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Study of mechanical behavior of ultra - high performance concrete (UHPC) reinforced with hybrid fibers and with reduced cement consumption

Estudio del comportamiento mecánico del hormigón de ultra-altas prestaciones (UHPC) reforzado con fibras híbridas y con consumo reducido de cemento

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Abstract

This article evaluated mechanical behavior of ultra-high performance concrete (UHPC) reinforced with hybrid steel and polypropylene fibers, with cement consumption of 250 kg/m³ and application of confining pressure in fresh state. The consistency of the mixture was analyzed, as well as mechanical properties of compressive strength, flexural strength and toughness. The percentages of hybridization were 50 to 100% of metal fibers and 0 to 50% of polypropylene fibers. Results showed that the compressive strength of the composite was 180 MPa (26100 psi), despite its low cement consumption of 250 kg/m³ (2.08 lb/gal), with 80% steel fibers and 20% polypropylene fibers. The combination of fibers increased the mixture's toughness. For the composition with 80% steel fibers and 20% polypropylene fibers, the strength for large deformations increased by 191% compared with the mixture with 100% steel fibers, pointing out the benefits of hybridization.

Keywords: *Ultra-high performance concrete (UHPC), hybrid fibers, low cement consumption, mechanical properties, and toughness*

Resumen

En este trabajo se evaluó el comportamiento mecánico de los hormigones de ultra-altas prestaciones (UHPC) reforzados con fibras híbridas de acero y polipropileno, con un consumo de cemento de 250 kg/m3 y aplicando una presión de confinamiento en su estado fresco. Se analizó la consistencia de la mezcla, las propiedades mecánicas de las resistencias a la compresión y flexión, así como la tenacidad. Se usaron porcentajes de hibridación del 50 al 100% de fibras metálicas y de 0 al 50% de fibras de polipropileno. Los resultados muestran que la resistencia a la compresión del compuesto fue de 180 MPa (26.100 psi), a pesar de su bajo consumo de cemento, de 250 kg/m³ (2,08 lb/gal), con 80% de fibras de acero y 20% de fibras de polipropileno. La combinación de fibras incrementó la tenacidad de la mezcla. Para esta misma composición, la resistencia para las grandes deformaciones aumentó en un 191% en comparación con la mezcla que contenía un 100% de fibras de acero, demostrando así los beneficios de la hibridación.

Palabras clave: Hormigón de ultra-altas prestaciones (UHPC), fibras híbridas, bajo consumo de cemento, propiedades mecánicas, tenacidad

1. Introduction

It is known that concrete has limitations towards its ability to resist tensile stresses, which can be compensated by the addition of steel bars or fibers that allow this material to be used in the most diverse structures (Yoo et al., 2017)(Yu et al., 2015a). The development and use of structural materials that contribute to the improvement of mechanical performance has become more frequent due to structures that are increasingly daring and demanding (Chasioti & Vecchio, 2017)(Kang et al. 2016)(Quinino, 2015). Considering the advantages obtained from this type of technology, it is necessary to understand deeply the behavior of elements and components as to improve their structural performance and increase system durability.

Ultra-high performance concrete (UHPC) has shown up as a promising civil construction material for the 21st century, as several studies have been developed regarding their structural behavior and other characteristics (Yoo et al., 2017)(AFGC, 2013)(Guo et al.,2018)(Safdar et al., 2016)(Shin et al., 2017).

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The mechanical properties of UHPC are superior to other concretes, surpassing compressive strength of 120 MPa and tensile strength of 8 MPa, with cement consumption higher than that of traditional concretes (Huang et al., 2017).

Concerning high consumption of binder, cement consumption turns out to be between 1100 and 1300 kg/m³ in most studies (Torregrosa, 2013). However, this high amount of cement is not necessarily the main factor that guarantees the material's mechanical properties, which are linked to other factors such as low porosity, high mixture compactness and reinforcement's usage (Alkaysi et al., 2016)(Christ, 2014)(Wille and Boisvert-Cotulio, 2015). Substituting cements for pozzolans, e.g. fly ash, can grant several benefits to concrete, such as high strength at advanced ages. A substitution of 50 to 60% of fly ash with respect to cement mass can improve the mixture's consistency, reduce water consumption and improve cracking behavior due to the reduction of heat from cement hydration (Wang and Park, 2015).

These superior mechanical properties come from the UHPC matrix packing, among other factors. The use of fine powders with different granulometric composition allows the packing of particles while reducing voids and eliminating the interfacial transition zone (Torregrosa, 2013). Likewise, the *excellent tensile strength and toughness of this composite result mainly from the addition of fibers to the mixture. The type of fiber used sharply affects the performance of the material regarding such properties (Kim et al., 2011). Fiber-reinforced concretes present a distinguishing pseudo-ductile behavior, evidencing an increase to the energy require to break the material (Nguyen et al., 2014).*

Adding more than one type of fiber with distinctive materials and sizes to the mixture improves effectiveness for preventing formation and spreading of cracks on zone submited to tensile stresses. Smaller fibers prevent microcracks, while larger fibers hinder the spread of cracks when these have wider opening (Shin et al., 2017)(Chen & Liu, 2005)(Yu et al., 2015b)

The introduction of more than one type of fiber with distinctive characteristics, be it with respect to the material or only the shape, leads to gains of fracture energy. A matrix with fiber hybridization behaves different from a matrix reinforced with a single type of fiber, which presents central cracking when subjected to simple tensile stress. Nevertheless, the appearance of small cracks before the development of the central fissure can be noted when more than one type of fiber is present (Yoo et al., 2017), culminating in distribution of stresses and increase of load-bearing capacity.

Extensive researches concerning mechanical behavior of UHPC have been developed at several universities, although there is a lack of relevant information on the behavior of this composite with low cement consumption and a hybrid mixture of fibers of steel and polypropylene (Yoo et al., 2017)(Nguyen et al., 2014)(Khan et al., 2017). Aiming to investigate and obtain more information about the mechanical behavior of UHPC in this study, the amounts of fibers of steel and polypropylene were varied and the mixtures were kept with low cement consumption and amount of fibers equals 3%.

2. Experimental procedure

2.1 Materials and proportions

The proportion of materials undertaken for this study was defined using the particle packing theory though the equation 1 (Fennis and Walraven, 2012), where the coefficient of distribution "q" is equal to 0.20.

$$\frac{APD}{100\%} = \frac{D^q - D^q_{min}}{D^q_{max} - D^q_{min}} \quad \textbf{(1)}$$

Table 1 shows the unit composition of the multiple percentages of hybridization of steel and polypropylene fibers, whereas the chemical composition of the binders used is displayed in Table 2.

Table 1. *Proportions of the mixtures experimented (kg/m^3)*

Mixture Type	Cement	Fly Ash	Silica Fume	Sand #1	Sand #2	Quartz powder	Steel fiber	Polyp. fiber
S0/P100	251.8	107.9	213.9	495.8	583.3	291.7	0	27.29
S50/P50	251.8	107.9	213.9	495.8	583.3	291.7	117.75	13.65
S60/P40	251.8	107.9	213.9	495.8	583.3	291.7	141.3	10.92
S70/P30	251.8	107.9	213.9	495.8	583.3	291.7	164.85	8.19
S80/P20	251.8	107.9	213.9	495.8	583.3	291.7	188.4	5.46
S90/P10	251.8	107.9	213.9	495.8	583.3	291.7	211.95	2.73
S100/P0	251.8	107.9	213.9	495.8	583.3	291.7	235.5	0

Table 2 – *Chemical composition of binders*

Material	**Chemical composition (%)**					
	SiO_2	CaO	Al_2O_3	Fe_2O_3	MgO	Others
Cement	19.53	63.19	3.91	2.89	1.94	8.58
Silica Fume	88.43	0.29	0.32	0.01	0.12	10.83
Fly Ash	69.3	0.9	26.1	1.8	0.05	1.85

Aside from cement with high initial strength, silica fumes and coal fly ashes were used as binders. The cement, silica fume and fly ash had surface areas of 4,190 cm^2/g, 200,000 cm^2/g and 3,890 cm^2/g respectively. The water/cement (w/c) ratio used was 0.45 and the water/binder ratio was 0.20.

The sands that were used were free of organic matter. Sand #1 had fineness modulus of 2.36 and sand #2 had of 2.42. Quartz powder was added to the mixture during development of UHPC due to its extremely fine grain-size distribution, with diameter of particles below 74 µm. The use of these aggregates with different characteristic sizes led to a better packing of particles, reducing voids caused by the compaction of grains.

A superplasticizer based on polycarboxylates had to be added due to the high amount of fines contained in the mixture and its low water/binder ratio. The admixture had density of 1.12 g/cm^3 and its dosage was set as a function of the mixture's slump, fixed in 3% of admixture with respect to the mass of binders.

The fibers used in the experiment are depicted in Figure 1, whereas their properties are presented in Table 3. A total fiber amount of 3% was adopted with respect to the mixture's total volume.

Table 3. *Properties of fibers used in the study*

Property	Steel	Polypropylene
Diameter	0.21 mm	12 µm
Length	13 mm	6 mm
Shape factor	62	500
Tensile strength	2750 N/mm^2	500-700 N/mm^2
Elastic modulus	200 GPa	5 GPa
Density	7.8 g/cm^3	0.91 g/cm^3

Figure 1. *Fibers used in the study*

Every mixture followed the same molding sequence, at which all elements were pre-mixed and then put in the vertical axis mixer. Later, 90% of the water and the superplasticizer were added until the mixture turned highly viscous. The mixer was left turned on with speed of 140 rpm for 12 minutes. After the mixture reached high viscosity, the fibers and the remaining water were added and mixed for another 3 minutes.

2.2 Test methods

The evaluations performed in this article followed standardized methods, aiming to reach the goals that were set.

2.2.1 Consistency

The consistency of the composite was evaluated through the (ASTM C 1437, 2013) method. The test consists of analyzing the mixture by measuring its horizontal spread after being molded in the shape of a standard cone and subjected to continuous impacts when the cone is removed, as shown in Figure 2.

Figure 2. Slump test for assessing consistency of UHPC

2.2.2 Axial Compression Tests

For the axial compression tests, cylindrical specimens were cast with dimensions of 50 x 100 mm (1.96 x 3.94 in.), using molds that allow a confining pressure to be applied while still fresh. Even though the material was not compacted, specimens were kept under confining pressure of 20 MPa (2900 psi) for a period of 24 hours, at a temperature of 21 ± 2 °C and relative humidity of 65 ± 10% after casting.

The samples were then demolded and left curing for 12 hours at 90°C and relative humidity of 100%. The thermal curing of the UHPC affects the hydration products, being formed early, and also accelerates the pozzolanic reactions in the quartz powder at 90 ºC (Richard and Cheyrezy, 1995)(Kang et al., 2018). At this temperature, the hydration reactions are accelerated, rapidly generating the calcium hydroxide consumed by pozzolans, and producing new hydrated crystals (Yazici et al., 2013). Thus, there is the transformation of the amorphous hydrates into crystalline hydrates, causing the UHPC to reach high resistances, since it has a large part of supplementary cementitious materials (SCM).

Later they were placed in an environment with controlled humidity of 65 ± 10% and temperature of 21 ± 2°C. The axial compression tests were performed according to specifications of ASTM C39M and counted with three specimens for each composition

2.2.3 Flexural Strength

To determine flexural strength and toughness, prismatic specimens were used with dimensions of 40 x 40 x 160 mm (1.57 x 1.57 x 6.30 in.), cast in metallic molds that allowed applying the same confining pressure of the cylindrical samples in fresh state. The equivalent bending/flexural strength was determined as per (ASTM C78M, 2013) and the toughness indices were obtained as recommended by (ASTM C1609, 2012). The mixture's I-Index was used to determine the toughness index, which corresponds to the division of the value obtained for the total area under the load-deflection curve by the area up to the point whose displacement is associated with the appearance of the first crack. These tests required the use of three specimens for each mixture as well.

2.2.4 Toughness Index

In order to increase reliability for plotting load-displacement curves, the displacement was controlled with an external Linear Variable Differential Transducer (LVDT) connected to a computer within a closed-loop system, which recorded vertical deformation and yielded the material's behavior. The displacement was controlled during load application and showed that its values increase vertically as the deformation of the specimen increases. Figure 3 represents the system used to determine the toughness of the samples analyzed, keeping in mind that four specimens were molded for each composition.

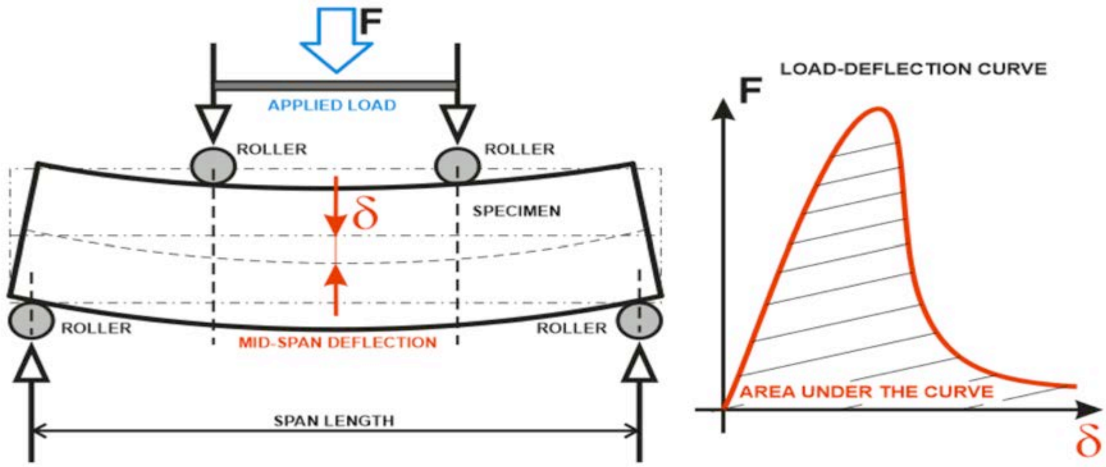

Figure 3. *Schematics for instrumentation of displacement measurement points for specimens subjected to the bending/flexural test*

3. Results and Discussion

3.1 Mixture consistency

The rheological behavior of UHPC was evaluated with respect to multiple proportions and the results are presented in Table 4.

Table 4. *Slump-flow of hybrid mixtures*

	S0/P100	S50/P50	S60/P40	S70/P30	S80/P20	S90/P10	S100/P0
Spread (mm)	210	216	219	218	220	221	240

The consistency of the matrix was reduced as more fibers were added due to its increasing consistency that was influenced by the gain of internal friction between components, a fact that is related to the shape and surface area of fibers. Moreover, metal fibers affect the mixture's consistency, making it necessary to determine a maximum percentage of fibers that can be added to the matrix (Rydval et al., 2016).

The large surface area of fibers, particularly those of polypropylene, increases friction between one fiber and another and between fibers and other materials, which restricts fluidity and mobility of the mixture. As polypropylene fibers are smaller than steel fibers – the diameter of a polymer fiber, for instance, is about 95% lower than the diameter of steel fibers – the resulting composite has higher fiber concentration (nearly 1.62 million fibers per kg, according to the manufacturer), which yields larger specific area (about 366 m^2/kg). Similar to the aggregate-paste interface, there is a transition zone on the fiber-matrix interface on which a layer of water is absorbed by the surface of fibers. The reduction of free water in the mixture reduces the space between fresh concrete particles, affecting fluidity negatively.

Comparing the consistency of mixtures with higher amounts of polypropylene fibers (S100/P0) to the one without polypropylene fibers (S0/P100) shows that the composite's opening reduces by 87.5%. It should be noted, though, that the consistency of UHPC was impaired due to water/binder rate and high amount of fibers. Lastly, the material displayed high relative fluidity, despite presenting non-Newtonian behavior upon application of energy (Martinie et al., 2010).

3.2 Mechanical strength

Figure 4 shows the compressive strength test results for different fiber mixtures. These values correspond to the arithmetic mean of four samples, for each mixture.

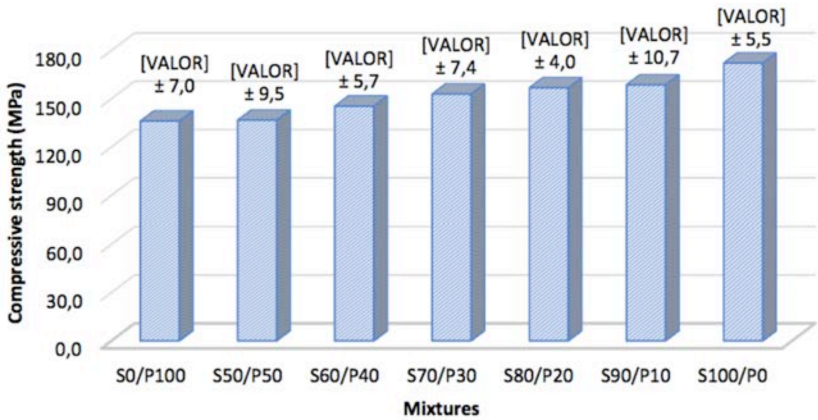

Figure 4. *Compressive strength of hybrid and reference samples*

Overall, compressive strength of composites is not significantly influenced by the addition of fibers, which have little relevance to fiber-reinforced concrete (Walraven, 2009). However, compressive strength can have slight increases due to the amount and shape of fibers, although the most significant increase results from amount rather than shape. Generally speaking, the changes are not really significant in terms of concrete strength values. As can be observed in Figure 4, compressive strength increases as the percentage of steel fibers in the hybrid mixture increases above 50% and the corresponding amount of polypropylene fibers reduces. The greater the quantity of steel fibers, the greater the compressive strength tends to be, minding the optimal amount of fibers that is compatible with the properties of the matrix and this reinforcement element. Samples containing only steel microfibers yielded compressive strength 26% higher than samples with polypropylene microfibers only. It should be noted that concrete compressive strength depends mostly on the properties of the cementitious matrix, and fibers act only in the post-cracking stage.

Despite some studies having already reported the advantages of using isolated polypropylene microfibers, higher synergy from their hybrid use with metallic microfibers was noteworthy (Wang, 2012). According to (Ren et al., 2018), due to the reduced size of metallic microfibers, it can be noted that there are no damages or even benefits to compressive strength, as observed in this study.

(Wu et al., 2017) analyzed the hybridization of fibers of the same materials and multiple sizes and reached results different from those of this study. Regarding shape, the best results pertained fiber hybridization and surpassed mixtures entirely of long fibers and entirely of short fibers. The authors also observed the same results for flexural strength. (Yoo et al., 2017) used metal fibers of varied sizes and added medium fibers besides short and long ones, therefore noticing that the hybrid mixtures yielded values higher than mixtures made of only one size of the material.

3.3 Toughness index

The behavior of samples reinforced with hybrid fibers was quite satisfactory in terms of bending and tensile stress. The load-deflection curves from the flexural strength test were used to determine toughness. A load-displacement graph was then plotted for each hybrid fiber mixture under analysis, whose potential values are shown in Figure 5.

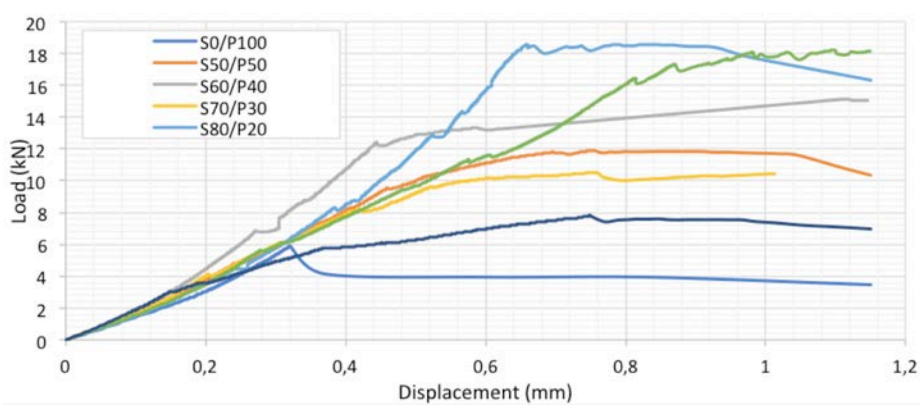

Figure 5. *Load-displacement curves of each hybrid fiber mixture*

Composites reinforced with a single type of fiber did not show increase of toughness or load-bearing capacity. It is noteworthy that hybridizing the fibers of the mixture more than doubled load capacity of the beams tested, compared with the non-hybrid fiber reinforced samples (S0/P100 and S100/P0). Maximum total deformation also differed significantly between samples tested, as in some cases – mixtures S80/P20 and S90/P10 – maximum deformation reached 1.6 mm (0.06 in.). As shown in Figure 5, every sample displays linear elastic behavior in the initial stage, with support capacity and displacement varying with respect to each mixture's ratio of materials. There is a significant difference regarding the rupture energy of each composite. The samples that showed greater toughness are those made of hybrid fiber blends with the following ratios: 80% to 90% of steel fibers and 20% to 10% of polypropylene fibers (samples S80/P20 and S90/P10), respectively.

(Thomas and Sorensen, 2017) reported decrease of maximum load and high deformations when performing hybridism of distinct metallic microfibers. Such results relate to those of this study.

Based on the load-displacement curves, the toughness indices for fiber-reinforced mixtures were calculated and listed in Table 5.

***Table 5.** Toughness index results for the composites tested*

Flexural Toughness Index	S0/P100	S50/P50	S60/P40	S70/P30	S80/P20	S90/P10	S100/P0
$I_{5\ (0.286)}$	0.28 ± 0.02	0.34 ± 0.03	0.23 ± 0.06	0.33 ± 0.09	0.38 ± 0.01	0.37 ± 0.04	0.25 ± 0.03
$I_{10\ (0.572)}$	1.57 ± 0.08	2.38 ± 0.09	2.32 ± 0.12	3.42 ± 0.19	2.81 ± 0.16	2.44 ± 0.22	1.94 ± 0.25
$I_{20\ (0.858)}$	-	5.69 ± 0.12	6.31 ± 0.27	8.00 ± 0.32	7.72 ± 0.35	6.17 ± 0.39	4.11 ± 0.42
$I_{30\ (1.144)}$	-	9.18 ± 0.13	10.16 ± 0.12	8.48 ± 0.21	13.98 ± 0.24	11.08 ± 0.14	6.43 ± 0.15
$I_{40\ (1.43)}$	-	12.28 ± 0.16	13.44 ± 0.18	11.49 ± 0.19	18.09 ± 0.27	16.01 ± 0.35	8.58 ± 0.11

Indices I_5, I_{10}, I_{20}, I_{30}, and I_{40} were used in the calculation of toughness factor. For this reason, this five Indices were multiples of a deformation of 0.286 mm (0.01 in.), value considered as the closest to most mixtures tested.

Indices I_5, I_{10}, I_{20}, I_{30}, and I_{40} were used to determine the toughness rates between the reference indices for each composite. Tables 6a and 6b summarize the percentage rates resulting from the relation between load-bearing capacity from displacement and load capacity when the first crack appeared.

Table 6. *Toughness indices for each composition*

a) Toughness ratios between deflection limits – in sequence.

Residual strength factor R (%)	Mixtures						
	S0/P1000	S50/P50	S60/P40	S70/P30	S80/P20	S90/P10	S100/P0
R $_{5-10}$	25.8 ± 1.4	40.8 ± 1.7	41.8 ± 1.9	61.8 ± 3.6	48.6 ± 1.2	41.4 ± 1.9	33.8 ± 2.1
R $_{10-20}$	-	33.1 ± 1.7	39.9 ± 1.4	45.8 ± 2.9	49.1 ± 2.5	37.3 ± 1.7	21.7 ± 1.8
R $_{20-30}$	-	34.9 ± 2.3	38.5 ± 1.8	4.8 ± 2.4	62.6 ± 1.7	49.1 ± 2.3	23.2 ± 2.9
R $_{30-40}$	-	31.0 ± 3.5	32.8 ± 1.8	30.1 ± 2.5	41.1 ± 3.5	49.3 ± 4.1	21.5 ± 1.8

b) Toughness ratios of indices I_{10}, I_{20}, I_{30}, and I_{40} in relation to the first index I5

Residual strength factor R (%)	Mixtures						
	S0P/100	S50/P50	S60/P40	S70/P30	S80/P20	S90/P10	S100/P0
R $_{5-10}$	25.8 ± 1.4	40.8 ± 1.7	41.8 ± 1.9	61.8 ± 3.6	48.6 ± 1.2	41.4 ± 1.9	33.8 ± 2.1
R $_{5-20}$	-	35.67 ± 3.1	40.53 ± 1.8	51.13 ± 3.9	48.93 ± 1.6	38.67 ± 2.2	25.73 ± 2.6
R $_{5-30}$	-	35.36 ± 2.9	39.72 ± 2.5	32.6 ± 2.7	54.4 ± 3.6	42.84 ± 4.9	24.72 ± 2.7
R $_{5-40}$	-	34.11 ± 3.7	37.74 ± 2.7	31.89 ± 3.7	50.6 ± 2.2	44.69 ± 2.9	23.8 ± 3.5

Graphically, Tables 6a and 6b show the differences between toughness ratios for each mixture and a comparison with the others. After determining the areas below the curves, it is possible to observe that the toughness indices vary expressively because of the different fiber mixtures, although the energy values for mixtures S80P20 and S90P10 were similar to each other. For mixture S0P100, with 100% of polypropylene fiber, it was not possible to determine the energy absorbed by the sample for high deformations, showing the inability of this fiber to avoid crack spreading as it has physical and geometric stiffness that is incompatible with the properties of the matrix's constituents. The mixture that yielded the best behavior was that whose reinforcement was 80% steel fiber and 20% polypropylene fiber (S80/P20), *as toughness ratios for this material are strikingly higher than the values found for other hybrid compositions, reaching toughness gains that overpass 60%, followed by the S90/P10 hybrid composite, with load-bearing capacity gain of approximately 49%. Composite S70/P30 yielded higher toughness gain for the first toughness indices, but this gain was not relevant for the subsequent indices.*

4. Concluding remarks

Based on the test results for reactive powder concrete samples reinforced with hybrid steel-polypropylene fibers and with reduced cement consumption, in terms of compressive strength, toughness and fracture energy, in addition to fresh state consistency, the following conclusions can be drawn:

Adding high amounts of polypropylene fibers to the mixture impairs its consistency. The high concentration of this fiber makes the mixture more cohesive as it favors internal friction and contributes to the contact between themselves and the other composite constituents, hindering fluidity and mobility;

The presence of steel fibers in the mixture improves the behavior of UHPC in terms of compressive strength without compromising the properties of the matrix;

The strategic combination of steel fibers and polypropylene fibers favored an increase in toughness for all percentages tested. The synergy arising from the introduction of two types of fibers, operating in different stages and regions inside the matrix increases the material's load-bearing capacity. At first, when there are only microcracks in the matrix, the presence of steel fibers has almost no effect and polypropylene fiber efficiency is rather limited, becoming active as microcracks start to coalesce in order to form more clearly defined cracks. Metal fibers play a crucial role in crack spreading, increasing the load bore and favoring matrix reinforcement, thus increasing the resistance to crack spreading.

Hybridizing the amount of steel fibers by 80% and 90%, and polypropylene fibers by 20% and 10%, respectively, provide increased toughness of the reinforced material for larger displacements. The load bearing capacity for mixture S80/P20 more than doubled compared with the non-hybrid mixtures, even for deflection limits 5.5 times above the deformation obtained until the appearance of the first crack. Similarly, composite S90/P10 presented very high fracture energy, demonstrated by its increased toughness in the final deflection range (15.5 times the displacement at the beginning of cracking).

Finally, the findings show that the hybridization of two types of fiber – steel and polypropylene –increases the toughness of the material significantly, as already reported by Lawler et al. (2002). Clearly, the mechanical properties of UHPC with hybrid fibers proved to be superior than the UHPC reinforced with only one type of fiber – especially in terms of increased flexural strength and toughness.

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