Evaluation of Shear Strength in Polyolefin Fiber-Reinforced Concrete

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Summary

This study evaluates the shear strength of polyolefin fiber-reinforced concrete and proposes an expression for calculating this parameter based on experimental results. Four concrete mixes were produced, each exhibiting an average compressive strength of 40 MPa. The variable parameter was the polyolefin fiber volume fraction (0%, 0.25%, 0.50%, and 0.75%). Shear strength tests were conducted on 12 prismatic concrete specimens with 100 mm × 100 mm × 400 mm dimensions. The results indicated that incorporating polyolefin fibers into the concrete increased shear strength by up to 30%, and the proposed expression led to shear strength values that were very close to those of the experimental ones.

1 INTRODUCTION

Concrete is a heterogeneous and fragile material with a low deformation capacity. It has high compressive strength but low tensile strength, which makes its rupture abrupt.

Concrete shear failure is also brittle and abrupt. In the structural design of reinforced concrete beams, closed vertical stirrups support shear force, while in the case of prestressed flat or mushroom slabs, stirrups or connectors (studs) are used.

One way to avoid this type of failure is to add dispersed and discontinuous short fibers randomly distributed to fresh concrete mass.

Fibers modify the concrete cracking mechanism due to their bridging action on the micro and macro cracks in the concrete matrix, which increases concrete fracture toughness.

In the microcracking process, bridging action (debonding, sliding, pull-out, or yield of fibers) affects the coalescence and propagation of microcracks. These effects delay and control macrocracking, increasing the energy demand for crack advancement.

Adding some type of fibers (especially steel fibers) to concrete beams can increase their shear strength and partially or entirely replace their transverse reinforcement, as these fibers have high tensile strength and high modulus of elasticity.

This increase in shear strength is related to the ability of concrete with fibers to resist and redistribute tensile stresses in the diagonal direction of the cracked beam, which causes the formation of different cracks with smaller widths.

Fibers added to plain concrete have the main advantages of increasing shear strength, gains in deformation capacity (ductility), deformation energy absorption (tenacity), impact resistance, and homogenization of crack distribution.

However, adding fibers to fresh concrete mass reduces its workability, which is directly proportional to the fiber volume fraction. To overcome this problem, water-reducing admixtures (plasticizers or superplasticizers) are used in concrete; the quantity depends on the cement mass of concrete.

This study conducted a test program to evaluate the shear strength of concrete reinforced with polyolefin fibers. An expression for calculating this parameter was proposed based on the experimental results of four concrete mixes.

2 SOME CONCRETE SHEAR TESTS

Different concrete tests and specimens were proposed to evaluate its shear strength along the failure plane. Push-offtests of Z-type specimen, as shown in Fig. 1, have been quite common in determining concrete shear strength. The specimen for this test is the union of two “L” shaped blocks connected through a plane in which the shear stresses, generated by a compression force, are distributed.

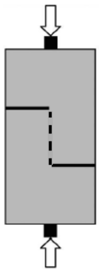

Fig. 1 Shear test scheme on Z-type specimen

This test is very sensitive to eccentricity in the application of compression force. If there is eccentricity, rupture may occur by bending rather than shear force. Furthermore, the specimen must be made of reinforced concrete, making adding fibers to the concrete difficult.

Other tests, which allow the propagation of cracks in a mixed mode (by opening the notch mouth and by shear) according to fracture mechanics, were developed for plain and fiber-reinforced concrete prisms, such as those shown in Fig. 2. In all of these prisms, there is a notch(s) made along its width on the lower edge or the outer edges.

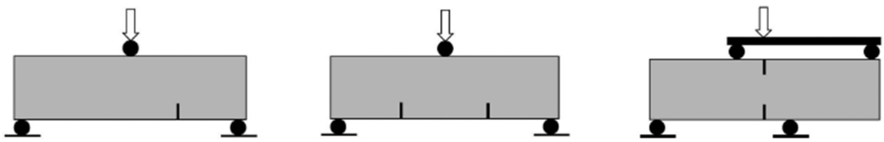

Fig. 2 Shear test scheme on concrete prisms with notch(s)

In Fig. 2 (left) and (middle), the concrete prism is simply supported and loaded with a concentrated load in the middle span. As shown in Fig. 2 (left), in the right shear span, a notch was made in the tension edge along the prism width so that the formation of a shear crack can be induced in the region from the top of the notch to the point of load application. In the case of Fig. 2 (middle), a notch was made in each shear span of the prism, which provokes the formation of two shear cracks (one in each shear span).

In Fig. 2 (right), the concrete prism is supported in two points and loaded with two concentrated loads. In the middle of its length, two notches were made along the prism width, one on its lower edge and the other on its upper edge, to cause the formation of a shear crack in the region between the top of the lower notch and the bottom of the upper notch.

Reference [1] recommends the test scheme illustrated in Fig. 3 to quantify the shear strength of plain and fiber reinforced concrete. The structural scheme of this test is similar to that shown in Fig. 2 (right). A notch was made along the perimeter in the middle of the concrete prism. When a concrete prism fails, a single rupture plane is formed by direct shear.

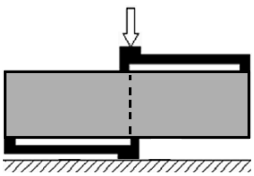

Fig. 3 Direct shear test scheme on simple notched concrete prism

Reference [2] indicates a direct shear failure test for steel fiber reinforced concrete prisms, whose structural scheme is presented in Fig. 4. Two notches were made along the perimeter of a concrete prism to induce more controlled crack planes.

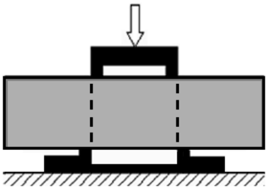

Fig. 4 Direct shear test scheme on the double notched concrete prism

The steel fiber reinforced concrete prism is supported on metallic apparatus at two points. It is supported using another metallic apparatus that simulates two concentrated loads whose ends are aligned with those of the two points of the lower apparatus. Thus, the prism ruptures due to double shear because two rupture planes are formed.

3 TEST PROGRAM

A total of 12 prismatic measuring 100 mm × 100 mm × 400 mm in size and 24 cylinders measuring 100 mm × 200 mm in size concrete specimens were cast in this study.

Four concrete mixes were performed: one plain and three polyolefin fiber reinforced concrete. The variable parameter was the polyolefin fiber volume fraction (V_f = 0%, 0.25%, 0.50% and 0.75%).

The steel molds of all concrete specimens were covered with plastic to prevent water loss. After the concrete had cured in 249 days, these molds were demolded, and tests were carried out to determine its shear strength, compressive strength, and splitting tensile strength, using a servo-hydraulic press with a capacity of 2000 kN.

3.1 Materials and Mixes

The concrete mix, without polyolefin fibers, was performed to achieve a compressive strength of 40 MPa. It was a proper mix of Portland cement (type III), fine aggregate (natural sand), coarse aggregate (crushed gneiss stone with a maximum size of 19 mm), potable water, and plasticizer (water-reducing admixture). Table 1 shows the concrete mix proportions used for each group.

Table 1 Concrete mixes proportions

Concrete mix	1	2	3	4
Cement (kg/m^3)	318	318	318	318
Sand (kg/m^3)	800	800	800	800
Coarse aggregate - maximum size 9.5 mm (kg/m^3)	515	515	515	515
Coarse aggregate - maximum size 19 mm (kg/m^3)	485	485	485	485
Water (kg/m^3)	97	97	97	97
Admixture (kg/m^3)	2.8	2.8	2.8	2.8
Fiber volume fraction (%)	0	0.25	0.50	0.75

The polyolefin fibers used in this study [3], shown in Fig. 5, are bi-component macrofibers with a structured surface and a rough surface that ensures bonding within the concrete mortar.

According to the manufacturer, these fibers serve as a structural reinforcement, increase the impact resistance of the concrete, prevent sedimentation (the subsequent settlement of the concrete matrix), create a high level of resistance for concrete structures exposed to aggressive water conditions, and can also be used in structural applications and prefabrication applications, such as slabs and concrete walls, industrial floors, outside standings, concrete repair works, concrete piles, special foundation works and different special applications. The recommended approximate dosage for polyolefin fibers as a structural reinforcement is 2.0 kg/m^3 to 7.5 kg/m^3 (V_f = 0,22% to 0,82%) of concrete. According to the manufacturer, the characteristics and properties of polyolefin fibers can be seen in Table 2.

Fig. 5 View of polyolefin fibers

Table 2 Polyolefin fibers properties and characteristics

Properties/characteristics	Value
Bulk density	0.91
Length (l_f)	35 mm
Number of fibers per kg	about 150,000
Tensile strength	600 MPa
Modulus of elasticity	> 11 GPa
Softening point	≈ 150 °C
Equivalent diameter (d_f)	0.50 mm

Comparing the micrograph shown in Fig. 6 (left), obtained from a scanning electron microscope [4], with that seen in Fig. 6 (right), according to the manufacturer's catalog [3], it was noted that the polyolefin fiber cross-section may resemble an elliptical section with axes measuring 0.70 mm × 0.35 mm in dimensions.

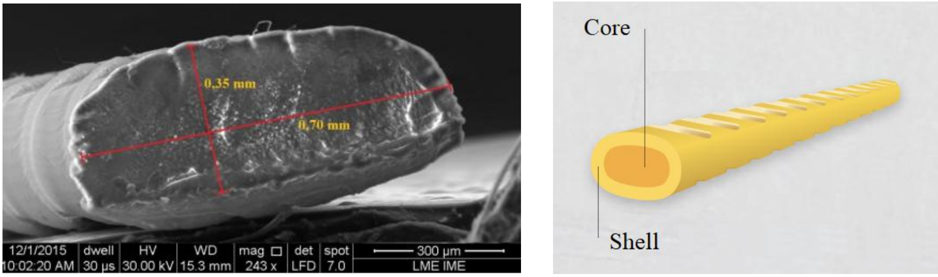

Fig. 6 3D-Views of a polyolefin fiber

3.2 Shear Tests

Fig. 7 shows the schematic of the shear test setup [1]. Because of the specimen's small cross-section dimensions, a notch was not made along the perimeter in the middle of the concrete prism.

The concrete shear strength τ_{max} was calculated as in (1).

$$\tau_{max} = {P_{max}}/{A} \tag{1}$$

where P_{max} is the maximum compressive load supported by the specimen, and A is the cross-section area of the shear plane of the specimen, which is 100 mm × 100 mm.

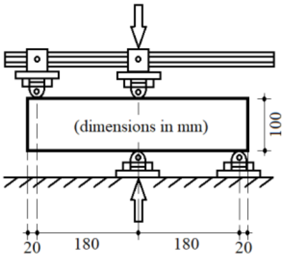

Fig. 7 Schematic of shear tests setup

4 RESULTS AND DISCUSSION

The average results of compressive strength f_{cm}, splitting tensile strength $f_{ct,spm}$, and shear strength τ_{max}, which were obtained by taking the average of three concrete specimens, are gathered in Table 3.

Table 3 Average results of concrete specimens

Concrete mix	f_{cm} (MPa)	$f_{ct,spm}$ (MPa)	τ_{max} (MPa)
1 – V_f = 0%	43.1	3.52	4.14
2 – V_f = 0.25%	41.4	3.20	4.55
3 – V_f = 0.50%	40.4	4.59	4.69
4 – V_f = 0.75%	39.2	3.63	5.38

In Fig. 8, the values of f_{cm} for each concrete mix tested can be seen from Table 3, which were between 39.2 MPa and 43.1 MPa. It can be observed that these values decreased with the increase in V_f up to about 9%, because polyolefin fibers have a lower modulus of elasticity than that of concrete and can create voids inside the concrete. Reference [4] reported the same behavior for polyolefin fiber reinforced concrete cylinders.

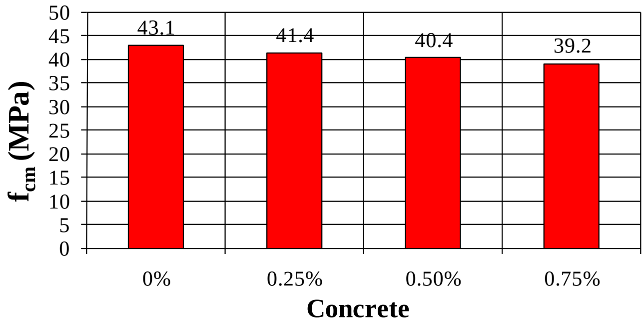

Fig. 8 Values of compressive strength for each concrete mix

On the other hand, the values of $f_{ct,spm}$, between 3.20 MPa and 4.59 MPa, shown in Fig. 9, tended to increase with the increment in V_f, except for concrete mix 2 (V_f = 0.25%). This can be explained by the fact that the 35 mm long fiber does not provide adequate anchorage between the cracked parts of the concrete cylindrical specimen.

When 0.25% polyolefin fibers were added to concrete, the value of $f_{ct,spm}$ decreased by about 9%, but for additions of 0.50% and 0.75%, the values of f_{ct},spm increased by about 30% and 3%, respectively.

In relation to splitting tensile strength, V_f = 0.50% seems to be the optimum value for this type of concrete tested.

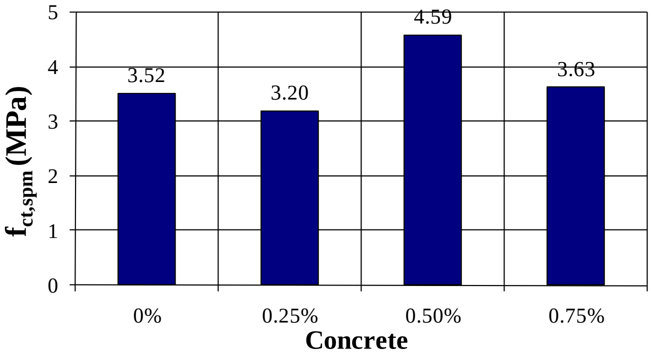

Fig. 9 Values of splitting tensile strength for each concrete mix

The values of τ_{max} for each concrete mix tested can be seen in Fig. 10, which were between 4.14 MPa and 5.38 MPa. It was verified that τ_{max} for plain concrete was equal to 4.14 MPa. With the addition of polyolefin fibers until $V_f = 0.75\%$, the values of τ_{max} growth up to 30%.

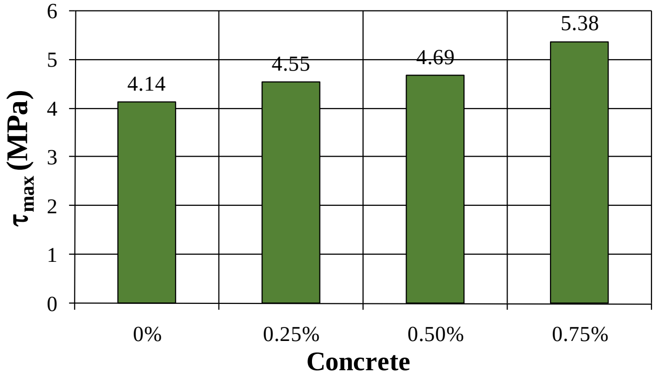

Fig. 10 Values of shear strength for each concrete mix

The shear strength of fiber-reinforced concrete depends on some parameters, such as plain concrete compressive strength f_c, and fiber parameters, such as volume fraction V_f, length l_f, and equivalent diameter d_f.

This study suggests evaluating the shear strength of polyolefin fiber reinforced concrete, as in (2), in which the first portion refers to the shear strength of plain concrete and the second one to the influence of polyolefin fibers.

$$\tau_{max} = \frac{0.3 \times f_c^{2/3}}{k_1} + k_2 \times V_f \times l_f / d_f \tag{2}$$

where f_c in MPa, V_f in %, $k_1 = 0.9$ and $k_2 = 0.02$.

Table 4 presents the experimental and calculated shear strength results of tested concrete specimens and the ratio between these results. It should be noted that each experimental value was found from the average of three tested specimens.

Fig. 11 compares the experimental shear strength values in this study's test program and the calculated shear strength as in (2).

The calculated shear strength results were lower than the experimental ones, except for the calculated result from the polyolefin fiber reinforced concrete specimen, which was $V_f = 0.50\%$.

On average, the experimental shear strength value was only about 1% higher than the calculated shear strength value.

Table 4 Experimental and calculated shear strength results

Concrete mix	$\tau_{max,exp}$ (MPa)	$\tau_{max,cal}$ (MPa)	$\tau_{max,exp} / \tau_{max,cal}$
1 – V_f = 0%	4.14	4.09	1.01
2 – V_f = 0.25%	4.55	4.49	1.01
3 – V_f = 0.50%	4.69	4.84	0.97
4 – V_f = 0.75%	5.38	5.19	1.04

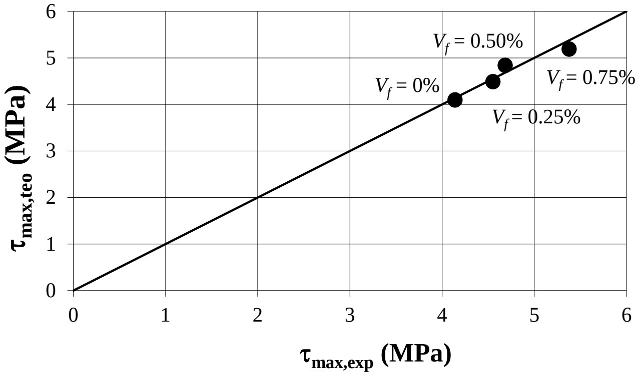

Fig. 11 Values of shear strength for each concrete mix

At the end of the shear test, the view of the plain concrete prism is illustrated in Fig. 12 (left), while the view of the polyolefin fiber-reinforced concrete prism of V_f = 0.50% is shown in Fig. 12 (right). It is noted that, due to the polyolefin fibers, there was no separation between the cracked parts in a concrete prism. This fact occurred for all polyolefin fiber reinforced concrete prisms tested. The higher the value of V_f, the less fragile and abrupt the rupture mode of concrete prisms.

Fig. 12 Views of concrete prims ruptured

5 CONCLUSIONS

From the results of centered uniaxial compression, diametrical compression, and shear tests of plain concrete and polyolefin fiber reinforced concrete (V_f = 0%, 0.25%, 0.50%, and 0.75%), the following conclusions were reached:

- the addition of polyolefin fibers to concrete led to an increase in its properties, except for the compressive strength of all polyolefin fiber reinforced concrete and for splitting tensile strength of polyolefin fiber reinforced concrete of V_f = 0.25%;
- concrete compressive strength values decreased with an increase in V_f by up to about 9%;

- splitting tensile strength and shear strength values increased with increment in V_f by up to approximately 30%;
- the expression proposed for shear strength of polyolefin fiber reinforced concrete led to values very close to experimental ones;
- the rupture mode of all polyolefin fiber reinforced concrete prisms was less fragile and abrupt than that of concrete prisms;
- polyolefin fiber, depending on its volume fraction, can be a good option for using in concrete structure works where greater ductility, tenacity, and control of cracking of concrete are desired.

Acknowledgments

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References

[1] Federation Internationale de la Precontrainte. 1982. *Shear at the Interface of Precast and in-situ Concrete*. Lausanne: FIB Report.

[2] JSCE-SF6. 1990. *Method of test for shear strength of steel fiber reinforced concrete*. Tokyo: JSCE.

[3] Contec Fiber. 2017. “Concrix HS35” Accessed January 13. https://contecfiber.com/en/

[4] Santana, Claudeny. 2017. “Propriedades de Concretos Projetados para Túneis”, MS thesis, Instituto Militar de Engenharia.