., Manathamsombat, C., Kim, D. J. (2015). Comparative electromechanical damage-sensing behaviors of six strain-hardening steel fiber-reinforced cementitious composites under direct tension. *Composites Part B: Engineering*, 69:159–168.

[8] Hoan, P. T., Thuong, N. T. (2019). Shear resistance of ultra-high-performance concrete reinforced with hybrid steel fiber subjected to impact loading. *Journal of Science and Technology in Civil Engineering (STCE)-NUCE*, 13(1):12–20.

[9] Song, J., Nguyen, D. L., Manathamsombat, C., Kim, D. J. (2015). Effect of fiber volume content on electromechanical behavior of strain-hardening steel-fiber-reinforced cementitious composites. *Journal of Composite Materials*, 49(29):3621–3634.

[10] Yazıcı, Ş., İnan, G., Tabak, V. (2007). Effect of aspect ratio and volume fraction of steel fiber on the mechanical properties of SFRC. *Construction and Building Materials*, 21(6):1250–1253.

[11] Sovják, R., Máca, P., Imlauf, T. (2016). Effect of fibre aspect ratio and fibre volume fraction on the effective fracture energy of ultra-high-performance fibre-reinforced concrete. *Acta Polytechnica*, 56(4): 319–327.

[12] Nguyen, D. L., Vu, T. B. N., Do, X. S., Tran, M. P. (2019). Using carbon black and ground granulated blast furnace slag for improvement of self-sensing capacity of high performance fiber-reinforced concretes. *Journal of Science and Technology in Civil Engineering (STCE) – NUCE*, 13(4V):151–158. (in Vietnamese).

[13] Nguyen, D.-L., Kim, D.-J., Thai, D.-K. (2019). Enhancing damage-sensing capacity of strain-hardening macro-steel fiber-reinforced concrete by adding low amount of discrete carbons. *Materials*, 12(6):938.

[14] Nguyen, D.-L., Thai, D.-K., Ngo, T.-T., Tran, T.-K., Nguyen, T.-T. (2019). Weibull modulus from size effect of high-performance fiber-reinforced concrete under compression and flexure. *Construction and Building Materials*, 226:743–758.

[15] Chen, C., Cheng, L. (2016). Theoretical solution to fatigue bond stress distribution of NSM FRP reinforcement in concrete. *Composites Part B: Engineering*, 99:453–464.

[16] ACI 318-14. *Building code requirements for structural concrete*.

[17] Ramadoss, P. (2008). Studies on high-performance steel fiber reinforced concrete under static and impact loads. PhD thesis, Structural Engineering Div., Anna Univ., Chennai, India.

[18] Xu, B. W., Shi, H. S. (2009). Correlations among mechanical properties of steel fiber reinforced concrete. *Construction and Building Materials*, 23(12):3468–3474.

[19] Thomas, J., Ramaswamy, A. (2007). Mechanical properties of steel fiber-reinforced concrete. *Journal of Materials in Civil Engineering*, 19(5):385–392.

[20] Wafa, F. F., Ashour, S. A. (1992). Mechanical properties of high-strength fiber reinforced concrete. *Materials Journal*, 89(5):449–455.