

# INFLUENCE OF GLASS AND POLYPROPYLENE FIBERS ON THE RESIDUAL TENSILE STRENGTHS OF HYBRID FIBER REINFORCED CONCRETE

Arthur Francisco Claro Ribeiro<sup>1</sup> Antonio de Paulo Peruzzi<sup>1</sup> Rodrigo Gustavo Delalibera<sup>1</sup> Carlos Eduardo Marmorato Gomes<sup>2</sup>

<sup>1</sup>Department of Civil Engineering, Universidade Federal de Uberlândia, Uberlândia, MG, 38.400-902, Brazil

arthribeiro@ufu.br, aperuzzi@ufu.br, delalibera@ufu.br

<sup>2</sup>Department of Civil Engineering and Architecture, Universidade de Campinas, Campinas, SP, 13.083-862, Brazil  
cemgomes@unicamp.br

## ABSTRACT

*This study aims to investigate the post-cracking behaviour of glass fiber (GF) and polypropylene (PP) reinforced concrete and the effect of hybrid fibre combinations on the mechanical properties of the composite. The effect of these dosages on Limit of Proportionality (LOP) and Residual Strength ( $f_r$ ), which were determined through bending Tensile Tests, had been used to analytically study the data obtained from six different concrete mixtures with different contents of fiber. Scanning Electron Microscopy (SEM) analyses were conducted to understand the fiber-matrix interface and identify potential fiber detachment. The M25-75 hybrid mix (25% GF and 75% PP fibers) exhibited the best post-cracking performance, with an LOP of 3.87 MPa and a Residual Strength of 1.80 MPa at 4% strain ( $f_{r4}$ ). In contrast, the M75-25 mix (75% GF and 25% PP fibers) showed the best performance in the elastic phase, with an LOP of 4.33 MPa and a lower Residual Strength of 1.22 MPa at 4% strain. These results suggest that while GF fibers enhance the LOP, PP fibers improve Residual Strength. Their hybridization achieves an equilibrium between Initial Strength and Ductility, therefore, hybrid concrete appears to be a viable alternative in structural application.*

**KEYWORDS:** FRC, glass fiber, polypropylene, hybridization

## I. INTRODUCTION

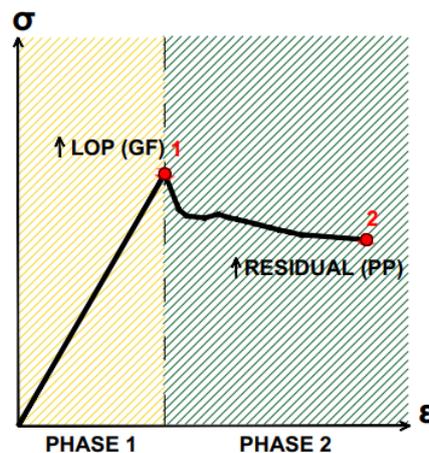
The high Compressive Strength and the fact that it can be poured into a mold means that concrete is useful for many structures. But one of the biggest disadvantages of this type of construction is that concrete has a low Tensile Strength that causes a lot of fatigue of it, which in turn in formation and propagation of cracks. If these are uncontrolled, the structural integrity and durability of the building can be affected [1]. It has been proven that the addition of fibers in concrete will enhance its Tensile Strength, minimize crack growth, increase the composites Toughness and Ductility [2][3][4][5][6], enhancing the mechanical properties and durability of concrete considerably.

To effectively increase the strength of concrete composites, it is crucial that the reinforcing fibers have a higher Young Modulus (Modulus of Elasticity) than the matrix. According to [7], the Modulus of Elasticity (E) of ordinary concrete is from 30 to 40 GPa and that of ordinary mortar is from 25 to 35 GPa. If the E of fibers added to the cement matrix is greater than E in cement, the strength of the composite will predominately be improved. Table 1 shows the mechanical properties of some also used fibers in construction [8].

**Table 1:** Mechanical properties of the various types of fibers used in cementitious matrices.

Material	Diameter (mm)	Density (g/cm <sup>3</sup> )	Young Modulus (GPa)	Tensile Strength (MPa)	Strain at failure (%)
Glass	100-1000	7.84	190 – 210	500 – 2,600	0.5 – 3.5
Glass	0.008-0.015	2.60	70 – 80	2,000 – 4,000	2 – 5
Asbestos	0.00002-0.0004	2.60	160 – 200	3,000 – 3,500	2 – 3
Polypropylene	20-400	0.90 – 0.95	1 – 10	450 – 760	15 – 25
Polyester	10 - 200	1.34 – 1.39	10 – 18	230 – 1,200	10 – 50
Polyethylene	25 – 1,000	0.92 – 0.96	5	80 – 600	3 – 100
PVA	14 - 650	1.30	29 – 36	800 – 1,500	5.7
Wood	-	1.50	71	900	-
Aramid	10	1.45	65 – 133	3,600	2.10 – 4
Carbon	9	1.90	230	2,600	1
Ordinary Concrete	-	2.40	30 – 40	1 – 4	0.005 – 0.015
Ordinary Mortar	-	2.10	25 – 35	2 a 4	0.005 – 0.015

Among the most widely studied fibers used in concrete are macrofibers of Glass Fiber (GF) and Polypropylene (PP). Each one has different characteristics influencing the performance of the concrete in different ways, as well as its viability regarding cost. A composite can be called “hybrid” when two or more types of fibers are rationally combined to obtain from the qualities of each one, properties that beneficially synergize the composite as a whole. This study aims to study the best hybridization ratio of GF and PP to be added to ordinary concrete, since each of them has distinct and, in a way, complementary properties, since the GF has high E but low deformation, and PP has low E but high deformation. Thus, GF can act mainly in Phase 1 (elastic) and, once this rupture has occurred, PP acts in the post-cracking Residual Deformation (Phase 2), as shown in Figure 1.

**Figure 1.** Representative stress x strain diagram of the CRF.

Glass fibers (GF) have a Modulus of Elasticity (E) ranging between 70 and 80 GPa and exhibit high Tensile Strength (2,000–4,000 MPa). These properties directly contribute to increasing the Limit of Proportionality (LOP), which represents the Maximum Stress the concrete can endure while maintaining elastic behavior in the cementitious composite. However, GF demonstrates limited deformation, and once the matrix fractures, it begins to exhibit permanent (plastic) deformations. GF primarily influences PHASE 1 of the material's behavior (see Fig. 1).

Polypropylene (PP) fibers, on the other hand, are known for their Energy Absorption capacity and high Tenacity. They have a lower Modulus of Elasticity (E) of 1–10 GPa, lower Tensile Strength (450–760 MPa) compared to GF, and a density of 0.90–0.95 g/cm<sup>3</sup>. While PP fibers contribute minimally to increasing the composite's Tensile Strength, they significantly enhance its Residual Strength. This refers to the composite's ability to retain part of its Tensile Strength after cracking, thus improving Ductility and delaying total failure. PP fibers mainly affect the material's post-cracking behavior, corresponding to PHASE 2 (see Fig. 1).

The layout of this paper is organized in the following way; Section II covers the experimental program, such as the selection and characterization of materials, mix proportioning, and the methods used for mechanical and structural performances evaluation. In Section III the experimental findings are provided. Finally, Section IV synthesizes the most important outcomes of the study, and suggests some future research directions in Hybrid fiber-reinforced concrete.

## II. METHODOLOGY

### 2.1 Hybridization of Fibers and Proportions

The hybridization process was based on a conventional reference concrete (REF) containing 0% GF and 0% PP. Five samples were prepared, varying the proportions of GF and PP, while maintaining a constant ratio of cement, aggregates, and additives across all mixtures. Using the notation M (mixture) n%GF - n%PP, the samples were designated as follows:

- Mixture 1: "M100-0" (100% GF; 0% PP)
- Mixture 2: "M75-25" (75% GF; 25% PP)
- Mixture 3: "M50-50" (50% GF; 50% PP)
- Mixture 4: "M25-75" (25% GF; 75% PP)
- Mixture 5: "M0-100" (0% GF; 100% PP)

The distribution of these mixtures is illustrated in Figure 2.

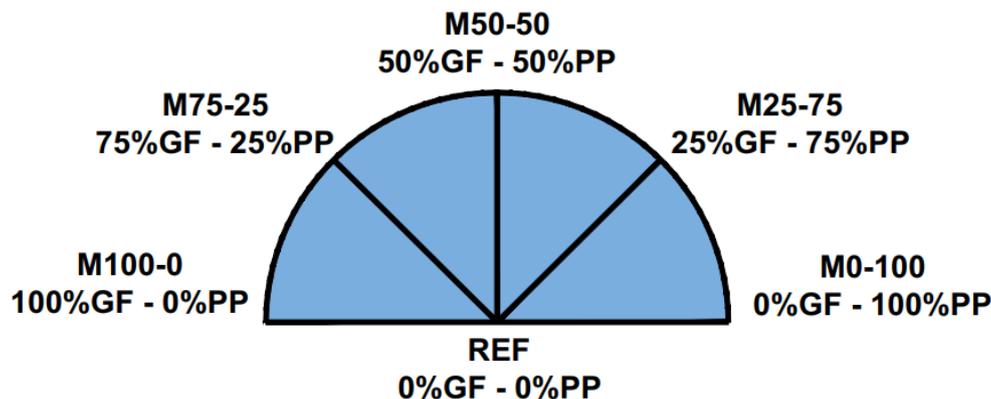


Figure 2. Mixtures and hybridization made.

The quantity of fibers added to concrete significantly influences its properties. A fiber content of less than 1% (low volume fraction) is primarily used to reduce shrinkage cracking. A content between 1% and 2% (moderate volume fraction) enhances the modulus of rupture, toughness, and impact resistance. Fiber contents exceeding 2% (high volume fraction) improve the composite's ability to harden through deformation, resulting in a high-performance composite [1]. In this research, it was observed that adding 2% fibers (relative to the volume of concrete) made the mixture unsuitable for conventional concreting due to poor workability. Therefore, the maximum fiber content was limited to 1% of the concrete volume. Table 2 presents the composition of the mixtures for each casting.

**Table 2.** Concrete mixture for each casting.

Mixture	GF (%)	PP (%)	GF (kg/m <sup>3</sup> )	PP (kg/m <sup>3</sup> )	Cement (kg/m <sup>3</sup> )	Sand #1,2mm (kg/m <sup>3</sup> )	Gravel #19mm (kg/m <sup>3</sup> )	Water (L)	Aditive* (b.c.w.)**
REF	0%	0%	0.00	0.00	350.20	810.72	1,071.62	192.61	1.62%
M100-0	100%	0%	26.80	0.00	350.20	810.72	1,071.62	192.61	1.62%
M75-25	75%	25%	20.10	1.15	350.20	810.72	1,071.62	192.61	1.62%
M50-50	50%	50%	13.40	4.55	350.20	810.72	1,071.62	192.61	1.62%
M25-75	25%	75%	6.70	6.82	350.20	810.72	1,071.62	192.61	1.62%
M0-100	0%	100%	0.00	9.10	350.20	810.72	1,071.62	192.61	1.62%

\* water-reducing additive type 2 RA2 (Superplasticizer) according to ABNT NBR 11768-1:2019.

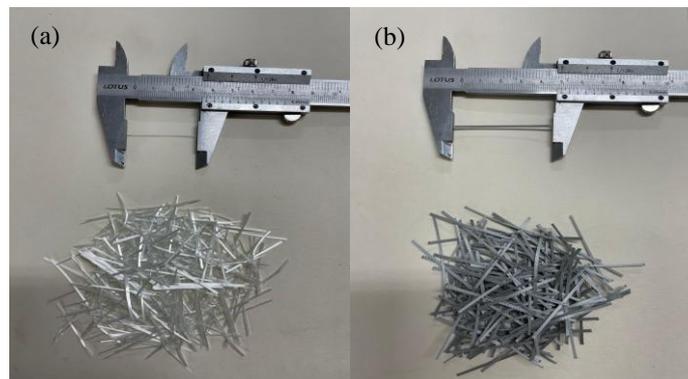
\*\*b.c.w – by cement weight.

## 2.2. Materials

The properties of the materials used to produce the CRF, as provided by the manufacturers, are summarized in Table 3 and illustrated in Figure 3. It is important to highlight that the glass fiber utilized in this study was of the Alkali-Resistant (AR) type.

**Table 3.** Physical and mechanical properties of the fibers used.

Fiber type	Density (kg/m <sup>3</sup> )	Length (mm)	Young Modulus (GPa)	Tensile Strength (MPa)
Glass fiber AR (GF)	2,680	36	72	1,700
Polypropylene fiber (PP)	910	50 ± 2	5.68	399 – 459

**Figure 3.** a) Glass fiber AR (GF) b) Polypropylene fiber (PP).

## 2.3. Tests Conducted

The tests shown in Table 4 were carried out to determine the mechanical behavior of the mixtures.

**Table 4.** Tests Conducted.

Tests	Standard	Total number of samples
Compression Test of cylindrical specimens	ASTM C39	36
Determination of Flexural Tensile Strengths (Limit of Proportionality and Residual Strengths)	EN 14651	24

Compression tests on cylindrical specimens were conducted in accordance with ASTM C39 [10]. The specimens measured 100 mm in diameter and 200 mm in height, and testing was performed using an Emic DL60.000 machine equipped with a 600 kN load cell. The evaluation of Flexural Tensile Strengths, including the Limit of Proportionality (LOP) and Residual Strengths, was performed in compliance with EN 14651 [11]. Tests were conducted on prismatic specimens measuring 150 mm x 150 mm x 550 mm. This standard evaluates the LOP and Residual Strengths ( $fr_1$ ,  $fr_2$ ,  $fr_3$ , and  $fr_4$ ). During testing, the applied load (N) was recorded as a function of the displacement at the notch, referred to as CMOD (Crack Mouth Opening Displacement). An extensometer positioned at the notch base measured displacements corresponding to  $fr_1$  (CMOD = 0.5 mm),  $fr_2$  (CMOD = 1.5 mm),  $fr_3$  (CMOD = 2.5 mm), and  $fr_4$  (CMOD = 3.5 mm). A universal testing machine with a 150 kN load cell and extensometer was used for these measurements.

Beyond the LOP, the test measured whether or not the concrete remained intact after developing cracks. According to the Brazilian standard ABNT NBR 16942:2021 requires concrete reinforced with fibers to present a Flexural Tensile performance of LOP of at least  $4.3 \text{ MPa} \pm 0.30 \text{ MPa}$  and residual CMOD Strengths of  $fr_1 = 1.5 \text{ MPa}$  and  $fr_4 = 1.0 \text{ MPa}$  regardless the fiber content used [17].

Microstructural analysis performed to study interaction between fibers and concrete matrix with respect to adhesion and response after cracking i.e., fiber rupture or fiber slippage. The scanning electron microscopy (SEM) analysis were conducted with a Tescan VEGA 3 LMU microscope at Chemistry Institute of Federal University of Uberlandia. This study focused on the adherence of the fibers to the matrix as well as the existence of a gap or cracks, where the fibers were considered to be adherent, but not well mechanically anchored, with regard to their effectiveness in mitigating crack propagation. SEM images were captured from 28-day-old concrete samples

### III. RESULTS AND DISCUSSION

Table 5 show the results of compression test of six concrete mixes. The analysis comparing the average Strengths showed a significant difference in range among the mixture providing evidence of the direct correlation between the incorporation of fibre and performance of concrete. The REF mix without any fibers showed the maximum Compressive Strength, which has an average value of 36.46 MPa. Conversely, the Compressive Strength of mixture M50-50 was the lowest with its average value of 27.66 MPa.

**Table 5.** Results of the Compressive Strength test.

Mixture	Sample	Maximum load (kgf)	Maximum load (N)	Compressive Strength (MPa)	Average Compressive Strength (MPa)	Standard deviation ( $\sigma$ )
REF	1	23,770	233,104	28,53*	36.46	2.00
	2	29,480	289,100	37.56		
	3	27,150	266,251	34.59		
	4	29,070	285,079	35.58		
	5	30,950	303,516	39.43		
	6	27,600	270,664	35.16		
M100-0	1	26,530	260,170	33.80	33.86	0.69
	2	26,120	256,150	33.28		
	3	26,670	261,543	33.30		
	4	26,640	261,249	33.94		
	5	27,450	269,193	34.97		
	6	24,360	238,890	31,03*		
M75-25	1	26,950	264,289	34.33	34.61	1.35

	2	28,670	281,157	35.80		
	3	28,620	280,666	35.74		
	4	26,720	262,034	34.04		
	5	28,390	278,411	35.45		
	6	25,870	253,698	32.30		
<b>M50-50</b>	1	22,860	224,180	28.54	27.66	1.10
	2	21,480	210,647	26.29		
	3	22,780	223,395	29.02		
	4	21,600	211,824	27.52		
	5	21,220	208,097	26.50		
	6	22,490	220,552	28.08		
<b>M25-75</b>	1	25,920	254,188	32.36	33.42	0.65
	2	26,200	256,934	33.38		
	3	26,970	264,485	33.68		
	4	23,440	229,868	29.27*		
	5	26,850	263,309	33.53		
	6	26,800	262,818	34.14		
<b>M0-100</b>	1	23,250	228,005	28.46	29.56	1.81
	2	25,800	253,012	31.89		
	3	24,880	243,989	31.70		
	4	23,450	229,966	29.28		
	5	23,220	227,710	28.42		
	6	22,110	216,825	27.61		

(\*) Samples discarded by Chauvenet criterium.

The results indicate that, in general, the incorporation of fibers reduces the Compressive Strength compared to the reference concrete (REF). This reduction aligns with findings from various studies involving different types of fibers [4][12][13][14][15][16]. Figure 4 illustrates the results obtained from the compression tests on the samples.

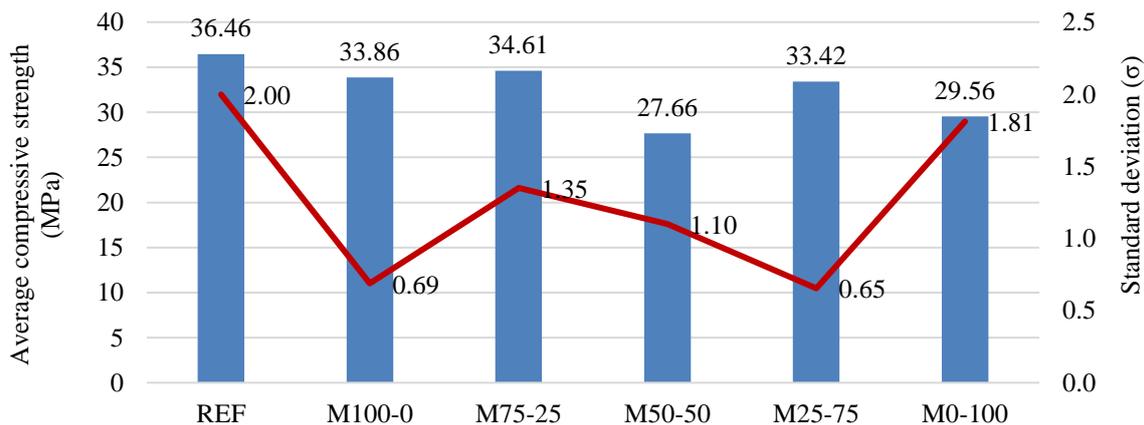


Figure 4. Graphical representation of the results of the Resistance to Compressive Test.

It is noteworthy that the standard deviations ( $\sigma$ ) were lower in the mixtures containing polypropylene (PP) fibers (M25-75 and M0-100), indicating greater uniformity in the results. This suggests more efficient dispersion of these fibers within the concrete matrix.

The flexural tensile tests provided essential information regarding the Limit of Proportionality (LOP) and the CMOD Residual Strengths ( $fr_1$ ,  $fr_2$ ,  $fr_3$ , and  $fr_4$ ). Figure 5 offers a detailed analysis of the

material's resistance capacity as a function of crack opening. It illustrates how the concrete withstands tensile stresses after the formation of micro-cracks and highlights the influence of each fiber type on the performance of the cementitious composite, both up to the first rupture (LOP) and in terms of Residual Strength (CMOD).

Figure 5. Stress vs. CMOD Curves

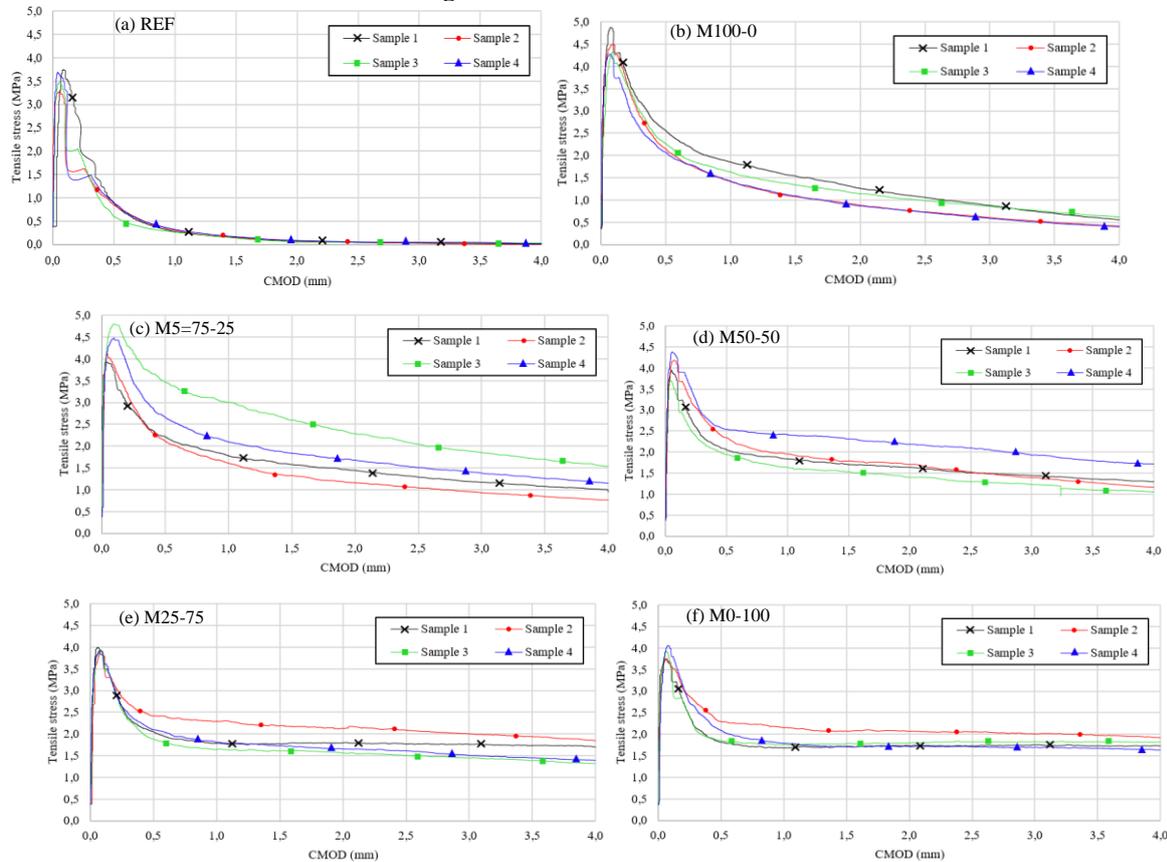


Table 6 shows the average LOP and Residual Resistance values for each type of sample.

Table 6. Results of the Flexural Tensile test.

Mixture	Sample	LOP - fL (MPa)	fr <sub>1</sub> (MPa)	fr <sub>2</sub> (MPa)	fr <sub>3</sub> (MPa)	fr <sub>4</sub> (MPa)
REF	1	3.76	0.90	0.15	0.00	0.00
	2	3.27	0.85	0.15	0.00	0.00
	3	3.47	0.60	0.13	0.00	0.00
	4	3.69	0.89	0.17	0.00	0.00
	<b>Average</b>	<b>3.55</b>	<b>0.81</b>	<b>0.15</b>	<b>0.00</b>	<b>0.00</b>
	<b>σ</b>	<b>0.22</b>	<b>0.14</b>	<b>0.01</b>	<b>0.00</b>	<b>0.00</b>
M100-0	1	4.87	2.56	1.54	1.06	0.70
	2	4.49	2.16	1.07	0.73	0.49
	3	4.32	2.27	1.34	0.98	0.73
	4	4.27	2.07	1.09	0.72	0.48
	<b>Average</b>	<b>4.49</b>	<b>2.26</b>	<b>1.26</b>	<b>0.87</b>	<b>0.60</b>
	<b>σ</b>	<b>0.27</b>	<b>0.22</b>	<b>0.22</b>	<b>0.17</b>	<b>0.13</b>
M75-25	1	3.93	2.22	1.58	1.29	1.07
	2	4.13	2.12	1.33	1.04	0.84
	3	4.80	3.48	2.60	2.04	1.70

	4	4.48	2.67	1.83	1.51	1.26
	<b>Average</b>	<b>4.33</b>	<b>2.62</b>	<b>1.83</b>	<b>1.47</b>	<b>1.22</b>
	<b><math>\sigma</math></b>	<b>0.38</b>	<b>0.62</b>	<b>0.55</b>	<b>0.43</b>	<b>0.36</b>
<b>M50-50</b>	1	3.95	2.06	1.70	1.51	1.36
	2	4.19	2.35	1.79	1.53	1.28
	3	3.70	1.94	1.53	1.29	1.10
	4	4.38	2.54	2.31	2.10	1.79
	<b>Average</b>	<b>4.05</b>	<b>2.22</b>	<b>1.83</b>	<b>1.61</b>	<b>1.38</b>
	<b><math>\sigma</math></b>	<b>0.29</b>	<b>0.27</b>	<b>0.34</b>	<b>0.34</b>	<b>0.29</b>
<b>M25-75</b>	1	4.00	2.05	1.77	1.77	1.74
	2	3.92	2.42	2.19	2.09	1.94
	3	3.94	1.88	1.61	1.50	1.39
	4	3.92	2.10	1.72	1.61	1.45
	<b>Average</b>	<b>3.95</b>	<b>2.11</b>	<b>1.82</b>	<b>1.74</b>	<b>1.63</b>
	<b><math>\sigma</math></b>	<b>0.04</b>	<b>0.22</b>	<b>0.26</b>	<b>0.25</b>	<b>0.26</b>
<b>M0-100</b>	1	3.74	1.82	1.72	1.73	1.74
	2	3.76	2.29	2.08	2.05	1.98
	3	3.94	1.85	1.79	1.82	1.83
	4	4.06	2.09	1.71	1.71	1.68
	<b>Average</b>	<b>3.87</b>	<b>2.01</b>	<b>1.82</b>	<b>1.83</b>	<b>1.80</b>
	<b><math>\sigma</math></b>	<b>0.15</b>	<b>0.22</b>	<b>0.17</b>	<b>0.16</b>	<b>0.13</b>

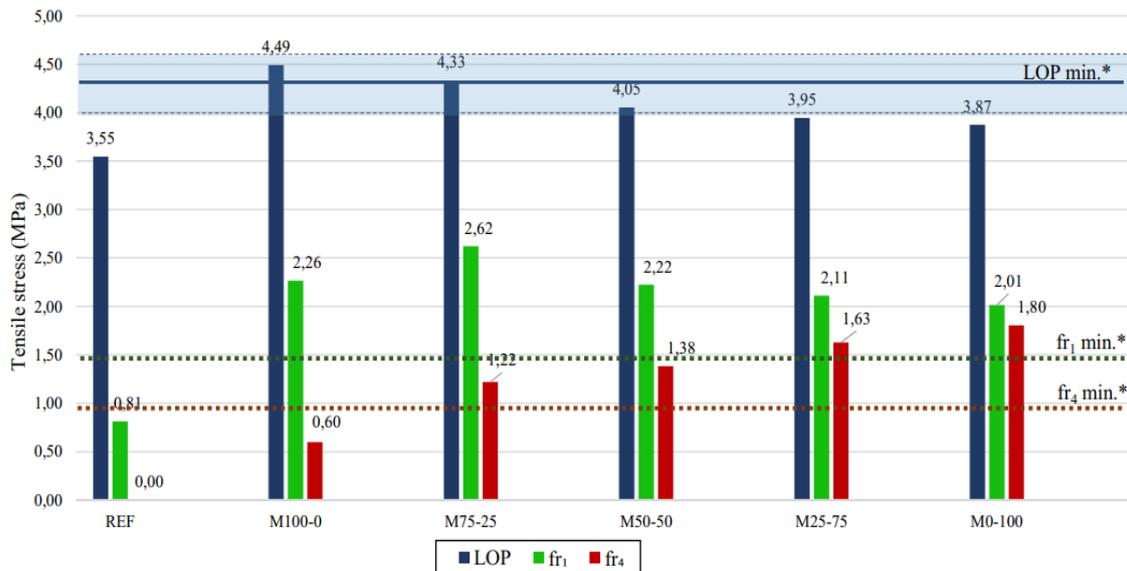
The results showed how the performances of the concrete mixtures in terms of LOP and Residual Strengths ( $fr_1$ ,  $fr_2$ ,  $fr_3$ ,  $fr_4$ ) varied significantly as the proportions of fibers varied. For instance, Mixture M100-0 showed an increment of over 25% in LOP more than the reference concrete (REF), with a value of 4.49 MPa compared to 3.55 MPa, respectively. This shows that the glass fibers (GF) works well in strengthening ordinary concrete by delaying the initiation of crack formation. This improvement is attributed to the higher modulus of elasticity (E) of GF compared to concrete, which contributes to a greater load-bearing capacity before the appearance of the first cracks. However, M100-0 showed moderate values of strength in CMOD Residual Strengths after cracking, at  $fr_1$  of 2.26 MPa and  $fr_4$  of 0.60 MPa. The  $fr_4$  value is lower than the 1.0 MPa recommended by the Brazilian standard [17], indicating that, while GF is effective in increasing the composite's strength (LOP), its contribution to post-cracking performance is limited.

The hybrid GF/PP composites M75-25 and M50-50 showed a more balanced performance between LOP and CMOD Residual Strengths. Mixture M75-25 stood out with an LOP value 4% lower than the 100% GF mixture (M100-0), but 22% higher than the conventional concrete (REF). Also, its CMOD Residual Strengths presented  $fr_1$  equal to 2.62 MPa (+ 16%) and  $fr_4$  equal to 1.22 MPa (+ 51%), as specified on the Brazilian standard [17]. This indicates that the combination of fibers contributes to a better redistribution of stresses leading to an improvement of both the load at first crack formation (LOP) and post-cracking behavior. This hybridization exploits the Initial Strength of GF with the Ductility and Energy Absorption capacitance of the PP.

As expected, the LOP of M50-50 was at 4.05 MPa, 7% lower than M75-25 but 14% higher than the LOP of conventional concrete (REF). The CMOD Residual Strengths for M50-50 were  $fr_1$  at 2.22 MPa (-15%) and  $fr_4$  at 1.38 MPa (+13%) which shows that an enhanced tougher mix of fibers results in a combined improvement in pre-cracking and post-cracking behavior, while still complying with the Brazilian standard [17].

The mixtures M25-75 and M0-100, which contain higher proportions of polypropylene (PP), exhibited lower LOP values compared to the mixture with 100% glass fibers (M100-0). Mixture M25-75 showed

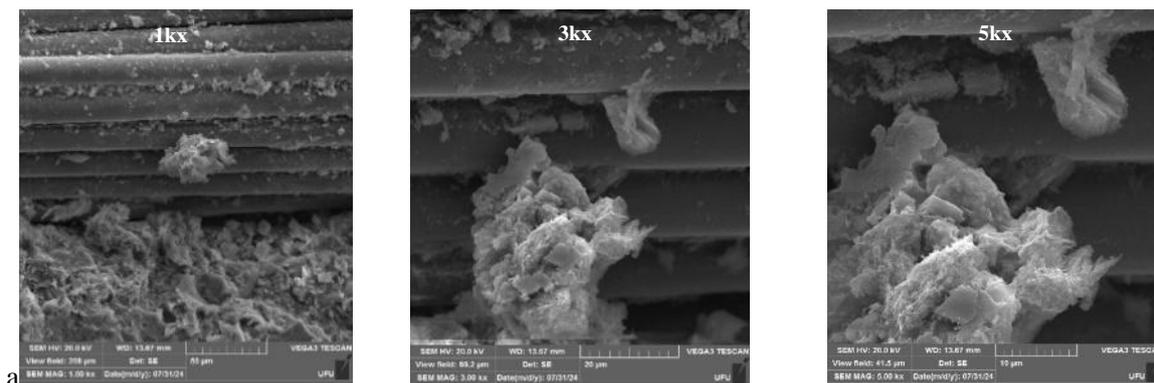
an LOP of 3.95 MPa (-13% compared to M100-0), while mixture M0-100 had an LOP of 3.87 MPa (-16% compared to M100-0). However, both mixtures demonstrated an increase in LOP compared to conventional concrete (REF), with improvements of +11% and +9%, respectively, although still below the minimum requirement of the Brazilian Standard [17]. This indicates that the contribution of PP in controlling initial cracking (LOP) is significantly lower than that of GF, despite the higher Residual Strength values ( $fr_1$ ,  $fr_4$ ) compared to the GF mixtures (e.g., M50-50). Specifically, for M25-75, the Residual Strengths were  $fr_1 = 1.82$  MPa (-18% compared to M50-50) and  $fr_4 = 1.63$  MPa (+18% compared to M50-50), while for M0-100,  $fr_1 = 1.82$  MPa (-18% compared to M50-50) and  $fr_4 = 1.80$  MPa (+30% compared to M50-50). Figure 6 illustrates the LOP and CMOD values for  $fr_1$  and  $fr_4$ .

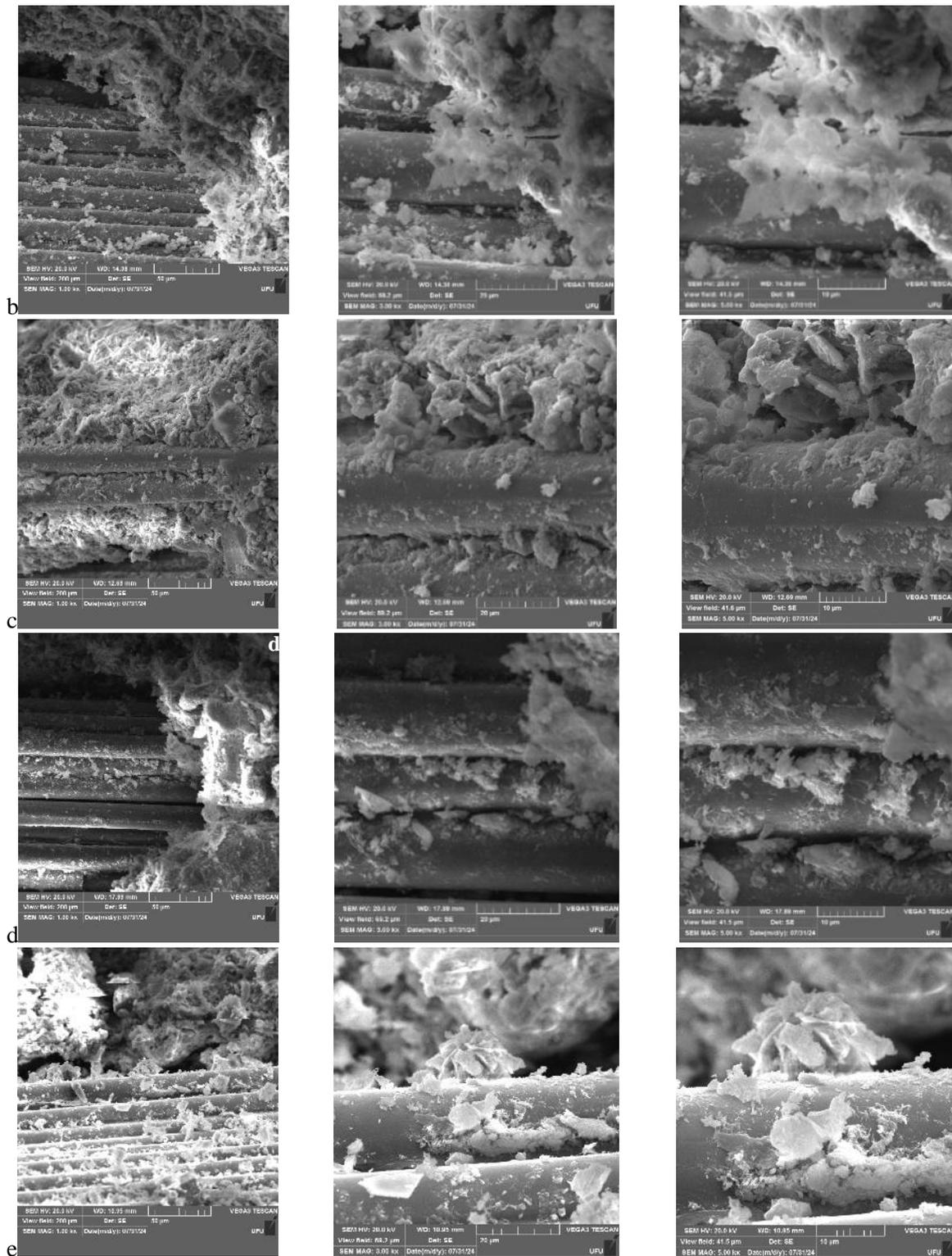


\* minimum values required by the ABNT NBR 16942 standard [17].

Figure 6. Graphical representation of the Flexural Tensile test results.

The investigation of the matrix-fiber interface of the developed composites by Scanning Electron Microscopy (SEM). The focus was put on investigating the fiber-matrix interaction and adhesion and correlating the fiber rupture with the mechanical response of the composite itself. The matrix-GF interface comprises of Figures 7 (a, b, c, d, e).

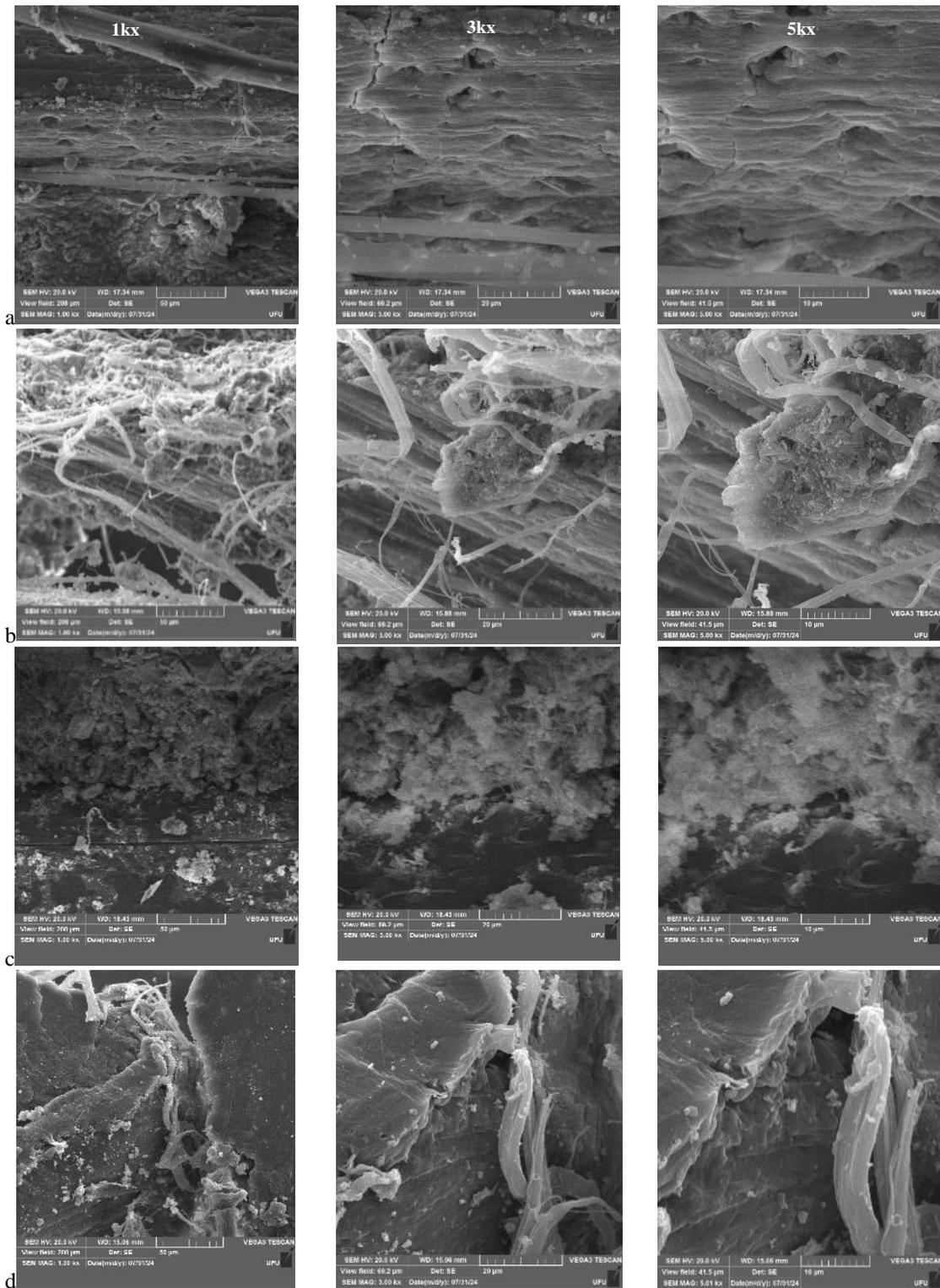


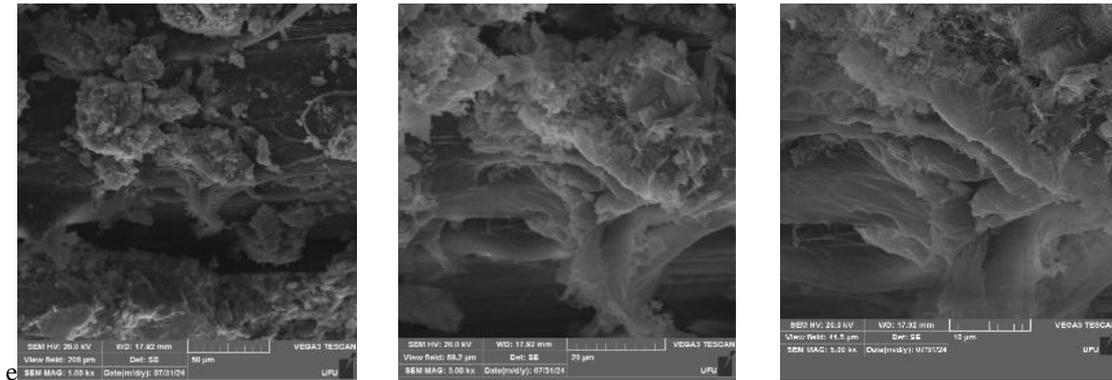


**Figure 7** – Microstructure of the matrix-GF interface from SEM (1kx, 3kx, 5kx).

These images also indicate good adhesion between glass fibers and cement matrix. This findings is consistent with existing literature, which indicates that glass fibers typically exhibit favorable bonding characteristics within cementitious composites due to their surface properties and resistance to alkali environments. Moreover, the images do not indicate any visible signs of deterioration/degradation of the fibres; a finding consistent with current studies [7][18] showing the durability of alkali-resistant (AR) glass fibres in concrete environments.

The matrix-PP interface is shown in figures 8 (a, b, c, d, e).





**Figura 8** – Microstructure of the matrix-PP interface from SEM (1kx, 3kx, 5kx).

Due to their high hydrophobic characteristic, the polypropylene fibers have a weak bond to the cement matrix. SEM images display a tendency of slippage in the fibers, as well as the presence of gaps at the fiber-matrix interface, a phenomenon supported by contemporary literature [19]. This behavior is due to the low surface energy of polypropylene, which hinders effective bonding with the cement matrix.

#### IV. CONCLUSION

The conclusions on the fiber reinforced concrete from the stress vs/CMOD graphs clearly show the positive effects of fibers on the LOP and post cracking behavior of the concrete. The addition of fibers improves the load bearing capacity of the composite in tension, helping to enhance the Residual Strength of composite, thereby delaying crack propagation. Thus, when the fibers are distributed uniformly within the matrix, the energy dissipation increases, and in mixtures, the combination of GF and PP fibers exhibits significantly greater LOP and Residual Strength than any other combination considered.

LOP of the M100-0 mixture was notably the highest, which supports the effect of GF in delaying crack initiation stage, however, the performance of post-cracking behavior was unable to compete with the mixtures with fibrous systems. The M0-100 mixture showed good Residual Strength, but had a lower LOP indicating the significant role of PP in post-cracking resistance. In contrast, the hybrid mixtures of GF and PP, particularly M75-25, showed the best overall performance, balancing a high LOP with excellent residual load-bearing capacity. This indicates that hybrid fiber reinforcement can provide the concrete with important properties suitable for specific applications.

It is recommended to study the effect of varying lengths and amounts of fiber in future works. Also, testing the behavior of fiber-reinforced concrete in more extreme loads due to cyclic loading or impact would give insights into the durability of fiber-reinforced concrete in real applications. Additionally, comparative studies between different types of fibers and cement consumption could help optimize mix proportions, balancing mechanical performance with economic viability.

#### ACKNOWLEDGEMENTS

The authors would like to thank FAPEMIG for providing the scholarship and Vergraf Brasil, CSN Cimentos Brasil S.A., Owens Corning and Concrefiber for donating the materials used in this research.

#### REFERENCES

- [1]. Mehta, P. K.; Monteiro, P. J. M. (2014) *Concreto: Microestrutura, Propriedade e Materiais*. 3ª ed. São Paulo: Ibracon.
- [2]. Bentur, A., & Mindess, S. (2007) *Fibre reinforced cementitious composites*. 2ª ed. London: CRC Press.
- [3]. Almeida, G. et al. (2019) *Macrofibers in Concrete: A Study on Durability and Toughness*, Journal of Materials in Civil Engineering.

- [4]. Peruzzi, A. de P. (2007) Estudo das alternativas de uso da fibra de vidro sem características álcali resistente em elementos construtivos de cimento Portland. Tese de Doutorado. Sao Carlos.
- [5]. Jiang, Z; Banthia, N. (2010) Size effects in flexural toughness of fiber reinforced concrete. ASTM: Journal of testing and evaluation. vol.38, No.3. pp1-7.
- [6]. Pils, S. E, Oliveira, P., Regoso, F. Paulon, V. A, Costella, M. F. (2019) Pervious concrete: study of dosage and polypropylene fibers addiction. IBRACON Estrut. Mater. DOI:<https://doi.org/10.1590/S1983-41952019000100009>.
- [7]. TEZUKA, I. (1989) Concreto armado com fibras. Sao Paulo: ABCP.
- [8]. LUCENA, C.T. (2017) Concreto reforçado com fibras de polipropileno: estudo de caso para aplicacao em painel de parede fina. Dissertacao Mestrado. Sao Carlos.
- [9]. American Society for Testing and Materials – ASTM C143/C143M. Standard Test Method for Slump of Hydraulic-Cement Concrete, 2020.
- [10]. American Society for Testing and Materials – ASTM C39/C39M. Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, 2021.
- [11]. European Committee for Standardization – EN 14651. Test Method for Metallic Fiber Concrete – Measuring the Flexural Tensile Strength (Limit of Proportionality, Residual), 2007.
- [12]. Storch, I. S. (2023) Estudo sobre a tensao de aderencia e das propriedades mecânicas em concretos autoadensaveis com baixo consumo de cimento reforçados com fibras de aço. Tese de Doutorado. São Carlos.
- [13]. Carneiro, R. C. (2018) Analise das propriedades do concreto autoadensavel com fibras de aço no estado plástico e endurecido com silica ativa e com filer calcario – Dissertacao Mestrado. Pato Branco.
- [14]. Gil, A. M. (2018) Contribuicao ao estudo de dosagem de concretos autoadensaveis reforçados com fibras metalicas. São Leopoldo.
- [15]. Medeiros, A. (2012) Estudo do comportamento a fadiga em compressao do concreto com fibras. Tese de Doutorado. Rio de Janeiro.
- [16]. Velasco, R. V. (2008) Concretos autoadensaveis reforçados com elevadas fracoes volumetricas de fibras de aço: propriedades reologicas, fisicas, mecanicas e termicas. Tese Doutorado. Rio de Janeiro.
- [17]. Associacao Brasileira De Normas Tecnicas - ABNT NBR 16942 Fibras polimericas para concreto – Requisitos e metodos de ensaio, 2021.
- [18]. Pardela, R., Aguila, M. (1992) Alkali-Resistant Glass Fibres in Cementitious Composites. Construction and Building Materials, Elsevier.
- [19]. Ekane, P. (1999) Polypropylene Fibres in Cement-Based Composites. Journal of Materials in Civil Engineering, American Society of Civil Engineers (ASCE).

## Authors

**Arthur Francisco Claro Ribeiro**, graduated in Civil Engineering from the Federal University of Uberlandia (UFU) in 2022 and has been working in the field ever since. He is currently studying for a master's degree in the Civil Engineering Department at the same university. His research interests include alternative and sustainable materials for construction, as well as the study of the non-metallic bars (GFRP), and hybridization of glass and polymer fibers to concrete.



**Antonio de Paulo Peruzzi**, Civil Engineer from University Federal of Sao Carlos (UFScar) in 1997, Master in Architecture and Urbanism from the University of Sao Paulo (USP) and Ph.D in Architecture, Urbanism and Technology from the University of Sao Paulo (USP). P.D., in Science and Material Engineering (USP) in light concrete. Works as a professor and researcher at the Faculty of Civil Engineering of the University Federal of Uberlandia (UFU) in fiber-reinforced concrete, non-metallic bars (GFRP) and magnesium oxide-based composites.



**Rodrigo Gustavo Delalibera**, He holds a bachelor's degree in Civil Engineering from the Sao Jose do Rio Preto School of Engineering (1999), a master's degree in Civil Engineering (Structural Engineering) from the University of Sao Paulo (2002), a Ph.D in Civil Engineering (Structural Engineering) from the University of Sao Paulo (2006) and a P.D. in Civil Engineering (Structural Engineering) from the University of Sao Paulo (2009). He is currently Associate Professor IV at the Federal University of Uberlandia . He has experience in Civil Engineering, with an emphasis on Concrete Structures, working mainly on the following subjects: pile caps, reinforced and prestressed concrete, foundations, numerical and experimental analysis



**Carlos Marmorato Gomes**, Civil Engineer from the University of Sao Paulo (USP) in 1995, Bachelor in Business Administration from the Association of Escolas Reunidas in 1993, Master in Architecture and Urbanism from the University of Sao Paulo (USP), Ph.D. in Science and Material Engineering from the Institute of Physics of Sao Carlos (USP). P.D. -I in Construction Materials - FZEA/USP and the P.D. -II in LSF building system - IAU/USP. Works as professor and researcher at the School of Civil Engineering, Architecture and Urbanism at UNICAMP in fiber-reinforced and magnesium oxide-based composites composites. Member of scientific and regulatory committees, also participates as a consultant and service provider to various companies through university extension activities.

