
**EFFECT OF HYBRIDIZATION ON THE MECHANICAL PROPERTIES OF
POLYPROPYLENE (PP) FIBER-REINFORCED CONCRETE (FRC)*****EFEITO DA HIBRIDIZAÇÃO COM FIBRAS DE POLIPROPILENO (PP) SOBRE AS
PROPRIEDADES MECÂNICAS DE UM CONCRETO REFORÇADO COM FIBRAS
(CRF)****Tiago Tadeu Amaral de Oliveira¹**Vladimir José Ferrari²***Abstract**

This study assessed the mechanical properties of polypropylene (PP) hybrid fiber-reinforced concrete (FRC). To this end, 10 FRC groups were investigated with respect to both macro- and micro-PP fibers. The hypothesis of this study is that the two types of PP fiber act together, contributing at different stages of the post-peak loading history of concrete in bending: due to greater dispersion in the cementitious matrix, microfibers would bridge the microcracks, whereas macrofibers would arrest the propagating macrocracks, substantially improving concrete toughness. To prove this hypothesis, four-point bending tests were performed on prism specimens (150 x 150 x 500 mm) according to the methodology described in the JSCE-SF4 Japanese standard (1984); cylindrical specimens (100 x 200 mm) were also molded and subjected to compression tests to obtain axial compressive strength, Young's modulus, and splitting tensile strength. The hybridization enabled production FRC with results 55 times greater than the simple concrete for the best group in terms of tenacity. As well observed also the CRFs presented residual stresses for displacements of $L / 600$ and $L / 150$ that did not occur in the simple concrete.

Keywords: fiber reinforced concrete, hybridization, polypropylene fibers.

Resumo:

Esta pesquisa baseia-se na investigação das propriedades mecânicas do concreto reforçado com fibras (CRF) híbridas de Polipropileno (PP). São duas formas de fibras a serem investigadas: macrofibras e microfibras de PP, para tanto foram estudados 10 grupos de CRF. A premissa da pesquisa é que as duas formas de fibras de PP trabalhem conjuntamente contribuindo em estágios distintos do histórico de carregamento do material na flexão: as microfibras devido a maior dispersão na matriz atuam na interceptação de microfissuras e com as macrofibras, espera-se a contribuição no sentido de evitar a propagação da fissuração de forma a aumentar a tenacidade do material. Para tanto, foram desenvolvidos ensaios de flexão em quatro pontos em corpos de prova prismáticos (150 x 150 x 500 mm) seguindo-se a metodologia indicada pela norma Japonesa JSCE-SF4 (1984). Foram também moldados corpos de prova cilíndricos (100 x 200 mm) e submetidos a ensaios de compressão para obtenção da resistência axial e do módulo de elasticidade, bem como, a resistência à tração indireta. Os resultados mostraram que através do processo de hibridização foi possível obter CRFs com tenacidade 55x maiores ao concreto simples no grupo que apresentou melhor resultado. Também foi observado que os CRFs apresentaram tensões residuais para deslocamentos de $L/600$ e $L/150$ na qual não ocorreram no concreto simples.

Palavras-chaves: concreto reforçado com fibras, hibridização, fibras de polipropileno.

¹Universidade Estadual de Maringá – Brasil, email: tiago_tao@hotmail.com

²Universidade Estadual de Maringá – Brasil, email: vladimirjf@hotmail.com

1. Introduction

It is known that short fibers can be incorporated into concrete to improve its tensile strength, ductility, and resistance to first-crack and crack growth (Lee, 2017).

According to Taerwe and Gysel (1996), the high Young's modulus and stiffness of steel fibers contribute to increased compressive strength and toughness of concrete; however, Hsie et al. (2008) alerted to the high content of steel fibers needed, which brings a disadvantage as to weight gain of the structural member and reduced workability of the mixture.

Kosa and Naaman (1990), alerted to the problem of corrosion associated with the use of steel fibers in chemically aggressive or alkaline environments. For this reason and others of economic nature, Maida et al. (2018) reported the increased interest in the application of synthetic fibers, including polypropylene (PP). According to Bayasi and McIntyre (2002), the good ductility, reduced diameter, and good dispersion of PP fibers in the cementitious matrix contribute to restrain crack growth.

Initially, this study was developed to contribute to the existing information on the behavior of hybrid PP fiber-reinforced concrete (FRC). More specifically, the purpose of this research is to assess the effect of hybridization, that is, addition of PP micro- and macrofibers to the concrete matrix consisting of fine and coarse aggregates (sand and 9.5 mm particle size gravel) aiming of obtain a FRC mixture with greater compressive strength and flexural toughness. To this end, a concrete mixture with 30 MPa strength was prepared; cylindrical specimens (100 x 200 mm) were molded and subjected to compression tests to obtain axial compressive strength, Young's modulus, and splitting tensile strength; four-point bending tests were performed on prism specimens (150 x 150 x 500 mm) according to the methodology described in the JSCE-SF4 Japanese standard (1984).

The purpose of this study was to improve the toughness of the concrete matrix through the addition only of PP fibers and to verify whether the hybridization using the addition of microfibers (12 mm in length and 1.8 μ m in diameter) and macrofibers (40 mm long and 0.69 mm in diameter) will have better mechanical behavior in relation to CRFs with only one type of fiber. The hypothesis of this study is that the two types of PP fiber act together, contributing at different stages of the post-peak loading history of concrete in bending.

2. Materials and Methods

This study aimed to assess the effect of hybridization with polypropylene (PP) micro- and macrofibers on the mechanical properties of fresh fiber-reinforced concrete (FRC).

2.1. Characterization of materials and FRC dosage

High early strength CPV-ARI Portland cement, was used to prepared the mixtures. Fineness modulus, specific gravity, and 28-day compressive strength of the cement used were determined in the Materials Laboratory of the Federal Technological University of Paraná (UTFPR/Campo Mourao). The following values were obtained: specific gravity = 3.10 g/cm³, fineness modulus = 0.45%, and 28-day compressive strength = 35.72 MPa.

Natural quartz sand obtained in the Parana River bed and commonly used in the production of concrete in the municipality of Campo Mourao, Parana state, was used as fine aggregate. This material was characterized as for particle size (ABNT NBR NM 7211), specific gravity (ABNT NBR NM 52), and bulk density/volume (ABNT NBR NM 45). Basalt gravel was utilized as coarse aggregate; this material was characterized according to particle size (ABNT NBR NM 7211) and specific gravity (ABNT NBR NM 53). Table 1 presents the attributes of these aggregates.

Table 1. Fine and coarse aggregate attributes

Properties	Fine aggregate	Coarse aggregate
Apparent specific gravity (g/cm^3)	2.65	2.89
Real specific gravity (g/cm^3)	1.47	1.46
Fineness modulus	2.03	1.53
Maximum dimension (mm)	2.36	9.5

MC-PowerFlow 3100 high-performance superplasticizer was used as admixture in order to provide each of the concrete mixtures with adequate workability (in terms of slump). Technical information on this admixture, according to the manufacturer, is shown in Table 2.

Table 2. Technical information on the superplasticizer

Properties	Value
Density (g/cm^3)	1,07
Color	Brown
Recommended dosage in relation to the mass of cement	0.2 a 5%

The cementitious matrix of the FRC mixtures analyzed in this study was composed of regular strength concrete dosed according to the method of the Brazilian Association of Portland Cement to achieve compressive strength of 30 MPa after 28 days for a slump value of 80-100 mm. The composition of this concrete mixture was defined as 1:1.43:1.92 (cement:sand:gravel) by weight with a water:cement ratio of 0.47.

In this study, two types of PP fibers were added to the FRC mixtures: fiber A (Figure 1a) is a macrofiber with 40 mm in length and 0.69 mm in diameter provided by *Viapol* enterprise; fiber B (Figure 1b) is a microfiber with 12 mm in length and 18 μm in diameter supplied by *MaccaFerri* enterprise. It is worth noting that both fibers are easily found in the region where this study was developed, facilitating reproduction of the assessed material. Table 3 shows other properties of these fibers according to their manufacturers.

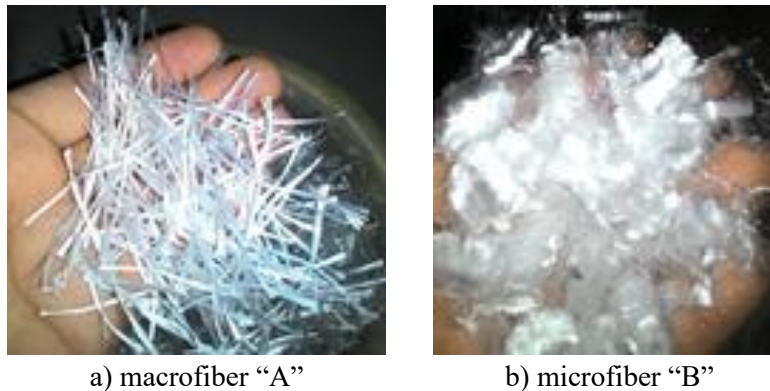


Figure 1. Polypropylene (PP) macro- and microfibers.

Table 3. Nominal values of the polypropylene (PP) macro- and microfiber properties

Properties	PP fibers	
	A: macro	B: micro
Length – l_f	40 mm	12 mm
Diameter - d_f	0.69 mm	18 μ m
Form factor - λ	58	66.66
Tensile strength (MPa)	600-650	300
Elastic modulus (GPa)	9.5	3

Type A macrofibers were added to the cementitious matrix at content rates of 0.3%, 0.6%, and 0.9% to evaluate their effect on the mechanical properties of FRC, resulting in groups 2, 3, and 4, identified as FRCA3B0, FRCA6B0, and FRCA9B0, respectively. Groups 5, 6, and 7 refer to FRC mixtures identified as FRCA3B3, FRCA3B6, and FRCA3B9, respectively, which were prepared using a type A macrofiber content rate of 0.3% with subsequent addition of type B microfiber content rates of 0.3%, 0.6%, and 0.9%.

Groups 8 and 9 refer to FRC mixtures identified as FRCA6B3 and FRCA6B6, respectively, which were prepared using a type A macrofiber content rate of 0.6% with subsequent addition of type B microfiber at content rates of 0.3% and 0.6%.

Finally, groups 10 and 11 refer to FRC cementitious matrices identified as FRCA9B3 and FRCA9B6, respectively, which were prepared using a type A macrofiber content rate of 0.9% with subsequent addition of type B microfiber at content rates of 0.3% and 0.6%.

Table 4 presents the 11 FRC groups analyzed in this study. For each group, three prismatic specimens (150 x 150 x 500 mm) and 12 cylindrical specimens (100 x 200 mm) were molded, resulting in 33 prismatic specimens and 132 cylindrical specimens.

Table 4. Fiber-reinforced concrete (FRC) groups analyzed

Groups	FRC	PP fiber volume*	
		Macrofiber A	Microfiber B
1	FRCA0B0	0%	0%
2	FRCA3B0	0.3%	0%
3	FRCA6B0	0.6%	0%
4	FRCA9B0	0.9%	0%
5	FRCA3B3	0.3%	0.3%
6	FRCA3B6		0.6%
7	FRCA3B9		0.9%
8	FRCA6B3	0.6%	0.3%
9	FRCA6B6		0.6%
10	FRCA9B3	0.9%	0.9%
11	FRCA9B6		0.3%
*In relation to the volume of concrete			

2.2. Molding of the fiber-reinforced concrete (FRC) mixtures

Mixtures were prepared using an electric concrete mixer with capacity of 500 l starting by mixing the aggregates and part of the kneading water. After that, cement and the remainder of the kneading water were added to the mixture. Finally, the fibers were added slowly and progressively with the concrete mixer in motion, and the slump test performed (Figure 2). MC-PowerFlow 3100 high-performance superplasticizer was used as admixture in each group, in sufficient amount and within the limits indicated by the manufacturer, to maintain concrete workability similar to that of the control group. Thus, the slump test was performed during specimen molding.

Demolding occurred 24 h later, with all specimens submerged in a vessel with water, where they remained for up to 48 h prior testing commencement.



(a) mixing



(b) slump test

Figure 2. Mixing and slump test

2.3. Test methods

Cylindrical specimens (100 x 200 mm) were assayed at the UTFPR-CM Materials Laboratory using a universal testing machine, EMIC manufactured, with reading of a double clamping electronic extensometer, as shown in Figure 3.

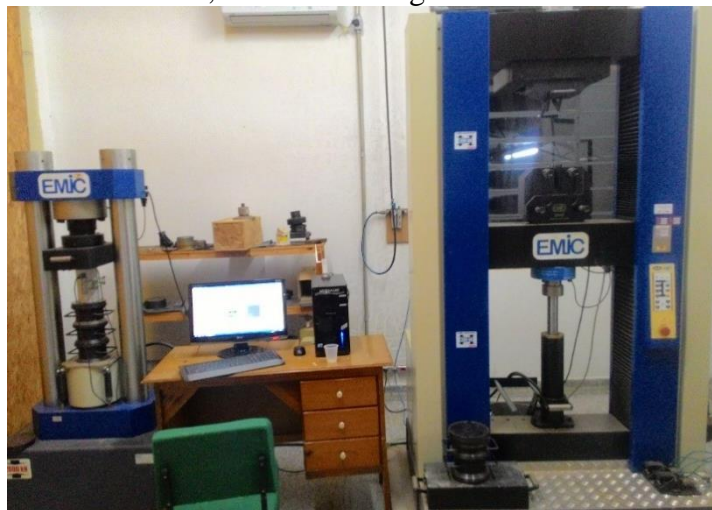


Figure 3. Compression test to obtain the Young's modulus.

Prismatic specimens (150 x 150 x 500 mm) representative of each FRC were subjected to four-point bending tests using a servo electric universal testing machine with a capacity of 600 kN. The machine, which has an interface for computer connection and electronic instrumentation, enabled acquisition of strength and strain data from two transducers through two channels.

The Compressive strength, elastic modulus and split tensile strength were tested following the methodology of the current Brazilian standards ABNT NBR 5739, ABNT NBR 8522 and ABNT NBR 7222 respectively. The four-point bending test based on the Japanese standard is the most commonly used in Brazil for FRC control due to its simpler design. In this study, the methodology described in the aforementioned standard was applied because this test has been performed without difficulties at the Laboratory of Civil Construction Materials of the State University of Maringá.

Vertical displacement of the prismatic specimens was recorded centrally on the span section of the specimen through the use of two Linear Variable Differential Transformers (LVDT) centralized on each side face using a Yoke type clamp. Figure 4 illustrates a prismatic specimen positioned in a universal testing machine prior to test performance. The side faces of the prismatic specimens submitted to the bending tests were the upper and lower surfaces when the specimens were molded, as prescribed in the JSCE-SF4 standard (1984).

Loading was applied to the specimen, continuously and without impact, by imposing a displacement rate of the machine platen of 0.15 mm/min until the central span section deflection reached the value of 3 mm.

This test procedure uses the open-loop control system.

The main difference between the open loop control system and the closed control system is that the closed system regulates the loading speed depending on the displacement of LVDT, that is, the real displacement of the specimen. In the open system, displacement speed is constant on the press platen. This may result in post-peak instability and increase the spacing between the points on the load vs. vertical displacement graph. Rupture of the specimens always occurred in the central third section, as shown in Figure 5. Thus, none of the bending assays were discarded.



Figure 4. Specimen positioned in universal testing machine.

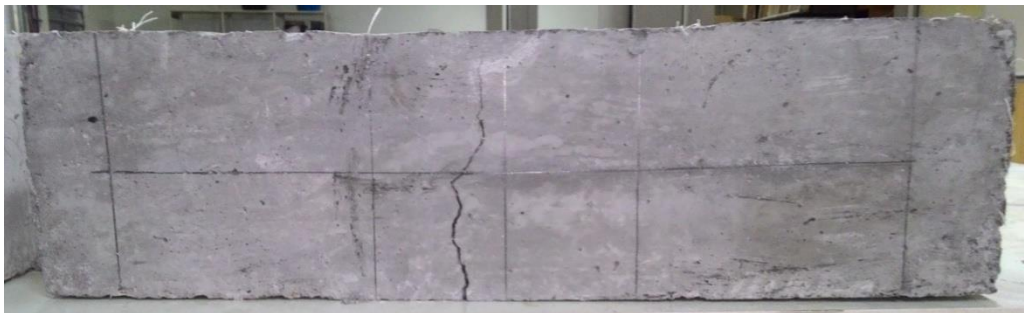


Figure 5. Rupture aspect of the specimens.

3. Results

3.1. Slump

Table 5 shows the slump values and the contents of the admixture (superplasticizer) used in each FRC group. It can be clearly observed that the slump values change according to content and type of fiber. A slump value of 170 mm was found for the control group (concrete without fibers). There was no need to add the superplasticizer to maintain the same slump value of the control concrete for type A macrofiber content rates of 0.3% and 0.6%.

Only for the type A macrofiber content rate of 0.9%, addition of 0.2% (the recommended minimum amount) of admixture was needed, resulting in a slump of 210 mm - a value higher than that of the control concrete.

Comparison between groups 2 and 3 and groups 5 and 8, respectively, evidenced that addition of type B microfiber compromised mixture workability, requiring addition of the superplasticizer. Group 7 with type B microfiber content rate of 0.9% was the FRC mixture that required the highest rate of admixture addition (1.4%). For this type B microfiber content rate, it was also verified the impossibility to proceed with molding when the mixtures were combined with the type B microfiber content rates of 0.6% and 0.9%, because of segregation formation due to lack of material flow.

Table 5. Content of the admixture used in each FRC group and the Slump values

Groups	FRC	Superplasticizer (%)	Slump (mm)
1	FRCA0B0	0.0	170
2	FRCA3B0	0.0	165
3	FRCA6B0	0.0	150
4	FRCA9B0	0.2	210
5	FRCA3B3	0.2	215
6	FRCA3B6	0.2	160
7	FRCA3B9	1.4	140
8	FRCA6B3	0.2	195
9	FRCA6B6	0.4	200
10	FRCA9B3	0.2	165
11	FRCA9B6	0.6	160

3.2. Axial compressive strength, Young's modulus, and splitting tensile strength

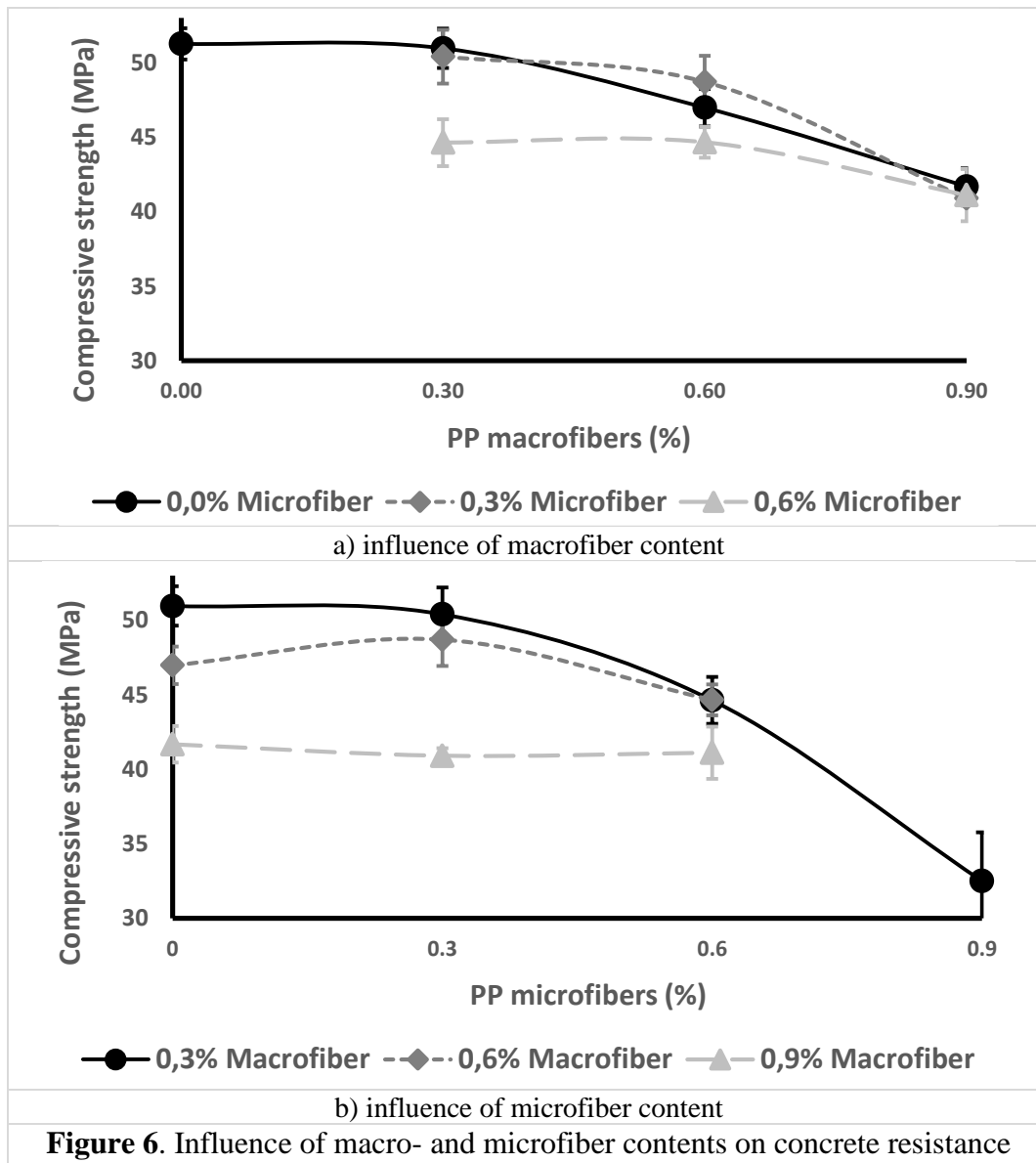
Table 6 shows the mean values for axial compressive strength (f_c), Young's modulus (E), and splitting tensile strength (f_{spl}) of the several FRC groups assayed in this study.

Table 6. Mean values of axial compressive strength, Young's modulus, and splitting tensile strength of the FRC groups used

Groups	FRC	f_c		E		$f_{sp,l}$	
		Mean (MPa)	Relation with the reference	Mean (GPa)	Relation with the reference	Mean (MPa)	Relation with the reference
1	FRCA0B0	51.26	-	36.95	-	4.27	-
2	FRCA3B0	50.96	0.99	35.10	0.95	4.44	1.04
3	FRCA6B0	46.98	0.92	33.45	0.91	4.97	1.17
4	FRCA9B0	41.69	0.81	31.90	0.86	4.11	0.96
5	FRCA3B3	50.40	0.98	35.08	0.95	4.60	1.08
6	FRCA3B6	44.63	0.87	34.98	0.95	4.31	1.01
7	FRCA3B9	32.51	0.63	28.17	0.76	3.88	0.91
8	FRCA6B3	48.70	0.95	30.70	0.83	4.73	1.11
9	FRCA6B6	44.65	0.87	29.20	0.79	4.32	1.01
10	FRCA9B3	40.91	0.80	28.28	0.76	4.09	0.96
11	FRCA9B6	41.11	0.80	29.03	0.79	4.24	0.99

Regarding axial compressive strength (f_c), Figure 6 illustrates the influence of macro- and microfibers on this property. Figure 6a clearly shows that the increase in type A macrofiber content rate leads to decreased f_c , with this decrease significantly more pronounced for the content rates of 0.6% and 0.9%. It can also be observed that hybridization at type A macrofibers content rate of 0.3% practically did not change f_c compared with that of concrete in the control group.

In Figure 6b, it is evidenced that hybridization at type B microfiber content rate of 0.3% did not significantly altered the f_c of concrete regardless of the type A macrofiber content rate, whereas for hybridization at type B microfiber content rate of 0.6%, the decrease in f_c is more significant.



With respect to the values obtained for the Young's modulus (E), it was observed that all FRC groups showed decreased results for this property compared with that of concrete in the control group. The influence of the macro- and microfibers on E is best visualized in Figure 7.

Figure 7a shows that increased type A macrofiber content rates resulted in a practically linear decrease in E values. Hybridization at type A macrofiber content rate of 0.3% with both type B microfiber content rates of 0.3% and 0.6% produced no change in the E value only for the FRC group containing type A macrofiber content rate of 0.3%, whereas for the type A macrofiber content rate of 0.6%, hybridization through the increase of type B macrofiber content rate caused reduction in the E values.

In Figure 7b, reduced values of E can be observed as a result of hybridization occurred by subsequent addition of type B microfibers to type A macrofibers. The higher the type A macrofiber content rate, the greater the reductions observed in the E values with the increase in type B microfiber content rate.

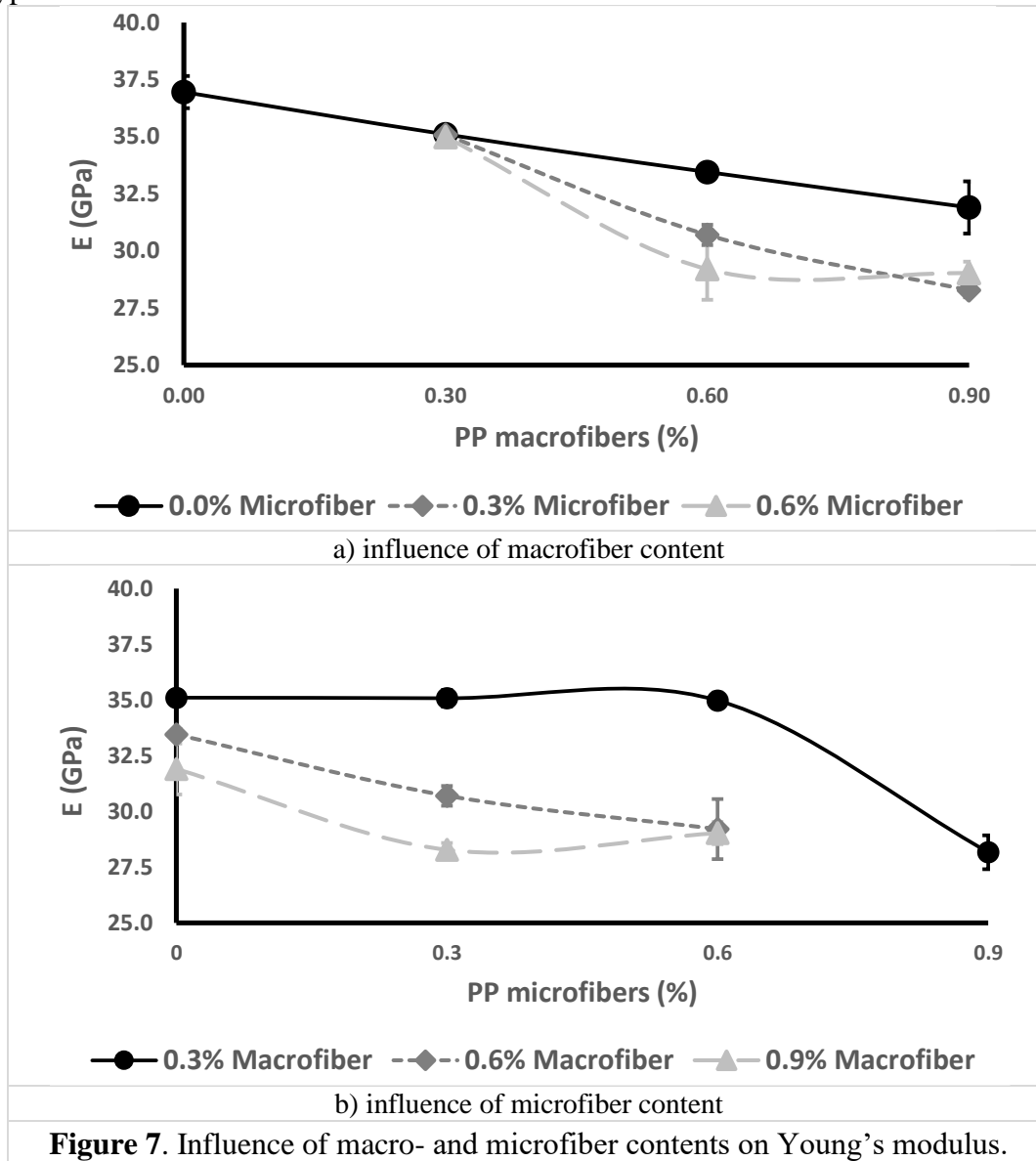
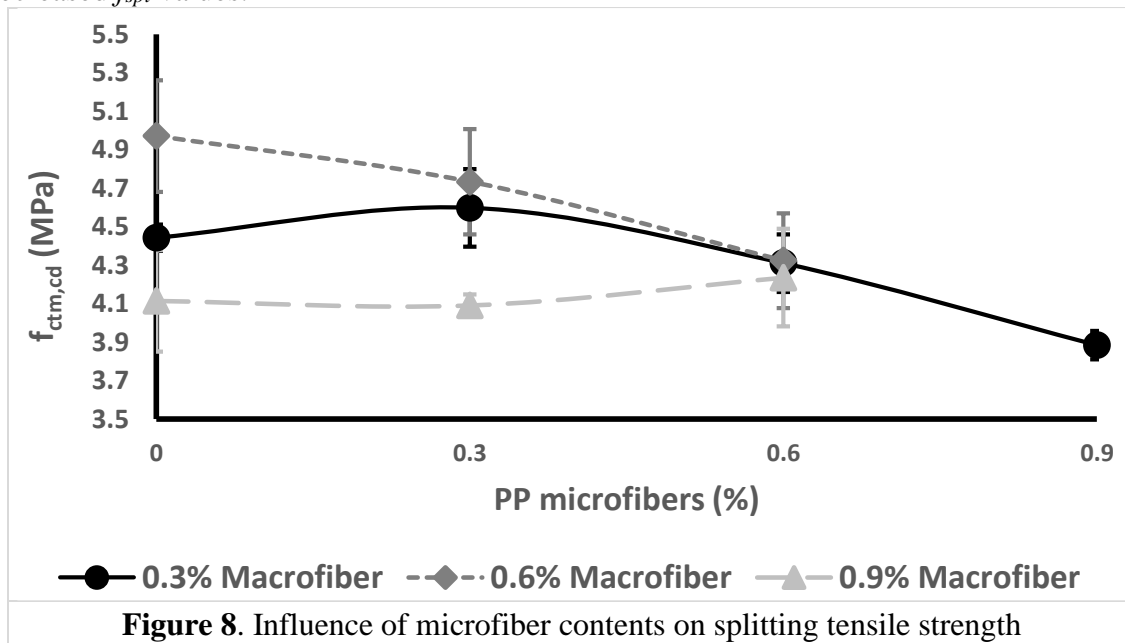


Figure 7. Influence of macro- and microfiber contents on Young's modulus.

Effect of hybridization at type A macrofiber content rate of 0.3% with addition of type B microfiber at content rates of 0%, 0.3%, and 0.6% showed splitting tensile strength (f_{spl}) values of 4.44 MPa, 4.60 MPa, and 4.31 MPa, respectively. Such f_{spl} values for these hybrid FRC groups were higher than that of concrete in the control group. Concerning hybridization at type A macrofiber content rate of 0.6% with addition of type B microfiber content rates of 0%, 0.3%, and 0.6%, f_{spl} values of 4.97 MPa, 4.73 MPa, and 4.32 MPa were found, respectively, which were all higher compared with that of the control concrete.

Hybridization at type A macrofiber content rate of 0.9% with addition of type B microfiber at content rates of 0%, 0.3%, and 0.6% resulted in f_{spl} values of 4.11 MPa, 4.09 MPa, and 4.24 MPa, respectively, and a tendency of slight increase in this property was observed with increased type B microfiber content rate.

Figure 8 illustrates the influence of type B microfiber content rate on splitting tensile strength. It can be verified that the f_{spl} value increases when type B microfiber at the content rate of 0.3% is added to the hybrid FRC mixtures with type A macrofiber contents of 0.3% and 0.9%, whereas for the type A macrofiber content of 0.6%, the hybridization resulted in decreased f_{spl} values.



3.3. Flexural tensile strength

The mean $P-\delta$ curves (with “ P ” as the load value and “ δ ” as the vertical displacement centrally to span section) that represent the behavior of each hybrid FRC group are illustrated in Figures 9 to 11. A curve of one specimen was selected for each CRF group for the representation.

Figure 9 shows the $P-\delta$ curves of the FRCA0B0 group together with those to which only type A macrofiber was added. Post-peak loading instability was observed in the FRC mixtures in groups 1 to 4, and it was not possible to record curve data after cementitious matrix rupture for groups 1 and 2, which refer, respectively, to the FRCA0B0 and FRCA3B0 concrete mixtures. Therefore, no information on post-peak loading is available for these groups.

Instability was also observed in groups 5 to 7, promoting spacing between the points in the graph soon after matrix rupture. Increase in fiber content reduced this effect in groups 8 to 11.

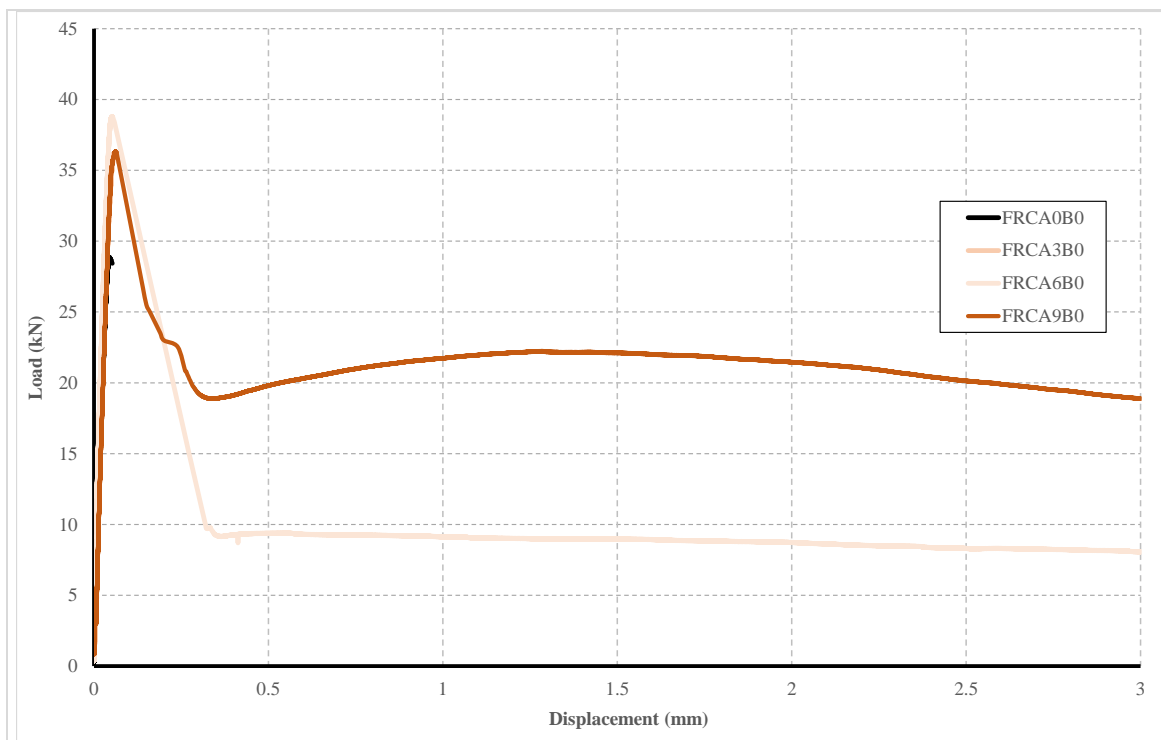


Figure 9. P-δ mean curves representative of concrete groups 1 to 4

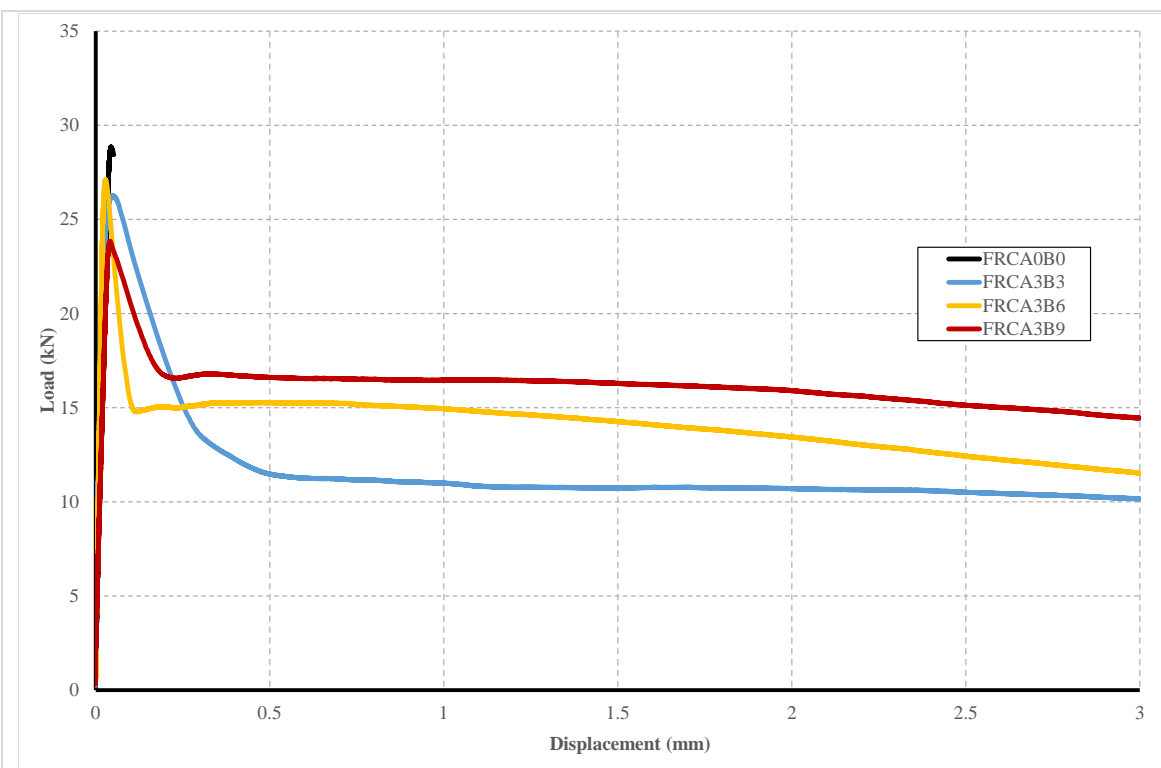


Figure 10. P-δ mean curves representative of concrete groups 5 to 7

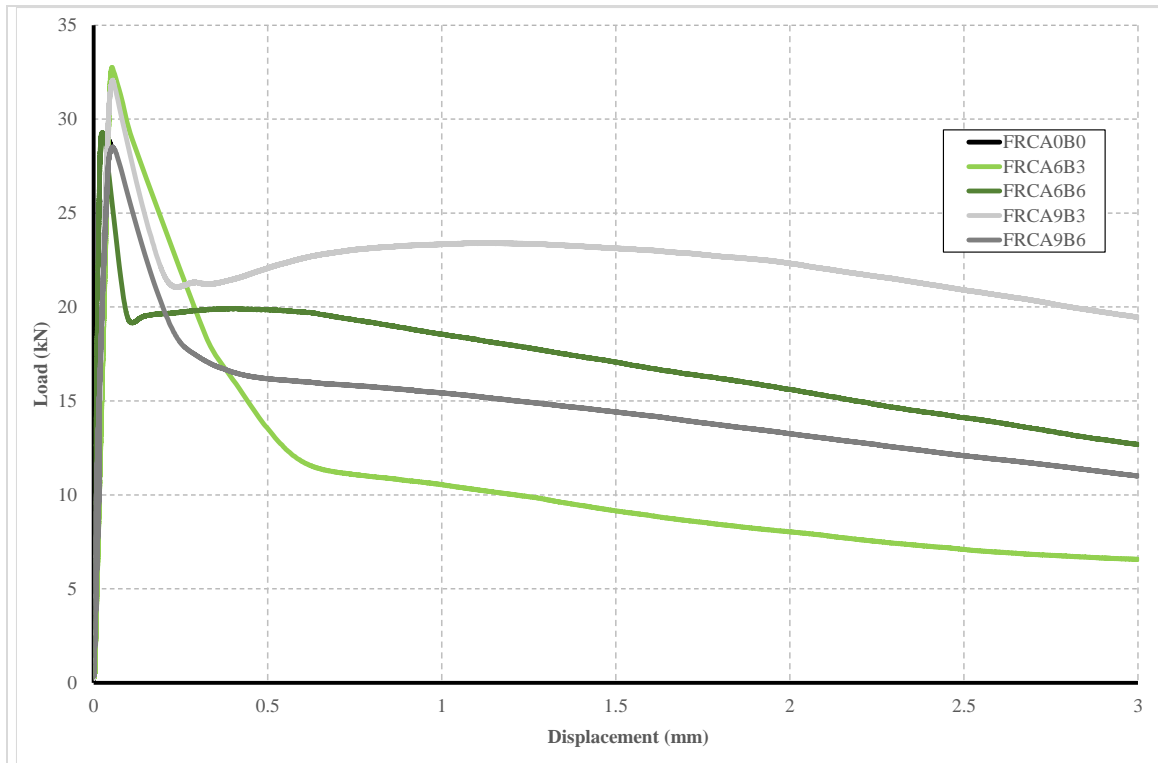


Figure 11. P- δ mean curves representative of concrete groups 8 to 11

The flexural tensile strength (σ_b) values shown in Table 7 were calculated according to the JSCE-SF4 standard (1984) as in equation (1). This property is then considered the highest σ_b value for FRC.

$$\sigma_b = \frac{P \cdot L}{b \cdot h^2} \quad (eq. 1)$$

Where:

- P : maximum load (N). It corresponds to the highest load value recorded throughout loading history;
- L : specimen span section (equal to 450 mm);
- b and h : width and height of the specimen span section, respectively. They refer to the mean values of two readings recorded in the central third of the specimen where rupture occurs.

Tensile cracking stress (f_{cr}), which is also shown in Table 7, was defined as the resistance to crack growth of FRC mixtures according to the concept described in the ASTM C1609 standard (2012). The values of f_{cr} were obtained with reference to the load corresponding to the end of the elastic straight section and the beginning of behavior change of each curve.

Table 7. Mean values of tensile cracking stress and ultimate flexural tensile strength of the FRC groups assessed

Groups	FRC	Cracking			Strength			σ_b/f_{cr}
		f_{cr} (MPa)	CV (%)	Relation with the reference	σ_b (MPa)	CV (%)	Relation with the reference	
1	FRCA0B	3.69	19.60	1.00	3.98	14.58	1.00	1.08
2	FRCA3B	3.88	6.25	1.05	4.69	2.72	1.18	1.21
3	FRCA6B	3.39	14.76	0.92	4.54	22.09	1.14	1.33
4	FRCA9B	4.30	10.87	1.16	4.79	4.19	1.20	1.11
5	FRCA3B	3.49	8.06	0.94	4.38	6.31	1.10	1.26
6	FRCA3B	4.31	15.36	1.17	4.66	14.19	1.17	1.08
7	FRCA3B	3.20	10.64	0.87	3.59	4.67	0.90	1.12
8	FRCA6B	2.99	1.44	0.81	3.43	3.74	0.86	1.15
9	FRCA6B	3.54	17.42	0.96	3.85	16.61	0.97	1.09
10	FRCA9B	3.09	14.28	0.84	3.47	8.70	0.87	1.12
11	FRCA9B	3.68	8.16	1.00	4.17	7.59	1.05	1.13

In FRC mixtures containing only PP type A macrofiber, gradual evolution of resistance to crack growth was not observed with increase in the content of this fiber. For content rates of 0.3% and 0.9%, increases in tensile cracking stress of 5% and 16% were observed in comparison to the control concrete, whereas the σ_b value decreased for the content rate of 0.6%. Therefore, the effect of type A macrofibers (at contents of 0.3% and 0.6%) on resistance to crack growth is quite discrete, whereas for the content of 0.9%, significant influence was observed, with σ_b value increase of up to 16%.

Type A macrofiber content rate of 0.3% with addition of type B microfiber content rates of 0.3%, 0.6%, and 0.9% did not improve resistance to crack growth. This finding suggests that addition of microfiber to macrofiber did not contribute to increased resistance to crack growth in the FRC mixtures assessed. The only exception was observed for the FRCA3B6 group, in which an increase of 19% in the σ_b value was found.

The effect of macro- and microfibers on resistance to crack growth is best be visualized in the graphs of Figure 12. In Figure 12a, it can be verified that a better response was obtained with the type A macrofiber content rate of 0.6% compared with the content rate of 0.3% for hybridization with all type B microfiber content rates. Figure 12b evidences that, except for the hybrid FRCA6B3 mixture, addition of type B microfiber did not improve resistance to crack growth when combined with type A macrofiber in the FRC mixtures analyzed.

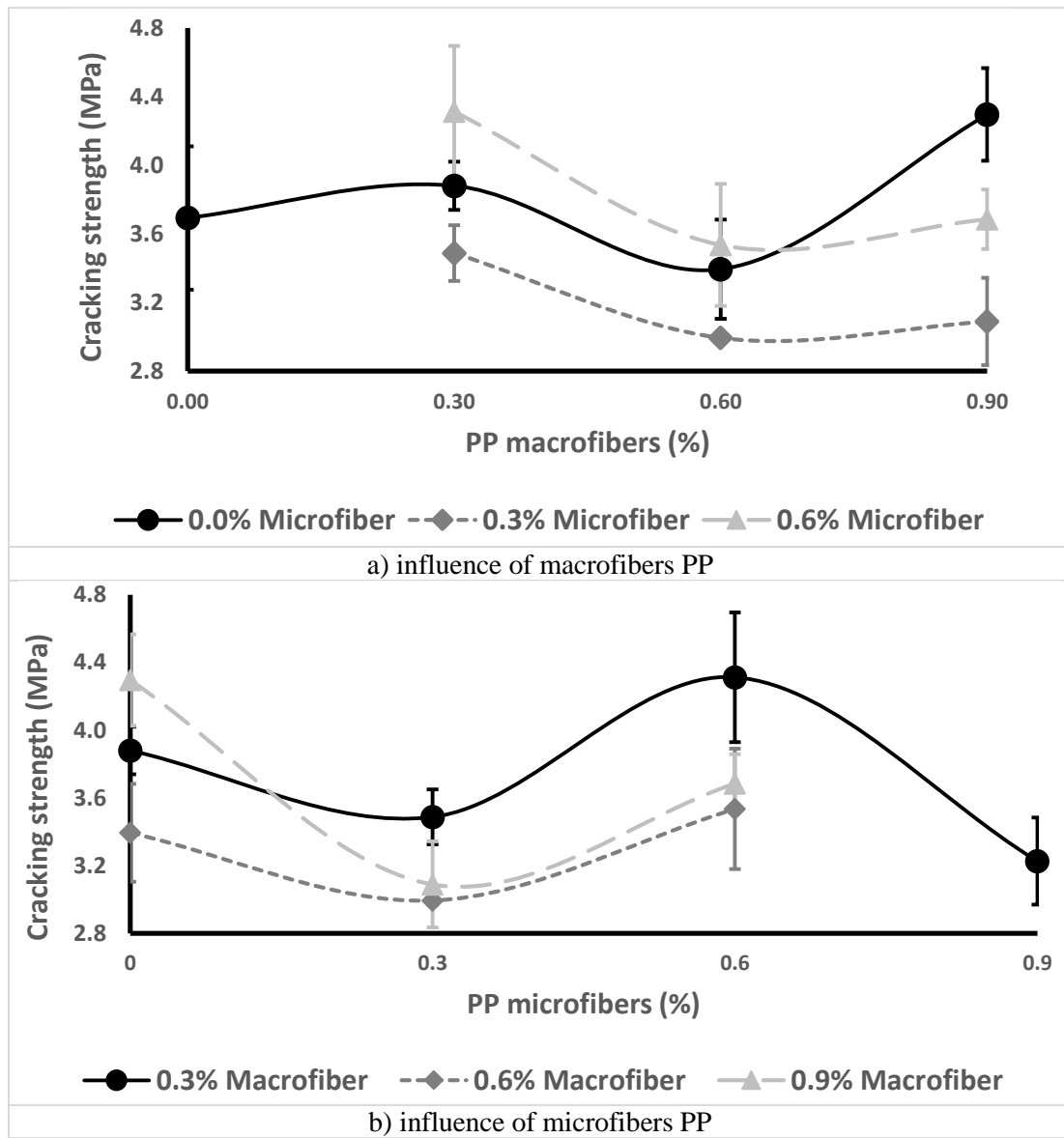


Figure 12. Effect of macro- and microfiber contents on resistance to crack growth.

For the type A macrofiber content rates of 0.3%, 0.6%, and 0.9%, non-gradual increases in flexural tensile strength (σ_b) occurred compared with the control concrete value, respectively, 18%, 14%, and 20%.

The type A macrofiber content rate of 0.3% with addition of type B microfiber at a rate of 0.3% did not improve the σ_b value. Similarly, addition of type B microfiber at the rates of 0.6% and 0.9% to the type A macrofiber content rates of 0.6% and 0.9%, respectively, did not result in increased σ_b values in the FRC mixtures evaluated.

The effect of the contents of macro- and microfibers on flexural tensile strength is best visualized in Figure 13. In Figure 13a, it can be verified that better results were obtained for the type B microfiber content rate of 0.6% compared with the content rate of 0.3%, and that

the values of σ_b for the concrete mixtures containing only type A macrofibers were higher than those for hybrid FRC mixtures. Figure 13b shows that hybridization provided similar σ_b results for the FRC groups with type A macrofiber content rates of 0.6% and 0.9%, with hybridization at the type A macrofiber content rate of 0.3% yielding higher σ_b values. This aspect shows that these contents, 0.3% of macrofiber and 0.6% of microfiber, stand out as for flexural tensile strength.

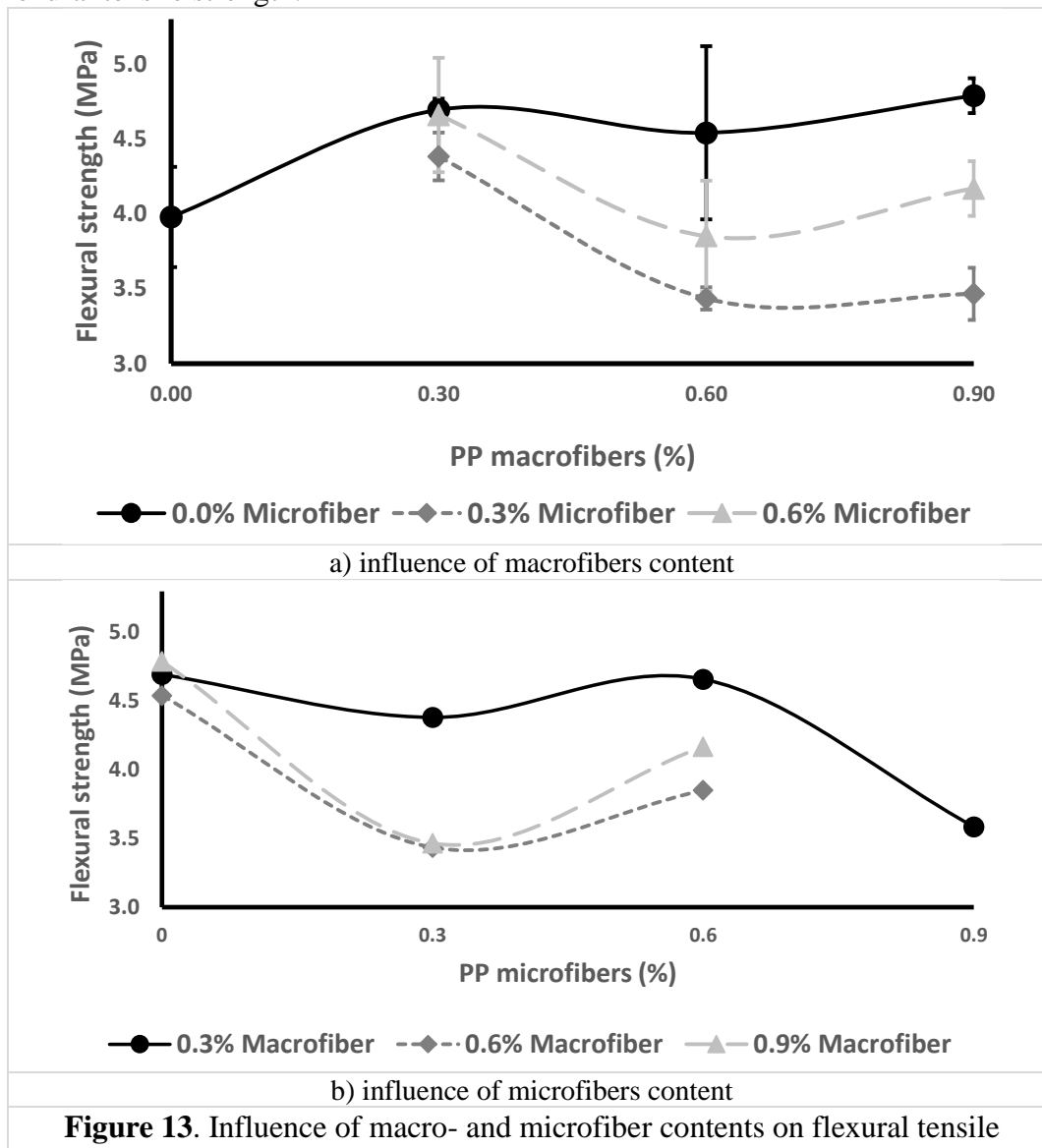


Table 9 also shows that σ_b values were higher than f_{cr} values in all FRC groups assessed. The most significant increases in tensile flexural strength in relation to tensile cracking stress were those observed for the FRCA3B0, FRCA6B0, and FRCA3B3 groups - 21%, 33%, and 26%, respectively. Hybridization did not significantly improve the concrete strength after

cracking, as the levels reached in these FRC mixtures, i.e., FRCA3B3, FRCA6B3, and FRCA9B3, were of the same level as those in mixtures containing only type A macrofibers.

3.4. Flexural toughness

With rupture of the concrete matrix, the macro- and microfibers would act to restrain crack growth: microfibers would bridge the microcracks, whereas macrofibers would arrest the propagating macrocracks. This performance after the matrix rupture is measured by the energy absorption capacity, thus an important parameter to assess the effect of fibers on the flexural behavior of FRC for higher strain levels of the concrete element.

In this study, the energy absorption capacity was evaluated according to the methodology described in the JSCE-SF4 standard (1984), in which the flexural toughness is expressed by the toughness index ($\bar{\sigma}_b$), measured as the area under a load-deflection curve in the bending of prismatic specimens (150 x 150 x 500 mm) with strain limit given by (span/150), as illustrated in Figure 14, that is, up to deflection of 3.00 mm.

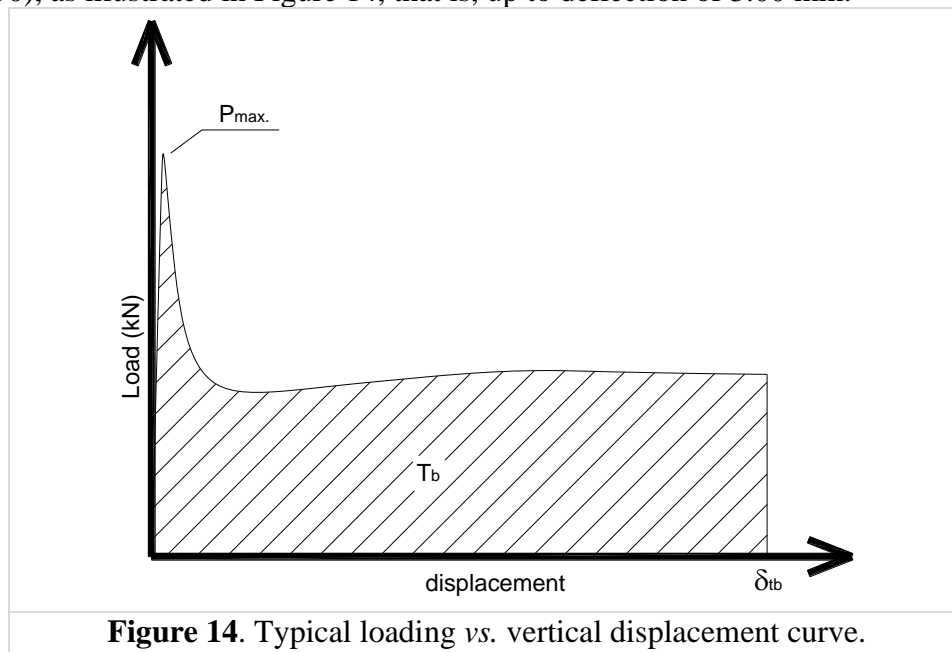


Figure 14. Typical loading vs. vertical displacement curve.

The flexural toughness index is calculated according to equation (2) and the $\bar{\sigma}_b$ values for each of the FRC groups studied are presented in Table 8.

$$\bar{\sigma}_b = \frac{T_b}{\delta_{tb}} \cdot \frac{L}{bh^2} \quad (eq. 2)$$

Where:

- T_b : flexural toughness, equivalent to the area under the P - δ curve in the interval from 0 to $\delta_{tb} = 3.00$ mm (in J).

Also based on the JSCE SF-4 standard (1984) and aiming to evaluate the post-crack performance, the concept of equivalent flexural strength ($R_{e,3}$) was adopted, calculated from the energy absorption capacity up to deflection of 3 mm and the first peak load (P). Thus, the value of the equivalent flexural strength ratio can be calculated from equation (3). The results are shown in Table 8.

$$R_{e,3} = \frac{T_b}{P_1 \cdot \delta_{tb}} \quad (eq. 3)$$

Table 8. Toughness index and equivalent flexural strength of the FRC mixtures

Groups	FRC	$\bar{\sigma}_b$ (N/mm ²)		$R_{e,3}$	
		Mean	CV (%)	Mean	CV (%)
1	FRCA0B0	0.05	10.19	1.14	4.17
2	FRCA3B0	0.07	7.21	1.45	4.65
3	FRCA6B0	1.52	11.24	34.67	25.98
4	FRCA9B0	2.67	2.38	55.91	4.48
5	FRCA3B3	0.99	3.68	22.64	5.06
6	FRCA3B6	1.34	5.93	31.41	7.79
7	FRCA3B9	1.75	10.33	48.95	14.36
8	FRCA6B3	1.84	6.19	53.53	8.72
9	FRCA6B6	2.07	8.44	54.29	11.44
10	FRCA9B3	2.30	17.94	61.16	19.28
11	FRCA9B6	2.78	7.06	68.16	2.65

Figure 15 shows the effect of macro- and microfibers on the flexural toughness index. In Figure 15a, it can be observed that increase in the content of type A macrofibers corresponded to a gradual increase in the $\sigma \bar{b}$ value, with content rate of 0.9% providing the most significant increase (green curve). Hybridization significantly improved the toughness index: addition of type B microfibers at the content rates of 0.3% and 0.6% resulted in an increase in this property compared with FRC mixtures containing only type A macrofibers.

Also with regards to the toughness index, remarking response was obtained for the type A macrofiber content rate of 0.9%, as depicted in Figure 15a. For this content, addition of type B microfibers at the content rate of 0.6% also enabled a 4% increase in the $\sigma \bar{b}$ value. Also in Figure 15b, a positive effect of hybridization on the flexural toughness is verified. For type A macrofiber content rate of 0.3%, the addition of type B microfibers resulted in gradual increase in flexural toughness (green curve). The same aspect was observed for the type A macrofiber content rate of 0.6%; the only exception observed was the combination of type A macrofiber content rate of 0.9% with type B microfiber content rate of 0.3%.

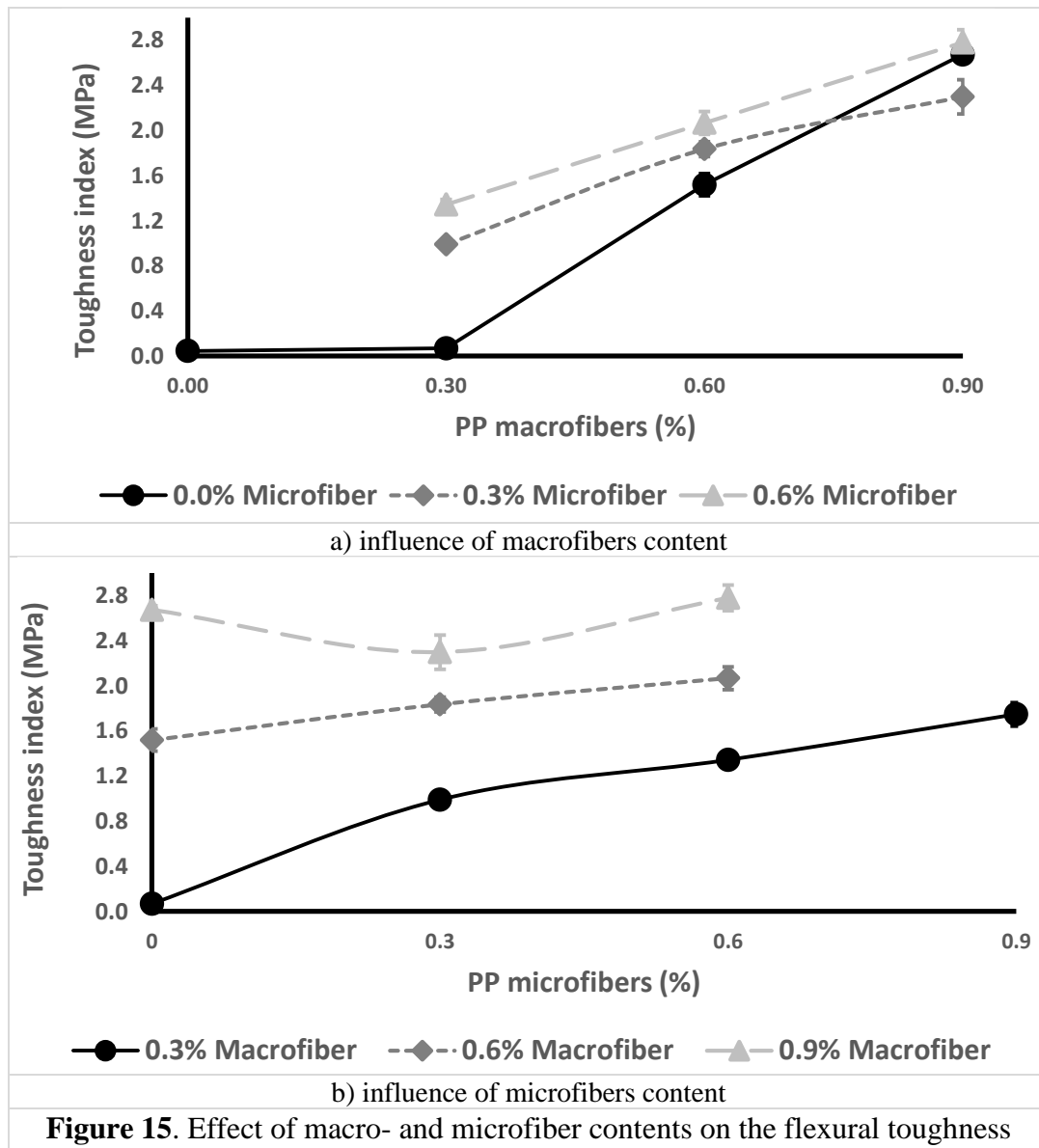


Figure 15. Effect of macro- and microfiber contents on the flexural toughness

Addition of all types of fibers provided increase in the flexural strength ratio, demonstrating that addition of fibers, regardless of type, resulted in a material with reduced loss at loading levels after rupture of the concrete matrix. However, type A macrofibers provided an even more significant increase in this ratio, as it can be observed in Figure 16.

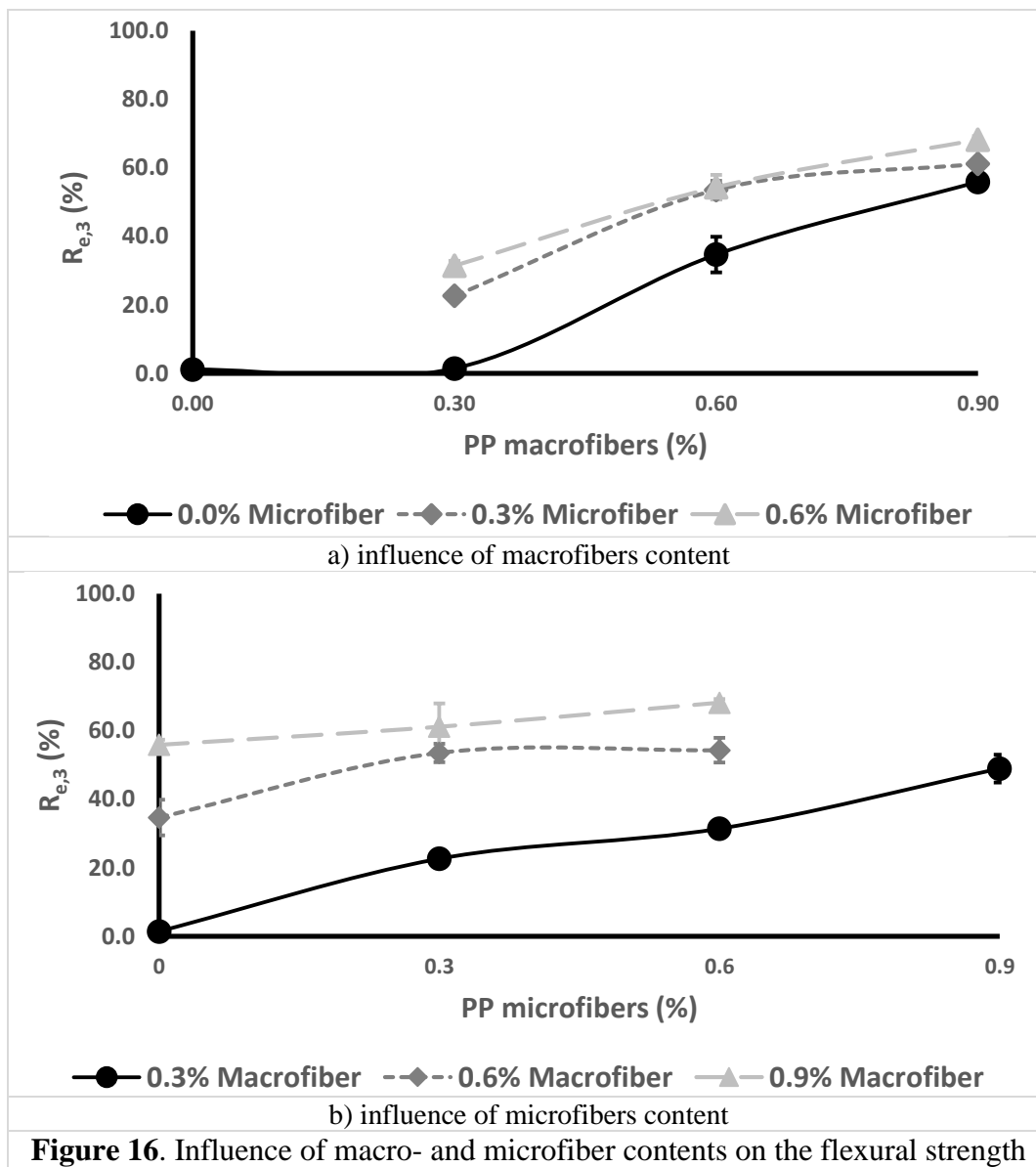


Figure 16. Influence of macro- and microfiber contents on the flexural strength

As the JSCE-SF4 standard (1984) does not address determination of residual flexural strength, the concept of the ASTM C 1609 (2002) standard was adopted to calculate the stresses associated with the vertical displacements of $L/600$ (0.75 mm) and $L/150$ (3 mm) according to equations 4 and 5, respectively.

$$f_{d,L/600} = \frac{P_{d,L/600} \cdot L}{b \cdot d^2} \quad (eq. 4)$$

$$f_{d,L/150} = \frac{P_{d,L/150} \cdot L}{b \cdot d^2} \quad (eq. 5)$$

Table 9 presents the residual flexural strength values for the FRC groups analyzed. Figure 17 shows the effect of type A macrofibers on the residual flexural strength values $f_{d,L/600}$ and $f_{d,L/150}$. Figure 18 presents the effect of type B microfibers on the referred stresses.

Table 9. Residual strength of the FRC mixtures

Groups	FRC	$f_{d,L/600}$ (MPa)		$f_{d,L/150}$ (MPa)		$f_{d,L/600}/f_{d,L/150}$
		Mean	CV (%)	Mean	CV (%)	
1	FRCA0B0	-	-	-	-	-
2	FRCA3B0	-	-	-	-	-
3	FRCA6B0	1.37	11.51	1.14	11.90	1.14
4	FRCA9B0	2.61	4.80	1.10	1.29	1.10
5	FRCA3B3	0.71	15.09	1.22	1.76	1.22
6	FRCA3B6	1.27	18.32	1.57	7.09	1.57
7	FRCA3B9	1.87	6.43	1.42	18.53	1.42
8	FRCA6B3	1.93	4.63	1.27	10.18	1.27
9	FRCA6B6	2.18	13.61	1.35	6.89	1.35
10	FRCA9B3	2.40	14.28	1.19	9.19	1.19
11	FRCA9B6	2.92	8.76	1.22	4.85	1.22

In Figure 17, it can be observed that the residual stresses increased with increased contents of type A macrofibers. Higher values of residual flexural strength were obtained with addition of type B microfiber content rate of 0.6% compared with the content rate of 0.3% of this type of fiber, for all type A macrofiber content rates investigated. It is also possible to verify that the highest residual stresses were obtained with the type A macrofiber content rate of 0.9%, highlighting the behavior of the FRCA9B6 group.

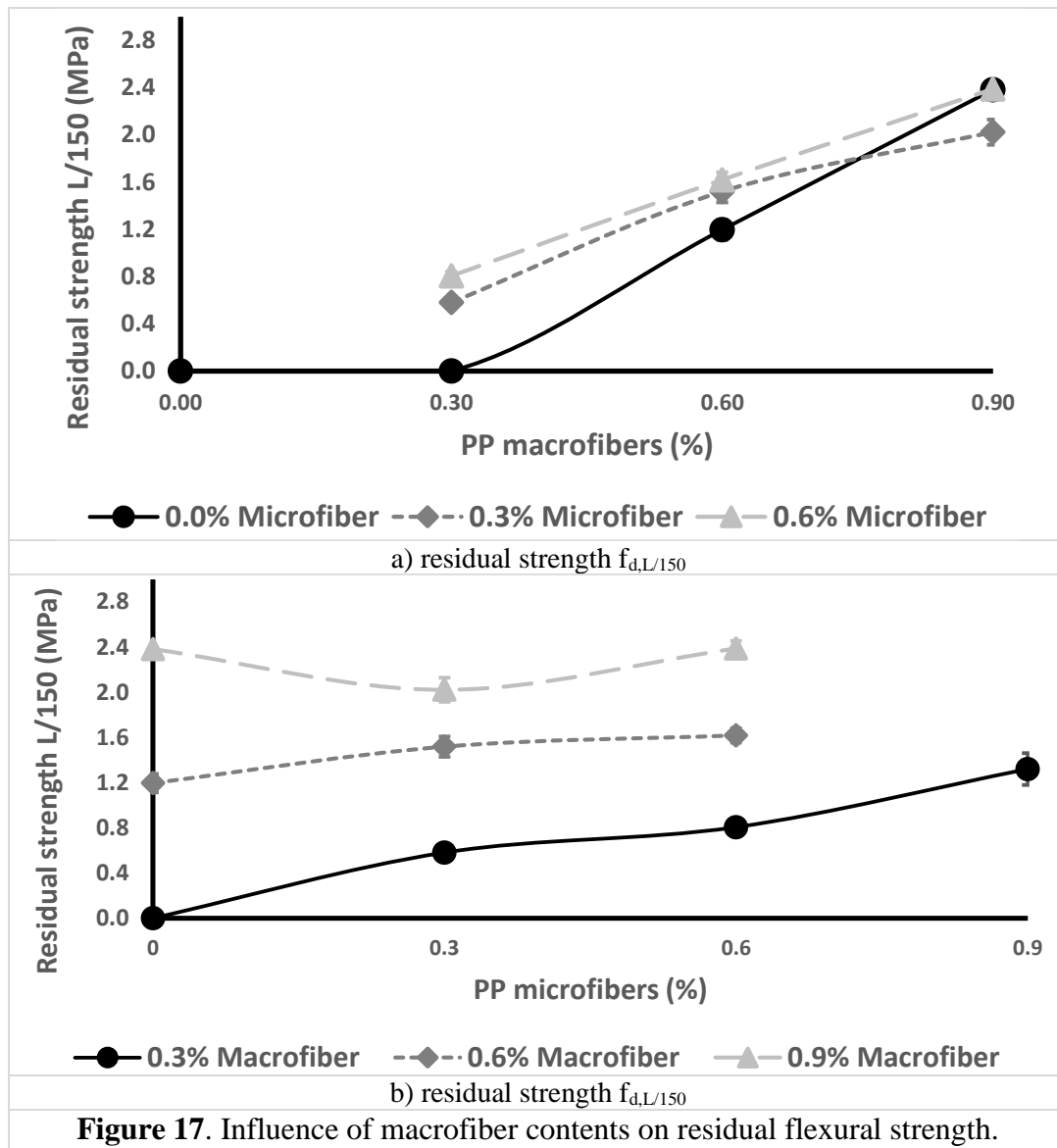


Figure 18 shows that the effect of hybridization resulted in gradual increase of the residual flexural strength values for the type A macrofiber content rate of 0.3%, as well as for the content rate of 0.6% of this type of fiber. As for the type A macrofiber content rate of 0.9%, hybridization provided no increase in residual stresses.

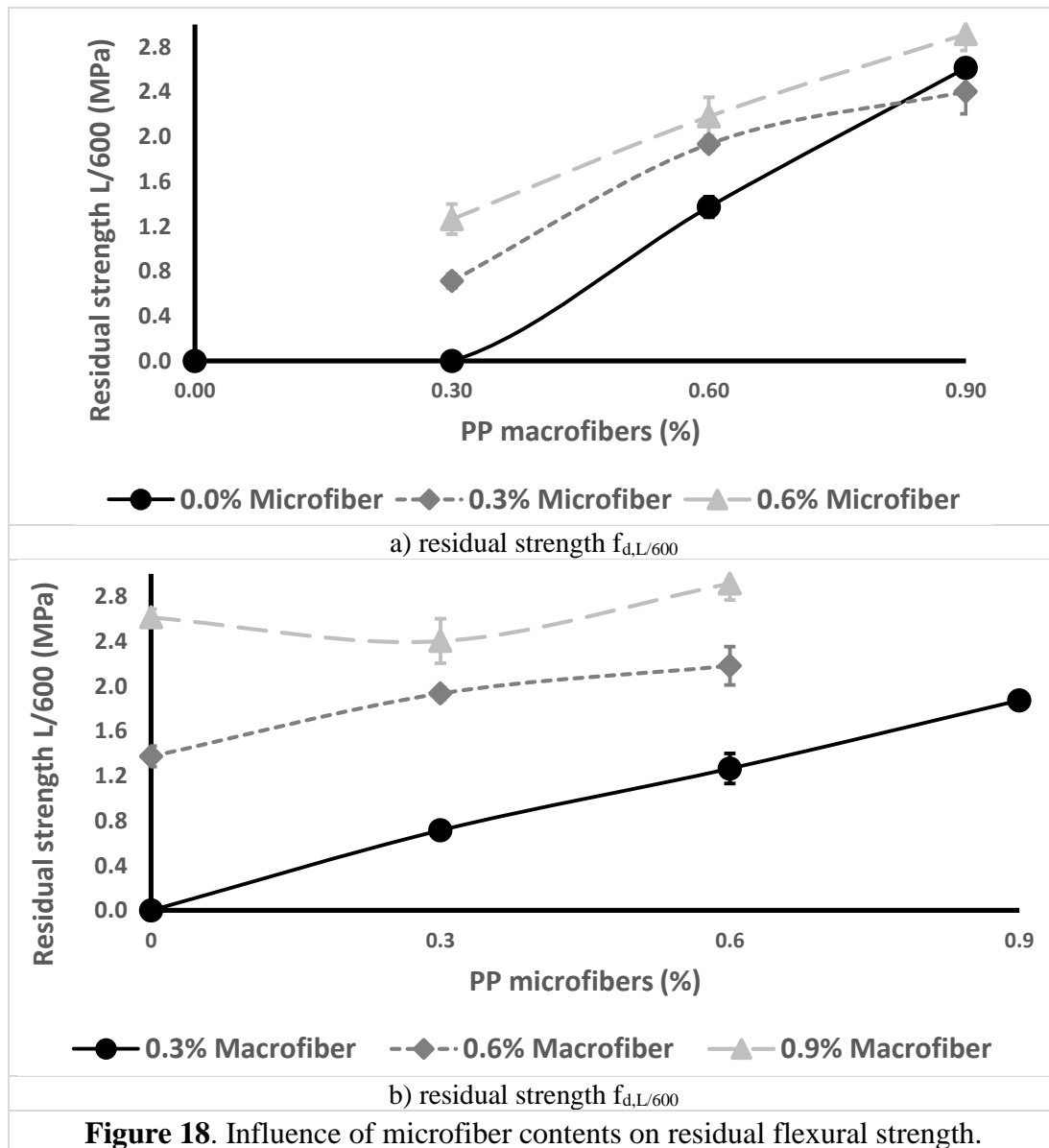


Figure 18. Influence of microfiber contents on residual flexural strength.

Another aspect to be observed is that the residual flexural strength of vertical displacement $L/150$ (3 mm) showed a very small reduction (for the FRC groups 3, 4, 5, 10, and 11) compared with that of equivalent vertical displacement of $L/600$ (0.75 mm). For FRC groups 3 and 4, which contained only type A macrofibers, reduction of 14% was observed in the residual flexural strength values, and for the other FRC groups, it did not exceed 22%. Therefore, the FRC groups containing only type A macrofiber at the content rates of 0.6% and 0.9% showed higher capacity to maintain the level of resistance to crack growth, not neglecting the response obtained with hybridization, especially for the FRCA9B3 and FRCA9B6 groups, which also presented post-peak tensile cracking stress levels higher than those for concrete containing only the type A macrofibers.

4. Conclusions

This study aimed mainly at investigating the effect of hybrid addition of PP fibers, at different content rates, on the behavior of concrete subjected to axial compressive strength, Young's modulus, splitting tensile strength, and four-point bending tests. Conclusions of this study are as follows:

- Addition of macrofibers at the contents of 0.3% and 0.6% did not cause significant change in decreased workability of the concrete mixture;
- Addition of microfibers compromised the workability of the concrete mixture, requiring addition of superplasticizer as admixture. At the content of 0.9%, microfibers greatly compromised the workability of the concrete mixture, requiring a large amount of admixture;
- Addition of macrofibers caused a decrease in axial compressive strength, more significant at the contents of 0.6% and 0.9%;
- Hybridization with 0.3% microfiber content practically did not change the axial compressive strength value, regardless of macrofiber content rate;
- All FRC mixtures showed lower Young's modulus values than that obtained for the control concrete. Reduction in the Young's modulus value increases with the increase in macrofiber content rate;
- Splitting tensile strength was increased with increasing macrofiber content rate: 4% increase with addition of 0.3% macrofiber content and 17% with addition of 0.6% content. Only hybridization with the microfiber content rate of 0.3% resulted in increased values of splitting tensile strength. Increase of 8% with addition of 0.3% microfiber to 0.3% macrofiber and increase of 11% with the combination of 0.3% microfiber with 0.6% macrofiber;
- Effect of macrofiber (at the contents of 0.3% and 0.6%) on resistance to crack growth was discrete; whereas at the content of 0.9%, the effect was on tensile cracking stress was 16%. Hybridization did not contribute to increase in resistance to crack growth, except for the CFRA3B6 group, in which an increase of up to 19% was observed in this property;
- Addition of macrofibers resulted in an increase in flexural tensile strength of FRC of up to 20% at the content rate of 0.9%. Hybridization influenced the increase in flexural tensile strength only at the content rate of 0.3% macrofiber, reaching 10% and 17% increases when combined with 0.3% and 0.6% microfiber contents, respectively;
- Addition of microfiber did not result in increased flexural tensile strength compared with the results of FRC mixtures containing only macrofibers;
- In all FRC groups, flexural tensile strength exceeded tensile cracking stress. The most significant increase observed was 33% for FRC mixture containing 0.6% macrofiber. Hybridization did not significantly improve in this behavior, since the levels observed were the same as those in mixtures containing only macrofibers;
- Increase in macrofiber content corresponded to a gradual increase in the flexural toughness index, with the content of 0.9% showing the most increased response;

- Hybridization resulted in concrete mixtures with greater flexural toughness. The increase in microfiber content corresponded directly to an increase in toughness;
- At the 0.3% microfiber content, the increase in toughness was 21% when added to concrete containing only the macrofiber at the content of 0.6%. With the increase in microfiber at the content of 0.6%, an even greater increase of 36% was observed ;
- At the 0.6% microfiber content, increase in toughness was only 4% when added to concrete containing only the macrofiber at the content of 0.9%;
- Residual stresses increased with increasing macrofiber content. With hybridization, better responses were also obtained for the values of these stresses;
- FRC mixtures containing macrofibers were those that presented the greatest capacity to maintain the post-crack resistance, noteworthy the similar behavior observed with the effect of hybridization.

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