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Estudio de presión y temperatura de curado en hormigones polvo reactivo (HPR) con cantidades diferentes de microfibras metálicas

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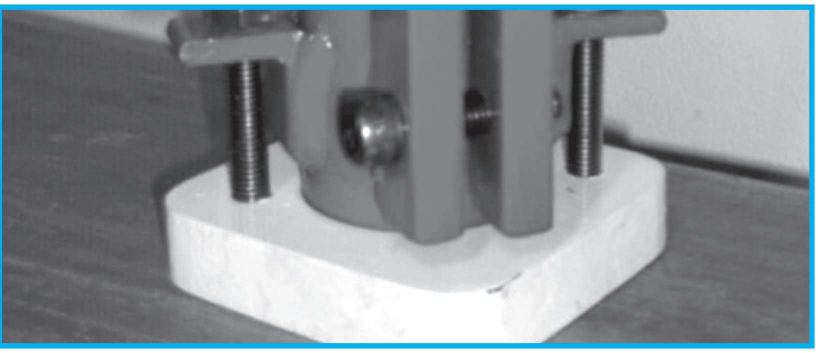

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Abstract

Reactive powder concrete (RPC) is one of the greatest breakthroughs in concrete technology, as it enables the manufacturing of thinner structures without passive reinforcement. That reduces the load in buildings and increases durability, especially in aggressive environments. The use of metallic microfibers is what provides the increase in tensile stress and the resulting elimination of reinforcements. However, it is also the most expensive material as well as the most difficult to obtain, which requires its maximum optimization. Therefore, the aim of this study was to compare the mechanical properties of the RPC with three amounts of metallic fibers, 1%, 3%, and 5% in volume in relation to the material total, after having determined the best curing temperature and effectiveness of the confining pressure in the fresh state. The mechanical properties studied were the axial compressive strength, flexural strength, tensile strength by splitting tensile test, and capillary absorption. The results showed that the fibers have little influence on compressive strength, since there was only a small increase as the amount of fibers was increased. However, for tensile strengths, either flexural or by splitting tensile test, the incorporation of microfibers allowed a significant improvement, obtaining gains of 392% for the flexural strength for the 5%, reaching 59MPa, in comparison with the 0%, which was 12MPa. There was also a decrease in capillary absorption.

Keywords: Reactive Powder Concrete (RPC); Metallic Microfibers; Mechanical properties, Construction Materials.

Resumen

Hormigón en Polvo Reactivo (HPR) es uno de los mayores avances en la tecnología del hormigón, ya que permite la fabricación de estructuras más delgadas sin armadura pasiva. Esto reduce la carga en edificios y aumenta la durabilidad, especialmente en ambientes agresivos. El uso de microfibras metálicas es lo que proporciona el aumento de la tensión de tracción y la eliminación de los refuerzos. Sin embargo, también es el material más caro, así como la más difícil de obtener, lo que requiere su optimización máxima. Por lo tanto, el objetivo de este estudio fue comparar las propiedades mecánicas del HPR con tres cantidades de fibras metálicas, 1%, 3%, y 5% en volumen en relación con el total de materiales, después de haber determinado la mejor temperatura de curado y la eficacia de la presión de confinamiento en estado fresco. Las propiedades mecánicas estudiadas fueron la resistencia axial de compresión, resistencia a la flexión, resistencia a la tracción por la prueba de tracción indirecta y la absorción capilar. Los resultados mostraron que las fibras tienen poca influencia en la resistencia a la compresión, ya que sólo había un pequeño aumento a medida que se aumentó la cantidad de fibras. Sin embargo, para la resistencia a la tracción, sea por la flexión o por la prueba de tracción indirecta, la incorporación de microfibras permitió una mejora significativa, la obtención de las ganancias de 392% para la resistencia a la flexión para el 5%, alcanzando 59MPa, en comparación con el 0%, que era 12MPa. También hubo una disminución en la absorción capilar.

Palabras Clave: *Hormigón en polvo reactivo (HPR); microfibras metálicas; propiedades mecánicas; materiales de construcción.*

1. Introduction

Concrete is the most used material in construction, ranging from the simplest to the most complex buildings. However, demands imposed on such an important option for structures are ever increasing. The notable evolutions of structural calculation, especially with the availability of computer software, as well as a bigger knowledge of the mechanical behaviors of concrete and steel, enable project designers to plan bolder structures in both structural and prestressed concrete (Tutikian et al., 2011). In such applications, conventional concrete either often does not meet the requirements or there are alternatives which present a more auspicious technical and economical ratio. Therefore, special mixtures with superior properties have been developed, such as high resistance concrete and ultra-high resistance concrete, namely reactive powder concrete (RPC). This material enables the manufacturing of elements with high performance and durability, due to its superior mechanical properties.

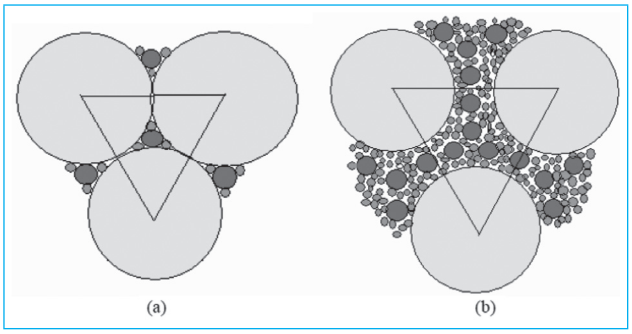
Sadrekarimi (2004) considers RPC an ultra-high performance concrete with high mechanical resistance, ductility and durability, a concrete made up of cement, sand, quartz powder, silica fume, superplasticizer admixture, microfibers and water. The constituents of RPC are basically ultra-fine materials, ranging between 0.5μm and 0.2mm, which provides perfect homogeneity and high density, eliminating internal voids and reducing the cracks created on the interface of the cementitious matrix and aggregates (Vanderlei, 2004). Since its composition does not present coarse aggregates, particle dispersion is hampered, making it extremely important to introduce superplasticizer admixture with great efficiency so as to assist in the mixture.

RPC without the incorporation of fibers is a very fragile material with low tensile strength. The introduction of fibers into the compound brings higher ductility and higher tensile strength to the material, while eliminating the brittleness of the concrete. That renders RPC a ductile material, inside which the dispersion of the fibers prevents the fissures from being prolonged (Banthia; Gupta, 2004).

Fibers can improve the distribution of efforts and the toughness of the concrete, partially replacing the steel used, reducing the prolongation of fissures (Ding et al., 2012).

Lee and Chisholm (2005) state that RPC's performance relies strongly on the optimization of the packing of particles. Perfect packing offers the mixture a higher degree of compactibility and workability as well as more mobility to the elements, allowing them to accommodate better. This phenomenon is shown in Figure 1.

Figure 1. *Optimization of the packing of particles (a) small particles fit into the void left by the larger particles. (b) the larger particles are pushed away by smaller particles*

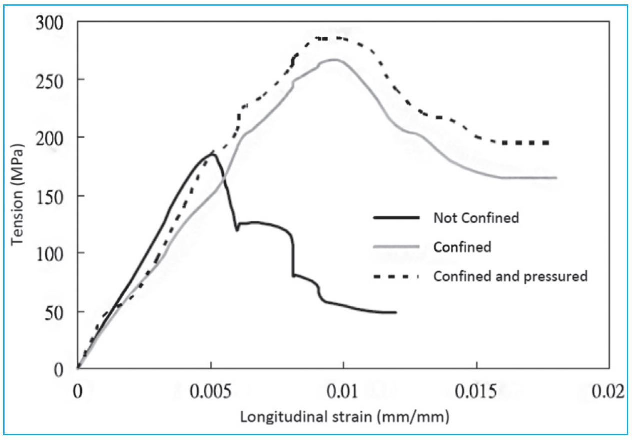


Source: Man, 2009.

RPC's cure requires even more care. It is recommended that thermal cure be used in high temperatures. According to Biz (2001), a thermal treatment during RPC's cure has beneficial effects because it accelerates the pozzolanic reactions. Even more benefits can be achieved if the thermal treatment is accompanied by confining pressure, reducing porosity thus allowing greater mechanical resistance. Submitting RPC to thermal cure with temperatures over 200°C, the quartz powder, which is a element of the mixture, is stimulated and presents pozzolanic properties. However, the only way to perform this thermal cure is by the use of autoclave, once there must be humidity in the environment.

The application of confining pressure still in the fresh state increases the density of the mixture and might eliminate the voids found in the material. Richard and Cheyreazy (1995) state that the compressive strength increases with density, as confining pressure is applied to the concrete still in the fresh state. The application of pressure in the fresh state also reduces considerably the harms caused by the high consumption of cement and the low quantity of water used in the admixture, such as autogenous shrinkage, while it also brings benefits in the elimination of the trapped air which results from the high energy required in the mixing of components (Ipek et al., 2011). Man (2009) compared the increase in compressive strength and longitudinal strain with three types of confinement and pressure. During the first test, the RPC was only thickened (not confined nor pressured); in the second instance, pressure was applied to the RPC, but the RPC was not confined (not confined, but pressured): lastly, in the third sample, pressure was applied to the RPC confined in the tube (confined and pressured). The results show that the sample to which the confining pressure was applied had the highest degrees of tension, followed by the non-confined but pressured RPC, which in turn was followed by the mixture with no confinement nor molding pressure, as shown in Figure 2.

Figure 2. *Compressive strength and longitudinal strain with three types of confinement and pressure*



Source: Man, 2009.

Therefore, the basic principle of RPC is a practically flawless internal micro-structure, with no such flaws as micro-cracks or capillary pores, the consequence of which is a higher level of resistance and durability. According to Mehta and Monteiro (2006), the type, the quantity, the size, the shape, and the distribution of the stages present in a solid constitute its micro-structure. According to Richard and Cheyreazy (1995), the characteristics which differentiate RPC from other concretes are:

- Better homogeneity by the elimination of coarse aggregates, since the maximum size of the aggregate must be smaller than 0.2 mm;
- Increase in the density of the mixture, optimizing granular mixture;
- Improvement of the cementitious matrix with pozzolanic additions, such as silica fume;
- Improvement of the micro-structure with a thermal treatment;
- Increased ductility by the introduction of metallic fibers in the mixture.

Therefore, it is intended to contribute to the study on RPC through the development of a mixture in the laboratory and the analysis of the mechanical properties both with and without confining pressure, with several curing temperatures and the introduction of three amounts of metallic fibers.

2. Aim of the research

This study aims to compare the mechanical properties of the reactive powder concrete (RPC) with three amounts of metallic fibers, 1%, 3%, and 5% in volume in relation to the material total, after having determined the best curing temperature and effectiveness of the confining pressure in the fresh state.

3. Materials and Method

3.1. Materials

For the development of this study, the dosage used was the one developed by Vanderlei (2004), which was approved in preliminary tests with the materials of this study, conducted by Christ (2011). The unit composition is shown in Table 1.

Table 1. *Dosage used*

Material	Unit composition in mass	Consumption (kg/m^3)
Cement	1	874
Sand	1,101	962
Quartz powder	0,235	205
Silica fume	0,246	215
Superplasticizer admixture	0,03	26
Water	0,18	157

The materials used in the research were cement, silica fume, quartz power, fine sand, superplasticizer admixture and drinking water.

The cement adopted was white Portland. It is a cement with high initial resistance, produced with finely ground and extremely pure limestone, and it has a low amount of C_3A. The chemical and physical analysis is shown in Table 2.

Table 2. *chemical and physical analysis of white Portland cement*

Chemical properties		Physical properties		
Elements químicos	**Percentage**	**Properties**	**Results**	**Unit**
SiO_2	26%	1 day	24	MPa
Al_2O_3	2,2%	2 days	42	MPa
Fe_2O_3	0,3%	7 days	61	MPa
CaO	70%	28 days	72	MPa
C_3S	77%	Set time	119	min
C_2S	15%	Expansion	1	mm
C_3A	3%	Fineness (Blaine)	392	m^2/kg
C_4AF	1%	Density	1100	kg/m^3
SO_3	2%			
MgO	0,6%			
Cl-	0,01%			

Table 3. *Silica fume characteristics*

Elements	%
SiO_2	94,3
$Al2O_3$	0,09
$Fe2O_3$	0,1
CaO	0,3
SO_3	-
MgO	0,43
K_2O	0,83
Na_2O	0,27

The silica fume presents density of 700 kg/m^3, and specific surface of approximately 30 m^2/g. Its characteristics are shown in Table 3. The quartz powder used is retained on the sieve number 200 and is made up basically of silicon dioxide (SiO_2). The fine sand used is quartzose with spherical grains and prewashed. The amount of material retained on each sieve was determined based on the packing of aggregates. Its distribution is shown in Table 4.

Table 4. *Granulometric distribution of sand*

Sieve #(mm)	% Retain	% Accumulated
1,2	0	0
0,6	11,8	11,8
0,3	74,2	86,0
0,15	11,5	97,5
Bottom	2,5	100
Fineness Modulus (FM)		1,97
Maximum size ($ø_{máx}$)		0,6

The superplasticizer admixture is a third generation compound developed for high performance concretes and based on a chain of polycarboxylic ether modified and chloride free.

Nowadays, the metallic fibers are not produced in Brazil. Measuring 13mm in length and 0.15mm in thickness, they qualify as microfibers.

Lastly, the water used came from the public water supply and was cooled down do 5°C in order to reduce the heat of hydration generated by the cement.

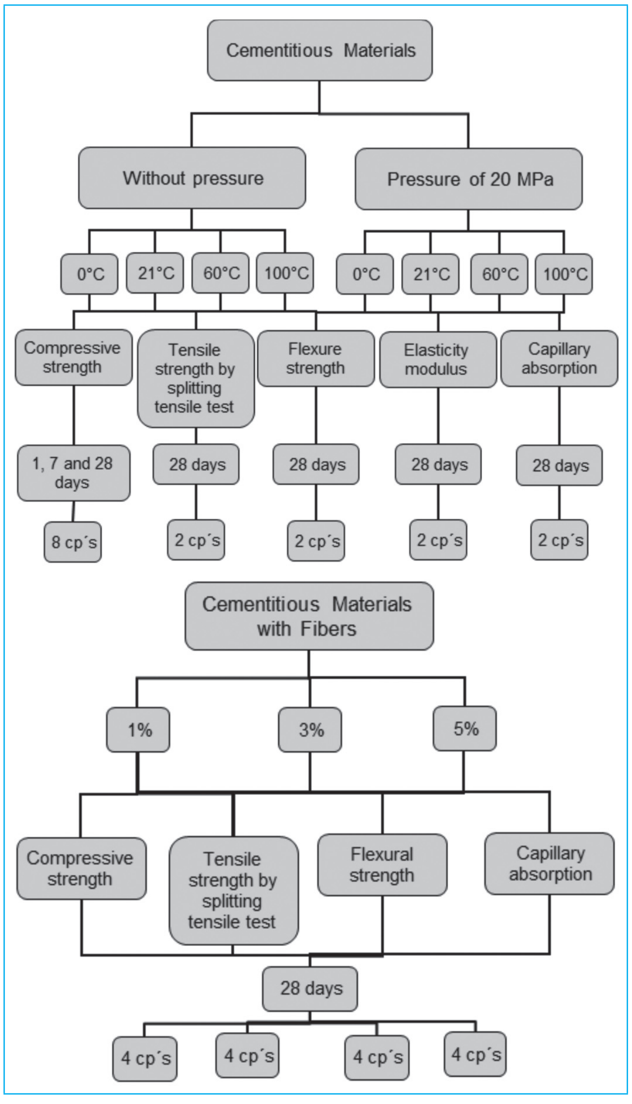
3.2. Method

In order to achieve the desired goal, a two-stage preliminary study was developed so as to obtain the best temperature for thermal cure and the analysis of the confining pressure on the RPC still in the fresh state. The first stage consisted in cure the RPC at 0, 21, 60 and 100°C, with and without the application of confining pressure. In the second stage, having determined the best curing temperature and the pressure density, the amounts of metallic fibers were changed (1, 3, and 5% in volume in relation to the material total). It was used samples (cp) of 5x10cm (high and diameter).

In the first stage, the compressive strength tests were performed at 1, 7, and 28 days, and tensile strength test, both flexural and by splitting tensile test, at 28 days. Based on the results it was determined that the best condition was for the mixtures healed at 100°C with confining pressure of 20 MPa (Christ, 2011).

Therefore metallic microfibers were incorporated into the mixture in such condition at the amounts of 1, 3, and 5%, so as to verify, after 28 days, the compressive strength, tensile strength by splitting tensile test, flexural strength, and capillary absorption. The flowcharts for the first stage and the second stage are shown in Fig. 3.

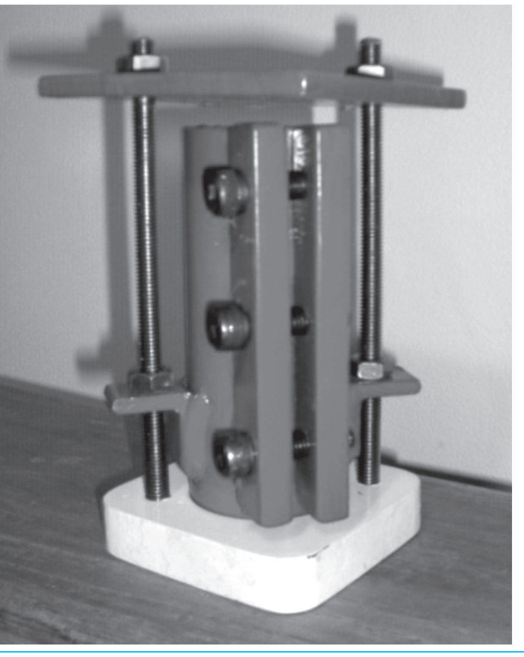
Figure 3. *Flowcharts for the first stage and the second stage*



The method used to obtain the best packing of aggregates was an adaptation of the ABNT NBR NM 45:2006 norm, determining the unit mass and the void volume.

The equipment used for the mixture of the constituents, in both stages, was a 40 liter mortar mixer with a horizontal axis, in order to achieve a homogeneous energetic mixture. The equipment used for the thermal cure was an oven normally used for drying materials. Lastly, for the application of confining pressure in the first state of the RPC and the 48 hours following the molding, the mold used was a special one developed by Christ (2011), shown in Fig. 4. The pressure applied to RPC still in the fresh state was 20 MPa and it was maintained for 48 hours.

Figure 4. *Mold used developed by Christ (2011)*



4. Presentation and analysis of results

After the predicted period, the tests in the hardened state were performed, having the RPC been healed for two days with constant confining pressure of 20 MPa, and afterwards they were accommodated in a moist curing environment until the age of testing.

Table 5 shows the results for the amounts of 0, 1, 3, and 5% in volume of metallic fibers in relation to the material total. The tests were compressive strength, flexural strength, tensile strength by splitting tensile test, and capillary absorption.

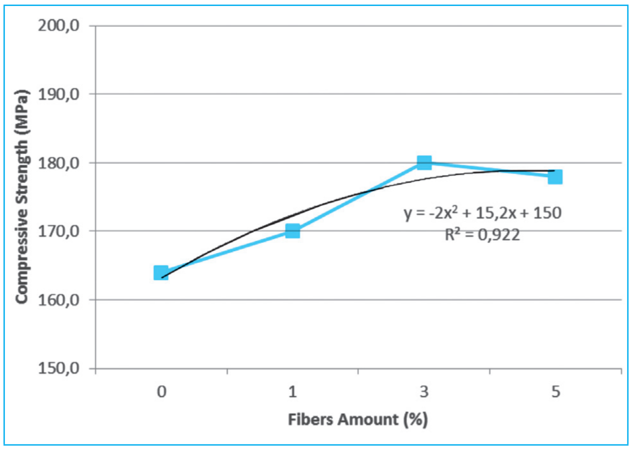
Table 5. *Results for the amounts of metallic fibers in relation to the material total*

Fibers Amount (%)	Compressive Strength (MPa)	Flexural Strength (MPa)	Tensile Strength by Splitting Tensile Test (MPa)	Capillary Absorption (g/cm²)
0	164,0	12,0	14,0	0,087
1	170,0	33,0	22,0	0,061
3	180,0	39,0	33,0	0,071
5	178,0	59,0	39,0	0,036

4.1. Compressive strength

Fig. 5 shows the behavior of the compressive strength in relation to the amount of metallic fibers in the mixture.

Figure 5. *Compressive strength in relation to the amount of metallic fibers*

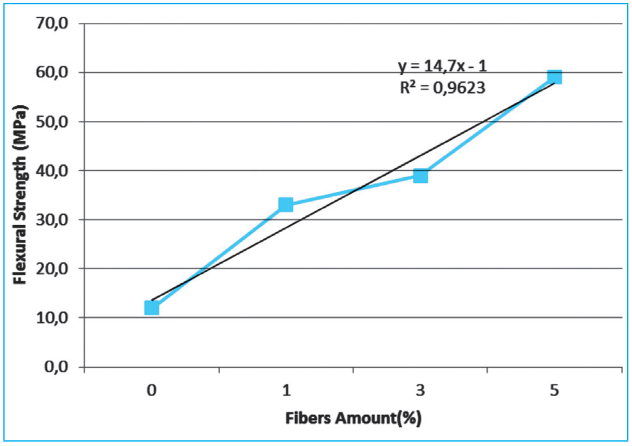


It is observed that the compressive strength presented a small increase with the insertion of metallic fibers, as was expected. The highest compressive strength, of 180 MPa for 3% worth of fibers, was 9.8% higher than the fiber free RPC. Among the RPC with metallic fibers the variation is very small, even becoming stable after 3%. It should be noted that the RPC with 5% worth of metallic fibers did not show decrease in strength, which could have occurred in case of material overdose.

4.2. Flexural strength

Fig. 6 shows the behavior of the flexural strength in relation to the percentage of metallic fibers.

Figure 6. *Flexural strength in relation to the percentage of metallic fibers*



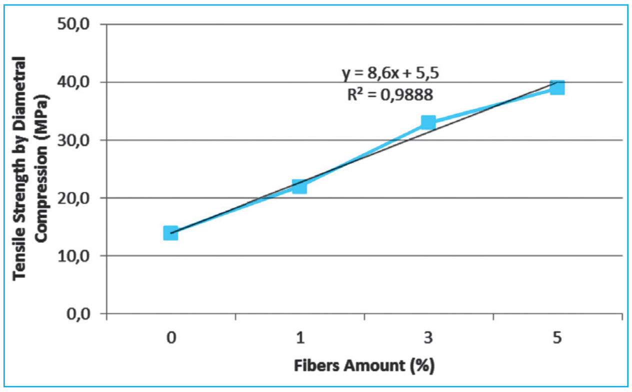
Flexural strength is a property which is highly influenced by the presence of metallic fibers. The results obtained in this study corroborate this trend. The RPC with 1% worth of fibers raised flexural strength in 175%, while the RPC with 3% showed gains of 225% and the one with 5% increased the reference value nearly fivefold, reaching 392%. It can still be observed that the flexural strength gain was next to linear and did not become stable with the higher percentage of fibers, i.e., it is still possible to increase the amount of fibers so as to have gains in this property, if needed.

4.3. Tensile strength by splitting tensile test

Figure 7 shows the ratio of tensile strength by splitting tensile test vs. the amount of metallic fibers in the RPC.

The fast propagation of micro-cracks due to applied strain is responsible for the low tensile strength of concrete. The introduction of metallic fibers will obstruct the propagation of such cracks and in turn increase the tensile strength of the material. The tensile strength by splitting tensile test of RPC without the addition of metallic fibers already presents considerable results, reaching 14 MPa. With the addition of the fibers to the compound, it can be noted that the tensile strength by splitting tensile test of the RPC increased 57% for the RPC with 1% worth of fibers, which confirms that fibers will absorb applied strain and redistribute it homogeneously therefore granting the material more tensile strength. The RPC with 3% and 5% showed gains of 135% and 178% respectively, compared with the fiber free mixture, which shows how much fibers contribute for this type of property. It was also observed that there was constant increase in tensile strength by splitting tensile test as the amount of fiber was increased. The tensile strength by splitting tensile test of the RPC with 5% worth of fiber was 18.2% in relation to that of the RPC with 3%. Therefore, it cannot be said that the amount of 5% worth of fiber is the upper limit, which makes it possible to add more fiber, if needed.

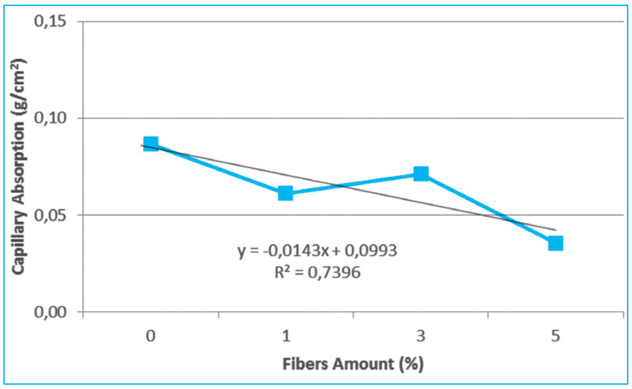
Figure 7. *Ratio of tensile strength by splitting tensile test vs. the amount of metallic fibers*



4.4. Capillary absorption

Fig. 8 shows the capillary absorption of the RPC in relation to the amount of fibers. It was observed that capillary absorption was extremely low, the amount of fibers notwithstanding, which allows the mixtures to be considered impermeable. A great part of the capillary absorption was due to the absorption of water particles on the walls of the samples, since the concretes were dry on the inside. In any event, there was a reduction, an approximately linear one, of the capillary absorption as the amount of fibers was increased.

Figure 8. *Capillary absorption of the RPC in relation to the amount of fibers*



5. Final considerations

After the tests, it can be concluded that the confining pressure and the temperature at 100°C were beneficial for the RPC. Besides, the introduction of metallic microfibers did not interfere in the compressive strength of the mixtures, although it allowed an increase in tensile strength by splitting tensile test and in flexural strength. It still contributed to a decrease in capillary absorption. All results from this study are valid for those quantities of fibers and the other materials. The interval of use of those materials cannot be extrapolated.

Therefore it is possible to verify that the manufacturing of RPC is possible with the use of materials found in southern Brazil, except the metallic microfibers, and that the larger the amount of metallic microfibers, the better the properties of the material.

Even though it is not the focus of this study, the use of RPC could increase, since the rise in its cost can be compensated by the gains in mechanical property and durability in specific situations. Other studies about RPC should focus on production costs.

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