Investigation of direct shear strength mechanisms of steel and PVA fiber-reinforced concrete

Investigação dos mecanismos de resistência ao cisalhamento direto em peças de concreto com fibras de aço e PVA

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Abstract

Some mechanical properties of concrete can be improved with the addition of other materials, such as the incorporation of fibers, which results in increased tensile strength and toughness, presenting post-cracking behavior that significantly contributes to the transfer of shear stresses, especially in planes that are propitious to the formation of cracks. To evaluate the effects of the addition of fibers to concrete, in terms of the ultimate shear strength and the mechanisms that constitute it, such as cohesion between the component materials, aggregate interlock, friction and dowel action, an experimental program was carried out. Two mixtures were produced from a conventional concrete mix, with the addition of 0.5% steel fibers and 0.2% synthetic polyvinyl alcohol, PVA fibers. Specimens for direct shear testing, push-off type, were molded, with and without transverse shear reinforcement, and a steel-concrete bond condition was set as a variable. The results showed that the addition of steel fibers results in a significant increase in the shear strength of concrete, an effect not observed with PVA fibers. The aggregate interlock and cohesion mechanisms were responsible for approximately 70% of the ultimate shear strength in all the concrete tested, while the rest was attributed to friction and the dowel effect.

Keywords: Direct shear; push-off; steel fibers; PVA fibers; dowel action.

Resumo

Algumas propriedades mecânicas do concreto podem ser melhoradas com a adição de outros materiais, como a incorporação de fibras, o que resulta no aumento da resistência à tração e tenacidade, apresentando um comportamento pós-fissuração que contribui significativamente na transferência de tensões cisalhantes, principalmente em planos propícios à formação de fissuras. Para avaliar os efeitos da adição de fibra ao concreto na resistência última ao cisalhamento e nos mecanismos que a compõe, tais como coesão entre os materiais componentes, engrenamento dos agregados, atrito e efeito de pino, um programa experimental foi realizado, no qual a partir de um traço de concreto convencional foram produzidos outros dois traços com adição de 0,5% de fibras de aço e 0,2% de fibras sintéticas de PVA. Corpos de prova para ensaios de cisalhamento direto do tipo *push-off* foram moldados, tendo como variável a ausência ou existência da armadura transversal ao plano de cisalhamento e sua condição de aderência. Os resultados mostraram que a adição de fibras de aço conferiu um acréscimo significativo na resistência ao cisalhamento do concreto, efeito este não observado com as fibras de PVA. Os mecanismos de coesão e engrenamento dos agregados foram responsáveis por aproximadamente 70% da resistência última ao cisalhamento em todos os concretos utilizados, enquanto o restante foi atribuído ao atrito e ao efeito de pino.

Palavras-chave: Cisalhamento direto; *push-off*; fibras de aço; fibras PVA; efeito de pino.

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Introduction

Concrete, with an annual consumption of more than 25 billion tons, is one of the materials most used in the construction industry due to its high compressive strength, ease of handling and the wide availability of raw materials (WANG *et al.*, 2019; TENG; AFROUGHSABET; OSTERTAG, 2018). However, despite its wide usage, this material has some limitations due to its low tensile strength, tendency to crack and loss of strength after cracking.

In conventional concretes, the formation of cracks is an obstacle, preventing the proper propagation of tension inside the material. Among the numerous improvements that are currently applicable, fiber-reinforced concrete (FRC) has been used in infrastructure works such as tunnels, roads, airports and parking lots (LIU *et al.*, 2021). The presence of fibers in concrete contributes to reducing the stress concentration at the end of the cracks, acting as a stress transfer bridge and decreasing their propagation speed (GRZYMSKI; MUSIAŁ; TRAPKO, 2019). Fibers also increase tensile strength and bending, absorb deformation energy and improve ductility (GALI; SUBRAMANIAM, 2019).

One of the most important aspects in the use of fibers is to guarantee its effectiveness in adherence to the cementitious matrix, since fiber-reinforced concrete is characterized by presenting an interfacial transition zone in the vicinity between the fiber and the matrix (XU; DENG; CHI, 2017). The microstructure in this zone is different, as the particulate nature of fresh concrete leads to the formation of water-filled spaces around the fibers, due to the inefficient packing of cement grains around their surface. This mechanism results in the formation of a porous region in relation to the cementitious matrix and is, consequently, less resistant, favoring their pullout (MUKHOPADHYAY; KHATANA, 2014).

In addition to the cost-benefit presented by concrete, steel is most used to produce fibers, as it has a high modulus of elasticity and high mechanical strength (WANG *et al.*, 2019). One of the great advantages of using steel in the manufacture of fibers is the wide variety of shapes and sizes that are achievable (e.g., with straight fibers or with hooks at the ends). Steel fibers with hooks improve the anchorage in concrete due to the plastic deformation that the hook has to suffer before the fiber is completely pulled out (ABDALLAH; FAN; REES, 2018).

Among the synthetic fibers, those produced with polyvinyl alcohol (PVA) stand out because they have high tensile strength, good adhesion to the alkaline cementitious matrix and high corrosion resistance. Their addition in composites is usually carried out to improve the properties of tenacity and high post-load peak strain due to strain hardening (ARAIN *et al.*, 2019). Furthermore, as it has a low specific mass, there is a small reduction in the overall weight of the structure.

However, according to Ghasemi, Ghasemi and Mousavi (2018), the improvements resulting from the addition of fibers do not yet have a quantification model, as they depend on several factors. These factors include the orientation of the fibers, their ability to adhere to the cement matrix and the kinetics of effects superposition of shear resistant mechanisms (LIU *et al.*, 2021; VITOR; SANTOS; TRAUTWEIN, 2018).

Since the proposition of the Shear Friction Theory (BIRKELAND; BIRKELAND, 1966), several studies have proposed equations to determine the shear strength of concrete structures by correlating this strength with the compressive strength, the transversal reinforcement ratio used and the compressive stress applied perpendicular to the plane (HOFBECK; IBRAHIM; MATTOCK, 1969; LOOV; PATNAIK, 1994; MATTOCK; HAWKINS, 1972; RANDL; ZILCH; MÜLLER, 2008; RUIZ; MUTTONI; SAGASETA, 2015; SOETENS; MATTHYS, 2017).

The main mechanisms of shear stress transfer are aggregate-matrix cohesion, aggregate interlock, friction between crack surfaces and transverse reinforcement dowel action. The relative contributions of these parameters vary with the vertical displacement of the shear plane and crack opening. It is known that cohesion comes from the physical and chemical bonds of the material; the aggregate interlock is dependent on the surface roughness and crack kinematics; and friction is directly linked to dowel action, the conditions of adhesion of the reinforcement to the concrete and the transfer of bending and tensile stresses of the bar (HUBER; HUBER; KOLLEGGER, 2019).

The main concern about the shear phenomenon is gaining an understanding of how the mechanisms act synergistically, overlapping in some situations, and affecting each other due to the sliding of the interface (RANDL, 2013). In other words, although the effects of the stress transfer mechanisms are understood separately, the effects resulting from the mutual action of these mechanisms are still being investigated in the literature.

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Associated with this, and observing the growing use of fibers in concrete, studies on the effects of fibers, either on their own or combined with conventional reinforcement, contribute to an understanding of the action of stress transfer mechanisms in fiber reinforced concrete. Therefore, this paper aims to evaluate the influence of fibers in the mechanisms of resistance and transfer of forces in direct shear in reinforced concrete.

Materials and methods

An experimental program was carried out by means of direct *push-off* shear tests on three different concrete mixes. The mixes varied with respect to steel and PVA fiber content, and the transversal reinforcements, both with and without contact with the cementitious matrix.

Materials

Two fiber-reinforced concrete mixes were produced from a reference mix of conventional concrete (CC), with an axial compressive strength close to 40 MPa. The addition of steel fiber reinforcement (SFRC) or synthetic fibers of polyvinyl alcohol (PVA-FRC), was carried out in the proportions (by volume) 0.5% and 0.2%, respectively. The quantities of materials required to produce 1 m³ of each of the mixes are presented in Table 1.

The binder used was Portland Cement of High Initial Resistance, CPV-ARI, with a specific mass of 3.05 g/cm³. The fine and coarse aggregates used were natural river sand and crushed basaltic rock, respectively, and their physical properties are shown in Table 2.

Wirand® model FF1 double-ended fibers were used to produce the SFRC and KURALON™ RF400 fibers were used to produce PVA-FRC, as shown in Figure 1(a) and (b), respectively. The mechanical properties are presented in Table 3.

Figure 1 – Fibers used.

(a) SFRC   (b) PVA
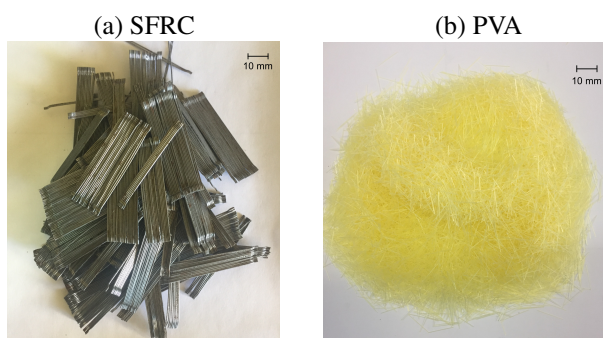
Source: The authors.

In these mixes, a superplasticizer additive (SP), composed of melamine-formaldehyde resin, was used in the proportion of 1.85% of the cement mass. This grade was used to obtain concrete with a slump close to 70 mm for all mixes.

Using a concrete mixer with an inclined axis, 45 liters of concrete were produced from each mix. Three prismatic specimens were molded for direct shear tests and six cylindrical specimens, 10 cm in diameter and 20 cm in height, were used to determine the axial compression strength, diametral tensile strength and modulus of elasticity.

All of the specimens were demolded and identified 24 hours after molding. The cylindrical specimens were subjected to curing in a tank of water saturated with lime and the specimens intended for direct shear tests were kept inside the laboratory, at an average temperature of 23.7ºC and average relative humidity of 63%, for 28 days.

Direct shear tests

To carry out the *push-off* direct shear test, specimens with dimensions similar to those used by Savaris (2016) were used, as shown in Figure 2. In the region of the shear plane, two solid wood fillets were inserted on the sides of the molds, to reduce the thickness of the specimen and induce rupture in this plane.

Figure 2 – Push-off test specimens dimensions
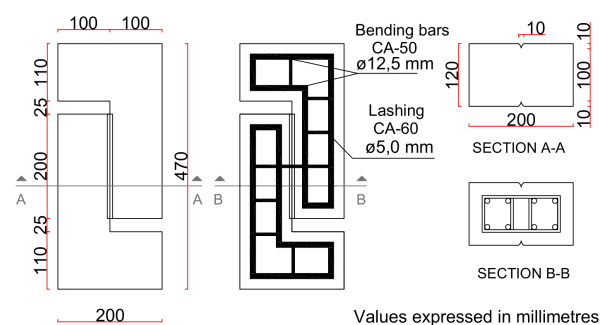
Source: The authors.

In all of the specimens used in the direct shear test, reinforcement was used to prevent cracking outside the shear plane. This consisted of CA-50 bars in a 12.5 mm diameter L-shape and CA-60 closed stirrups of 5.0 mm. To evaluate the different shear strength mechanisms, nine specimens were molded (three from each concrete mix), with the following reinforcement configurations transversal to the shear plane:

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Table 1 – Materials proportions of concretes mixtures (kg/m^3).

Mix	Cement	Coarse aggregate	Fine aggregate	Water	Fibers	SP
CC	430	1050	795	180	0	0
SFRC	430	1050	795	180	40	2.58
PVA-FRC	430	1050	795	180	2.50	2.58

Source: The authors.

Table 2 – Physical properties of aggregates.

Properties	Fine aggregate	Coarse aggregate
Finesse Module	2.12	-
Maximum characteristic dimension (mm)	-	9.52
Powder Material Content (%)	0.75	1.42
Dry specific mass (g/cm^3)	2.71	3.07
Saturated dry surface specific mass (g/cm^3)	2.67	2.88
Specific mass (g/cm^3)	2.64	2.79

Source: The authors.

Table 3 – Materials proportions of concretes mixtures (kg/m^3).

Fiber	Length (mm)	Diameter (mm)	Tensile strength (MPa)	Deformation at rupture (%)	Young Modulus (GPa)
Steel	50	1.0	>1100	<4	210
PVA	12	0.20	975	9	27

Source: Adapted of Wirand® (2021) and Kuraray (2021).

C1 specimens: to determine the shear strength of concrete without transverse reinforcement, Figure 3(a).

C2 specimens: consisting of two 6.3 mm diameter CA-50 steel bars, Figure 3(b), resulting in a reinforcement ratio of 0.3117%, to determine the shear strength of concrete with transverse reinforcement.

C3 specimens: the same reinforcement as the C2 specimen was used, but the bars were greased and wrapped with plastic hoses, Figure 3(c), to quantify the portion attributed to the transverse reinforcement dowel action, but without restriction of the crack opening caused by the reinforcement cross section.

Test instrumentation

The shear strength tests were performed on a universal testing machine with a load capacity of 300 kN. The prismatic specimens were positioned under an articulated base and, using a servo controller, the load was applied with a displacement rate of 0.5 mm/min. The load value was measured using a load cell installed next to the articulated base at the end of the hydraulic piston.

Figure 3 – Push-off specimens models.

(a) C1

(b) C2

(c) C3
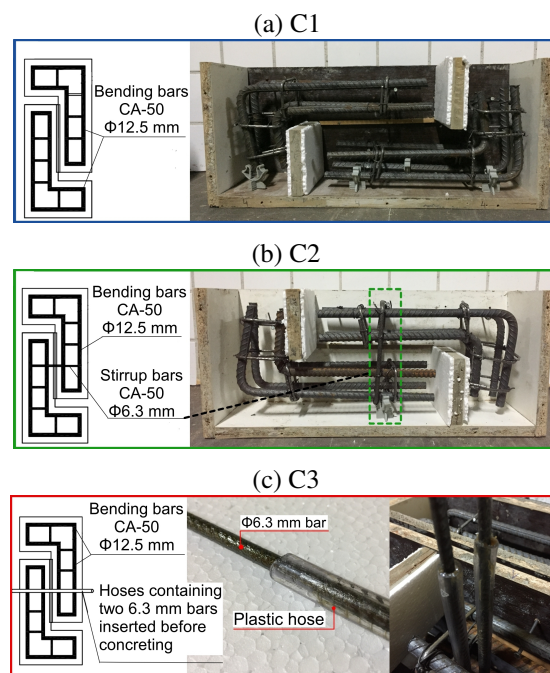
Source: The authors.

The relative and total vertical displacements, as well as the opening of cracks, were measured using three displacement transducers, installed according to Figure 4, and rigid metal bars that were glued to the specimens with epoxy resin. The tests were filmed, allowing the continuous reading of the strain gauges alongside the evolution of the load application.

Figure 4 – Direct shear test instrumentation.
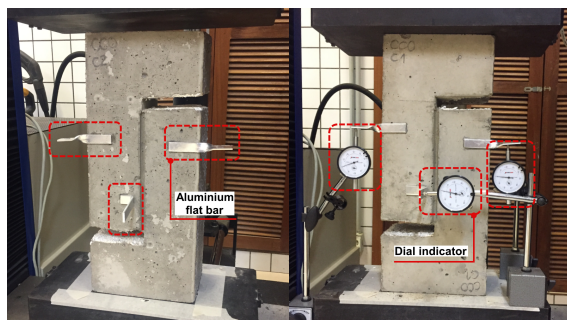
Source: The authors.

Results and discussion

Concrete properties

Table 4 presents the results of the slump test of the concrete mixes evaluated in the fresh state, as well as the averages of the compressive strength (f_{cm}), diametral tensile strength (f_{tm}) and modulus of elasticity (E_c), in the hardened state.

Table 4 – Physical and mechanical properties of fibers

Mix	Slump test (mm)	f_{cm} (MPa)	f_{tm} (MPa)	E_c (GPa)
CC	70	53.5	4.4	37.6
SFRC	74	60.9	6.3	39.8
PVA-FRC	75	59.2	3.7	37.3

Source: The authors.

The addition of steel fibers (SFRC) resulted in increased compressive strength, which is not a consensus among researchers. It is important to mention that no statistical analyses were performed on these properties, due to the small number of molded specimens. Therefore, these values may be just variability in the results of the evaluated specimens. Similar results were presented by Thomas and Ramaswamy (2007).

However, according to Khaloo *et al.* (2014) and Nguyen Tan and Kanda (2020), any addition of fibers only results in a decrease in compressive strength at fiber contents above 1.0%. Araújo *et al.* (2014) also stated that the compressive strength began to be impaired. Such a lack of consensus regarding the results in the literature may be related to the lack of uniformity and agglomeration of fibers resulting from their low dispersion in the concrete mass during mixing. In the present paper, the adequate dispersion of fibers in the concrete did not allow the formation of agglomerates, justifying an increase in the compressive strength.

The mix with the addition of PVA fibers showed a small increase in compressive strength and a reduction in tensile strength, diverging from the results of other researchers (ARAIN *et al.*, 2019; WANG *et al.*, 2019), where there was an increase in tensile strength. The polymeric fiber used showed good adhesion to the cementitious matrix, but it is possible that its anchoring mechanism, its length and/or its low content were not sufficient to ensure an effective tensile strength.

The modulus of elasticity of concrete showed little variation, similar to that observed by Thomas and Ramaswamy (2007) and Araújo *et al.* (2013), however, this emphasizes the need for specific studies on the modulus of elasticity, with a greater number of specimens, in order to statistically prove these results.

Shear strength

After the rupture of the specimens, the ultimate shear stresses were determined, as shown in Table 5. As expected, there is an increase in shear strength with the insertion of the reinforcement, especially when there is adhesion between the reinforcement and the concrete, proving the existence of distinct mechanisms of shear strength.

Table 5 – Physical and mechanical properties of fibers

Mix	Specimen	Ultimate shear stresses (MPa)
CC	C1	5.08
	C2	7.18
	C3	5.37
SFRC	C1	6.25
	C2	8.99
	C3	8.14
PVA-FRC	C1	4.92
	C2	7.08
	C3	5.81

Source: The authors.

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Figure 5 shows the shear stress vs. shear crack opening and a different behavior of the concrete mixes was evidenced. In conventional concrete, Figure 5(a), the C1 and C3 models showed sudden rupturing after reaching the ultimate shear stress.

Figure 5 – Shear stress vs. shear crack opening

(a)

(b)

(c)
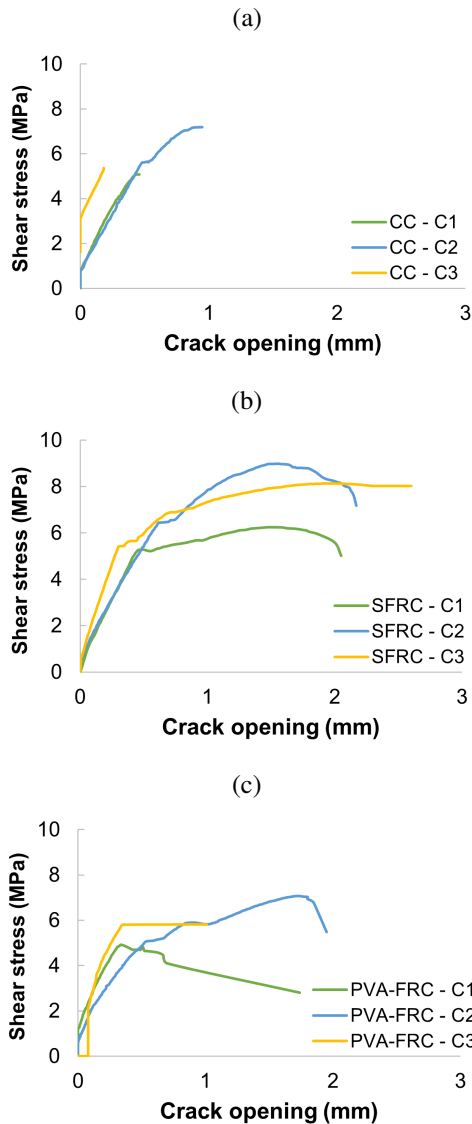
Source: The authors.

Similar to the observations of the tensile strength of concrete, in the C1 specimens with the addition of steel fibers, Figure 5(b) there was an increase in shear strength, while with the addition of PVA fibers, Figure 5(c), the strength remained close to conventional concrete, but with increased ductility of the material. According to Garcez (2009) and Arain *et al.* (2019) the presence of fibers at the interface, even if minimal, should give the concrete some increase in its shear strength. Therefore, the most accepted hypothesis in this situation is that the length of the fiber used, together with its anchoring mechanism, was

not sufficient to guarantee the necessary reinforcement in the shear strength, as well as in the tensile strength.

For the three evaluated mixes, the C2 specimens showed post-cracking behavior with increased shear strength, due to the effective action of the transverse reinforcement. When crack formation occurs, the dowel action, aggregate interlock, and friction between the crack faces, guaranteed by the restriction to the crack opening generated by the transverse reinforcement, continued to cause the transfer of forces, resulting in the highest ultimate shear stresses.

With the suppression of concrete adhesion to the steel bar in the C3 specimens, there was a reduction in shear strength in relation to the C2 model specimens, probably due to the reduction in the compression effect on the crack faces generated by the reaction of the steel bars when pulled. However, the ultimate strength of these specimens presented values higher than the C1 specimens, which proves the effect of dowel action on the shear strength, despite its small magnitude.

Analysis of shear strength mechanisms

In the analysis of the shear strength mechanisms, it was considered that, in the C1 model specimens, the shear strength is given only by the cohesion between the concrete particles and the aggregate interlock. In the model C3 specimens, the dowel action is added due to the presence of the transverse reinforcement, but without adherence to the concrete, avoiding the transfer of tensile stresses to the bars. In the model C2 specimens, the afore mentioned mechanisms act simultaneously with the friction between the crack surfaces, due to the compression force generated by the transverse reinforcement in reaction to the crack opening.

The proportions of shear stress resisted by the different resistance mechanisms are presented in Table 6. In the three evaluated mixes, the cohesion and aggregate interlock represent approximately 70% of the total resistance of the specimen. Despite this pattern, through Figure 6(a)-(c) it is possible to visualize a difference in the surface of the concrete. Comparing Figure 6(b) and Figure 6(c) it is possible to note that CRF-PVA had less fibers across the shear plane than CRFA. This possibly caused the redistribution of forces and stress concentrations in places with a lower concentration of fibers. As commented before, probably the length of the PVA fiber was not enough to guarantee the stress transfer through the crack.

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Table 6 – Physical and mechanical properties of fibers

Mix	Cohesion + aggregate interlock (C1)	Dowel action + friction (C2-C1)	Dowel (C3-C1)	Total (C2)
CC	5.08	2.10	0.29	7.18
SFRC	6.25	2.74	1.89	8.99
PVA-FRC	4.92	2.16	0.89	7.08

Source: The authors.

Later, according to Soltani and Ross (2017), with the rupture of cohesion and formation of the crack, the forces are resisted by friction and the dowel action; in this study, this corresponds to approximately 30% of the shear resistance of the parts.

Figure 6 – Crack surface of C1 specimen.

(a)

(b)

(c)
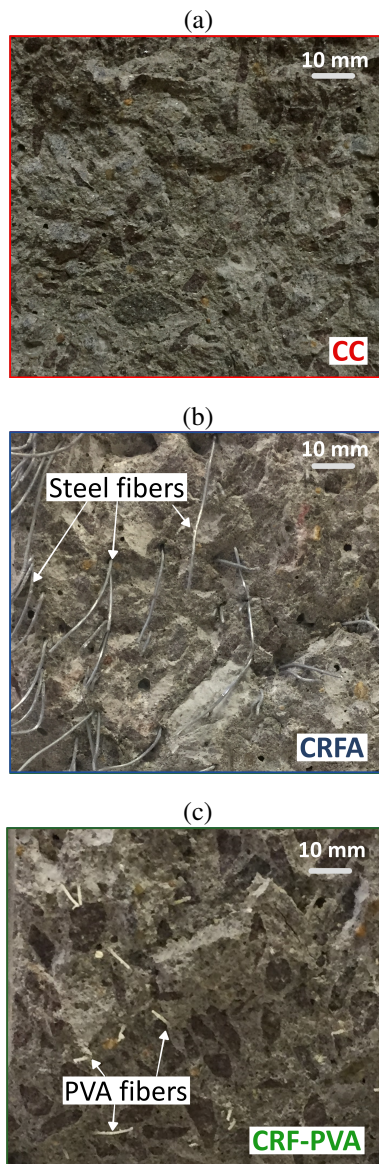
Source: The authors.

As mentioned before, the addition of fibers showed an increase in shear strength in the parts without transverse reinforcement; this corresponds to the cohesion and aggregate interlock and is proportional to the increase in the concrete tensile strength.

Analyzing the resistance obtained with the insertion of the reinforcement without adhesion, considered to be dowel action (C3-C1), an increase in this portion can be seen with the addition of fibers, mainly for steel fibers. This can be explained due to the transversal reinforcement restricting the displacement vertical of the shear plane and thus the fibers act by restricting the opening of the shear crack, maintaining the aggregate interlock and friction.

However, when the sum of the dowel action and friction is evaluated, the resistance variation between the mixes is lower than that found for the dowel action portion alone. Thus, it appears that, although the strength of conventional concrete has a lower contribution from dowel action, this is compensated by a higher proportion of frictional strength, either by a reduction in the roughness of the crack surface or less adherence of the concrete to the steel bars due to the addition of fibers. According to Randl, Zilch and Müller (2008), the strength portions attributed to cohesion, friction and dowel action depend on the crack surface roughness and, in this study, it is verified that the type of fiber used also influences the interrelationship of these portions.

Conclusions

The influence of the addition of steel and PVA fibers on the mechanical properties and strength mechanisms of reinforced concrete parts subjected to direct shear, was evaluated in this paper, using *push-off* tests with different transverse reinforcement conditions. The main conclusions are presented below:

The addition of fibers to concrete resulted in reduced workability compared to conventional concrete, requiring the use of a superplasticizer additive to correct it.

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The mechanical properties of concrete were changed by the addition of fibers, with variations in compressive strength and modulus of elasticity, however, a larger number of specimens must be tested to assess whether these variations are statistically significant.

The use of steel fiber resulted in an increase of approximately 25% in the ultimate shear strength when compared to CC for concrete parts with and without transverse reinforcement, while the use of PVA fibers resulted in a reduction of approximately 12% in this strength.

The portion of shear strength attributed to the cohesion and aggregate interlock (which is usual in structures without transverse reinforcement) corresponded to 70% of the ultimate shear strength of pieces with transverse reinforcement, regardless of the type of fiber used.

The shear strength mechanisms attributed to the dowel action and friction between the shear crack surfaces presented magnitude variations when different types of fiber were adopted, due to the reduction of the roughness of the fractured surface and adherence to the transversal reinforcement.

Studies must be carried out to compare the effects observed in direct shear tests with the results obtained in reinforced concrete beams, as these are subject to bending and shearing. Other mechanisms, such as the arc effect and compression chord, also contribute to shear strength.

Acknowledgments

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