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ANALYSIS OF THE MECHANICAL PROPERTIES OF ADVANCED CEMENTITIOUS COMPOSITES OF REACTIVE POWDER CONCRETES WITH HYBRIDIZATION OF METAL AND POLYPROPYLENE MICROFIBERS

ANÁLISE DAS PROPRIEDADES MECÂNICAS DE COMPÓSITOS AVANÇADOS À BASE DE PÓS-REATIVOS COM HIBRIDIZAÇÃO DE MICROFIBRAS METÁLICAS E DE POLIPROPILENO

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ABSTRACT

The pursuit of higher quality materials is necessary to ensure the construction durability and performance, increasing comfort and living conditions for users. The advanced cementitious composite of reactive powder concrete (RPC) is a result of this effort, by which the coarse aggregate is replaced with a compacted fine aggregate and integrated with structural microfibers, reducing voids, providing mechanical packing and increasing compressive strength, tensile strength and ductility, in comparison to the conventional concretes. This paper analyzed the physical and mechanical properties of hybrid composites with metal and polypropylene microfibers, with content values of 100%, 75% and 50% of metal fibers and 0%, 25% and 50% of polypropylene fibers, besides the reference composition, with no fibers. The mixtures behavior was evaluated concerning specific gravity, total absorption, void ratio, compressive strength and tensile flexure, and surface abrasion wear, with the aid of scanning electron microscopy (SEM). The results showed improved mechanical properties by the combination of fibers. When evaluating the different percentages of microfibers, it was found that RPC 100/0 showed better properties for the mechanical characterization tests. Regarding material performance in the physical tests, RPC 75/25 displayed reduction of voids and increase of specific gravity, and lesser damages in the surface abrasion test because of its homogeneity and surface density.

Keywords: microfiber, reactive powder concrete, durability.

RESUMO

A busca por materiais de maior qualidade é necessária para garantir a durabilidade e desempenho das construções, aumentado o conforto e condições de moradia para os usuários. Portanto, materiais inovadores com potencial para este fim estão sendo pesquisados. O compósito cimentíceo avançado a base de Concreto de Pós-Reativos (CPR) é resultado deste esforço, onde agregados graúdos são substituídos por agregados miúdos empacotados e com a incorporação de microfibras metálicas, reduzindo vazios, promovendo refinamento dos poros e aumentando a resistência à compressão, tração e ductilidade, quando comparado com os concretos convencionais. Este artigo analisou as propriedades físicas e mecânicas de compostos híbridos com microfibras metálicas e de polipropileno, com os valores de 100%, 75% e 50% de fibras metálicas e 0%, 25% e 50% de fibras de polipropileno, além da mistura referência, sem fibras. O comportamento das misturas foi avaliado em função da massa específica, absorção total e volume de vazios, resistência à compressão e tração na flexão e resistência à abrasão, além da análise da microscopia eletrônica de varredura (MEV). Os resultados mostraram que as propriedades mecânicas aumentaram com a hibridização das fibras. Quando comparados os diferentes percentuais de microfibras, concluiu-se que o CPR 100/0 apresentou os melhores resultados nos ensaios mecânicos. Com relação ao desempenho das misturas nos ensaios físicos, o CPR 75/25 apresentou uma redução de vazios e aumento da massa específica, e menos defeitos após o ensaio de abrasão, devido à homogeneidade e densidade superficial.

Palavras-chave: microfibras, compósitos cimentíceos avançados, durabilidade.

1 – INTRODUCTION

The growing need to design durable and slender structures challenges concrete technology to seek more efficient and optimized solutions. Concrete, despite its structural flexibility, does not perform satisfactorily in certain applications. This fact motivates the study of special compositions, enabling optimized and innovative structures with no prejudice to safety and reliability (TUTIKIAN; ISAIA; HELENE, 2011). An example of such composites is the advanced cementitious composite of reactive powder concrete (RPC). It is a material designed to be used in high performance structures, being composed of particles having a maximum dimension of less than 2 mm (VANDERLEI; GIONGO, 2006).

Removing coarse aggregates from concrete, increasing the density and applying pressure in the fresh state, combined with heat curing, yield a matrix with very high levels of compressive strength. However, ductility is comparable to conventional mortar, requiring the incorporation of fibers to increase tensile strength and durability (RICHARD; CHEYREZY, 1995). The incorporation of fibers creates a tension transmission current around them, thus redistributing them. According to El Deebs and Naaman (1995), the insertion of fibers also has the advantage of not requiring concrete reinforcement, reducing the possibility of corrosion and increasing productivity in execution of structure. Additional advantages are lower permeability, increased density compared to conventional concrete and elimination of voids, features that expand the possibilities of application. Nevertheless, the lack of knowledge about the material, its durable characteristics and optimal fiber content, as well as the absence of technical standards, restrict its use.

Using metal microfibers is crucial to ensure ductility, tensile strength in flexure and other properties obtained from conventional concrete reinforcement. However, their use should be as minimal as possible, because they are costly and difficult to get in most consumer centers. On the other hand, polypropylene microfibers are cost-effective and abundant; and as they act in the pre-cracking stage of the matrix, at certain content levels, they can partially replace metal microfibers and improve tension distribution within the matrix. Therefore, this study aims to contribute with knowledge about the durable capacity of RPC by performing physical and mechanical tests with analysis of the composite at different content percentages of metal and polypropylene microfibers, evaluating the hybridity of fibers.

2 – REACTIVE POWDER CONCRETE (RPC) TECHNOLOGY

The weakness of the construction industry lies, among other things, in the misuse of materials (BASHEER; KROOP; CLELAND, 2001; CALAVERA, 2001). In the case of concrete, this fact is due to input availability, the apparent ease of executing the structures and lack of knowledge about the product features. It is also considered the use of cement with high initial resistance and high water-cement ratio, with no concern for the durability of structures (ISAIA, 2011; MEHTA, 1999). The study of adequate employment and durability of materials promote the proper use of resources and the development of high-strength concrete (HSC), high-performance concrete (HPC) and ultra-high-performance concrete (UHPC). HPC has, in addition to high mechanical strength, workability and ease of spreading, long-term mechanical properties, high strengths in low ages, toughness and long life cycle in various environments (HOLLAND, 1993).

According to Zdeb (2013), RPC is a class of concrete, considered to be a development of HPC in the evolution of the material. It has a high percentage of silica fume in its composition and reduced water-binder ratio, around 0.20. Czarnecki, Kurdowski and Mindess (2008) affirmed the material is characterized as an evolvement of concrete, with improvements in its microstructure, such as minimized porosity, matrix modification and increased homogeneity due to the exclusive use of fine aggregates. Other properties that make the RPC attractive for several uses are mechanical strength close to 200 MPa, tensile strength in flexure of up to 140 MPa and rupture energy of 40 kJ/m^2 (DUCTAL, 2013).

Vanderlei and Giongo (2006) explained the main principles to obtain the material are the following: eliminating coarse aggregates to get increased homogeneity; heat curing for improvements in the microstructure; using steel fibers to enhance ductility; and improving the material density by particle size distribution and particle packing.

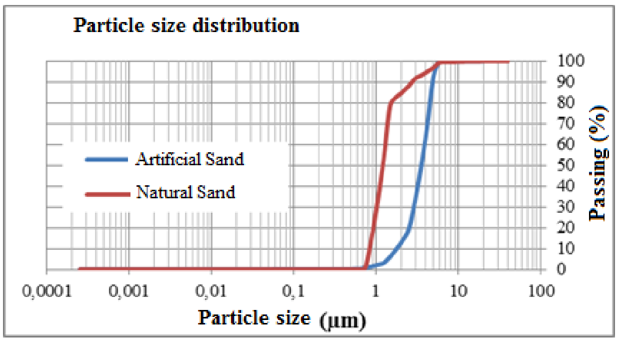
When microfibers are not added, the material shows only high compressive strength values, with no tension distribution along the parts. Incorporating fibers reduces material brittleness as their internal distribution in the concrete acts in opposition to the extension of cracks (CHRIST; TUTIKIAN, 2013). Since the behavior of the fibers incorporated into the concrete depends on the material composition, shape and interaction with the paste, using hybrid fibers becomes interesting and beneficial. Polypropylene microfibers tend to act in the pre-cracking stage of the matrix, avoiding the development of cracks, while metal microfibers act in the crack propagation stage, preventing them from increasing in size and eventually rupturing the concrete. Therefore, RPC is expected to have high durability due to low water-cement ratio, high resistance to external agents and low permeability (VANDERLEI, 2004).

In this paper, four types of hybrid fiber RPC were dosed using 100% of metal microfibers, 75% of metal microfibers and 25% of polypropylene microfibers, 50% of each, and zero fibers, used as reference. For the comparative study, the following tests were performed for the four types of RPC: specific gravity, total absorption and void ratio, tensile strength in flexure, compressive strength and surface abrasion wear, with the aid of scanning electron microscope (SEM) analysis.

3 – MATERIALS AND METHODS

In order to improve particle size packing, two types of sand were used. The sands were produced with mechanical casting process (artificial sand) and fine quartz sand (natural sand), with particle size distribution as shown in Figure 1.

Figure 1 – Size distribution of sands



High early strength cement was used, on which a laser particle size distribution test was performed (ISO 13320, 2009). The test showed an average particle diameter of 16.59 nm, with average particle size of 5 µm, as shown in Figure 2. Similarly, the quartz powder sample was tested, in Figure 3, obtaining an average length of 32.7 nm and a diameter of 21.44 nm.

Figure 2 – Particle size distribution of cement

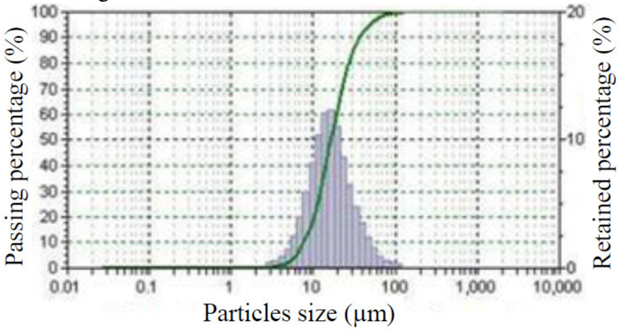
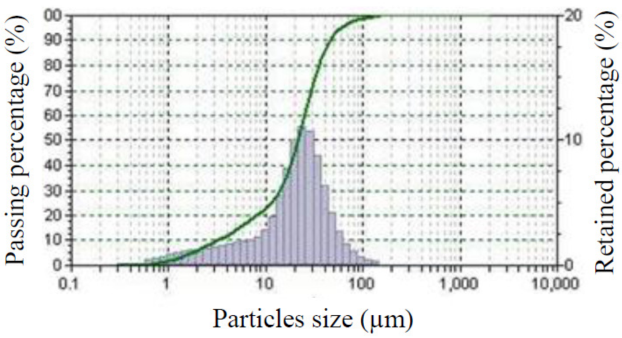


Figure 3 – Particle size distribution of quartz powder



The analysis with silica fume yielded an average length of 375 nm, with an average diameter of 246 nm. The result of the laser particle size distribution test is shown in Figure 4. The fly ash used to partially replace the cement in the RPC mix had particle size distribution as shown in Figure 5.

Figure 4 – Particle size distribution of silica fume

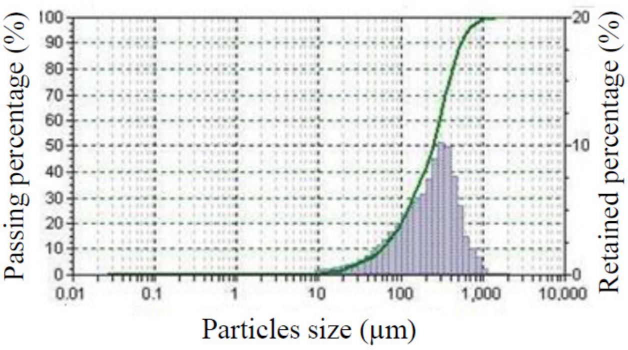
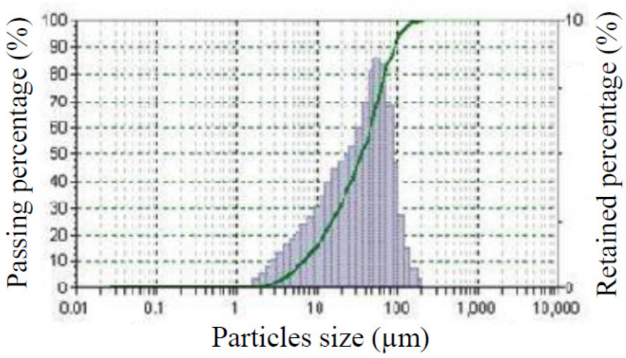


Figure 5 – Particle size distribution of fly ash



Superplasticizer and viscosity modifier admixtures were used, which properties are shown in Table 1.

Table 1 – Property of chemical additives

Characteristics	Superplasticizer	Modifier Viscosity
Physical state	Liquid	Liquid
Color and odor	turbid yellow / characteristic odor	Transparent/ characteristic odor
Density g/cm^3	1,10 +/– 0,02g/cm3	1 +/– 0,02g/cm^3
pH (pure product)	5,5 +/– 1,0	9,0 à 10,5

The metal microfibers have 13 mm in length and 0.11 mm in diameter. These values for the polypropylene fibers are 6 mm and 0.012 mm, respectively. About the unit mix, the water-binder ratio was 0.22. The mixture was made in a vertical axis mixer for RPC. Pressure was applied on the samples, then, them were cured for 24 hours at 90 °C, which were kept in a temperature-controlled chamber at 23 +/– 2 °C and saturated humidity condition. Molds allowing the application of pressure on the specimens were used, in two types: 5x10 cm cylindrical molds and prismatic 16x4x4 cm molds, standardized, as shown in Table 2.

Table 2 – Mechanical and physical analysis

Mechanical Analysis	Normalization
Compressive strength	ASTM C39
Tensile strength	ASTM C1609
Physical Analysis	Normalization
Total water absorption, density and void ratio	ASTM C642
Surface wear	CIENTEC Method

The mixture composition was defined in a study by Christ (2014), replacing cement with fly ash at 30% to reduce cement consumption. Based on this mix, various percentages of metal and polypropylene microfibers were used, as shown in Table 3.

Table 3 – Concrete's composition and fibers use percentage

Cement	Natural sand	Sand GRC	Silica fume	Quartz powder	Fly ash
1	1.97	2.32	0.85	1.16	0.43
Fiber type		RPC 1 100/0	RPC 2 75/25	RPC 3 50/50	RPC 4 0/0
Steel		100	75	50	0
Polypropylene		0	25	50	0

4 – RESULTS AND ANALYSIS

The results and analysis are described in the following sections.

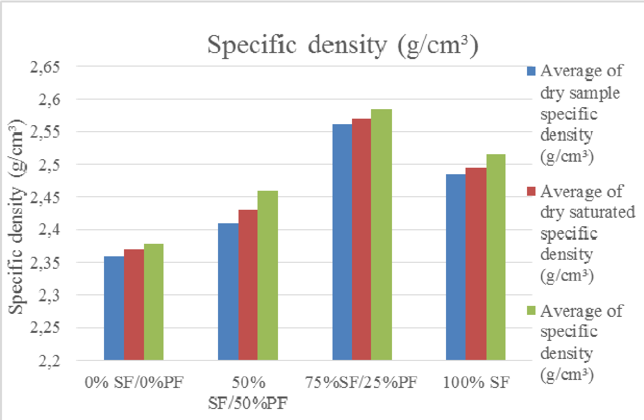
4.1 Specific gravity

Table 4 and Figure 6 show the results for specific density (sd).

Table 4 – Results for specific density

Sample	Sd. of dry sample (g/cm³)	Sd. of saturated sample (g/cm³)	Real specific density (g/cm³)
100% SF	2.49	2.5	2.52
	2.48	2.49	2.51
75% SF 25% PF	2.56	2.57	2.59
	2.56	2.57	2.58
50% SF 50% PF	2.41	2.43	2.46
	2.41	2.43	2.46
0% SF 0% PF	2.38	2.39	2.40
	2.34	2.35	2.36

Figure 6 – Specific density of the samples



Results show that the specific density for dry and saturated samples was virtually the same because of the reduced number of pores. The highest values for dry, saturated and real specific density were obtained by using 75% and 25% of metal and polypropylene microfibers respectively. Thus, it has been observed that for the materials used in this research there is no direct relation between the use of fibers and specific density variation.

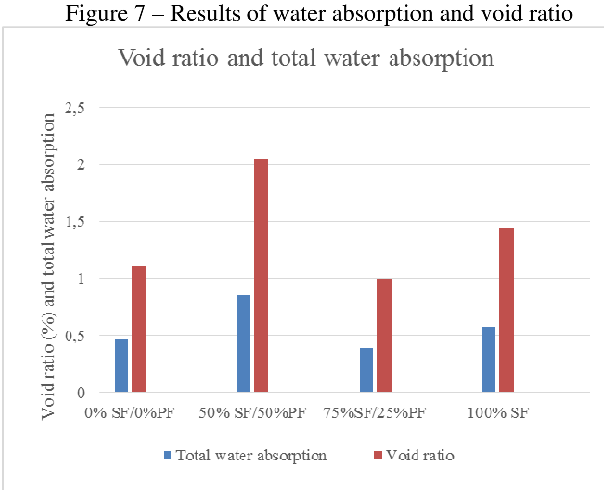
4.2 Total absorption and void ratio

Table 5 and Figure 7 show the results obtained for total absorption and void ratio in the different compositions.

Table 5 – Total water absorption and void ratio

Sample	Total water absorption (%)	Average of total water absorption (%)	Void ratio (%)	Average void ratio (%)
100% SF	0.61	0.58	1.51	1.44
	0.55		1.37	
75% SF 25% PF	0.39	0.39	1.01	1.00
	0.39		1.00	
50% SF 50% PF	0.85	0.85	2.05	2.05
	0.85		2.05	
0% SF 0% PF	0.46	0.47	1.08	1.11
	0.49		1.14	

Figure 7 – Results of water absorption and void ratio



The results obtained for average total absorption prove that the material is compact, with reduced void volume and insignificant water absorption. The lowest value was obtained in RPC mix 75/25, in agreement with the results from the specific density test. These values suggest that hybridity is viable, producing satisfactory results even in comparison with concrete without microfibers.

Regarding the void ratio, it is observed that the results are in agreement with those for specific density. The mix that showed the lowest void ratio was RPC 75/25. There are indications that the global behavior of fibers occurs satisfactorily, where material voids are reduced, most notably when compared with the mix without fibers.

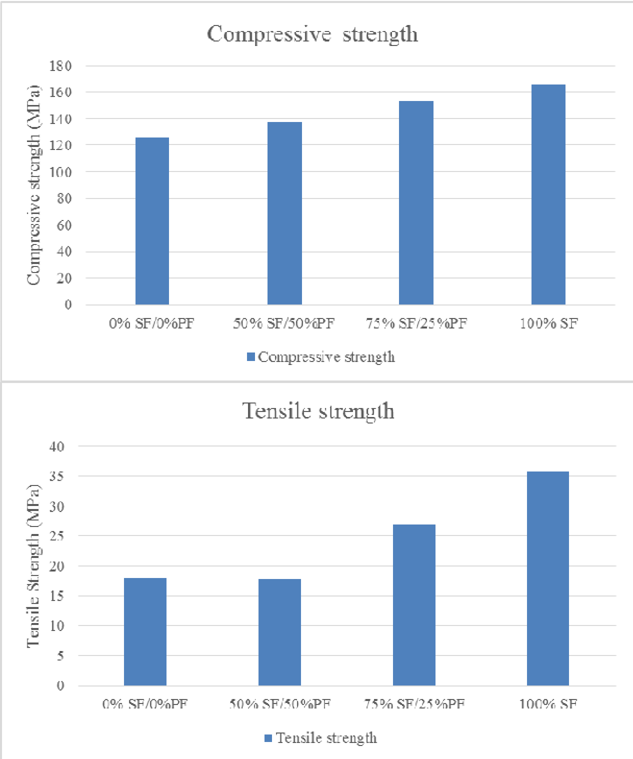
4.3 Compressive and tensile strength in flexure

Table 6 shows the results for compressive and tensile strength. Figure 8 shows the results in a graph.

Table 6 – Compressive and tensile strength results (Age of 28 days)

Sample	Compressive Strength			Tensile strength		
	Load (kN)	Tension (MPa)	Potenc. value (MPa)	Load (kN)	Tens. (MPa)	Potenc. value (MPa)
100% SF	269.9	132.1	165.5	12.7	23.8	35.8
	338.2	165.5		14.1	26.4	
	331.3	162.2		19.1	35.8	
75% SF 25% PF	285.5	139.7	153.0	6.6	12.4	27.0
	312.6	153.0		14.4	27.0	
	292.9	143.4		11.5	21.6	
50% SF 50% PF	246.9	120.9	136.9	7.6	14.3	17.8
	279.7	136.9		9.4	17.6	
	265.7	130.1		9.5	17.8	
0% SF 0% PF	121.6	59.5	125.6	9.6	18.0	18.0
	256.5	125.6		9.0	16.9	
	189.8	92.9		8.1	15.2	

Figure 8 – a) Compressive strength values, b) Tensile strength values



During the compression strength test, it was observed that the material did not show deformation, with sharp break for all RPC samples. The highest values for mechanical compressive strength were obtained with increased use of metal fibers, where the rate of growth between them was directly proportional. The RPC without fibers has lower values than the RPC with fibers for tensile strength in flexure, requiring the addition of fibers to reach satisfactory results. It is observed that performance improves with the use of steel microfibers, being directly proportional to the increase of mechanical tensile strength in flexure for RPC 100/0 and RPC 75/25. The values obtained for mechanical compressive and tensile strength were similar to those reported in the literature.

Regarding the results for compressive strength, RPC mix 75/25 showed a 7.5% reduction in relation to RPC 100/0. Comparing the same mixes, there is a reduction of 24.6% in the values for tensile strength in flexure. Thus, it was denoted that the main action related to metal microfibers is to improve the tensile strength. Comparing the values obtained for RPC 100/0 and the others, there is a linear decrease in the values for compressive strength. A linear reduction is observed in the values for tensile strength in flexure, except for the mix without fibers, which is not significantly different from RPC 50/50.Thus, even though hybrid fibers have a positive aspect, using them in the proportion of 50:50 for each type of microfiber proved ineffective, being practically the same as the results of the reference mix, without fibers.

4.4 Surface abrasion wear

Prior to the surface abrasion wear test a Scanning Electron Microscopy (SEM) test was carried out to determine the sample surfaces. Figure 9 (a and b) shows the SEM image for the sample without fibers (RPC 0/0).

Figure 9 – SEM Images– Reference sample – 0% SF/0% PP

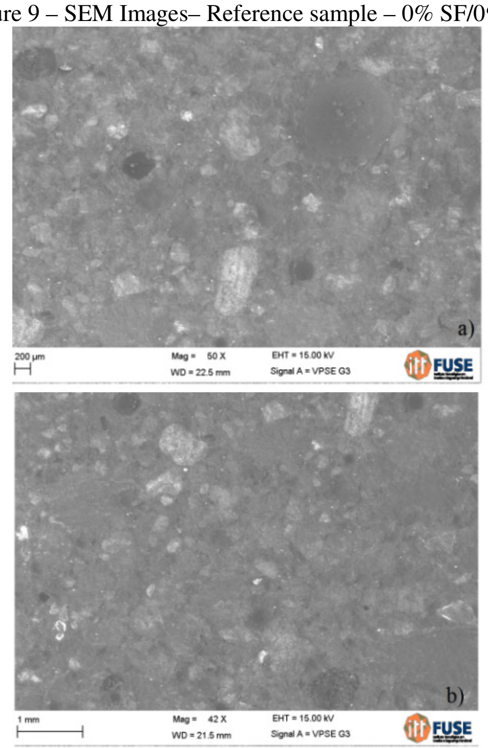


Figure 9 shows little difference in color, which suggests, according to the test method, that there are no relevant differences in surface depth, i.e., there is not much void volume. Such voids were quantified with computer graphics software aid, with average value of 6.7%. Similarly, Figure 10 shows the SEM image for sample RPC 100/0 prior to the surface abrasion wear test.

In Figure 10, the darker color indicates the presence of fibers, unevenly distributed; also, the incorporation of fibers does not create a transition zone between them and the paste, with no voids in their interface. Voids were quantifiers by computer graphics software with average value of 7.2%. Moreover, besides the fibers, there is little difference in hue, i.e., the surface has homogeneous depth. Figure 11a shows sample RPC 75/25 prior to the abrasion test. Figure 11b shows sample RPC 50/50.

Figure 10 – SEM Images – Sample RCP 100% SF

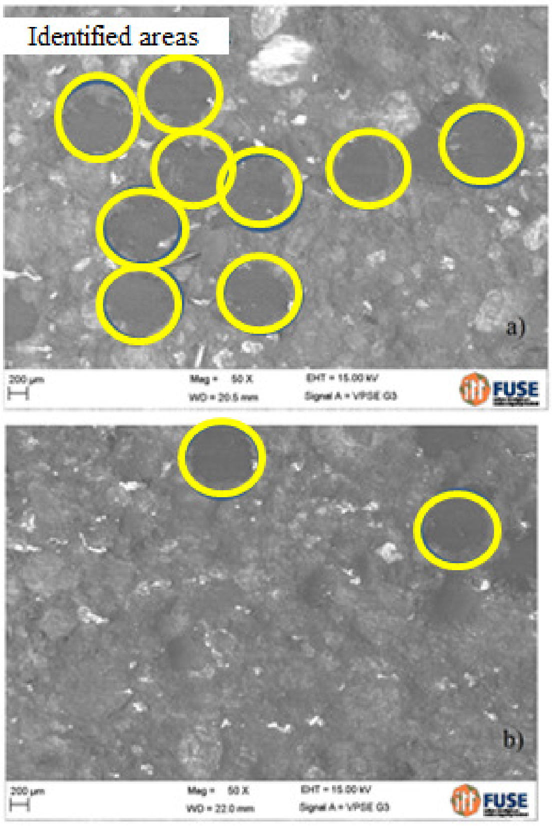
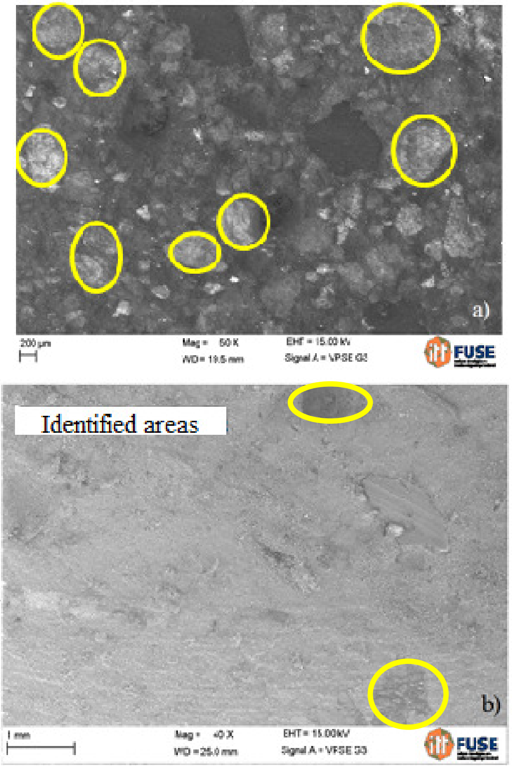


Figure 11 – a) SEM of sample 75% SF/25%PF, b) Sample 50% SF/50% PF



In Figure 11a, metal fibers are indicated by circular lighter colors and voids by darker colors. Besides, the presence of polypropylene fibers can be observed. As mentioned above, voids were quantified, with 6.1% of surface area. In image b, RPC mix 50/50 is clearly homogeneous and the presence of voids is irrelevant in depth, with average value of 6.2%. It was observed that polypropylene microfibers act as coating to the metal fibers, providing greater protection against external agents. After image registration, an abrasion test was performed by passing massive steel balls through the specimens. This test aims to determine whether such abrasion causes damage to the concrete sample. To evaluate the damage, depth values are measured at five different points before and after the test. Results shown in Table 7 represent the variation in height between specimens before and after abrasion wear.

Table 7 – Results of Wear test

Sample	Wear profundity (mm)	
	Individual	Average
0/0 01	6.05	6.52
0/0 02	7.00	
100/0 01	2.28	2.18
100/0 02	2.09	
75/25 01	1.46	1.48
75/25 02	1.50	
50/50 01	2.64	2.60
50/50 02	2.56	

According to the results, the use of fibers, at any proportion, increased the material strength in relation to wear. The most significant damage reduction occurred with RPC 75/25, which displayed a depth value 77% lower in relation to the matrix without fibers (RPC 0/0). This matrix had the highest wear, showing aggression by abrasion on fine particles. It should be emphasized that the result of such analysis shows RPC mix 75/25 as the most favorable, in accordance with the values obtained in the void ratio, specific density, and water absorption tests. Figure 12 shows RPC 0/0 samples after the test.

In Figure 12a it is possible to see that there was damage, indicating that the passing of balls caused surface wear on the concrete. In 12b, wear can be observed in the area showing the path taken by the ball. Figure 13 shows samples of RPC 100/0 and RPC 75/25.

Figure 12 – SEM Results – Sample 0% SF 0% PP

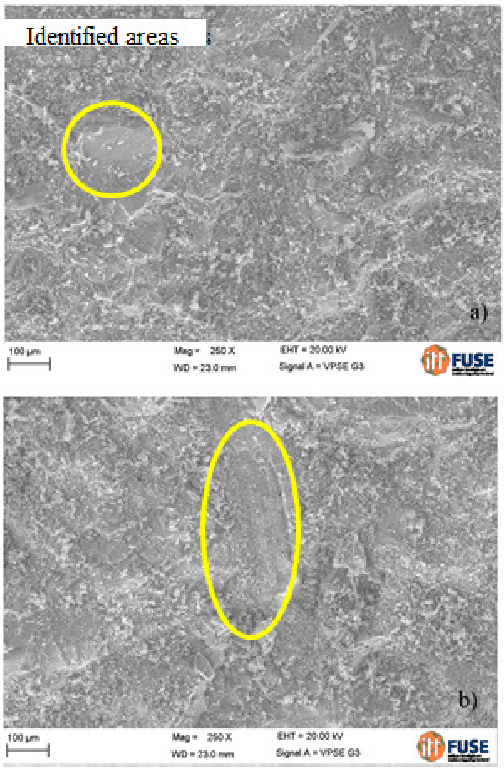
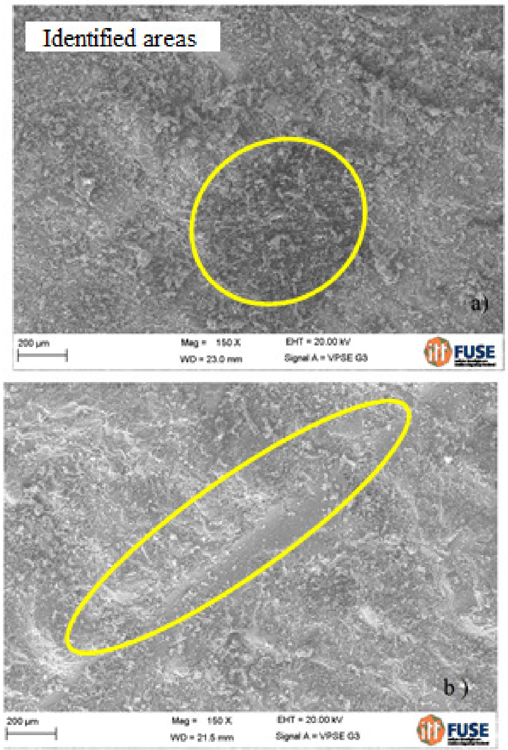
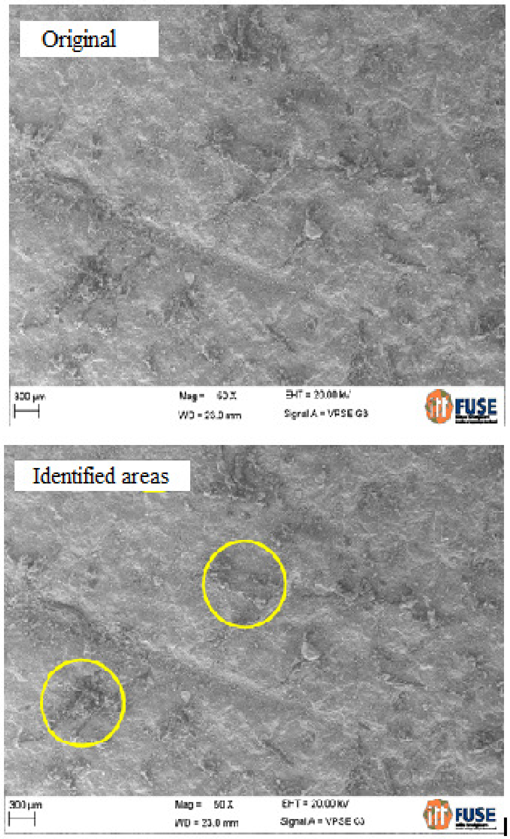


Figure 13 – SEM Results a) RCP Sample 100% SF, b) RCP 75% SF /25% PF



In Figure 13a the image does not show uniform surface damage, only in the identified area, with a spherical and shallow failure. In Figure 13b, a path of surface wear can be observed, however, it is not deep as the image does not show significant color variation. Figure 14 shows the image for sample RPC 50/50.

Figure 14 – SEM Results Sample 50%SF /50% PF



In Figure 14 the affected areas can be viewed according to the round markings, indicating no damage in depth. Similarly to Figure 13, in Figure 14 the wear damage caused by the ball can be seen but with no significant depth.

CONCLUSIONS

After this study it was possible to conclude that the mix with 100% of metal fibers showed the best results for tensile and compressive strength. When analyzing the values of the compression test, there is a linearity between the use of fibers and the values for all unit mixes. Also, the values did not decrease significantly by replacing metal microfibers with polypropylene microfibers (7.5% reduction for RPC 75/25 and 17.3% for RPC 50/50, both in relation to RPC 100/0). These values were more significant for tensile strength in flexure, with reductions of 24.6% and 50.3%, respectively. Therefore, these tests showed that the use of metal microfibers has a positive impact when evaluating tensile strength in flexure.

Additionally, the high values obtained for the mixes where microfibers were used at any proportion showed that their use did not harm the samples by the fiber-paste interface. The scanning electron microscopy test did not indicate any void in this area.

In the absorption, specific density, void ratio, and surface abrasion wear tests, the mix with the highest performance was RPC 75/25, having satisfactory performance in the mechanical tests with no significant losses in relation to the use of 100% of metal fibers. These results are in agreement with the void percentage obtained by computer graphics software in the images of the scanning electron microscope analysis.

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