Visual Abstract

Experimental investigation on the mechanical behavior of concrete reinforced with Alfa fibers

Tidjani Messas
Materials, Geomaterials and Environment Laboratory, Badji Mokhtar University, Abbès Laghrour University, Algeria.
messas_tidjani@univ-khenchela.dz, https:// orcid.org / 0000-0002-0399-3541

Djamel Achoura
Materials, Geomaterials and Environment Laboratory, Badji Mokhtar University, Algeria.
achoudj@yahoo.fr, https://orcid.org/0000-0003-1692-3523

Abdelaziz Boutrid
Mineral Processing and Environmental Laboratory, Badji Mokhtar University, Abbès Laghrour University, Algeria.
abdelaziz.boutrid@univ-khenchela.dz, https://orcid.org/ 0000-0002-1041-3904

Belgacem Mamen
Abbès Laghrour University, Algeria.
belgacem.mamen@univ-khenchela.dz, https://orcid.org/ 0000-0003-2342-9363

ABSTRACT. Currently, the reinforcement of ordinary concrete with synthetic fibers poses ecological problems because the manufacturing process of these products is very polluting. Plant fiber composites are a new challenge for environmental protection. The present article aims to investigate the mechanical behavior of concrete reinforced with natural fibers, called alfa fibers. Compression and three-point bending tests have been performed on cubic and prismatic samples, respectively. Different fiber lengths (2.5, 5, and 8 cm) and content (0.6, 1.2, and 1.8 % by volume) of alfa fibers have been used to examine their influence on the mechanical behavior of the fiber-reinforced concrete. The obtained results show that for a volume content of 1.2 % of plant fibers of 5 cm length, the tensile strength of the reinforced concrete increases up to 54.41 % compared to the ordinary concrete (BT). However, for a content of 1.8 % of fibers with 8 cm length, both the compressive and tensile strength of the reinforced concrete decrease slightly. At this level, an excess of both fiber content and their length produces the formation of voids within concrete. Moreover, such an excess made the hydration reaction slower. It is worth noticing that the orientation of fibers also plays a significant role in the nucleation and propagation of microcracks. The fibers arranged both horizontally and obliquely are more resistant to microcracking than those oriented in the loading direction.

KEYWORDS. Fiber-reinforced concrete; Alfa fiber; fiber length; volume

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fraction; mechanical behavior; microcracks.

INTRODUCTION

Today, concrete is the main building material used in civil, industrial constructions and bridges due to its features, such as versatility and durability in many environments. Nevertheless, it has a certain brittleness, low tensile strength, and low ductility. Therefore, faster collapse is observed after the first signs of fracture or other pathologies [1]. These disadvantages have restricted its use. Consequently, the need to develop fiber-reinforced concrete offers the possibility to overcome such a drawback.

The inclusion of fibers in concrete used in civil constructions reduces its conventional brittleness by providing better tensile strength [2-4]. Fibers are discontinuous elements of variable nature, uniformly distributed in the matrix according to a random or forced orientation. The addition of fibers to concrete allows to absorb and dissipate energy and reduce the propagation of cracks. They also improve the post-cracking behavior of concrete. Several types of fibers can be used, such as steel [5-7], polypropylene [8-11]. The fiber should be chosen according to the needs of the work required. Over the past decade, bio-fibers have replaced synthetic fibers to produce environmentally friendly concrete because several types of these fibers are available and abundant in some parts of the world.

Various studies on the influence of natural fibers on the strength, properties, and structural behavior of concrete proof that the inclusion of natural fibers improves the mechanical properties of concretes and gives a better resistance to crack propagation. In recent years, many natural fibers have been used to reinforce the ordinary concrete: find wood fibers [12-13], date palm fibers [14-16], bamboo [17-19], coconut [20-22], and Alfa [23-25].

The natural fiber examined here is the Alfa (Stippa tenacissima), a bushy plant that belongs to the Poaceae family with upright stems 60 to 150 or even 200 cm long. The sheath of the leaves presents auricles from 10 to 12 mm of height. This species is native to the arid regions of the western Mediterranean basin, and mainly used in both the paper and rope industries. This plant does not need additional water to grow, nor the use of pesticides or amendment.

The effect of Alfa reinforcement on the mechanical properties of concrete has not been widely studied to date [23-25]. They reported that 1 % of Alfa fibers is the most suitable intake for concrete reinforcement. More specifically, our results reveal that a fiber content of 1.2 % (by volume) with a length of 5 cm can be considered as the optimal parameters for Alfa fiber-reinforced concrete. These results show the key role of Alfa fibers: they delay cracking and reduce concrete bursting better than polypropylene. Additionally, the Alfa fibers offer economic and environmental benefits to society.

This work aims to investigate the effect of Alfa fibers on the mechanical behavior of the reinforced concrete. Compressive and three-point bending tests are performed with different fiber contents (0.6, 1.2, and 1.8 % by volume). For each of the above content, three different fiber lengths (2.5, 5, and 8 cm) are examined.

MATERIALS

The mixture of fiber-reinforced concrete examined is prepared according to the standard NF P 18-101 [26].

Cement

The cement used is a CEM II/A-42 Portland-composite cement, produced by Hadjar Soud Cement Company-Skikda (Algeria). It consists mainly of Clinker ≥ 74 wt %, Gypsum (4–6 wt %), Limestone (16–18 wt %), and slag ≤ 20 wt %. The physical characteristics and chemical composition are summarized in Tabs. 1 and 2, respectively.

Apparent density (g/cm^3)	Absolute density (g/cm^3)	Normal consistency (%)	Fineness (retained on 0.065 mm sieve) (%)	Initial setting time (H/min)
1.057	3.00	27	3.1	2/34

Table 1: Physical properties of CEM II/A-42 Portland-composite cement.

Elements	CaO	Al_2O_3	SiO_2	Fe_2O_3	MgO	NaO_2	K_2O	Cl^-	SO_3
wt %	62.80	5.68	22.25	3.52	0.74	0.27	0.47	0.004	1.94

Table 2: Chemical composition of CEM II/A-42 Portland-composite cement.

Aggregates

The aggregates, according to the NF P 15-433 [27], consist of crushed limestone sand (0/4 mm) and siliceous sand dune (0-1, 25 mm). Two gravels crushed limestone ((4/8) and (8/16) mm) coming from the same quarry are employed in the mixture as the crushed sand. The physical characteristics of the aggregates are presented in Tabs. 3 and 4.

Physical characteristics	Crushed limestone sand	Sand dune
Apparent density (t/m^3)	1.561	1.2
Absolute density (t/m^3)	2.5	2.3
Sand equivalent (%)	64.06	85
Water absorption (%)	2.3	2.45
Fineness modulus	3.76	1.6
Cleanliness	0.75	0.9

Table 3: Physical characteristics of crushed and dune sand.

Physical characteristics	Gravel (4/8)	Gravel (8/16)
Apparent density (t/m^3)	1.431	1.428
Absolute density (t/m^3)	2.56	2.56
Flattening coefficient (%)	11.25	9.43
Water absorption (%)	1.1	0.9
Micro Deval in presence of water (%)	13.74	13.74
Los Angles coefficient (%)	29.63	29.63

Table 4: Physical characteristics of gravels crushed limestone.

Alfa fibers

Alfa plant presents numerous morpho-physiological adaptations that allow it to withstand extreme environments, particularly the complex Mediterranean ecosystem. As shown in Fig. 1a, the Alfa leaf is a circular, smooth, shiny, and solid ribbon. Its diameter decreases gradually from the bottom to the top [25]. To determine the fracture stress of Alfa fiber, a uniaxial test is carried out by using the Zwick Roell apparatus shown in Fig. 1b. The load-displacement curve is shown in Fig. 1c. The chemical composition, physical and mechanical properties are reported in Tabs. 5-7, respectively.

(a) (b) (c)

Figure 1: a) Alfa fibers, b) Zwick Roell apparatus and c) Load-displacement curve.

Cellulose	Hemicelluloses	Lignin	Ash	Wax
45 %	24 %	24 %	2 %	5 %

Table 5: Chemical composition of Alfa fibers [28].

Microfibril angle (°)	Diameter (mm)	Length (mm)
31	1 - 2	10 - 1000

Table 6: Physical properties of Alfa fibers.

Young's modulus (GPa)	Elongation (mm)	Tensile stress (MPa)	Density	Breaking stress (MPa)
14.48	2.27	200.56	0.89	645.82

Table 7: Mechanical tensile properties of Alfa fibers.

EXPERIMENTAL PROCEDURE

The specimens are prepared according to the standard NF EN 12390-2 [29]. The mixing is carried out by employing a concrete mixer of capacity 50 L. For the ordinary concrete, the mixing time is taken to be about five minutes, whereas and for the fiber-reinforced concrete is more than six minutes. The Alfa fibers are added into the tank during the mixing phase with a specific content. Then, the compaction procedure is performed on a vibrating table for a one minute. Finally, the samples are removed from the molds after 24 hours and stored in a saturated humid medium at a temperature of 20±2°C (see Fig. 2a). Tab. 8 reports the specimen's designation, together with the corresponding fiber length and content by volume.

Designation	BT	BFV1	BFV2	BFV3	BFV4	BFV5	BFV6	BFV7	BFV8	BFV9
Fiber length (cm)	-	5	2.5	5	2.5	5	2.5	8	8	8
Content (%)	-	1.2	1.2	0.6	0.6	1.8	1.8	1.8	1.2	0.6

Table 8: Specimen designation, length and content of Alfa fibers.

To evaluate the compressive strength of the above samples, compression tests are carried out on cubic specimens of dimension (10 x 10 x 10) cm at the age of 28 days, according to the standard NF EN 12390-3 [30], by using a testing machine "UTEST" of 2000 kN capacity (see Fig. 2b). For the tensile strength evaluation, three-point bending tests are performed on notched prismatic specimens (10 x 10 x 40) cm according to the NF EN 12390-5 [31] standard by using a "STRASSENTEST" testing machine with a maximum capacity of 100 kN (see Fig. 2c).

(a) (b) (c)

Figure 2: Experimental procedure: (a) fiber reinforced-concrete samples; (b) uniaxial compression testing and (c) three-point bending testing.

RESULTS AND DISCUSSION

Effect of Alfa fiber content and length on compressive strength

In Fig. 3 is plotted the influence of fiber content on the compressive strength, for different values of fiber length. The results obtained show that all the curves related to fiber lengths of (2.5 and 5 cm) are characterized by a similar trend. The highest value of the compressive strength is that of ordinary concrete (BT), equal to 57.7 MPa. However, the lowest value is obtained for BF V9 specimen with 32.19 MPa, for a fiber content of 1.8 % and a fiber length of 8 cm. A decreasing in the compressive strength is observed for a fiber content greater than 1.2 %. At a content of 1.8 %, the drop in compressive strength ranges about 26.42 % for fibers of 5 cm in length, 31.19 % for fibers of 2.5 cm, and 44.21 % for ones of 8 cm in length. Here, the drop in strength is calculated compared to the initial compression strength of ordinary concrete.

This decrease is essentially due to the nature of the fibers (vegetable fiber) containing mainly cellulose, thus causing a slowing down of the hydration process. The morphology of the fibers (smooth fiber) decreases the adherence matrix-fiber and consequently decreases the resistance to the compression.

The influence of fiber length on the compressive strength is presented in Fig. 4 for different values of fiber content. Based on the results obtained, the compressive strength decreases by increasing fiber length. The maximum recorded drop in compressive strength is around 25.51 MPa. This decreasing is due to the disruption of the matrix's crystal lattice arrangement due to the inclusion of longer fibers and the formation of urchin balls during the concrete casting (see Fig. 4).

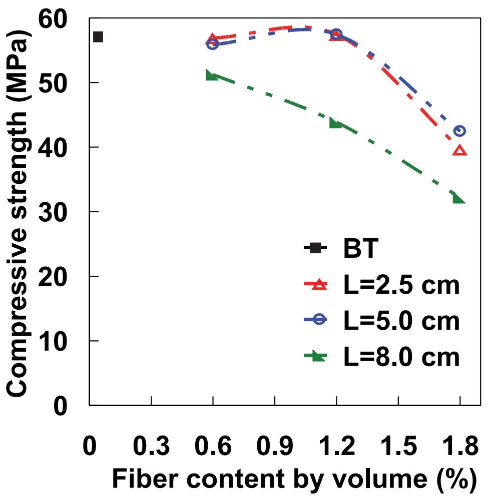


Figure 3: Effect of fiber content on the compressive strength of concrete.

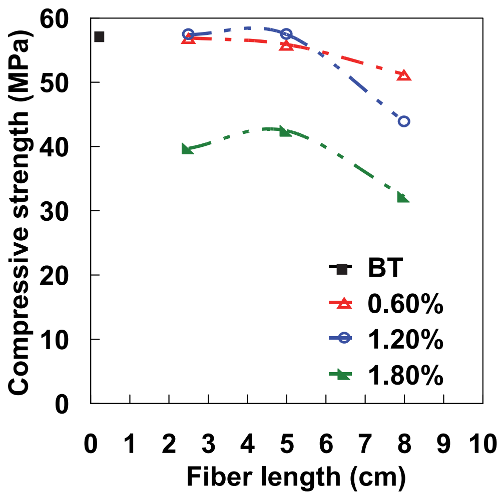


Figure 4: Effect of fiber length on the compressive strength of concrete.

Effect of Alfa fiber content and length on tensile strength

According to Fig. 5, an enhancement in tensile strength is observed only when the concretes reinforced with fibers having a length of 2.5 and 5 cm. Furthermore, no improvement is obtained for a content of 1.8 %; this is due to a possible disorder in the distribution of fibers in the concrete volume.

Regarding the influence of fiber length on tensile strength, it remains relatively constant compared to that of the ordinary concrete (BT) that is 6.12 MPa (see Fig. 6). The strength is around 6.12 MPa for reinforced concrete with fibers length of 8 cm and a content of 0.6 and 1.2 %. However, for fiber-reinforced concrete using fibers length of 8 cm and content of 1.8 %, the strength is estimated at around 6.30 MPa.

According to the ordinary concrete tensile strength (BT, see Fig. 6), the maximum improvement of the tensile strength of reinforced concrete is obtained with fibers of 5 cm in length and contents of 0,6 % and 1.2 %. The obtained resistances are respectively 9,45, and 9,15 MPa for the specimens BF V2 and BF V5, with gains in the percentage of resistances respectively of the order 54,41 % and 49,51 %. Here, the gain in strength is calculated compared to the tensile strength of ordinary concrete. With the same content and fiber of 2.5 cm in length, the strengths are respectively of the order of 8.55 MPa for the specimen BF V1 and 8.10 MPa for that BF V4. Their percentage increase strength is 39.70 and 32.35 %, respectively. As previously mentioned, percentage increase strength is calculated compared to the tensile strength of ordinary concrete.

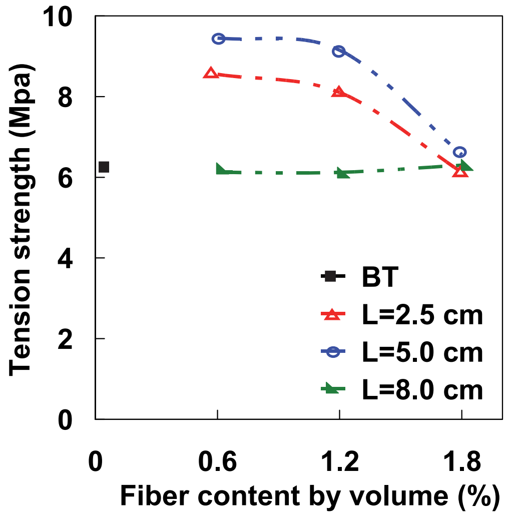


Figure 5: Influence of fiber content on the tension strength.

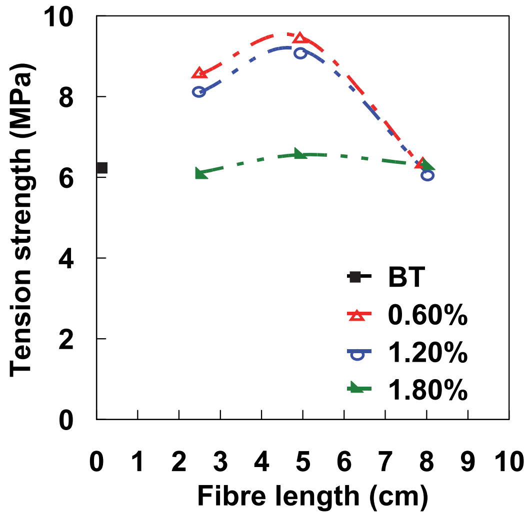


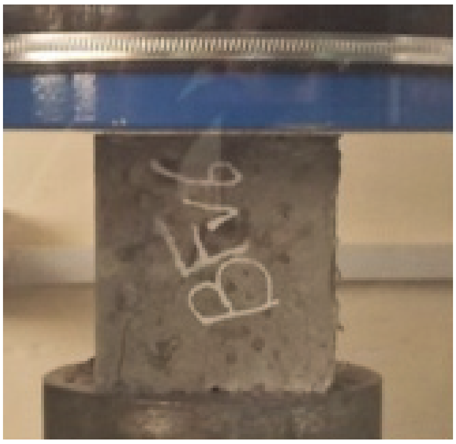
Figure 6: Effect of fiber length on the tension strength of concrete.

FAILURE

Compressive failure

Figs. 7a and 7b show the compressive failure modes of ordinary concrete and fiber-reinforced concrete, respectively. The ordinary concrete specimen breaks abruptly and collapses during the compression test. In contrast, the sample with fiber-reinforced concrete nucleates cracks that propagate progressively up to the material fails. The addition of Alfa fibers take up the stresses caused by the deformations and thus slows down the nucleation of cracks. Crack propagation in compression-loaded fiber reinforced concrete specimens is strongly influenced by the orientation of the fibers [25]. On the one hand, fibers aligned perpendicular to the cracking plane oppose the nucleation of cracks. On the other hand, fibers aligned parallel to the cracking plane have little influence on the propagation of microcracks. Based on the microstructure analysis of the present investigation, the majority of the fibers are arranged perpendicular and oblique to the cracking plane.

(a)



(b)

Figure 7: Compressive failure of a specimen made of: (a) ordinary concrete and (b) fiber-reinforced concrete.

Tensile failure

During the tensile test (Fig. 8), the fiber-reinforced concrete specimens, contrary to ordinary concrete, show microcracks during the elastic step. At a given load value, the microcracks become visual, and then progressively propagate and increase in width, leading to a decrease in the residual strength of the fiber-reinforced concrete because of the loss of adhesion between the fibers and the cementitious matrix.

Figure 8: Tensile fracture of Alfa fiber concrete specimen.

SEM micrographs of Alfa-reinforced concrete and ordinary concrete are respectively shown in Figs. 9a-c and d-f. These SEM micrographs demonstrate two zones with different aspects. The texture of the first zone, adjacent to the Alfa fibers, appears to be uncracked (see Figs. 9b-c). This suggests a better adhesion between the concrete and the Alfa fibers. This better adhesion contributes to the limitation of cracking and the formation of hydrated phases in the cementitious matrix. However, the second zone within the ordinary concrete shows multi-identified cracks producing a localized damage zone (see Figs. 9e-f).

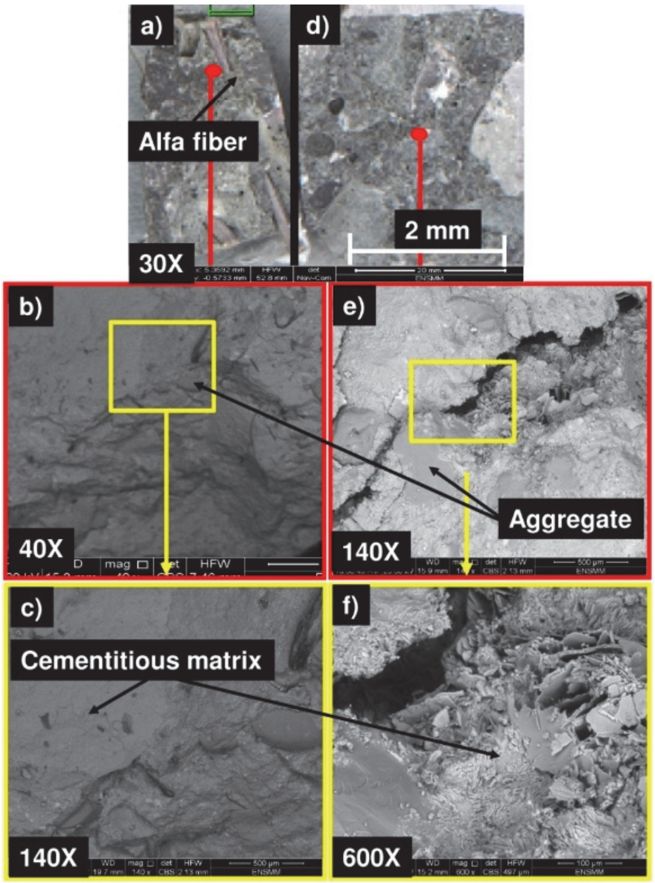


Figure 9: SEM micrographs: (a-c) Alfa-reinforced concrete and (d-f) ordinary concrete.

In Fig. 10a the load-deflection curves obtained under three-point bending test for the specimens BT, BFV7, BFV8, and BFV9 are reported, whereas in Fig. 10b those related to BT, BFV3, BFV6 and BFV9 specimens are shown. The curves plotted show that for ordinary concrete, in the first elastic stage, the load varies in a quasi-linear manner up to a given load. At this point, the resistance drops abruptly. For fiber reinforced concretes, three stages are observed: a linear trend characterized the first stage, whereas in the descending branch (second stage); the fibers limit the cracks and their opening by sewing. Finally, in the third stage, the load tends to be constant and is vanished only after a large deformation. This decreasing is due to the presence of fibers at the level of the crack. The failure then occurs either by tearing or by fiber breakage.

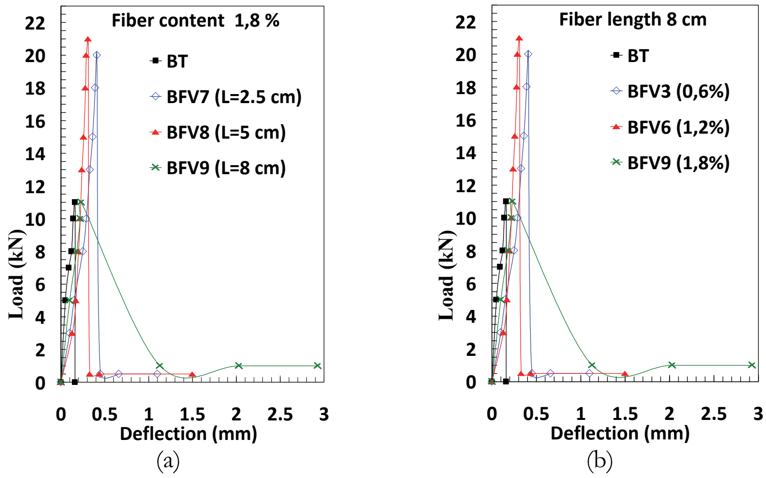


Figure 10: Load-deflection curve: (a) for a fiber content of 1.8 % and (b) for a fiber length of 8 cm.

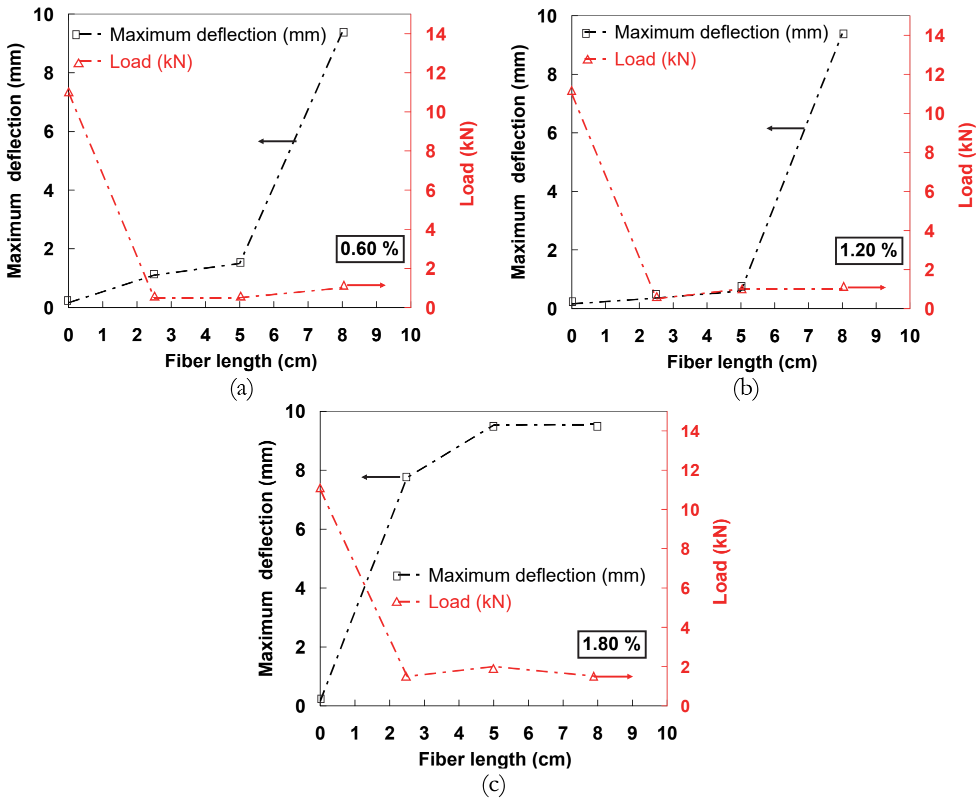
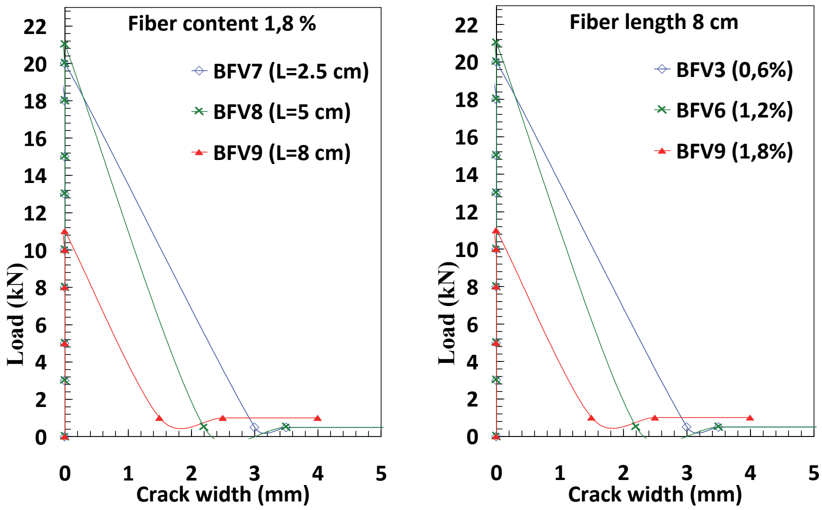


Figure 11: Maximum deflection versus fiber length for fiber content: (a) 0.60 %, (b) 1.20 %, and (c) 1.80 % by volume.

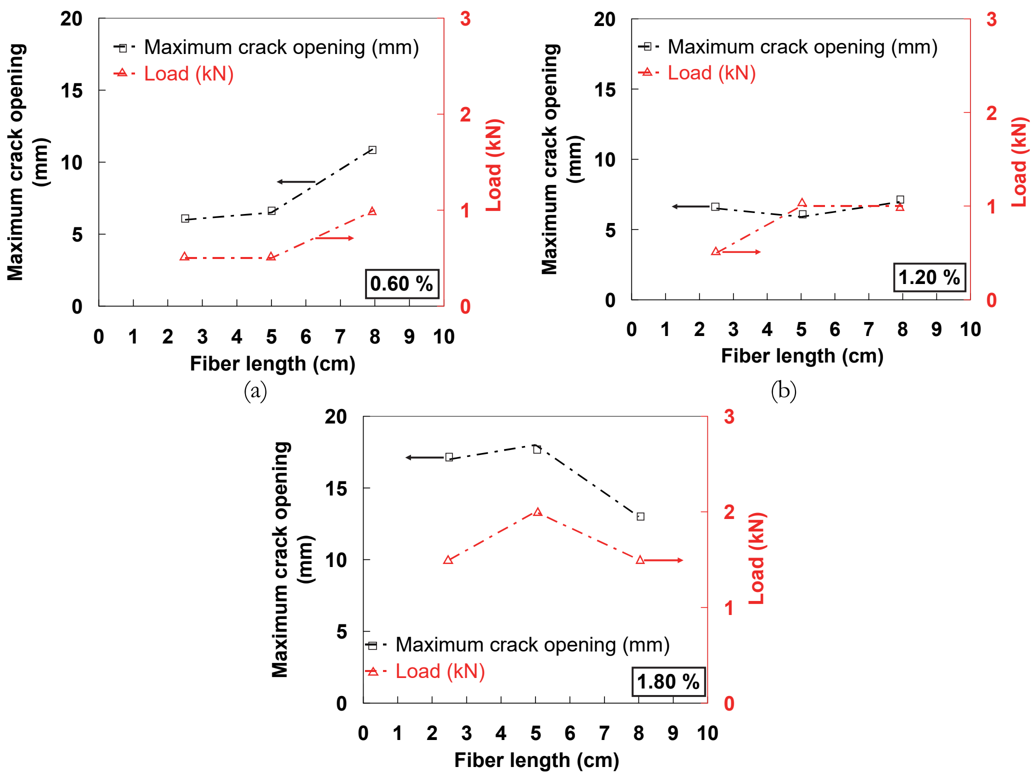
Figs. 11a-c show the improvement of the ductility of concrete. For the length of Alfa fibers more than 5 cm, the deflection is negatively affected by the presence of fibers. The mechanical behavior in tensile bending of the different types of concrete is better by using short fibers 2.5 cm in length. By considering the fibers content, a content of 1.20 % leads to good results in terms of deflection.

In Fig. 12 the load-crack width curves obtained under three-point bending test for the specimens BFV7, BFV8, and BFV9 are reported, whereas in Fig. 12b those related to BFV3, BFV6 and BFV9 specimens are shown. The load- crack opening curves in Fig. 12 show a linear elastic trend up to a given load value corresponding to the nucleation of the first crack. The maximum load varies according to the fiber length and content. Then the trend is characterized by a load deceasing and an increasing in the crack opening. Finally, the curves become flattered (horizontal) and then vanishonly after a large crack, confirming that the specimens have reached their total failure (see Fig. 12a and Fig. 12b).



(a) (b)

Figure 12: Load-crack width curve: (a) for a fiber content of 1.8% and (b) for a fiber length of 8 cm.



(a) (b)

(c)

Figure 13: Maximum crack opening versus fiber length for fiber content: (a) 0.60 %, (b) 1.20 %, and (c) 1.80 % by volume.

It can be observed that the fiber length is an important factor that greatly affects the mechanical behavior and cracking of the concrete for the different contents examined. Thus, the crack opening of the specimen reinforced with Alfa fibers of 8

cm length can reach 13 mm without breaking for a content of 1,8 %, whereas the reinforced one with fibers of 5 cm length can reach 18 mm.
The length of the fibers and their contents become essential parameters characterizing the opening of cracks. Indeed, the load required to pull out the fibers is a function of the adherent length of the fiber, see Fig. 14.

Figure 14: Resistance of Alfa fibers to crack propagation.

CONCLUSION

The objective of the present study is to evaluate the performance and mechanical behavior of Alfa fiber reinforced concrete by varying two parameters, that is the fiber content and length. The main conclusions drawn from this research study are:

- The addition of Alfa fibers in the concrete does not increase the compressive strength. On the contrary, a slight decreasing has been found for fiber content 0.6 and 1.2 % by volume. On the other hand, this fall is remarkable, with a content of 1.8 %. In particular, for the case with a length of 8 cm, one can explain it by slowing down the phenomenon of hydration because of the presence of the cellulose and the discontinuity of the crystalline network of the cement matrix with the formation of balls (excess of fibers).
- The higher compressive strength of fiber-reinforced concrete is obtained for a content 1.2 % of fibers with a length of 5 cm (BFV 5), whose compressive strength is close to that of the ordinary concrete (57.7 MPa).
- The addition of Alfa fibers in concrete allowed the increase of the tensile strength compared to that of the ordinary concrete (BT), particularly for fiber contents of 0.6 and 1.2 % and lengths of 2.5 and 5 cm. The gains of tensile strength going up to the value of 54,41 %.
- On the other hand, a fiber content of 1.8 % and a length of 8 cm did not give satisfaction or significant improvements in tensile strength. For this point, the gain in strength has been calculated compared to the tensile strength of ordinary concrete.
- Overall, the addition of Alfa fibers has a favorable effect on the crack nucleation and post-cracking behavior.
- The failure mode of the tested specimens shows that the inclusion of Alfa fibers improves the ductility of the concrete. This ductility varies according to the content and the length of Alfa fibers.

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